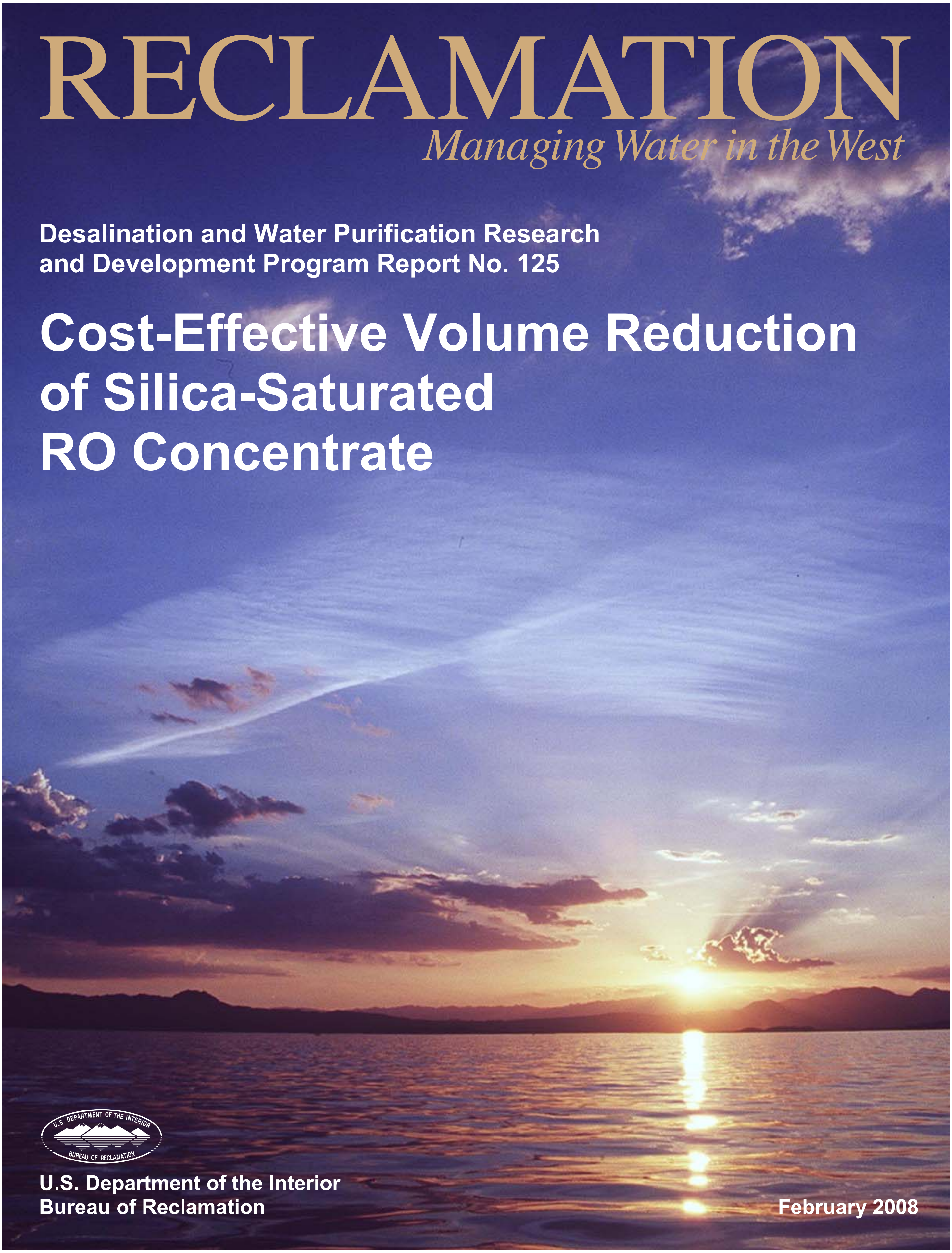

RECLAMATION

Managing Water in the West

Desalination and Water Purification Research
and Development Program Report No. 125

Cost-Effective Volume Reduction of Silica-Saturated RO Concentrate

U.S. Department of the Interior
Bureau of Reclamation

February 2008

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14. ABSTRACT ***(Maximum 200 words)***

This project was undertaken to investigate volume reduction of silica-saturated reverse osmosis concentrate via lime treatment and ion exchange softening and to find possible uses for the sludge solids that are generated during the lime treatment process. Laboratory studies regarding deep-well injection of the concentrate were also conducted. The results from the lime-treatment studies showed that the concentrate volume could be reduced by up to 70% through second-pass RO treatment, thereby raising the overall recovery to 96% without fouling the membranes. When operated above 96% recovery, the principal foulant was found to be calcium fluoride. The ion exchange work showed that if all the hardness is removed from the concentrate, the silica concentration can exceed 1000 mg/L as long as the pH is high (at or near 11.0). Attempts to use the lime sludge solids for arsenic removal or in roadway base materials were largely unsuccessful. The most promising use of the solids was for pretreatment of silica-saturated RO concentrate to reduce the silica concentration, but additional work needs to be done to demonstrate its economic feasibility. Before injecting the concentrate into geo-thermally heated dolomite, the pH will have to be reduced to about 6.0 to avoid precipitation of calcium carbonate.

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lime treatment, silica removal, calcium fluoride fouling, ion exchange, concentrate injection.

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Cost-Effective Volume Reduction Of Silica-Saturated RO Concentrates

Prepared for Reclamation Under Agreement No. 04-FC-81-1051

by

Dr. Anthony J. Tarquin

University of Texas at El Paso

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Water and Environmental Services Division
Water Treatment Engineering Research Team
Denver, Colorado

February 2008

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Disclaimer

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El Paso Water Utilities (EPWU) provided funding, physical facilities, and personnel for a variety of tasks including equipment installation, plumbing and electrical work, equipment maintenance/replacement, and extensive laboratory analytical services. Without the unwavering support of John Belliew and many, many other individuals at all levels in EPWU, we would have had no chance of accomplishing the objectives of this project.

Special thanks also go to GE-Osmonics for providing a reverse osmosis pilot unit, to CDM Inc. for providing the lime treatment pilot plant, to Dr. Vivek Tandon for directing the studies regarding the use of lime sludge solids in mortar and roadway base materials, to Dr. Larry Murr for doing the electron microscope work, and to Dr. Bob Ning of King Lee Technologies for providing antiscalants and conducting a membrane autopsy.

Finally, this project would not have been completed without the steadfast help of the undergraduate and graduate students at UTEP who devoted many of their waking hours to completing this investigation.

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Abbreviations and Acronyms

°C	degrees Celsius
%	percent
As	arsenic
AWWA	American Water Works Association
cm	centimeter
EBCT	empty bed contact time
EBV	empty bed volume
EPWU	El Paso Water Utilities
ft	feet
g	gram
gpd	gallons per day
gpm	gallons per minute
in.	inch or inches
kPa	kilopascal
LSS	lime sludge solids
m	meter
m^3	cubic meter
m^3/s	cubic meters per second
mgd	million gallons per day
mg/L	milligrams per liter
mL	milliliter
mL/min	milliliters per minute
NF	nanofiltration
OMC	optimum moisture content
ppb	parts per billion
ppm	parts per million
psi	pounds per square inch
PVC	polyvinyl chloride
RO	reverse osmosis
TDS	total dissolved solids
TxDOT	Texas Department of Transportation

1. Executive Summary

Increased demands for potable water have resulted in many communities considering desalting as an option for alleviating the water supply problem. For inland communities, disposal of the brine concentrate can represent a major obstacle in implementing a membrane system. The presence of silica in some groundwater exacerbates the brine concentrate problem because it limits the extent to which water can be extracted from the brackish water supply, resulting in the generation of even larger volumes of waste concentrate. This project was undertaken to investigate volume reduction of silica-saturated reverse osmosis concentrate via lime treatment and ion exchange softening, and to find possible uses for the lime sludge solids that are generated during the lime treatment process.

The results of the lime-treatment studies showed that the concentrate volume could be reduced by up to 70 percent (%) through second-pass RO treatment, thereby raising the overall project recovery to 96% without fouling the membranes with silica. When the system was operated at higher recoveries (above 96% overall recovery), the principal foulant, as determined by an autopsy of the membranes, was found to be calcium fluoride.

For injecting the concentrate into geo-thermally heated dolomite, the pH will have to be reduced to about 6.0 in order to avoid precipitation of calcium carbonate.

The ion exchange work showed that essentially all of the hardness can be removed from RO concentrate using a sodium-charged, strong-acid cation exchange resin and that the resin can be successfully regenerated with commercially-available, extra-coarse water-softening salt. The softened concentrate can support a silica concentration of over 1,000 milligrams per liter (mg/L) as long as the pH remains high (at or near 11.0).

Attempts to use the waste lime sludge solids in productive ways were largely unsuccessful. The solids will remove some arsenic from contaminated well water, but the removal rate is relatively low. Substituting sludge solids for some of the sand or cement in mortar weakened the mixture. Similar results were obtained when the solids were added to roadway base materials. The most promising use of the solids was for pretreatment of silica-saturated RO concentrate to reduce the silica concentration prior to lime treatment. This use of sludge solids should be investigated further to obtain additional data under long-term, continuous flow conditions. In any case, the feasibility of this application would certainly be site-specific.

2. Introduction

El Paso Water Utilities (EPWU), in partnership with Fort Bliss (a U.S. Army installation), has constructed the largest inland reverse osmosis (RO) desalting plant in the United States. The plant opened in August 2007, treating 18 million gallons per day (mgd) of brackish groundwater and supplying 27.5 mgd of product water after blending.

A problem faced by EPWU is what to do with the concentrate that is generated in the reverse osmosis process, since the most common disposal option of surface water discharge is not available. Of the other four remaining conventional concentrate disposal options (sewer discharge, subsurface injection, land disposal, and evaporation ponds), subsurface discharge emerged as the most feasible for El Paso [1, 2]. However, research funded by the Bureau of Reclamation and others indicated that it might be economically feasible to recover additional water from the silica-saturated concentrate through lime treatment, thereby possibly rendering evaporation and/or other options more viable [3]. This project investigated the extent to which silica-saturated RO concentrate could be further concentrated following silica removal through lime treatment. Because the lime treatment process generates large amounts of calcium-containing sludge, this project also investigated possible beneficial uses of the waste sludge solids. Finally, some studies were conducted relative to ion exchange removal of hardness from the concentrate to possibly allow for further recovery of water from the concentrate without fouling the membranes with silica.

3. Conclusions and Recommendations

Based on the results of this study, the following conclusions and recommendations can be made:

1. In membrane desalting operations where silica is the parameter that limits water recovery, lime treatment is an effective process for eliminating silica as the recovery-limiting parameter. In this study, it was shown that more than 70% of the water in silica-saturated reverse osmosis concentrate could be recovered, raising the overall system recovery to approximately 96%.
2. Lime treatment of silica-saturated reverse osmosis concentrate, followed by second and third pass RO, appears to be a cost-effective option for concentrate volume reduction. For the conditions prevalent in this study, the lime treatment option is clearly superior to deep-well injection from an economic point of view, probably resulting in net income to EPWU.
3. Following lime treatment of silica-saturated reverse osmosis concentrate, a membrane autopsy revealed that silica was not one of the membrane foulants. The predominant compound found on the membrane surface was calcium fluoride.
4. When sulfuric acid was used to reduce the pH of RO-1 concentrate after lime treatment, calcium sulfate precipitation became a problem when recovery of water from the concentrate exceeded about 50%. The problem was eliminated by switching from sulfuric acid to hydrochloric acid to lower the pH.
5. Laboratory simulations of deep-well injection of the concentrate revealed that a significant amount of calcium carbonate would precipitate rather quickly in the proposed geo-thermally active injection zone unless the pH were lowered to about 6.0 before injection. At the lower pH, it appears that one or more compounds of silica will precipitate at a relatively slow rate. Whether or not this could be a problem is dependent on the size of the fractures in the dolomite formation.
6. Lime sludge solids (generated from a treatment process that precipitates silica from RO concentrate) can be used to remove some silica from the concentrate through pre-treatment that consists of an up-flow column that contains the dried sludge solids. The effectiveness of the sludge solids decreases rather rapidly, but the solids can be reused after some drying. The economic feasibility is dependent on several factors, including the capital and operating costs and savings from reduced lime purchases and sludge disposal. The economics of the process are likely to be case-dependent until more specific information becomes available about operating details and procedures.

7. Lime sludge solids can remove some arsenic (As) from As-contaminated well water that is passed through a column of previously dried sludge solids. However, the amount of arsenic removed per gram of sludge solids appears to be too low to justify the process.

8. A sodium-charged, strong acid cation exchange resin is effective for removing essentially all of the hardness from RO concentrate that has total dissolved solids (TDS) and hardness concentrations of 7,000 mg/L and 1,850 mg/L, respectively. The process is repeatedly reversible using commercially available water-softening salt.

9. Reverse osmosis concentrate that has no hardness can support a silica concentration of at least 1,000 mg/L, as long as the pH is high (at or near 11.0). At a pH of 8.0, the sustainable silica concentration drops to less than 200 mg/L.

10. Attempts to use dried lime sludge solids as a substitute for some of the cement or sand in mortar mixtures were largely unsuccessful. Sludge solids added to roadway base materials also resulted in poor performance during triaxial testing.

