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Increasing Recovery of Inland Desalters by Combining EDR and SPARRO Technologies to Treat Concentrate

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Over a 6-month month period, the EDR/SPARRO combination process was tested at the City of Corona, California, Temescal Desalter. The EDR process operated for a total of 1,950 hours on RO concentrate, and the EDR/SPARRO combination operated periodically for two months and included 200 hours of combined operating time. The overall recovery of the combined system would be 85 percent, compared with a recovery of 60 to 65 percent for the EDR operating on its own. The increase in recovery for the EDR/SPARRO combination would reduce the volume of brine for final disposal by 57 percent, and increase overall recovery of the desalter to around 96.6 percent.

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Acronyms and Abbreviations

AF	acre-foot
AFY	acre-feet per year
AWC	American Water Chemicals
CA	cellulose acetate
Carollo	Carollo Engineers, Inc.
CIP	clean-in-place
DC	direct current
DWR	California Department of Water Resources
ECIP	electrode clean-in-place
EDR	electrodialysis reversal
EDX	energy dispersive x-ray spectroscopy
EMWD	Eastern Municipal Water District
f^2	square feet
FTIR	Fourier Transform Infrared
GE	General Electric Water and Process Technologies
gpm	gallons per minute
HMI	human machine interface
IWVWD	Indian Wells Valley Water District
kgal	thousand gallons
kg/hr	kilograms per hour
kPa	kilopascal
kWh	kilowatt hour
lb/hr	pounds per hour
L/min	Liters per minute
m^2	square meters
m^3	square meters
m^3/d	cubic meters per day
m/s	meters per second
mgd	million gallons per day
mg/L	milligrams per liter
MPa	megapascal
mS/cm	milli-Siemens per centimeter
NF	nanofiltration
NPF	normalized permeate flow
NSP	normalized salt passage
NSR	normalized salt rejection
O&M	operation and maintenance

PFD	process flow diagram
PLC	programmable logic controller
PRS	pressure reducing station
psig	pounds per square inch gauge
Reclamation	Bureau of Reclamation
RO	reverse osmosis
SARI	Santa Ana Regional Interceptor
SAWPA	Santa Ana Watershed Project Authority
SEI™	Superimposed Elemental Imaging
SEM	scanning electron microscopy
SPARRO	Slurry Precipitation and Recycle Reverse Osmosis
TCF	temperature correction factor
TDS	total dissolved solids
TFC	thin film composite
TOC	total organic carbon
UCLA	University of California at Los Angeles
VDC	volts direct current
XPS	x-ray photoelectron spectroscopy
ZLD	zero liquid discharge
µm	micrometer
µS/cm	microsiemens/centimeter

1. Executive Summary

To increase the supply of usable water in the United States, technologies focused on increasing recovery and decreasing waste from the treatment of impaired water sources need to be developed. To help achieve these goals, the electrodialysis reversal (EDR) /slurry precipitation and recycle reverse osmosis (SPARRO) process combination aims to decrease the cost of desalination by decreasing concentrate volume, and making desalination a more attractive alternative for inland utilities where traditional methods of disposal (ocean discharge) are not feasible.

Combining EDR and SPARRO technologies overcomes some of the limitations of both processes. The major limitation of the EDR process is scaling in the concentrate loop. Typically, the EDR process can only recover water up to the point that the solubility limits of the sparingly soluble salts in the concentrate loop are exceeded. One of the limitations of the SPARRO process is its relatively large footprint due to the limited membrane area in tubular modules and, therefore, it tends to be more suited to treating smaller, more concentrated streams.

Over a 6-month period, the EDR/SPARRO combination process was tested at the City of Corona, California, Temescal Desalter. The EDR process operated for a total of 1,950 hours on reverse osmosis (RO) concentrate from the desalter. The EDR/SPARRO combination operated on and off for a 2-month period and included 200 hours of combined operating time.

Many of the project goals were achieved. Notably, it was demonstrated that the two processes can operate well in combination, and that the EDR process automatically adjusts its hydraulic balance to accommodate return flows to the EDR brine loop from the SPARRO process. The combined operating time was, however, less than what was aimed for. This was for two major reasons. First, it was difficult to control the flow rate of concentrate from the EDR unit. If future testing is to be done, the SPARRO unit needs to be sized to take all the concentrate blowdown from the EDR. As part of this, better level and flow control equipment needs to be provided. Second, the high concentrations of bicarbonate in the EDR concentrate impacted the process. The bicarbonate values were higher than had been experienced during previous test work and caused significant precipitation of calcium carbonate within the SPARRO system, despite the presence of the gypsum seed. This was not anticipated, and resulted in the formation of large solid flakes not experienced in previous studies, which caused problems in the membranes and other areas of the process. Testing at the end of the study showed that pH suppression of the feed from the EDR allowed for release of a high percentage of the bicarbonate as carbon dioxide (CO_2). In future testing, pH suppression should be used as a pretreatment step ahead of the SPARRO unit to reduce the bicarbonate concentration and to limit formation of calcium carbonate within the SPARRO system.

Using the values obtained from the pilot study and extrapolating them to account for a system in which all EDR concentrate would be fed to the SPARRO unit, the overall recovery of the combined system would be 85 percent. This compares with a recovery of 60 to 65 percent for the EDR operating on its own. The increase in recovery for the EDR/SPARRO combination would reduce the volume of brine for final disposal by 57 percent; and increase the overall recovery at the desalter to around 96.6 percent.

A preliminary cost estimate showed that using the EDR/SPARRO combination would make economic sense where current brine disposal costs are high and where the cost of alternative water sources is also high.

The EDR/SPARRO combination shows promise as an approach to treat brine streams to achieve near-zero liquid discharge (ZLD) and recover the solid by-product for reuse. Further work is needed to address the challenges experienced during the pilot testing before a firm recommendation for the application of this approach at full scale can be made.

2. BACKGROUND

As water scarcity becomes more of an issue in many regions throughout the United States, there is a growing interest in desalination of impaired water sources. One of the major limitations of desalination is the concentrated waste stream that is produced by traditional technologies such as RO. Typically, RO can recover between 70 and 85 percent of the influent water from brackish sources depending on the chemistry of the feedwater, resulting in a significant amount of concentrate that requires disposal. Brackish sources that are predominately sodium and chloride in nature can have recovery levels of 90 percent. However, these are not the focus of this study. The disposal of the concentrate stream is often challenging and can be cost prohibitive for locations where ocean disposal is not feasible. Even for inland regions of Southern California where regional concentrate pipelines to the ocean exist, concentrate disposal is becoming more costly and more challenging due to issues with pipeline scaling, maintenance, and decreased line capacity. Figure 1 shows a photograph of a portion of the Inland Empire Brine Line (formerly the Santa Ana Regional Interceptor [SARI] line) showing internal scale formation.

To reduce the cost of concentrate disposal, the recovery of the desalting process needs to be increased. However, increasing recovery can be challenging because the overall recovery of a desalination process is determined by the concentration of the least soluble of the sparingly soluble salts present (e.g., calcium carbonate, calcium sulfate, and silica). To recover water beyond the solubility limit, solid salts must be removed from the process. Several processes, including lime softening followed by a secondary desalting unit, have been tested. While these processes successfully reduce concentrations of sparingly soluble salts, they can use a significant amount of chemicals and produce a large amount of solid waste.

Figure 1.—Pipeline scaling of highly concentrated brine lines (Santa Ana Watershed Project Authority [SAWPA], 2010).

To reduce the amount of chemical used and waste produced, Carollo Engineers, Inc. (Carollo) conceived a new treatment approach using a combination of two membrane processes. This technology approaches concentrate minimization from a different angle by allowing salts to precipitate, in a controlled manner, in the secondary desalting unit instead of removing salts ahead of secondary desalting. The approach makes use of EDR as a secondary desalting process by connecting it to the concentrate line of an existing RO process train, and using SPARRO to treat and reduce the scaling potential of the EDR concentrate loop. The SPARRO process allows salts to precipitate naturally, as concentration increases, on calcium sulfate seed crystals, does not require chemicals, and produces a solid calcium sulfate product that could be used as a useful resource by other industries.

2.1 Description of Unit Processes

EDR has been used for water desalination for over 50 years. The SPARRO process is less well known in water treatment, but this process has been experimented with in the mining industry to treat highly concentrated mining waste since the mid-1980s, and more recently to treat agricultural drainage streams and pilot studies referred to earlier. The concept of seeding is well known and practiced in the application of vapor compression evaporator technology.

2.1.1 Electrodialysis Reversal

EDR is an electrochemical separation process that uses a direct current (DC) voltage and ion exchange membranes to desalinate water. A schematic diagram of the EDR process is shown on Figure 2. As shown, the feed enters the product compartment and positive ions are attracted towards the cathode while negative ions are attracted to the anode. As the ions travel through the membrane stack, positive ions pass through cationic membranes and are rejected by anionic membranes and vice versa for negative ions. Alternating cationic and anionic membranes create product compartments and concentrate compartments within the membrane stack.

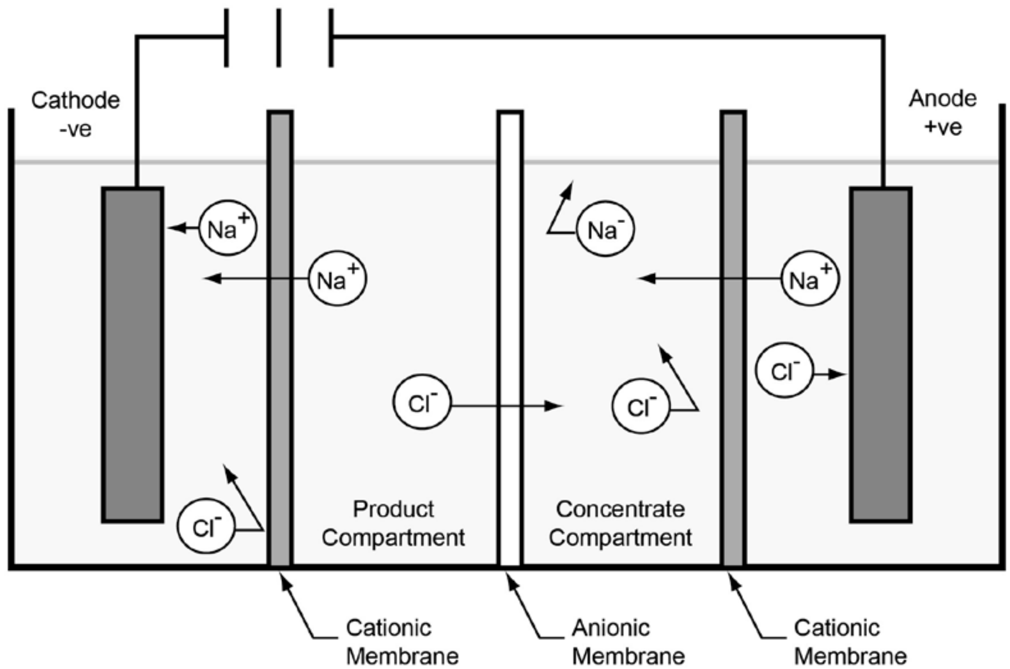


Figure 2.—EDR schematic.

2.1.2 Slurry Precipitation and Recycle Reverse Osmosis

The SPARRO process is a hybrid of conventional RO technology. It incorporates the recirculation of seeded slurry through the RO system, promoting homogeneous nucleation and precipitation of super saturated salts from the solution. This process was first developed to treat cooling tower blowdown from power plants high in calcium and sulfate ions. Seed crystals (gypsum) are introduced to the feed stream, which are then pumped into tubular RO membranes. As the water is concentrated along the membranes, the solubility products of calcium sulfate, silicates, and other scaling salts are exceeded; and they preferentially precipitate on the seed material rather than on the membranes. A schematic of the seeding concept in the SPARRO process is shown on Figure 3.

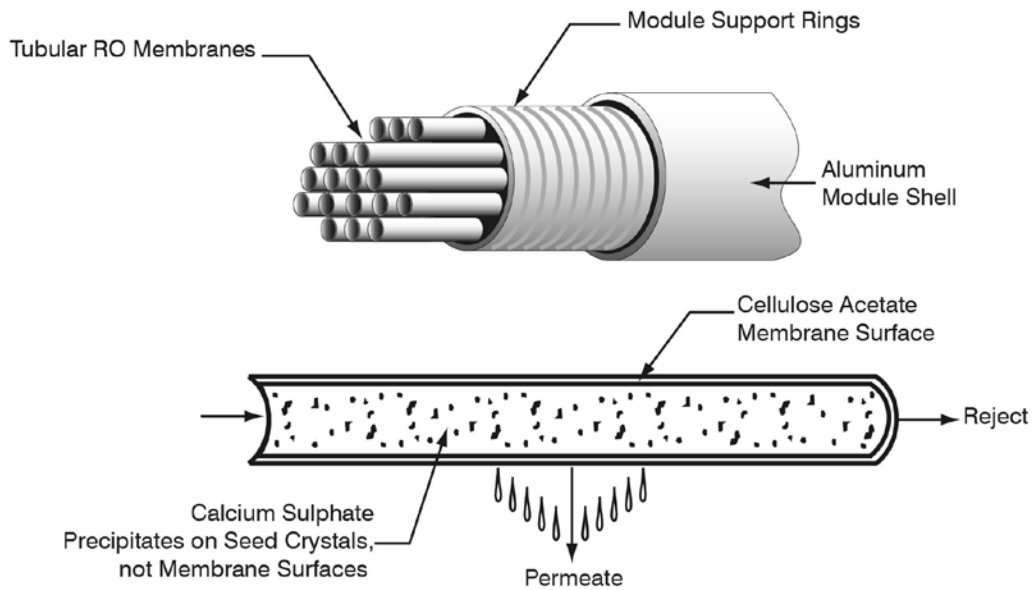


Figure 3.—Schematic of seeding concept in SPARRO.

2.1.3 EDR/SPARRO Process Combination

The combination of the EDR and SPARRO process overcomes some of the limitations of both processes. The major limitation of the EDR process is scaling in the concentrate loop. Typically, the EDR process can only recover water up to the solubility limits of the least soluble of the present sparingly soluble salts in the concentrate loop. One of the limitations of the SPARRO process is its relatively large footprint due to the limited membrane area in tubular membranes and, therefore, it tends to be more suited to treating smaller, more concentrated streams.

The two processes have a synergistic relationship. The EDR provides the SPARRO unit with a highly concentrated, low-flow stream overcoming the footprint issues of the SPARRO process, while the SPARRO process removes solid salts (calcium sulfate) in a controlled manner helping to overcome the solubility limitation of the EDR process. Combining the strengths of the two processes increases the overall recovery of the EDR system beyond the recovery that can be feasibly achieved, and at the same time produces a high-quality solid gypsum by-product ($CaSO_4 \cdot 2H_2O$) that may be used in other industries. A schematic of the EDR/SPARRO process is shown on Figure 4.

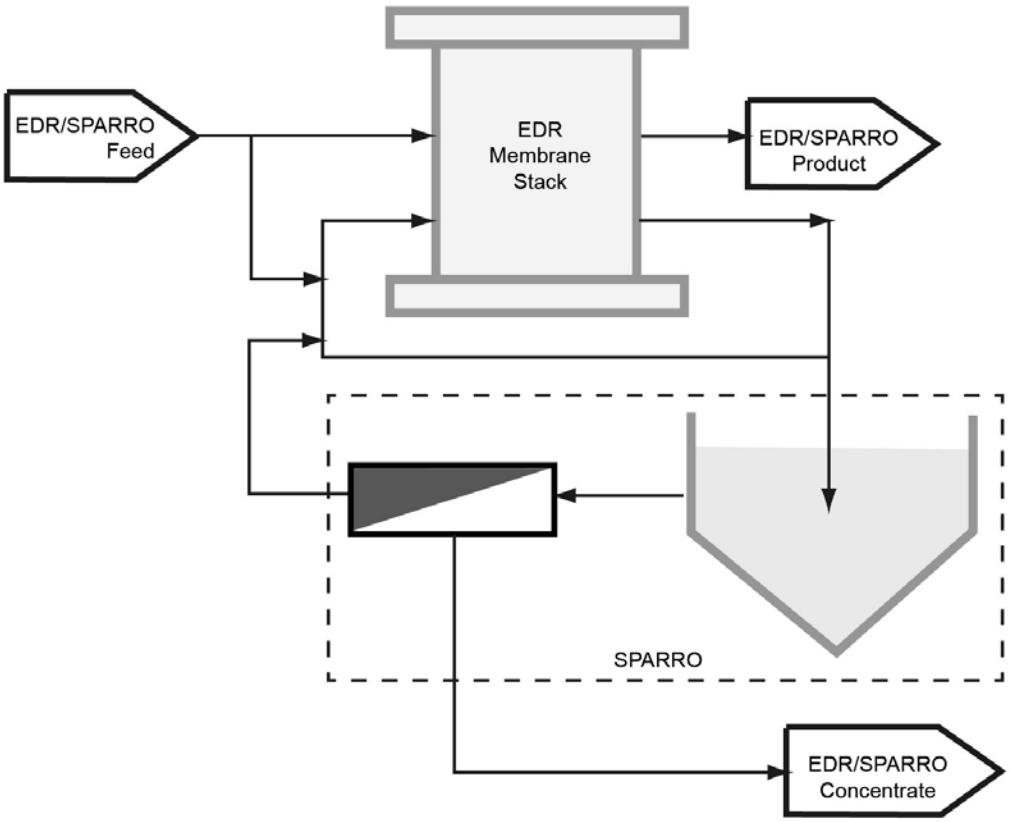


Figure 4.—EDR/SPARRO schematic.

2.2 Previous Research

The EDR process has been extensively tested over the last 50 years, and there are several full-scale EDR water treatment facilities currently in operation. Recently, EDR has been gaining popularity as a concentrate treatment alternative with several pilot studies being performed (California Department of Water Resources [DWR], 2010 and Reclamation, 2008). The seeded RO process has been tested at the pilot-scale for treating cooling tower blowdown (O'Neail et al., 1981), and the SPARRO process has been tested at pilot-scale for treating highly scaling mine water (Juby, 1996), and more recently for treating secondary concentrate (Reclamation, 2008 and DWR, 2010).

2.2.1 SPARRO Pilot Testing 2008

The SPARRO process was tested at the Eastern Municipal Water District (EMWD) in Sun City, California, in 2008. The complete results of the study have been published in the 2008 study (Reclamation, 2008). For the 2008 study, the pilot unit was operated as a batch process for approximately 3 hours per day over several days and nanofiltration (NF) membranes were used in the SPARRO membrane vessel. The permeate produced from the SPARRO process was removed and periodically sampled for laboratory analysis. The concentrate leaving the membrane vessel was piped through a pressure-reducing system and returned to the feed tank. The solution in the feed tank was allowed to increase in concentration to simulate operation at different water recovery levels. Solid gypsum was not removed from the system in this case and, therefore, the gypsum concentration in the feed solution increased with time.

The SPARRO process was tested on a concentrate solution that was supersaturated with calcium sulfate and had a total dissolved solids (TDS) concentration of 18,600 milligrams per liter (mg/L). Water quality data from the testing is summarized in Table **1**. The SPARRO process, with NF membranes, was able to achieve an overall salt rejection of 50 to 60 percent and a permeate flux rate as shown on Figure 5. The highest recovery that was achieved during operation was about 60 percent, as shown on Figure 6. In this case, the SPARRO system was operated in batch mode with recycle and, hence, a linear trend in recovery from 0 to 60 percent was observed. The recovery was limited by the size of equipment and not by membrane scaling. After 180 minutes of operation, the feed volume in the tank had decreased to below the level of the mixer and the system had to be shut down to prevent settling of the gypsum seed crystals.

Table 1.—Summary of SPARRO Water Quality Data (Reclamation, 2008 at EMWD)

Parameter	Units	Feed	Product	Concentrate
TDS	mg/L	18,600	10,400	22,300
Sodium	mg/L	4,100	1,700	5,500
Calcium	mg/L	2,200	950	1,600
Magnesium	mg/L	600	300	700
Chloride	mg/L	9,900	5,700	10,600
Sulfate	mg/L	2,200	600	3,300
Bicarbonate	mg/L	200	100	300

The success of the seeded technique could be inferred not only from the apparent concentration increase of gypsum seeds in the system as shown on Figure 6, but also from scanning electron microscopy (SEM) imaging and energy dispersive x-ray spectrometer (EDX) analysis of the resulting gypsum seed. The presence of crystallites in the 1- to 5-micrometer (µm) size range on larger gypsum seeds (10 to 50 µm) (Figure 7) indicates that mineral salts precipitated on the seed crystals. EDX analysis (Figure 7) confirmed that predominantly only calcium and sulfate precipitation occurred, shown by the large “Ca,” “O,” and “S” identification peaks, indicating a predominantly calcium sulfate by-product.

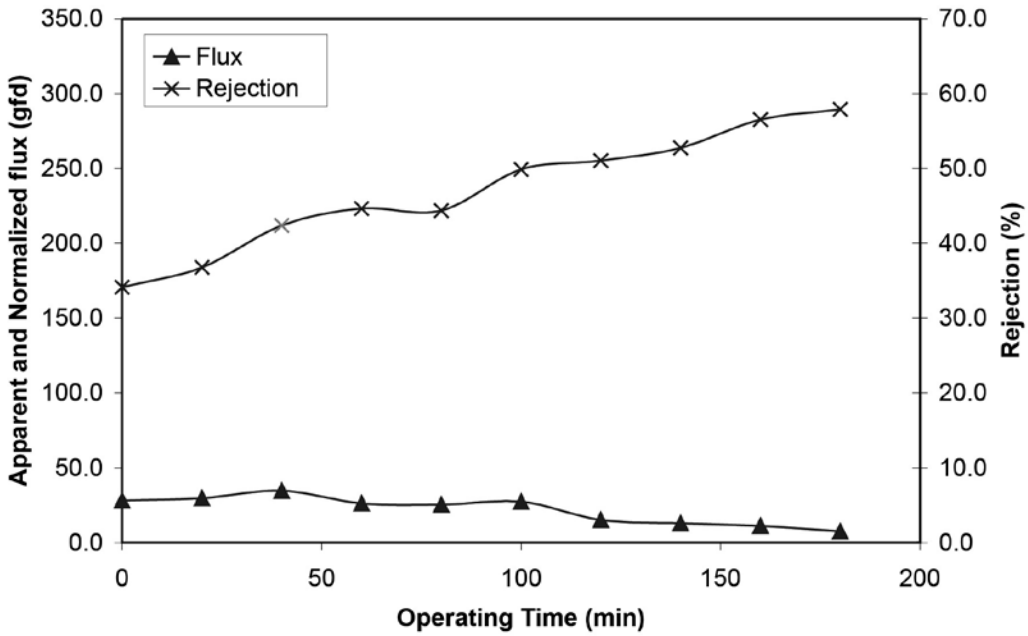


Figure 5.—SPARRO permeate flux and rejection.

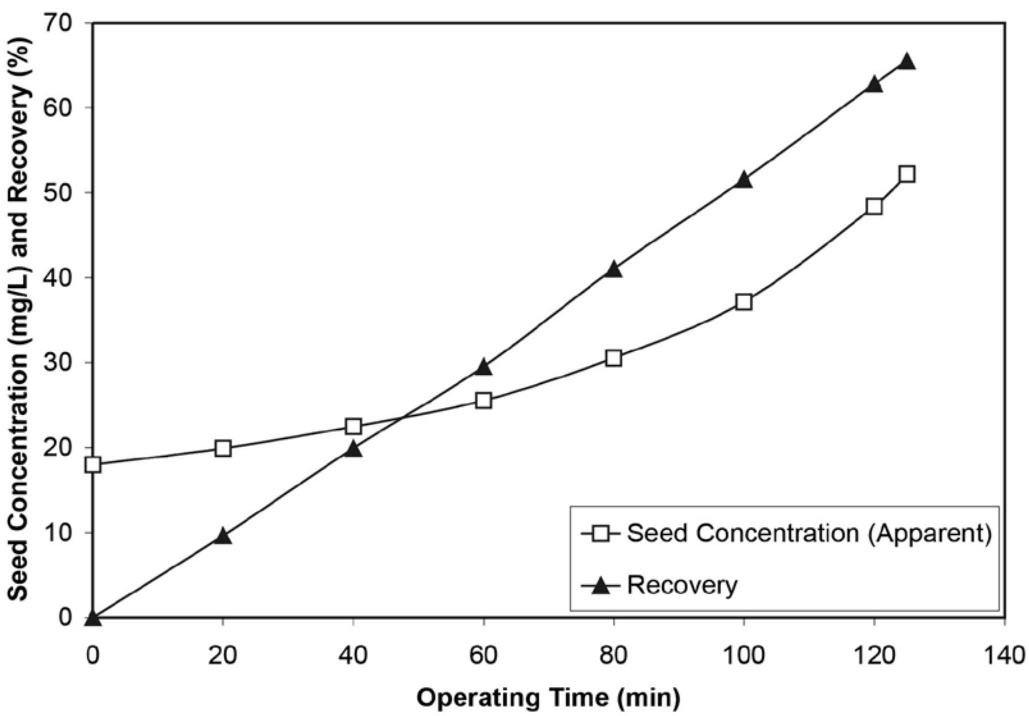


Figure 6.—SPARRO recovery and apparent seed concentration.

