REVERSE OSMOSIS FIELD STUDY

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by

Yoram Cohen[1] and **Panagiotis D. Christofides**
Water Technology Research Center
Chemical and Biomolecular Engineering Department
University of California Los Angeles (UCLA)
Los Angeles, CA

UCLA Project Participants:
Anditya Rahardianto, John Thompson, Han Gu,
Michal Uchymiak, Alex Bartman, Brian McCool, Aihua Zhu

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[1] Y. Cohen, E-mail: yoram@ucla.edu, Tel: (310) 825- 8766

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1. SYNOPSIS

High recovery desalting of San Joaquin Valley agricultural drainage (AD) water at the DP-25 test site (Panoche Water and Drainage District) was studied as an illustrative test case for: (a) demonstrating rapid field evaluation of reverse osmosis (RO) desalting; (b) evaluating the technical feasibility of RO concentration demineralization to enable water recovery enhancement via secondary RO desalting; and (c) developing preliminary process design specifications for high recovery RO desalting. Rapid field evaluation of RO desalting at the DP-25 test site was first demonstrated using a small-scale Membrane Monitor (MeMo) system, which enabled direct and online detection/characterization of membrane mineral scaling. The MeMo system allowed rapid field evaluation of feed filtration requirements, optimization of antiscalant treatment, and estimation of the water recovery level corresponding to the membrane scaling threshold under field conditions. Based on optimal RO operating conditions, derived using the MeMo system, a pilot-scale mini-mobile-modular (M3) RO system was subsequently utilized to evaluate and demonstrate the technical feasibility of sustained RO desalting operations of the DP-25 source water. The M3 RO desalting system was able to operate at water recovery levels below or near the membrane scaling threshold (i.e., up to 63%) without any detectable membrane scaling problems, even when significant feed water quality variations were encountered. The feasibility of primary RO concentrate desupersaturation by a two-step chemically-enhanced seeded precipitation process (CESP) was evaluated in order to assess the feasibility of secondary RO desalting of the primary RO concentrate. The CESP process can be a less chemical intensive concentrate treatment process relative to conventional precipitation softening. It was shown, via field tests using small laboratory and bench-scale crystallizers, that desupersaturation of the AD RO concentrate was technically feasible. Process model analysis indicated that the integration of CESP and secondary RO desalting can enhance overall water recovery up to 87% or higher. Based on both experimental and process analysis results, preliminary process design specification and cost estimates for high recovery desalting at the DP-25 test site were developed. The results of the study suggest that rapid systematic field testing using the MeMo RO diagnostic system and the M3 RO pilot system, operated under model-based control with advanced monitoring, along with systematic process analysis, is an effective approach for accelerated development and demonstration of cost-effective solutions for high recovery AD water desalting under field conditions.

2. BACKGROUND

2.1. Overview

The management of high-salinity agricultural drainage (AD) water is a major challenge in the western San Joaquin Valley (SJV), CA. In this region, restricted AD water management options, prolonged drought, and dwindling irrigation water supplies have led to soil salinity build-up resulting in negative impact of agricultural productivity in the region. As a part of an overall strategy for managing Western SJV AD water, reverse osmosis (RO) desalination has been considered as a promising treatment approach for reclaiming and reusing SJV AD water. RO desalting of SJV AD water, however, is technically and economically challenging. Despite decades of research and testing, there is presently no significant, production-scale RO desalting plant operating in the western SJV.

The main challenge in implementing RO technology for AD water reclamation and reuse is the fact that most SJV AD source waters, due to high sulfate content, are near or at saturation with respect to the mineral salt gypsum ($CaSO_4 \bullet H_2O$) [1]. As product water is recovered from SJV AD water, RO desalting results in the concentration of mineral salt ions along the axial direction of the membrane channel. If sparingly soluble mineral salts (e.g., gypsum, calcite and barite) are concentrated above their solubility limits, mineral salt crystallization may occur in the bulk fluid and on the membrane surface, leading to membrane mineral scaling, membrane surface blockage, loss of membrane productivity, and, consequently, shortening of membrane useful life. Without an effective scale mitigation strategy, RO desalting of SJV AD water is often feasible only at very low water recovery levels (<20%), generating high volumes of brine concentrate that are costly to dispose at inland locations. Antiscalant treatment may partially enhance the water recovery levels to a moderate range of 50-80%, depending on source water quality, antiscalant type, and antiscalant dose.

Various membrane scaling mitigation methods and RO desalting process configurations have been proposed for high recovery desalting of SJV AD water [1-3], ranging from antiscalant treatment to the integration of a variety of pretreatment and inter-stage treatment processes (e.g., chemical precipitation and ion-exchange). However, there is significant geographical and temporal water quality variations of SJV AD water resources (i.e., with respect to salinity and ion composition) [1-3]. Therefore, it is extremely difficult to develop a treatment process that would be cost-effective for desalting feed water from a specific SJV AD water source without site-specific understanding of the unique and complex characteristics of the target source water and associated range of treatment options. In this respect, a trial-and-error pilot-testing approach is costly and of sub-optimal success. A cost-effective RO desalting process for specific water source water is best achieved through a systematic field evaluation that assesses treatment process requirements at a fundamental level targeting optimization of process configuration and operating conditions through rapid development of a unique process operation knowledge base.

2.2. Membrane Monitor (MeMo) and the M3 RO pilot desalting system

Over the past decade, the UCLA Water Technology (WaTeR) Center has been actively developing advanced systems and methodologies for rapid field evaluation of membrane desalting processes. For example, a unique Membrane Monitor (MeMo), which enables direct and real-time observation of chemical and physical transformation at membrane surfaces (e.g., membrane mineral scaling), has been developed as a versatile RO diagnostic tool for a wide range of objectives, including rapid membrane-scaling diagnostic, antiscalant selection and dose optimization, and early detection/real-time monitoring of membrane scaling in spiral-wound RO membrane modules [4-6]. In the MeMo system, reverse osmosis desalting is carried out within a well-characterized plate-and-frame RO membrane test cell (**Figure 1**), capable of utilizing any flat-sheet RO membranes and processing any feed water of interest. The reverse osmosis process concentrates ions in the feed water toward the membrane surface, generating a concentration polarization profile that is easily adjustable (i.e., via feed flow rate and operating pressure adjustments). Using the MeMo system, one can directly observe and record in real time any optically-visible chemical and physical transformations (e.g., membrane mineral scaling and even biofouling) that can result from the exposure of the membrane surface to the feed water. By correlating the time-varying characteristics of the chemical/physical transformations (e.g., membrane surface coverage of mineral salt crystals) with the ion concentration level near the membrane surface in the MeMo system, one can predict the RO operating conditions (e.g., antiscalant dose, water recovery levels, etc.) that would be expected for such transformation to occur (or to be averted) in a larger -scale RO desalting system. Because of its small size and ease of operation, the MeMo system allows rapid generation of experimental data over a wide range of operating conditions directly in the field. The MeMo system can be used to rapidly generate critical information on desalting process feasibility, optimal process configuration, and feasible range of operating conditions for designing pilot-scale demonstration testing studies. During the operation of a pilot-scale RO system, the MeMo system is integrated with the pilot RO system as a process monitor (or operated separately to guide the selection of optimal operating conditions),

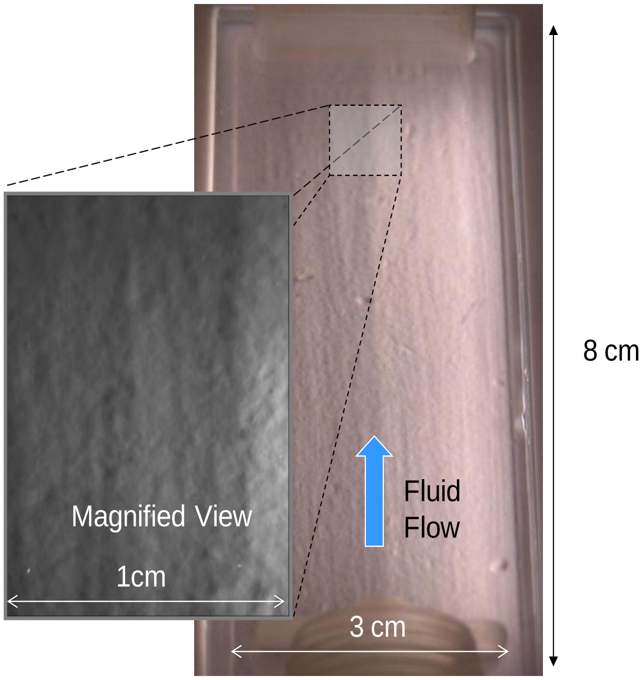

Figure 1. *Images of RO membrane surface as viewed through the Membrane Monitor (MeMo). With MeMo, simultaneous monitoring of the overall wetted membrane area and the magnified membrane area near the fluid exit allows for characterization of both single and multiple clusters of mineral scale crystals.*

In addition to the MeMo system, the UCLA WaTeR Center has developed a Mini, Mobile, Modular (M3; **Figure**) RO desalting system as an advanced platform for rapid evaluation and demonstration of RO desalting. The M3 system is composed of modular unit operations (pretreatment, pumping, RO desalting, etc.) that are readily reconfigurable. Real-time data acquisition is achieved using various online monitors and sensors. In addition to a small footprint, the M3 system weighs less than 750 lbs and can be readily transported in a cargo van. Using the M3 RO pilot, coupled with the unique capabilities of the MeMo system, a complete desalting process can be configured, optimized, and demonstrated in the field within a short period of time.

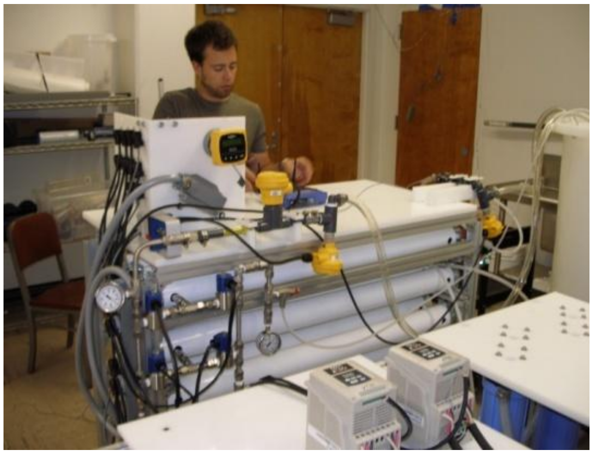

Figure 2. *Photograph of M3 RO desalination system.*

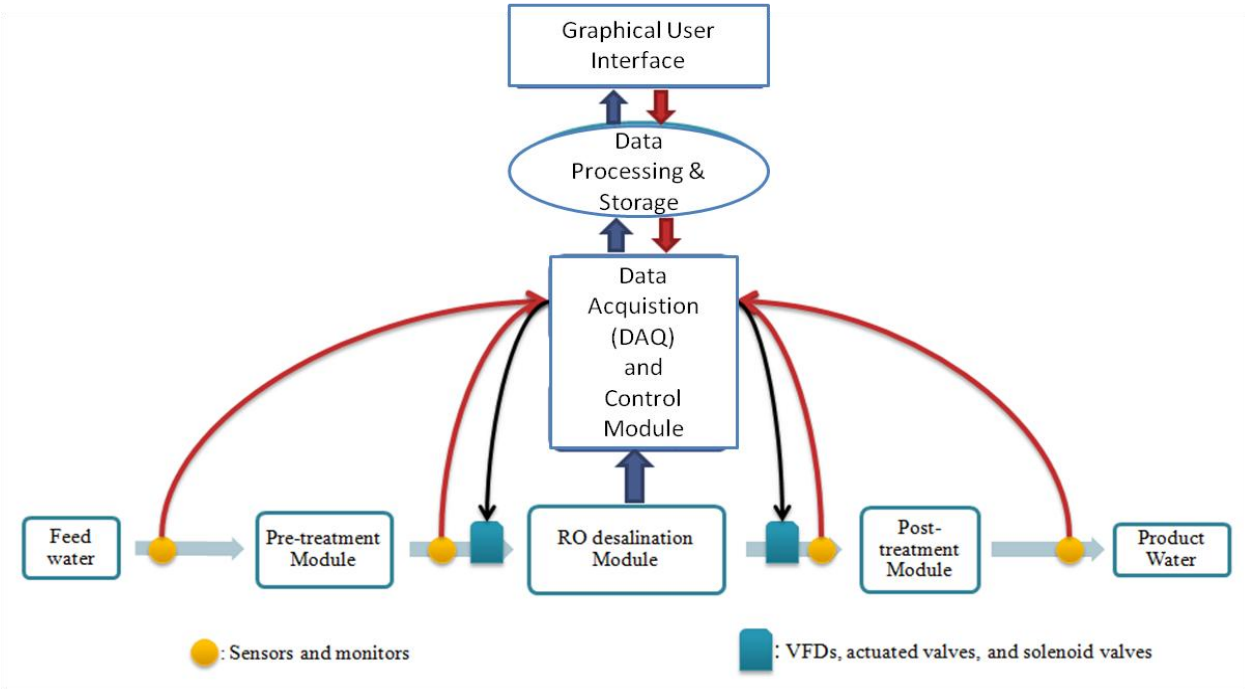

Figure 3. Modular design block diagram of Mini-Mobile-Modular (M3) desalination system.

2.3. High recovery RO desalting

The UCLA WaTeR Center has also been active in developing new and improved processes from high recovery desalting of brackish water. For example, the integration of intermediate concentrate demineralization (ICD) with RO desalting has been reported as a promising approach for concentrate minimization in a variety of brackish water desalting applications [1, 7-12]. In the ICD approach, a primary RO (PRO) step desalts the brackish source water up to a water recovery level just below the threshold of membrane mineral scaling. Mineral scale precursors are subsequently removed from the PRO concentrate in an ICD step in which sparingly soluble mineral salts are precipitated and subsequently removed via solids-liquid separation (e.g., sedimentation and filtration). The ICD step lowers the mineral scaling propensity of the PRO concentrate, thereby enabling additional product water recovery from the PRO concentrate in a subsequent secondary RO (SRO) desalting step and reducing the final volume of the residual SRO concentrate waste.

Previous laboratory and pilot-scale studies have shown that conventional precipitation softening (CPS) is an effective, but chemical-intensive ICD method [1, 9, 10]. For example, CPS, which involves calcium ion removal as $CaCO_3$, can be applied for desupersaturating/ undersaturating PRO concentrate with respect to calcium-containing mineral scalants (e.g., gypsum ($CaSO_4 \bullet 2H_2O$) and calcium carbonate ($CaCO_3$)) [1, 10]. Precipitation softening relies on the use of alkaline chemicals (e.g., $Ca(OH)_2$ (lime), NaOH, or Na_2CO_3) to generate the required PRO concentrate supersaturation for inducing and driving $CaCO_3$ precipitation. The alkaline chemicals are needed in (at least) stoichiometric amounts with respect to the desired extent of calcium removal, which in turn dictates the attainable level of overall water recovery enhancement via a subsequent SRO desalting step.

An alternative ICD method is needed when the supersaturated mineral scalants of concern in the PRO concentrate is stabilized by antiscalant carryover from the PRO desalting step. Inoculation of the supersaturated PRO concentrate with seed crystals can enable concentrate desupersaturation via precipitative seed crystal growth [8, 13, 14]. Because the pre-existing PRO concentrate supersaturation is utilized to drive precipitative crystal growth, coupled with the potential ability for recycling and reuse of seed crystals, seeded precipitation may potentially be a less chemical-intensive ICD method than chemical precipitation (e.g., precipitation softening via caustic, lime, or soda ash addition). However, antiscalant carryover from the PRO concentrate can significantly retard or inhibit crystal growth in seeded precipitation and can thus significantly lower the rate of concentrate desupersaturation [14].

A two-step chemically-enhanced seeded precipitation (CESP) process was recently demonstrated at UCLA [15] for accelerated desupersaturation of antiscalant-containing, gypsum-supersaturated model solutions, for reverse osmosis (RO) concentrate from RO desalting of agricultural drainage water of high mineral scaling propensity. In the UCLA patent pending CESP process [15, 16], $CaCO_3$ precipitation is first induced via lime dosing for antiscalant scavenging, followed by subsequent $CaSO_4$ precipitation via gypsum seeding for concentrate desupersaturation. The lime-precipitated $CaCO_3$ particles were able to scavenge antiscalants, thereby facilitating subsequent $CaSO_4$ precipitation to progress with minimal retardation.

A potential implementation of CESP as an intermediate concentrate demineralization (ICD) step in a high recovery desalting process is shown schematically in **Figure 4**. In this process configuration, the function of primary RO (PRO) desalting, in addition to recovering product water, is to increase the gypsum supersaturation of the PRO concentrate up to the limit imposed by the effectiveness of antiscalant treatment (i.e., SI_G=$SI_{G,max}$). In the subsequent ICD step, desupersaturation of the PRO concentrate via CESP is achieved through sequential addition of lime and gypsum seed crystals, utilizing two separate reactors for lime pretreatment (LP) and gypsum seeded precipitation (GSP). Solids from the GSP reactor are partially recycled in order to minimize make-up gypsum seed crystals. After solids-liquid separation (e.g., via sedimentation and microfiltration), the desupersaturated PRO concentrate is subsequently desalted via secondary RO (SRO) in order to enhance the overall product water recovery. To further enhance the overall water recovery, part of the residual SRO concentrate can be recycled to the ICD feed, while the remaining residual concentrate is purged from the process for residual concentrate management or disposal.

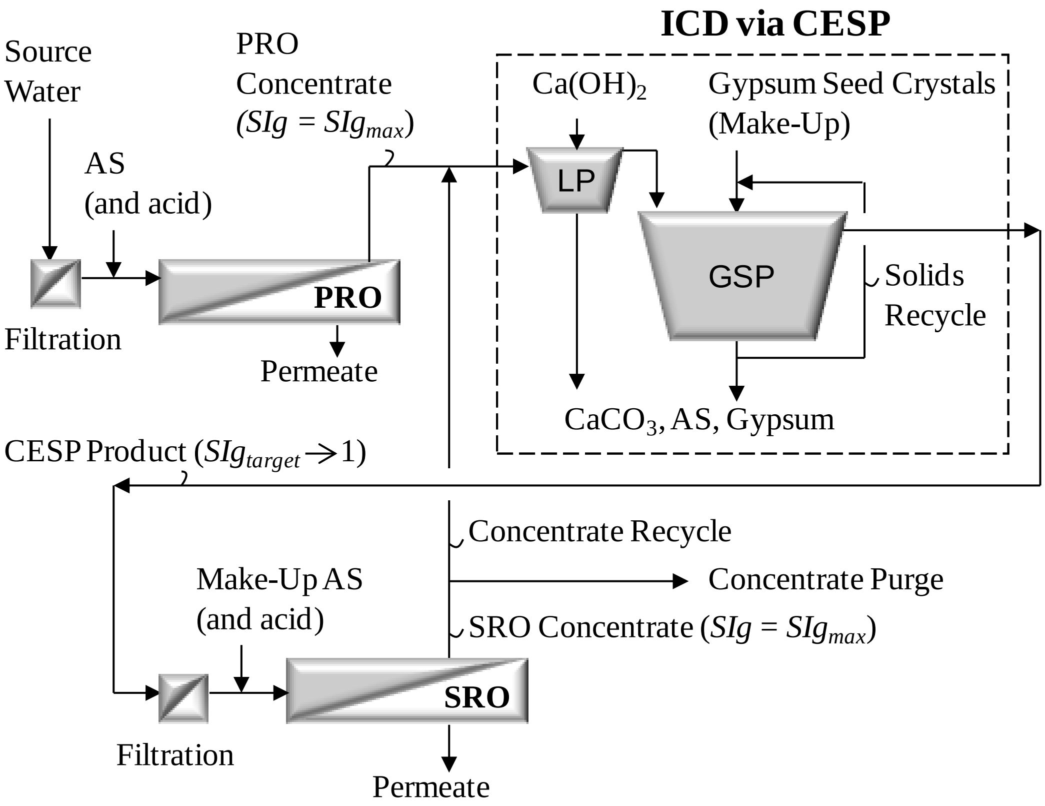

Figure 4. *A high recovery desalting process that integrates primary RO (PRO) desalting, intermediate concentrate demineralization (ICD) via chemically enhanced seeded precipitation (CESP), and secondary RO (SRO) desalting. AS: antiscalant,* SI_G*: gypsum saturation index, AP: alkaline pretreatment step of CESP, GSP: gypsum seeded precipitation step of CESP.*

3. GOAL AND OBJECTIVES

The goal of the present field study was to demonstrate a rapid and systematic approach for determining process requirements of high recovery RO desalting of San Joaquin Valley agricultural water. Using advanced process evaluation platforms (i.e., the MeMo and the M3 systems) and methodology, the approach was demonstrated in the field using AD water source from Drainage Sump 25 (DP-25) in the Panoche Water and Drainage District (PWDD). The specific objectives were:

A. *Rapid evaluation of agricultural drainage water desalting*

1. Deploy the M3 RO desalination system at DP-25 test site
2. Install the appropriate feed water pretreatment system for the M3
3. Investigate scaling propensity of the drainage water at DP-25 test site and its controllability with commercial antiscalant usage and feed flow reversal
4. Perform batch tests to evaluate the feasibility of accelerated chemical demineralization via chemically-enhanced seeded precipitation CESP.
5. Develop cost estimate for high recovery

B. *Bench-scale RO concentrate desupersaturation evaluation and preliminary desalination system design specifications*

1. Carry out small scale crystallization tests to evaluate the potential of desupersaturation of the primary RO concentrate via CESP for further desalting in a secondary RO desalting stage to increase water recovery
2. Develop system design specifications for the integrated RO-chemical demineralization process

4. RO DESALINATION RECOVERY LIMITS

4.1. RO Desalination Recovery Limits

The product water recovery, Y, of an RO desalination process is defined as the ratio of the volumetric permeate flow rate, Q_P, to the feed flow rate, Q_F ($Y = Q_P/Q_F$). As permeate is withdrawn from the feed stream, the retentate stream is concentrated by a factor, CF, defined as the ratio of the salt concentration in the retentate, C_R, to that in the feed, C_F, and is related via a material balance to the recovery and the observed salt rejection, R_S ($R_S = 1 - C_P/C_F$, where C_P is the permeate salt concentration) as given below [3]:

$$CF = \frac{1 - Y(1 - R_S)}{1 - Y} \tag{1}$$

As the permeate recovery increases, the concentrations of sparingly soluble mineral salts in the membrane channel increase and can exceed their saturation levels. As a consequence, membrane scaling may occur leading to permeate flux decline and eventually shortening of the membrane useful life. The saturation level for a given mineral salt *i* can be expressed conveniently in terms of its saturation index, SI_i, defined as,

$$SI_i = \frac{IAP_i}{K_{SP,i}} \tag{2}$$

where IAP_i is the ion activity product of the constituent ions and $K_{SP,i}$ is the solubility product. Often, the RO feed is dosed with antiscalant (AS) additives to enable RO operation at or above saturation for the mineral scalant of concern (i.e. $SI_i \geq 1$). The scaling threshold is the *SI* above which membrane scaling is likely to occur even with the use of antiscalants. For example, recommended scaling thresholds when using appropriate antiscalants, for gypsum, silica, and calcite are SI_G = 2.3–4, SI_S = 1–3, and SI_C = 63-790, respectively, [17]. It is noted that the saturation index of calcite, due to its strong pH dependence, can be reduced by acid dosing. However, a recent study [4] indicates that operating at reduced pH in waters rich in sulfate may be counterproductive because, while the SI_C may decrease, the rate of gypsum precipitation may increase due to the decreased bicarbonate concentration, reducing the positive effect of bicarbonate in retarding gypsum scale formation.

The recovery limits for a given water sample are determined by the *CF* at which the retentate concentrations reach either the mineral salt scaling thresholds or the CF at which the osmotic pressure reaches the maximum rated operating pressure of the RO pressure vessels (typically 600 psi for brackish water membranes). Accordingly at the determined CF limit, the recovery limit is determined from rearrangement of Eq. (1):

$$Y = \frac{CF - 1}{CF - 1 + R_S} \tag{3}$$

In the present work, saturation indices at the different operating conditions and osmotic pressures were calculated with multi-electrolyte aqueous speciation software [18, 19]. Recovery limits were estimated at the selected *CF* values based on 98% salt rejection.