11. Additional long-term, continuous flow studies regarding silica removal using dried lime sludge solids should be conducted. The same is true for ion-exchange softening of RO-1 concentrate with possible resin regeneration using the salts from evaporated RO-2 concentrate. Once accurate process data have been obtained, a detailed economic analysis should be conducted.

4. Work Performed and Description of Systems

The primary focus of this project involved lime treatment of silica-saturated RO concentrate for the purpose of maximizing water recovery through additional membrane treatment. Since the lime treatment process generates a large volume of sludge solids, some of the work included investigating possible uses for the sludge byproduct from the treatment process. Additional work was directed toward the alternative of deep-well injection by conducting laboratory studies that investigated what would happen if raw and pH-adjusted RO concentrate were injected into a geo-thermally heated dolomite formation. The results from these investigations are presented in separate sections of this report.

4.1 Lime Treatment Pilot Plant Setup

The lime treatment studies that were conducted in this project were essentially a continuation of a Reclamation-funded project that ended in 2004 [3]. That project showed that a second stage RO system could be used to recover a significant amount of water from the concentrate (thereby further concentrating the concentrate) if the silica concentration were reduced by lime treatment before the second stage RO treatment. In any treatment system that involves membrane concentrate, the amount of water that can be recovered from the concentrate (in the concentrate treatment system) is a function of the recovery in the primary membrane system. That is, for a given final concentrate composition (or single parameter concentration, such as silica), more water can be recovered from a concentrate that is generated in a system operating at 70% recovery than one operating at 80% recovery. Therefore, it makes more sense to discuss performance in terms of overall system recovery, because only 20% recovery of the concentrate from a primary system that is operating at 85% produces essentially the same concentrate volume and chemical composition as 60% recovery of concentrate from a primary system that is operating at 70% recovery (total system recovery is 88% in both cases). Thus, overall system performance will be reported as well as the recovery in the concentrate treatment system itself.

Figure 1 is a schematic of the pilot plant that was set up at the Montana Booster Station field site owned by El Paso Water Utilities. Concentrate from the primary RO unit (identified as RO-1) flowed into a 55-gallon, or 0.21 cubic meter (m^3), feed tank at a rate of about 1 gallon per minute (gallon/min), or 0.0038 cubic meters per minute (m^3/min). Lime was added with a positive displacement chemical feed pump and the mixture flowed into a three-compartment flocculator that had a total volume of 75 gallons (0.284 m^3). After settling, the pH was adjusted to below 4.0, an antiscalant was added (Y-2K Plus from King Lee) at 4 parts per million (ppm), and the water was pumped through three cartridge filters (20, 10, and 5 microns) before it was degassed in an 8-in. (20.3 cm) diameter column that was 4 feet (ft), or 1.22 meters (m) tall. The degassed water flowed into a 500-gallon (1.89 m^3) tank from where it was pumped into the secondary RO unit (i.e., RO-2). Because of equipment limitations, it was necessary to recycle RO-2 concentrate back to the feed tank of the lime unit in order to study high recoveries. As it turned out, it was difficult to operate the system that way because there was a long lag time to reach equilibrium after the recirculation rate was changed. This resulted in continuous changes in the quality of the feed water to the RO-2 unit, which, in turn, changed the permeate and concentrate flows. Therefore, it was nearly impossible to establish tightly-controlled equilibrium conditions. Nevertheless, stable conditions were maintained long enough to collect data that are believed to be reasonably reliable.

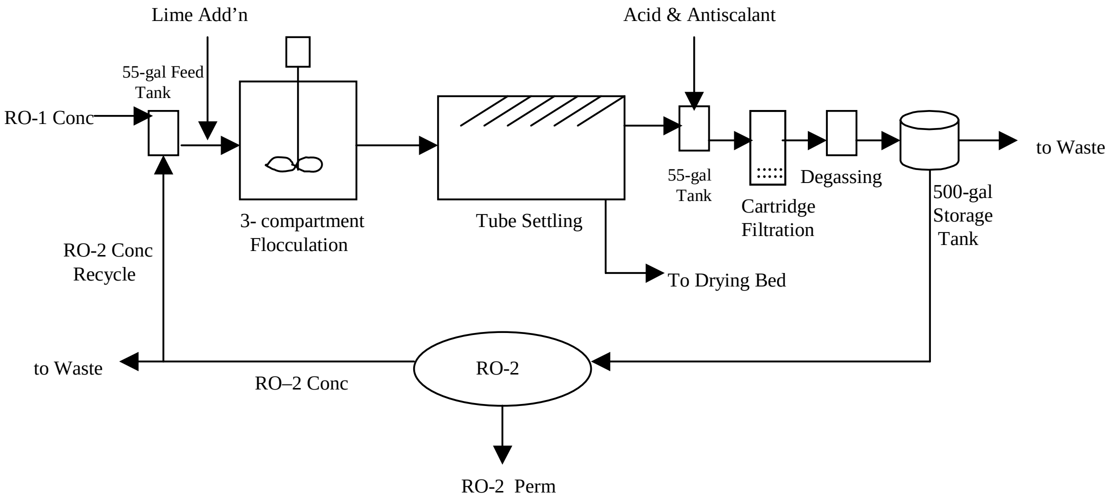


Figure 1. Schematic of Lime Treatment Pilot Plant.

4.2 Laboratory Studies

While most of the work in this project involved lime treatment studies that were conducted at the pilot plant level, other studies were carried out at the laboratory level. The concentrate injection work was performed in plastic containers that ranged in size from 1 to 20 liters. The initial tests were performed at room temperature and were conducted to obtain a general indication of what parameters were likely to be the most important. All of the subsequent tests were conducted at an elevated temperature of 70 degrees Celsius (°C) under conditions similar to those at the actual injection site.

The ion exchange work was done using a continuous flow setup with columns that were up to 1½ inches (in.), or 3.81 centimeters (cm) in diameter. The flow rates ranged from 20 to 125 milliliters per minute (mL/min).

The arsenic removal studies (using lime sludge solids) were performed the same way. The experiments that involved using lime sludge solids to pre-treat RO-1 concentrate for silica removal were done in the laboratory and in the field. Two different sizes of laboratory columns were used in the lab: one that was 7/8-in. (2.22 cm) outside diameter, and the other that was 2 in. (5.08 cm). The field studies were done in a column with 4-in. (10.16 cm) outside diameter and a 55-gallon (0.21 m^3) drum that had the inlet at the bottom. The flow rates ranged from 5 to 250 mL/min.

The tests that involved using lime sludge solids in mortar or roadway base materials were done in the lab using conventional soil test equipment (compression testing machine by Instron, etc).

5. Analysis of Results

5.1 Lime Treatment Studies

Since the primary objective of this part of the study was to determine how much water could be recovered from the concentrate before silica or some other constituent would foul the membranes, the lime dosage was set high enough so that the silica concentration after lime treatment would be below 30 mg/L at all times. This required a lime dosage of about 600 mg/L in the flocculator. Table 1 shows the characteristics of RO-1 concentrate before and after lime treatment when the primary RO-1 unit was operating at 86% recovery. Some of the values in the "After Lime Treatment" column are higher than those in the "RO-1 Concentrate" column because they include the recirculated flow that was returned to the head of the lime unit. Table 1 clearly shows that over 90% of the silica was removed from the concentrate as a result of the lime treatment. There was also significant removal of magnesium, barium, and fluoride, with most of the other parameters remaining relatively unchanged.

Following lime treatment, the pH of the water was reduced from above 11.0 to below 4.0. At the beginning of the study, sulfuric acid was used for reducing the pH. However, as the recovery in RO-2 was increased to the 50% range (93% overall recovery), membrane fouling was observed. In order to determine what was causing the fouling, a sample of precipitate from the RO-2 feed tank was examined through electron microscopy, and it was determined to be calcium sulfate, as shown in the photographs of figure 2. The acid was then switched to hydrochloric for the remainder of the study.

Table 1. RO-1 Concentrate Before and After Lime Treatment

Parameter	RO-1 Concentrate	After Lime Treatment	Percent Change
Barium, mg/L	0.94	0.523	-44%
Bromide, mg/L	1.93	2.09	8%
Fluoride, mg/L	4.12	1.01	-75%
Chloride, mg/L	4,880	4,880	0%
Alkalinity, mg/L	525	530	1%
Calcium, mg/L	772	901	17%
Hardness, mg/L	2,790	2,160	-23%
Magnesium, mg/L	206	<1	-100%
Nitrate-N, mg/L	0.94	0.97	3%
Potassium, mg/L	119	120	1%
Sodium, mg/L	2,680	2,720	1%
Sulfate, mg/L	905	866	-4%
Silica, mg/L	152	10	-93%
Conductivity, µS/cm	12,800	13,300	4%
pH	7.7	11.1	-

Figure 2. Electron Microscope Pictures of Calcium Sulfate Precipitate.

After the switch from sulfuric to hydrochloric acid, recoveries above 50% were investigated. The system worked very well for recoveries up to about 70% (96% overall recovery). Table 2 shows the chemical characteristics of the concentrate before and after treatment at a recovery rate of 67% (95% overall recovery). As mentioned previously, many of the lime treatment effluent values are higher than the influent values because recirculation of RO-2 concentrate occurred ahead of the lime unit. Table 3 shows typical operating parameters of the RO-2 unit at about 67% recovery.

Table 2. Chemical Characteristics at 67% Recovery of Concentrate

Parameter	RO-1 Concentrate	Lime Effluent	RO-2 Permeate	RO-2 Concentrate
Bromide, mg/L	1.29	1.94	0.4	2.53
Fluoride, mg/L	3.34	1.07	0.9	3.11
Chloride, mg/L	3,690	4,950	784	7,170
Calcium, mg/L	582	1040	78.2	1,520
Magnesium, mg/L	153	6.6	2	10.8
Nitrate-N, mg/L	0.76	0.98	0.24	1.37
Potassium, mg/L	84	108	20.9	162
Sodium, mg/L	1,990	2,720	377	4,010
Sulfate, mg/L	680	1,990	124	3,000
Silica, mg/L	142	9	3	12
Conductivity, µS/cm	12,900	16,000	4,000	26,000
pH	8.1	11.1	3.0	2.9

Table 3. Typical Operating Parameters at 67% Recovery of Concentrate (95% Overall Recovery)

Operating Parameter	Units[1]				
	psi	kPa	gpm	m^3/min	gpd/ft^2
Pre-cartridge pressure	52	358	—	—	—
Post- cartridge pressure	50	345	—	—	—
RO-2 primary pressure	291	2,005	—	—	—
RO-2 final pressure	289	1,991	—	—	—
Concentrate flow	—	—	0.41	0.093	—
Permeate flow	—	—	0.22	0.05	—
Flux	—	—	—	—	4.0

[1] psi = pounds per square inch; kPa = kilopascal; gpm = gallons per minute; m^3/min = cubic meters per minute; gpd/ft^2 = gallons per day per square foot

In raising the recovery to the 70% range, the system became more difficult to control. It was attempted to keep the recovery in the 70-72% range, but most of the time it was closer to 75%, and on some occasions, it spiked up to nearly 80% during overnight hours. The system was operated this way for about 1½ months, and the RO membrane eventually became fouled. Table 4 shows the concentration for some of the constituents of the feed stream (i.e., RO-1 concentrate) and the product steams during that period of time.

Table 4. Typical Chemical Characteristics at 70% Recovery of Concentrate (96% Overall Recovery)

Parameter	Units	RO-1 Concentrate	RO-2 Permeate	RO-2 Concentrate
Alkalinity	mg/L $CaCO_3$	525	0	0
Chlorides	mg/L	3,980	1,700	10,500
Ca Hardness	mg/L $CaCO_3$	1,440	620	6,060
Total Hardness	mg/L $CaCO_3$	1,870	620	6,130
Silica	mg/L	134	6	27
Sulfates	mg/L	1,260	150	2,275
Conductivity	µS/cm	12,820	8,440	34,070
TDS	mg/L	7,440	2,370	20,030
pH	pH units	8.1	2.2	2.1

The silica concentration never got above 40 mg/L in the RO-2 concentrate, but the TDS concentration in the permeate and concentrate streams reached 2,930 and 24,800 mg/L, respectively. In order to determine what caused the membrane to foul, an autopsy was conducted by King Lee Technologies, and they determined that the primary foulant was calcium fluoride (59%). Other compounds on the membrane were calcium carbonate (11%) and calcium sulfate (8%). The complete autopsy report is included as Appendix A of this document.

EPWU has extensive experience in lime treatment technology at their conventional water treatment plants and at the Fred Hervey Water Reclamation Facility. The lime treatment process that was studied in this project is currently under consideration for implementation at the Fort Bliss/EPWU Desalination Facility (now known as the Kay Bailey Hutchinson Desalination Plant) that came online in August 2007 Removing the silica from the concentrate will result in additional water recovery while reducing the volume of the concentrate, thereby prolonging the life of the injection wells and adding other viable concentrate management options.

5.2 Concentrate Injection Studies

Since a commonly used alternative in concentrate management is the throw-away option of injection, preliminary evaluations were conducted to determine the suitability of the concentrate for disposal through deep-well injection. The first tests were conducted at room temperature, wherein RO-1 concentrate was put in 20-liter plastic containers and tested weekly for various parameters. The pH was varied between 6.0 and 8.0, and some of the containers contained a small amount of dolomite, which was collected during construction of the test injection well, or concrete. The results showed that a significant amount of precipitation occurred in only one container, the one that had concrete in the bottom. The precipitants included calcium, silica, and possibly other compounds that were not measured.