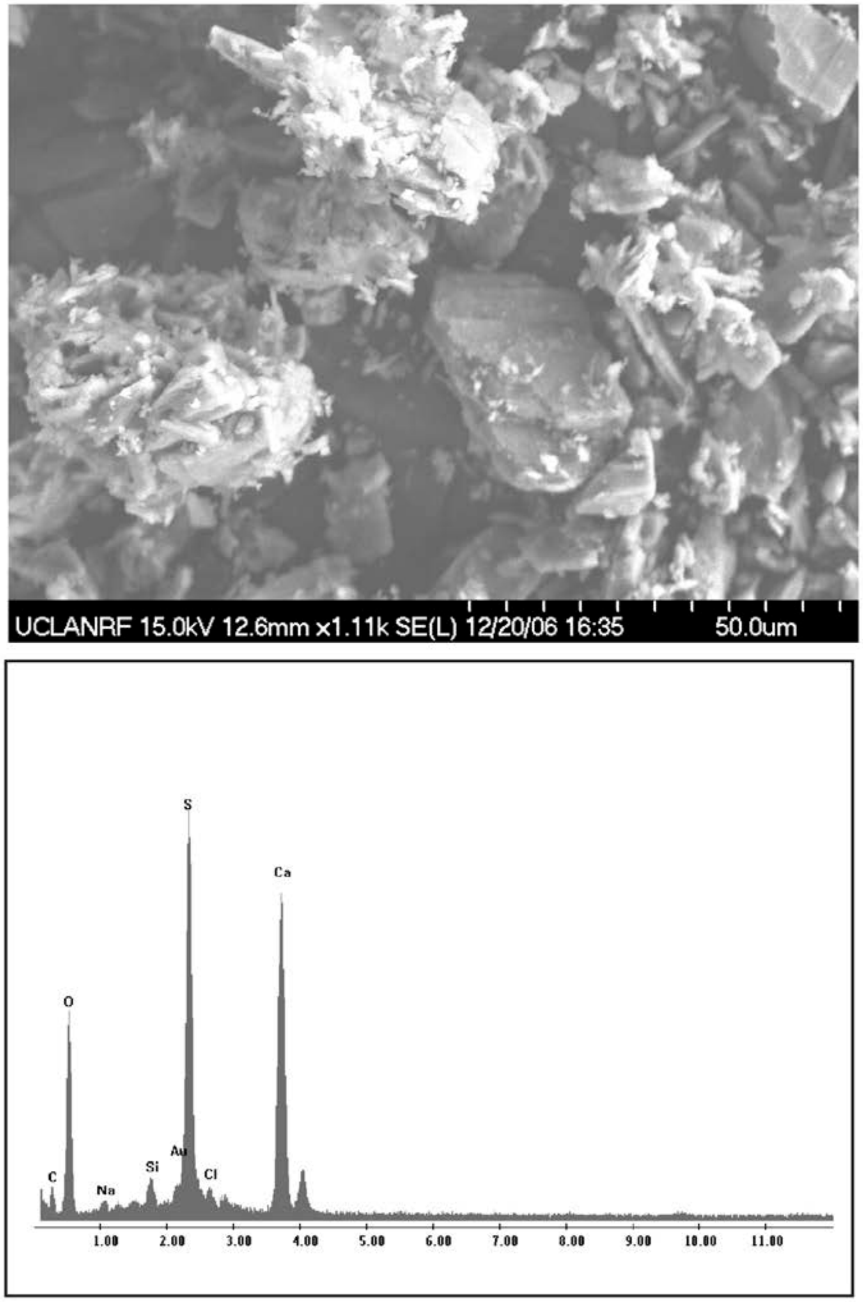


Figure 7.—SEM and EDX analysis of gypsum seed (Reclamation, 2008).

The integrity of the tubular NF membrane was intact for the duration of the SPARRO testing, as demonstrated by the data shown on **Figure 8**. The permeate conductivity was monitored throughout the pilot-testing duration and remained constant at around 21 milli-Siemens per centimeter (mS/cm). In addition, the clarity of the permeate stream was monitored throughout plant operation. If the seeded slurry had punctured the membrane surface, the damage would translate to an increase in the permeate conductivity and/or visible turbidity in the water. No such observations were made during the course of testing.

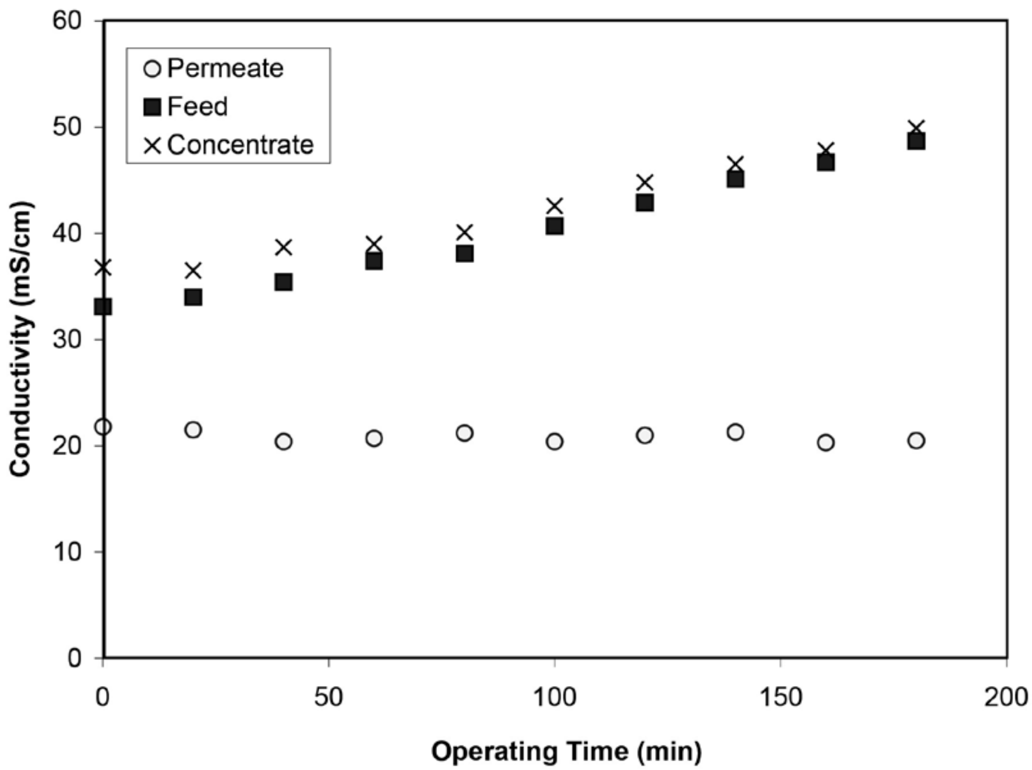


Figure 8.—SPARRO feed, permeate, and concentrate conductivity.

2.2.2 EDR/SPARRO Testing 2010

The EDR/SPARRO process combination was tested at the Indian Wells Valley Water District (IWVWD) in Ridgecrest, California, during 2009 and 2010. The results are published in a California Department of Water Resources report (DWR, 2010). During this pilot testing, the SPARRO system was tested in conjunction with an EDR unit for a 2-week period, using tubular RO membranes, to determine whether the overall recovery of the EDR unit could be increased. Similar to the previous study, the SPARRO process was operated with the EDR batch-wise, but in this case for approximately 8 hours per day. During the other 16 hours of the day, the EDR was operated without the SPARRO unit to compare EDR performance, both with and without the SPARRO system.

The EDR/SPARRO combination resulted in a greater recovery than EDR only (Figure 9). The average recovery with the EDR alone was 77 percent, whereas recovery of the EDR/SPARRO combination unit was 84 percent. This 7-percent increase equates to a 37-percent reduction (1.6 gallons per minute [gpm] to 1.0 gpm) in concentrate flow from the EDR unit. Such a reduction would have a significant cost benefit for any downstream concentrate disposal process, be it a highly capital-intensive brine concentrator or double-lined evaporation pond.

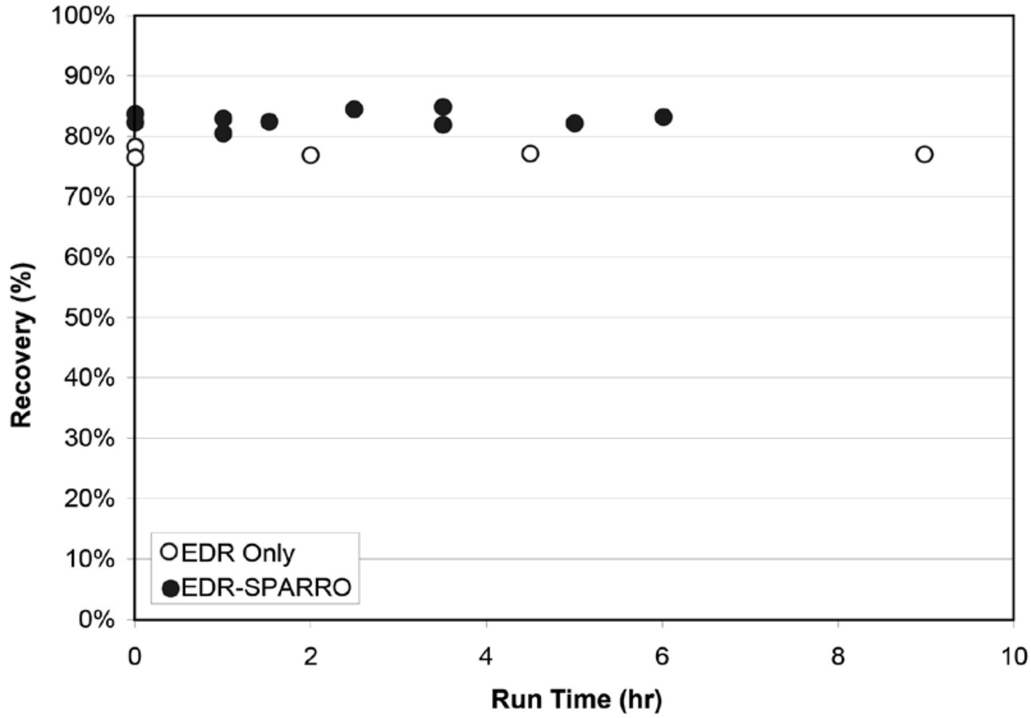


Figure 9.—EDR recovery with and without SPARRO operation.

In addition to increased recovery, the SPARRO process improved the performance of the EDR. The EDR product conductivity was consistently 10 microsiemens/centimeter (µS/cm) lower when operating with the SPARRO than without. The SPARRO unit also improved the quality of the EDR makeup water. The makeup water in the EDR process is used to replace the volume of water that is lost to the concentrate blowdown and is typically comprised of EDR feedwater. In the EDR/SPARRO process, a portion of the EDR makeup is replaced with permeate from the SPARRO process. By replacing the EDR makeup with SPARRO permeate, the concentrations of sparingly soluble salts are reduced in the EDR concentrate loop. The SPARRO process reduced the calcium, sulfate, and silica concentrations in the EDR makeup flow by 72, 43, and 77 percent, respectively (Figure 10).

DWR (2010) concluded that the EDR/SPARRO process combination was able to improve EDR performance and increase EDR recovery, but further testing to determine the reliability of the process was necessary.

2.3 Economic Value

Due to the highly scaling nature of concentrate streams, concentrate disposal costs remain a substantial limiting factor to many inland desalination processes. Therefore, one of the more attractive benefits of the EDR/SPARRO process is the substantial reduction of concentrate production and increased recovery ultimately reducing the expense of desalination. An additional economic advantage of the SPARRO process is that the solid gypsum produced has potential to be a marketable by-product. A preliminary market survey of the gypsum by-product has been conducted and is included in Appendix A.

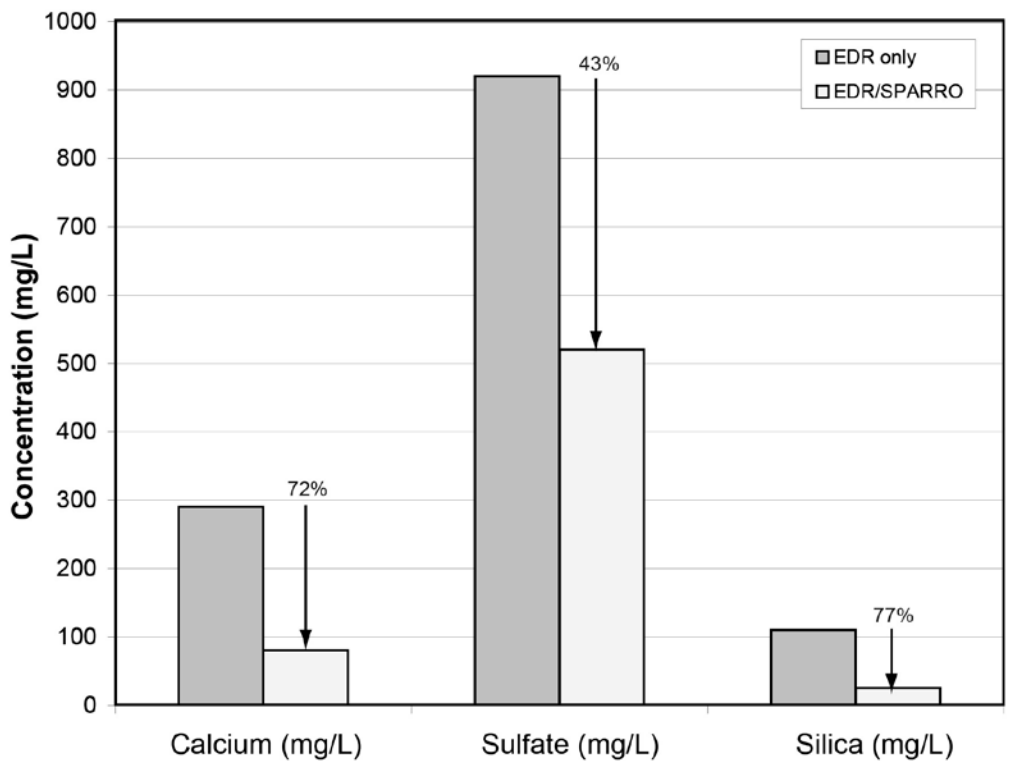


Figure 10.—EDR/SPARRO makeup flow concentration changes.

By improving the economics of inland desalination and concentrate management, this project is applicable to many inland utilities that are considering brackish groundwater desalination. For many inland utilities where ocean disposal is not feasible, concentrate management is a major factor in the success of the project. The EDR/SPARRO process combination aims to increase water production and decrease concentrate volume, which can significantly reduce the cost of concentrate disposal or final treatment in a ZLD or near-ZLD process, making inland desalination more feasible.

Because the cost of treating concentrate streams increases exponentially for a near-ZLD system using mechanical evaporation, a relatively small increase in recovery for a secondary treatment process such as EDR has a significant impact on reducing the cost of the final concentrate disposal step(s); thereby having a positive impact on the cost of the overall concentrate management treatment train.

2.4 Project Goals and Objectives

The preliminary pilot studies at EMWD and IWVWD showed the technical feasibility of applying the EDR/SPARRO concept to concentrate treatment. The major goal of this pilot project was to further develop the EDR/SPARRO process combination to increase recovery and reduce waste from traditional desalination processes. The specific goals of the pilot project were to:

- Determine the technical feasibility of continuous operation of the EDR/SPARRO process combination.
- Establish the optimum operating parameters of the EDR/SPARRO process.
- Estimate capital and operation and maintenance (O&M) costs of the EDR/SPARRO process.
- Investigate marketability of high-purity gypsum solids produced in the EDR/SPARRO process.

For this project to prove successful, the EDR/SPARRO process combination must be reliable during continuous operation at pilot-scale, demonstrate increased EDR recovery and better overall EDR performance, produce a high-quality gypsum by-product, and improve the economics of inland desalination and concentrate management. Should the goals of this pilot project be realized, the potential for future application would be significant. The future step in developing this process would be to build and operate a demonstration-scale unit to further refine the operation of the process and prove the concept at larger scale.

3. TECHNICAL APPROACH

The overall approach for this project was first, to design and construct a SPARRO pilot unit capable of continuous operation, then operate it in combination with an EDR unit treating concentrate from an existing RO desalting facility. To determine the benefits of the EDR/SPARRO combination, the performance of the EDR/SPARRO system was compared to the operation of a standalone EDR unit on the same desalter concentrate feedwater. Comparing the performance of the two technologies helped determine whether the addition of the SPARRO process in the concentrate loop of the EDR provided meaningful process benefits.

The pilot skids were housed adjacent to an existing RO train at the Temescal Desalter, owned and operated by the City of Corona, California (Figure 11). The complete pilot consisted of two separate units. The first was the EDR unit provided by General Electric Water and Process Technologies (GE). The second unit was the SPARRO unit, which was custom built for this application.

Figure 11.—15-mgd (56,775 m^3/d) Temescal desalter.

The original pilot plan called for a 3-month testing period. The EDR unit was operated independently for the first month to establish a baseline. Then the SPARRO unit was connected into the EDR concentrate loop for 2 months. The goal during this time was to operate the SPARRO unit continuously with the EDR unit to determine various operational parameters for full-scale operation.

During operation, each process stream was sampled to perform a detailed water quality analysis. The following sections describe the pilot facility; pilot implementation, start-up, commissioning, and operation; sampling and monitoring; and data interpretation methodologies.

3.1 Pilot Plant Facility

The EDR and SPARRO skids were set up in the northeast corner of the Temescal Desalter adjacent to RO Process Train 4. A simplified site layout is provided on Figure 12.

3.1.1 Source Water for Pilot Testing

The Temescal Desalter is an existing groundwater RO facility owned and operated by the City of Corona. This 15-million gallon per day (mgd) (56,775 cubic meters per day [m^3/d]) facility includes preliminary filtration of RO feed through 5-micron cartridge filters before entering a 10.3-mgd (38,986 m^3/d) RO treatment process. This facility has been operating for approximately 9 years. The RO plant is comprised of four treatment trains, each in a two-stage array and operating at 86-percent recovery. Three of the four trains are designed to produce 2.3 mgd (8.706 m^3/d) while the fourth is larger, producing 3.4 mgd (12,869 m^3/d). RO Train 3 supplied concentrate to the pilot plant.

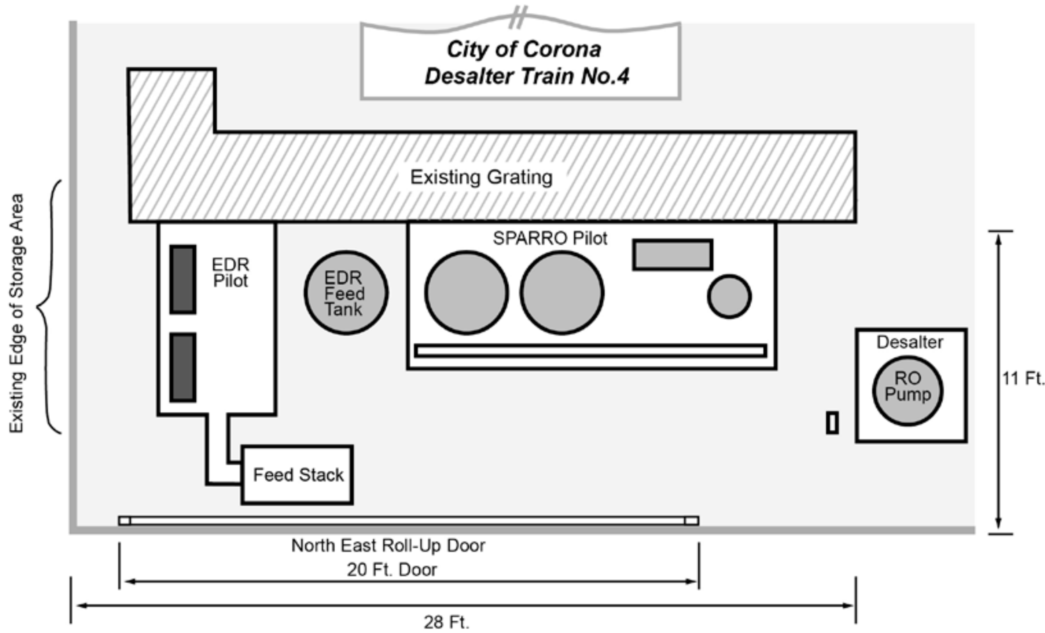


Figure 12.—Pilot facility site layout.

For this study, the City of Corona was asked to reduce the recovery in RO Train 3 from 86 percent to 80 percent to simulate conditions that would be expected for the full scale application of the EDR/SPARRO combination. An earlier study had shown that at 86 percent recovery, the RO trains are operating in a high-risk area with respect to scale formation and require regular cleaning to maintain operation. If a downstream EDR/SPARRO process was to be provided to increase the recovery beyond 86 percent, then lowering the RO recovery to 80 percent would provide a less stressful operating environment for the RO membranes, and would reduce operational risk by limiting the scale forming conditions to a smaller downstream process.

3.1.2 Electrodialysis Reversal

A mobile EDR piloting skid was leased from GE for the pilot testing. The Aquamite IV pilot unit was housed in the northeast corner of the Temescal Desalter building. A process flow diagram (PFD) and a photograph of the pilot unit are shown on **Figure 13** and **Figure 14**, respectively. The unit used a single EDR membrane stack with two electrical and four hydraulic stages. An electrical stage comprises one cathode and one anode separated by a series of cationic and anionic membranes and spacers. The number of hydraulic stages indicates the number of passes the product water makes through the electrical stages. Specific attributes of the GE pilot EDR unit are summarized in Table **2**.

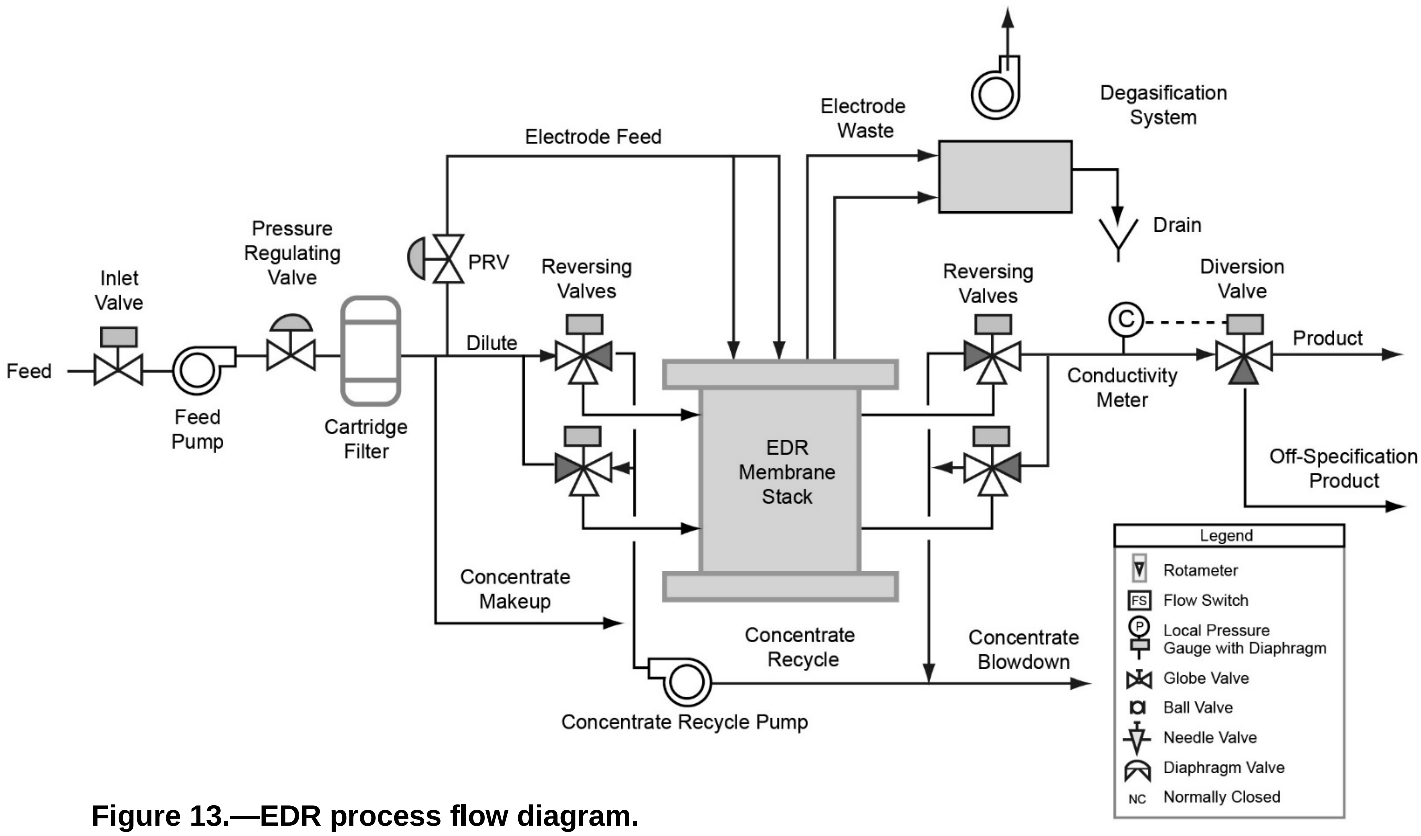


Figure 13.—EDR process flow diagram.

Figure 14.—Photograph of EDR pilot skid.

Table 2.— EDR Pilot Design Criteria

Parameter	Value
Feed Flow (gpm)	10.5 (39.7 L/min*)
Product Flow (gpm)	6.3 (23.8 L/min)
Blowdown Flow (gpm)	2.8 (10.6 L/min)
Brine Makeup Flow (gpm)	2.5 (9.5 L/min)
Overall Recovery (%)	~60
Electrical Stages	2
Hydraulic Stages	4
Cell Pairs	45/35/45/35
Salt Rejection (%)	70-80

*L/min = Liters per minute

The EDR membranes are separated by spacers to carry both brine and product water streams. Each electrical stage also has two corresponding hydraulic stages. All the feedwater to the EDR passes through each electrical stage twice to provide greater residence time for ion transfer. Water developed within the concentrate cell pairs is circulated back to the concentrate system within a concentrate loop. A small booster pump is used to circulate the concentrate loop through the stack. To control scaling in the concentrate loop, a portion of the loop must be removed, which creates a reject stream. This process of brine removal is referred to as brine “blowdown” and the dilution and replenishment of the brine loop is referred to as “brine makeup.”

The EDR cathode and anode operations were programmed to alternate every 15 minutes by reversing the polarity, or direction, of current flow. This aided in preserving the integrity of the membranes by preventing scale buildup. During charge reversal, approximately 60 seconds in duration, the high TDS concentrate is flushed from the membrane stack and diverted to waste.

Two chemicals were added to the EDR process in order to control scaling in the concentrate loop and electrode chambers. Hydrochloric acid in an 18-percent solution was used to control the pH to 7.1 and 17 to 20 mg/L of anti-scalant (hypersperse MDC 706) was added to prevent scaling. Hydrochloric acid was dosed every 8 hours for a period of 30 minutes to reduce the pH in the electrode flow to 2 or less. This allowed for cleaning of the electrodes and was referred to as electrode clean-in-place (ECIP). The hydrochloric acid feed pump was adjusted during commissioning to provide a clean-in-place (CIP) pH of 2 or less.

While chemicals are added to help control scaling, it is still necessary to periodically chemically clean the EDR membrane stack. During operation, EDR performance metrics are monitored to determine if a CIP procedure is needed. These metrics include the differential pressure and electrical resistance of the membrane stack. When either of these metrics fall out of their normal range, a CIP is required. During the CIP, all influent and effluent valves are closed and water is recirculated, using the concentrate loop pump, through the membrane stack. Hydrochloric acid is added to the loop to maintain the pH below 1 for 1 hour. This process is repeated as needed. After the cleaning process is finished, a cleaning flush sequence is initiated at the human machine interface (HMI). This sequence reopens the influent and effluent valves and operates the EDR with the voltage off for 30 minutes.