4.2. Recovery Limits for an RO Desalination Plant

As water permeates through an RO membrane, rejected salt ions accumulate near the membrane surface leading to a concentration at the membrane surface greater than the bulk concentration. Concentration polarization results in the scaling threshold that is reached at the membrane surface at a lower concentration relative to the retentate concentration, and thus a lower recovery limit than estimated based on a mixed-cup average retentate concentration as in Eq. (3). Accordingly, recovery limits were estimated for RO plant operation by accounting for concentration polarization at the exit of the tail element of a typical RO process (based on typical concentration polarization allowance) under manufacturers' recommended operating conditions. For example, a manufacturer may specify that the concentration polarization modulus, *CP*, be no greater than 1.1 (i.e. $C_M / C_B \leq 1.1$) in a spiral-wound RO membrane element [20]. The concentration polarization modulus can be estimated for an RO process based on film theory [21]:

$$CP = \frac{C_M}{C_B} = (1 - R_S) + R_S \exp\left(\frac{J}{\bar{k}_m}\right) \tag{4}$$

where J is the permeate flux and $\bar{k}_m$ is the average feed-side mass transfer coefficient and C_B is the bulk retentate concentration which is considered to be invariant along the membrane channel (i.e. $C_B = C_F$). The concentration polarization modulus depends on the operating conditions of a specific RO process (e.g. applied & osmotic pressures, and cross-flow velocity. It is noted that when the applied pressure approaches the retentate osmotic pressure in the exit region of the element, the flux approaches zero and $\lim_{J \to 0} CP = 1$, in which case $C_B = C_M$ (i.e. the boundary layer fills the channel) [22]. In the present work, a generalized single-parameter relationship accounting for concentration polarization in the exit region of the tail element was defined relating the membrane concentration to the retentate concentration by a factor α ($1 < \alpha \le 1.2$ based on typical RO process operating conditions [20, 23]) such that $C_M = \alpha \cdot C_R$. Thus, product water recovery may be estimated based on a revised version of Eq. (3) accounting for the allowable level of concentration polarization [3]:

$$Y = \frac{CF/\alpha - 1}{CF/\alpha - (1 - R_S)} \tag{5}$$

Following the above approach, recovery limits were first estimated based on the bulk CF for which the concentration reaches the scaling threshold for the limiting mineral scalant (e.g., $SI_G = 2.5$) and then were corrected to account for concentration polarization using Eq. (5) The factor α may be assigned a typical operational value based on spiral-wound membrane manufacturers' guidelines (e.g., $\alpha = 1.1$) in order to estimate recovery limits.

4.3. Estimating RO process recovery using the MeMo system

The field-deployable plate-and-frame membrane monitor (MeMo) system in the present study operated at very low recoveries (<2%) while the M3 RO plant was expected to operate at significantly higher recoveries (e.g., >35%). Therefore, in order to appropriately relate operational recovery data from the above two RO systems, the level of concentration polarization in the MeMo system was adjusted such that the salt concentration at the membrane surface would be at the range encountered in plant-scale RO systems operating at higher recoveries relative to the MeMo system. The equivalent recovery for the MeMo system is defined as the recovery at which a full-scale RO system would experience a concentration at the membrane surface in its retentate exit region equivalent to the average membrane surface concentration in the MeMo system. The average surface concentration for the MeMo system was found by calculating an average concentration polarization modulus, $\overline{CP}$ defined as $\overline{CP} = \bar{C}_M / C_F$ where $\bar{C}_M$ is the average concentration at the membrane surface), for the membrane channel from a correlation developed specifically for the rectangular RO channel of the MeMo system[6] based on extensive CFD simulations. Given the calculated average level of concentration polarization, $\overline{CP}$, the average SI_i at the membrane surface ($\overline{SI}_{M,i}$) in the MeMo system, $\overline{SI}_i$, was calculated for the conditions present at the membrane surface as indicated below [3]:

$$\overline{SI}_{M,i} = \frac{IAP_{M,i}}{K_{SP,i}} = \frac{\overline{CP}^n}{K_{SP,i}} \prod_j C_{B,j} \cdot \gamma_j \tag{6}$$

where $IAP_{M,i}$ is the ion activity product at the membrane surface for mineral salt i, $C_{B,j}$ is the bulk concentration of mineral salt's constituent ion j, γ_i is the activity coefficient of ion j at the membrane surface, and n is the number of ions in mineral salt i. This approach accounts for changes in both ion concentrations and activity coefficients assuming that the level of concentration polarization is the same for all ions. The equivalent recoveries were then calculated from Eq. (5) assuming a reasonable RO element concentration polarization allowance of 10% ($\alpha = 1.1$).

5. RAPID EVALUATION OF RO DESALTING PROCESS

5.1. Rapid deployment of MeMo and M3 systems

The UCLA Membrane Monitor (MeMo) system and the Mini-Mobile-Modular (M3) RO desalination system were transported via a cargo van over a distance of 240 miles from the UCLA campus to the DP-25 test site (10 miles west of Firebaugh, CA). Including loading/unloading, transport, and installation, the MeMo and M3 systems were ready for testing in less than 12 hours (**Fig. 5**).

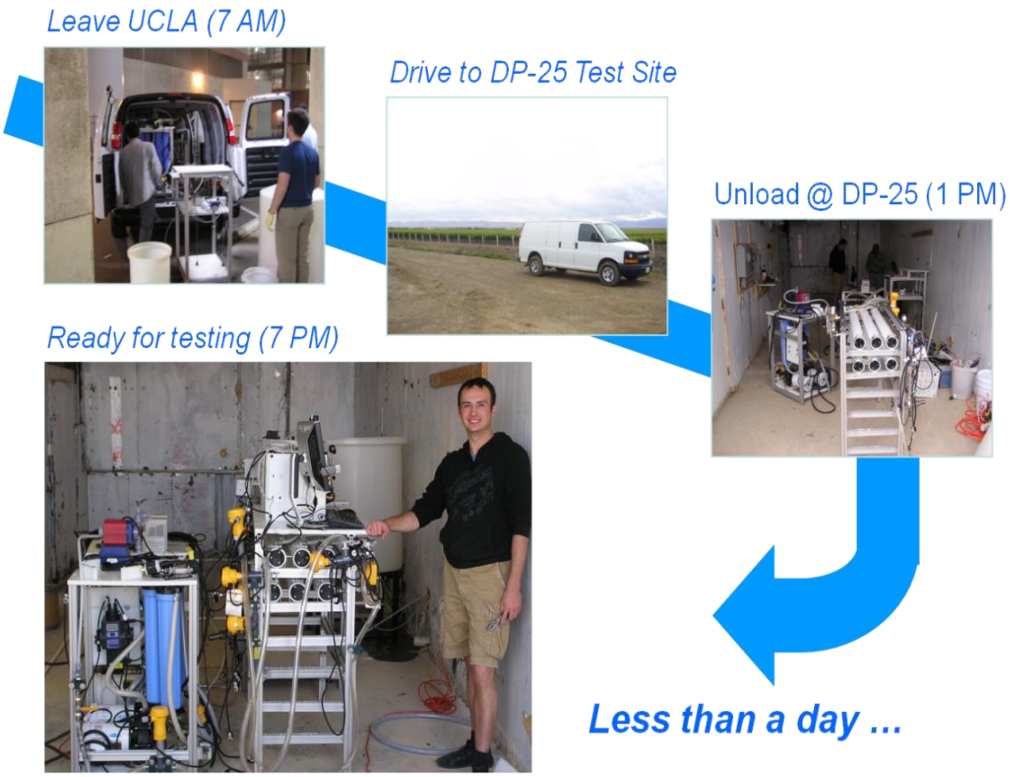

Figure 5. *Rapid deployment of UCLA Mini-Mobile-Modular (M3) RO desalination system to DP-25 test site in Panoche Water & Drainage District (PWDD).*

5.2. Membrane scaling propensity

Given that membrane mineral scaling is often the main challenge in RO desalting of AD water in San Joaquin Valley [1], the membrane scaling propensity of RO desalting the AD source water at DP-25 was first assessed via mineral solubility analysis. The saturation indices for the identified mineral scalants were calculated using a rigorous multi-electrolyte aqueous speciation software [18], based on AD water quality data for the DP-25 site determined at two different sampling dates. As listed in Appendix A, the total dissolved solids (TDS) content of the AD water was 8,500 mg/L on 4/8/09 and 14,440 mg/L on 5/19/09, respectively. Sulfate ions accounted for about 50% of the TDS content.

Despite the significant difference in TDS content of the AD source water at the two different sampling dates, the gypsum saturation index values were similar at SI_G~0.9. RO desalting of the above AD water source would result in increased SI_G of the RO concentrate with increasing water recovery. Based on solubility analysis it was predicted that, at RO water recovery >6-10%, the RO concentrate stream would become supersaturated (i.e., $SI_G > 1$) potentially leading to gypsum scaling of the RO membrane. Antiscalant treatment would be required to suppress gypsum scale formation, but is typically effective only to a maximum SI_G in the range of 2.3-4 [17], depending on the antiscalant type and dose. Given the above range of maximum SI_G for effective antiscalant treatment for mitigation of gypsum scaling, the maximum attainable water recovery was estimated to be in the range of 59%-77% (**Fig. 6**). The maximum attainable water recovery would be slightly lower in the range of 55%-75% when the effect of concentration polarization (in the tail RO element) is considered (assuming α=1.1; Eq. (5)).

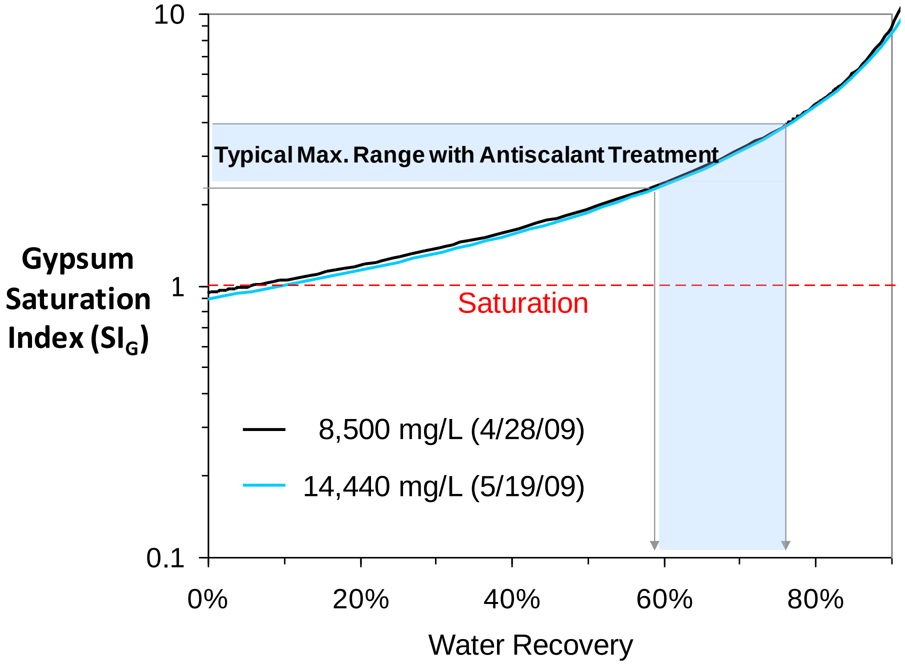

Figure 6. *The relationship between gypsum saturation index of the RO retentate stream and RO water recovery level in RO desalting of AD water at DP-25 test site. Gypsum saturation index was calculated based on feed water quality data of two different samples having different total dissolved solids (TDS) content. (Note: In order to account for concentration polarization, the recovery and saturation index have to be adjusted as per Eqs. 5 and 6, respectively).*

At the source water native pH of 7.5-7.6, the AD source water was also supersaturated with respect to $CaCO_3$ (SI_C = 3.1-4.6). Further analysis (not shown) indicated that, with RO desalting up to a water recovery level 90% (89%, assuming α=1.1), the SI_C of the RO concentrate (at the native pH) would remain well below ~ 60 [17], which is the typical maximum allowable SI_C for effective antiscalant treatment for mitigating $CaCO_3$ scaling. This analysis suggested that feed water pH adjustment may not be necessary for suppression of $CaCO_3$ scaling when antiscalant treatment is employed. Maintaining pH at a level of 7.5-8.5 can keep the bicarbonate ion sufficiently elevated to aid in gypsum scale suppression as shown in a previous UCLA study [4]. It is noted that, at water recovery above 70% (67%, assuming α=1.1), antiscalant treatment for mitigation of silica scaling may be necessary as silica would become supersaturated.

5.3. Rapid development and demonstration of the feasibility of RO desalting

Process requirements and feasibility of RO desalting of AD water were evaluated at the DP-25 field site via systematic field tests following the methodology summarized in **Figure 7**. Process development involved optimization of feed-filtration and antiscalant treatment, as well as evaluation of feed-flow reversal to mitigate mineral scale formation. In this process development stage, optimal process operating conditions (e.g., pre-filtration configuration, antiscalant type and dose) were determined and water recovery limits (to ensure effective mitigation of gypsum scaling) were estimated using the MeMo system. A reasonable 10% RO module concentration polarization allowance (α=1.1) was assumed in estimating RO water recovery limits based on MeMo operating conditions, (e.g., see **Section 4.3**). In the subsequent process demonstration stage, the optimal process operating condition was tested and refined using the M3 system. The performance of the M3 membrane modules was monitored to evaluate the feasibility of maximizing product water recovery while averting membrane mineral scaling.

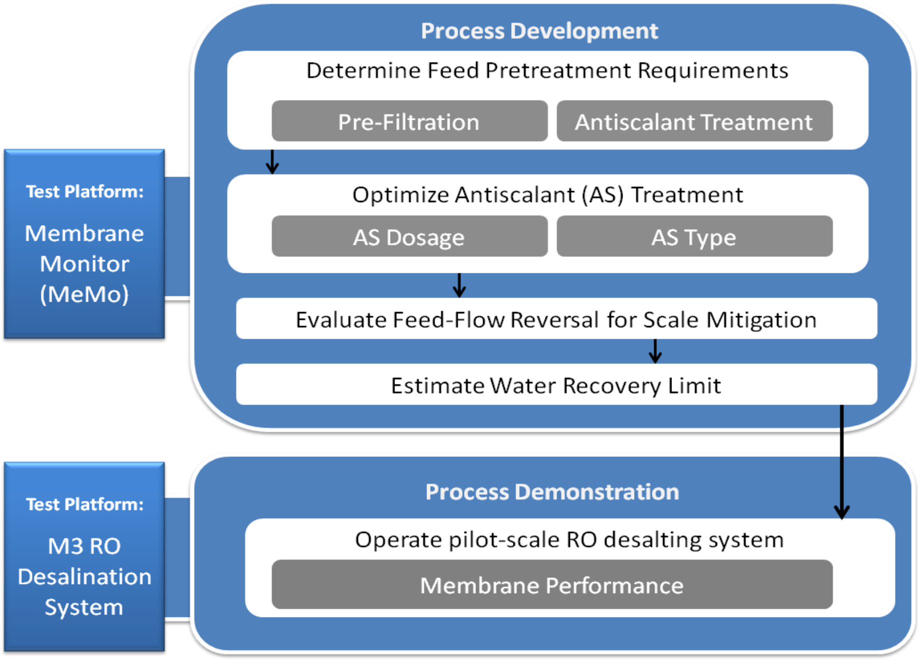

Figure 7. *Overall methodology for rapid field development and demonstration of RO desalting. AS: antiscalant.*

5.3.1 RO desalting process development

5.3.1.1. Evaluation of RO pretreatment requirements

The RO feed water pretreatment included feed-filtration for suspended solids removal and antiscalant dosing for suppression of membrane mineral scaling. The RO feed pretreatment system was first configured as illustrated in **Figure 8** (RO Feed Pretreatment Configuration 1, FPC1). Subsurface drainage water was pumped into an existing holding tank using the existing well pump and feed water intake system. Water from the holding tank was then fed into a series of 5 micron and 0.45 micron filter cartridges for feed-filtration. Antiscalants, when employed, were metered into the feed water near the cartridge filter inlet. To evaluate the effectiveness of the RO feed pretreatment system, the pre-filtered feed water was desalted in the MeMo system for direct online monitoring of any transformation (e.g., mineral scaling and biofouling) occurring at the membrane surface (e.g., due particle deposition or mineral scale crystallization).

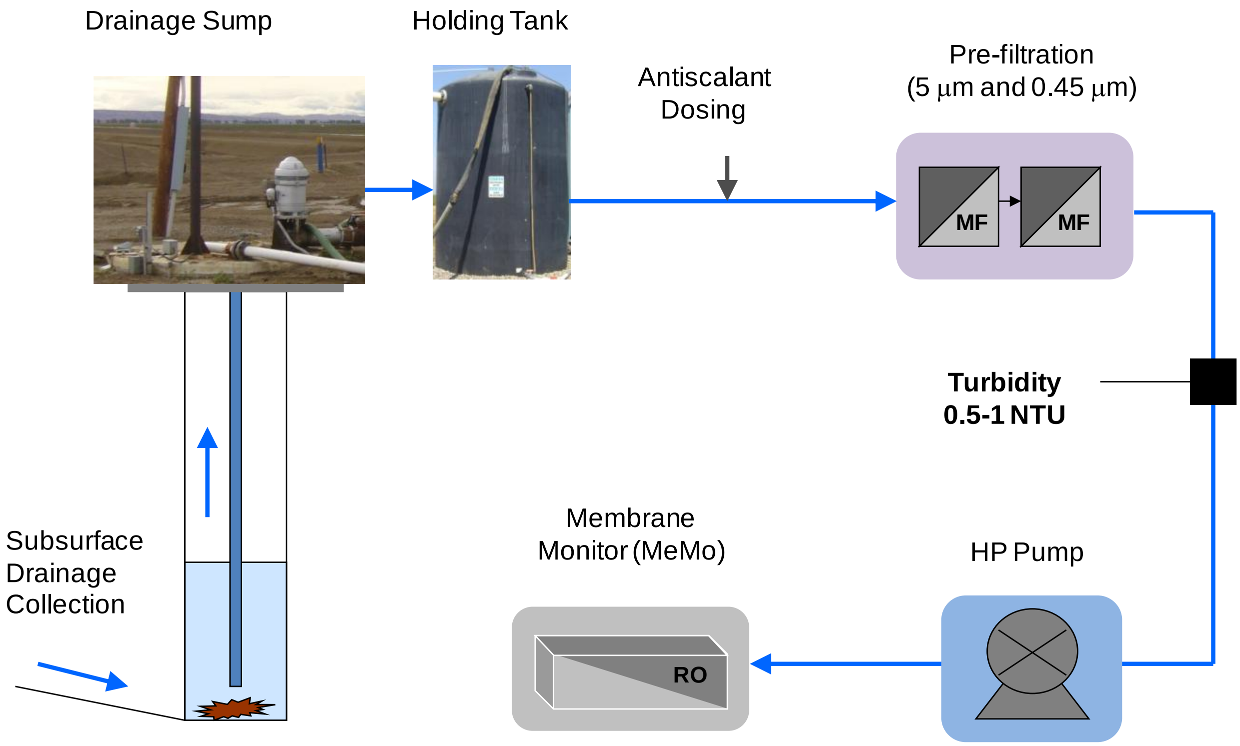

Figure 8. *RO Feed Pretreatment Configuration 1 (FPC1). The performance of the RO feed pretreatment configuration was evaluated using the Membrane Monitor (MeMo).*

Rapid 60-min tests using the MeMo system indicated that cartridge filtration, as implemented in the RO Feed Pretreatment Configuration 1, was insufficient for mitigating particle deposition. The feed water turbidity level (0.5-1 NTU) was not sufficiently low as fine powdery material deposited rapidly on the membrane surface during MeMo operation at SI_G ~1.7 without antiscalant treatment (**Fig. 9a**). Given the supersaturated conditions, it was postulated that suspended particulates in the feed promoted gypsum crystal nucleation and seeding crystals growth, thereby exacerbating particulate deposition. The application of antiscalant treatment (3 mg/L of Flocon 260 antiscalant; BWA Water Additives, Tucker GA) partially reduced the extent of particulate deposition retard crystal nucleation and growth, even at a higher initial SI_G of 3.1 (**Fig. 9b**). Membrane scaling was avoided with an alternate feed water line and enhanced filtration (through the addition of a media filter) in combination with antiscalant dosing as depicted in **Fig. 10** and described below.

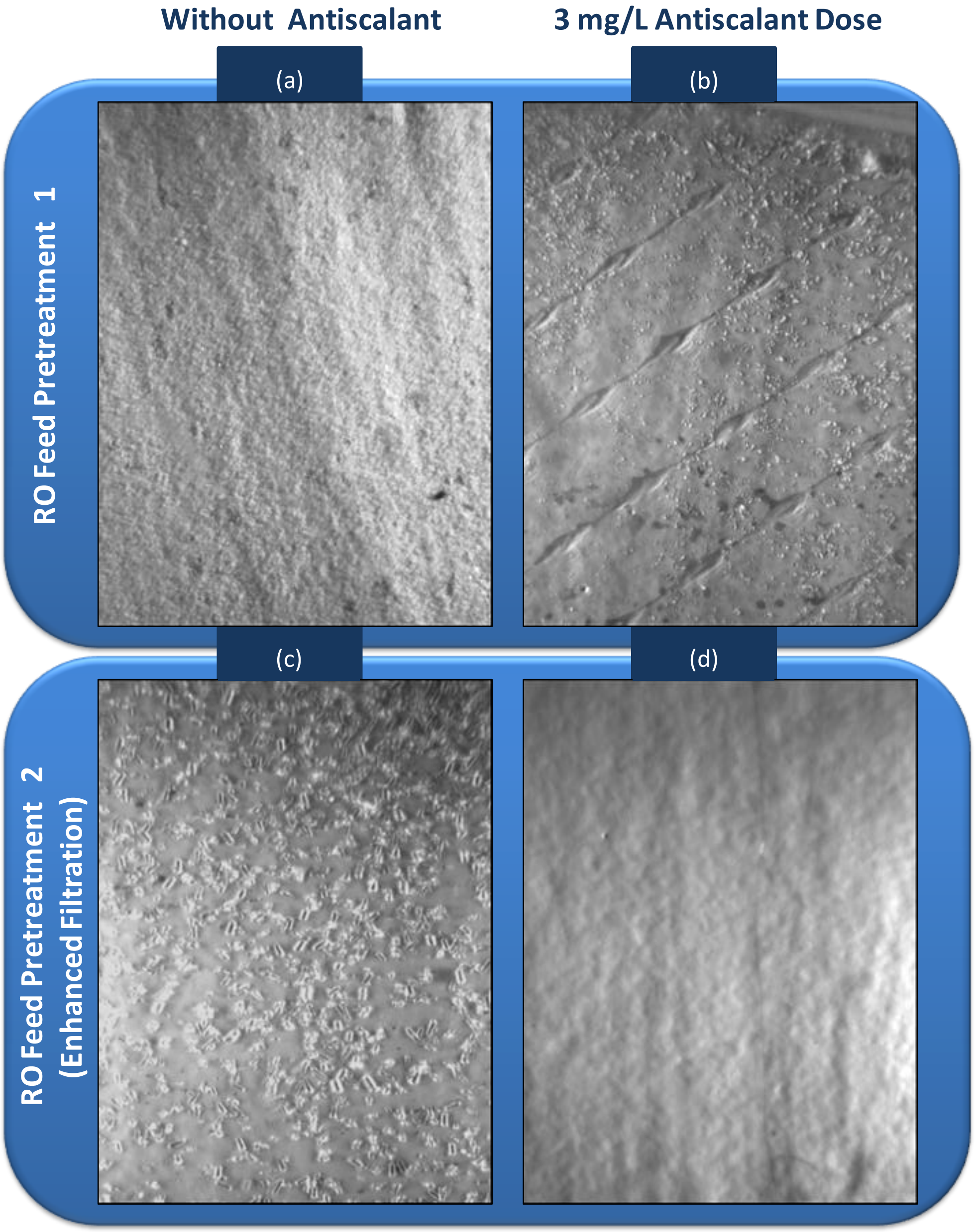

Figure 9. *Membrane surface images taken after 60 minutes of RO desalting with MeMo to compare (a-b) RO Feed pretreatment Configurations 1 (FPC1;* ***Fig. 7****) and (c-d) FPC2 (i.e., with enhanced filtration;* ***Fig. 8****). Antiscalant pretreatment consisted of dosing the RO feed water with 3 mg/L of Flocon 260. Initial* SI_G *at the membrane surface: (a) 1.7 (b-d) 3.1. Note: The observed grooves ion the membrane coupon (b) are due to the spacers of the membrane element from which the membrane coupon was taken for evaluation in the MeMo RO cell.*