The results from this test led to the decision to conduct additional tests under conditions that were more representative of the injection zone. Specifically, the injection wells are in a geo-thermally active area where the injection zone temperature is 70 °C. Therefore, the next set of tests were conducted with RO-1 concentrate at various pHs in one-liter plastic bottles that were filled with crushed dolomite and incubated in a water bath at 70 °C. Samples were removed from the bottles after 3, 6, 9, 15, and 30 days and tested for several parameters. The test results revealed that some precipitation had occurred and that it was most pronounced in the samples that had the highest pH. Figure 3 shows the initial concentration of several parameters at day 0 and after day 9 for the sample with no pH adjustment. (See table B1 in Appendix B for data.) It shows that calcium and alkalinity had the largest reductions from their initial concentrations and that most of the other parameters were relatively unchanged.

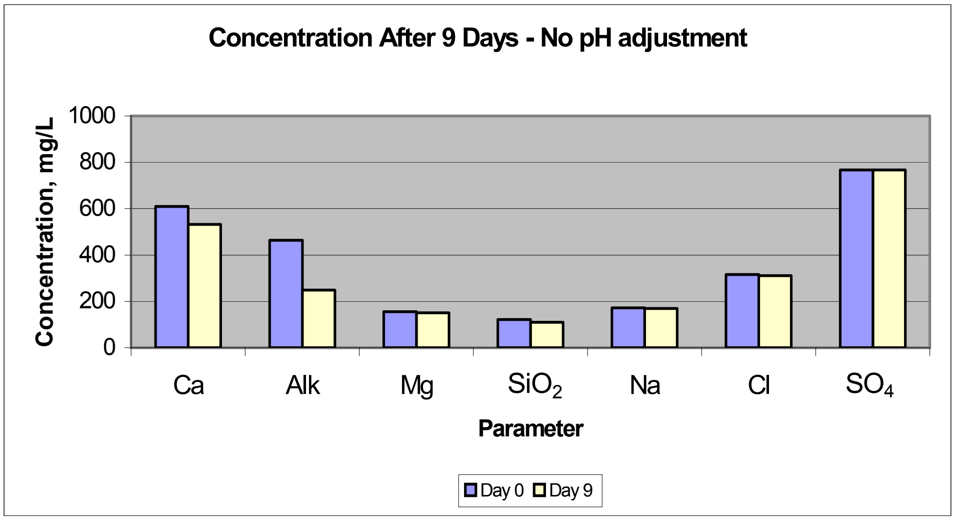


Figure 3. Concentration of Various Parameters After 9 Days in Sample with No pH Adjustment.

In order to better observe the effect of time and pH on precipitation, the experiment was re-run after the pH had been adjusted to 5.0, 6.0, and 7.0. The samples were tested after each of the first 5 days for hardness, alkalinity, pH, and conductivity. The results are presented in tables B2 through B5 of Appendix B, with the hardness and alkalinity data plotted in figures 4 and 5, respectively.

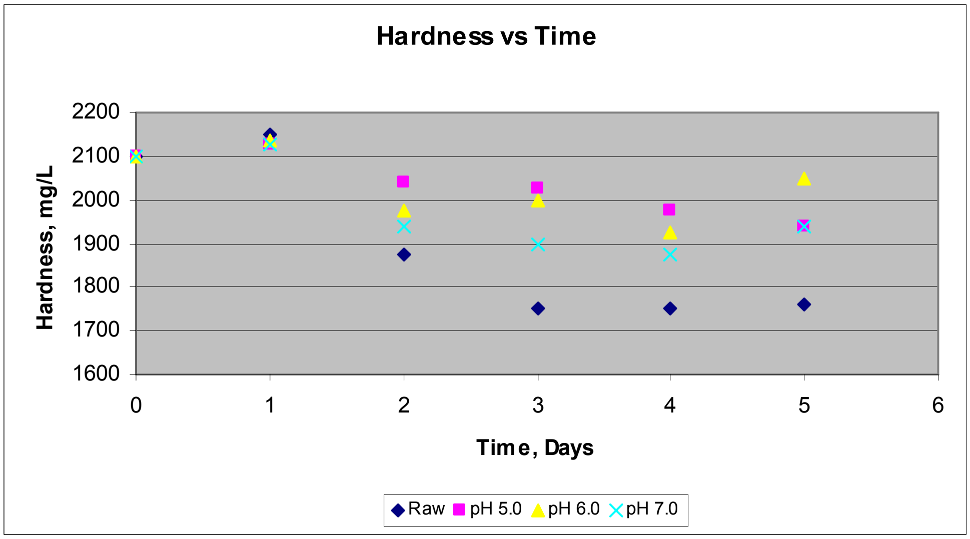


Figure 4. Hardness Versus Time for RO-1 Concentrate in Dolomite at 70 °C.

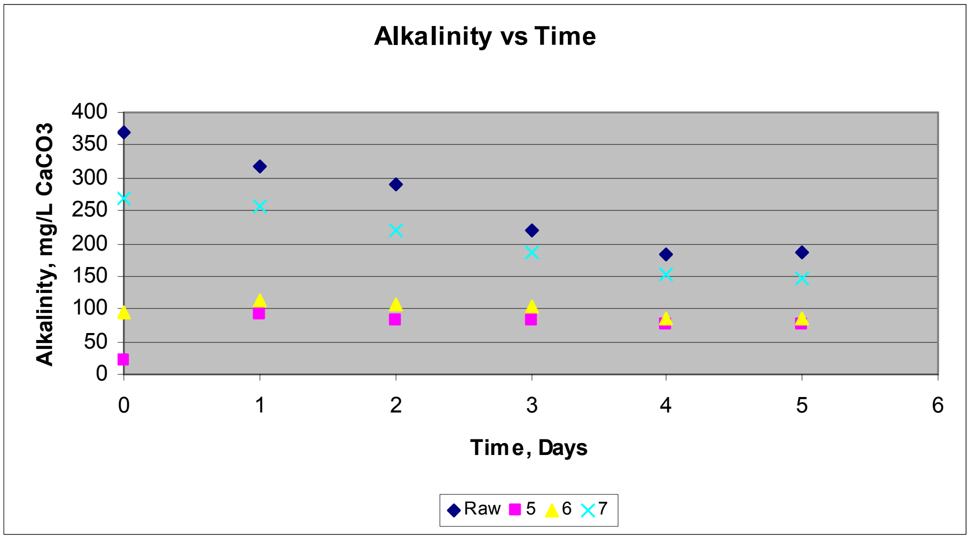


Figure 5. Alkalinity Versus Time for RO-1 Concentrate in Dolomite at 70 °C.

Both figures clearly show that pH has a significant effect on hardness and alkalinity concentrations, with greater reductions in hardness than in alkalinity on an equivalent weight basis at all pHs. Therefore, hardness is probably precipitating with something else besides alkalinity, possibly silica. The alkalinity actually increased in the sample with the initial pH of 5.0, probably due to dissolution of dolomite. This phenomenon also explains why the pH of all of the test samples reached equilibrium at about 7.6 within the 5-day test period as shown in figure 6.

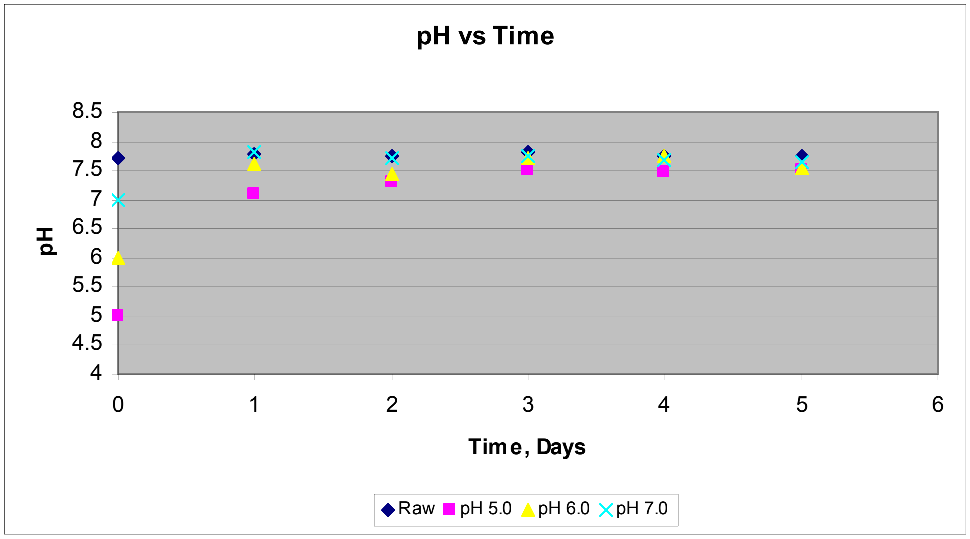


Figure 6. pH Versus Time for RO-1 Concentrate in Dolomite at 70 °C.

From these results, it is clear that the pH of the concentrate will have to be reduced in order to slow down or eliminate precipitation that might threaten the integrity of the injection formation.

5.3 Ion Exchange Studies

The ion exchange experiments were carried out in ¾-in. (1.91 cm) and 1.5-in. (3.81 cm) diameter columns that were 18 in. (45.7 cm) and 14 in. (35.6 cm) long, respectively. RO-1 concentrate (TDS approximately 7,000 mg/L) that had a hardness concentration averaging 1,850 mg/L was passed through a sodium-charged strong-acid cation exchange resin to reduce the hardness to less than 5 mg/L. The usual flow rates were about 30 mL/min in the small column and 90 mL/min in the larger one. The resin was then regenerated using commercially available extra coarse water-softening salt in a countercurrent flow regime. This process was repeated several times to demonstrate that no irreversible fouling had occurred. (See Appendix C for the raw data.) Figure 7 is a plot of the hardness in the regenerant (i.e., hardness removed from the resin) during three of the regeneration processes for the small column.

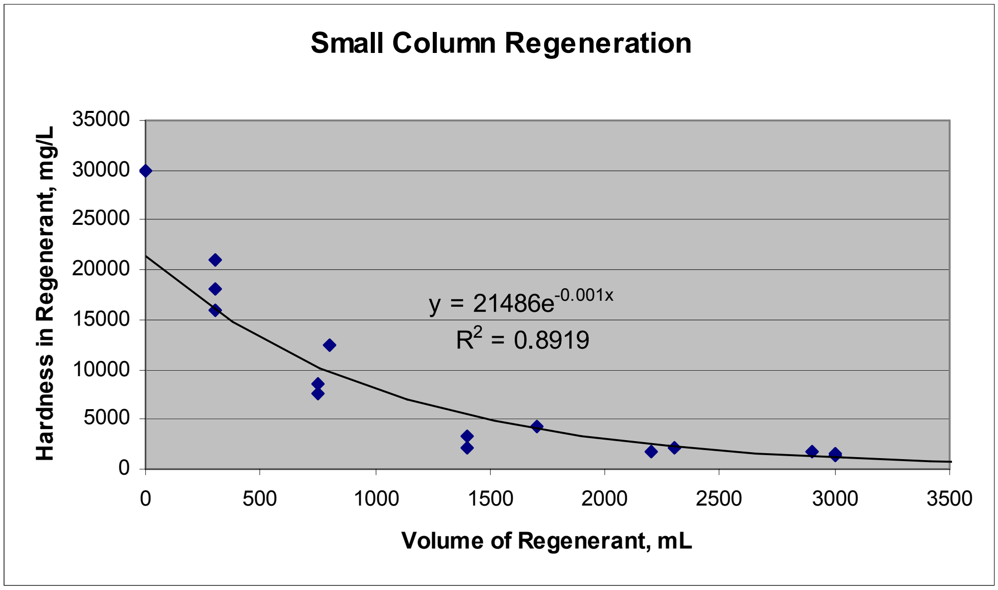


Figure 7. Hardness in Effluent of Small Column During Regeneration.

Integration of the area under the curve yielded a mass of 20.04 grams (g) of hardness removed from the resin. The calculated amount of hardness that was removed by the resin was 21.4 g, indicating that the concentrate softening process is reversible (within experimental error). Similar results were obtained with the larger column.

The next step was to determine if the softened water would support higher concentrations of silica without precipitating something from the solution. Various concentrations of sodium silicate were added to softened and un-softened RO-1 concentrate, and the hardness and silica concentrations were measured 30 and 60 minutes later. The data are included in Appendix C. Figure 8 shows that, for the unsoftened water, the hardness decreased as the silica concentration increased for the 30-minute time period, meaning that precipitation had occurred. For the 60-minute waiting period, the decrease was slightly larger. The final silica concentration in the RO-1 concentrate was in the 150 mg/L range. (See table C3 in Appendix C for data.)

For the *softened* water, however, there was no apparent precipitation as the silica concentration increased. Figure 9 shows the silica concentration in the concentrate as a function of the amount of sodium silicate added. (See table C4 in Appendix C for data.) There was clearly no precipitation of silica, as the concentration was increased from the original concentration of 130 mg/L in the concentrate to the final value of about 900 mg/L. However, the pH of the solution at that time was high at 10.9.