3.1.3 Slurry Precipitation and Recycle Reverse Osmosis

The SPARRO skid has a footprint of approximately 5 feet by 20 feet (1.5 by 6.1 m) and was installed just to the southwest of the EDR adjacent to the RO Train 4. A photograph of the SPARRO skid in position is shown on **Figure 15**. The main components of the SPARRO pilot include a slurry feed tank, high-pressure feed pump, pressure vessel, tubular RO membrane elements, hydrocyclone separator, concentrate tank, and permeate tank. Design criteria for the SPARRO pilot unit are summarized in Table **3**.

Figure 15.—Photograph of SPARRO skid.

Table 3.—SPARRO Pilot Design Criteria

Parameter	Value
Raw Feed Flow (gpm)	1 – 1.5 (3.8 – 5.7 L/min)
Membrane Feed Flow (gpm)	3.5 (13.2 L/min)
Product Flow (gpm)	0.5 – 1.0 (1.9 – 3.8 L/min)
Recovery (%)	50 – 66
Feed Pressure (psi)	300 – 600 (2.1 to 4.1 MPa)
Concentrate Flow Velocity (ft/s)	~ 4.2 (1.3 m/s)
Cyclone Feed Pressure (psi)	> 20 (138 kPa)
RO Membrane Vessels (No.)	2
Membrane Area per Vessel (ft^2)	28 (2.6 m^2)

MPa = megapascal
m/s = meters per second
kPa = kilopascal
f^2 = square feet
m^2 = square meters

The pilot SPARRO unit was designed to treat 1 to 1.5 gpm (3.8 to 5.7 L/min) of EDR concentrate and consists of two tubular RO membrane vessels. A PFD of the SPARRO pilot unit is shown on **Figure 16**. Each membrane vessel housed eighteen 12-foot (3.7 meter [m]) long tubular RO membranes for a total membrane area of 28 square feet (2.6 m^2) per vessel. The permeate from both modules was collected in a permeate break tank before being discharged. The concentrate from Pressure Vessel 2 was conveyed to a pressure reducing station (PRS) that consisted of a short section of 3/8-inch (9.5 mm) stainless steel tubing. The PRS was incorporated into the design of the pilot skid because the high pressure and abrasive nature of the slurry would cause significant wear to a control valve. Following the PRS, concentrate slurry is sent to a hydrocyclone separator where smaller particles and most of the liquid are separated (overflow) from the larger particles (underflow). This separation allows for individual control of the gypsum solids mass balance and liquid TDS by wasting calculated volumes of the high suspended solids cyclone underflow and the high TDS cyclone overflow, respectively. About 0.5 gpm (1.9 L/min) of the overflow was continuously wasted to maintain TDS levels in the system. The remaining liquid in the overflow (2.0 gpm – 7.6 L/min) was returned to the concentrate tank. The larger, heavier gypsum solids in the underflow were typically discharged into the concentrate tank, which continually overflowed into the slurry feed tank. Gypsum solids were regularly removed from the underflow manually to maintain the solids balance in the system. These solids, collected in waste buckets until decommissioning, were retained incase re-seeding was required and also for sampling purposes.

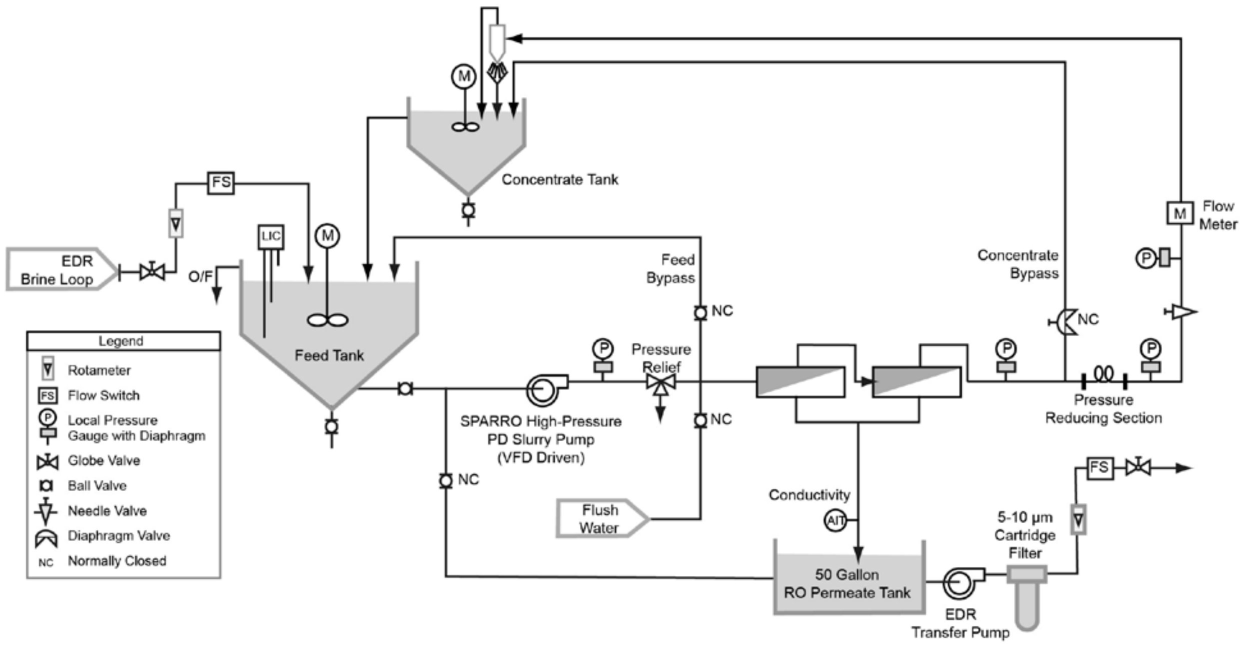


Figure 16.—SPARRO process flow diagram.

3.1.4 EDR/SPARRO

In the EDR/SPARRO process combination, water is fed to the EDR membrane stack as normal where product and concentrate streams are produced as described above. The difference in the EDR/SPARRO process is how the concentrate blowdown is handled. In this process, the EDR blowdown is fed to the SPARRO unit for further treatment. The EDR blowdown is concentrated further in the SPARRO process—allowing calcium sulfate to precipitate on the gypsum seeds. The SPARRO permeate is then fed back to the EDR concentrate loop to help reduce the scaling potential of the EDR concentrate. The SPARRO concentrate is recycled back through the cyclone separator and wasted as describe above.

During Phase II of the pilot testing , the EDR unit was connected to the SPARRO process by transferring a portion of the EDR blowdown to the SPARRO feed tank and by returning SPARRO permeate to the EDR concentrate loop. A PFD of the EDR/SPARRO process is shown on **Figure 17**. One of the original concerns with the operation of this process was the potential effects on the EDR controls of pumping the SPARRO permeate back into the EDR concentrate loop. However, this concern was quickly alleviated when the two processes were combined. The EDR control system seamlessly adjusted to the addition of the SPARRO permeate by reducing the makeup flow from the EDR feed.

Originally, the SPARRO skid was designed to treat the entire EDR blowdown flow plus the EDR "off spec" product that would typically go to waste. This arrangement would provide the highest overall recovery and is how a full-scale system would be designed and operated. However, during the first few weeks of operation of the EDR unit the feed, product, and concentrate flow were increased due to differences in the estimated and the measured water quality, and to provide greater cross-flow velocity in the EDR stack. Because the EDR concentrate flow increased to more than the originally anticipated amount of 1.5 gpm (5.7 L/min), approximately 1.5 gpm of EDR blowdown was supplied to the SPARRO pilot and the remaining blowdown and “off-spec” product were sent to drain. This operational change lessened the overall beneficial effects of the SPARRO process on EDR operation.

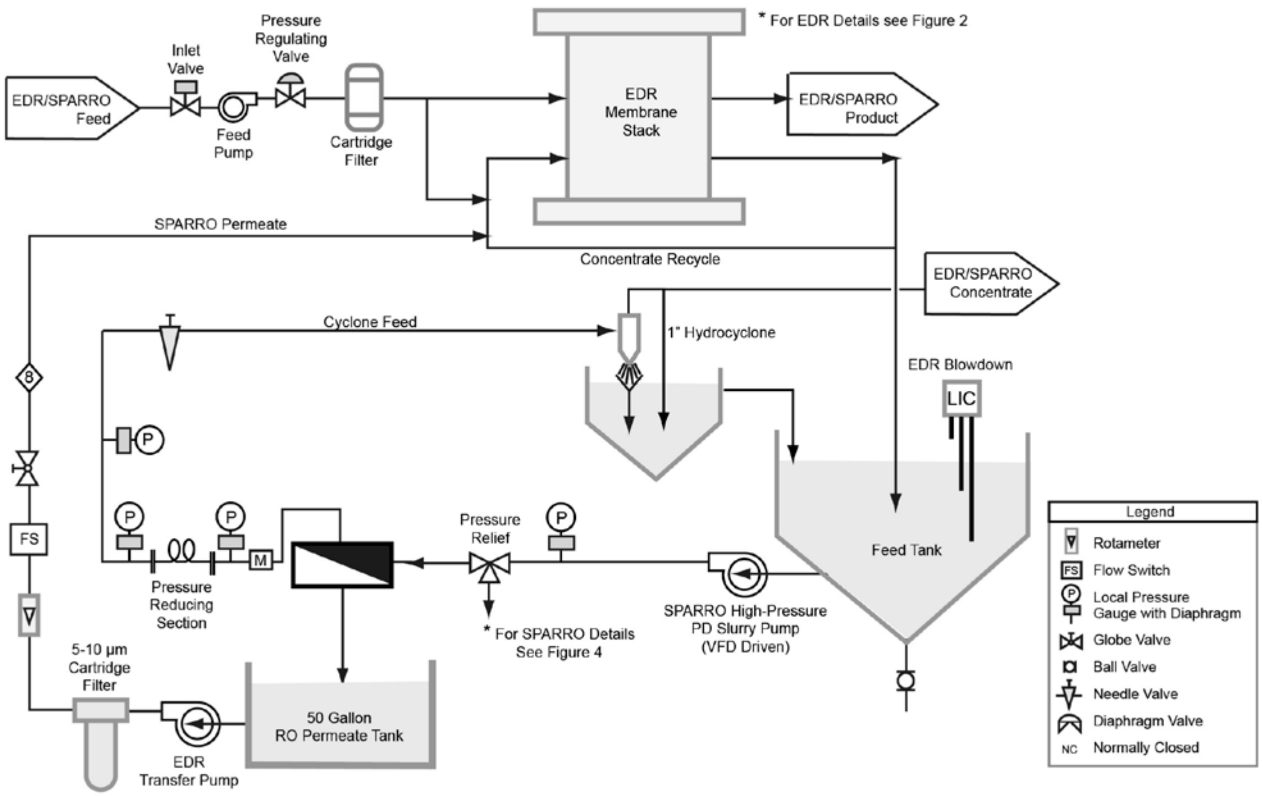


Figure 17.—EDR/SPARRO Process Flow Diagram Schematic

3.2 Pilot Plant Setup, Commissioning, and Operating Protocol

The pilot testing consisted of commissioning, Phase I testing, and Phase II testing. After the EDR unit arrived on site, the unit was installed and commissioned. Initially, treated water, not concentrate, was used to determine if the pilot unit was operating correctly. There were some operational issues that resulted during initial start-up requiring a strip down of the EDR stack and cleaning of the electrode compartments. Once commissioning was complete, the feed stream was switched to the RO concentrate stream from Train 3. The operational parameters, including recovery, product conductivity, and chemical addition were set based on EDR modeling results using the existing RO concentrate quality data presented in Table **4**. Setup and commissioning took approximately 2 weeks.

Table 4.—Temescal Desalter RO Concentrate Data

Parameter	Units	RO Concentrate(1)
pH	-	6.9
Conductivity	µmhos/cm	5,475
TDS	mg/L	4,670
Sodium	mg/L	595
Calcium	mg/L	595
Magnesium	mg/L	150
Chloride	mg/L	835
Sulfate	mg/L	1,415
Bicarbonate	mg/L	785
$CaCO_3$ Saturation Level	%	90 - 100
$CaSO_4 \cdot 2H_2O$ Saturation Level	%	> 100

Notes: Train 3 operating at 80 percent recovery.
µmhos/cm = micromhos per centimeter

After the EDR pilot unit commissioning, Phase I testing began and lasted approximately 4 weeks. During this time, the EDR unit was operated continuously and optimized to determine proper chemical dosing and maximum reliable recovery. To determine the maximum reliable recovery, the recovery of the EDR pilot unit was gradually increased and the pilot operator monitored the unit for signs of scaling. Phase I established the baseline conditions for comparison with Phase II results. At the end of Phase I testing, a CIP was performed on the EDR unit in preparation for Phase II testing.

At the start of Phase II testing, the EDR pilot unit was coupled to the SPARRO unit. Initially, the SPARRO pilot unit was commissioned using clean water to determine proper operation. After proper functionality had been determined, food-grade gypsum ($CaSO_4.2H_2O$) was added to the SPARRO feed tank and mixed to produce a concentration of approximately 18 gallons per liter (g/L). After the gypsum was added, the feed tank remained continuously mixed for the remainder of testing to prevent the gypsum from settling. Commissioning and start-up of the SPARRO process took approximately 1 week.

Once the SPARRO unit was commissioned, the EDR unit was brought online at the baseline conditions and the EDR concentrate was sent to the SPARRO unit.

Operational parameters such as SPARRO feed pressure, solids production, and maximum reliable recovery were recorded. At the end of Phase II, the EDR unit was returned to its original configuration and a final EDR CIP was performed before it was decommissioned. SPARRO membranes were removed and sent for autopsy, and the SPARRO unit was cleaned before decommissioning. During both Phase I and Phase II of the pilot study, the product and concentrate from all operating units was recombined and disposed of with the concentrate from the Temescal Desalter.

3.3 Pilot Sampling and Monitoring

Both manual and automated data collection systems were used during this pilot. Manual data collection consisted of the following:

- EDR: Conductivity and temperature readings on the feed, product and concentrate (blowdown) streams.
- SPARRO: Flow rate in the feed stream, permeate and cyclone overflow streams, slurry feed tank level, conductivity in the feed, permeate and cyclone overflow streams, and feed tank, concentrate tank and cyclone overflow solids concentrations.

Automatic data collection was limited to the EDR system, and consisted of the following:

- EDR: Date, time, runtime, pH, conductivity, temperature, stack voltages, current drawn, pump speeds, electrode flows, concentrate recycle flows, concentrate blowdown flows, concentrate makeup flows, pressures, and differential pressures.

Field testing used the Myron L Company 6P Ultrameter II™ to measure pH, conductivity, and temperature for both pilots. Additionally, samples were collected from the EDR feed, EDR product, EDR concentrate blowdown, SPARRO permeate, and SPARRO concentrate for laboratory analysis by E.S. Babcock & Sons, Inc. (Babcock). The list of chemical analyses is presented in Table **5**. For each parameter, one sample per stream was sent to Babcock for analysis each week and the rest were tested on site. This approach was used in order to reduce the cost of outside laboratory analysis while still providing sufficient analyses from a certified laboratory to give confidence in the results. All samples for chemical analyses were collected as grab samples.

Table 5.—List of Chemical Analysis

Stream No.			1	2	3	4	5	6	7
Stream Name			RO Conc/ EDR Feed	EDR Product	EDR Conc	SPARRO Feed	SPARRO Permeate	SPARRO Conc	SPARRO Solids
Parameter	Total Est. Samples	Type(1)	Sampling Frequency (per Week)						
pH	300	G	5	5	5	5	5	5	0
Temperature	300	G	5	5	5	5	5	5	5
Conductivity	300	G	5	5	5	5	5	5	5
Alkalinity	144	G	3	3	3	3	3	3	0
TDS	144	G	3	3	3	3	3	3	0
Total Organic Carbon (TOC)	144	G	3	3	3	3	3	3	0
Total Suspended Solids (TSS)	100	G	1	1	1	1	1	5	5
Sulfate	144	G	3	3	3	3	3	3	0
Sodium	144	G	3	3	3	3	3	3	0
Calcium	144	G	3	3	3	3	3	3	0
Magnesium	144	G	3	3	3	3	3	3	0
Chloride	144	G	3	3	3	3	3	3	0
Total Silica	96	G	3	1	1	1	3	3	0

Notes: G = grab sample

3.4 Interpretation of Performance Data

EDR data is not normalized because there is no established normalization procedure. EDR analysis is usually conducted on hydraulic and electrical performance data. Hydraulic performance data is used to determine salt rejection, production, and recovery. Electrical data collected is used to determine the energy demand of the system at different recoveries and to generate a profile of the resistance of each stage. Resistance was calculated as the ratio of applied voltage to current.

The SPARRO pilot is influenced by feedwater composition, temperature, and operating factors such as pressure and system recovery. In order to distinguish between variations over time in these feed and operating characteristics and any performances changes due to fouling and scaling problems, the data must be normalized. Normalization allows a comparison of the actual performance to be given while the influences of operating parameters are taken into account. Reference performance was based on measured initial performance.

Two parameters used to evaluate the performance of the SPARRO system are normalized permeate flow (NPF) and normalized salt passage (NSP). NPF is the permeate flow normalized for feed concentration, temperature, and applied transmembrane pressure. NSP is the salt passage normalized for feed concentration, transmembrane pressure, and the feed-concentrate salt concentration. The salt passage in this study was expressed as the percent rejection, thus the normalized salt rejection (NSR) would be equal to 100 percent minus the NSP. The NPF and NSP equations are as follows:

Normalized Permeate Flow

$$Q_{npa} = \frac{(NDP_s)(TCF_s)}{(NDP_a)(TCF_a)}(Q_{pa})$$

where:

Q_{npa}	=	NPF under actual conditions, gpm
NDP_s	=	Net driving pressure at standard conditions, psig
NDP_a	=	Net driving pressure under actual conditions, psig
TCF_s	=	Temperature Correction Factor (TCF) based on standard temperature
TCF_a	=	TCF based on actual temperature
Q_{pa}	=	Actual permeate flow, gpm
TCF	=	$1.03^{(T-25)}$ where TCF_s uses T_s and TCF_a uses T_a
NDP	=	$P_f - \frac{\Delta P_{fb}}{2} - P_p - \pi_{fb} + \pi_p$
P_f	=	High-pressure feed pump discharge pressure, psig
P_b	=	Concentrate pressure, psig
P_p	=	Permeate pressure, psig
ΔP_{fb}	=	Differential pressure at standard conditions, psig
	=	$P_f - P_b$
π_{fb}	=	Feed-brine osmotic pressure, psig
	=	$\frac{(0.03851)(C_{fb})(T+273.15)}{\left(1000 - \frac{C_{fb}}{1000}\right)}$

π_p	=	Permeate osmotic pressure, psig
	=	$\dfrac{(0.03851)(C_p)(T+273.15)}{\left(1000-\dfrac{C_p}{1000}\right)}$
C	=	TDS, mg/L
	=	$EF_{sn} \times U$
EF_{sn}	=	TDS to conductivity ratio
U	=	Conductivity, µS/cm

Note: Generic equations presented.

Normalized Salt Passage

$$\%SP_{nspa} = \frac{NDP_a \times (C_{fbs})(C_{fa})}{NDP_s \times (C_{fba})(C_{fs})} \times \left[\%SP_a\right]$$

where:

$\%SP_{nspa}$	=	NSP under actual conditions, %
NDP_s	=	Net driving pressure at standard conditions, psig
NDP_a	=	Net driving pressure under actual conditions, psig
C_{fbs}	=	Feed-brine salt concentration at standard conditions, mg/L
C_{fba}	=	Feed-brine salt concentration under actual conditions, mg/L
C_{fs}	=	Feed salt concentration at standard conditions, mg/L
C_{fa}	=	Feed salt concentration under actual conditions, mg/L
C_{pa}	=	Permeate salt concentration under actual conditions, mg/L
$\%SP_a$	=	Actual salt passage, the amount of salt that passes through the membrane into the permeate stream, %
	=	$\dfrac{C_{pa}}{C_{fa}}$

Normalized Salt Rejection

$$NSR = 100\% - NSP$$

where: NSR = NSR, %

NSP = NSP, %

4. Results and Discussion

Pilot operation began in January 2013 and finished in June 2013. The EDR unit was operated for a total of 1,950 hours during both phases of operation

The EDR/SPARRO combination was operated on and off for a 2-month period overall; during this period, the EDR operated a total of 1,150 hours of which 200 hours included operation in combination with the SPARRO unit. Unfortunately, due to numerous mechanical and instrumentation challenges, the SPARRO unit was only able to achieve continuous steady-state operation periodically and not for the entire Phase II period as originally planned. Details are presented below.

4.1 Feedwater Quality

Concentrate from RO Train 3 was the raw water source for the pilot plant. The RO concentrate was piped to a break tank from where a separate pump transferred flow to the EDR feed tank. Grab samples were collected at frequent intervals and used to characterize EDR influent water quality. Table **6** summarizes the average and maximum values for individual raw water parameters measured throughout the study. The table also includes the number of samples for which data were obtained. The average value presented in the table represents the average of the laboratory samples collected during the pilot study.

Table 6.—RO Train 3 Concentrate - EDR Feedwater Quality(1)

Parameter	Units	# of Samples	Average	Maximum
Alkalinity	mg/L	14	1,130	1,300
Total Dissolved Solids (TDS)	mg/L	18	5,128	6,300
Total Organic Carbon (TOC)	mg/L	3	4	4
Total Suspended Solids(2)	mg/L	18	≤ 6	12
Sulfate	mg/L	18	1,511	1,800
Sodium	mg/L	18	549	640
Calcium	mg/L	14	759	820
Magnesium	mg/L	14	162	210
Chloride	mg/L	14	890	930
Total Silica	mg/L	14(3)	157	170

Notes: (1) RO Train 3 was operated at a recovery of 80 percent.
(2) Out of 18 samples, all but 1 were below detection limits.
(3) Four additional samples were analyzed for silica on site. However, the results were less than half of the laboratory values and were thus excluded from the data set.

The laboratory analyses indicate a consistent feedwater quality throughout the pilot test. This is highlighted by the consistent EDR feed, product and blowdown TDS shown on **Figure 18**. As shown in Table **6**, RO concentrate has high salinity (5,128 mg/L TDS) as well as high levels of alkalinity, calcium, sulfate, and silica.

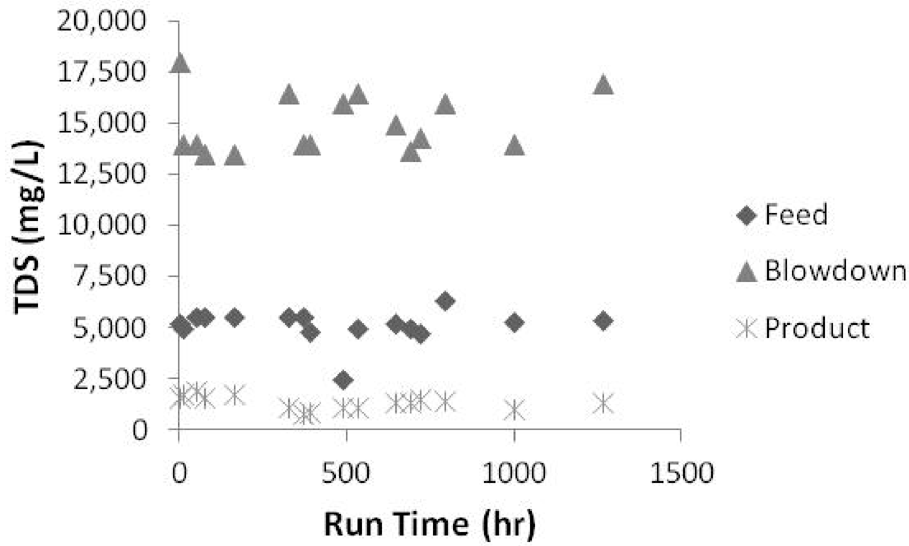


Figure 18.—EDR feed, product, and blowdown TDS.

4.2 EDR Performance Results – Phase I (Baseline Condition)

During the Phase I operating period, the EDR unit operated for almost 800 hours and was evaluated for hydraulic and electrical performance. After initial EDR stack scaling problems, the unit was operated continuously, with limited shutdowns for the remainder of the pilot study. Overall, EDR operation was stable and the long runtimes allowed performance trends to be established. The EDR experienced few operational disturbances and operated nearly continuously from mid-March 2013 until it was decommissioned in June 2013.

4.2.1 Hydraulic Performance

GE Process monitored the performance of the EDR remotely. The data obtained by GE is presented in a report that is included in Appendix B. In addition to the data collected automatically by the EDR programmable logic controller (PLC), Carollo monitored feed, product, and concentrate flows periodically from on-site readings. This data is shown on **Figure 19**. As the data shows, GE made small modifications to the pilot at hour 330 increasing the flow rate to the EDR. Prior to this point, the blowdown flow was around 1.5 gpm (5.7 L/min) and all flow could have gone to the SPARRO unit for treatment. However, after the flow adjustment was made, the EDR PLC was set to maintain the EDR feed pump to produce a product flow of 6.8 gpm (25.7 L/min), and the blowdown increased to around 2.8 gpm (10.6 L/min), which was greater than the capacity of the SPARRO unit. All flows were very stable throughout Phase I as can be seen on **Figure 19**.

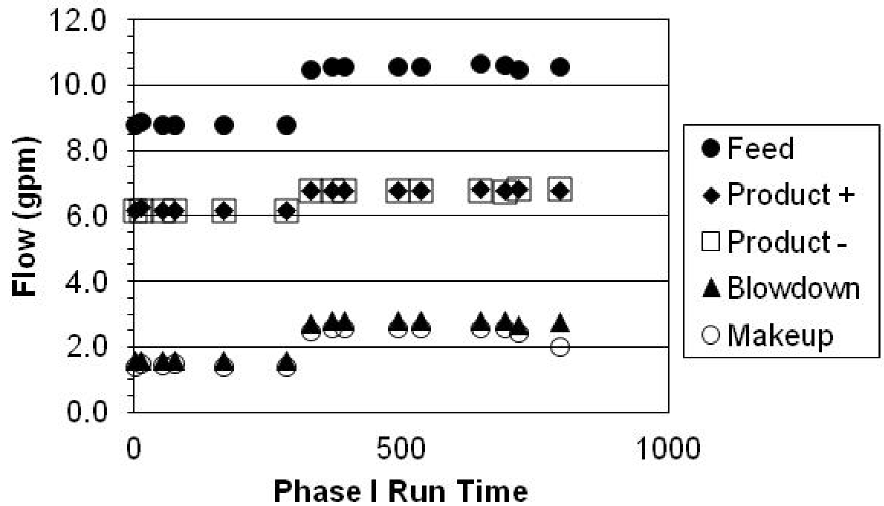


Figure 19.—EDR flows.