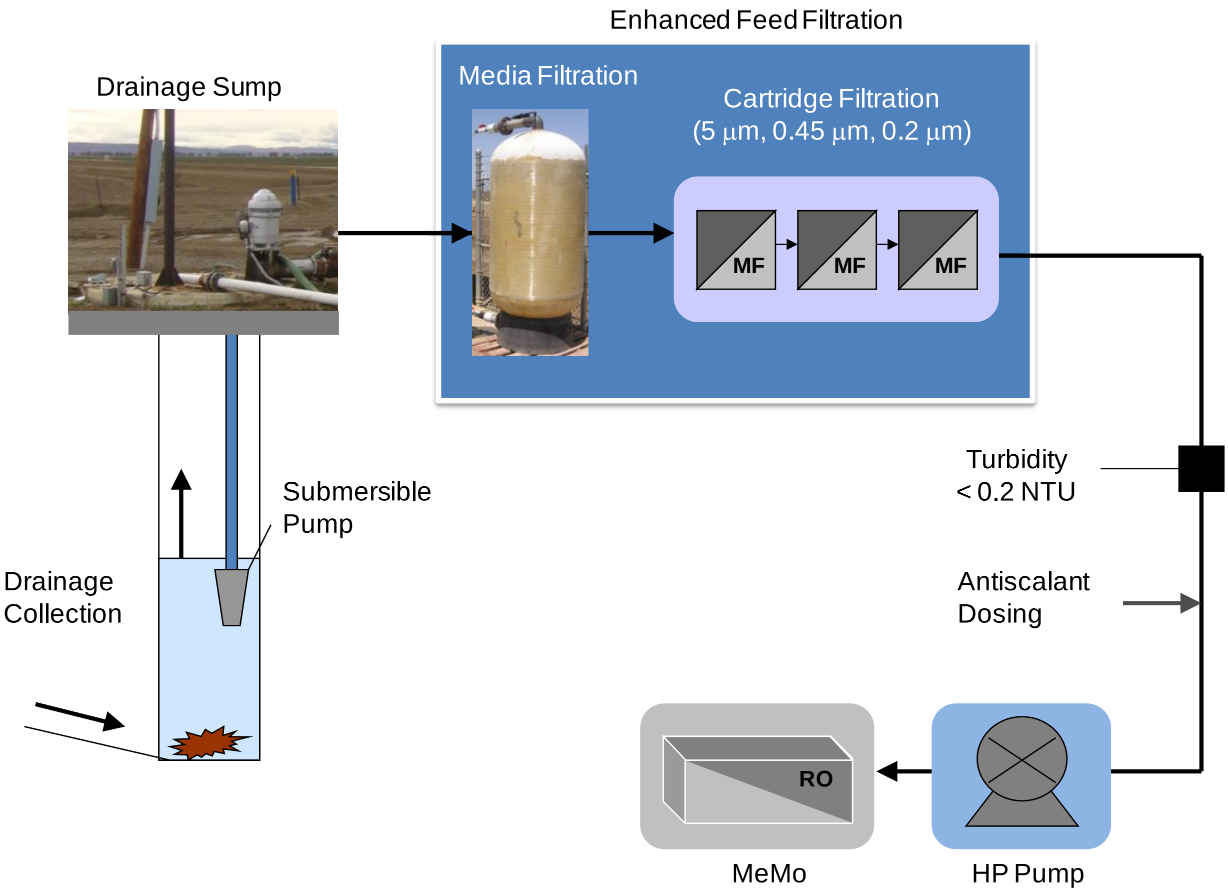

Figure 10. *RO Feed Pretreatment Configuration 2 (FPC2). The performance of the RO feed pretreatment configuration was evaluated using the Membrane Monitor (MeMo).*

With RO Feed Pretreatment Configuration 1 (**Fig. 8**), it was suspected that, given the existing feed water intake positioning close to the bottom of the well, hydrodynamic disturbances near the bottom of the well (created by the suction effect of the existing well-pump) resulted in suspension of small particles that entered the system, thereby resulting in RO feed turbidity level (0.5-1 NTU) that was insufficient to avoid RO membrane fouling. To avoid this problem, an alternative feed line was utilized, using a submersible pump positioned near the top of the well for feed intake and bypassing the holding tank (**Fig. 10**). Furthermore, enhanced filtration was added by including media filtration and an additional cartridge filter (0.2 micron) as implemented in RO Feed Pretreatment Configuration 2 (FPC2; **Fig. 10**). Using the MeMo system (operated at an initial SI_G of 3.1), the effectiveness of the alternate feed line and enhanced feed filtration was demonstrated for reducing the extent of fine particulate deposition on the RO membrane surface, as well as for a more effective antiscalant treatment to mitigate mineral scaling. Reduced extent of fine particulate deposition was indeed observed during MeMo operation without antiscalant treatment. Mineral salt crystals did not deposit on the membrane surface as fine particulates (from the bulk solution), but formed (i.e., nucleated) and grew directly on the membrane surface (i.e., surface crystallization; **Fig. 9c**). Given the gypsum supersaturation conditions (SI_G of 3.1) in the membrane scaling test, it was expected that the mineral salt crystals observed on the membrane surface would be gypsum; this was confirmed by the shape of gypsum rosettes on the membrane surface under scaling conditions. With antiscalant treatment (3 mg/L Flocon 260), mineral scale formation within the 60-min rapid testing period was suppressed as was evident from the lack of mineral salt crystals on the membrane surface (**Fig. 9d**). The above results confirmed that both enhanced removal of suspended particulates and antiscalant treatment are required for pre-treating/pre-conditioning the AD source water (and can be achieved via FPC2) prior to RO desalting.

5.3.1.2. Optimization of antiscalant treatment

The appropriate antiscalant type and the required antiscalant dose for mitigating mineral scaling were determined for RO desalting of the DP-25 AD water, pretreated by enhanced feed filtration (i.e., FPC2; **Fig. 10**). For this purpose, rapid membrane scaling tests, utilizing different antiscalant type and dose, were conducted under field conditions using the MeMo system. Given that antiscalant treatment is expected to effectively mitigate gypsum scaling at SI_G of up to 2.3-4, the maximum attainable water recovery, as predicted via mineral solubility analysis (see **Section 5.2**), was expected to be in the range of 55%-75% (with RO module concentration polarization allowance of 10%; α=1.1, see Eq. 5). In order to optimize antiscalant treatment, membrane scaling tests were first conducted, using the MeMo system, at a reasonable initial SI_G of 3.1 at the membrane surface, which was selected in order to mimic the supersaturation condition in an RO desalting process that would operate at an equivalent water recovery of 66% (with α=1.1). Time-lapsed MeMo membrane surface images, taken during the rapid membrane scaling tests, were analyzed to quantify the time evolution of the surface mineral scale (percent) coverage in the magnified portion of the MeMo membrane surface (e.g., see **Fig. 1**)

Two types of antiscalants were selected for field testing, based on antiscalant testing in previous laboratory studies [4, 24]: PC504T (Nalco Co., Naperville, IL) and Flocon 260 (BWA Water Additives, Tucker, GA). Compared at the same initial gypsum saturation index (SI_G=3.1) and antiscalant dose in the feed (3 mg/L), the evolution of surface mineral scale coverage on the RO membrane was significantly slower with feed treatment with PC504T (Nalco Co., Naperville, IL) than with Flocon 260 (BWA Water Additives, Tucker GA) as shown in **Fig. 11a**. These results suggest that PC504T was more effective in delaying the onset of scaling (i.e., nucleation) and reducing the growth rate of gypsum crystals on the membrane surface, (i.e., retarding gypsum scaling), thereby resulting in fewer gypsum crystals on the membrane surface (**Fig. 11b**). On this basis, PC504T was selected for antiscalant treatment in RO desalting of the AD source water.

The extent of antiscalant retardation of gypsum scaling, in part, is governed by the antiscalant dose. For MeMo operation at an initial SI_G of 3.1, corresponding to an equivalent water recovery of 66% (α=1.1), increasing the PC504T antiscalant dose in the RO feed from zero to 3 mg/L was sufficient to significantly reduce the surface scale coverage from >40% to below 3% over a 10-hour period (**Fig. 12**). One would expect that RO operation with either a slightly higher antiscalant dose (>3 mg/L) or at slightly lower equivalent water recovery (<66%) would be required in order to completely suppress membrane gypsum scaling. For the present study, a fixed PC 504T antiscalant dose of 3 mg/L in the RO feed was selected as optimal, considering that antiscalant overdosing may potentially cause membrane fouling and/or increase the potential for biofouling [17]. The water recovery limit corresponding to this optimal antiscalant dose was determined accordingly, as described **Section 5.3.1.4**.

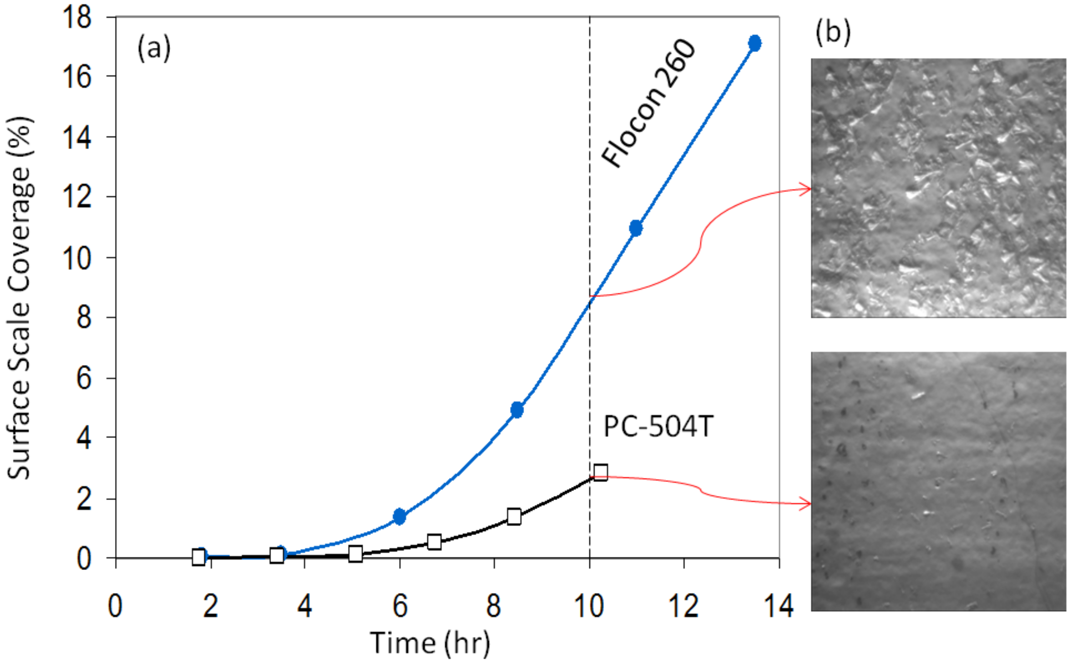

Figure 11. *Time evolution of surface mineral scale coverage of RO membranes for MeMo operation with antiscalant treatment using Flocon 260 and PC504T antiscalants. Antiscalant concentration: 3 mg/L, Initial* SI_G *at membrane surface: 3.1, Equivalent RO process recovery: 66%.*

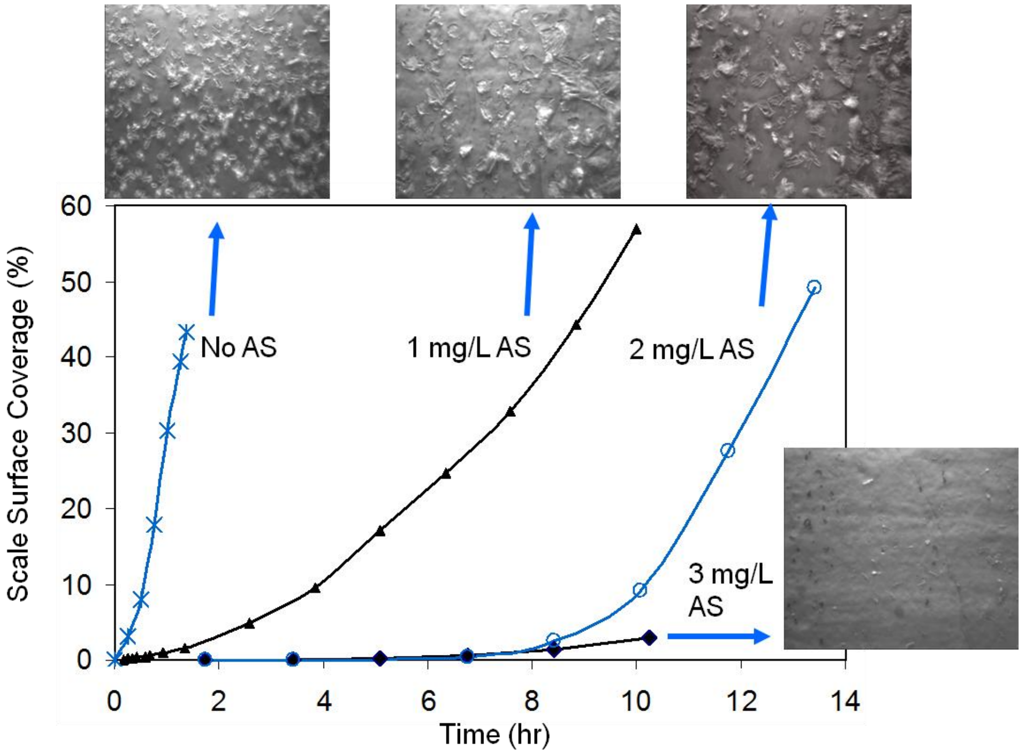

Figure 12. *Impact of antiscalant dosage on the time evolution of surface mineral scale coverage of RO membranes during MeMo operation with antiscalant treatment using PC504T antiscalant. Antiscalant concentration: 3 mg/L, Initial* SI_G *at membrane surface: 3.1, Equivalent RO process recovery: 66%.*

5.3.1.3. Evaluation of feed-flow reversal for membrane scaling mitigation

Recently, feed-flow reversal in RO/NF operation has been demonstrated as an effective, novel approach for mitigating membrane scaling in some brackish water desalting applications [5]. Using this approach, periodic changes of the feed flow direction reverses the axial direction of the concentration boundary layer development. In the forward-flow direction, the membrane areas near the concentrate fluid exit, which are prone to scale formation (near fluid exit), are exposed to a higher solute concentration. Reversal of the flow direction, just prior to the onset of mineral scaling, exposes the same membrane areas to a lower solute concentration below mineral saturation, dissolving mineral nuclei and crystals that have formed thereby resetting the crystallization induction times.

The challenge of RO operation in a feed-flow reversal model for AD water desalting is when the AD source water is at or near saturation with respect to gypsum. Under such a condition, which was the case for the DP-25 source water, the crystallization induction time on membrane surfaces would not be "reset" when nucleating crystals are exposed to feed water that is near or above saturation. If used in conjunction with antiscalant treatment, however, feed-flow reversal can prolong the crystallization induction time, which was evident from FFR operation of the MeMo system with 3 mg/L PC504T antiscalant feed treatment and operation at an initial SI_G of 3.1 (equivalent RO process recovery of 66%). Relative to normal forward-flow RO operation, the crystallization induction time was prolonged from ~5 hours to ~15 hours with FFR operation (**Fig. 13**). Therefore, in the case of AD water desalting, FFR operation may be beneficial for enhancing the effect of antiscalant treatment to mitigate membrane mineral scaling enabling operation with a reasonably low antiscalant dosage and lower frequency of membrane cleaning.

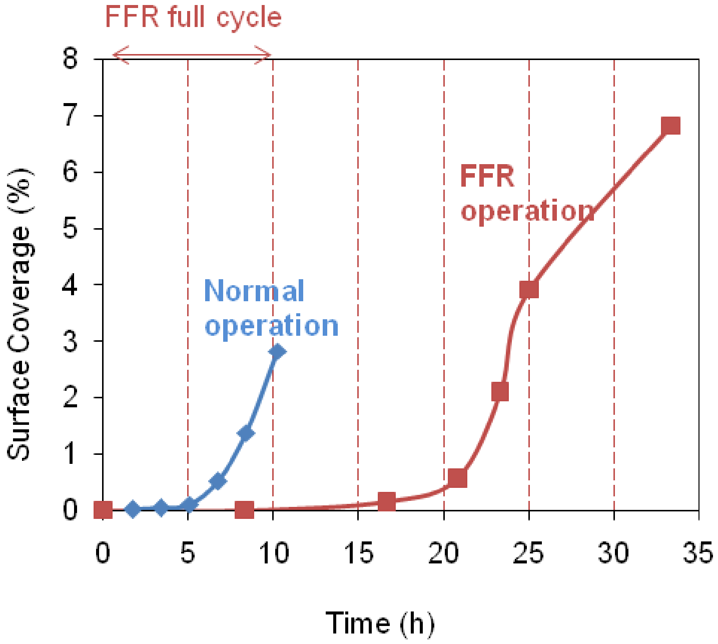

Figure 13. *Comparison of surface scale coverage for RO desalting in MeMo under normal and feed-flow-reversal (FFR) operation modes. In the FFR operation, feed flow is reversed every 5 hours (i.e., 10-hr full FFR cycle). Antiscalant dose: 3 mg/L PC504T; Initial* SI_G *at membrane surface: 3.1; Equivalent RO process recovery: 66%.*

5.3.1.4. Estimation of water recovery limit for RO desalting of AD water

Given enhanced feed filtration (with Feed Pretreatment Configuration 2, **Fig. 9**) and optimal PC504T antiscalant dose of 3 mg/L (in the RO feed), the water recovery limit was determined experimentally in the field. In determining the water recovery limit, the membrane scaling threshold (i.e., the lowest SI_G at which membrane scaling would occur) was determined by desalting the pretreated AD source water using the MeMo system, operated at successively increasing SI_G (at the membrane surface) from ~1.9 to ~3.1 over a 45-hour period (**Fig. 14**). Early indications of scale formation were first detected near the end of a 7-hour MeMo operation at SI_G of 2.9 (*t*=25-32 h). Upon increasing SI_G to 3.1 during a subsequent 12-hour period (t=33-45h), the appearance and growth of gypsum crystals on the membrane surface became clearly visible, indicating that the gypsum supersaturation level was sufficiently high to overcome the antiscalant capacity for retardation of gypsum crystallization. Therefore, it is reasonable to conclude that the membrane scaling threshold was approximately at the equivalent RO plant recovery of 64% (**Fig. 14**; estimated based on α=1.1, Eq. 5) at SI_G~2.9.

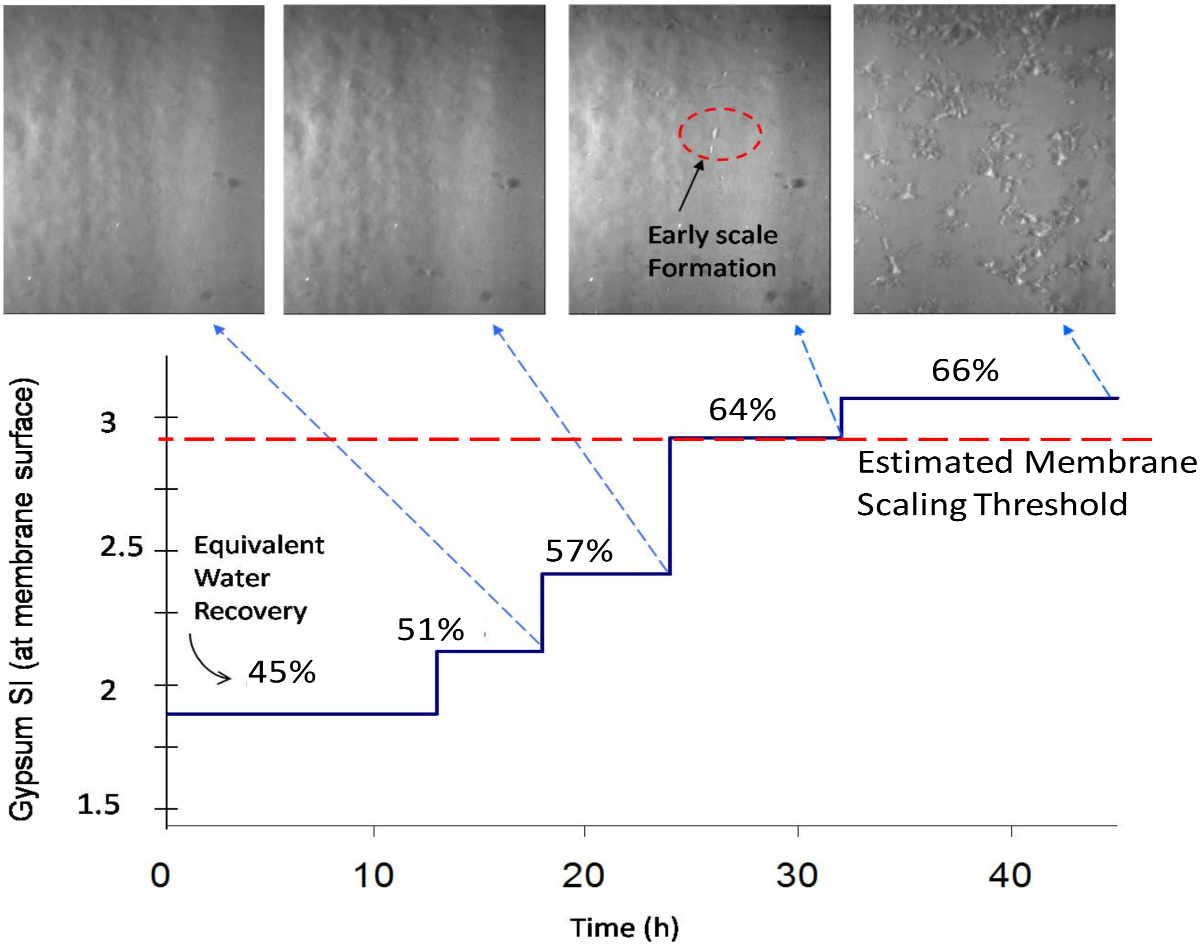

Figure 14. *Membrane surface images take during AD water desalting using MeMo at successively increasing gypsum saturation index near the membrane surface. The corresponding equivalent water recovery was calculated for an RO process with RO module concentration polarization allowance of 10% (α=1.1; see Eq. 5). Antiscalant treatment: 3 mg/L PC504T in RO feed.*

In order to completely suppress mineral scaling while maximizing product water recovery, RO desalting should be operated at a water recovery corresponding at the maximum SI_G just below the membrane scaling threshold. MeMo operation at SI_G of 2.5 (equivalent recovery of 59%), conservatively lower than the membrane scaling threshold SI_G of 2.9 (equivalent recovery of 64%), did not reveal membrane scaling over an extended operational period of 17 hours. Membrane scaling was not observed throughout the entire membrane channel in the MeMo system, including in the magnified portion of the membrane area (**Fig. 15**). Therefore, it is expected that, with enhanced feed-filtration and 3 mg/L of PC504T antiscalant treatment, the water recovery limit of RO desalting of the AD source water would be within a narrow range of 59%-64% (i.e., maximum SI_G=2.5-2.9), assuming RO module concentration polarization allowance of 10% (α=1.1).

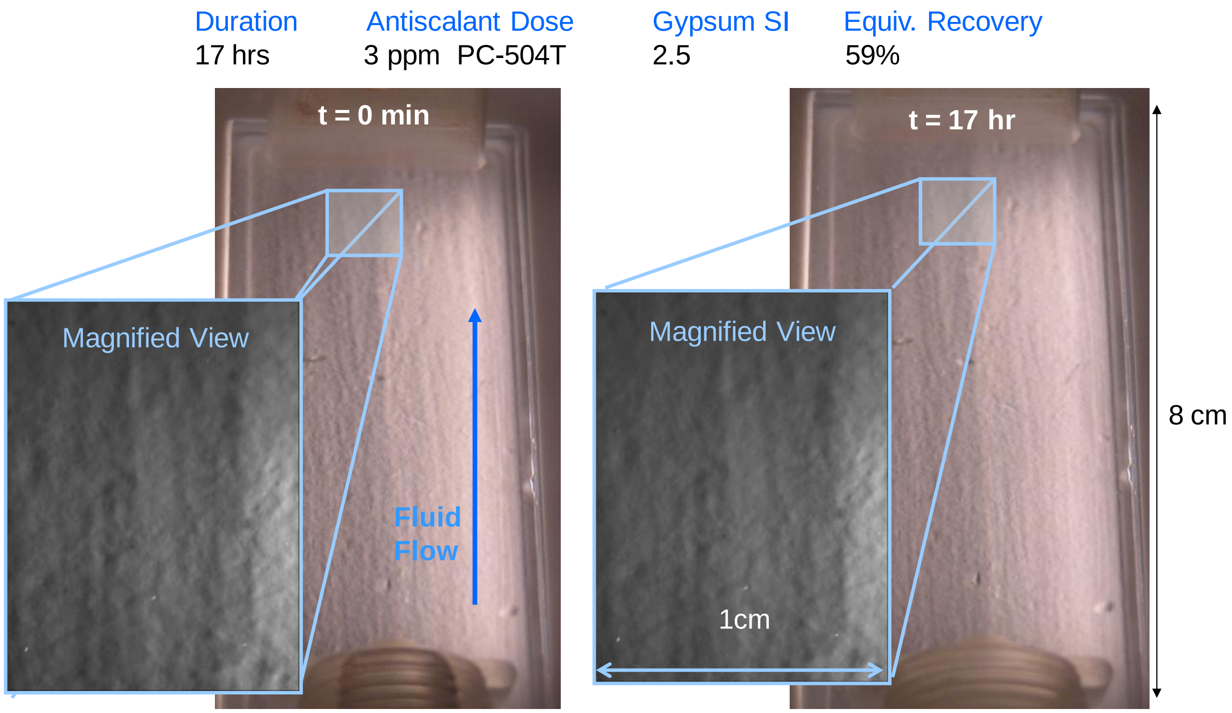

Figure 15. *Membrane surface images taken at the beginning (t=0 min) and the end (t=17 h) of a membrane scaling run with PC504T antiscalant treatment. Antiscalant dose: 3 mg/L, Gypsum saturation index near the membrane surface: 2.5, Equivalent RO process water recovery of 59%.*

5.3.2. RO desalting process demonstration

5.3.2.1. Overview

In the process demonstration stage, the optimal RO desalting process operating conditions, determined using the MeMo system, were evaluated and refined using the pilot-scale M3 RO desalting system. As illustrated in **Fig. 16**, the M3 system was fed with RO feed water from the optimized RO feed pretreatment/conditioning system, which consisted of: a) enhanced feed filtration (i.e., media filtration and cartridge micro-filtration) of AD source water to reduce feed turbidity below 0.2 NTU; and b) dosing of 3 mg/L PC-504T antiscalant of the filtered AD feed water to mitigate mineral scaling. The pretreated RO feed water was desalted in the M3 system, which utilized six RO membrane elements arranged in series (XLE 2540 elements, DOW FilmTec Corp., Minneapolis, MN). In order to monitor membrane mineral scaling in the tail RO membrane element of the M3 system, the MeMo system was interfaced with the M3 system directing to the MeMo RO feed channel a side stream of RO concentrate from the M3 RO desalting system.