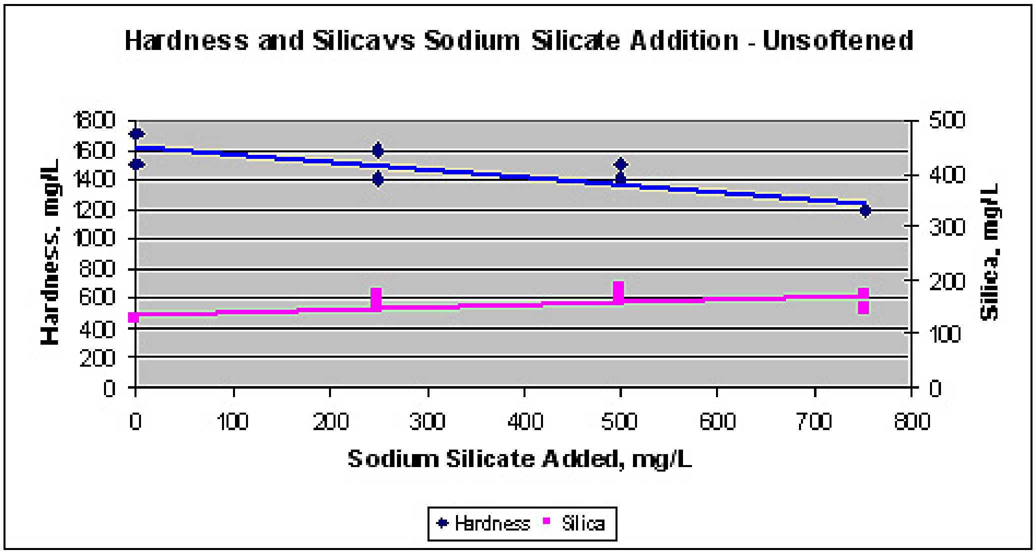


Figure 8. Maximum Silica Concentration Sustainable in RO-1 Concentrate.

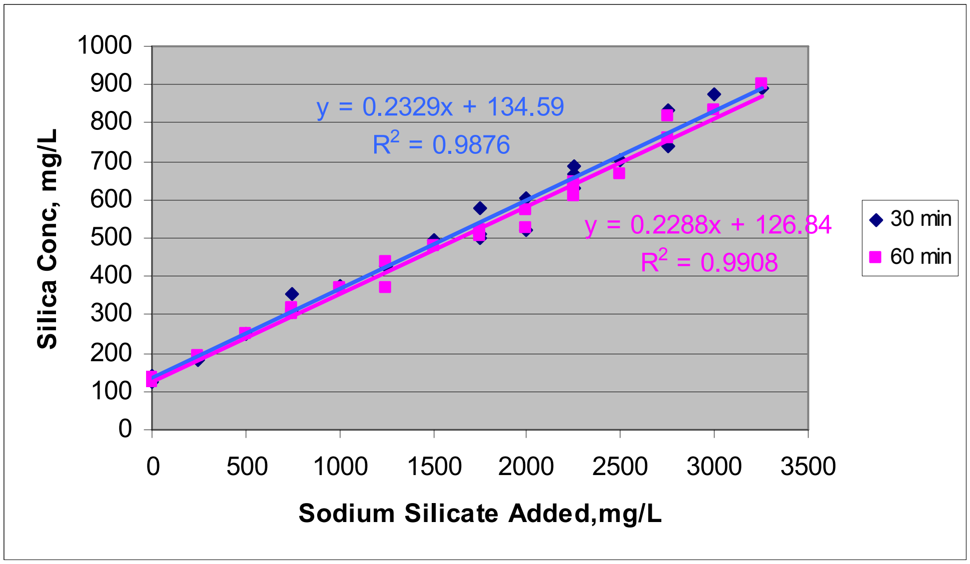


Figure 9. Silica Concentration Versus Amount Added to Softened RO-1 Concentrate.

In order to determine the effect of pH on silica solubility in the softened concentrate, the pH of the concentrate was reduced in various increments from 10.9 to 8.0 after 2,250 mg/L of sodium silicate had been added. As shown in figure 10, silica precipitated from the concentrate as the pH was lowered, with the equilibrium value appearing to be in the 200 mg/L range. Clearly, pH has a much greater effect on silica solubility in the concentrate than does the total hardness. Thus, even if all of the hardness is removed from RO-1 concentrate prior to second-pass RO treatment, the pH will have to be elevated in order to prevent silica from precipitating from the concentrate.

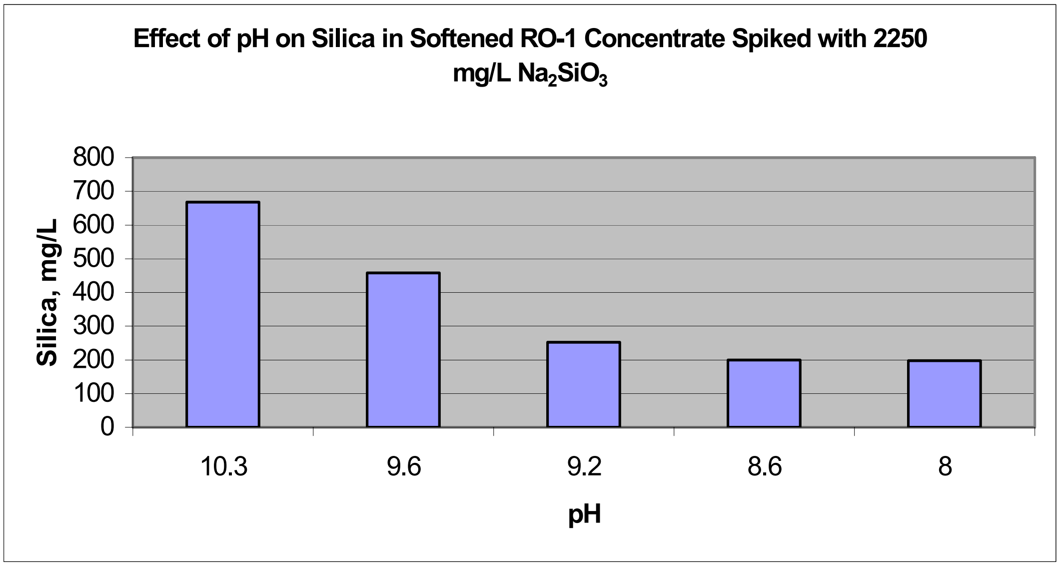


Figure 10. Effect of pH on Silica Solubility in Softened RO-1 Concentrate.

While these results would indicate that it is possible to recover some of the water from softened concentrate via second-pass RO, the cost-effectiveness of such a system would probably be questionable without an effective way to recover and reuse some of the salt that is used in the regeneration process. A crude laboratory experiment showed that the residue left from evaporating the softened RO-2 concentrate could be used to regenerate the ion exchange resin, but the stoichiometry of the process is unknown at this time.

Calcium fluoride precipitation would probably not be a problem in a system such as this, but a number of other problems are sure to arise during continuous flow testing of the process. Whether or not it would ever be practicable to recover salt at the full-scale level of a large municipal operation is uncertain at this time.

5.4 Arsenic Removal Studies

The arsenic studies involved using lime sludge to remove arsenic from contaminated well water by passing the water through a column containing dried sludge. The studies were carried out in a small glass column that had an outside diameter of ¾ in. (1.91 cm) and a length of 8 in. (20.3 cm). The column was filled with small pieces of dried sludge from the lime treatment unit. Glass wool was placed in each end of the column to retain the sludge. The mass of sludge placed in the column was either 10 or 16 g, with the volume varying between 25 and 45 mL. Water from two EPWU wells that contained arsenic was pumped upward through the column at different rates to study the effect of detention time on arsenic removal. Table 5 shows the dates and conditions under which the experiments were conducted, with empty bed contact times (EBCT) varying from 1.8 to 6.3 minutes.

Table 5. Arsenic Test Conditions

Experiment No.	Date	Sludge Wt. (g)	Sludge Volume (mL)	Flow Rate (mL/min)	EBCT (min)
1	11/7/2005	16	35	15.2	3
2	3/22/2006	16	35	15.1	2.3
3	5/23/2006	10	25	4	6.3
4	5/24/2006	10	25	9.2	2.7
5	5/25/2006	10	25	14	1.8
6	6/6/2006	16	35	13.4	2.6

Experiments 1 and 2 were conducted approximately four months apart using the *same sludge* in the *same column* to determine if previously used sludge would regain its ability to remove arsenic. As shown in figure 11, arsenic removal was much lower the second time around (see table D1 in Appendix D for data).

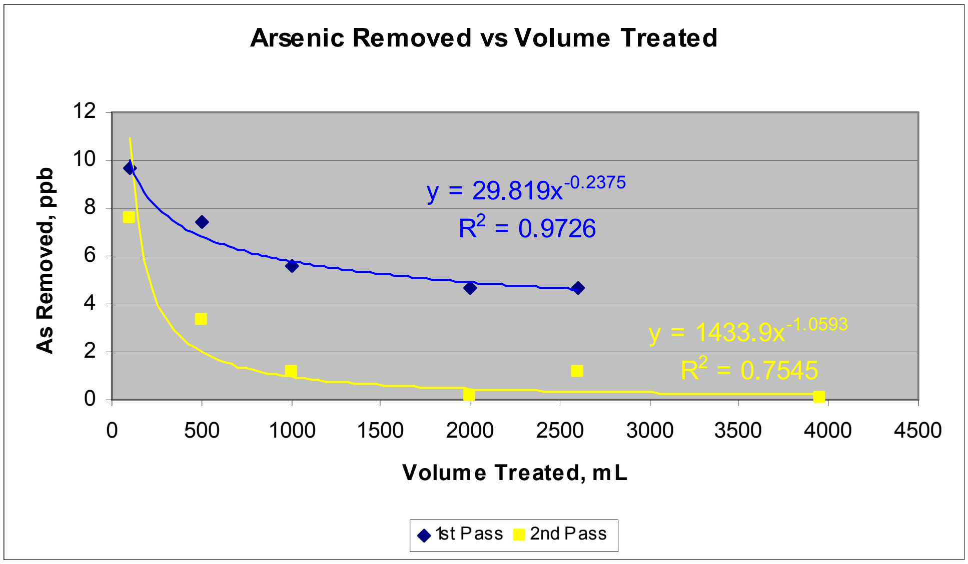


Figure 11. Arsenic Removed Versus Volume Treated by Lime Sludge Solids.

In order to quantify the effectiveness of the sludge solids, the removals were calculated in terms of mass of arsenic removed per gram of sludge solids in the column. The results of those calculations are shown in figure 12. (See table D1 in Appendix D for data.)

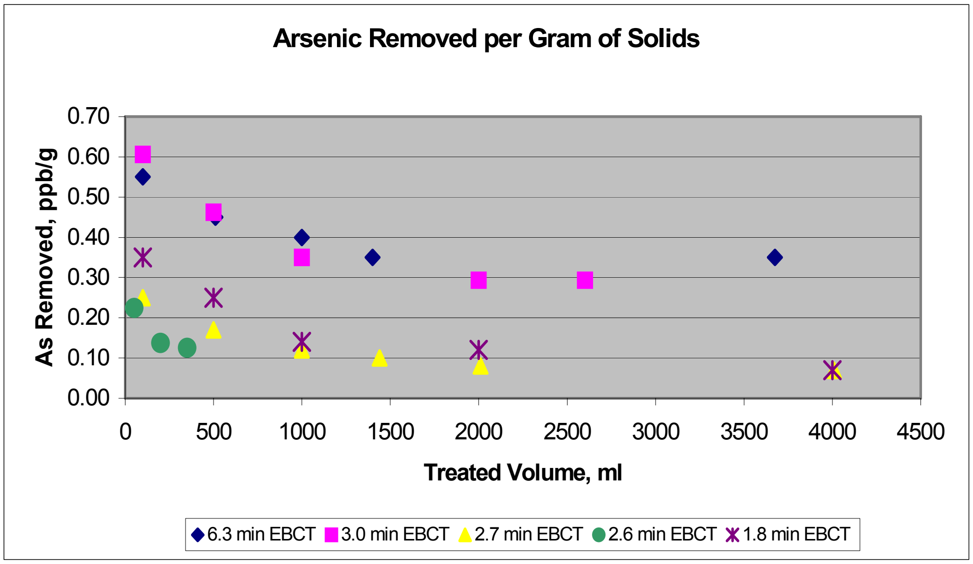


Figure 12. Arsenic Removed per Gram of Lime Sludge Solids.

Figure 12 shows that lime sludge solids do remove arsenic, and, in general, for a given volume of water treated, the mass of arsenic removed per gram of sludge solids increases as the EBCT increases. In order to determine the amount of water that could be treated by a given mass of sludge solids, the best-case scenario was considered, which is represented by the point that is farthest to the right on the x-axis and highest on the y-axis in figure 12, a removal of 0.35 parts per billion per gram (ppb/g) at 3,675 mL treated. If it is assumed that a minimum removal of 5 ppb would be required, then the mass of solids necessary to treat 3675 mL of water would be 14.3 g. A 10,000-gallon (37.85-m^3) tank filled with sludge solids would contain 15,140,000 g of solids, which would treat (15,140,000/14.3)*3675 = 3,890,874,126 mL of water, or slightly more than one million gallons (3,785 m^3). That is, after treating one million gallons of water, the solids would have to be replaced. This level of performance would not be sufficient to treat the water from *one* well for *1 day*. Thus, it does not appear to be feasible to use lime sludge solids to remove arsenic from well water.