Figure 20 shows the EDR system recovery. The EDR recovery is limited by the solubility of the least soluble of the sparingly soluble salts present in the RO concentrate stream in so far as it can be counteracted by the anti-scalant. In this pilot, calcium sulfate ($CaSO_4$) was the limiting factor to EDR recovery. As **Figure 20** demonstrates, the recovery was initially set to 70 percent and then adjusted to 65 percent around 300 hours when the feed flow rate was increased, where it remained for most of the study.

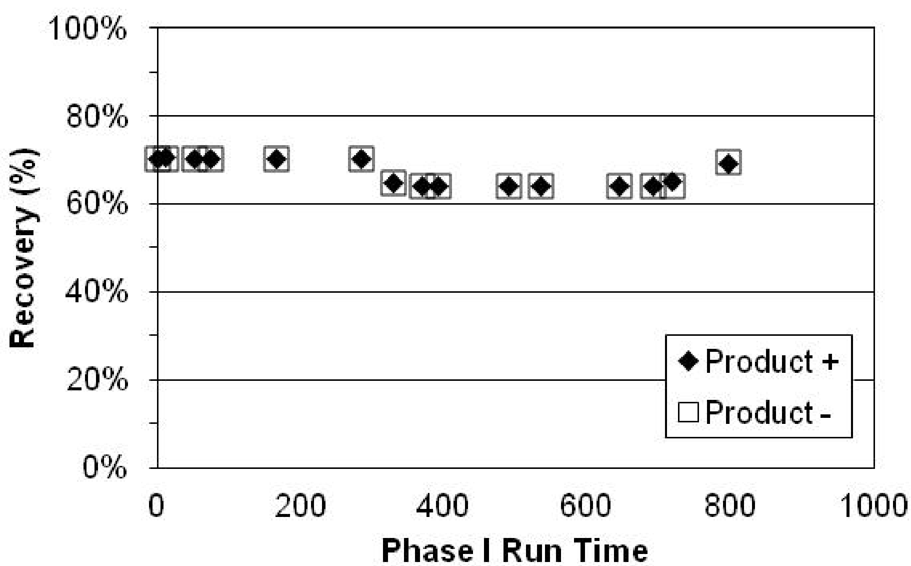


Figure 20.—EDR system recovery.

Feed pressure in the EDR unit is an important performance indicator. If the membrane stack begins to scale, the stack inlet pressure increases. **Figure 21** shows the EDR stack inlet pressure for Phase I, and as shown, the inlet pressure was stable after the initial jump at hour 330. Although higher pressures were observed during negative polarity cycles, these were constant. The slight upward trend in the latter quarter of Phase I signifies little to no scaling occurred in the membrane stack.

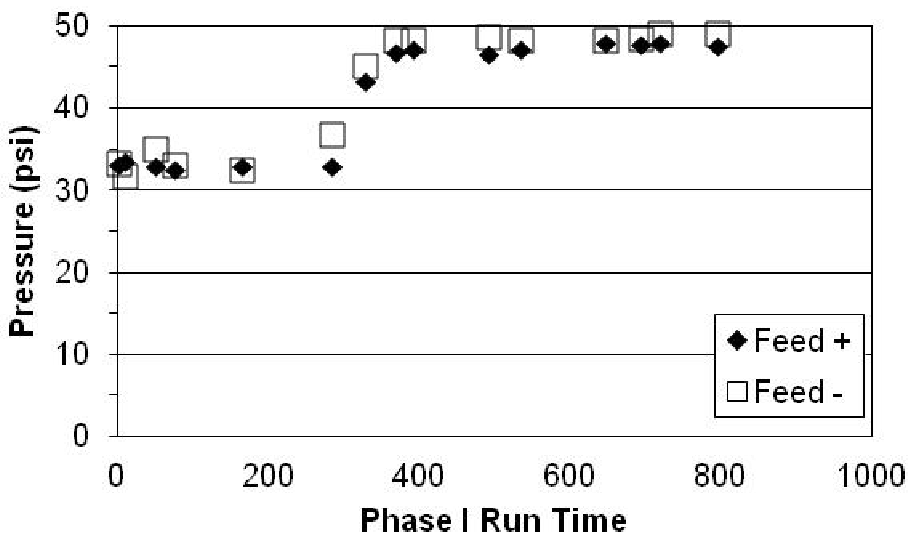


Figure 21.—EDR feed pressure (Note: 30 psi = 207 kPa).

4.2.2 Salt Rejection

Figure 22 shows the EDR salt rejection during Phase I testing. The values were calculated based on the conductivity of feed and product samples collected on site. The EDR performed well during Phase I: rejecting approximately 60 to 70 percent initially, and then 75 to 80 percent of salts after the adjustment at 330 hours. During Phase I operation, the positive polarity outperformed the negative polarity due to higher voltages achieved during the positive cycle. Less voltage provides less force on the ions in solution causing lower removal efficiency. As can be seen, the salt rejection was stable during Phase I.

4.2.3 Electric Performance

Voltage and resistance are two important parameters in EDR operation. The voltage correlates to the power usage and salt rejection. Higher voltages require greater power consumption and increased salt rejection. The voltages observed during Phase I were +43 volts direct current (VDC) and -41 VDC, for the positive and negative cycles, respectively. As scale forms in the membrane stack, it is more difficult for the current to flow through the stack, thus the resistance increases. With greater resistance, less energy is available to remove TDS. The stack resistance observed during Phase I is shown on **Figure 23**. Similar to the other EDR performance parameters, resistance was determined to be very stable for both stage 1 and stage 2 in both polarities. The resistance results confirm no significant scale formation occurred in the membrane stack during Phase I testing.

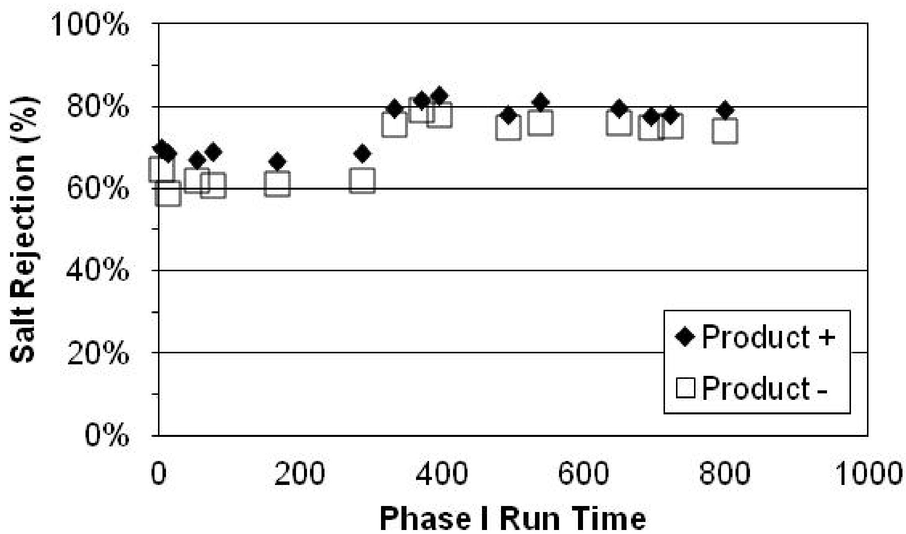


Figure 22.—EDR salt rejection.

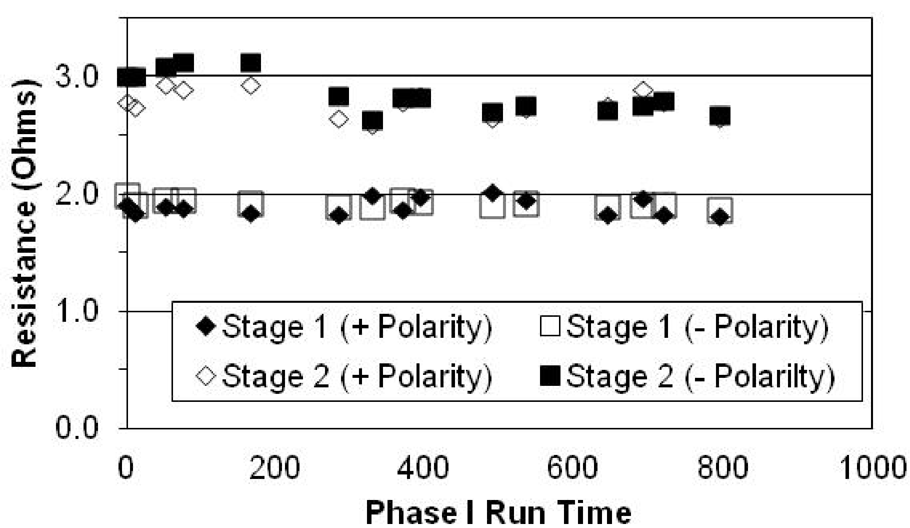


Figure 23.—EDR resistance

One observation during Phase I was the voltage differences between positive and negative polarity. These differences were caused by the direct current drives that supply the voltage. DC drives are designed for a voltage range of -600 VDC and +600 VDC. Since the pilot operated at +43 VDC and -41 VDC, only a small portion of this range was used. In DC drives, there are separate diode bridges that produce the positive and negative polarities. These diode bridges cause a slight difference in the applied voltage, between 2 to 5 VDC. At full-scale, the stack voltages are much higher, between 300 to 600 VDC, thus the small difference between polarities will have much less effect on water quality produced with the polarity switches in a full scale system.

4.2.4 Water Quality

Comprehensive mineral analysis was conducted on grab samples collected from EDR feed, product, and concentrate streams. Water quality analysis results are shown in Table **7**. The water quality data shows the EDR unit can effectively remove TDS from the RO concentrate. In Table **7**, product TDS concentrations are 26 percent of TDS feed concentrations indicating an average TDS rejection of 74 percent. Additionally, Table **7** shows a high reduction in sulfate concentration by an average of 94 percent and calcium concentration by an average of 90 percent. Silica concentrations remain unaffected in all streams because the silica is not charged and therefore there is no driving force for it to pass through the membranes. The average alkalinity (HCO_3) rejection was 48 percent.

Table 7.—Average EDR Water Quality – Phase I (Baseline Condition)

Parameter	Units	# of Samples	EDR Feed	EDR Product	EDR Conc.
Alkalinity	mg/L	11	1,111	589	2,100
Total Dissolved Solids (TDS)	mg/L	14	5,086	1,354	14,928
Total Organic Carbon (TOC)	mg/L	3	4	2	<10
Total Suspended Solids	mg/L	14	≤ 6[1]	ND[2]	35
Sulfate	mg/L	14	1,530	90	4,743
Sodium	mg/L	14	535	310	1,160
Calcium	mg/L	11	744	76	2,376
Magnesium	mg/L	11	150	14	578
Chloride	mg/L	11	882	239	2,783
Total Silica	mg/L	11	153	153	153

Notes: (1) Out of 14 samples, 13 were below detection limits.
(2) ND = Not Detected.

4.3 SPARRO Performance Results

Phase I involved operating the EDR independently of the SPARRO system. Phase II involved operating the EDR and SPARRO units together. In order for the two systems to operate as a combined system, system flow balance was critical. All flow entering the SPARRO system needed to be evenly matched with discharge, be it permeate or blowdown flow. The most critical parameter was flow from the EDR. Because the two processes were not sized for each other (as discussed earlier), only a portion of the EDR blowdown could be accepted by the SPARRO unit. Too much flow from the EDR would result in an overflow of the SPARRO feed tank, a loss of solids, and potential scaling of the SPARRO system. On the other hand, too little flow from the EDR would result in a loss of volume in the SPARRO feed tank, a resulting thickening of the gypsum solids and potential blockage of the membrane system due to feed slurry that is too thick. A manual flow control valve in the feed line from the EDR and level switches in the SPARRO feed tank (both high and low) were installed to prevent such operational upsets. However, even with these control measures in place, maintaining the flow from the EDR presented numerous challenges and limited continuous steady state operation.

4.3.1 SPARRO Start-up

The SPARRO pilot plant began operation in April. The unit was isolated from the EDR pilot initially. Operation began on RO permeate from the desalter just to check all systems and then EDR concentrate was introduced to increase the TDS. Commercial gypsum powder ($CaSO_4.2H_2O$) was added to the feed tank at a concentration of about 18 g/L to provide the initial mass of gypsum seed. No further use of the commercial grade gypsum was required. The system was operated on EDR brine blowdown for some time without returning SPARRO permeate back to the EDR unit, while solids and TDS was allowed to build up in the system and stabilize.

4.3.2 Water Quality

Average values for the SPARRO feed (EDR blowdown), permeate and concentrate water quality data are shown in Table **8**. A total of four sets of analytical data were obtained, one for each of the operating periods of the plant, which is discussed in the next section. However, a few analyses were missing from one of the data sets; hence, the total number of samples for some parameters was three.

In terms of the average values in Table **8**, the SPARRO unit received feed from the EDR blowdown stream with an average TDS of 14,259 mg/L, and produced a permeate stream with a TDS of 4,750, representing an average salt rejection of 66.7 percent. The concentrate from the SPARRO unit had an average TDS value of 16,000 mg/L.

Suspended solids in the SPARRO feed stream (from the EDR) averaged 88 mg/L, indicating that some scale was beginning to form by the time the EDR blowdown reached the SPARRO feed tank. The SPARRO permeate stream had non-detect suspended solids for all but the last sample. Sulfate, sodium, calcium, magnesium, chloride, and silica concentrations in the SPARRO permeate were significantly lower than the concentrations in the SPARRO feed, as expected. Average reductions were 87 percent for sulfate, 38 percent for sodium, 94 percent for calcium, 85 percent for magnesium, 54 percent for chloride, and 46 percent for silica.

Table 8.—Average SPARRO Water Quality – Phase II

Parameter	Units	# of Samples	SPARRO Feed	SPARRO Product	SPARRO Conc.
Alkalinity	mg/L	3	1,833	220	1,350
Total Dissolved Solids (TDS)	mg/L	4	14,259	4,750	16,000
Total Organic Carbon (TOC)	mg/L	3	8	3	19
Total Suspended Solids	mg/L	4	88	<6(1)	3,101
Sulfate	mg/L	4	4,150	515	3,275
Sodium	mg/L	4	1,319	816	1,779
Calcium	mg/L	3	2,633	170	2,300
Magnesium	mg/L	3	620	92	1,067
Chloride	mg/L	3	2,600	1,200	4,267
Total Silica	mg/L	3	147	79	217

Notes: All but one sample were Not Detected (ND).

4.3.3 Hydraulic Performance

Figure 24 presents the variation in EDR concentrate flow to the SPARRO unit during the 200-hour operating period, as well as the SPARRO blowdown and permeate flows. The vertical lines on **Figure 24** show the limits for performance of four separate periods of time that correspond to four sets of membranes that were tested. Details on the membranes are presented later.

Figure 24 shows a fair amount of variation in the EDR concentrate flow during Period 1, between 1 and 2 gpm (3.8 and 7.6 L/min). This was caused by some of the operational issues associated with the requirement to only treat a portion of the EDR concentrate blowdown flow. Better control of the EDR concentrate flow was achieved during Periods 2 through 4. For the most part, the SPARRO permeate flow remained fairly constant around 0.7 to 0.8 gpm (2.6 to 3.0 L/min). Similarly, the SPARRO blowdown was fairly constant around 0.5 gpm (1.9 L/min), except for some time during Period 1.

Figure 25 shows the variation in SPARRO stream pressure for feed, concentrate, cyclone feed and permeate. Most variation in the SPARRO feed pressure occurred in Period 1. It can be seen that the pressure increased from 300 psi (2,067 kPa) to above 500 psi (3,446 kPa), indicating membrane fouling or scaling was occurring. The concentrate pressure followed the same trend.

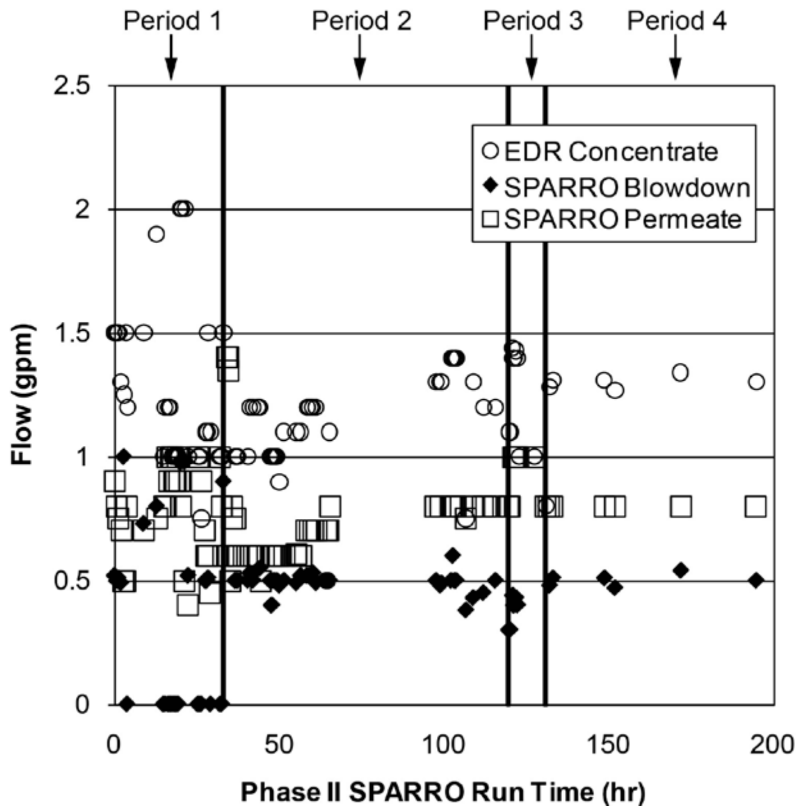


Figure 24.—SPARRO feed, permeate, and blowdown flows.

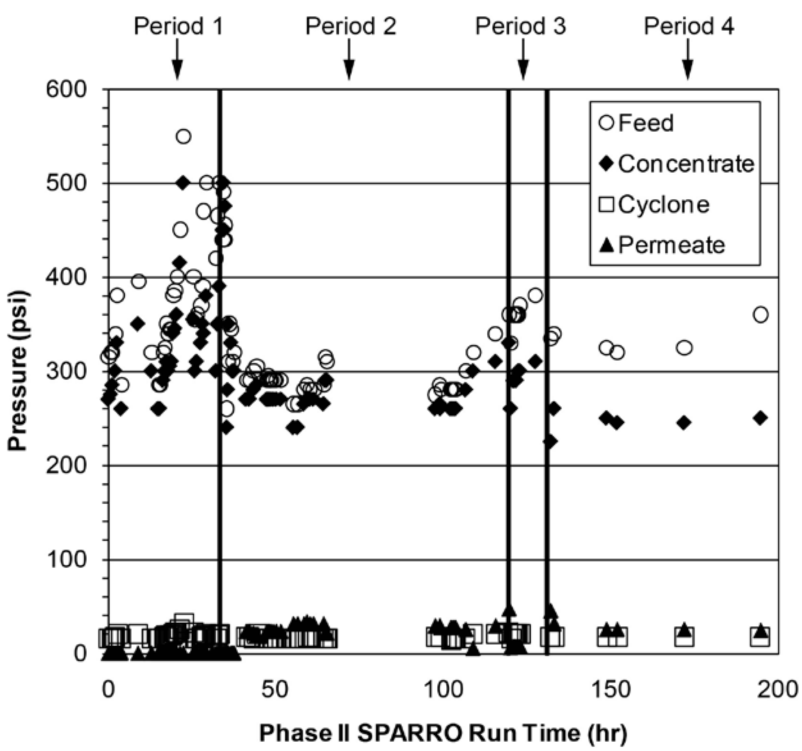


Figure 25.—PARRO stream pressures.

In Period 2, the SPARRO feed and concentrate pressures were significantly more stable and remained in the 250 to 300 psi (1,723 to 2,067 kPa) range after an initial decline from 500 psi (3,446 kPa). Periods 3 and 4 showed stable performance for the feed and concentrate pressures.

The cyclone feed pressure was maintained around 20 psi (138 kPa) for the duration of the pilot test. The permeate pressure varied from very low values in Period 1 to around 30 psi (207 kPa) for the rest of the test periods.

4.3.4 Membrane Performance

As mentioned above, four sets of membranes were tested during the pilot test. Table **9** presented details of each membrane set and shows the corresponding operating period that is shown on the figures that are presented in this section.

Table 9.—Details of Membrane Sets Tested

Period Shown on Figures	Membrane Set	Membrane Type Details	Comment
1	1	TFC Polyamide	Type AFC99
2	2	CA-CDA16 5000030	Manufactured June 25, 2004
3	3	CA-CDA16 5000048	Manufactured June 10, 2004
4	4	CA-CDA16	Manufactured 2004

TFC = thin film composite

Figure 26 presents the SPARRO recovery for all four operating periods. There was significant variability in recovery during Period 1, but much more consistent performance for the other three periods, in which the recovery was around 60 percent.

Figure 27 presents the normalized salt rejection (NSR) for each membrane set. It can be seen that the thin film composite (TFC) membranes started with a very high salt rejection, but this steadily decreased with time for the first 20 hours or so and then dropped rapidly to around 50 percent rejection. It was at this point that it was decided to replace these membranes. Cellulose acetate (CA) membranes were used for the remainder of the study. As shown on **Figure 27**, the best rejection achieved with the CA membranes was around 80 percent. This is thought to have been because these membranes were all from an old batch manufactured in 2004. A standard salt rejection test was performed on the first set of CA membranes (Period 2), which confirmed that the “new” membranes were no longer performing to the manufacturer’s specifications. Table **10** shows the results of the standard salt test and shows that over a 45-minute period while operating on a

NaCl solution (1,560 mg/L NaCl) at as close to the flux and pressure stipulated by the manufacturer, the average salt retention was only 67 percent, compared with 94 percent when the membranes were new.

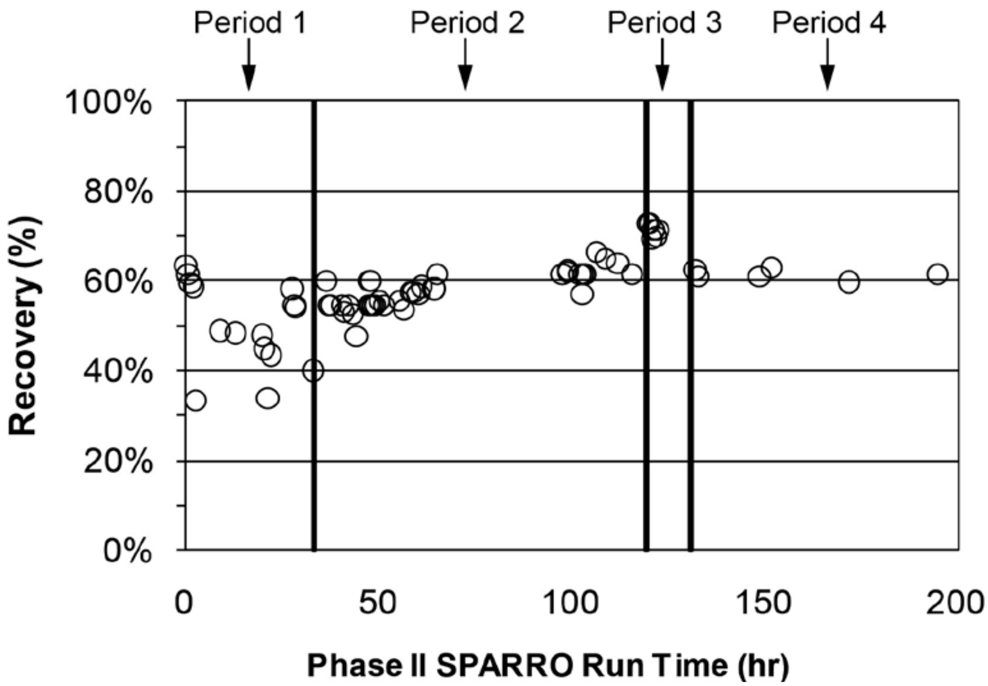


Figure 26.—SPARRO recovery.

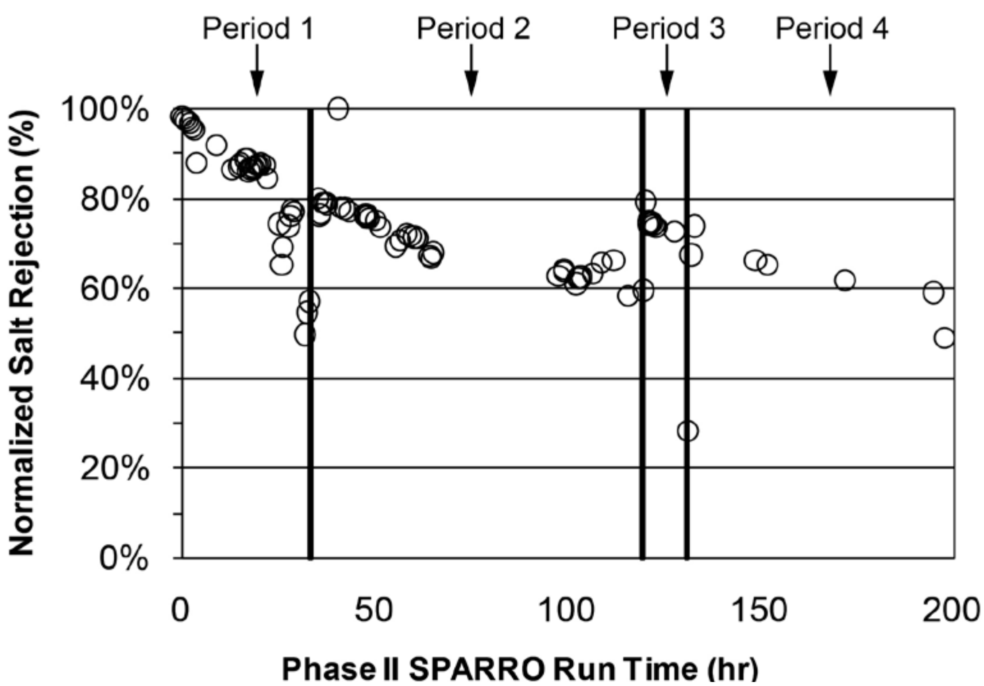


Figure 27.—SPARRO salt rejection.

Table 10.—Results of Standard Salt Rejection Test on Second Set of Membranes

Time	Temp °C	Feed Tank Cond μS/cm	Permeate Cond μS/cm	Permeate Flow gpm	Feed Pressure psi	Rejection %
1:30 pm	24.9	3650	1215	1.4	440	66.7
1:45 pm	25.2	3490	1145	1.4	440	67.2
2:00 pm	25.5	3460	1095	1.4	440	68.4
2:15 pm	25.7	3383	1161	1.35	465	65.8

Although the "new" CA membranes had a lower salt rejection than the manufacturer's specifications, the measured salt rejection of 67 percent was still adequate for this test work. As **Figure 27** shows, there was some steady decline in the salt rejection for the first and third sets of CA membranes. The operating time for the second set of CA membranes (Period 3) was too short to draw any meaningful conclusions.