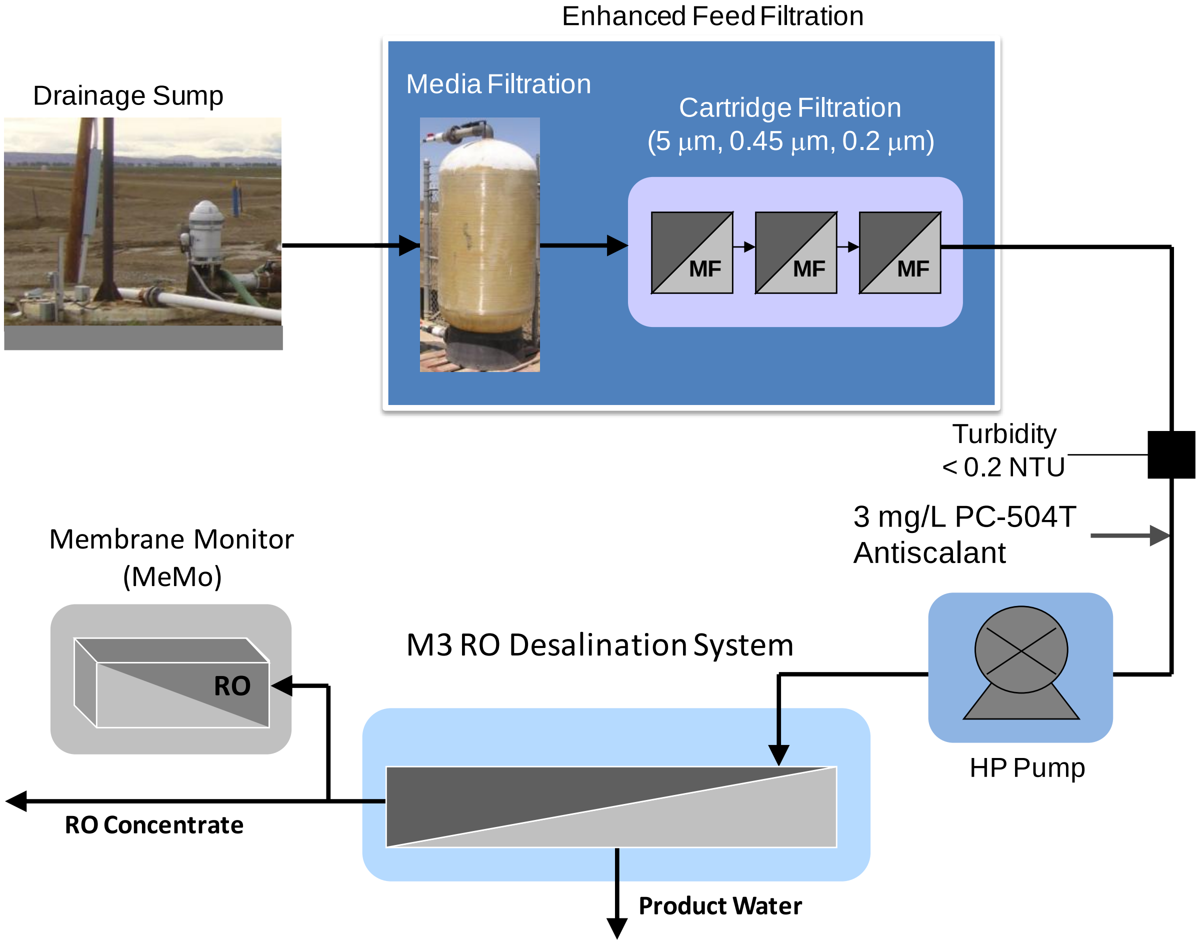

Figure 16. *Configuration of pilot-scale RO desalting process for desalting AD source water at the DP-25 test site. The M3 RO desalting system utilized 6 RO membrane elements arranged in series (DOW FilmTec XLE 2540). The MeMo system was installed and configured to monitor membrane scaling in the tail RO membrane element of the M3 system.*

5.3.2.2 Water recovery and productivity

The M3 system was operated over a period of about two weeks. In the first 8 days, the M3 system was operated at a conservatively safe water recovery range of 47-53% (**Fig. 17a**), well below the membrane scaling threshold recovery level of 64% (as predicted from the MeMo field tests; **Fig. 14**). In the last day of operation (Day 13), the M3 system was operated continuously for 16 hours at 63% water recovery, just below the membrane scaling threshold of 64% (**Fig.**

17a). During each day of M3 operation, the feed and permeate volumetric flow rates were stable (**Fig. 18**), indicating that the M3 system could be operated at sustained water productivity. One should note that, the measured product water recovery (**Fig. 17a**; based on permeate flow measurements) is related to the measured brine concentration factor (**Fig. 17b**; based on conductivity measurements) by Eq. 1 (**Section 4.1**); both measurements provided consistent results. It is also noted that the M3 system was taken offline on Day 6 and Days 9-12 due to maintenance work on the drainage sump pumps, media filter and setup for concentrate demineralization tests.

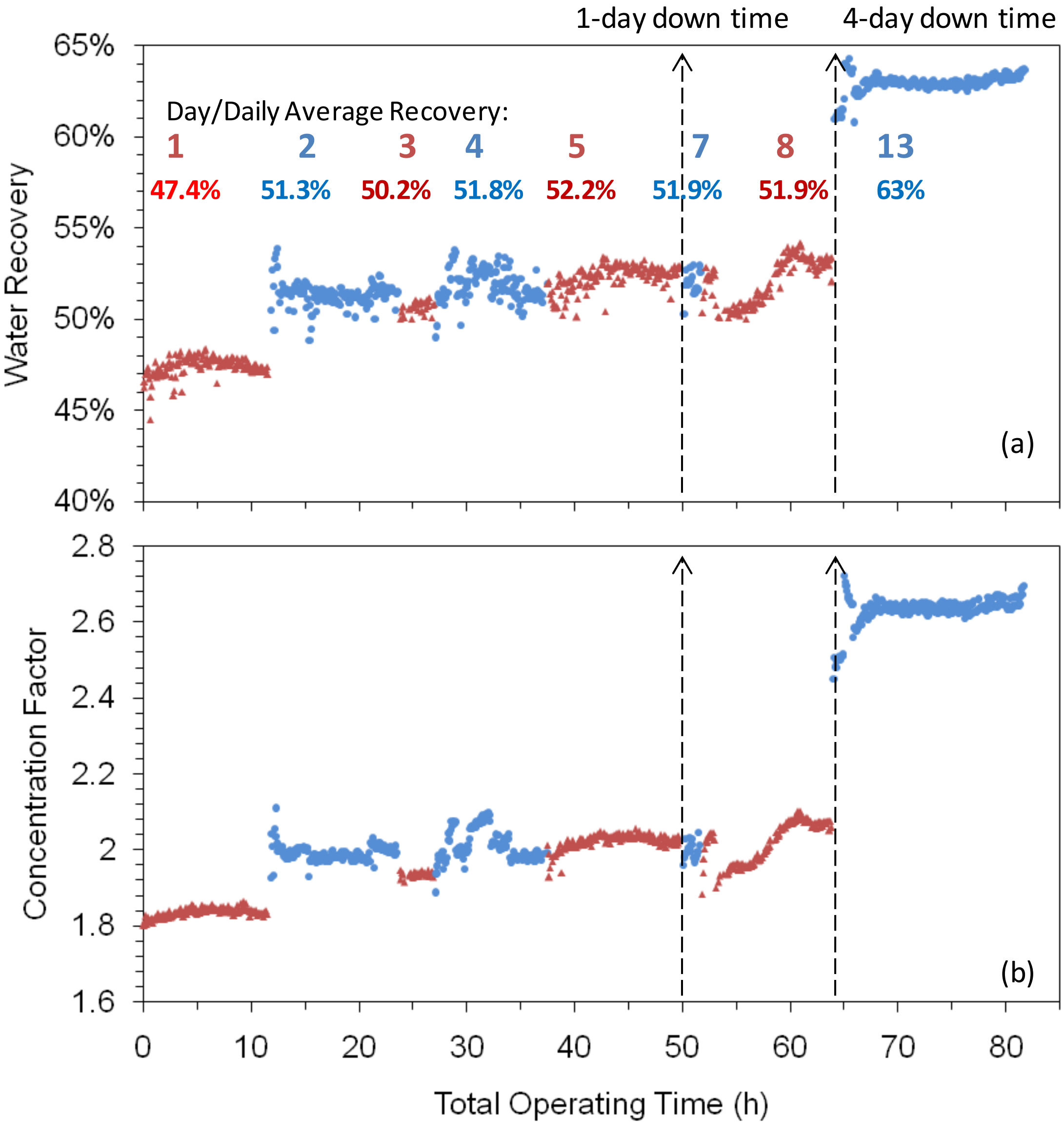

Figure 17. *(a) Water recovery and (b) RO brine concentration factor (*$CF=C_{brine}/C_{feed}$*) during RO desalting of AD source water at DP-25 site using the M3 RO desalting system. Water recovery was calculated based on permeate and brine volumetric flow rates, while the brine concentration factor was calculated based on feed and brine conductivity measurements. PC-504T antiscalant dose in RO feed: 3 mg/L.*

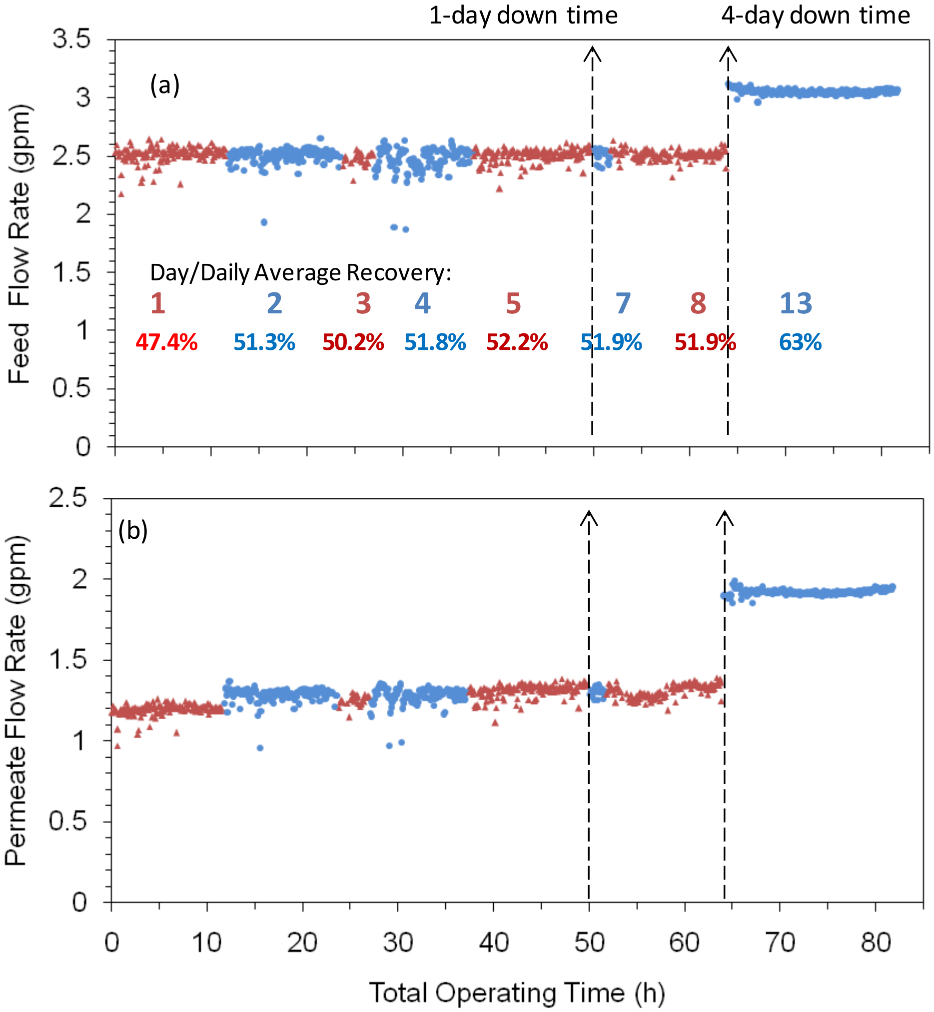

Figure 18. *(a) Feed and (b) permeate volumetric flow rates during RO desalting of AD source water at DP-25 site using the M3 RO desalting system. PC-504T antiscalant dose in RO feed: 3 mg/L*

5.3.2.3. Stable performance of M3 RO membrane elements

Throughout the operation of the M3 system, the performance of the RO membrane elements with respect to permeate productivity and salt rejection were stable, even when the M3 system was operated at 63% water recovery, just below the membrane scaling threshold (i.e., ~64% water recovery). Progressive decline in normalized permeate flux or progressive increase in normalized salt passage were not observed, indicating that there was no progressive membrane fouling/scaling or deterioration of membrane separations selectivity. In any given day of M3 operation, the average overall permeate flux, normalized per standard methods [25] and plotted in **Fig. 19** relative to the time average permeate flux in the first 2 hours (of the respective day of

M3 operation), fluctuated by less than ±10%. The normalized salt passage was also stable, averaging at ~2.4% and fluctuating within the range of 1.7-2.8% (**Fig. 20**).

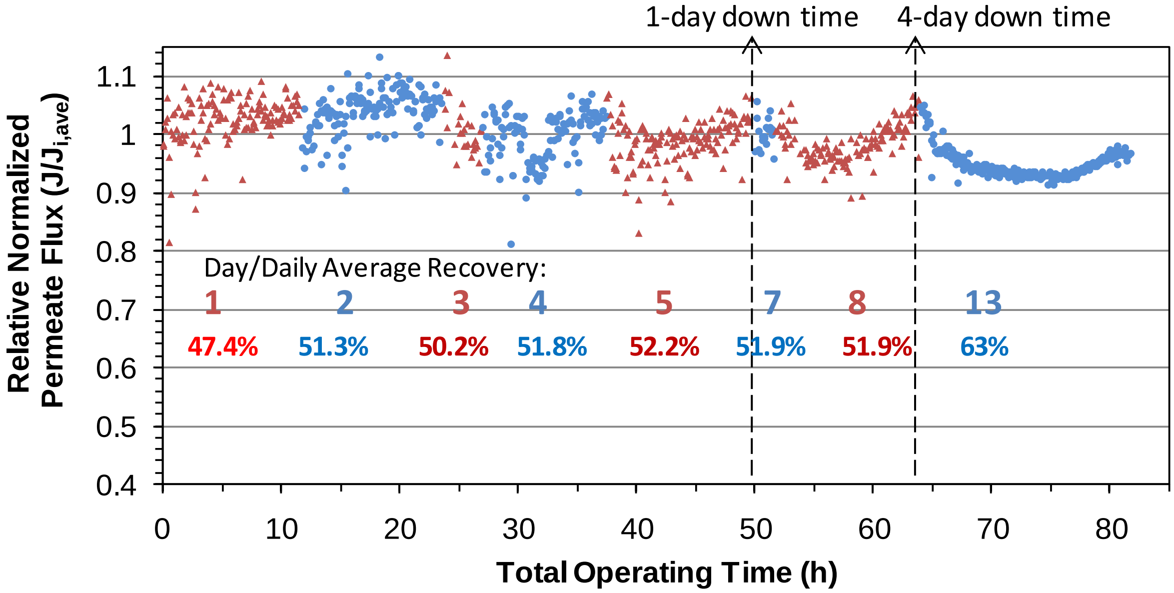

Figure 19. *Normalized permeate flux (J) of RO membrane elements (six DOW Filmtec XLE 2540 elements in series) during RO desalting of AD source water at DP-25 site using the M3 RO desalting system). The normalized flux is plotted relative to the time average normalized flux in the first 2 hours in the respective day of M3 operation ($J_{i,ave}$). PC-504T antiscalant dose in RO feed: 3 mg/L.*

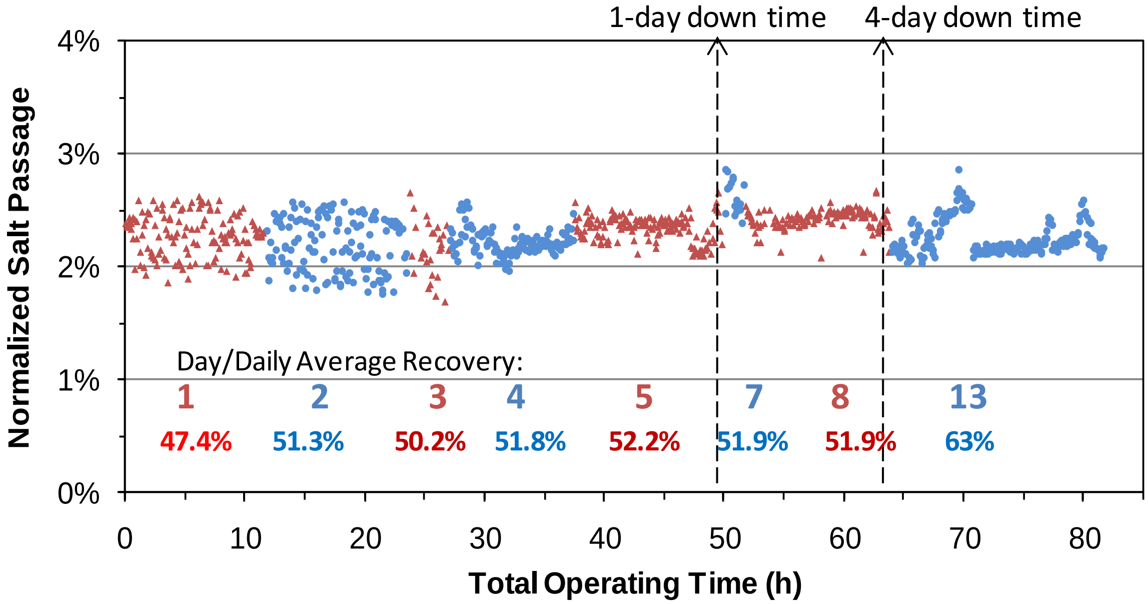

Figure 20. *Normalized salt passage of RO membrane elements (six DOW Filmtec XLE 2540 elements in series) during RO desalting of AD source water at DP-25 site using the M3 RO desalting system). PC-504T antiscalant dose in RO feed: 3 mg/L.*

5.3.2.4. *Absence of membrane mineral scaling*

Throughout the operation of the M3 RO pilot system (at the water recovery range of 47-63%), the MeMo system indicated that mineral scaling did not occur at the tail element of the M3 system. In monitoring for the occurrence of membrane scaling, the ion concentrations generated at the membrane surface of the MeMo system were adjusted to be at the highest ion concentrations that would be expected in the tail RO element of the M3 system (assuming a maximum RO element concentration polarization (CP) allowance of 20%, i.e. α= 1.2). For M3 operation at the conservative safe water recovery range of 47%-53%, images of the magnified portion of the MeMo membrane surface, at the beginning and the end of M3 operation, were essentially unchanged (**Figs. 21**). There was no indication of membrane scaling in both the magnified portion and the entire membrane coupon in the MeMo system for M3 operation over a period of 16 hours at 63% recovery (**Fig. 22**), which was near the estimated membrane scaling threshold water recovery of 64%.

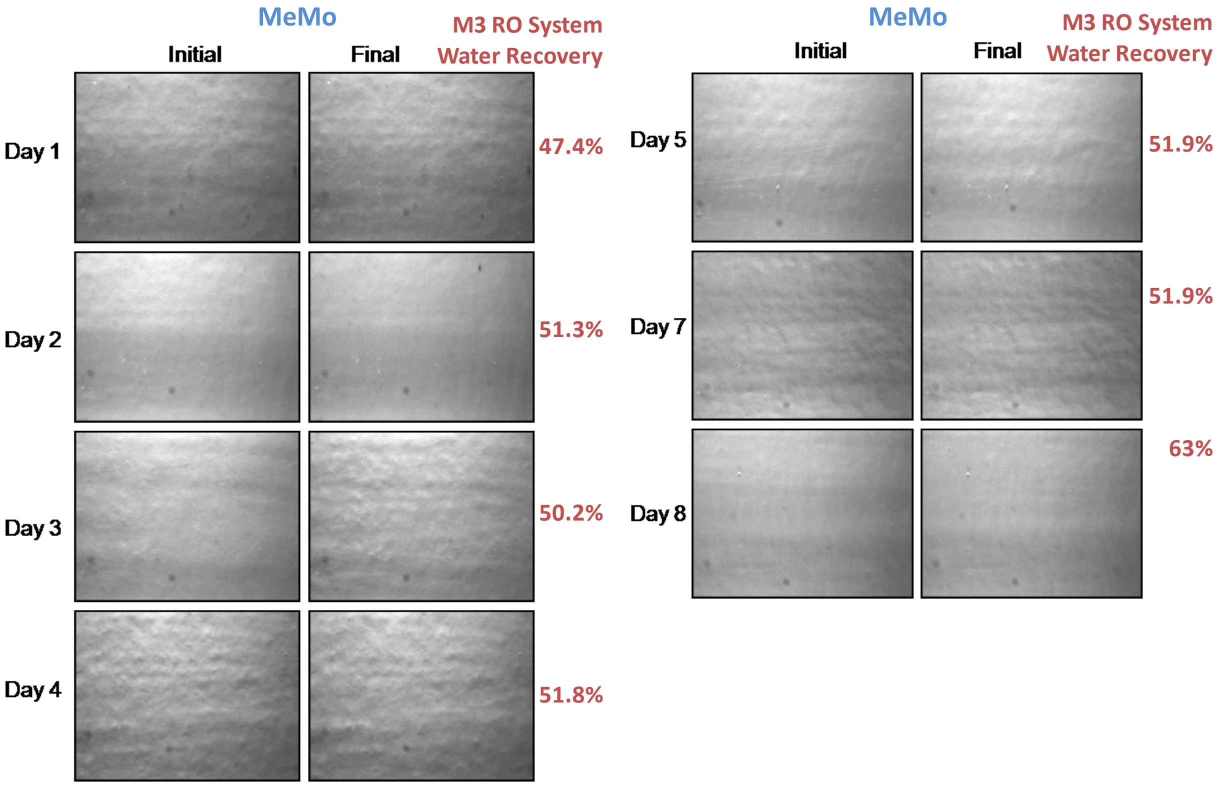

Figure 21. *Images of MeMo membrane surface taken at the beginning and the end of M3 operation. The MeMo system, connected the M3 concentrate line, was configured for detecting membrane scaling in the tail element of the M3 RO system. The MeMo system was operated at initial concentration polarization level (CP) of 1.2.*