5.5 Silica Removal Using Lime Sludge Solids

As stated previously, the column tests (up-flow) were done both in the lab and in the field. The data are included in Appendix E. Figure 13 is a plot of the percentage of silica removed versus the volume of RO-1 concentrate that was treated using the small lab columns and, as figure 13 shows, the lime sludge solids do remove some of the silica from the concentrate. The amount removed was related to the volume treated, with removals starting at about 60% but dropping fairly rapidly.

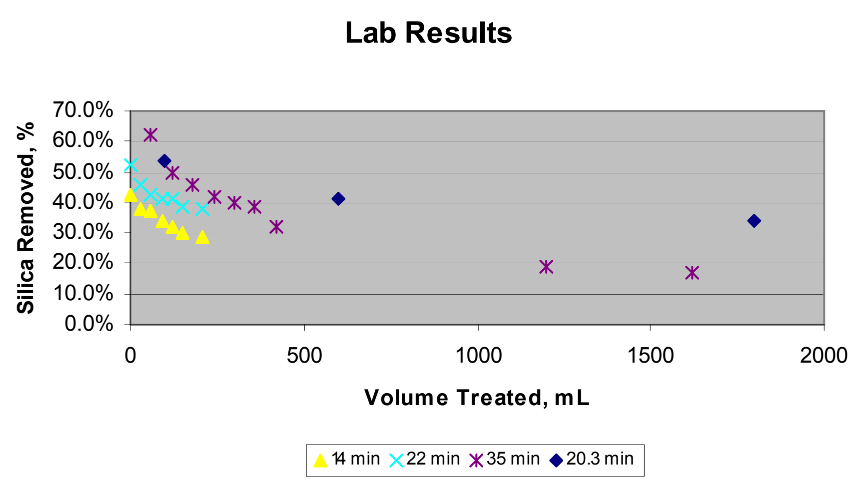


Figure 13. Silica Removed Versus Volume Treated - Lab Columns.

The results from the field units, a 4-in. (10.2-cm) PVC column and a 55-gallon (0.21-m^3) drum, were similar to those from the lab. In order to get an indication of how long the units would perform at a given level, the treatment volumes (EBV) from both the lab and field units were converted into the number of empty bed volumes that they represented. The results are plotted in figure 14, and it shows that lab and field results are similar and that silica removal is down to about 20% after 40 EBVs. The legend shows the *empty bed contact time* and source of the data, lab (L) or field (F). The exponential equation that was used to describe the data in figure 14 has a fairly high statistical correlation coefficient (R^2) value of 0.7.

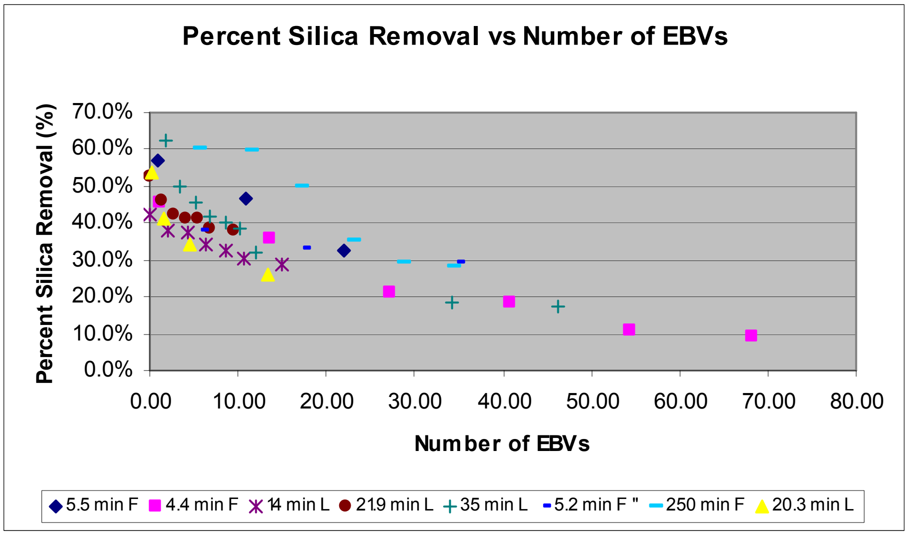


Figure 14. Percent Silica Removed Versus Empty Bed Volumes – Lab and Field.

If it is assumed that the silica concentration in the RO-1 concentrate is in the range of approximately 150 mg/L, and that it would be desirable to reduce it by at least 20% prior to additional RO treatment, then, as stated above, the dried sludge solids would be effective for about 40 EBVs. For a contact time of approximately 60 minutes, the treatment by the sludge solids would be effective for only about two days. However, if the water is drained from the sludge solids and they are allowed to dry out, the solids are likely to recover most of their ability to remove silica.

Table 6 shows the results from using the same sludge for about 1½ months after various periods of resting. The data show the percent removals 60 minutes after flow through the column was restarted following random resting periods.

In general, the performance appears to be decreasing slightly as the number of treatment cycles increase. At this time, it is not known how long the solids would be effective or what the optimum resting period between treatment cycles should be, so this would be a worthy investigation.

At full-scale, a system to treat 3 mgd (7.89 m^3/min) using a column (or tank) with an EBCT of 60 minutes would have a volume of 125,000 gallons (473.1 m^3) and would be 51 ft (15.5 m) in diameter and 8 ft (2.4 m) high. It would function properly for 2 days, depending on what percentage of silica one wanted to remove, after which a standby unit would have to be put online.

Table 6. Silica Removal After 60 Minutes – Same Solids

Date	Percent Removal After 60 Minutes
12/21/04	32%
12/22/04	31%
12/23/04	30%
1/5/05	30%
1/6/05	30%
1/7/05	34%
1/14/05	25%
1/20/05	25%
1/21/05	34%
1/26/05	18%
1/27/05	10%
1/28/05	22%
2/2/05	24%
2/4/05	20%
2/7/05	18%

Although such a treatment system is obviously doable, the willingness of a public utility to engage in such an undertaking is questionable. From an economic point of view, there would be a savings in the lime treatment dosage and in sludge disposal costs. Whether or not the savings would offset the capital and operating costs involved is questionable until more specific information is obtained about how such a system would have to be operated.

While this study focused on silica removal using *dried* sludge solids, it is likely that some silica reduction would be obtained by recirculating *wet* sludge, the previously formed calcium silicate precipitate in the solids contact clarifier. This operation would add relatively little cost to the treatment process, and even if it were only marginally effective in removing silica, it might be economically attractive because there would be savings in the downstream processes of lime addition, sludge dewatering, and sludge disposal. Therefore, recirculation of wet sludge in the lime treatment process should be investigated at the lab and pilot-scale levels.

5.6 Lime Sludge Solids in Mortar and Roadway Base Materials

Because a large amount of sludge would be generated in removing silica by the lime treatment process, it would be helpful if the sludge solids could be beneficially used in some way. An obvious way to dispose of large quantities of dried sludge solids would seem to be through incorporation of the solids into materials associated with transportation infrastructure. A preliminary review of literature indicated that the solids might be a suitable substitute for some of the constituents in mortar or roadway base materials [4, 5].

Mortar typically consists of cement, lime, sand, and water. Our first experiments focused on substituting some of the lime sludge solids (LSS) for some of the solid materials in mortar. A typical mortar mix served as the control, with the absolute volume method used to determine the relative amounts of the components in the test mixtures. A water-cement ratio of 0.5 was used for all of the mixes. The compositions of the control mixture and the test mixtures are shown in table 7.

The mixes were molded in 3-in.x 6-in. (7.6-cm x 15.2-cm) cylinders and tested to determine the 28-day compressive strength per American Society for Testing and Materials (ASTM) C-109. To expedite the curing, the prepared specimens were submerged in water at 142 degrees Fahrenheit (°F), or 61 °C, for 7 days to simulate 28-day curing. For each component, two specimens were prepared and tested. Therefore, a total of 10 specimens were tested.

Table 7. Mortar Mix Design

Components	Control Mix (gal)	Replace Lime w/LSS (gal)	Replace 10% Cement w/LSS (gal)	Replace 10% Sand w/LSS (gal)	Replace 30% Cement w/LSS (gal)
Cement	6.38	6.38	5.74	6.38	4.47
Sand	15	15	15	13.5	15
Lime	1.12	0	1.12	0	1.12
LSS	0	1.12	0.64	2.72	3.03
Water	3.19	3.19	2.87	3.19	2.23
Totals	25.69	25.69	25.37	25.79	25.85

The test results, which are shown in figure 15, are the average compressive strengths measured from the two specimens. The results indicate that the control mix exhibited the maximum strength of more than 3,000 pounds per square inch (psi), or 20,670 kilopascal (kPa), with all of the test mixtures exhibiting strengths of 10% lower or more, indicating that the lime sludge solids are not a viable alternative for replacing any of the components of mortar.

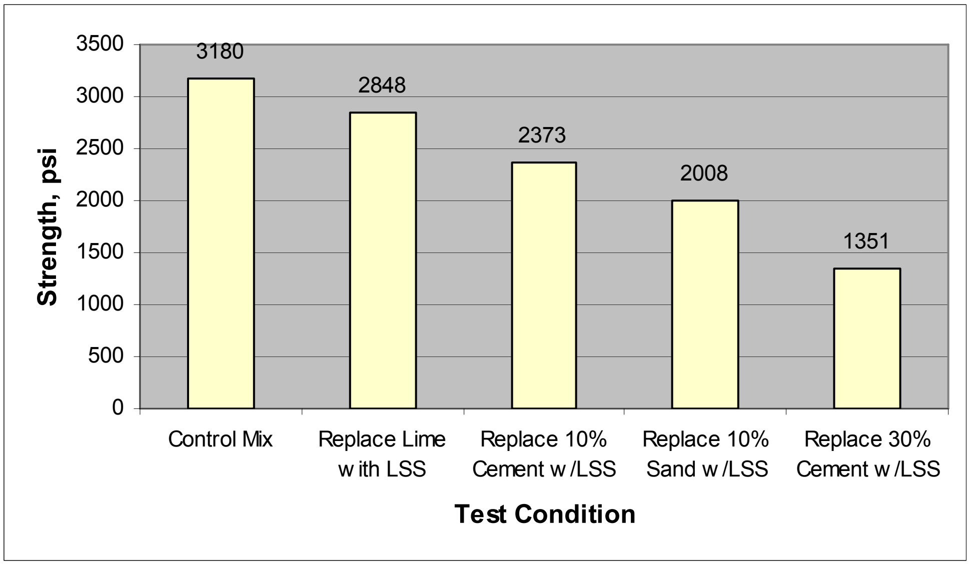


Figure 15. Compressive Strength of Mortar Mixes.

To evaluate the potential for using the lime sludge solids in roadway base materials, a typical El Paso base material was obtained from a Texas Department of Transportation (TxDOT) contractor and it was designated as the control mix (0% LSS). The lime sludge solids were evaluated as a replacement for lime and as a replacement for the fine materials in the control mix.

To find the strength properties of the base material, a standard testing procedure, Tex-117-E Triaxial Compression Test, specified by TxDOT was followed. To determine the feasibility of replacing lime with lime sludge solids, the Tex-121-E Soil Lime Test procedure was followed in addition to the Tex-117-E procedure.

These procedures can be divided into three major steps. The first step is to find the optimum moisture content of the soil. Specimens are compacted with different moisture contents, and the densities of the specimens are found.

The optimum moisture content (OMC) is obtained from the specimen with the maximum density. The second step of the process is to prepare the specimens at the OMC and keep them at room temperature for capillary wetting for a specified time. The wetting time limit depends on the type of material used and whether the base material is stabilized with lime or not. The third step of the process is to test the specimens for compressive strength. Test specimens of 6 in. (15.2 cm) in diameter and 8 in. (20.3 cm) high are compacted in three layers, each layer compacted with 50 blows. For this study, three different wetting conditions were evaluated: no capillary wetting, capillary wetting for 10 days, and capillary wetting for 10 days followed by sitting on the counter for 7 days. The experimental design in this study is shown in the first three columns of table 8.

Table 8. Average Strength of Base Materials

Wetting Condition	LSS (%)	Lime (%)	Average Strength (psi)	Loss of Strength (%)
No capillary wetting, tested after 24 hours	0	0	79.8	
	5	0	64.1	19.6
	10	0	47.7	40.2
10 days capillary wetting	0	0	57.8	
	10	0	44.5	23
No capillary wetting, tested after 24 hours	5	0.25	56.9	28.6
	5	1	60.2	24.5
	10	0.25	50.9	36.2
10 days capillary wetting plus 7 days counter	5	0.25	55.8	3.3
	5	1	81.9	-41.8
	10	0.25	50.9	11.8

The experiments involved replacing base material fines with lime sludge solids. The test results shown in table 8 suggest that specimens containing the lime sludge solids lost strength by more than 20%, regardless of the wetting conditions, indicating that lime sludge solids are not able to stabilize the base material or serve as a replacement for the fines within the base materials.

The final tests involved adding a small amount of lime to the lime sludge solids to see if fortified sludge solids would stabilize the soil. At 0.25% lime, there was very little change in the strength of the base material. The addition of lime at 1% did increase the strength of the base material to that of the 0% LSS control.