Figure 28 shows the NPF for all membrane sets. The results for Period 1 confirm the very wide variation in performance that was observed for the TFC membranes.

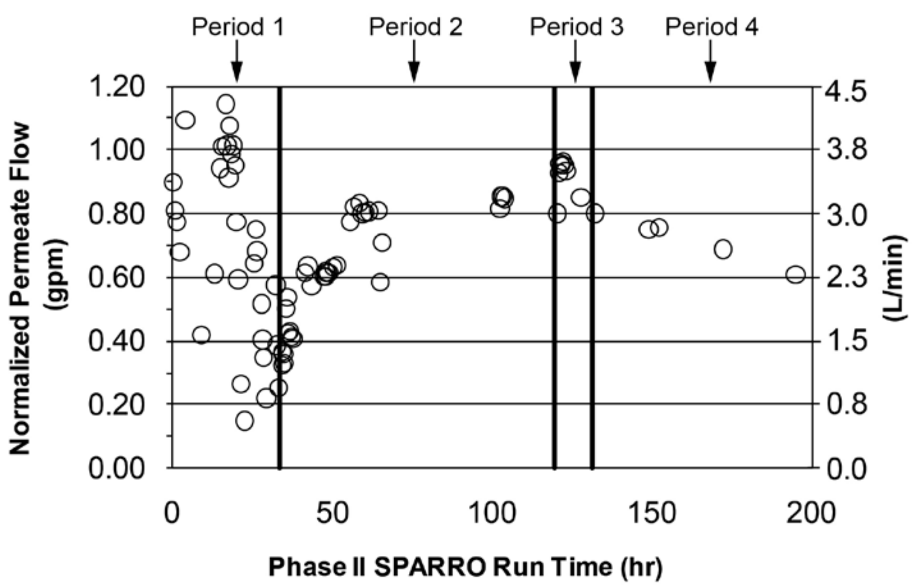


Figure 28.—SPARRO normalized permeate flow.

During Period 2 (first set of CA membranes), there was an increase in normalized permeate flow (NPF) with time, which corresponds to the decrease in NSR (**Figure 27**), indicating that the salt leakage across the membrane and the permeability were increasing. These results indicate potential hydrolysis of the CA membrane.

During Period 4, the NPF decreased with time, and the NSR showed a similar trend. A decrease in NPF is indicative of membrane fouling or scaling occurring. The declining salt rejection suggests higher salt leakage, but this could have resulted from the lower permeate flow.

4.3.4.1 Operational Issues and Observations With Respect to Membrane Performance

4.3.4.1.1 (a) First Membrane Set (Period 1)

As mentioned, the SPARRO unit was initially fitted with TFC polyamide tubular RO membranes. During the initial operating period before the unit achieved 24-hour operation, a decline in membrane flux was observed. Each day when the unit was restarted, the flux declined a bit more and so did the permeate quality. After 2 weeks of operation in this mode, the performance was such that the membranes were unsuitable for operation. There was no evidence of seed leakage through the membranes. It was decided to replace the membranes with a set of CA membranes in an attempt to reduce any effects of membrane fouling that may have been occurring in the TFC membranes due to their typically rougher surface than CA membranes. Samples of the TFC membranes were sent away for membrane autopsy. Results of the autopsy are presented below.

4.3.4.1.1.1. TFC Membrane Autopsy

All 18 membrane tubes from pressure vessel number two (the downstream pressure vessel) were removed and sent to American Water Chemicals (AWC) for autopsy. In line with the observed performance in the pilot unit, the autopsy showed that the salt passage in two of the tubes that were tested had increased to over 45 and 47 percent of the manufacturer’s specification, and that the flux in both cases had also increased dramatically. This indicated that the membrane integrity had been severely compromised.

Dye penetration testing on the same two tubes showed heavy penetration to the permeate side of the membrane indicating that the polyamide layer had been severely damaged.

On inspection of the tubes, it was noted that the surface was covered with a white foulant, which was mostly inorganic in nature and analysis showed that the precipitate was almost completely calcium carbonate. This was confirmed by scanning electron microscopy (SEM)/ Energy Dispersive (EDS) analysis and Fourier Transform Infrared (FTIR) analysis.

Figure 29 shows a Superimposed Elemental Imaging (SEI^{TM}) output of the precipitate of calcium carbonate, silts, and clays. The green color represents calcium carbonate, and almost the entire membrane surface was covered with it. The red areas are silica deposits. It is worth noting that although there was calcium sulfate slurry flowing through the membrane, there is almost no evidence of $CaSO_4$ on the membrane surface.

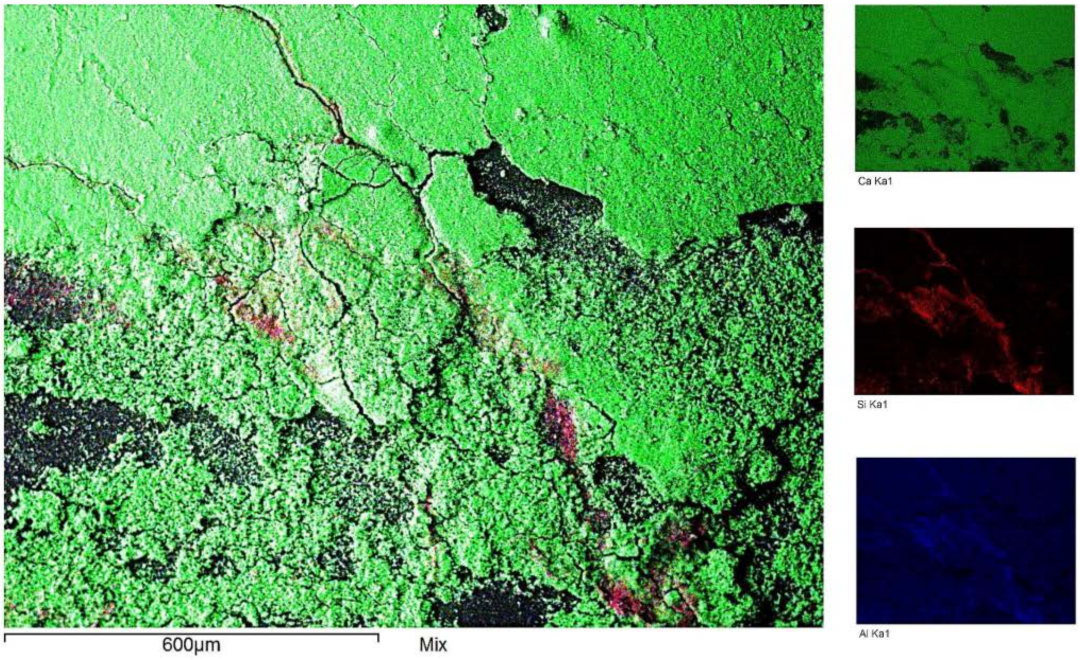


Figure 29.—SEI™ image of a portion of TFC membrane tube showing dominance of calcium carbonate on membrane surfaces.

A notable feature of several of the membrane tubes was orange staining sporadically on the permeate side of the membrane. **Figure 30** shows an example of this.

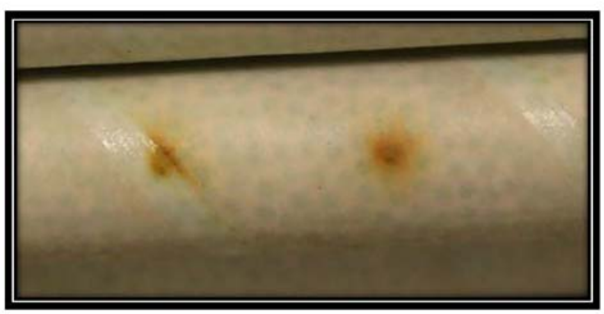


Figure 30.—Sporadic staining on the permeate side of membrane tubes.

Analysis of the cross-section where the stains occurred showed that delamination of the membrane had occurred at that point. In addition to calcium carbonate penetration through the membrane there was also evidence of stainless steel having penetrated the membrane. The orange color was likely rust from the iron residue. This is a rather puzzling result, and suggests that there may have been shavings of stainless steel from the manufacturing of the pilot unit that may not have been flushed from the system prior to membrane loading, and which may have caused damage to the membranes during the first few hours of operation.

Inspection of the cleaned membrane surface showed other disconcerting results. Long tears were observed in the polyamide layer completely exposing the pores of the polysulfone layer. It is not clear how such tears could have occurred, but since the pilot unit remained out of service for several months after manufacture, it is possible that portions of the membrane may have dried out and deteriorated due to inadequate preservation of the membrane.

Two membrane tubes from the first pressure vessel (upstream vessel) were also sent for autopsy. The autopsy in this case was not as extensive as that performed for the membrane tubes in the second pressure vessel, but it showed the same trend of significantly lower salt rejection and significantly higher flux rates than those at the time of manufacture. Dye penetration testing also showed moderate to heavy penetration to the permeate side of the membrane. This result, coupled with the low salt rejection and high flux confirmed that the polyamide layer had incurred extensive damage, similar to that identified in the membrane in the second pressure vessel.

The findings of these membrane autopsies are significant for several reasons:

1. Piercing of the membrane surface by shavings of stainless steel would obviously seriously impact any conclusions associated with the performance of the TFC membranes (Period 1).

2. The long tears in the polyamide layer observed on the piece of clean membrane are also cause for concern, and indicate that the integrity of the membranes may have been impacted before the test work even started. This and the holes caused by the stainless steel shavings could well explain the rapid decline in salt rejection and increase in NPF observed during the testing.

3. The presence of calcium carbonate (calcite) covering the membrane surface was unexpected. This indicates that calcium carbonate was precipitating in the presence of calcium sulfate crystals. This was unexpected because it was assumed that the driving force for gypsum precipitation would be greater than for calcite formation because crystals of gypsum were present, and as gypsum precipitates, so the driving force for calcite precipitation would decrease. Since there was no calcite seed in the system, scaling by calcite could occur, which seems to have been the case, compounding the effects of membrane damage that appear to have been present since the start of operation.

Overall, the TFC membrane performance discussed earlier (Period 1) is likely due to the damage caused during storage of the pilot unit prior to operation, the stainless steel shavings and then formation of calcium carbonate scale on the membrane surface.

4.3.4.1.2 (b) Second Membrane Set (Period 2)

As discussed, the CA membranes that were fitted into the plant were manufactured in 2004 (see Table **9**).

After about 1 week of operation on EDR brine without returning permeate to the EDR brine loop, the SPARRO permeate was returned to the EDR unit and both systems were operated together. When this occurred, the EDR unit automatically adjusted (reduced) the concentrate makeup flow. So the operation of the EDR unit remained stable whether the SPARRO unit was returning flow to the EDR or not. Performance appeared to be stable. During this period, the EDR brine was discharged directly into the SPARRO feed tank; the level in the tank was controlled by setting a manual flow control valve.

During the night, the flow rate of brine from the EDR unit dropped and as a result, the SPARRO feed tank level gradually dropped to below the level of the mixer, which resulted in thicker-than-desired seed being pumped into the membranes. It appears that the pressure in the EDR brine loop dropped, which reduced the brine feed flow rate to the SPARRO feed tank, resulting in the problems described.

As a result of this operational issue, the performance of the membranes was severely impacted, so much so that the salt rejection dropped to unacceptably low values. Because operation could no longer continue, it was decided to obtain another set of CA membranes.

4.3.4.1.3 (c) Third Membrane Set (Period 3)

After the problems encountered with the variable EDR blowdown flow and pressure, modifications were made to the EDR brine piping to avoid a similar event. A new EDR brine pump was installed to transfer EDR brine to the SPARRO feed tank independently of the EDR, to maintain the flow rate even when the EDR brine pressure varied. The second set of CA membranes had the same manufacturing date as the first, and also had similar salt rejection properties.

The new CA membranes were put into operation and the SPARRO unit permeate was again fed back to the EDR. **Figure 31** shows the EDR performance data recorded by the EDR PLC for the period of May 23 to June 6. The reduction in concentrate makeup flow indicates when the SPARRO unit was online and returning permeate to the EDR. As indicated by the results highlighted in the black box on **Figure 31**, the makeup flow reduced from 2.3 gpm (8.7 L/min) to about 1.6 gpm (6.0 L/min) during this period, a reduction of 30 percent.

Although the combined systems operated well together, further operational issues on the SPARRO unit prevented continuous operation. New level switches installed in the SPARRO feed tank failed after a short period of time and again resulted in damage to the CA membranes due to a low tank level pumping situation. It is thought that the aggressive environment in the feed tank caused the level switches to fail. Also, pieces of scale from the inside of the tanks began to break off, which caused pressure fluctuations in the SPARRO system. A screen was added to the feed tank outlet to limit the amount of hard scale that could get drawn into the high pressure feed pump. It became evident that without some additional level control in the SPARRO feed tank the system would not function correctly.

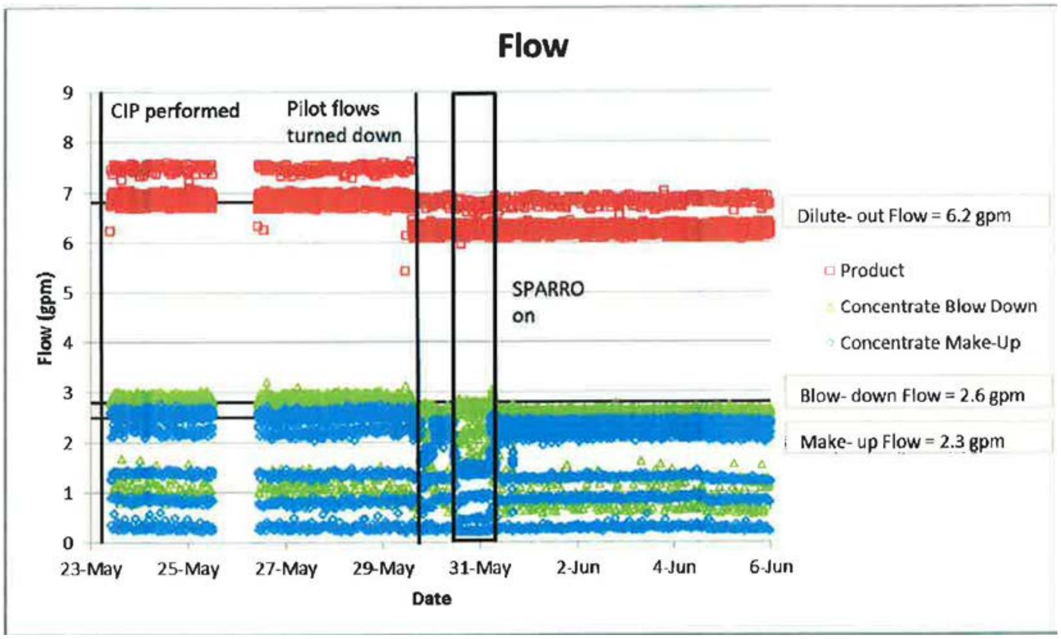


Figure 31.—EDR flow data indicating effect of returning SPARRO permeate to EDR brine loop.

4.3.4.1.4 (d) Fourth Membrane Set (Period 4)

In an attempt to obtain further combined operating time with the EDR and SPARRO units, the pilot test was extended for a few weeks and a third set of CA membranes was obtained and installed in the SPARRO unit. Once again, this batch of membranes had similar salt rejection and flux properties to the previous two sets.

New level control instruments with interlocks to shut down the feed pump were also installed. After some initial testing while operating on EDR brine, the SPARRO unit was put online and its permeate was returned to the EDR unit. **Figure 32** shows this period of operation for the SPARRO and EDR units together. In this case, it shows a 4-day continuous operating period from June 7 to June 11. On the fourth day, it became necessary to shut down the EDR unit briefly due to a leak. The SPARRO unit had to be taken off-line during this period and was flushed as usual. When the EDR was back online and the SPARRO was brought back into service, the feed pressures were significantly higher than normal. Investigation showed that one of the module tubes was almost completely blocked with large pieces of scale from the tanks that must have occurred during flushing. This module was isolated and the plant was restarted with one module online. However, pressure fluctuations in the feed stream, presumably caused by flakes of scale, did not allow stable performance to be maintained and so the unit was shut down.

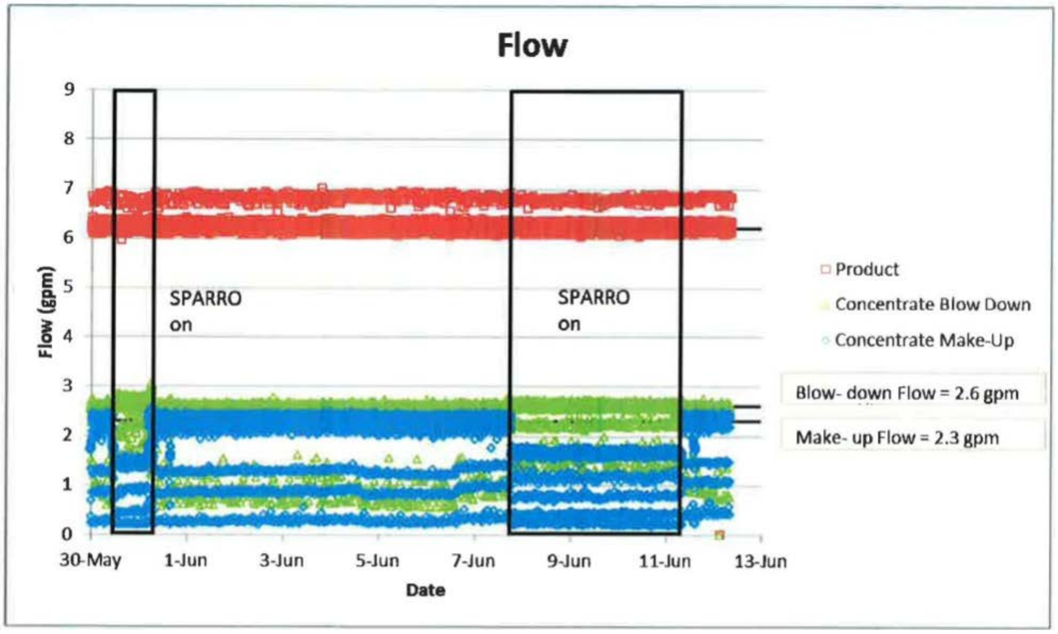


Figure 32.—EDR Flow Data Showing 4-Day Operation of EDR with SPARRO Permeate Returned to EDR Brine Loop

During the 4-day period in which the SPARRO permeate was returned to the EDR brine loop, the makeup flow rate reduced from 2.3 to 1.6, as before; a decrease of 30 percent. This resulted in an increase in recovery of the EDR of 5 percent. As the SPARRO unit was not sized to treat all concentrate blowdown from the EDR, the EDR recovery could have increased by 20 percent if all concentrate blowdown went to the SPARRO. This was based on a recovery of 60 percent in the SPARRO system.

4.3.5 Solids Production

When the SPARRO unit was treating brine from the EDR unit, solids production was estimated at around 2.4 pounds per hour (lb/hr) (1.1 kilograms per hour [kg/hr]) from field measurements based on the amount of solids settling in a calibrated column. Operation of the cyclone system was challenging in the beginning due to the size of the underflow opening. Cyclone blockages became an issue as the concentration of solids in the system increased. However, the underflow opening size was increased and much more stable operation resulted. Modifications were made to the overflow side of the cyclone too in order to improve performance.

Solids removed from the system from the underflow were collected in buckets for sampling and in case makeup solids were needed in the system. Samples of the underflow and overflow solids were sent for analysis for size distribution and composition. The results of these analyses are shown in Appendix A.

4.3.5.1 Solids Quality

In Section 4.3.4.1.1.1, the TFC membrane autopsy was presented and it was noted that calcium carbonate was found on the membrane surface. By the time the results of the membrane autopsy were available, the pilot testing project was almost over. As mentioned, precipitation of calcium carbonate was not expected and at that point it became clear that the solids being produced by the SPARRO unit may be a mixture of gypsum and calcium carbonate, rather than a mostly pure sample of calcium sulfate that had been produced during previous pilot studies.

At the end of the study, samples of solids taken from various places in the SPARRO pilot plant were sent to the University of California at Los Angeles (UCLA) for SEM examination, EDX analysis, and also x-ray photoelectron spectroscopy (XPS) analysis. The results for five samples are presented below.

1. **Scale from the Feed Tank:**

   A thin layer of scale formed on the SPARRO feed tank during pilot operation. At times pieces of the scale broke off and fell into the seed slurry. In order to prevent these flakes getting drawn into the feed pump and being pumped through the membranes, a screen was installed inside the tank around the pump suction inlet.

   Figure 33 shows two SEM images of the scale. XPS analysis of the scale showed that it contained very low levels of sulfur, indicating that the material was mostly calcium carbonate (calcite) in nature.

2. **Cyclone Underflow Solids:**

   A sample of the cyclone underflow was examined using an SEM and an image is shown in the top photograph of Figure 34. The average particle size in the underflow was 35 µm, as determined by Omya Inc. The lower graphic on Figure 34 shows an SEM-EDX output obtained by Omya Inc. showing that the material was composed mainly of calcium, sulfur, and oxygen, suggesting a significant amount of calcium sulfate. An EPS analysis of this material indicated that it was about 79 percent gypsum (calcium sulfate) and 21 percent calcium carbonate.

3. **Cyclone Overflow Solids:**

   Figure 35 shows an SEM image (top) of the solids collected from the cyclone overflow. The average solids particle size in the overflow was 11 µm in diameter, as determined by Omya Inc. Note that the magnification is a lot higher in this image than on Figure 34. The lower image on Figure 35 is the SEM-EDX spectra for the overflow solids as determined by Omya Inc. As was the case for the cyclone underflow, the composition of the overflow solids suggests a high concentration of calcium sulfate.

   An XPS analysis of the cyclone overflow determined that it consisted of about 73 percent gypsum and 27 percent calcium carbonate.

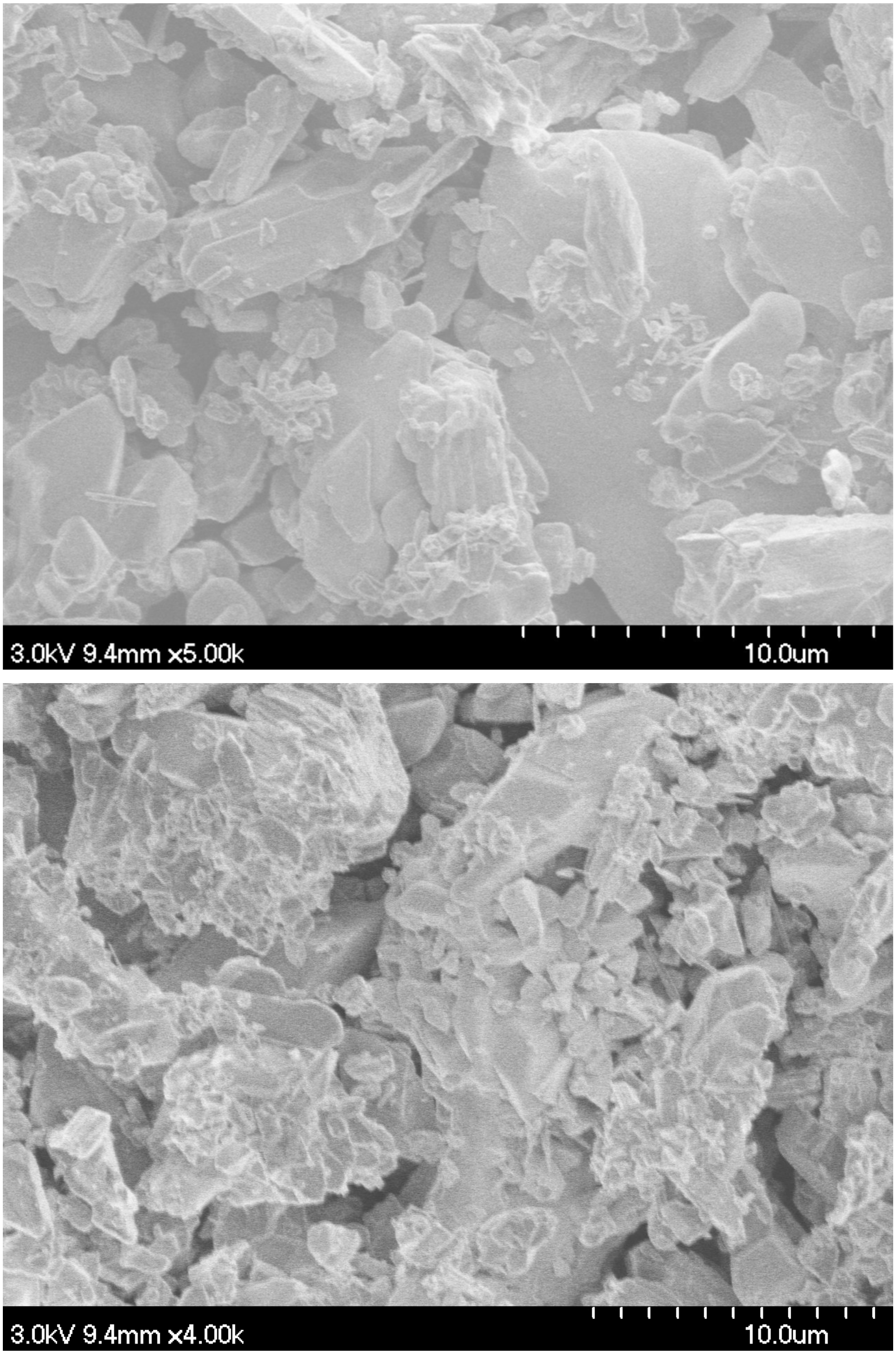
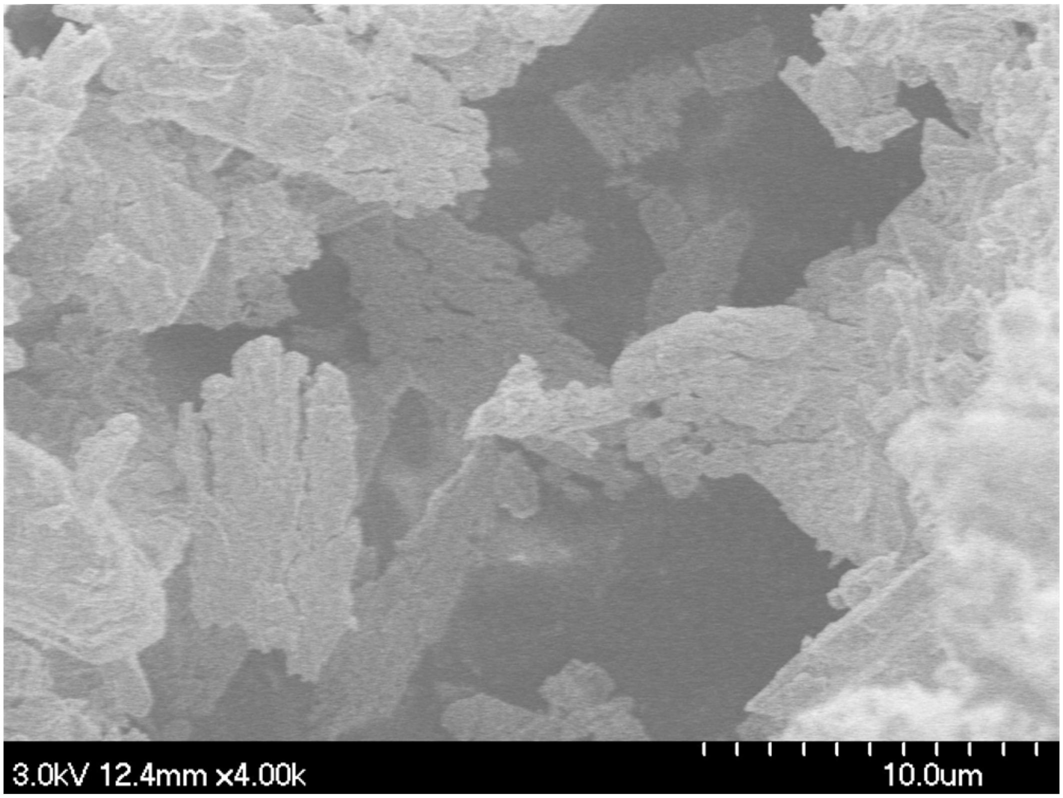


Figure 33.—SEM images of scale layer formed on inside of sparro feed tank.