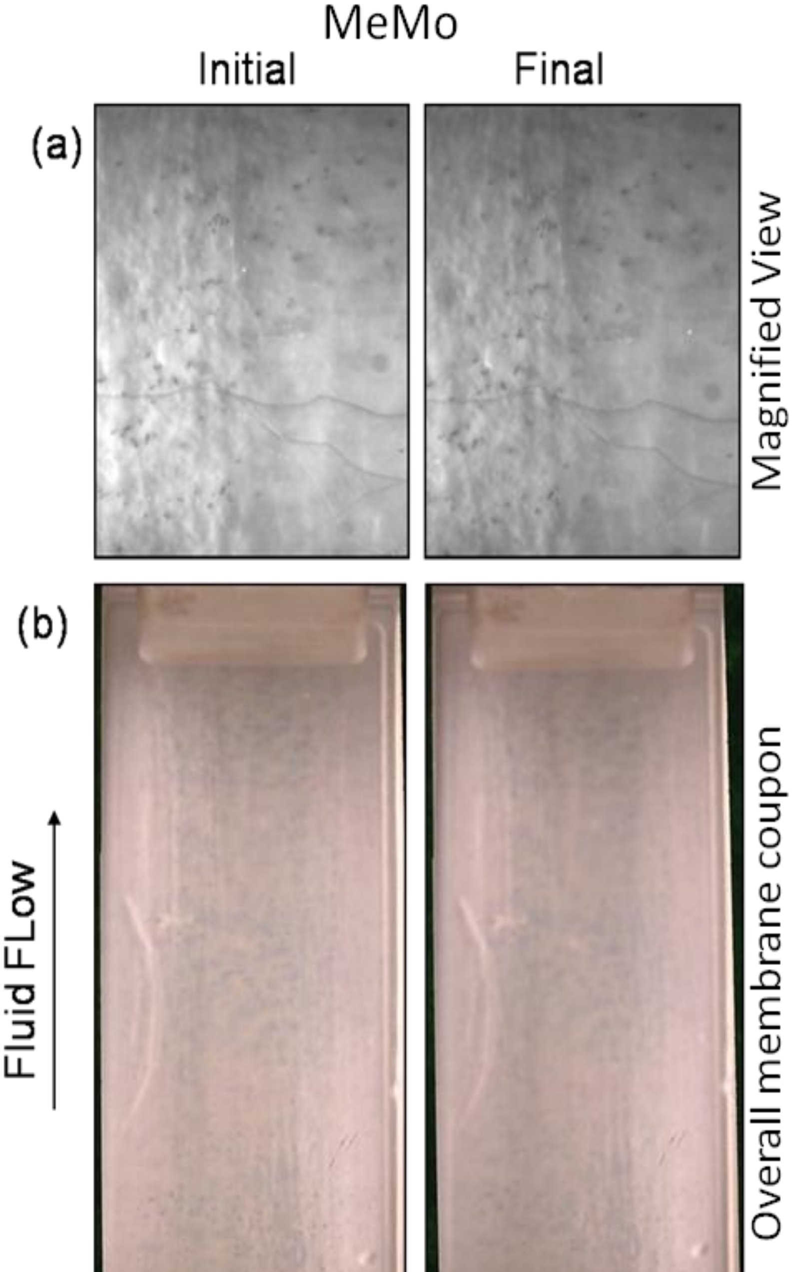

Figure 22. *Images of MeMo membrane surface taken at the beginning and the end of M3 operation at 63% water recovery over a period of 16 hours (Day 13). The MeMo system, connected the M3 concentrate line, was configured for detecting membrane scaling in the tail RO element of the M3 RO system. MeMo was operated at initial concentration polarization level (CP) of 1.2.*

5.3.2.5. Feed water quality variations

During the operation of the M3 desalting system, RO feed water TDS was normally within a range of 10,000 mg/L to 11,500 mg/L. At these feed water TDS levels, the permeate TDS was consistently below 500 mg/L, averaging ~370 mg/L (**Fig. 23**). The applied feed pressure to maintain the permeate flow (**Fig. 18**) was in the range of 180-200 psig when operating at ~47-52% recovery and ~270-290 psig when operating at 63% water recovery (**Fig. 24a**). It is noted that significant temporal fluctuation of feed water TDS occurred in Days 7-8 operation, affecting permeate quality and feed pressure requirement. During the M3 operation in Days 7-8, feed water TDS varied from 12,000 mg/L to 15,800 mg/L over a short time span of 1-2 hours. Given the feed water was taken directly from the well without any significant holding capacity, the observed variability of the RO feed salinity should closely represent the actual salinity in the drainage well, as affected by well conditions and surrounding agricultural activities. The significant variation in RO feed salinity led to significant variability of the RO permeate TDS, which increased to as high as 580 mg/L TDS (**Fig. 23**). With M3 operation at ~52% recovery in Day 7-8, temporal variation in feed water TDS resulted in significant fluctuations in the applied feed pressure, ranging from 200 psig to 242 psig (**Fig. 24a**). The above results suggest that temporal fluctuations of feed water quality can occur over a very short time span, indicating that AD water desalting at the DP-25 site would require advanced automated process control in order to ensure stable RO system operation.

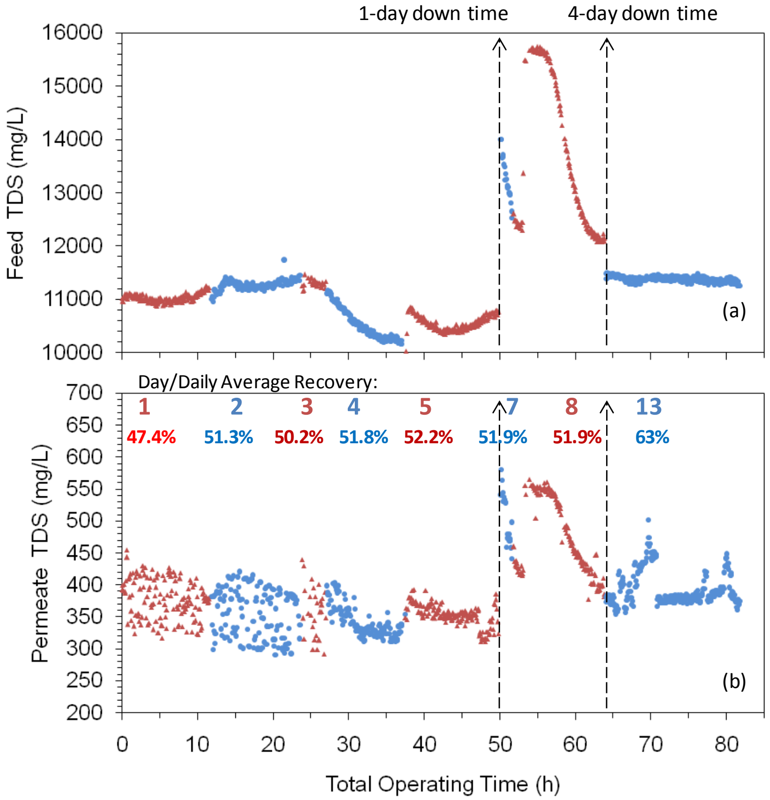

***Figure 23**. Total dissolved solids concentrations in RO (a) feed and (b) permeate streams during RO desalting of AD source water at DP-25 site using the M3 RO desalting system. Total dissolved solids concentrations were based on online conductivity measurements. PC-504T antiscalant dose in RO feed: 3 mg/L.*

One should note that, during each day of the M3 operation, the feed-channel differential pressure drop in the RO membrane elements remained stable (**Fig. 24b**), with values depending on the feed water flow rate (**Fig. 18a**) and with no indication of progressive increase in the RO feed-channel differential pressure drop. These results were consistent with membrane element performance data in **Fig. 19**, which confirmed that the M3 system did not experience membrane fouling during the field testing.

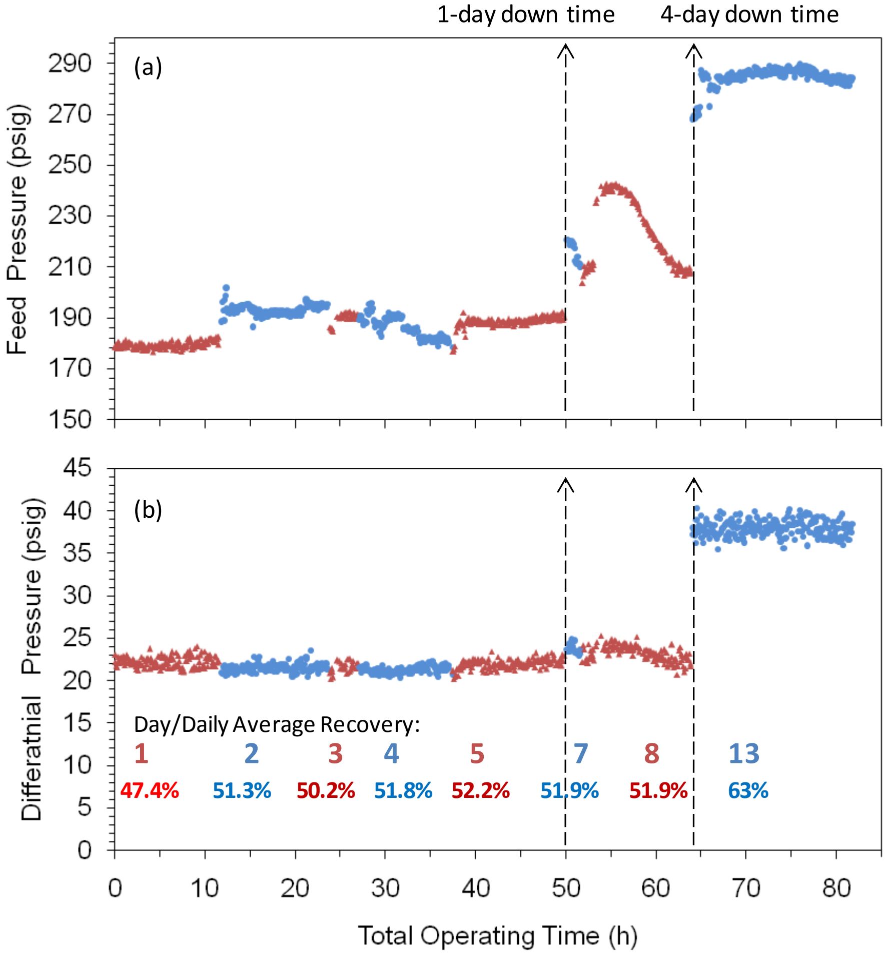

Figure 24. *(a) Feed pressure and (b) feed-channel differential pressure drop during RO desalting of AD source water at DP-25 site using the M3 RO desalting system. PC-504T antiscalant dose in RO feed: 3 mg/L.*

5.3.2.6. Water quality analysis

Grab samples of RO feed, concentrate, and permeate streams were taken on Day 8 of the M3 operation for water quality analysis. The complete water quality data are listed in **Appendix A** (**Section 11**). During sampling (at ~11 am), significant temporal fluctuation of source water salinity occurred, with the TDS increasing rapidly from to 12,000 mg/L to ~15,800 mg/L (**Fig. 25**). As a consequence, RO concentrate and permeate TDS levels also increased rapidly from ~25,000 mg/L to 30,000 mg/L (**Fig. 25**) and from ~400 mg/L to 580 mg/L (**Fig. 26**). Therefore, one must clearly consider the impact of such large temporal feed water quality fluctuation in the interpretation of the permeate and concentrate water quality.

Ionic composition of the first-pass RO permeate is summarized in **Table 1**. While the TDS was well below 500 mg/L, nitrate and boron levels were measured at levels of 119 mg/L and 20.2 mg/L. These results indicate that, depending on the desired product water end-use, "polishing" of the first-pass RO permeate may therefore be necessary to achieve the desired boron and nitrate concentrations. Options that should be considered for first-pass RO permeate "polishing" include the use of a second-pass RO, ion exchange, and continuous electrodeionization (CEDI).

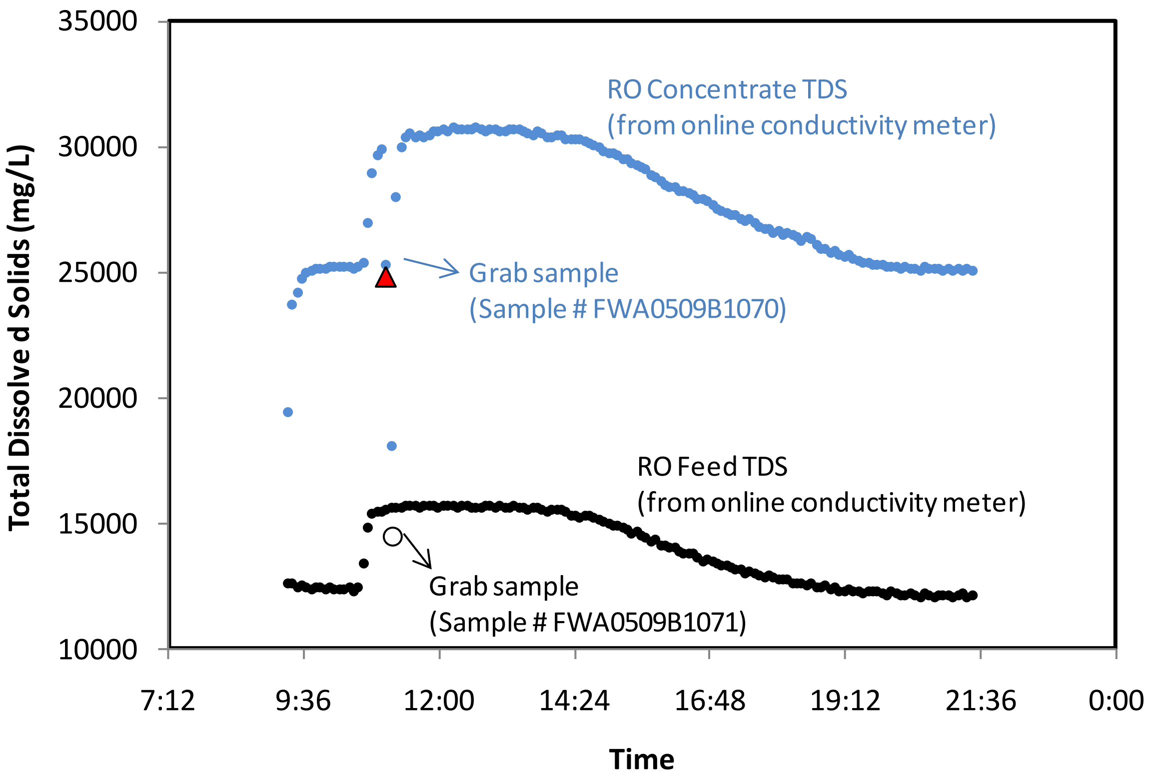

Figure 25*. Total dissolved solids concentrations in M3 RO system feed and concentrate streams, based on online conductivity measurements and grab sampling. Day: 8, RO recovery: 51.9%.*

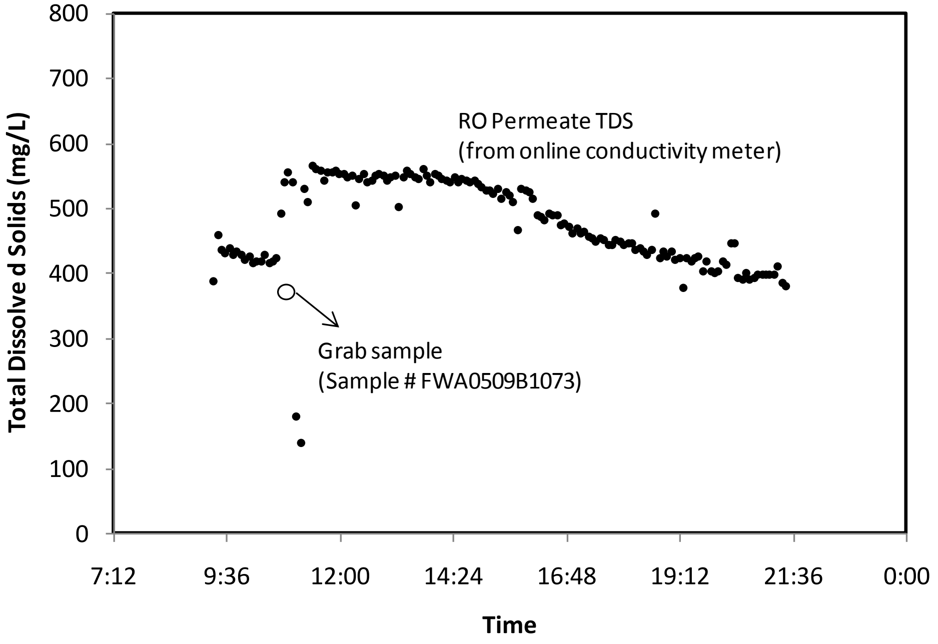

***Figure 26**. Total dissolved solids concentration in M3 RO system permeate stream, based on online conductivity measurements and grab sampling. Day: 8, RO recovery: 51.9%.*

***Table 1.** Permeate water quality from first-pass RO desalting of AD water at DP-25 test site. Complete water quality data is shown in **Appendix A**.*

Analyte	Value	Units
Total Dissolved Solids	371	mg/L
pH	6.4	pH unit
Boron	20.2	mg/L
Calcium	2	mg/L
Sodium	106	mg/L
Selenium	0.003	mg/L
Nitrate	119	mg/L
Chloride	87	mg/L
Sulfate	11	mg/L
Total Alkalinity	11	mg/L
Silica (SiO2)	0.6	mg/L

5.4. Enhanced boron removal via second-pass RO

Preliminary evaluation of the feasibility of enhancing boron removal via a second-pass RO stage was conducted by desalting permeate samples from the field study in a laboratory-scale plate-and-frame RO system at an elevated pH of 10 (by NaOH dosing), utilizing several commercial RO membranes from Hydranautics (Oceanside, CA). As listed in **Table 2**, boron rejection in the range of 81.6%-90.6% was feasible, with the boron concentration reduced from the first-pass permeate concentration of 14.4 mg/L to second-pass RO concentration levels of as low as 1.35 mg/L. Higher boron rejection may be feasible with second pass RO operation at higher pH levels (e.g., pH~11). Further testing should be conducted, including consideration of other permeate "polishing" methods (e.g., CEDI, ion exchange, etc.)

Table 2. *Boron removal from first-pass RO permeate via second-pass RO desalting at alkaline pH of 10 (by NaOH dosing). Average boron concentration in first-pass RO permeate sample is 14.4 mg/L.*

Second RO pass RO Membrane	Second RO pass Boron Rejection	Second RO Pass Permeate Boron Concentration (mg/L)
LFC1	81.6%	2.67
ESPA2	78.4%	3.14
ESPAB	83.5%	2.372
SWC4+B	90.6%	1.353

6. INTERMEDIATE CONCENTRATE DEMINERALIZATION (ICD)

6.1. Overview

Intermediate concentrate demineralization (ICD) of RO concentrate can enable subsequent water recovery enhancement via secondary RO desalting [1, 7-12]. In the ICD step, mineral scale precursors are removed from the PRO concentrate by precipitating sparingly soluble mineral salts, followed by subsequent solids-liquid separation (e.g., sedimentation and filtration). The ICD step lowers the mineral scaling propensity of the PRO concentrate, thereby enabling additional product water recovery from the PRO concentrate in a subsequent secondary RO (SRO) desalting step and reducing the final volume of the residual SRO concentrate waste.

For RO concentrate from AD water desalting, ICD via conventional precipitation softening has been shown to be feasible, but chemically intensive [1]. As an alternative, potentially less chemical-intensive ICD process, a UCLA patent-pending two-step chemically-enhanced seeded precipitation (CESP) was recently demonstrated for accelerated desupersaturation of antiscalant-containing, gypsum-supersaturated RO concentrate [15]. In the CESP process, $CaCO_3$ precipitation is first induced via lime dosing for antiscalant scavenging (i.e., lime pretreatment step), followed by subsequent $CaSO_4$ precipitation via gypsum seeding for concentrate desupersaturation (i.e., gypsum seeded precipitation step; **Section 2.2**). It was previously demonstrated that lime-precipitated $CaCO_3$ particles were capable of antiscalant scavenging, thereby facilitating subsequent $CaSO_4$ precipitation to progress with minimal retardation [15].

In order to evaluate the feasibility of the CESP process for accelerated desupersaturation of RO concentrate from AD water desalting at DP-25 test site, batch precipitation studies were conducted using RO concentrate from the M3 RO desalting system. Batch precipitation studies were first conducted in a small-scale 1-L crystallizer and were subsequently done in a larger, bench-scale crystallizer (20 L).

6.2. Small-scale field evaluation of chemically-enhanced seeded precipitation

Several small-scale chemically-enhanced seeded precipitation (CESP) experiments were conducted in a 1-L crystallizer, utilizing concentrate samples from the M3 pilot RO system that was operating at a target recovery of ~52%. At this recovery, the PC-504T antiscalant concentration in the RO concentrate was ~6.2 mg/L. Using a batch of the RO concentrate, the lime pretreatment step of the CESP process was first initiated by dosing the RO concentrate with 0.3 g/L of lime (at t=10 min; **Fig. 27**) in order to scavenge dissolved antiscalants. Subsequent gypsum seeding (at t=30 min**; Fig. 27**) initiated the GSP step, in which concentrate desupersaturation occurred through $CaSO_4$ precipitation on gypsum seed crystals. The CESP process was able to reduce the calcium ion activity in the RO concentrate from ~0.009 M to 0.005 over a period of 90 min (i.e., lime pretreatment and GSP periods), reducing the RO concentrate SI_G from ~1.7 to ~1.2. Comparison of the CESP process with a process involving gypsum seeding only (GSP) demonstrated the effectiveness of the lime pretreatment step in scavenging dissolved antiscalants; without lime pretreatment, gypsum seeding of the RO concentrate resulted in negligible decline of the SI_G in the treated RO concentrate. Demineralization of the RO concentrate was feasible, as shown in the example of **Fig. 27** based on results from the small-scale crystallizer tests; however, further optimization would be required in order to further increase the concentrate desupersaturation rates.

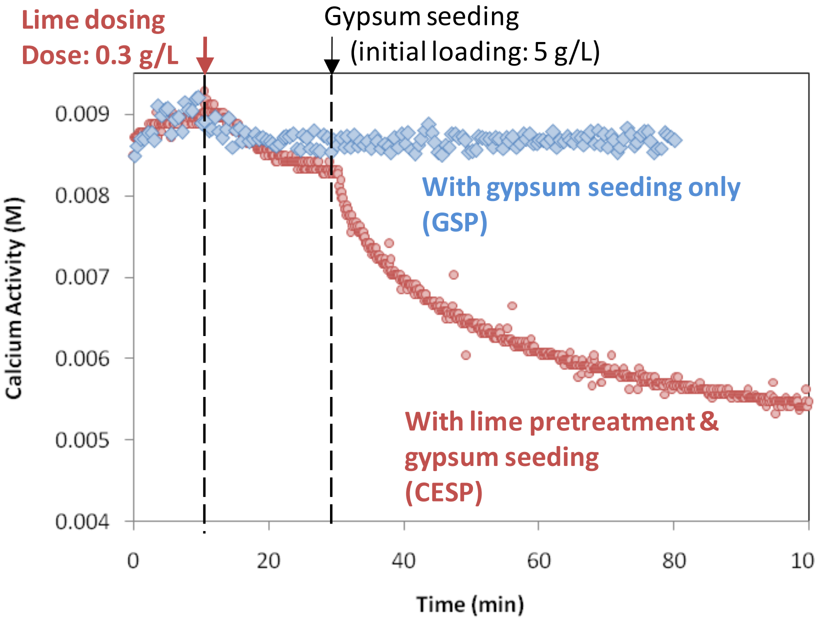

Figure 27*. Time evolution of calcium ion activity during RO concentrate desupersaturation via gypsum seeded precipitation (GSP; i.e., gypsum seeding only) and chemically-enhanced seeded precipitation (CESP; i.e., sequential lime dosing and gypsum seeding) in a small-scale 1-L crystallizer. RO concentrate sample was obtained from M3 system, operating at 53% recovery with 3 mg/L PC504T antiscalant dosing in the M3 feed.*

6.3. Bench-scale field evaluation of ICD via CESP

Bench-scale experiments were conducted in a 20-L crystallizer (**Fig. 28**) in order to demonstrate the feasibility of accelerated concentrate desupersaturation via the CESP process. RO concentrate was obtained from the M3 pilot system, operating at 52% recovery with 3 mg/L PC-504T antiscalant dose in the RO feed (~6.2 mg/L in the RO concentrate). The bench-scale CESP experiments were performed by first transferring the M3 RO concentrate into the 20-L crystallizer. The calcium, pH and temperature probes and support platform were then lowered into the crystallizer to a depth such that the tips of the probes would be fully submerged in the solution and then the stirring impeller was engaged. After a ten minute stabilization period, lime was added to the AD RO concentrate (at t=10 min), followed by gypsum seeding (at t=30 min). Precipitation was allowed to continue for 70 minutes after gypsum seeding. Grab samples of the RO concentrate, before and after CESP treatment, were obtained for water quality analysis, allowing quantification of the scale precursor removal achieved during the CESP process.