However, the addition of such a large amount of lime would not seem to be a cost-effective solution for disposal of the lime sludge solids.

6. Economic Considerations for Lime Treatment of RO Concentrate

In considering the economics of the lime treatment process, a number of assumptions have to be made [6]. Some of these assumptions are mentioned in this section, but all the information used in the calculations is included in Appendix F. The basic treatment system considered here is similar to that shown in figure 1 and includes lime treatment, second-pass RO (RO-2), third-pass RO (RO-3), blending of RO-3 permeate, pond evaporation of RO-2 and RO-3 concentrates, and solids disposal via landfill. The primary RO system (RO-1) is assumed to be operating at 85% recovery, with RO-2 and RO-3 at recoveries of 73% and 95%, respectively.

Table 9 summarizes the costs associated with the lime treatment RO system, and as the table shows, the capital cost is over $14,000,000 for treating 3 mgd (7.89 m^3/min) of concentrate.

Table 9. Costs for RO Treatment of Lime-Treated Concentrate

Cost Item	Capital Cost ($)	Annual Cost ($/yr)
Building and Auxiliaries	$ 307,769	$ 24,696
Post-treatment, storage, pumping	854,511	68,568
Lime Equipment	1,540,000	123,574
Lime	-	253,147
Chemicals	-	64,000
Solids Disposal	-	17,047
RO-2 Equipment	1,035,220	83,069
RO-2 Operating Cost	-	834,839
RO-3 Equipment	1,035,220	83,069
RO-3 Operating Cost	-	139,720
Blending Well	500,000	40,121
Blend Pumping	-	99,394
Excavation	1,869,294	149,997
Liner Cost	5,895,007	473,031
Fencing	125,379	10,061
Personnel (Operators)	-	150,000
Contingencies,10%	1,285,463	105,619
Total Cost	$14,140,096	$2,695,256
Revenue		2,897,346
Net Income		$ 177,396

When the capital costs are converted into annual costs and added to the operation and maintenance (O&M) costs, the total cost per year is $2,719,950, which is slightly *less* than the revenue received from the sale of the extra water recovered from the concentrate.

The capital cost of the currently preferred alternative of deep-well injection is $9.7 million. When the capital costs are amortized and added to the O&M costs, the annual cost for deep-well injection is $1.6 million per year. Since there is no offsetting revenue associated with this option, the lime treatment alternative is clearly more cost-effective than deep-well injection. Furthermore, an extra 4 mgd (10.5 m^3/min) of product water is generated in the lime treatment process.

The unit costs and other estimates used in these calculations are best estimates that are believed to be accurate. Even if they are on the low side by as much as, say 20%, the lime treatment option is still more cost-effective than the deep-well injection option. On the other hand, if the costs turn out to be lower than the estimates used here, or if the income is higher, then the lime treatment option is clearly superior to injection and will actually generate a significant amount of revenue that would result in a reduction in the unit cost of water produced by the project.

References

1. Mickley, Mike, “Concentrate Management,” prepared for the Joint Water Reuse and Desalination Task Force, October 2005.

2. CDM, Inc, *Basis of Design Document, Brine Disposal,* prepared for El Paso Water Utilities, April 2002.

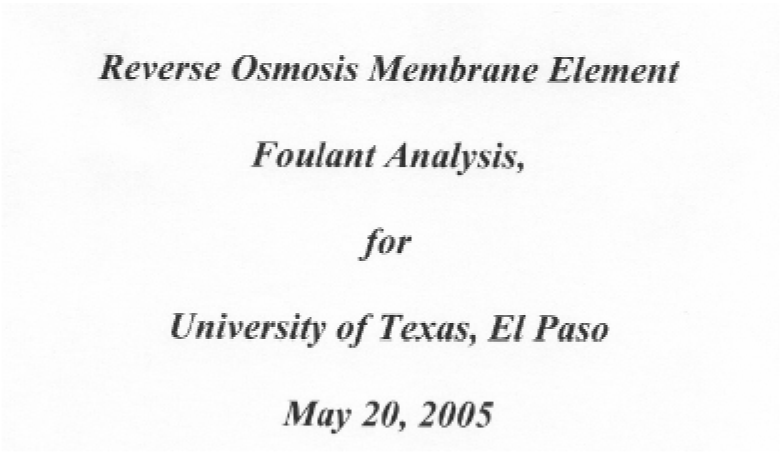
3. Tarquin, Anthony, *Volume Reduction of High-Silica RO Concentrate Using Membranes and Lime Treatment, Desalination and Water Purification Research and Development Program Report No. 108*, Bureau of Reclamation, February 2004.

4. Forum@aggregateRESEARCH.com, February 3, 2005.

5. http://www.fal-g.com/aboutus.htm

6. American Water Works Association (AWWA), *Manual of Water Supply Practices, Reverse Osmosis and Nanofiltration,* AWWA M46, 1999.

Appendix A: King Lee Membrane Autopsy Results



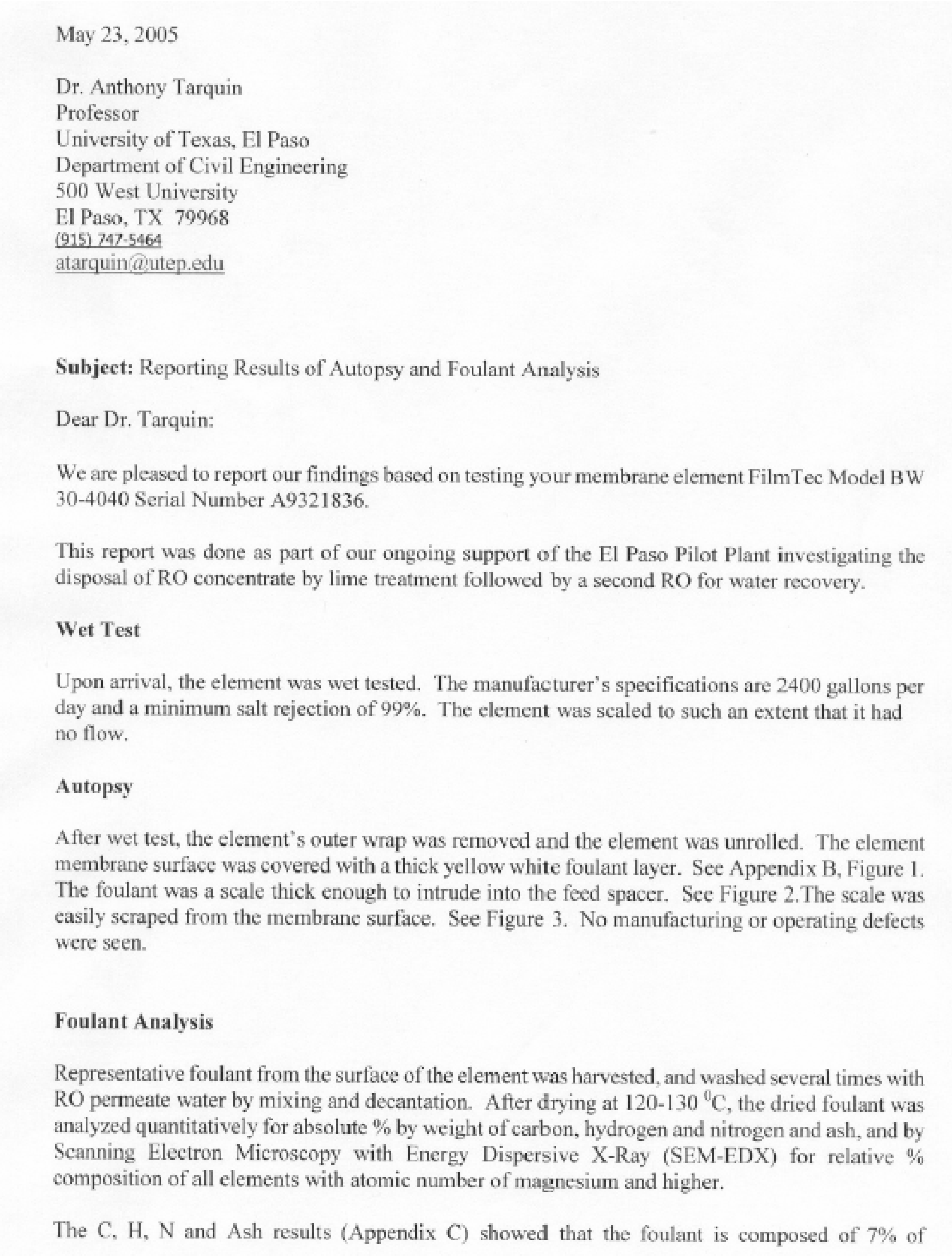
Reverse Osmosis Membrane Element

Foulant Analysis,

for

University of Texas, El Paso

May 20, 2005



May 23, 2005

Dr. Anthony Tarquin
Professor
University of Texas, El Paso
Department of Civil Engineering
500 West University
El Paso, TX 79968
(915) 747-5464
atarquin@utep.edu

Subject: Reporting Results of Autopsy and Foulant Analysis

Dear Dr. Tarquin:

We are pleased to report our findings based on testing your membrane element FilmTec Model BW 30-4040 Serial Number A9321836.

This report was done as part of our ongoing support of the El Paso Pilot Plant investigating the disposal of RO concentrate by lime treatment followed by a second RO for water recovery.

Wet Test

Upon arrival, the element was wet tested. The manufacturer's specifications are 2400 gallons per day and a minimum salt rejection of 99%. The element was scaled to such an extent that it had no flow.

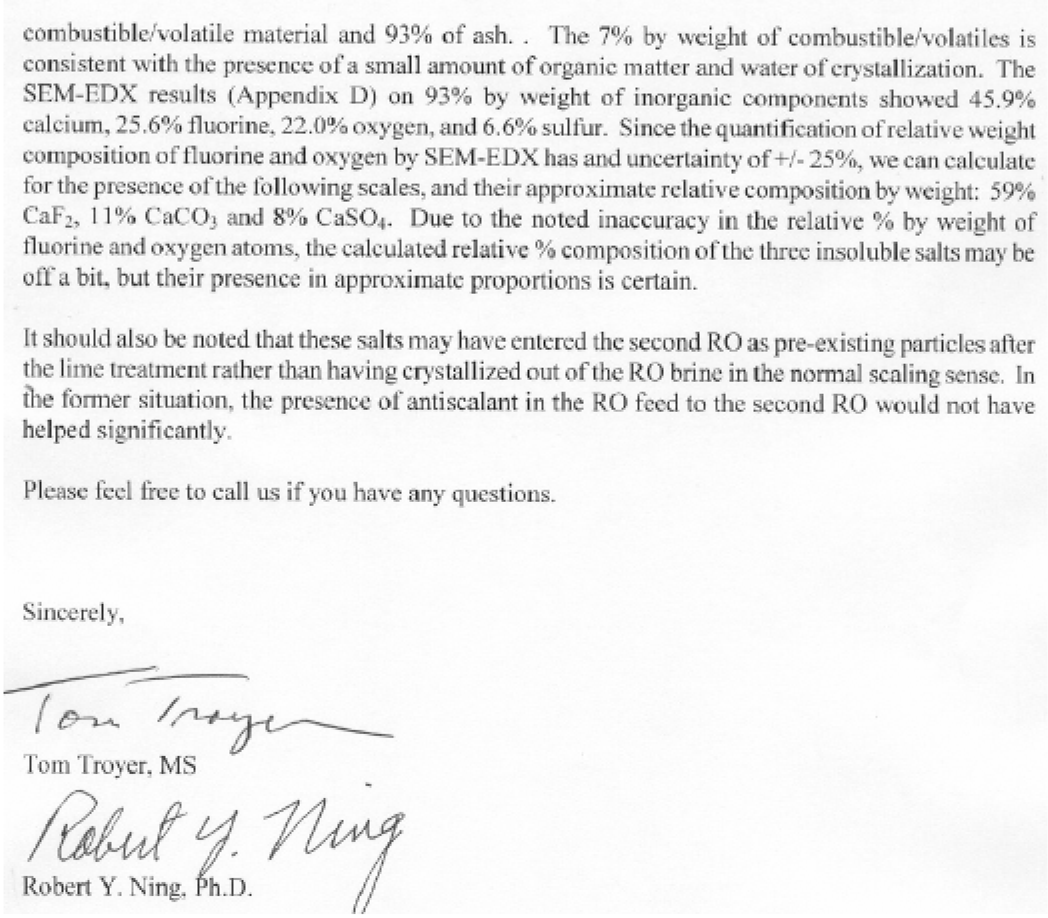
Autopsy

After wet test, the element's outer wrap was removed and the element was unrolled. The element membrane surface was covered with a thick yellow white foulant layer. See Appendix B, Figure 1. The foulant was a scale thick enough to intrude into the feed spacer. See Figure 2.The scale was easily scraped from the membrane surface. See Figure 3. No manufacturing or operating defects were seen.

Foulant Analysis

Representative foulant from the surface of the element was harvested, and washed several times with RO permeate water by mixing and decantation. After drying at 120-130 ^{0}C, the dried foulant was analyzed quantitatively for absolute % by weight of carbon, hydrogen and nitrogen and ash, and by Scanning Electron Microscopy with Energy Dispersive X-Ray (SEM-EDX) for relative % composition of all elements with atomic number of magnesium and higher.