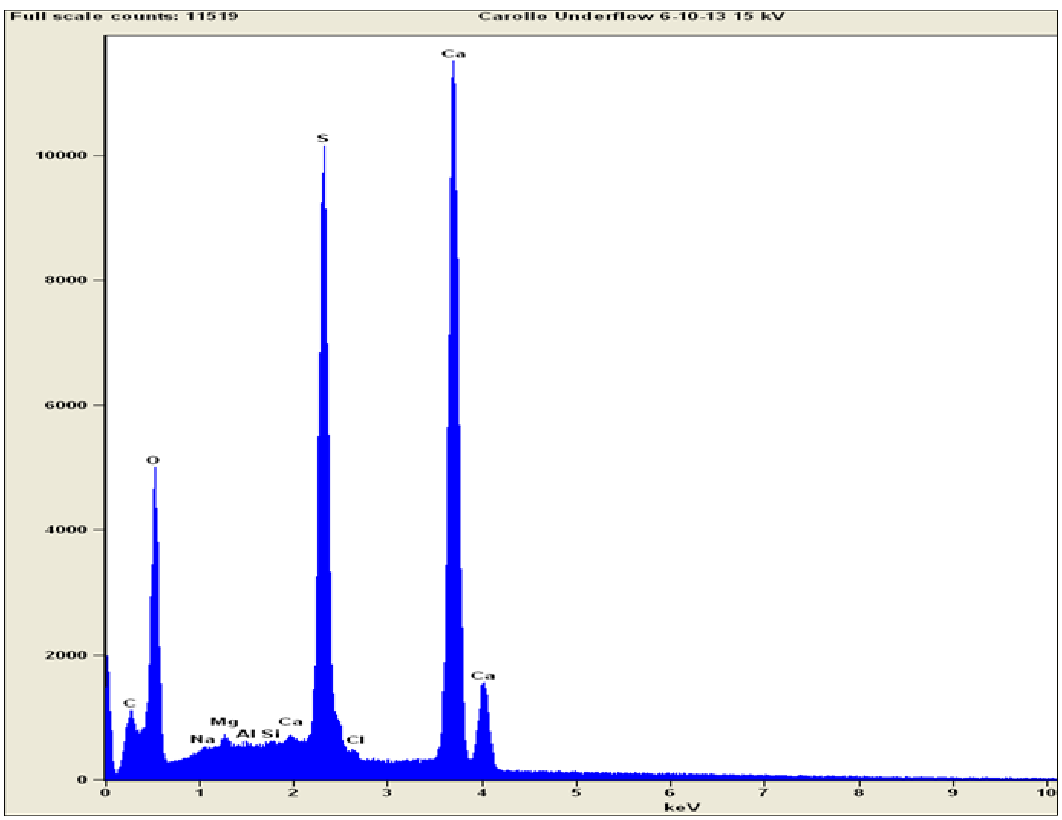


Figure 34.—SEM image of solids from cyclone underflow from SPARRO pilot plant (top) and SEM-EDX spectra of the solids.

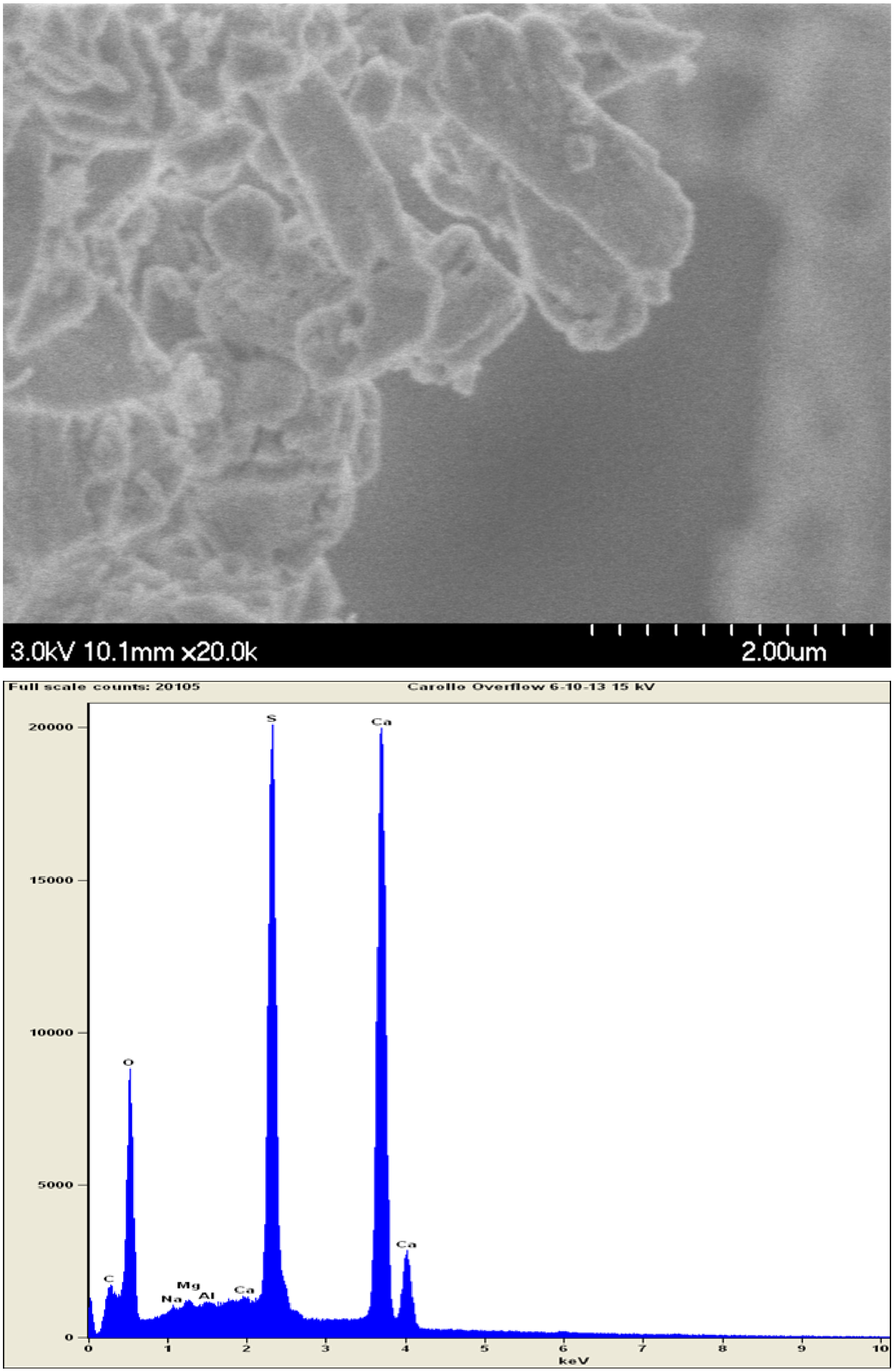


Figure 35.—SEM image of solids in SPARRO cyclone overflow (top) and SEM-EDX spectra of the solids.

4. **Solids on CA Membrane Surface:**

Some solids were removed from a CA membrane tube at the end of the testing period. This material had accumulated inside the membrane tube. An SEM image of the solids is shown on Figure 36.

An XPS analysis of this solids showed that it was a mixture of gypsum and calcium carbonate; approximately in the ratio of 79:21 percent.

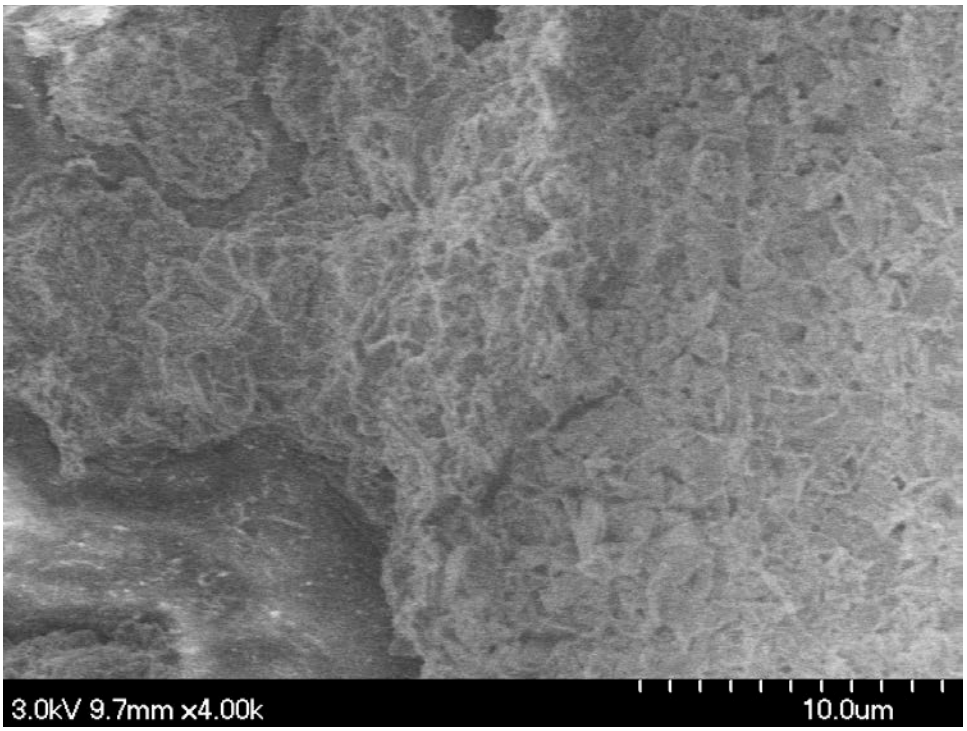


Figure 36.—SEM image of scale collected from inside CA membrane.

5. **TFC Membrane Surface:**

A piece of TFC membrane collected after Period 1 testing was sent for an independent SEM analysis at UCLA. An SEM image of the deposit on the surface of the membrane is shown on Figure 37. As can be seen the surface is completely covered by the solid. The membrane autopsy, presented earlier, concluded that this material was calcium carbonate. An XPS analysis confirmed that the material consisted of approximately 83 percent calcium carbonate and about 16 percent gypsum.

6. **Solid Sample Collected from SPARRO Overflow Tank System:**

To reduce the mass of solids discharged to drain during the pilot testing, a series of three buckets was set up to allow solids in the cyclone overflow to be captured. A sample of solids from the outlet nozzle of the second bucket was analyzed under and SEM. Figure 38 presents an image of the crystals in the solid. It can be seen from the magnification that these are much larger crystals than those shown earlier. An XPS analysis of these solids showed that the material consisted of mainly calcium carbonate (87 percent) and gypsum (13 percent).

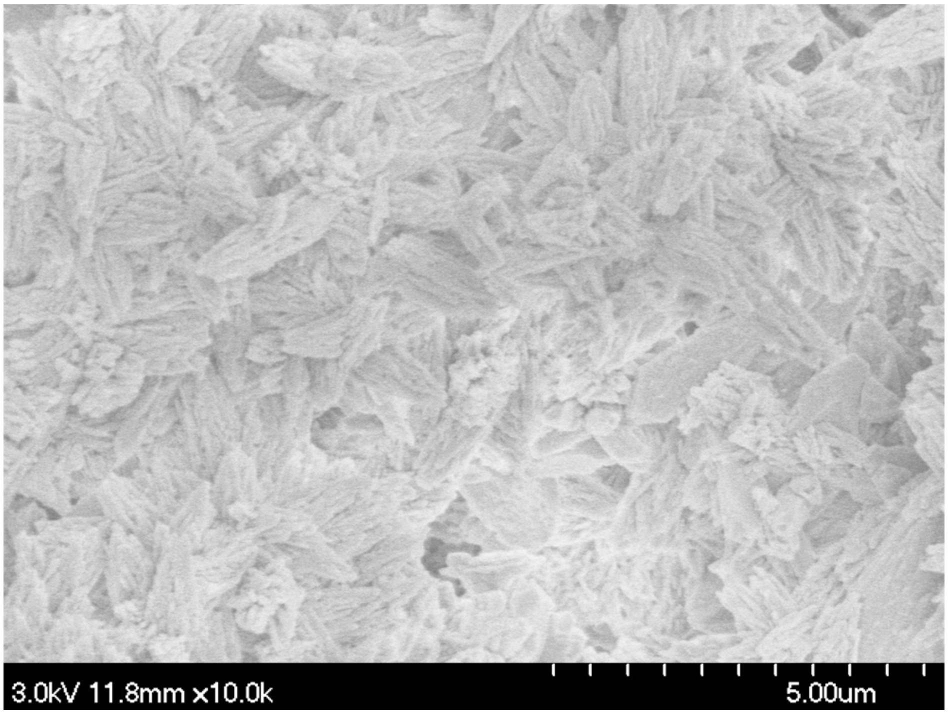


Figure 37.—SEM image showing surface of a TFC membrane covered by a deposit.

Figure 38.—SEM image of solids from SPARRO unit.

4.3.5.2 Mass Balance Analysis of Solids Composition

It should be possible to determine what was removed within the system, and therefore what solids could have formed by examining the changes in chemistry across the SPARRO process. A mass balance was performed across the SPARRO process based on the laboratory analyses of the EDR blowdown stream (feed to the SPARRO process), the SPARRO permeate stream, and the SPARRO blowdown stream.

Table **11** shows the results of the mass balance analysis for the constituents (alkalinity, sulfate, sodium, calcium, chloride and silica) for the operational Periods 2, 3, and 4. Period 1, in which the TFC membranes were installed, was excluded from the data set because several constituents were missing from the analysis. Due to the limited operating time of the SPARRO unit, only one full laboratory data set is available for each of the operating periods, which limits the accuracy of the data. The data in the table present the percent change in the constituent mass balance across the SPARRO process. A change of 0 percent would mean that the mass of a given constituent that entered with the EDR blowdown was accounted for in the SPARRO permeate and concentrate streams.

Table 11.—Mass Balance Around SPARRO Unit for Multiple Constituents

Period Shown on Figures	Percentage (%) Change in Constituent Across SPARRO					
	ALK	SO_4	Na	Ca	Cl	SiO_2
2	69	66	19	49	19	21
3	64	54	10	66	-16	-5
4	59	63	11	59	12	1

On the other hand, a change of 100 percent would mean that the constituent did not leave the SPARRO process, and presumably accumulated as a solid. The analysis includes the constituents sodium (Na) and chloride (Cl) as well. Since it is not expected that these constituents will be taken up in any solids that form in the process, they provide a check on the accuracy of the mass balance. As shown in the Table **11**, for Period 2 both sodium and chloride showed a 19-percent change. For Period 3, the change was 10 percent and 16 percent, respectively, and for Period 4 it was 11 percent and 12 percent, respectively. We would not expect complete accuracy of the mass balance given the variability of analytical procedures, and in this case, the data variation is within about 20 percent. For the other constituents, except for silica (SiO_2), the changes across the SPARRO process are much larger, as would be expected. The silica variation for Period 2 was 21 percent, while for the other two periods it was close to zero.

Based on the water chemistry of the EDR blowdown, there is significantly more calcium (Ca) than sulfate (SO_4) on a molar basis (from the mg/L values in Table 7). Thus, in terms of gypsum precipitation, the sulfate would be the limiting constituent. The results in Table **11** indicate that between 54 and 66 percent of the sulfate formed into gypsum.

As gypsum forms, it will tie up calcium. Based on the amount of sulfate that precipitated, the amount of calcium that was lost to gypsum formation can be calculated. Any remaining calcium that was lost from the mass balance presumably precipitated as calcium carbonate. If all the remaining calcium did indeed precipitate as calcium carbonate, then the ratio of gypsum to calcium carbonate in the solids can be calculated. Table **12** shows results of the gypsum and calcium carbonate solids formed for the three operating Periods, based on the data in Table **11**. As shown, the resulting solids mixture was dominated by gypsum. In two cases the ratio was around 80:20, for gypsum to calcite (calcium carbonate) and for Period 3 there was a lot more calcite formed. However, an inspection of the raw data for Period 3 shows the sulfate value in the EDR blowdown as 3,000 mg/L, which is significantly lower than the average for the whole study (around 4,600 mg/L). If the sulfate value had been 4,000 mg/L, the ratio of gypsum to calcite would be 79:21, very similar to the values for Periods 2 and 4.

The total solids formation data in Table **12** suggests that on average about 3.8 lb/hour (28.6 gpm or 1.7 kg/hr) of solids was forming within the SPARRO process. This is significantly higher than the production rate presented earlier (2.4 lb/hour) based on measured solids values. The difference in production rates is probably due to the accuracy limitations of both the mass balance data as well as the settling method used to estimate the solids concentration.

Table 12.—Predicted Solids Formation Based on Mass Balance

Period Shown in Figures	Gypsum Solids (g/min)	Calcite Solids (g/min)	Total Solids (g/min)	Gypsum %	Calcite %
2	24.8	6.6	31.4	79	21
3	13.6	10.8	24.4	56	44
4	21.5	5.0	26.5	81	19

The results from the mass balance analysis show several things:

1. The mass balance itself, based on the sodium and chloride values is probably accurate to within about 20 percent.

2. Not all the calcium available precipitated with sulfate to form gypsum, and calcite solids formed between 20 and 40 percent of the solids produced by the SPARRO unit, assuming that the sulfate value reported in Period 3 is correct. The calcite concentration was confirmed by the XPS analyses of solid samples collected.

3. The formation of calcite only accounts for about 65 percent of the change in alkalinity observed in the process. It is assumed that the remaining alkalinity was lost from the system as carbon dioxide.

4.4 EDR/SPARRO Combination Performance Results

The EDR unit was operated for a total 1,950 hours with 1,150 hours in Phase II. However, only 200 hours of operation were achieved in conjunction with the SPARRO unit. The EDR was analyzed for hydraulic and electrical performance while operating with the SPARRO unit and compared to operational data collected during Phase I. The following sections discuss EDR data collected during combined EDR/SPARRO operation.

4.4.1 Water Quality

Comprehensive mineral analysis was conducted on grab samples collected from EDR feed, product, and blowdown streams as well as the SPARRO concentrate and permeate streams. Water quality analysis results are shown in Table **13** The water quality data shows the EDR/SPARRO system can effectively remove TDS from the RO concentrate. In Table **13** product TDS concentrations are 21 percent of TDS feed concentrations. Additionally, Table **13** shows a drastic reduction in sulfate concentration by 95 percent and calcium concentration by 92 percent. These values are similar to those observed during Phase I.

Table 13.—EDR/SPARRO Water Quality - Phase II

Parameter	Units	EDR Feed	EDR Prod.	EDR Conc.	SPARRO Prod.	SPARRO Conc.
Alkalinity	mg/L	1,100	510	1,900	130	270
Total Dissolved Solids (TDS)	mg/L	5,350	1,150	15,500	4,750	16,000
Total Organic Carbon (TOC)	mg/L	4	2	7	ND	15
Total Suspended Solids (TSS)	mg/L	ND	ND	20	ND	1,855
Sulfate	mg/L	1,490	74	4,400	815	3,300
Sodium	mg/L	570	270	1,400	815	1,755
Calcium	mg/L	800	67	3,000	110	2,900
Magnesium	mg/L	200	22	640	55	1,000
Chloride	mg/L	920	200	2,800	1,000	4,200
Total Silica	mg/L	170	150	160	65	150

Notes: ND = Not Detected.

One of the advantages of the EDR/SPARRO process is the improved water quality of the EDR makeup water. The EDR feed, which is typically used for makeup flow, shows an average TDS of 5,350 mg/L. This is the quality of the water used as brine makeup during Phase I operation. During Phase II, the EDR makeup flow was a combination of EDR feed and SPARRO permeate flow. As shown in Table **13**, the SPARRO permeate had a lower TDS than the EDR feed, and had significantly lower concentrations of calcium, magnesium, silica, sulfate, and bicarbonate. By lowering the concentrations of these constituents, the scaling potential of the EDR concentrate loop is reduced. The water quality of the EDR makeup flow during Phase I and Phase II of the project are compared in Table **14**.

Table **14** compares the EDR feed stream quality with that of the SPARRO product stream that was returned to the brine loop as a portion of the makeup water. In terms of TDS, the SPARRO product water had a lower TDS than the EDR feedwater (4,750 mg/L compared with 5,350 mg/L). More significantly, other parameters associated with scale formation in the brine loop, such as alkalinity, sulfate, calcium, magnesium and silica, were all considerably lower in the SPARRO product water: 220 mg/L compared with 1,200 mg/L for alkalinity; 515 mg/L compared with 1,444 mg/L for sulfate; 170 mg/L compared with 813 mg/L for calcium; and 79 mg/L compared with 170 mg/L for silica. Only sodium and chloride had higher concentrations in the SPARRO product, which would not result in adverse conditions in the brine loop. During combined EDR/SPARRO operations, the SPARRO product provided 0.8 gpm (3.0 L/min) of the required 2.6 gpm (9.8 L/min) brine makeup in the EDR, or 31 percent.

Table 14.—Comparison of EDR Brine Make-up Quality with and without EDR/SPARRO combined operation – Phase II

Parameter	Units	EDR Feed/Brine Makeup	SPARRO Product/Brine Makeup
Alkalinity	mg/L	1,200	896
Total Dissolved Solids (TDS)	mg/L	5,275	5,164
Total Organic Carbon (TOC)	mg/L	4	4
Total Suspended Solids (TSS)	mg/L	ND	ND
Sulfate	mg/L	1,444	1,156
Sodium	mg/L	596	664
Calcium	mg/L	813	614
Magnesium	mg/L	203	168
Chloride	mg/L	920	1,007
Total Silica	mg/L	170	142

Notes: ND = Not Detected.

One thing to note is that, due to changes in EDR flow, the SPARRO unit was undersized for the EDR pilot unit. Because of this, only a portion of the EDR blowdown flow was treated by the SPARRO unit. This resulted in less SPARRO product flow than would have been produced if the SPARRO could have processed the entire EDR blowdown flow. It is estimated from the pilot data that the SPARRO permeate would comprise 60 percent of the EDR makeup flow for a full-scale facility. This would further improve the makeup flow quality beyond what is shown in Table **14**.

4.4.2 Hydraulic Performance

During Phase II operations, EDR feed, product, and concentrate flows were monitored from on-site readings similar to Phase I. Data from Phase II is compared to that collected during Phase I on **Figure 39**. The EDR feed pump was controlled by the EDR's PLC and was set to maintain a product flow of 6.2 gpm (23.5 L/min). All flows were very stable throughout Phase II.

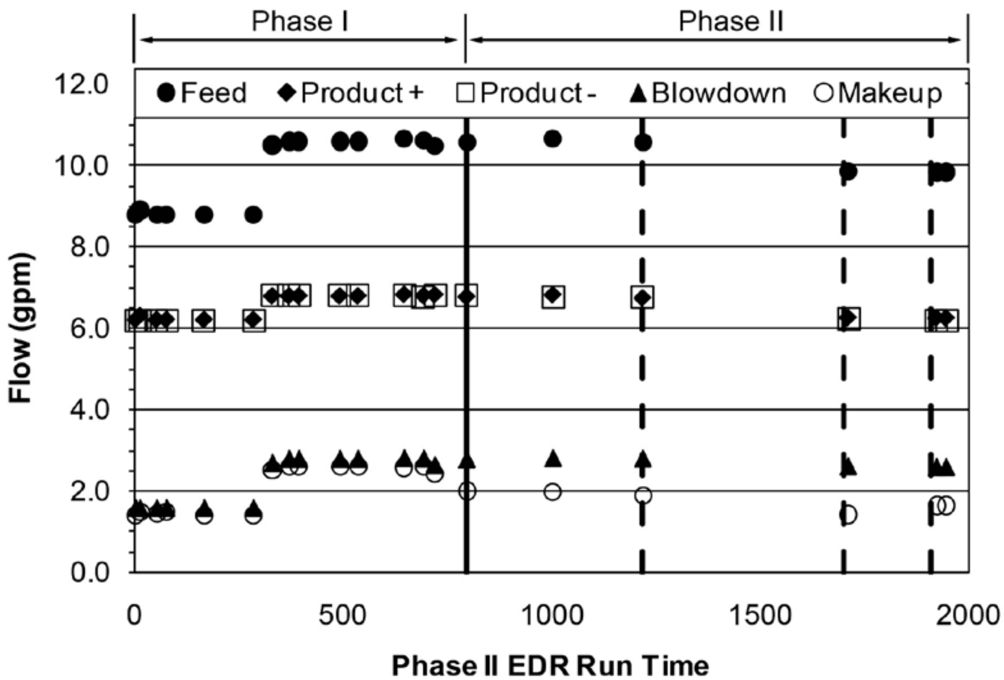


Figure 39.—Phase II EDR flows.