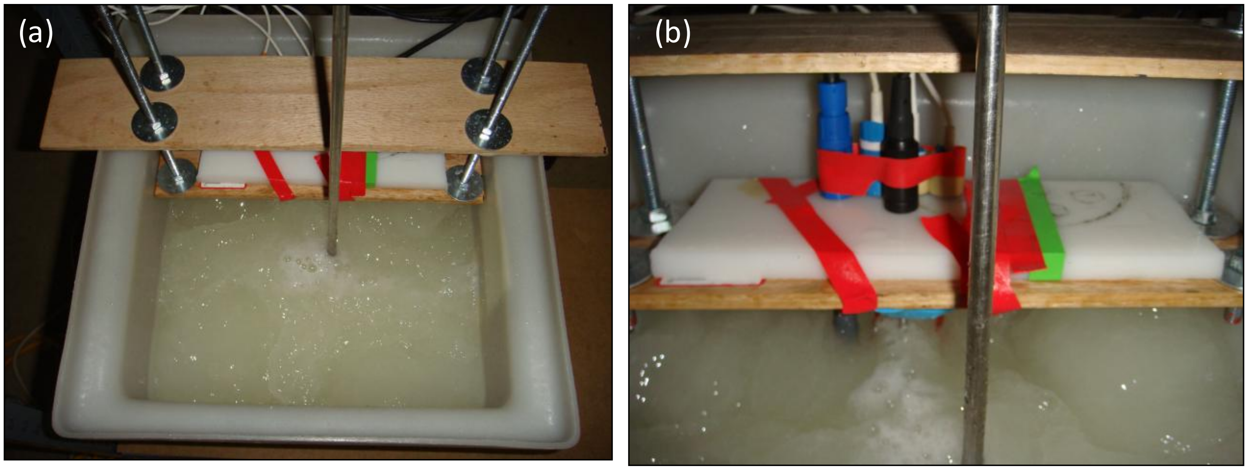

Figure 28. *(a) 20-liter crystallizer unit during brine demineralization and (b) close-up view of calcium ion, pH, and temperature probes in the unit.*

The feasibility of CESP was demonstrated at the bench-scale (20 L) with 0.25-0.35 g/L of lime dose and at least 5 g/L of initial gypsum seed loading, as can be deduced from the experimental results depicted in **Fig. 29**. The gypsum saturation index (SI_G) of the RO concentrate was reduced from ~1.7 to ~1.1 over a total period of 90 minutes (i.e., lime pretreatment and GSP periods). Results of water quality analysis indicated that the CESP process also provided some degree of removal of ionic species other than the targeted calcium, sulfate, and carbonate (i.e., alkalinity) ions (**Table 3**), possibly via co-precipitation removal. These include partial removal of ortho-phosphate (44%) and strontium (19%). Further study is warranted to determine if co-precipitation removal processes can be enhanced in CESP.

Comparison of **Fig. 27** (small batch test) and **Fig. 29** indicate that the drop of calcium activity was significantly lower during the lime treatment step of the small-scale test than that during the bench-scale test. Given that the small- and bench-scale tests employed RO concentrate from two different batches, it was likely that, during the small-scale test, the bicarbonate content in the RO concentrate was significantly lower, resulting in reduced generation of $CaCO_3$ precipitate and thus reduced initial drop of calcium activity upon lime dosing. Notwithstanding, both the small- and bench-scale tests resulted in final calcium activity (at 100 min) that were relatively close (between 0.045-0.055 mM), indicating that sufficient $CaCO_3$ precipitated to scavenge the dissolved antiscalant and allow RO concentrate desupersaturation with respect to gypsum.

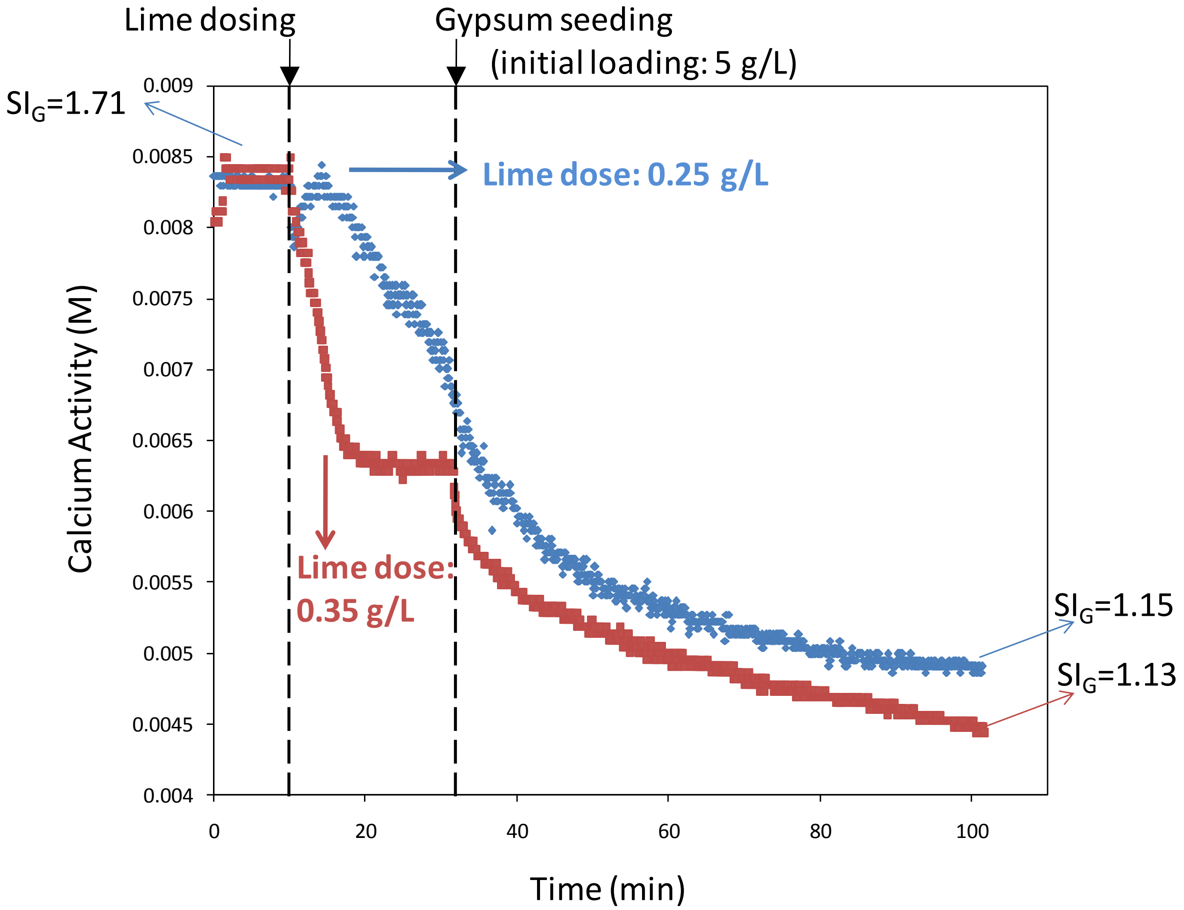

Figure 29. *Time evolution of calcium ion activity during RO concentrate desupersaturation via chemically-enhanced seeded precipitation (CESP; i.e., sequential lime dosing and gypsum seeding) in a bench-scale 20-L crystallizer. RO concentrate sample was obtained from M3 system, operating at 53% recovery with 3 mg/L PC504T antiscalant dosing in the M3 feed.*

Table 3. *Water quality of RO concentrate before and after CESP treatment. RO concentrate was obtained from the M3 system, operating to desalt AD water from the DP-25 site at 52% recovery with 3 mg/L PC-504 antiscalant dosing in the RO feed.*

Analyte		**Concentration**			**% Removal**	
Sample ID		FWA 0509B1072	FWA 0509B1076	FWA 0509B1077		
Description		RO Conc.	Treated Conc. 1	Treated Conc. 2	Treated Conc. 1	Treated Conc. 2
Lime dose	mg/L		250	350	250	350
Dissolved boron	mg/L	47.6	45.9	46.6	3.6%	2.1%
Dissolved calcium	mg/L	897	606	595	32.4%	33.7%
Dissolved magnesium	mg/L	879	831	815	5.5%	7.3%
Dissolved nitrate	mg/L	951	950	946	0.1%	0.5%
Dissolved o-phosphate	mg/L as P	0.09	0.05	0.05	44%	44%
Dissolved selenium	mg/L	2.72	2.66	2.64	2.2%	2.9%
Dissolved silica (SiO_2)	mg/L	71.7	70.8	69.5	1.3%	3.1%
Dissolved sulfate	mg/L	12400	11500	11500	7.3%	7.3%
Total alkalinity	mg/Las $CaCO_3$	491	313	241	36.3%	50.9%
Total arsenic	mg/L	0.022	0.02	0.02	9.1%	9.1%
Total selenium	mg/L	2.86	2.88	2.76	-0.7%	3.5%
Total strontium	mg/L	16.1	13.1	13	19%	19%
pH	pH Units	7.6	8.4	8.6		
Calcite saturation index		9.57	25.8	29.6		
Gypsum saturation index		1.71	1.15	1.13		
Silica saturation index		0.584	0.361	0.281		

6.4. Analysis of water recovery enhancement via CESP and secondary RO desalting

Given the feasibility of accelerated concentrate desupersaturation of RO concentrate from AD water desalting at the DP-25 test site, the water recovery enhancement that is feasible via secondary RO desalting can be calculated from a process model in order to develop process design charts. For example, the relationships between the maximum attainable water recovery of the PRO-ICD-SRO process (see **Section 2.2, Fig. 4**), the ICD reactor product stream saturation index, and the ratio of SRO concentrate recycle-to-purge volumetric flow ratio (Γ) are shown in the example design chart in **Fig. 30** for an illustrative test case of high-recovery desalting of the gypsum-saturated AD source water with ~11,000 mg/L TDS. In developing this design chart, a rigorous multi-electrolyte process simulator [19] was employed. A maximum SI_G value of 2.5 was specified as a reasonable upper limit for both the PRO and SRO concentrate gypsum supersaturation levels (see **Fig 4**), considering that the membrane scaling threshold was estimated to be at SI_G~ 2.9 with the level of antiscalant treatment in the present study (3 mg/L of PC-504T antiscalant dose in PRO feed; see **Fig. 14**). This maximum SI_G limit sets the maximum attainable water recovery level of the PRO desalting step at ~63% (**Fig. 30**). The maximum attainable water recovery of the overall PRO-ICD-SRO process depends on the water recovery enhancement provided by the SRO desalting step, which is governed by gypsum saturation in the SRO feed and therefore in the ICD product stream. A fraction of the water recovery enhancement (**Fig. 30**) provided by the SRO desalting step is due to the reduction of SI_G in the lime pretreatment reactor (**Fig. 4**) that results from $CaCO_3$ precipitation. One should note that the required lime dose in the lime pretreatment reactor is dependent, in part, on the SRO concentrate recycle-to-purge ratio (Γ). In order to simplify the presentation of the example design chart (**Fig. 30**), the chart was generated for a reasonable fixed lime dose of 0.25 g/L relative to the PRO concentrate volumetric flow rate.

The design chart in **Fig. 30** demonstrates the theoretical feasibility of the PRO-ICD-SRO process in enhancing the overall water recovery of AD water desalting to well above the PRO recovery level of ~63%. With CESP as the ICD process, SRO desalting of the ICD product stream could enhance the overall water recovery up to a maximum level of 87% (i.e., without SRO concentrate recycling, Γ=0). In this limiting case, CESP treatment would have to reduce the gypsum supersaturation level of the ICD product stream to the thermodynamic limiting value (SI_G=1), which may be achieved in practice by controlling the residual antiscalant concentration level, gypsum seed loading, and the fluid residence time in the GSP reactor (**Fig. 4**). The limit imposed by gypsum saturation of the ICD product stream (SI_G=1) on overall water recovery can be overcome by recycling part of the SRO concentrate stream to the LP reactor feed (i.e., increasing Γ>0). For example, a target water recovery of 90% can be achieved by carrying the CESP treatment toward saturation (SI_G=1) and partially recycling the SRO concentrate stream at Γ=0.41 (**Fig. 34**). It is noted that the maximum attainable water recovery level was calculated based a specified maximum level of SI_G in the bulk RO concentrate stream. Because ion concentrations near RO membrane surfaces are higher than in the bulk solution (due to concentration polarization), the practical water recovery would be lower than the above calculated maximum attainable level. Based on Eq. 5 (**Section 4.2**), it is estimated that, with typical RO operation with 10-20% module concentration polarization allowance, the attainable overall recovery range for the upper and lower bounds would be reduced by ~1%-12% relative to the estimates based on the average RO brine concentration.

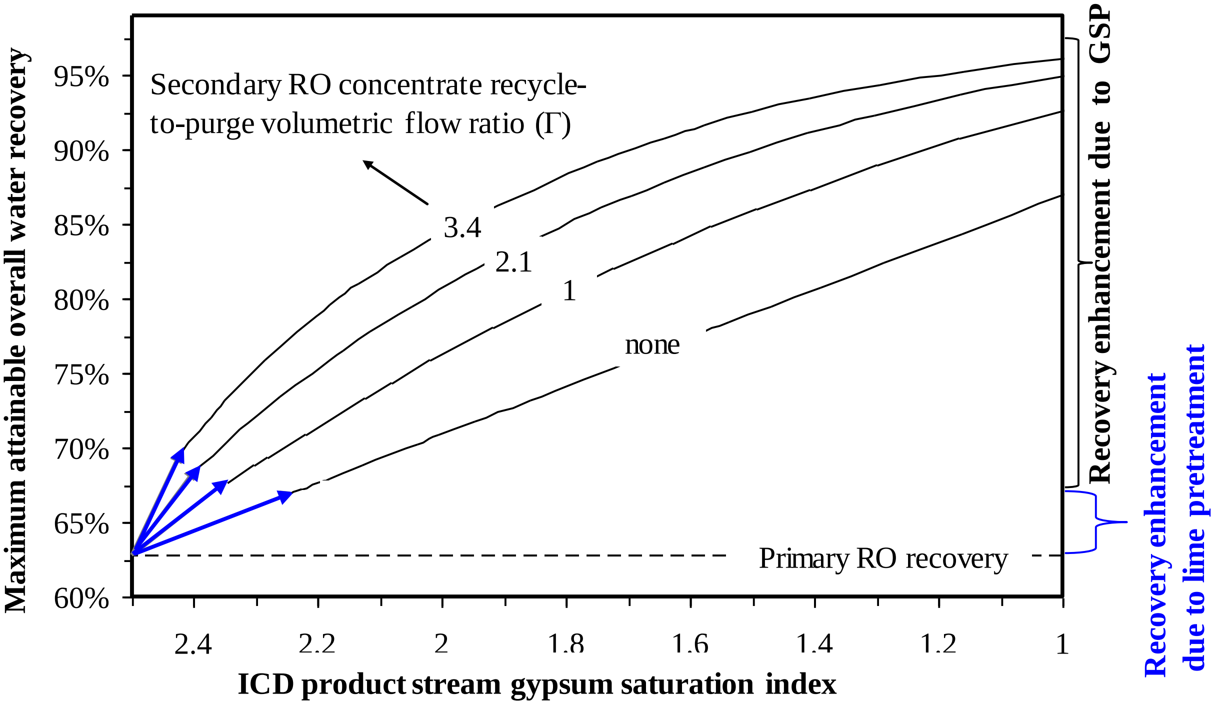

Figure 30. *Calculated maximum attainable range of overall water recovery over a range of gypsum saturation index in the ICD product stream and secondary RO (SRO) concentrate recycle-to-purge ratio (Γ) for desalting an agricultural drainage source water (SI_G ~1, TDS: ~11,000 mg/L) water using the PRO-ICD-SRO approach, utilizing CESP for ICD (see* ***Fig. 12****). The solid curves represent the limit imposed by the specified maximum gypsum saturation levels (SI_G=2.5) of the primary RO (PRO) and SRO concentrate streams on the range of overall water recovery, based on a range of ICD product stream SI_G and Γ. The straight arrows represent water recovery enhancement that would result from calcium ion reduction in the lime pretreatment step of CESP. The CESP lime dose was fixed at 3.37 mM relative to the PRO concentrate volumetric flow rate.*

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7. PRELIMINARY PROCESS DESIGN SPECIFICATIONS

A. *Feed Water*

Agricultural Drainage Water at DP-25 test site (Panoche Water and Drainage District)

B. *Primary RO desalting*

a) Feed Intake

-Feed intake system design should minimize entrainment of particulates into the RO feed

b) RO Feed Filtration

-Media filtration, followed by microfiltration (to 0.2 μm)
-Target RO feed turbidity level: <0.2 NTU

c) Antiscalant Treatment

-Antiscalant Type: Nalco PC-504T or others with similar or better performance
-Feed antiscalant dose: 3 mg/L
-Operate below the membrane scaling threshold

  - Estimated membrane scaling threshold: $SI_G = 2.9$
  - Estimated RO water recovery at membrane scaling threshold: ~ 64%

-Operation with feed-flow reversal may enhance the effect of antiscalant treatment by prolonging crystallization induction time.

C. *Water Recovery Enhancement*

Water recovery enhancement may be feasible via intermediate concentrate demineralization (ICD), followed by secondary RO desalting. ICD can be accomplished either via conventional precipitation softening or by a less chemical intensive method of Chemically-Enhanced Seeded Precipitation (CESP).

Chemically-Enhanced Seeded Precipitation

- Lime requirement (typical): 0.25-0.35 g/L
- Gypsum seed loading: > 5 g/L
- Maximum attainable overall water recovery via secondary RO desalting: 87% (higher may be possible via secondary RO concentrate recycling)

D. *First Pass RO Permeate Polishing*

Polishing of first-pass RO permeate may be necessary to reduce boron and nitrate concentrations to desired levels. Second pass RO desalting at pH >10 may reduce boron concentration to <2 mg/L. Further testing is required, including consideration of other permeate “polishing” methods (e.g., ion exchange or continuous electrodeionization).

8. PRELIMINARY DESALTING PROCESS COST ESTIMATES

Preliminary cost estimates for high recovery desalting of SJV AD water (at feed concentration basis of 11,000 mg/L TDS) were made based on estimates of major operating cost components: electrical energy for RO desalting, antiscalant usage for mitigation of mineral scaling, and, chemical usage for intermediate concentrate demineralization (alkaline chemicals/make-up gypsum seed crystals). These cost estimates assumed ideal operations of PRO and SRO membrane desalting at the limit of thermodynamic restriction [22] and intermediate concentrate demineralization. Electrical energy cost was estimated assuming 100% pump efficiency, ERD efficiency (η) of 0.95, and a reasonable electrical energy price of \$0.1/kWh. Chemical costs were based on a reasonable retail prices of antiscalant solution (~35% solids content at \$10/L) and reasonable market prices of soda-ash (\$190/metric-ton), hydrated lime ($Ca(OH)_2$, \$100/metric-ton), and crude gypsum (\$7.5/metric-ton). Electrical energy and chemicals are the major cost components for high recovery desalting and thus should provide the necessary information for initial process selection and design. The present partial cost estimate does not include capital cost, cost of membrane replacement, financial cost, brine disposal cost, and feed filtration cost as these costs are highly system dependent and their evaluation would require detailed process and system design, which is beyond the scope of the present field study.

Based on the above assumptions, the operating cost (i.e., electricity and antiscalant treatment) of primary RO desalting at 63% recovery was estimated to be ~\$0.10/m^3 of permeate, 57% of which is electrical consumption. The use of an energy recovery device (ERD) could reduce the operating cost of primary RO desalting to \$0.08/m^3 assuming ERD efficiency of 95%. It is noted that, at present, ERDs for inland water desalting at high recovery are not yet available at such high efficiencies.

The cost estimates for water recovery enhancement via intermediate concentrate demineralization (ICD) and subsequent secondary RO (SRO) desalting were calculated for the case of ICD via conventional precipitation softening (CPS; e.g., see [1]) and ICD via chemically-enhanced seeded precipitation (CESP). The operating costs were estimated based on the specific chemical requirements of the CPS and CESP processes in meeting the same targeted overall RO water recovery levels (i.e., via secondary RO desalting). The dependence of the extent of demineralization (and thus the attainable overall water RO water recovery) on ICD chemical consumption differs between the CPS- and CESP-based processes. The attainable water recovery of PRO-CPS-SRO is a function of calcium removal, which is highly dependent on the alkaline chemical dose. For the overall water recovery range of 68-96%, the ICD chemical cost (sodium carbonate usage) of the PRO-CPS-SRO process increases with RO recovery by almost a factor of 8 from \$0.025/m^3 to \$0.20/m^3 of total product water. This rise in cost is due to the increase in alkaline requirement from 0.9 to 9.7 mmol/L with respect to the PRO feed volume (i.e., alkaline volumetric flow rate into ICD per PRO feed volumetric flow rate). As a consequence, the total operating cost of PRO-CPS-SRO monotonically increases with increasing water recovery due to increasing energy and alkaline costs (**Fig. 31**). In contrast, the attainable water recovery of the PRO-CESP-SRO process, for a given lime dose and gypsum seed addition rate, is dictated by the extent of desupersaturation, which depends on the RO concentrate residence time in the ICD reactor. Within the overall water recovery range of 68-96%, the ICD chemical cost of PRO-CESP-SRO process remains within a moderately narrow range of \$0.014/m^3 - \$0.07/m^3 for reasonable ranges of lime dose and make-up gypsum seed loading of 1.3-2.8 mmol/L and 0.4-5.1 g/L with respect to the PRO feed volume, respectively. Based on these ICD chemical cost ranges, the total operating cost (electricity and chemical costs) of the PRO-CESP-SRO process is within the range of \$0.10-0.24/m^3 product water, as depicted in **Fig. 31**. There appears to be a minimum in the total operating cost of the PRO-CESP-SRO process at ~84-85% water recovery as energy cost overtakes chemical cost (**Fig. 31**). The operating cost of the PRO-CESP-SRO process is consistently lower than that of PRO-CPS-SRO process at overall water recovery above 68%.

For a target overall RO water recovery of 90%, the total operating cost of the PRO-CESP-SRO process is estimated to be in range of \$0.12-0.16/m^3 of product water (at the low and high lime dosages and make-up gypsum seed crystal loading). The PRO-CSP-SRO process cost is estimated to be significantly higher at \$0.31/m^3 (at the minimum required soda-ash dosage). Therefore, for high recovery desalting of San Joaquin Valley agricultural drainage water, ICD via CESP appears to be most promising when compared to ICD via conventional precipitation softening (CPS).

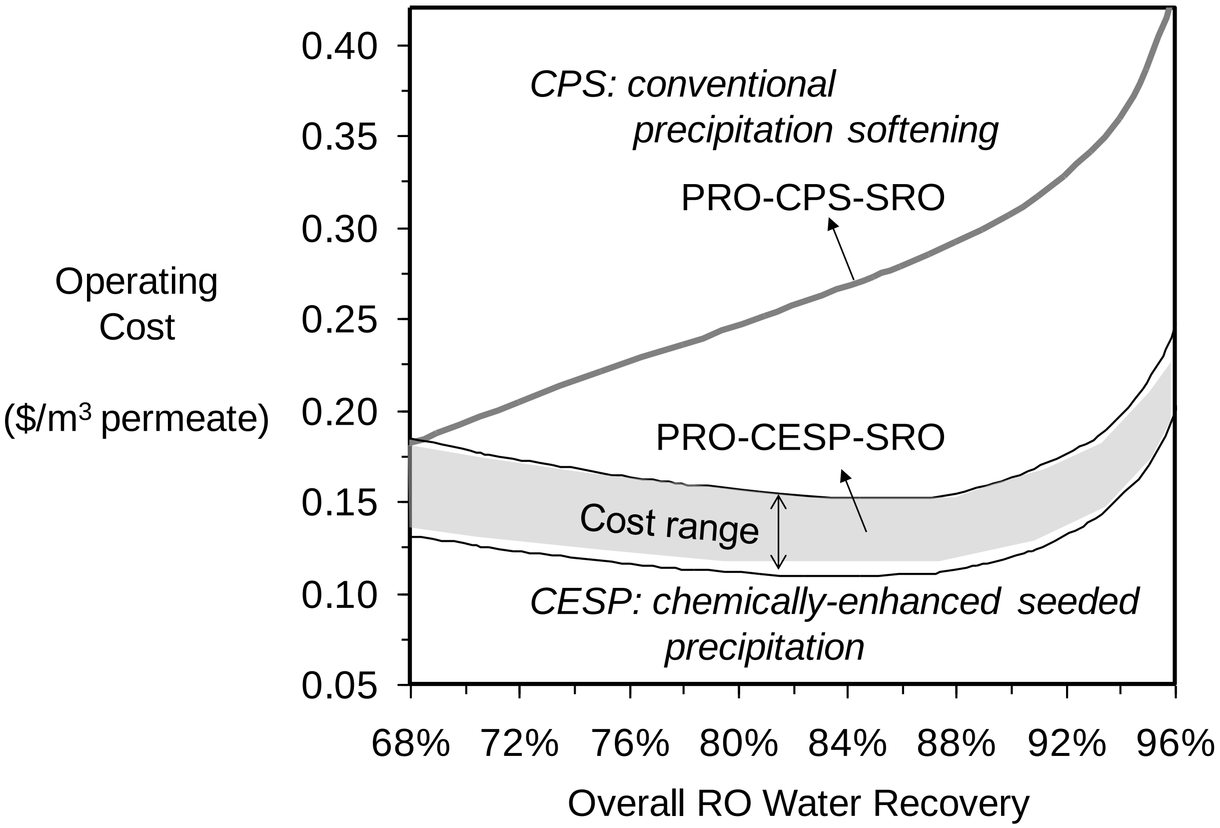

***Figure 31**. Comparison of operating costs between PRO-CPS-SRO and PRO-CESP-SRO processes for desalting San Joaquin Valley AD water (feed TDS~11,000 mg/L). RO: maximum SI_G=2.5 (with antiscalant treatment), 100% pump efficiency, energy recovery efficiency (ERD) of 95% from RO concentrate streams. Operating costs does not include costs of feed filtration, membrane filtration, capital cost, nor brine disposal.*

9. SUMMARY & RECOMMENDATIONS

Focusing on the challenge of high recovery desalting of San Joaquin Valley agricultural drainage (AD) water at the DP-25 test site (Panoche Water and Drainage District) as an illustrative test case, the present study: (a) demonstrated rapid field evaluation of reverse osmosis (RO) desalting; (b) evaluated the technical feasibility of RO concentrate demineralization to enable water recovery enhancement via secondary RO desalting; and (c) developed preliminary process design specifications for high recovery RO desalting.