The C, H, N and Ash results (Appendix C) showed that the foulant is composed of 7% of



combustible/volatile material and 93% of ash. . The 7% by weight of combustible/volatiles is consistent with the presence of a small amount of organic matter and water of crystallization. The SEM-EDX results (Appendix D) on 93% by weight of inorganic components showed 45.9% calcium, 25.6% fluorine, 22.0% oxygen, and 6.6% sulfur. Since the quantification of relative weight composition of fluorine and oxygen by SEM-EDX has and uncertainty of +/- 25%, we can calculate for the presence of the following scales, and their approximate relative composition by weight: 59% CaF_2, 11% $CaCO_3$ and 8% $CaSO_4$. Due to the noted inaccuracy in the relative % by weight of fluorine and oxygen atoms, the calculated relative % composition of the three insoluble salts may be off a bit, but their presence in approximate proportions is certain.

It should also be noted that these salts may have entered the second RO as pre-existing particles after the lime treatment rather than having crystallized out of the RO brine in the normal scaling sense. In the former situation, the presence of antiscalant in the RO feed to the second RO would not have helped significantly.

Please feel free to call us if you have any questions.

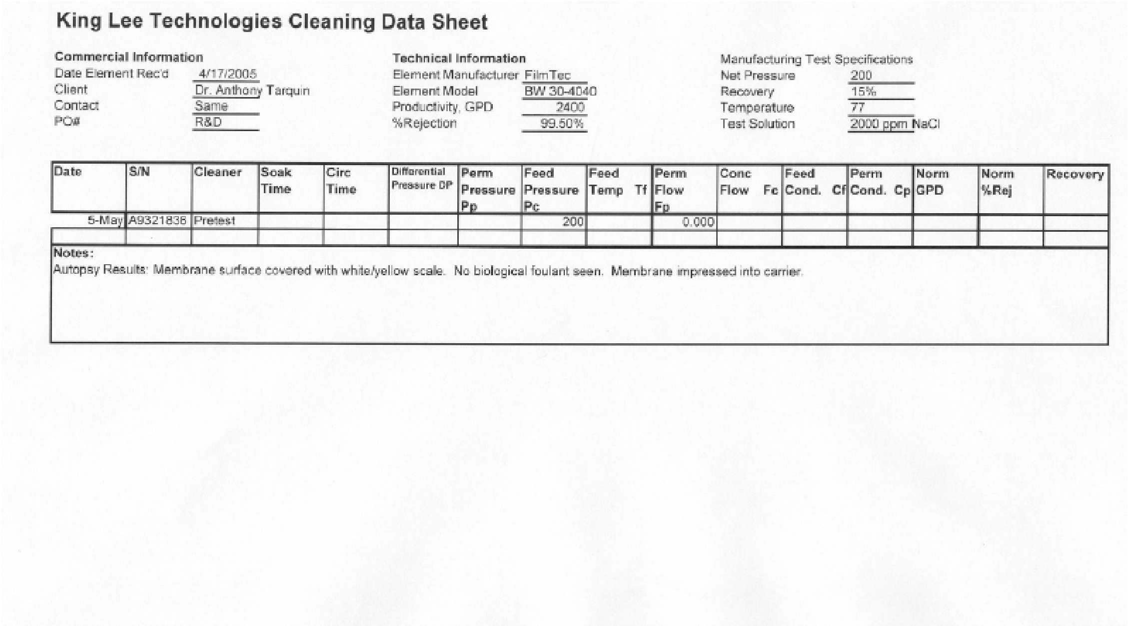
Sincerely,

Tom Troyer

Tom Troyer, MS

Robert Y. Ning

Robert Y. Ning, Ph.D.



King Lee Technologies Cleaning Data Sheet

Commercial Information
Date Element Rec'd 4/17/2005
Client Dr. Anthony Tarquin
Contact Same
PO# R&D

Technical Information
Element Manufacturer FilmTec
Element Model BW 30-4040
Productivity, GPD 2400
%Rejection 99.50%

Manufacturing Test Specifications
Net Pressure 200
Recovery 15%
Temperature 77
Test Solution 2000 ppm NaCl

Date	**S/N**	**Cleaner**	**Soak Time**	**Circ Time**	**Differential Pressure DP**	**Perm Pressure Pp**	**Feed Pressure Pc**	**Feed Temp Tf**	**Perm Flow Fp**	**Conc Flow Fc**	**Feed Cond. Cf**	**Perm Cond. Cp**	**Norm GPD**	**Norm %Rej**	**Recovery**
5-May	A9321836	Pretest					200		0.000						

Notes:
Autopsy Results: Membrane surface covered with white/yellow scale. No biological foulant seen. Membrane impressed into carrier.

Pictures of Autopsied Element

Figure 1. Unrolled Element

Figure 2. Membrane Foulant Close Up

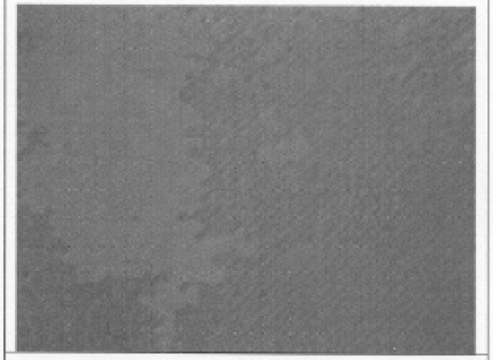
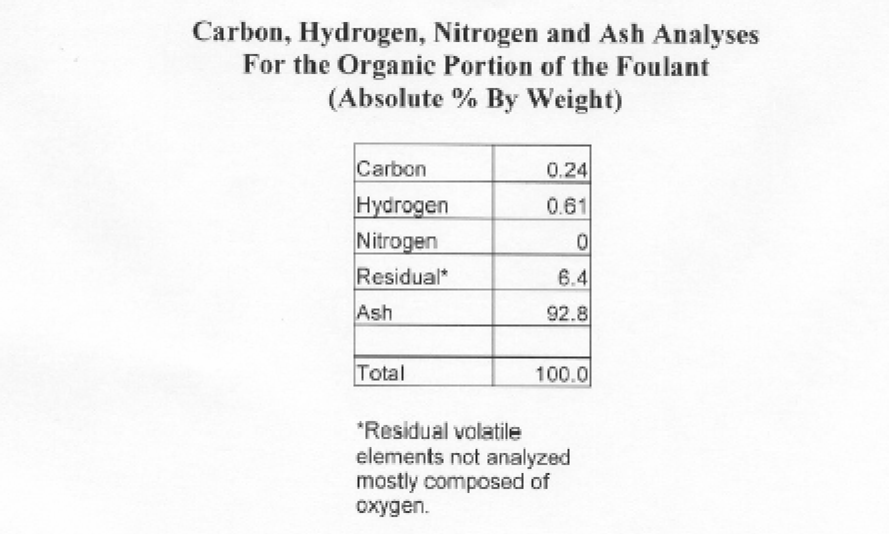


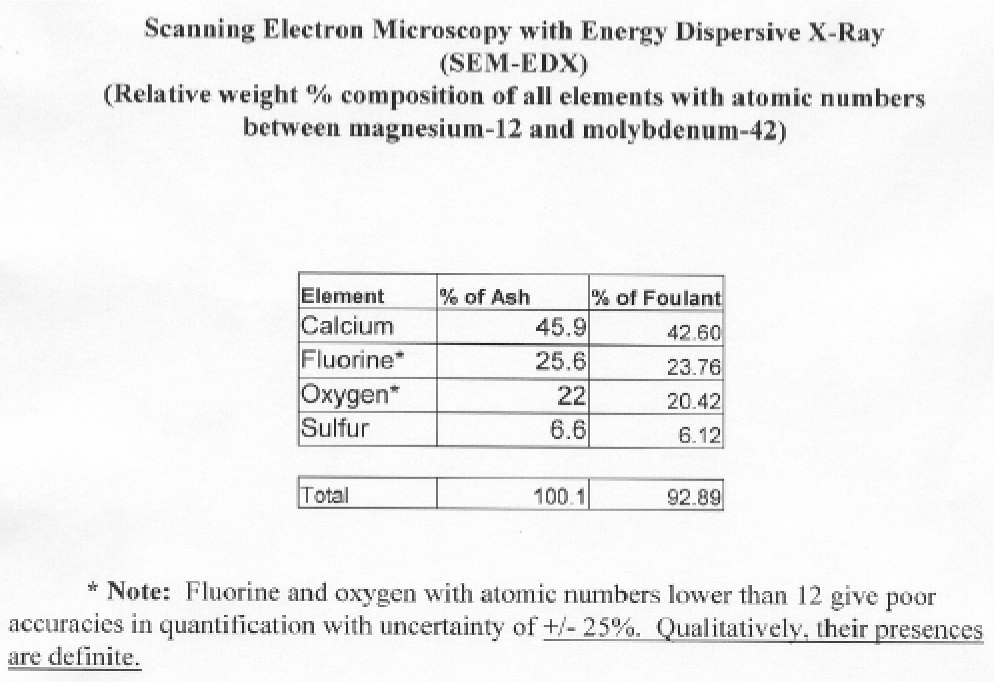
Figure 3. Collected Foulant



Carbon, Hydrogen, Nitrogen and Ash Analyses For the Organic Portion of the Foulant (Absolute % By Weight)

Carbon	0.24
Hydrogen	0.61
Nitrogen	0
Residual*	6.4
Ash	92.8
Total	100.0

*Residual volatile elements not analyzed mostly composed of oxygen.



Scanning Electron Microscopy with Energy Dispersive X-Ray (SEM-EDX) (Relative weight % composition of all elements with atomic numbers between magnesium-12 and molybdenum-42)

Element	% of Ash	% of Foulant
Calcium	45.9	42.60
Fluorine*	25.6	23.76
Oxygen*	22	20.42
Sulfur	6.6	6.12
Total	100.1	92.89

* **Note:** Fluorine and oxygen with atomic numbers lower than 12 give poor accuracies in quantification with uncertainty of +/- 25%. Qualitatively, their presences are definite.

Appendix B: Concentrate Injection Data

Raw Data - No pH Adjustment – 70° C

Parameter	Units	Day 0	Day 9
Ca	mg/L	610	532
Alk	mg/L	464	249
Mg	mg/L	156	151
SiO2	mg/L	122	110
Na	mg/L	172	169
Cl	mg/L	316	311
SO4	mg/L	767	767
TDS	mg/L	7,280	6,910
Cond	µS/cm	10,600	10,300

Hardness Data (mg/L $CaCO_3$) for Samples in Dolomite at 70° C

Time, days	Raw	pH 5.0	pH 6.0	pH 7.0
0	2,100	2,100	2,100	2,100
1	2,150	2,125	2,137.5	2,125
2	1,875	2,037.5	1,975	1,937.5
3	1,750	2,025	2,000	1,900
4	1,750	1,975	1,925	1,875
5	17,62.5	1,937.5	2,050	1,937.5

Alkalinity Data (mg/L $CaCO_3$) for Samples in Dolomite at 70° C

Time, days	Raw	pH 5.0	pH 6.0	pH 7.0
0	370	20	95	270
1	317.5	92.5	112.5	255
2	290	82.5	107.5	220
3	220	82.5	102.5	187.5
4	182.5	77.5	85	152.5
5	187.5	75	85	147.5

pH Data for Samples in Dolomite at 70° C

Time, days	Raw	pH 5.0	pH 6.0	pH 7.0
0	7.7	5	6	7
1	7.78	7.09	7.61	7.83
2	7.75	7.31	7.44	7.72
3	7.82	7.52	7.7	7.76
4	7.73	7.48	7.73	7.69
5	7.75	7.5	7.55	7.65

Appendix B (Continued)

Conductivity Data (µS/cm) for Samples in Dolomite at 70° C

Time, days	Raw	pH 5.0	pH 6.0	pH 7.0
0	11,510	11,930	11,880	11,690
1	11,360	11,865	11,575	11,305
2	11,110	11,730	11,590	11,295
3	11,190	11,650	11,540	11,325
4	11,110	11,550	11,380	11,340
5	11,045	11,495	11,410	11,330

Appendix C: Ion Exchange Data

Small Column Regeneration Data

Date	Volume (mL)	Hardness (mg/L)
10/22/2004	0	30,000
	300	16,000
	800	12,400
	1,700	4,200
	2,300	2,200
	2,900	1,750
11/2/2004	0	30,000
	300	21,000
	750	7,600
	1,400	2,100
	2,200	1,700
	3,000	1,400
11/5/2004	0	30,000
	300	18,000
	750	8,500
	1,400	3,300
	3,000	1,600

Large Column Regeneration Data

Date	Volume (mL)	Hardness (mg/L)
3/16/2005	0	30,000
	1,000	14,000
	3,000	2,000
	5,000	900
5/18/2005	0	30,000
	1,000	22,000
	2,000	16,000
	4,000	4,200
	6,000	1,900
	7,000	1,300

Table C3. Silica and Hardness in Unsoftened Concentrate After Sodium Silicate Addition

Na_2SiO_3 Added (mg/L)	Silica after 30 Minutes (mg/L)	Silica after 60 Minutes (mg/L)	Hardness after 30 Minutes (mg/L)	Hardness after 60 Minutes (mg/L)
0	128	129	1,700	1,600
0	131	127	1,500	1,500
250	150	148	1,600	1,600
250	171	160	1,400	1,500
500	165	157	1,500	1,400
500	180	156	1,400	1,400
750	146	139	1,200	1,200
750	171	150	1,200	1,200