As shown on **Figure 39**, the EDR feed, product, and blowdown flows were similar throughout Phase I and II. The solid vertical line represents the beginning of Phase II and the dashed vertical lines represent the SPARRO membrane replacements corresponding to Periods 1, 2, 3, and 4 as discussed earlier. The EDR run time during Phase II represents the total EDR run time. However, the data shown for Phase II represents EDR/SPARRO operation. The data for EDR only operation during Phase II is not shown for clarity. While the EDR product and blowdown flows were adjusted slightly during Phase II, the noticeable difference in Phase I and Phase II operation is the makeup flow. During Phase I the makeup and blowdown flows are similar, while in Phase II the makeup flow is less than the blowdown flow. This is due to the addition of SPARRO permeate as make up. This addition reduces the EDR feed and make-up flows, increasing the overall recovery of the system. The recovery of the process during Phases I and II are compared on **Figure 40**.

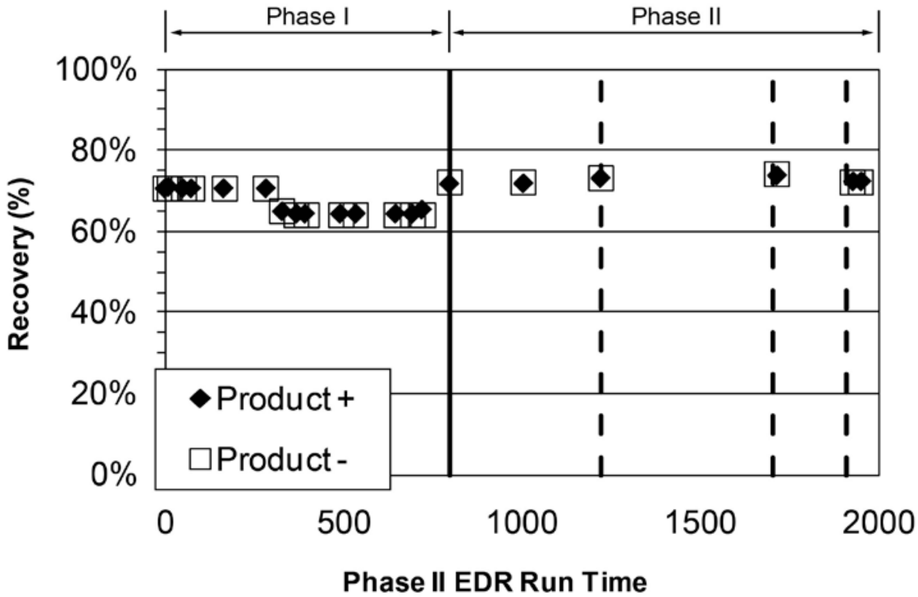


Figure 40.—Phase II EDR System Recovery

As shown on **Figure 40**, the addition of the SPARRO unit increased the recovery of the process during Phase II. During Phase I, the EDR was operated at 65 percent recovery. During Phase II, the system recovery was increased to 78 percent. It is estimated that the recovery could have been as high as 85 percent if the SPARRO pilot was sized to treat 100 percent of the EDR blowdown. Even with the inefficiencies of the pilot plant, the addition of the SPARRO unit decreased the total concentrated waste flow by 37 percent. This would increase to 57 percent if all the EDR blowdown was treated in the SPARRO process.

Feed pressure in the EDR unit is another important performance indicator. As the membrane stack begins to scale, stack inlet pressure increases (see **Figure 41**). As shown on **Figure 41**, the feed pressure at the start of Phase II was a similar to that of Phase I. During Phase I, the slight upward trend in feed pressure which continued into Phase II, indicating that a small amount of scaling was occurring in the EDR unit. During Phase II, the feed pressure reached 50 pounds per square inch gauge (psig), which is toward the high end of typical EDR operation, indicating the need for a CIP. Also around this time, the EDR pilot unit was having control issues and was shutting down during flow reversals. These shutdowns were caused by the higher pressures, which caused the feed pump to operate close to 100 percent speed, and the response times of the EDR control system. At this time, the pilot team decided to reduce the product and blowdown flows of the EDR, which decreased the EDR feed pressure and stabilized the EDR performance for the second half of the Phase II operation.

Overall, the hydraulic performance of the EDR during Phase II was similar to its performance during Phase II. The addition of the SPARRO unit to the EDR concentrate loop had no negative effects on EDR hydraulic performance, while it increased the overall recovery by 13 percent and reduced concentrate volume by 37 percent.

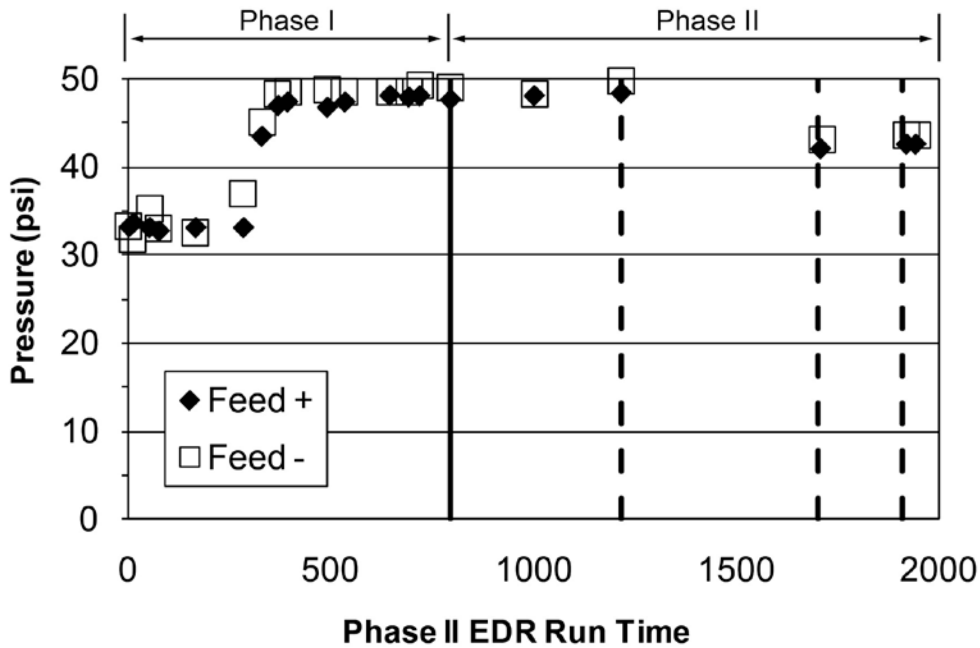


Figure 41.—EDR feed pressure (Note: 30 psi = 207 kPa)

4.4.3 Salt Rejection

Figure 42 shows the EDR salt rejection during Phase I and Phase II testing. The EDR performed well during Phase II, rejecting approximately 79 percent and 76 percent salts during the positive and negative polarities, respectively. Compared to Phase I operation, the salt rejection did not noticeably change with the addition of the SPARRO unit, although the average TDS of the EDR product was slightly lower during Phase II.

4.4.4 Electric Performance

Voltage and resistance are two important parameters in EDR operation. During Phase II, the pilot operated at +44 VDC and -42 VDC. These values are similar to those observed during Phase I operation. The stack resistance observed during Phase II is shown on **Figure 43** and indicated that the EDR performance remained stable during Phase II operation. Similar to the other EDR performance parameters, resistance was determined to be very stable for both Phase I and Phase II in both polarities. This is another indication that adding the SPARRO unit to the EDR concentrate loop had a positive effect on EDR performance.

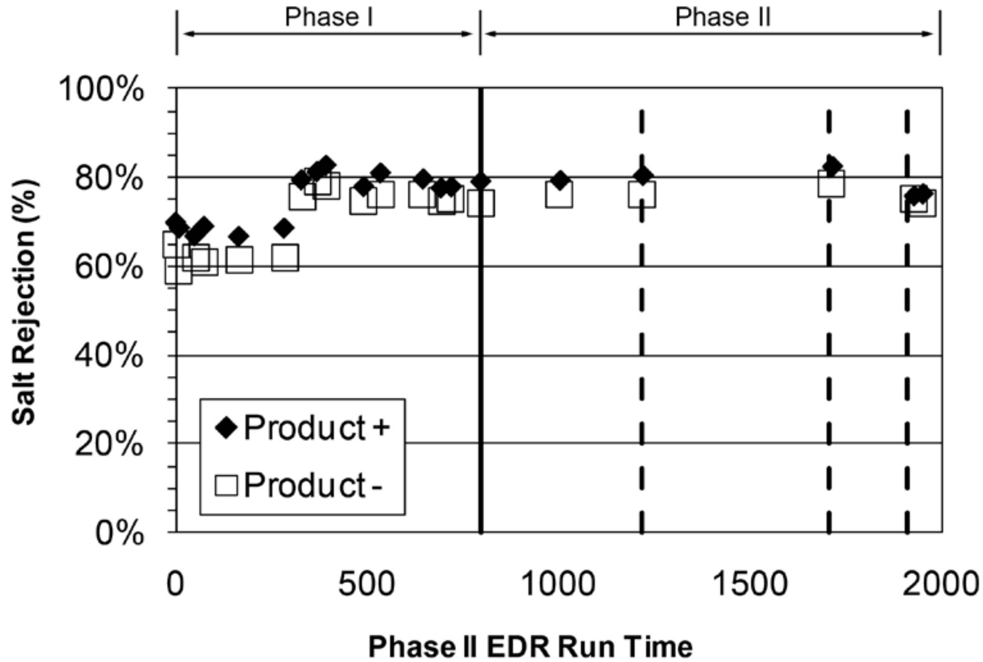


Figure 42.—EDR salt rejection.

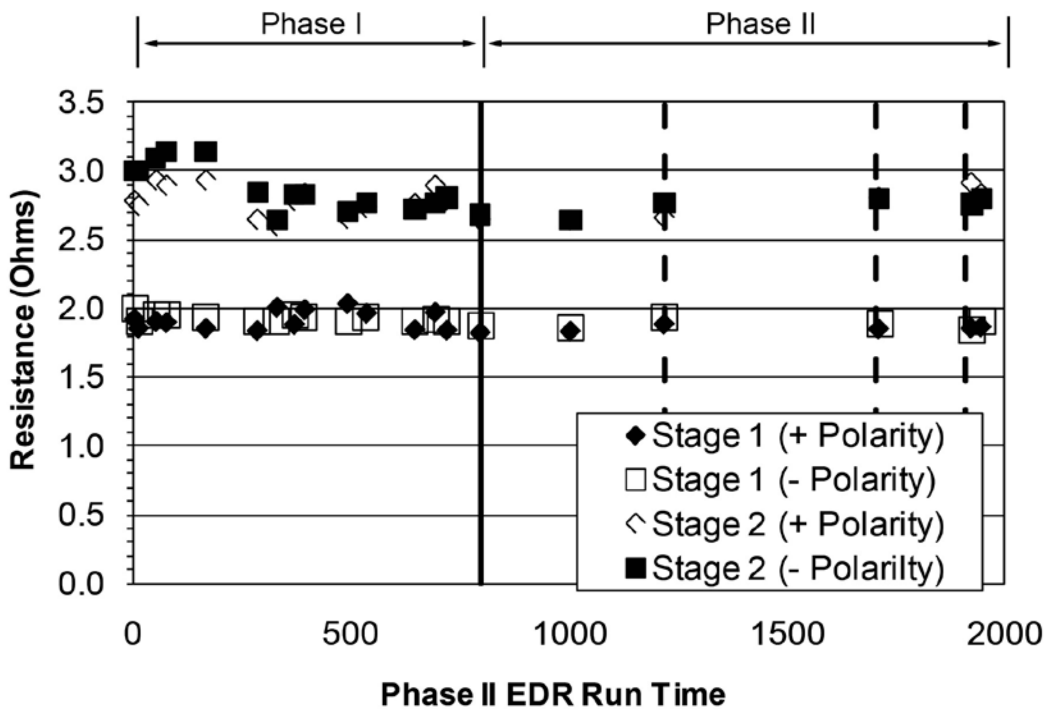


Figure 43.—Phase II EDR Resistance

5. PRELIMINARY COST ANALYSIS

A preliminary capital and operation and maintenance (O&M) cost estimate was developed for the EDR/SPARRO process based on pilot data. The cost presented represents the capital and O&M costs associated with an EDR/SPARRO process designed to treat 1 mgd of RO concentrate. Detailed capital and O&M cost information is presented in Appendix C.

5.1 Cost Estimate Assumptions

Several baseline cost assumptions were required to complete the cost estimate for the concentrate treatment process. These assumptions include O&M factors, such as cost for power, chemicals, etc., and estimates of process capital cost based on past projects and vendor quotes. At the time of this cost estimate (November 2013), the Los Angeles-based *Engineering News-Record* construction cost index was 11321.

5.1.1 Operation and Maintenance Cost Assumptions

A list of the assumptions used to determine the O&M costs of the EDR/SPARRO is presented in Table **15**.

Table 15.—Operation and Maintenance Cost Assumptions

Parameter	Units	Value
Labor Costs (with benefits)	$/hr	$48
Hydrochloric Acid (36%)	$/lb	$0.11
EDR Anti-Scalant	$/lb	$1.00
Sulfuric Acid (93%)	$/lb	$0.08
SPARRO Cleaning Chemicals	$/lb	$3.50
EDR Membrane Replacement	$/1,000 gal	$0.20
SPARRO Membrane Replacement	$/1,000 gal	$0.95
Sludge Disposal	$/AF	$100
Electrical Power	$/kWh	$0.13

AF = acre foot
kWh = kilowatt hour

5.1.2 Capital Cost Assumptions

Several planning level cost assumptions were made based on vendor quotes for equipment and rule-of-thumb parameters for membrane treatment costs. A summary of capital cost assumptions is shown in Table **16**.

Table 16.—Capital Cost Assumptions

Parameter	Cost
Piping	5% of equipment costs
Site Work	5% of equipment costs
Electrical Equipment	18% of equipment costs
Instrumentation	10% of equipment costs
Building Cost	$150 per square foot for chemical building $250 per square foot for EDR/SPARRO building
Contingency	20% of direct costs
Contractor General Conditions	5% of direct costs plus contingency
Contractor Overhead and Profit	12% of direct costs plus contingency
Sales Tax	8.75% of equipment costs

5.2 Cost Estimate for 1 mgd (3.785 m^3/d) EDR/SPARRO

Using the stated assumptions and vendor quotes, an overall capital cost was developed. The detailed cost estimates can be found in Appendix C.

5.2.1 Capital Cost Estimate

The planning level capital cost estimate for the EDR/SPARRO process is summarized in Table **17**. The construction cost estimate for an EDR/SPARRO system designed to treat 1.0 mgd of RO concentrate is $9.7 million, and includes a 20-percent contingency, but excludes engineering costs. This estimate includes chemical systems, treatment equipment, storage tanks, pumps, and other ancillaries required for treatment.

5.2.2 Operation and Maintenance Cost Estimate

The planning level O&M cost estimate for the treatment facilities is summarized in Table 18. The total annual O&M cost is estimated at $0.97 million, which includes electrical costs, chemical costs, membrane replacement costs, solids disposal costs, and labor costs.

Table 17.—Capital Cost Estimate ($ per year)

Parameters	Value
EDR[1]	$1,820,000
SPARRO	$2,700,000
Chemical Systems	$150,000
Buildings	$850,000
Yard Piping and Site Work[2]	$450,000
Electrical[3]	$490,000
Instrumentation[4]	$270,000
Subtotal Direct Cost	***$6,730,000***
Contingency (20%)	$1,350,000
Subtotal	***$1,350,000***
Estimated Equipment Cost	**$8,080,000**
Contractor General Conditions (5%)	$395,000
Contractor Overhead and Profit (12%)	$947,000
Sales Tax (8.75%)	$288,000
Subtotal	***$1,630,000***
Estimated Construction Cost[5]	**$9,700,000**

Notes: (1) Vendor quote plus allowance for installation.
(2) 10 percent of equipment cost.
(3) 18 percent of equipment cost. Vendor quote for EDR includes electrical.
(4) 10 percent of equipment cost. Vendor quote for EDR includes instrumentation.
(5) Construction cost estimate is for a system designed to treat 1.0 mgd of RO concentrate. Excludes engineering costs.

Table 18.—Operation and Maintenance Cost Estimate ($ per year)

Parameters	Value
Chemical Costs	$200,000
Sludge Disposal Costs	$93,000
Membrane Replacement Costs	$150,000
Power Costs	$420,000
Labor and Staffing Costs	$105,000
Total Cost	**$968,000**

5.3 Cost Analysis

EDR/SPARRO process combination aims to make desalination a more attractive alternative for inland utilities where traditional methods of disposal (ocean discharge) are not feasible by decreasing concentrate volume and providing a near-ZLD system. The EDR/SPARRO process provides two benefits for O&M

costs: increased water production from existing sources and decreased concentrate volume requiring disposal or further treatment if considering full ZLD. To put the capital and O&M costs for the EDR/SPARRO process in perspective, the unit costs of water produced are summarized in Table **19**.

Table 19.—Unit Cost Estimate for EDR/SPARRO Process

Parameters	$/AF	$/kgal	$/m^3
Capital Costs(1)	$894	$2.74	$0.72
O&M Costs	$1,036	$3.18	$0.84
Total Cost	**$1,930**	**$5.92**	**$1.56**

Notes: (1) Assuming a 20-year term and an annual fixed interest rate of 6 percent.

As shown, the total cost is estimated to be around $1,930 per AF of water produced ($5.92/kgal; $1.56 per cubic meters [m^3]), which is close to the cost of seawater desalination.

An RO facility operating at 80-percent recovery and producing 1 mgd (3,785 m^3/d) of brine would produce 4 mgd (15,140 m^3/d or 4,480 acre-feet per year [AFY] of product water). A typical cost of this water is $550/AF ($1.69 per thousand gallons [kgal]; $0.45/m^3), and the disposal cost for the brine is around $300/AF ($0.92/kgal; $0.24/m^3) of product produced (typical for disposal in a regional brine line in southern California). Treating the brine in the EDR/SPARRO process would recover an additional 929 AFY (3,139 m^3/d), increasing the total production to 5,409 AFY (18,279 m^3/d), and an overall recovery of 96.6 percent. Brine discharge would drop by 80 percent, and the cost of brine disposal per AF of product water would fall to less than $50/AF ($0.15/kgal; $0.04/m^3). The average cost of produced water would now be $782/AF ($2.40/kgal; $0.63/m^3). This is still lower than the cost of imported potable water in southern California, and easily justifiable.

In summary, the overall combined cost of production and brine disposal for the RO facility at 80-percent recovery would be around $850/AF ($2.61/kgal; $0.69/m^3), and the overall cost for an RO/EDR/SPARRO combination operating at 96.6-percent recovery would be $832/AF ($2.55/kgal; $0.67/m^3), with the production of 20 percent more water.

O&M costs could be lowered by local incentive programs to reduce dependence on imported water supplies, and some reduction in solids disposal cost by beneficial use of the gypsum byproduct may also be possible.

It should be noted that the viability of this approach would need to be validated on a case-by-case basis, based both on the economics and also on the quality of the water produced by the EDR/SPARRO process combination.

In the case of the water treated during the pilot testing, Table **20** shows the results of blending RO desalter water with the product water from the EDR/SPARRO process. As shown, the blended TDS in this case would be around 320 mg/L, and the calcium concentration would increase to 16 mg/L as calcium, providing a conditioning effect to the water.

Table **20** does not include all EPA and California Drinking Water parameters, and these would need to be checked. However, understanding that the City of Corona already bypasses untreated well water around the desalter, it is anticipated that in this case the product water would meet all drinking water requirements.

Table 20.—Combined Water Quality from RO Desalter and EDR/SPARRO Process

Parameter	Units	RO Product Water	Blended RO and EDR/SPARRO Product
Alkalinity	mg/L	30	117
Total Dissolved Solids (TDS)	mg/L	130	318
Sulfate	mg/L	8	21
Sodium	mg/L	32	76
Calcium	mg/L	7	16
Magnesium	mg/L	2	4
Chloride	mg/L	28	56
Total Silica	mg/L	2	24

6. SUMMARY AND CONCLUSIONS

6.1 Summary

This project has demonstrated that the EDR and SPARRO processes can operate together as a combined process treating RO concentrate and increase the recovery of the EDR system, while producing a lower TDS product water. Overall recovery of the EDR process was demonstrated to increase from 60 to 65 percent when operating in isolation to 78 percent when operating together with the SPARRO unit. In a full scale system, the combined recovery could be as high as 85 percent if the SPARRO unit is sized to take all blowdown flow from the EDR process. When treating RO concentrate from a desalter operating at 80 percent recovery, the overall recovery would increase to around 96.6 percent when the RO concentrate is treated by the EDR/SPARRO combination.

Significant operational challenges were experienced with the SPARRO pilot unit. These were related to controlling the flow rate from EDR and an unexpectedly large production of calcium carbonate. Due to these operational issues, the combined operating time of the EDR/SPARRO processes was only about 200 hours. Nevertheless, even in that short time, the benefits of the combined process performance was evident.

Specific conclusions relative to each of the project goals are presented in the next section.

6.2 Progress with Respect to Project Goals

1. **Determining technical feasibility of continuous operation of the EDR/SPARRO process combination**.

   The work demonstrated that it is possible to combine the two processes and operate continuously. Moreover, the EDR unit automatically adjusts its hydraulic balance whether or not the SPARRO unit is returning flow to the EDR brine loop. However, continuous operation was limited to a maximum of about 200 hours. This was not due to an inherent issue associated with the combined process, but rather to two major causes:

   a. Difficulty with controlling the flow rate of concentrate from the EDR unit. If future testing is to be done, the SPARRO unit needs to be sized to take all the concentrate blowdown from the EDR; and better quality of level and flow control equipment needs to be provided.

   b. The impact of high concentrations of bicarbonate in the EDR concentrate. These values were higher than had been experienced during previous test work and caused significant precipitation of calcium carbonate within the SPARRO system, which was not anticipated. This resulted in the formation of large solids flakes not experienced in other seeded RO testing, which caused problems in the membranes, and other areas of the process. Testing at the end of the study showed that pH suppression of the feed from the EDR allowed for release of a high percentage of the bicarbonate as CO_2. In future testing, pH suppression should be used as a pretreatment step ahead of the SPARRO unit to reduce the bicarbonate concentration to limit formation of calcium carbonate within the SPARRO system.

2. **Establish the optimum operating parameters of the EDR/SPARRO process.**

   Not much progress was made towards achieving this goal due to the limited time the combined processes were able to operate continuously.

3. **Estimate capital and O&M costs of the EDR/SPARRO process.**

Estimates of capital and O&M cash were presented in Section 5. Those values show that the combined capital and O&M costs would translate to a cost of around $1,930/AF ($5.92/kgal; $1.56/m^3$) of additional product produced by the EDR process. While this is expensive water, when considering the additional volume of product produced, and the substantial savings in brine disposal costs, the additional costs appear to be justifiable. For example, a 5-mgd RO facility producing water at $550/AF ($1.69/kgal; $0.45/m^3$), with brine disposal costs of $300/AF ($0.92/kgal; $0.24/m^3$), for a total of $850/AF ($2.61/kgal; $0.69/m^3$), would be expected to have a combined cost of $832/AF ($2.55/kgal; $0.67/m^3$) when the brine is treated by the EDR/SPARRO combination, and produce 20 percent more water.

4. **Investigate marketability of high-purity gypsum solids produced in the EDR/SPARRO process.**

   Due to the presence of high concentrations of bicarbonate in the EDR concentrate stream and the resulting precipitation of calcium carbonate, the gypsum purity was not as high quality as had been obtained on other source waters. In fact, the gypsum to calcium carbonate (calcite) ratio ranged between 60:40 and 80:20, respectively.

Nevertheless, the preliminary market analysis showed that there are industries that would be willing to consider taking the solid gypsum by-product from a full-scale facility. A plant treating 1 mgd (3,785 m^3/d) through the EDR process would produce more solids that could be taken by one of the interested industries. Based on what potential users would possibly pay for the by-product, sale of a portion of the by-product from a hypothetical EDR/SPARRO plant treating 1 mgd of RO concentrate, would offset a portion of the solids disposal cost. Details are provided in Appendix A. Landfill disposal alone would be the worst-case cost and would be about $158,000/year. Giving the product away as a soil amendment would be expected to cost about $67,000/year.

Overall, the project did achieve the goal of further developing the EDR/SPARRO process combination. Positive aspects of the study include:

- Continuous operation (24 hours per day) of the combined processes was achieved, which had not been done previously. In previous work, the maximum operating time for the combined processes was around 8 hours.

- The EDR process operated without concern for the SPARRO system. In other words, turning the SPARRO system on or off did not upset the EDR process, it simply automatically adjusted to the new process conditions.

- When the EDR/SPARRO combination was operational, there was an improvement in the performance of the EDR process. Notably, the recovery increased, and there was 15 percent improvement in product quality, in terms of a reduction in product TDS. Using the values obtained from the pilot study and extrapolating them to account for a system in which all EDR concentrate would be fed to the SPARRO unit, the overall recovery of the combined system would be 85 percent. This compares with a recovery of 60 to 65 percent for the EDR operating on its own. The increase in recovery for the EDR/SPARRO combination would reduce the volume of brine for final disposal by 57 percent, a significant amount.

- The pilot study demonstrated some shortcomings of the SPARRO pilot unit, particularly with respect to the level of automation and the quality of the instrumentation that is needed in this application to withstand the extremely harsh environment encountered in this study. While the best effort was made to build a robust pilot plant with the available project budget, more funds would have been needed in order to overcome the mechanical and instrumentation difficulties encountered.

- Even with all the process issues encountered, and the need to replace the membranes several times during the operating period, the membrane replacement was not due to puncturing of the membranes or damage by the recirculating gypsum seed. Unfortunately, this study did not turn out to be a true test of the membranes in a seeded slurry environment due to what appears to be very poor condition of the first set of membranes (TFC membranes) at start-up, and the unacceptably high formation of calcite (calcium carbonate) which appeared to overwhelm the system, and formed despite the presence of calcium sulfate seed, coating the membrane tubes, system pipe work and tanks. Future testing will require a conditioning step to remove excess alkalinity before the EDR blowdown enters the SPARRO feed tank.

- Despite the many positive aspects of this study and the positive cost estimates for the EDR/SPARRO combination, it is too early to recommend this treatment approach. Additional testing will be needed to address the hydraulic control issues, confirm that calcium carbonate precipitation can be mitigated, and demonstrate longer operation of the membranes in the seeded mode in this application to confirm performance.