Rapid field evaluation of RO desalting at the DP-25 test site was first demonstrated using a small-scale Membrane Monitor (MeMo) system, which enabled direct and online detection/characterization of membrane mineral scaling. The MeMo system allowed rapid field evaluation of feed filtration requirements, optimization of antiscalant treatment, and estimation of the water recovery level corresponding to the membrane scaling threshold. Based on optimal RO operating conditions, determined using the MeMo system, a pilot-scale mini-mobile-modular (M3) RO system was subsequently utilized to evaluate desalting of the AD source water and demonstrate the technical feasibility of sustained RO desalting operations. The M3 RO desalting system was able to operate at water recovery levels below or near the MeMo-predicted membrane scaling threshold (i.e., up to 63%) without membrane scaling, even when significant feed water quality variation were encountered over the course of the field study. Depending on the targeted end-use of the product water, permeate “polishing” via second-pass RO or other means may be necessary for further reduction of boron and nitrate concentrations.

In order to enable water recovery enhancement via secondary RO (SRO) desalting, primary RO (PRO) concentrate desupersaturation was evaluated using a two-step chemically-enhanced seeded precipitation process. This process should be less chemical intensive process relative to conventional precipitation softening (CPS). The CESP process was shown to be feasible for desupersaturation of the AD RO concentrate via field tests in both small- and bench-scale crystallizers. Theoretical process analysis indicates that the integration of CESP and secondary RO desalting can enhance overall RO water recovery at the DP-25 site up to 87% or higher. Based on experimental and process analysis results, preliminary process design specification and cost estimates for high recovery desalting at the DP-25 test site were developed. The results suggest that the integrated PRO-CESP-SRO desalting process can potentially be more cost effective, relative to the PRO-CPS-SRO process, for high recovery desalting of AD water, suggesting that expanded field testing of the PRO-CESP-SRO process is warranted for larger-scale demonstration and optimization of the approach.

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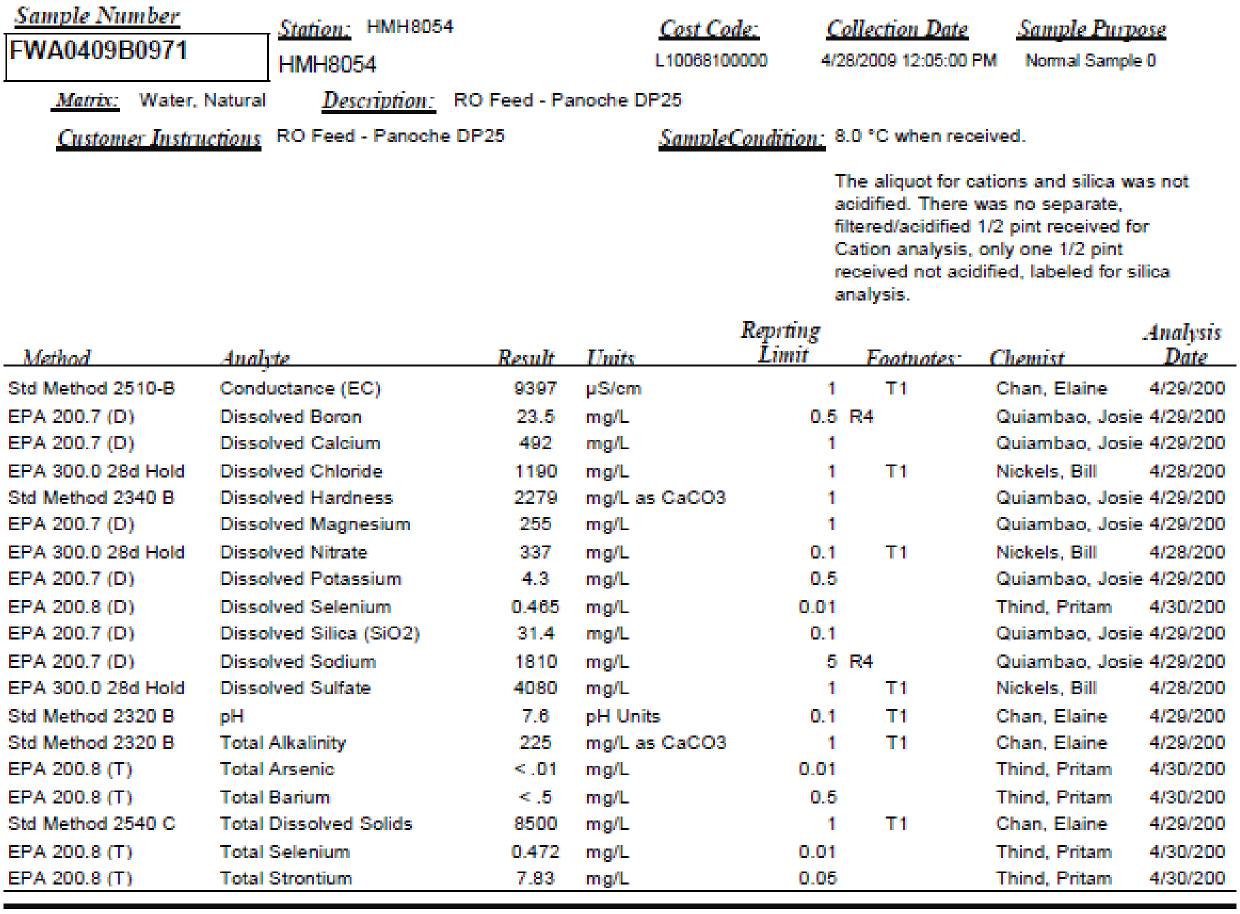
11. APPENDIX A: WATER QUALITY DATA

A1. Water quality data of M3 RO process streams

Grab Sample A1 was obtained prior to operation of the M3 system. Grab samples B1-B3 were obtained on Day 8 of the M3 operation. All grab samples were analyzed by CA Department of Water Resources Bryte Laboratory in Sacramento, CA.

Grab Sample A1

ID: FWA0409B0971
Sampling point: Raw RO feed
Time: 4/28/2009, 12:05 pm



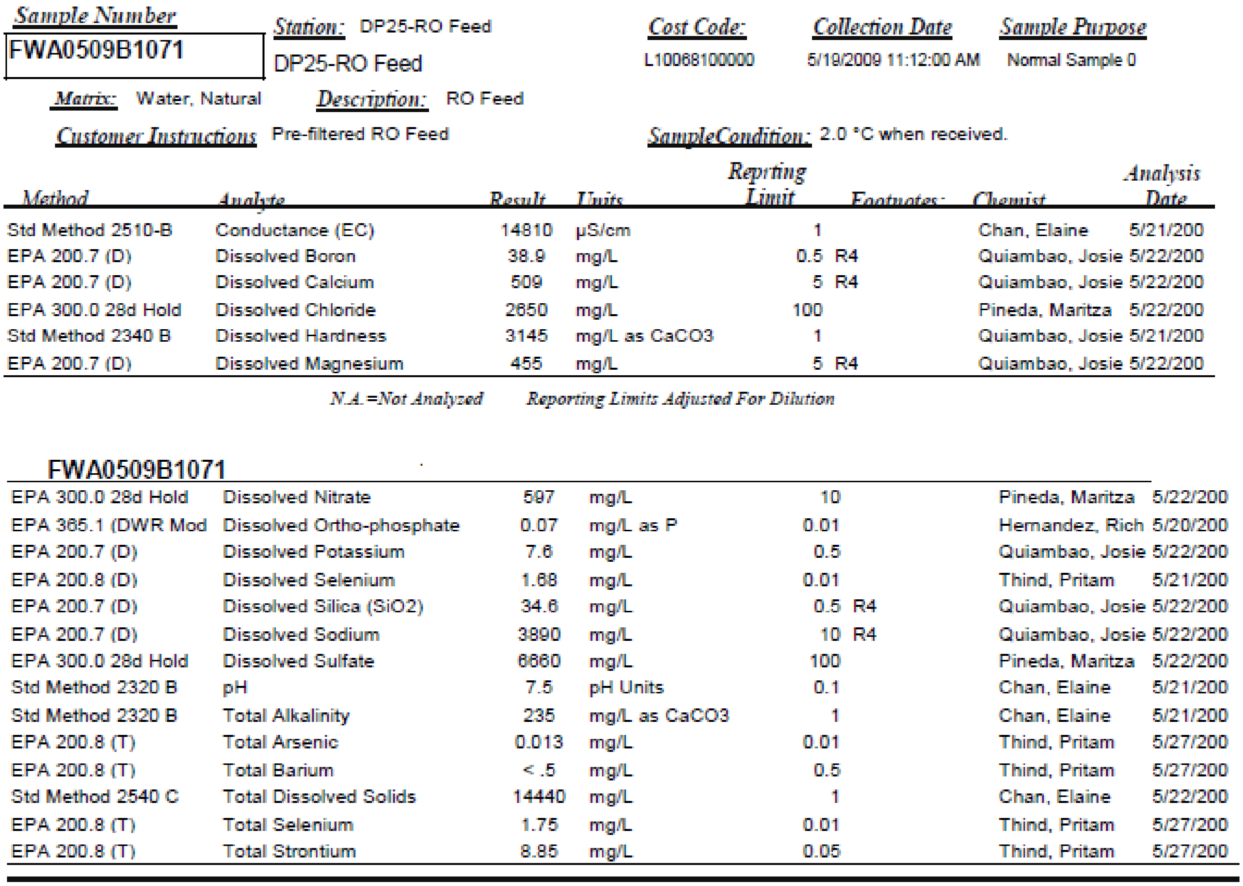
Sample Number FWA0409B0971
Station: HMH8054
HMH8054
Cost Code: L10068100000
Collection Date 4/28/2009 12:05:00 PM
Sample Purpose Normal Sample 0
Matrix: Water, Natural
Description: RO Feed - Panoche DP25
Customer Instructions RO Feed - Panoche DP25
SampleCondition: 8.0 °C when received.

The aliquot for cations and silica was not acidified. There was no separate, filtered/acidified 1/2 pint received for Cation analysis, only one 1/2 pint received not acidified, labeled for silica analysis.

Method	Analyte	Result	Units	Reprting Limit	Footnotes:	Chemist	Analysis Date
Std Method 2510-B	Conductance (EC)	9397	µS/cm	1	T1	Chan, Elaine	4/29/200
EPA 200.7 (D)	Dissolved Boron	23.5	mg/L	0.5	R4	Quiambao, Josie	4/29/200
EPA 200.7 (D)	Dissolved Calcium	492	mg/L	1		Quiambao, Josie	4/29/200
EPA 300.0 28d Hold	Dissolved Chloride	1190	mg/L	1	T1	Nickels, Bill	4/28/200
Std Method 2340 B	Dissolved Hardness	2279	mg/L as CaCO3	1		Quiambao, Josie	4/29/200
EPA 200.7 (D)	Dissolved Magnesium	255	mg/L	1		Quiambao, Josie	4/29/200
EPA 300.0 28d Hold	Dissolved Nitrate	337	mg/L	0.1	T1	Nickels, Bill	4/28/200
EPA 200.7 (D)	Dissolved Potassium	4.3	mg/L	0.5		Quiambao, Josie	4/29/200
EPA 200.8 (D)	Dissolved Selenium	0.465	mg/L	0.01		Thind, Pritam	4/30/200
EPA 200.7 (D)	Dissolved Silica (SiO2)	31.4	mg/L	0.1		Quiambao, Josie	4/29/200
EPA 200.7 (D)	Dissolved Sodium	1810	mg/L	5	R4	Quiambao, Josie	4/29/200
EPA 300.0 28d Hold	Dissolved Sulfate	4080	mg/L	1	T1	Nickels, Bill	4/28/200
Std Method 2320 B	pH	7.6	pH Units	0.1	T1	Chan, Elaine	4/29/200
Std Method 2320 B	Total Alkalinity	225	mg/L as CaCO3	1	T1	Chan, Elaine	4/29/200
EPA 200.8 (T)	Total Arsenic	< .01	mg/L	0.01		Thind, Pritam	4/30/200
EPA 200.8 (T)	Total Barium	< .5	mg/L	0.5		Thind, Pritam	4/30/200
Std Method 2540 C	Total Dissolved Solids	8500	mg/L	1	T1	Chan, Elaine	4/29/200
EPA 200.8 (T)	Total Selenium	0.472	mg/L	0.01		Thind, Pritam	4/30/200
EPA 200.8 (T)	Total Strontium	7.83	mg/L	0.05		Thind, Pritam	4/30/200

Grab Sample B1

ID: FWA0509B1071
Sampling point: Pre-filtered RO feed
Time: 5/19/2009, 11:12 am



Sample Number
FWA0509B1071

Station: DP25-RO Feed
DP25-RO Feed

Cost Code: L10068100000

Collection Date 5/19/2009 11:12:00 AM

Sample Purpose Normal Sample 0

Matrix: Water, Natural

Description: RO Feed

Customer Instructions Pre-filtered RO Feed

SampleCondition: 2.0 °C when received.

Method	*Analyte*	*Result*	*Units*	*Reprting Limit*	*Footnotes:*	*Chemist*	*Analysis Date*
Std Method 2510-B	Conductance (EC)	14810	µS/cm	1		Chan, Elaine	5/21/200
EPA 200.7 (D)	Dissolved Boron	38.9	mg/L	0.5	R4	Quiambao, Josie	5/22/200
EPA 200.7 (D)	Dissolved Calcium	509	mg/L	5	R4	Quiambao, Josie	5/22/200
EPA 300.0 28d Hold	Dissolved Chloride	2650	mg/L	100		Pineda, Maritza	5/22/200
Std Method 2340 B	Dissolved Hardness	3145	mg/L as CaCO3	1		Quiambao, Josie	5/21/200
EPA 200.7 (D)	Dissolved Magnesium	455	mg/L	5	R4	Quiambao, Josie	5/22/200

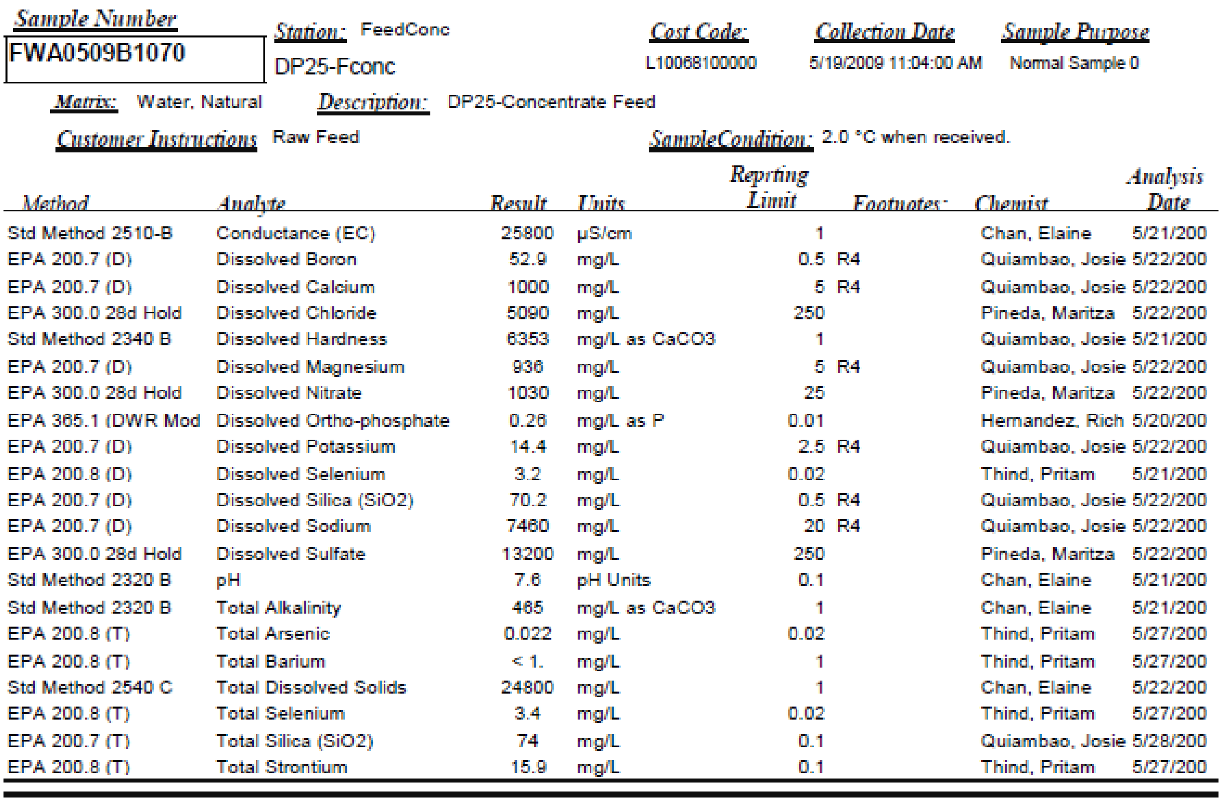
N.A.=Not Analyzed *Reporting Limits Adjusted For Dilution*

FWA0509B1071

EPA 300.0 28d Hold	Dissolved Nitrate	597	mg/L	10		Pineda, Maritza	5/22/200
EPA 365.1 (DWR Mod	Dissolved Ortho-phosphate	0.07	mg/L as P	0.01		Hernandez, Rich	5/20/200
EPA 200.7 (D)	Dissolved Potassium	7.6	mg/L	0.5		Quiambao, Josie	5/22/200
EPA 200.8 (D)	Dissolved Selenium	1.68	mg/L	0.01		Thind, Pritam	5/21/200
EPA 200.7 (D)	Dissolved Silica (SiO2)	34.6	mg/L	0.5	R4	Quiambao, Josie	5/22/200
EPA 200.7 (D)	Dissolved Sodium	3890	mg/L	10	R4	Quiambao, Josie	5/22/200
EPA 300.0 28d Hold	Dissolved Sulfate	6660	mg/L	100		Pineda, Maritza	5/22/200
Std Method 2320 B	pH	7.5	pH Units	0.1		Chan, Elaine	5/21/200
Std Method 2320 B	Total Alkalinity	235	mg/L as CaCO3	1		Chan, Elaine	5/21/200
EPA 200.8 (T)	Total Arsenic	0.013	mg/L	0.01		Thind, Pritam	5/27/200
EPA 200.8 (T)	Total Barium	< .5	mg/L	0.5		Thind, Pritam	5/27/200
Std Method 2540 C	Total Dissolved Solids	14440	mg/L	1		Chan, Elaine	5/22/200
EPA 200.8 (T)	Total Selenium	1.75	mg/L	0.01		Thind, Pritam	5/27/200
EPA 200.8 (T)	Total Strontium	8.85	mg/L	0.05		Thind, Pritam	5/27/200

Grab Sample B2

ID: FWA0509B1070
Sampling point: RO concentrate
Time: 5/19/2009, 11:04 am



Sample Number FWA0509B1070

Station: FeedConc
DP25-Fconc

Cost Code: L10068100000

Collection Date 5/19/2009 11:04:00 AM

Sample Purpose Normal Sample 0

Matrix: Water, Natural

Description: DP25-Concentrate Feed

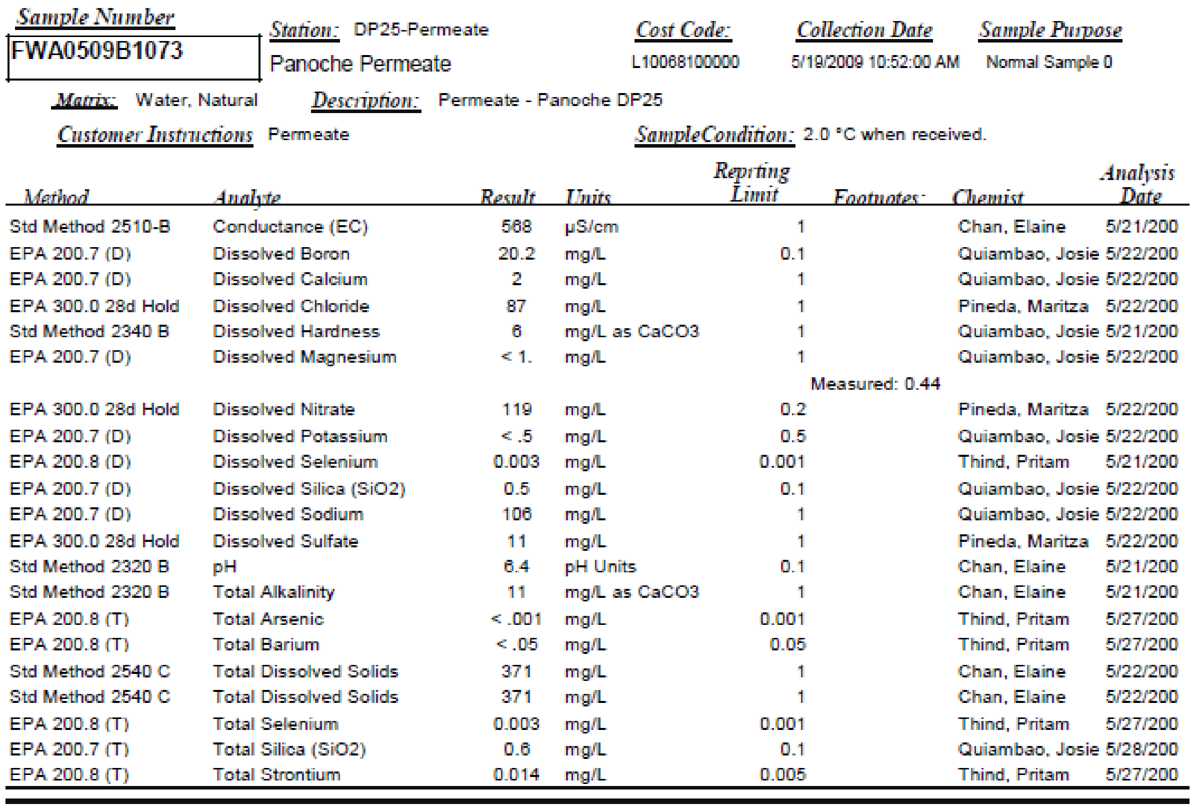
Customer Instructions Raw Feed

SampleCondition: 2.0 °C when received.