Table C4. Silica Concentration in Softened Concentrate After Sodium Silicate Addition

Na_2SiO_3 Added (mg/L)	Silica after 30 Minutes (mg/L)	Silica after 60 Minutes (mg/L)	Na_2SiO_3 Added (mg/L)	Silica after 30 Minutes (mg/L)	Silica after 60 Minutes (mg/L)
0	127.5	128	1,500	495	477
0	130	123.5	1,750	502	520
0	139	123.8	1,750	579	516
0	136	134	1,750	513	503
0	141	136.5	2,000	522	575
0	130	123	2,000	605	526
0	137	135.8	2,250	628	610
250	183.3	190.8	2,250	686	646
500	252.5	249.3	2,250	667	638
750	355	319.5	2,500	701	665
750	307.5	301.5	2,750	737	759
1,000	377	372	2,750	833	818
1,250	428	372	3,000	874	832
1,250	426	435	3,250	889	902

Table C5. Effect of pH on Silica Concentration (2,250 mg/L Na_2SiO_3 Added)

pH	Silica
10.3	668
9.6	458
9.2	252
8.6	200
8	197

Appendix D: Arsenic Removal Using Lime Sludge Solids Data

Arsenic Removal Lab Test Data

Date Performed: 11/7/05
Flow rate = 15.2 mL/min
Volume = 45 mL
Wt solids = 16 g
EBCT = 3.0 min

Volume (mL)	Time (minutes)	As conc (ppb)	Removal (ppb)	Removal (%)	No. EBVs	Removal/g (ppb/g)
0	0	0	17.7	1		
100	6.6	8	9.7	55%	2.2	0.61
500	32.9	10.3	7.4	42%	11.1	0.46
1,000	65.8	12.1	5.6	32%	22.2	0.35
2,000	131.6	13	4.7	27%	44.4	0.29
2600	171.1	13	4.7	27%	57.8	0.29

Date Performed: 3/22/06 using previously used sludge
Flow rate = 15.1 mL/min
Volume = 35 mL
Wt solids = 16 g
EBCT = 2.3 min

Volume (mL)	Time (minutes)	As conc (ppb)	Removal (ppb)	Removal (%)	No. EBVs	Removal/g (ppb/g)
0	0	17.9	0			
100	6.6	10.3	7.6	42%	2.9	0.48
500	33.1	14.6	3.3	18%	14.3	0.21
1,000	66.2	16.7	1.2	7%	28.6	0.08
2,000	132.5	17.7	0.2	1%	57.1	0.01
2,600	172.2	16.7	1.2	7%	74.3	0.08
3,950	261.6	17.8	0.1	1%	112.9	0.01

Date Performed: 5/23/06

Flow rate = 4 mL/min

Volume = 25 mL

Wt solids = 10 g

EBCT = 6.3 minutes

Volume (mL)	Time (minutes)	As conc (ppb)	Removal (ppb)	Removal (%)	No. EBVs	Removal/g (ppb/g)
0	0	12.5	0			
100	25	7	5.5	44%	4	0.55
510	127.5	8	4.5	36%	20.4	0.45
1,000	250	8.5	4	32%	40	0.4
1,400	350	9	3.5	28%	56	0.35
3,675	918.75	9	3.5	28%	147	0.35

Date Performed: 5/24/06

Flow rate = 9.2 mL/min

Volume = 25 mL

Wt solids = 10 g

EBCT = 2.7 minutes

Volume (mL)	Time (minutes)	As conc (ppb)	Removal (ppb)	Removal (%)	No. EBVs	Removal/g (ppb/g)
0	0	12.5				
100	10.9	10	2.5	20%	4	0.25
500	54.3	10.8	1.7	14%	20	0.17
1,000	108.7	11.3	1.2	10%	40	0.12
1,440	156.5	11.5	1	8%	57.6	0.1
2,010	218.5	11.7	0.8	6%	80.4	0.08
4,010	435.9	11.8	0.7	6%	160.4	0.07

Date Performed: 5/25/06

Flow rate = 14 mL/min

Volume = 25 mL

Wt solids = 10 g

EBCT = 1.8 minutes

Volume (mL)	Time (minutes)	As conc (ppb)	Removal (ppb)	Removal (%)	No. EBVs	Removal/g (ppb/g)
0	0	12.5				
100	7.1	9	3.5	28%	4	0.35
500	35.7	10	2.5	20%	20	0.25
1,000	71.4	11.1	1.4	11%	40	0.14
2,000	142.9	11.3	1.2	10%	80	0.12
4,000	285.7	11.8	0.7	6%	160	0.07

Date Performed: 6/6/06

Flow rate = 13.5 mL/min

Volume = 35 mL/min

Wt solids = 16 g

EBCT = 2.6 minutes

Volume (mL)	Time (minutes)	As conc (ppb)	Removal (ppb)	Removal (%)	No. EBVs	Removal/g (ppb/g)
0	0.0	12.6				
50	3.7	9	3.6	29%	1.4	0.23
200	14.8	10.4	2.2	17%	5.7	0.14
350	25.9	10.6	2	16%	10.0	0.13

Appendix E: Silica Removal Using Lime Sludge Solids Data

Lab Data - New Sludge - Small Column

Date	Column Volume (mL)	Time (minutes)	Silica (mg/L)	Removal (mg/L)
18-May-04	177	0	101	0
		1	48	53
		30	54.5	46.5
		60	58.1	42.9
		90	59.6	41.4
		120	59.2	41.8
		150	62.2	38.8
		210	62.7	38.3
19-May-04	177	0	62.4	0
		1	36	26.4
		30	38.6	23.8
		60	39.1	23.3
		90	41.1	21.3
		120	59.2	20.2
		150	43.5	18.9
		210	44.3	18.1
26-May-04	177	0	131	0
		60	49.6	81.4
		120	65.6	65.4
		180	71	60
		240	76.2	54.8
		300	78.6	52.4
		360	80.8	50.2
		420	89	42
		1,200	106.5	24.5
		1,620	108.6	22.4

Lab Data - New Sludge - Large Column

Date	Column Volume (mL)	Time (minutes)	Silica (mg/L)	Removal (mg/L)
9-Feb-05	405	0	140	
		5	65	75
		30	82.5	57.5
		90	92.5	47.5
		270	103.5	36.5

Appendix E (Continued)

Field Data - New Sludge - Field Column

Date	Column Volume (mL)	Time (minutes)	Silica (mg/L)	Removal (mg/L)
12-Jul-2004	9,900	0	169	
		5	73	96
		60	90	79
		120	114	55
14-Jul-2004	9,900	0	184	
		5	100	84
		60	118	66
		120	145	39
		180	150	34
		240	164	20
		300	167	17
		1,410	183	1
5-Aug-04	9,900	0	218	
		1	131	87
		30	135	83
		90	146	72
		180	154	64
		1,260	173	45
		1,315	172	46
		1,570	181	37

Field Data - New Sludge - Drum

Date	Drum Volume (L)	Time (days)	Silica (mg/L)	Removal (mg/L)
20-Nov-04	208	0	148	
		1	59	89
		2	60	88
		3	74	74
		4	96	52
		5	105	43
		6	106	42

Appendix E (Continued)

Silica Removal Using Same Sludge Solids		
21-Dec-04	**Air passed through column over weekend to dry sludge**	
Time	**Silica (mg/L)**	**Flow (mL/min)**
11:45 AM	138.0	20
12:15 PM	86.3	
12:45 PM	94.0	
1:15 PM	103.0	
1:45 PM	104.3	
22-Dec-04	**Air passed through sludge column overnight to dry it**	
Time	**Silica (mg/L)**	**Flow (mL/min)**
11:30 AM	138.0	20
12:00 PM	84.0	
12:30 PM	95.0	
1:00 PM	96.0	
1:30 PM	100.8	
23-Dec-04	**Air passed through sludge column overnight to dry it**	
Time	**Silica (mg/L)**	**Flow (mL/min)**
11:30 AM	138.0	23
12:00 PM	94.0	
1:00 PM	100.3	
2:00 PM	100.8	
5-Jan-05	**Column dried since last test; glass wool removed**	
Time	**Silica (mg/L)**	**Flow (mL/min)**
12:00 PM	132.0	21
12:30 PM	92.0	
1:00 PM	92.8	
1:30 PM	100.5	
6-Jan-05	**Column dried overnight**	
Time	**Silica (mg/L)**	**Flow (mL/min)**
11:00 AM	111.0	24
11:30 AM	65.0	
12:00 PM	77.8	
12:30 PM	84.3	
1:00 PM	78.3	
1:30 PM	77.3	
2:00 PM	80.3	
2:30 PM	87.5	

Appendix E (Continued)

7-Jan-05	**Column dried overnight**	
Time	**Silica (mg/L)**	**Flow (mL/min)**
12:30 PM	132.0	24
1:00 PM	86.3	
1:30 PM	86.8	
2:00 PM	87.3	
14-Jan-05	**Column dried since last time**	
Time	**Silica (mg/L)**	**Flow mL/min)**
10:30 AM	Started	21
11:00 AM	88.3	
11:30 AM	91.3	
12:00 PM	100.8	
20-Jan-05	**Column dried since last time**	
Time	**Silica (mg/L)**	**Flow (mL/min)**
10:00 AM	146.0	24
10:30 AM	106.5	
2:00 PM		
3:00 PM		
4:00 PM	118.5	
21-Jan-05	**Column dried since last time**	
Time	**Silica (mg/L)**	**Flow (mL/min)**
10:30 AM	134.0	18
11:00 AM	86.4	
12:00 PM	91.8	
1:00 PM	97.0	
4:30 PM	103.5	
26-Jan-05	**Column dried since last time**	
Time	**Silica (mg/L)**	**Flow (mL/min)**
11:30 AM	135.0	20
12:00 PM	110.0	
1:00 PM	113.5	
2:00 PM	113.8	
3:00 PM	124.8	
27-Jan-04	**Column dried since last time**	
Time	**Silica (mg/L)**	**Flow (mL/min)**
10:30 AM	135.0	20
11:00 AM	120.5	
1:00 PM	124.3	
2:00 PM	133.0	

Appendix E (Continued)

9-Feb-05	New sludge	
Time	Silica (mg/L)	Flow (mL/min)
1:00 PM	140.0	
1:30 PM	82.5	20
2:30 PM	92.5	
5:30 PM	103.5	

15-Feb-04	Column dried since last time	
Time	Silica (mg/L)	Flow (mL/min)
9:30 AM	143	20
10:30 AM	114	
4:30 PM	124	

16-Feb-05	Column dried since last time	
Time	Silica (mg/L)	Flow (mL/min)
12:00 PM	144	20
12:30 PM	58.5	
1:30 PM	104	
2:30 PM	113.5	
3:30 PM	113.75	
5:00 PM	112.25	

20-Feb-05	Column dried since last time	
Time	Silica (mg/L)	Flow (mL/min)
11:30 AM	146.0	20
12:00 PM	105.5	
1:00 PM	113.8	
3:30 PM	117.0	
4:30 PM	113.5	
5:30 PM	107.5	

21-Feb-05	Column dried since last time	
Time	Silica (mg/L)	Flow (mL/min)
11:30 AM	146.0	20
12:00 PM	99.8	
1:00 PM	102.5	
2:00 PM	109.8	
7:15 PM	132.8	

22-Feb-05	Column dried since last time	
Time	Silica (mg/L)	Flow (mL/min)
10:00 AM	136	20
10:30 AM	103.25	
1:30 PM	114.5	
2:30 PM	120	

Appendix F: Economic-Related Data

Economic-Related Data	
Lime Treatment Cost Data	
Reactor/clarifier ($)	$560,000
Lime silo/feeder ($)	$130,000
Thickener/press ($)	$250,000
Sand filter ($)	$600,000
Lime cost ($/lb)	$0.046
Solids disposal cost - pickup, hauling, disposal ($/cu yd)	$5.88
Sludge density (lbs/cu ft)	70
Equipment life (yrs)	20
Recovery of lime-softened water (%)	95%
Evaporation Pond Data	
Evaporation rate (in/yr)	50
Liner cost ($/sq ft)	0.60
Liner life (yrs)	20
Excavation ($/cu yd)	$3.00
Fence ($/LF)	$10.00
Flow storage (months)	5
Excavation amortization time (yrs)	20
RO-Related Cost Data	
Buildings ($)	$250,000
RO equipment capital cost ($/mgd)	$480,000
Membranes ($/80 sq ft)	$300
Membrane life RO-2 (yrs)	3
Membrane life RO-3 (yrs)	6
Power cost ($/kw-hr)	$0.06
Antiscalant cost ($/9-lb gallon)	$11
RO Operating Data	
RO-2 operating pressure (psi)	300
RO-3 operating pressure (psi)	130
Pump and motor efficiency (%)	75%
RO-2 flux (gpd/sq ft)	6
RO-2 recovery (%)	73%
RO-3 flux (gpd/sq ft)	25
RO-3 recovery (%)	95%
Other Data	
Initial RO-I concentration volume (mgd)	3
Interest rate (%)	5%
Water selling price ($/1,000 gal)	$2.00
Blending ratio (total volume/RO perm)	2