Method	*Analyte*	*Result*	*Units*	*Reprting Limit*	*Footnotes:*	*Chemist*	*Analysis Date*
Std Method 2510-B	Conductance (EC)	25800	µS/cm	1		Chan, Elaine	5/21/200
EPA 200.7 (D)	Dissolved Boron	52.9	mg/L	0.5	R4	Quiambao, Josie	5/22/200
EPA 200.7 (D)	Dissolved Calcium	1000	mg/L	5	R4	Quiambao, Josie	5/22/200
EPA 300.0 28d Hold	Dissolved Chloride	5090	mg/L	250		Pineda, Maritza	5/22/200
Std Method 2340 B	Dissolved Hardness	6353	mg/L as CaCO3	1		Quiambao, Josie	5/21/200
EPA 200.7 (D)	Dissolved Magnesium	936	mg/L	5	R4	Quiambao, Josie	5/22/200
EPA 300.0 28d Hold	Dissolved Nitrate	1030	mg/L	25		Pineda, Maritza	5/22/200
EPA 365.1 (DWR Mod	Dissolved Ortho-phosphate	0.26	mg/L as P	0.01		Hernandez, Rich	5/20/200
EPA 200.7 (D)	Dissolved Potassium	14.4	mg/L	2.5	R4	Quiambao, Josie	5/22/200
EPA 200.8 (D)	Dissolved Selenium	3.2	mg/L	0.02		Thind, Pritam	5/21/200
EPA 200.7 (D)	Dissolved Silica (SiO2)	70.2	mg/L	0.5	R4	Quiambao, Josie	5/22/200
EPA 200.7 (D)	Dissolved Sodium	7460	mg/L	20	R4	Quiambao, Josie	5/22/200
EPA 300.0 28d Hold	Dissolved Sulfate	13200	mg/L	250		Pineda, Maritza	5/22/200
Std Method 2320 B	pH	7.6	pH Units	0.1		Chan, Elaine	5/21/200
Std Method 2320 B	Total Alkalinity	465	mg/L as CaCO3	1		Chan, Elaine	5/21/200
EPA 200.8 (T)	Total Arsenic	0.022	mg/L	0.02		Thind, Pritam	5/27/200
EPA 200.8 (T)	Total Barium	< 1.	mg/L	1		Thind, Pritam	5/27/200
Std Method 2540 C	Total Dissolved Solids	24800	mg/L	1		Chan, Elaine	5/22/200
EPA 200.8 (T)	Total Selenium	3.4	mg/L	0.02		Thind, Pritam	5/27/200
EPA 200.7 (T)	Total Silica (SiO2)	74	mg/L	0.1		Quiambao, Josie	5/28/200
EPA 200.8 (T)	Total Strontium	15.9	mg/L	0.1		Thind, Pritam	5/27/200

Grab Sample B3

ID: FWA0509B1073
Sampling point: RO Permeate
Time: 5/19/2009, 10:52 am



Sample Number FWA0509B1073
Station: DP25-Permeate
Panoche Permeate
Cost Code: L10068100000
Collection Date 5/19/2009 10:52:00 AM
Sample Purpose Normal Sample 0
Matrix: Water, Natural
Description: Permeate - Panoche DP25
Customer Instructions Permeate
SampleCondition: 2.0 °C when received.

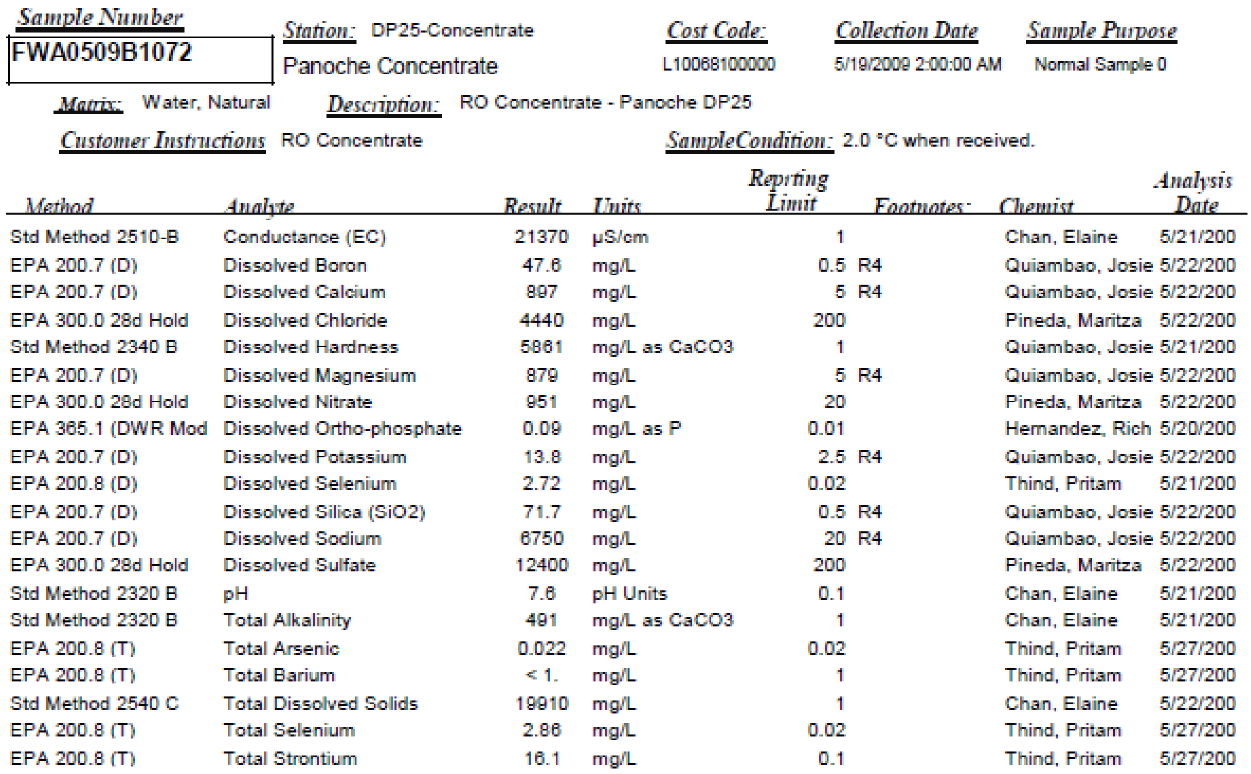
Method	Analyte	Result	Units	Reprting Limit	Footnotes:	Chemist	Analysis Date
Std Method 2510-B	Conductance (EC)	568	µS/cm	1		Chan, Elaine	5/21/200
EPA 200.7 (D)	Dissolved Boron	20.2	mg/L	0.1		Quiambao, Josie	5/22/200
EPA 200.7 (D)	Dissolved Calcium	2	mg/L	1		Quiambao, Josie	5/22/200
EPA 300.0 28d Hold	Dissolved Chloride	87	mg/L	1		Pineda, Maritza	5/22/200
Std Method 2340 B	Dissolved Hardness	6	mg/L as CaCO3	1		Quiambao, Josie	5/21/200
EPA 200.7 (D)	Dissolved Magnesium	< 1.	mg/L	1		Quiambao, Josie	5/22/200
					Measured: 0.44		
EPA 300.0 28d Hold	Dissolved Nitrate	119	mg/L	0.2		Pineda, Maritza	5/22/200
EPA 200.7 (D)	Dissolved Potassium	< .5	mg/L	0.5		Quiambao, Josie	5/22/200
EPA 200.8 (D)	Dissolved Selenium	0.003	mg/L	0.001		Thind, Pritam	5/21/200
EPA 200.7 (D)	Dissolved Silica (SiO2)	0.5	mg/L	0.1		Quiambao, Josie	5/22/200
EPA 200.7 (D)	Dissolved Sodium	106	mg/L	1		Quiambao, Josie	5/22/200
EPA 300.0 28d Hold	Dissolved Sulfate	11	mg/L	1		Pineda, Maritza	5/22/200
Std Method 2320 B	pH	6.4	pH Units	0.1		Chan, Elaine	5/21/200
Std Method 2320 B	Total Alkalinity	11	mg/L as CaCO3	1		Chan, Elaine	5/21/200
EPA 200.8 (T)	Total Arsenic	< .001	mg/L	0.001		Thind, Pritam	5/27/200
EPA 200.8 (T)	Total Barium	< .05	mg/L	0.05		Thind, Pritam	5/27/200
Std Method 2540 C	Total Dissolved Solids	371	mg/L	1		Chan, Elaine	5/22/200
Std Method 2540 C	Total Dissolved Solids	371	mg/L	1		Chan, Elaine	5/22/200
EPA 200.8 (T)	Total Selenium	0.003	mg/L	0.001		Thind, Pritam	5/27/200
EPA 200.7 (T)	Total Silica (SiO2)	0.6	mg/L	0.1		Quiambao, Josie	5/28/200
EPA 200.8 (T)	Total Strontium	0.014	mg/L	0.005		Thind, Pritam	5/27/200

A2. Assessment of accelerated concentrate desupersaturation

***Analytical Lab**: DWR Bryte Laboratory*
Description: Samples of RO concentrate was taken before and after RO concentrate treatment via chemical-enhanced seeded precipitation (for RO concentrate desupersaturation).

Grab Sample C1

ID:	FWA0509B1072
Sampling point:	RO Concentrate before treatment via chemically-enhanced precipitation
Time:	5/19/2009, 2:00 am



Sample Number	Station:	Cost Code:	Collection Date	Sample Purpose
FWA0509B1072	DP25-Concentrate Panoche Concentrate	L10068100000	5/19/2009 2:00:00 AM	Normal Sample 0

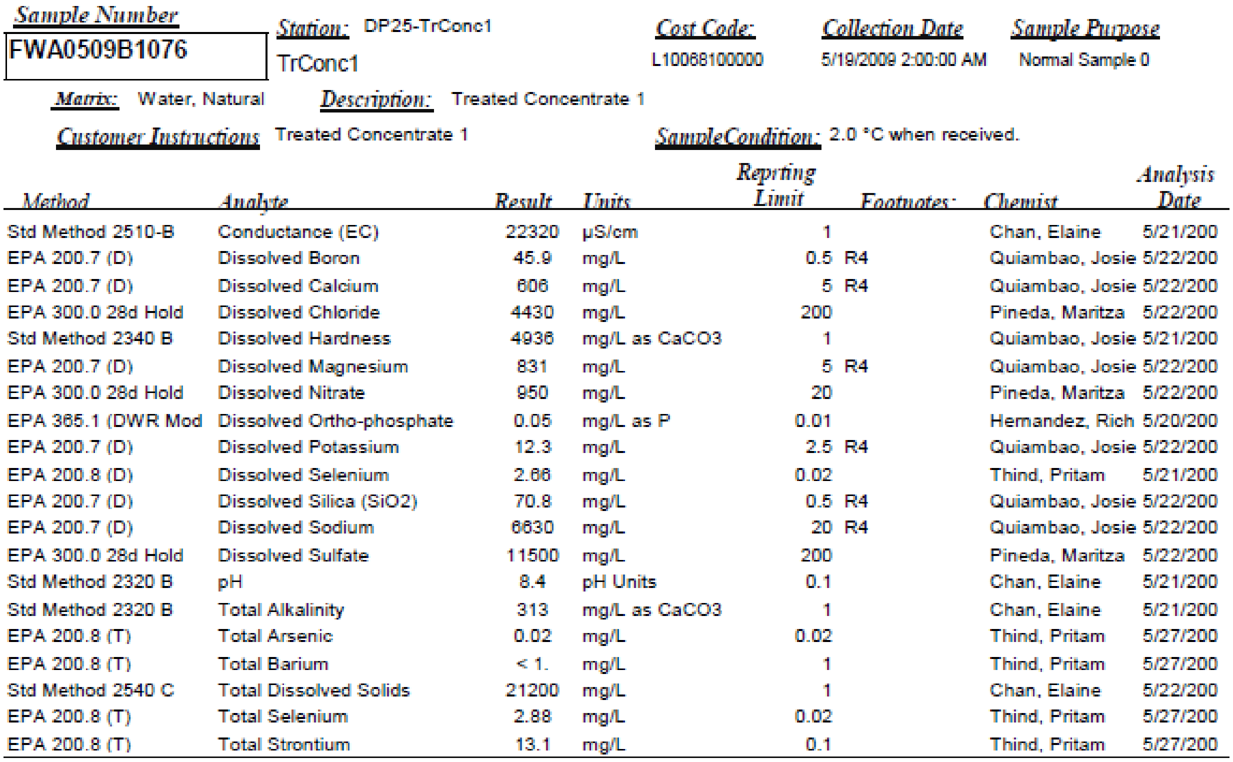
Matrix: Water, Natural **Description:** RO Concentrate - Panoche DP25

Customer Instructions RO Concentrate **SampleCondition:** 2.0 °C when received.

Method	Analyte	Result	Units	Reprting Limit	Footnotes:	Chemist	Analysis Date
Std Method 2510-B	Conductance (EC)	21370	µS/cm	1		Chan, Elaine	5/21/200
EPA 200.7 (D)	Dissolved Boron	47.6	mg/L	0.5	R4	Quiambao, Josie	5/22/200
EPA 200.7 (D)	Dissolved Calcium	897	mg/L	5	R4	Quiambao, Josie	5/22/200
EPA 300.0 28d Hold	Dissolved Chloride	4440	mg/L	200		Pineda, Maritza	5/22/200
Std Method 2340 B	Dissolved Hardness	5861	mg/L as CaCO3	1		Quiambao, Josie	5/21/200
EPA 200.7 (D)	Dissolved Magnesium	879	mg/L	5	R4	Quiambao, Josie	5/22/200
EPA 300.0 28d Hold	Dissolved Nitrate	951	mg/L	20		Pineda, Maritza	5/22/200
EPA 365.1 (DWR Mod	Dissolved Ortho-phosphate	0.09	mg/L as P	0.01		Hernandez, Rich	5/20/200
EPA 200.7 (D)	Dissolved Potassium	13.8	mg/L	2.5	R4	Quiambao, Josie	5/22/200
EPA 200.8 (D)	Dissolved Selenium	2.72	mg/L	0.02		Thind, Pritam	5/21/200
EPA 200.7 (D)	Dissolved Silica (SiO2)	71.7	mg/L	0.5	R4	Quiambao, Josie	5/22/200
EPA 200.7 (D)	Dissolved Sodium	6750	mg/L	20	R4	Quiambao, Josie	5/22/200
EPA 300.0 28d Hold	Dissolved Sulfate	12400	mg/L	200		Pineda, Maritza	5/22/200
Std Method 2320 B	pH	7.6	pH Units	0.1		Chan, Elaine	5/21/200
Std Method 2320 B	Total Alkalinity	491	mg/L as CaCO3	1		Chan, Elaine	5/21/200
EPA 200.8 (T)	Total Arsenic	0.022	mg/L	0.02		Thind, Pritam	5/27/200
EPA 200.8 (T)	Total Barium	< 1.	mg/L	1		Thind, Pritam	5/27/200
Std Method 2540 C	Total Dissolved Solids	19910	mg/L	1		Chan, Elaine	5/22/200
EPA 200.8 (T)	Total Selenium	2.86	mg/L	0.02		Thind, Pritam	5/27/200
EPA 200.8 (T)	Total Strontium	16.1	mg/L	0.1		Thind, Pritam	5/27/200

Grab Sample C2

ID: FWA0509B1076
Sampling point: RO Concentrate after treatment via chemically-enhanced seeded precipitation, 1st sample
Time: 5/19/2009, 2:00 am

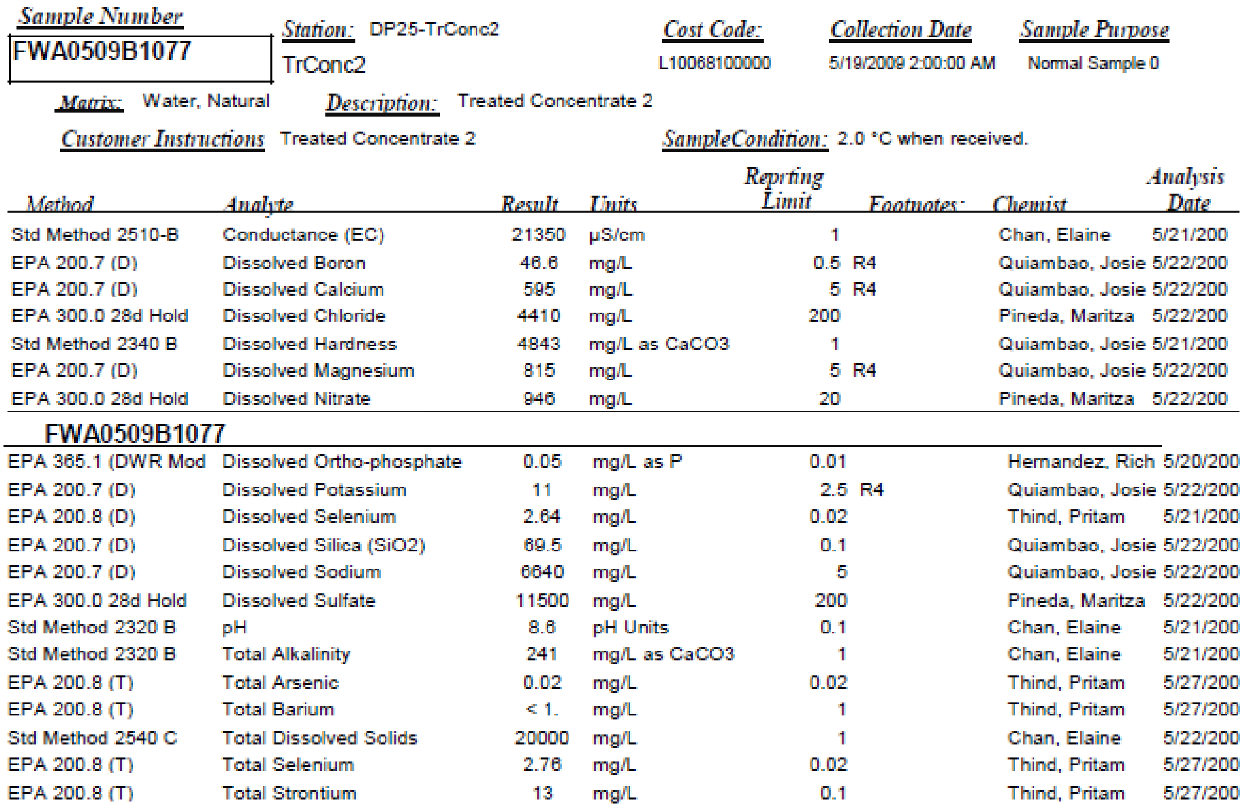


Sample Number FWA0509B1076
Station: DP25-TrConc1 TrConc1
Cost Code: L10068100000
Collection Date 5/19/2009 2:00:00 AM
Sample Purpose Normal Sample 0
Matrix: Water, Natural
Description: Treated Concentrate 1
Customer Instructions Treated Concentrate 1
SampleCondition: 2.0 °C when received.

Method	*Analyte*	*Result*	*Units*	*Reprting Limit*	*Footnotes:*	*Chemist*	*Analysis Date*
Std Method 2510-B	Conductance (EC)	22320	µS/cm	1		Chan, Elaine	5/21/200
EPA 200.7 (D)	Dissolved Boron	45.9	mg/L	0.5	R4	Quiambao, Josie	5/22/200
EPA 200.7 (D)	Dissolved Calcium	606	mg/L	5	R4	Quiambao, Josie	5/22/200
EPA 300.0 28d Hold	Dissolved Chloride	4430	mg/L	200		Pineda, Maritza	5/22/200
Std Method 2340 B	Dissolved Hardness	4936	mg/L as CaCO3	1		Quiambao, Josie	5/21/200
EPA 200.7 (D)	Dissolved Magnesium	831	mg/L	5	R4	Quiambao, Josie	5/22/200
EPA 300.0 28d Hold	Dissolved Nitrate	950	mg/L	20		Pineda, Maritza	5/22/200
EPA 365.1 (DWR Mod	Dissolved Ortho-phosphate	0.05	mg/L as P	0.01		Hernandez, Rich	5/20/200
EPA 200.7 (D)	Dissolved Potassium	12.3	mg/L	2.5	R4	Quiambao, Josie	5/22/200
EPA 200.8 (D)	Dissolved Selenium	2.66	mg/L	0.02		Thind, Pritam	5/21/200
EPA 200.7 (D)	Dissolved Silica (SiO2)	70.8	mg/L	0.5	R4	Quiambao, Josie	5/22/200
EPA 200.7 (D)	Dissolved Sodium	6630	mg/L	20	R4	Quiambao, Josie	5/22/200
EPA 300.0 28d Hold	Dissolved Sulfate	11500	mg/L	200		Pineda, Maritza	5/22/200
Std Method 2320 B	pH	8.4	pH Units	0.1		Chan, Elaine	5/21/200
Std Method 2320 B	Total Alkalinity	313	mg/L as CaCO3	1		Chan, Elaine	5/21/200
EPA 200.8 (T)	Total Arsenic	0.02	mg/L	0.02		Thind, Pritam	5/27/200
EPA 200.8 (T)	Total Barium	< 1.	mg/L	1		Thind, Pritam	5/27/200
Std Method 2540 C	Total Dissolved Solids	21200	mg/L	1		Chan, Elaine	5/22/200
EPA 200.8 (T)	Total Selenium	2.88	mg/L	0.02		Thind, Pritam	5/27/200
EPA 200.8 (T)	Total Strontium	13.1	mg/L	0.1		Thind, Pritam	5/27/200

Grab Sample C3

ID: FWA0509B1077
Sampling point: RO Concentrate after treatment via chemically-enhanced precipitation, 1st sample
Time: 5/19/2009, 2:00 am



Sample Number FWA0509B1077
Station: DP25-TrConc2 TrConc2
Cost Code: L10068100000
Collection Date 5/19/2009 2:00:00 AM
Sample Purpose Normal Sample 0
Matrix: Water, Natural
Description: Treated Concentrate 2
Customer Instructions Treated Concentrate 2
SampleCondition: 2.0 °C when received.

Method	Analyte	Result	Units	Reprting Limit	Footnotes:	Chemist	Analysis Date
Std Method 2510-B	Conductance (EC)	21350	µS/cm	1		Chan, Elaine	5/21/200
EPA 200.7 (D)	Dissolved Boron	46.6	mg/L	0.5	R4	Quiambao, Josie	5/22/200
EPA 200.7 (D)	Dissolved Calcium	595	mg/L	5	R4	Quiambao, Josie	5/22/200
EPA 300.0 28d Hold	Dissolved Chloride	4410	mg/L	200		Pineda, Maritza	5/22/200
Std Method 2340 B	Dissolved Hardness	4843	mg/L as CaCO3	1		Quiambao, Josie	5/21/200
EPA 200.7 (D)	Dissolved Magnesium	815	mg/L	5	R4	Quiambao, Josie	5/22/200
EPA 300.0 28d Hold	Dissolved Nitrate	946	mg/L	20		Pineda, Maritza	5/22/200
FWA0509B1077							
EPA 365.1 (DWR Mod	Dissolved Ortho-phosphate	0.05	mg/L as P	0.01		Hernandez, Rich	5/20/200
EPA 200.7 (D)	Dissolved Potassium	11	mg/L	2.5	R4	Quiambao, Josie	5/22/200
EPA 200.8 (D)	Dissolved Selenium	2.64	mg/L	0.02		Thind, Pritam	5/21/200
EPA 200.7 (D)	Dissolved Silica (SiO2)	69.5	mg/L	0.1		Quiambao, Josie	5/22/200
EPA 200.7 (D)	Dissolved Sodium	6640	mg/L	5		Quiambao, Josie	5/22/200
EPA 300.0 28d Hold	Dissolved Sulfate	11500	mg/L	200		Pineda, Maritza	5/22/200
Std Method 2320 B	pH	8.6	pH Units	0.1		Chan, Elaine	5/21/200
Std Method 2320 B	Total Alkalinity	241	mg/L as CaCO3	1		Chan, Elaine	5/21/200
EPA 200.8 (T)	Total Arsenic	0.02	mg/L	0.02		Thind, Pritam	5/27/200
EPA 200.8 (T)	Total Barium	< 1.	mg/L	1		Thind, Pritam	5/27/200
Std Method 2540 C	Total Dissolved Solids	20000	mg/L	1		Chan, Elaine	5/22/200
EPA 200.8 (T)	Total Selenium	2.76	mg/L	0.02		Thind, Pritam	5/27/200
EPA 200.8 (T)	Total Strontium	13	mg/L	0.1		Thind, Pritam	5/27/200

A3. Assessment of boron removal via second-pass RO desalting

Analytical Lab*: UCLA Chemistry Department Laboratory*

Description: Samples of first pass RO permeate samples, obtained from field study, were analyzed in the UCLA Chemistry Department Laboratory for boron content. These samples were also further desalted in UCLA laboratory's lab-scale plate-and-frame RO unit under alkaline pH conditions (pH ~10) in order to generate second pass RO permeate. Second-pass RO desalting experiments were done using four different RO membranes and the resulting permeate samples were analyzed for boron content.

Sample	**RO Membrane**	**Manufacturer**	**Boron, mg/L**	**Notes**
1st Pass RO Permeate	XLE	DOW Filmtec	14.53	Sample from field study
1st Pass RO Permeate (duplicate)	XLE	DOW Filmtec	14.35	Sample from field study
2nd Pass RO Permeate	LFC1	Hydranautics	2.67	Sample generated in UCLA lab
2nd Pass RO Permeate	ESPA2	Hydranautics	3.14	Sample generated in UCLA lab
2nd Pass RO Permeate	ESPAB	Hydranautics	2.372	Sample generated in UCLA lab
2nd Pass RO Permeate	SWC4+B	Hydranautics	1.353	Sample generated in UCLA lab