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Appendix A

PRELIMINARY MARKET SURVEY FOR GYPSUM BY-PRODUCT

APPENDIX A

AGREEMENT NUMBER: R11AC81537

PRINCIPAL INVESTIGATOR: GRAHAM JUBY

US DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

DESALINATION AND WATER PURIFICATION
RESEARCH AND DEVELOPMENT (DWPR)

INCREASING RECOVERY OF INLAND DESALTERS BY
COMBINING EDR AND SPARRO TECHNOLOGIES
TO TREAT CONCENTRATE

MARKET SURVEY FOR SOLIDS GENERATED DURING TREATMENT

OCTOBER 2013

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COMBINING EDR AND SPARRO TECHNOLOGIES TO INCREASE RECOVERY AT INLAND DESALTERS

1.0 INTRODUCTION

As water scarcity continues to increase in many regions throughout the United States, there is a growing interest in desalination of impaired water sources. One of the major limitations of desalination is the concentrated waste stream that is produced by traditional technologies such as reverse osmosis (RO). Typically, RO can recover between 70 and 85 percent of the influent water, resulting in a significant amount of concentrate that requires disposal. The disposal of the concentrate stream is often challenging and can be cost prohibitive for locations where ocean disposal is not feasible. Even for inland regions of Southern California where a regional concentrate pipeline to the ocean exists, concentrate disposal is becoming more costly and is not sustainable due to issues with pipeline scaling, maintenance, and decreased line capacity.

To reduce the cost of concentrate disposal, the recovery of the desalting processes needs to be increased. However, increasing recovery can be challenging because the overall recovery of a desalination process is determined by the concentration of the least soluble sparingly soluble salt (e.g., calcium carbonate, calcium sulfate, silica). To recover water beyond the solubility limit, solid salts must be removed from the process. Several processes, including lime softening followed by a secondary desalting unit, have been tested. While these processes successfully reduce concentrations of sparingly soluble salts, they can use a significant amount of chemicals and produce a large amount of solid waste.

To reduce the amount of chemical used and waste produced, Carollo conceived a new treatment approach using a combination of two proven membrane processes. This technology approaches concentrate minimization from a different angle by allowing salts to precipitate, in a controlled manner, in the secondary desalting unit instead of removing salts ahead of secondary desalting. The approach makes use of EDR as a secondary desalting process and SPARRO to treat and reduce the scaling potential of the EDR concentrate loop. The SPARRO process allows salts to precipitate naturally, as concentration increases, on calcium sulfate seed crystals, does not require chemicals, and produces a solid calcium sulfate product that could be reused by other sectors/industries, thus providing a useful resource.

2.0 PURPOSE

This report aims to identify various market sectors that may be interested in the gypsum solids produced in the SPARRO process and to compare the solids purity measured during pilot testing to the purity requirements of different industries. Additionally, the report evaluates the marketability of the gypsum solids and postulates on whether the solids could be sold or donated to offset a portion of the O&M Costs.

3.0 TECHNOLOGY BACKGROUND

EDR has been used for water desalination for over fifty years. The SPARRO process is less well known in water treatment, but has been experimented with in the mining industry to treat highly concentrated mining waste since the mid-1980s, and more recently to treat agricultural drainage water and RO/EDR concentrate. The concept of seeding is well known and practiced in the application of vapor compression evaporator technology.

3.1 Electrodialysis Reversal (EDR)

EDR is an electrochemical separation process that uses a direct current (DC) voltage and ion exchange membranes to desalinate water. A schematic diagram of the EDR process is shown in Figure 1. As shown, the feed enters the product compartment and positive ions are attracted towards the cathode and negative ions are attracted to the anode. As the ions travel through the membrane stack, positive ions pass through cationic membranes and are rejected by anionic membranes and vice versa for negative ions. Alternating cationic and anionic membranes create product compartments and concentrate compartments within the membrane stack.

The product and concentrate compartments create the product (desalted) and concentrate streams, respectively. The product stream is fed to the downstream process and most of the concentrate stream is recycled back to the membrane stack creating the concentrate loop. To control the total dissolved solids (TDS) concentration in the concentrate loop and avoid scale formation within the membrane stack, a portion of the flow is wasted as concentrate blowdown and the volume is made up (concentrate makeup) with EDR feed water. A process flow diagram (PFD) of the EDR system is shown in Figure 2.

3.2 Slurry Precipitation and Recycle Reverse Osmosis (SPARRO)

The SPARRO process is a hybrid of conventional RO technology. It incorporates the recirculation of seeded slurry through the RO system, promoting homogeneous nucleation and precipitation from the solution. This process was first developed to treat cooling tower blowdown from power plants high in calcium and sulfate ions. Seed crystals (gypsum) are introduced to the feed stream, which is then pumped into tubular RO membranes. As the water is concentrated along the membranes, the solubility products of calcium sulfate, silicates, and other scaling salts are exceeded; and they preferentially precipitate on the seed material rather than on the membranes. A schematic of the SPARRO process is shown in Figure 3.

A PFD of one configuration of the SPARRO process is shown in Figure 4. As indicated, in this configuration water is fed to the SPARRO feed tank. The SPARRO feed tank contains the gypsum seed crystals which are initially added as food-grade gypsum. The slurry mixture in the feed tank is then fed to the tubular RO membrane elements producing permeate and concentrate streams. The permeate is removed from the process and the concentrate/slurry mixture is recycled back to the feed tank through a cyclone separator. In the cyclone separator, a majority of the solids are separated from the concentrated liquid. This separation allows for individual control of the gypsum solids mass balance and liquid TDS by individually wasting calculated volumes of the high suspended solids cyclone underflow and the high TDS cyclone overflow, respectively.

3.3 EDR/SPARRO Process Combination

The combination of the EDR and SPARRO process overcomes some of the limitations of both processes. The major limitation of the EDR process is scaling in the concentrate loop. Typically, the EDR process can only recover water up to the solubility limits of the sparingly soluble salts in the concentrate loop. One of the limitations of the SPARRO process is its relatively large footprint due to the limited membrane area in tubular modules and, therefore, it tends to be more suited to treating smaller, more concentrated streams.

In the EDR/SPARRO process, water is fed to the EDR membrane stack as normal where product and concentrate streams are produced as described above. The difference in the EDR/SPARRO process is how the concentrate blowdown is handled. In this process the EDR blowdown is fed to the SPARRO unit for further treatment. The EDR blowdown is concentrated further in the SPARRO process allowing calcium sulfate to precipitate on the gypsum seeds. The SPARRO permeate is then fed back to the EDR concentrate loop to help reduce the scaling potential of the EDR concentrate. The SPARRO concentrate is recycled back through the cyclone separator and wasted as describe above. A PFD of an example EDR/SPARRO process combination is shown in Figure 5.

The two processes have a synergistic relationship. The EDR provides the SPARRO unit with a highly concentrated, low-flow stream overcoming the footprint issues of the SPARRO process, while the SPARRO process removes solid salts (calcium sulfate) in a controlled manner helping to overcome the solubility limitation of the EDR process. Combining the strengths of the two processes increases the overall recovery of the EDR system beyond the recovery that can be feasibly achieved on its own, and at the same time produces a solid gypsum by-product ($CaSO_4 \cdot 2H_2O$) that can potentially be used in other industries.

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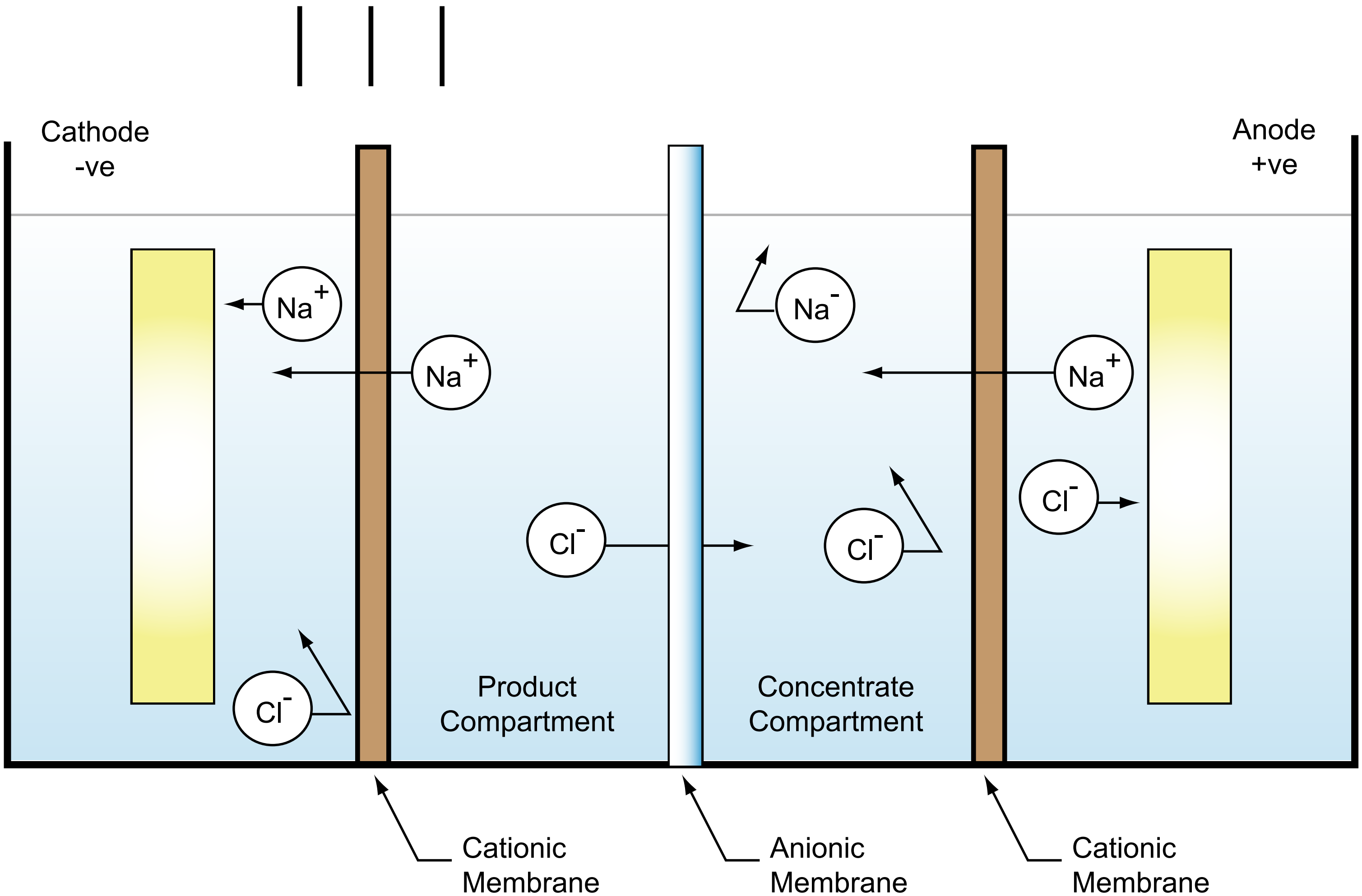

EDR SCHEMATIC

FIGURE 1

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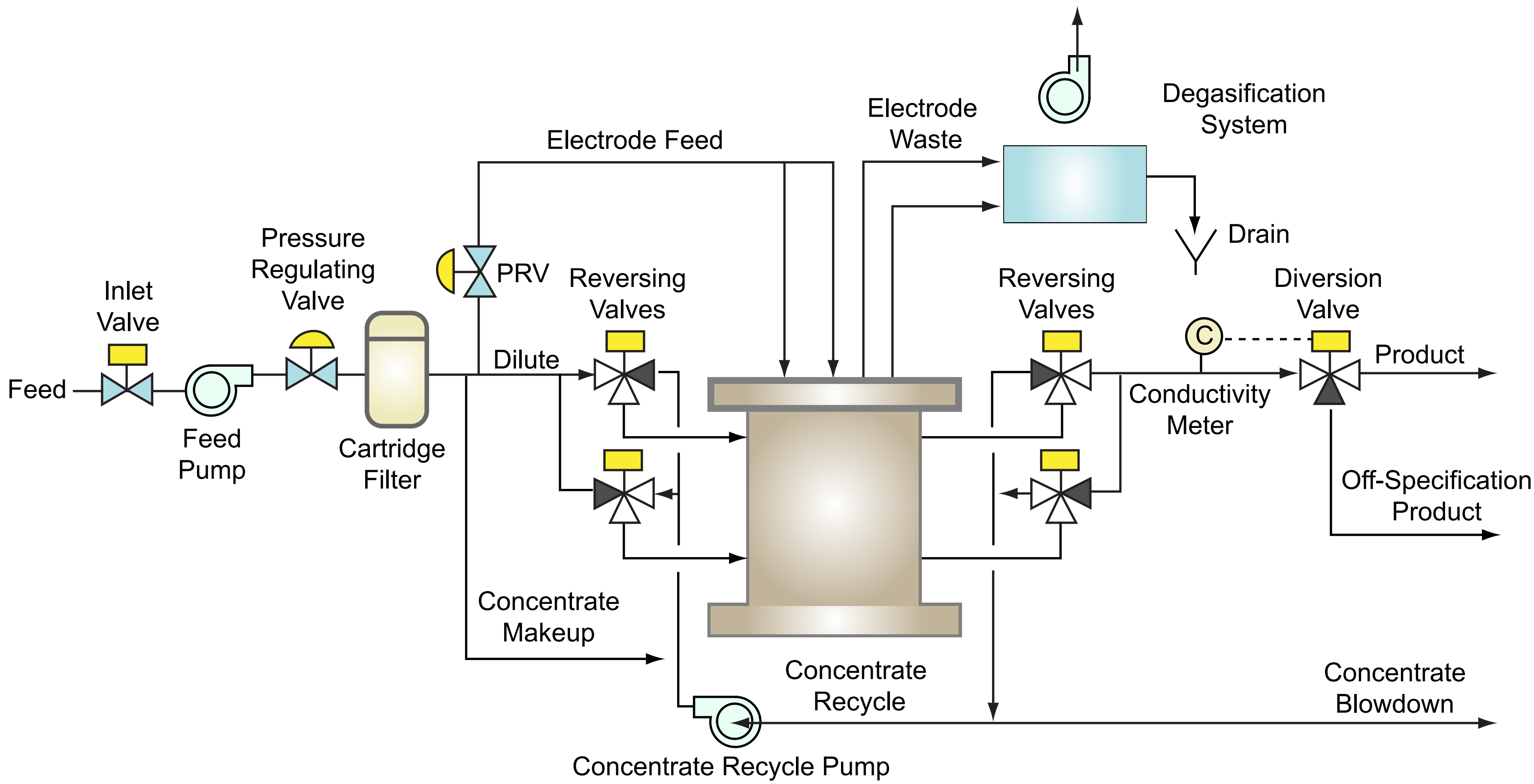

EDR PROCESS FLOW DIAGRAM

FIGURE 2

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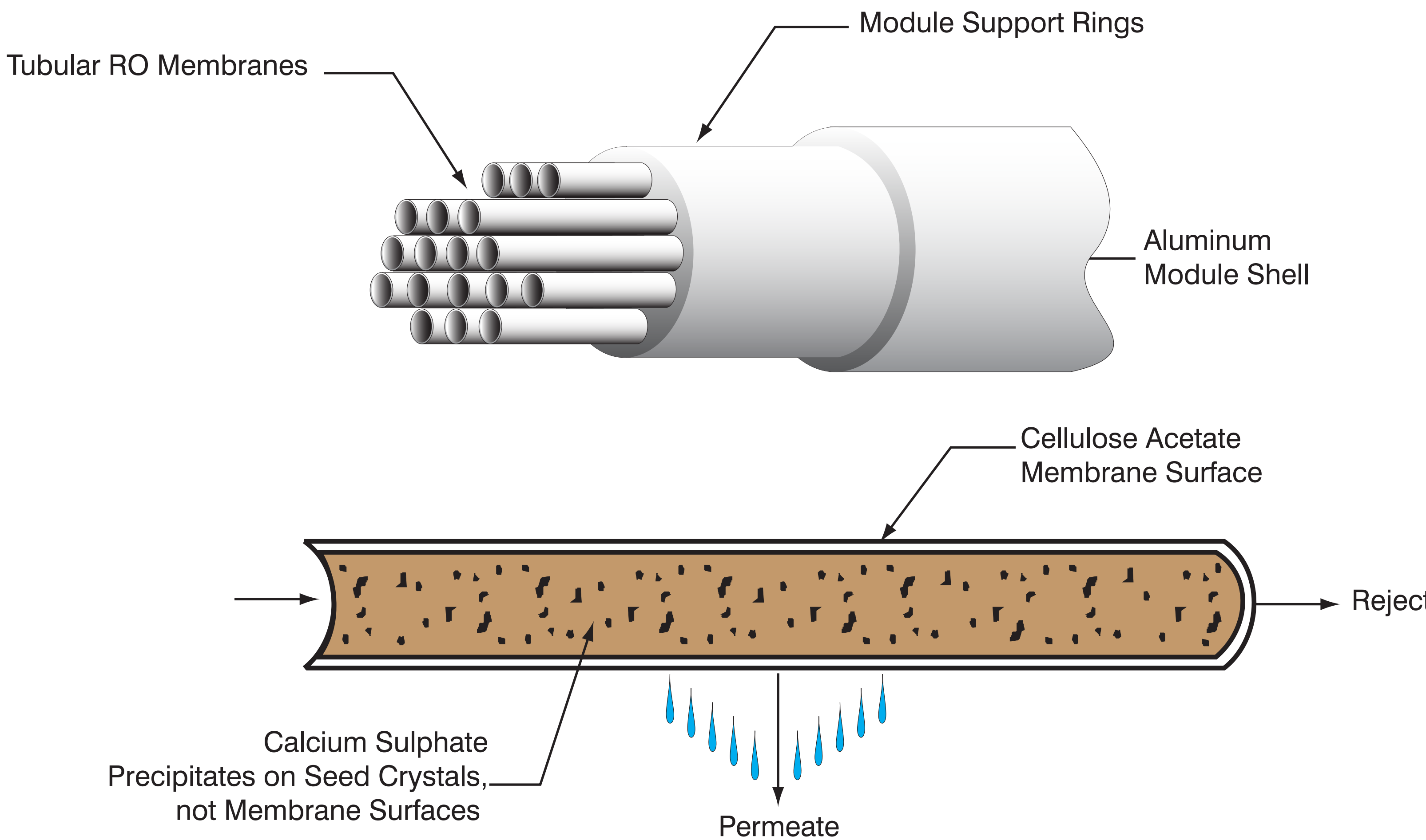

SPARRO SCHEMATIC

FIGURE 3

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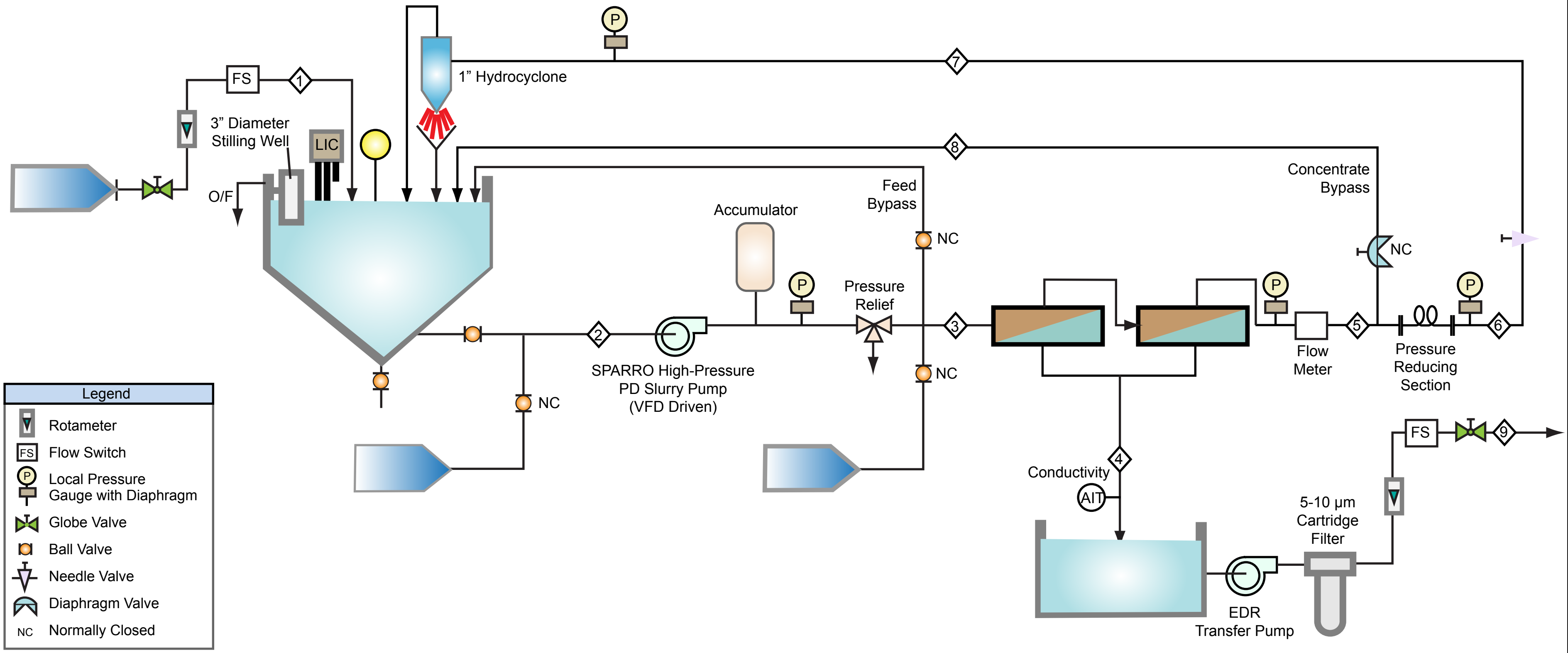

Parameter	1	2	3	4	5	6	7	8	9
	EDR Blowdown	Pump Suction	SPARRO Feed	Permeate	High Pressure Concentrate	Low Pressure Concentrate	Cyclone Feed	Concentrate Bypass	EDR Return
Flow (gpm)	1.0-1.5		3.5-4.0	~1.0	2.5-3.0	2.5-3.0	2.5-3.0		~1.0
Pressure (psi)			400-600		240-440	80-100	~50		~10
Conductivity (µS/cm)	9,000-16,500	10,000-18,000		200-1,500					200-1,500
TDS	12,500	13,800	13,800	1,380					1,380
TSS (g/L)	<<1	10-15	10-15	Nil	14-21	14-21	14-21		Nil
Calcium (mg/L)	1,700	1,900	1,900	100					100
Sulfate (mg/L)	3,600	4,000	4,000	200					200
Sodium (mg/L)	1,200	1,300	1,300	130					130
Magnesium (mg/L)	440	500	500	25					25
Chloride (mg/L)	2,000	2,200	2,200	230					220

SPARRO PROCESS FLOW DIAGRAM

FIGURE 4

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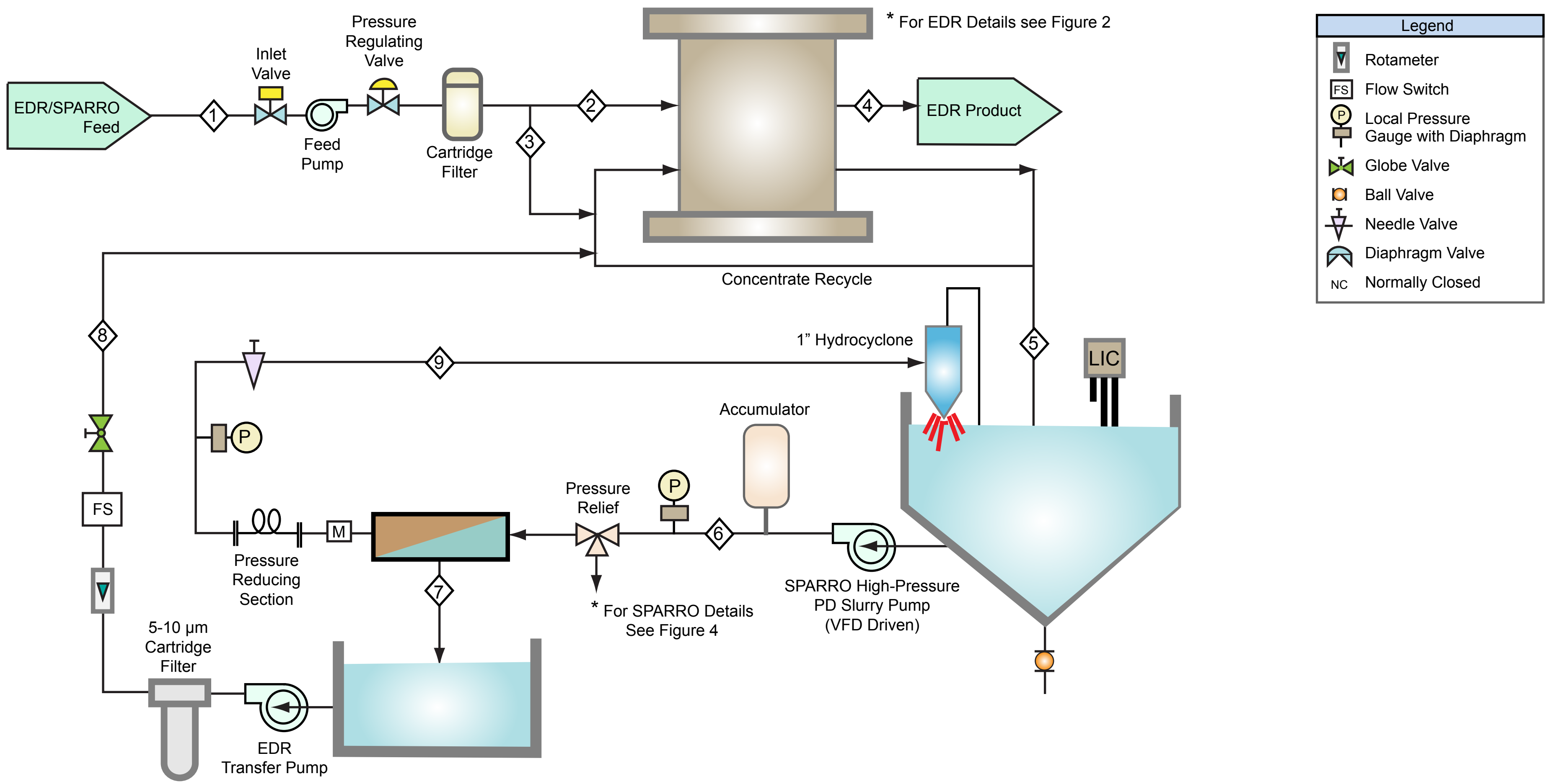

Parameter	1	2	3	4	5	6	7	8	9
	EDR Feed	Dilute	Concentrate Makeup	EDR Product	EDR Blowdown	Sparro Feed	Sparro Permeate	EDR Return	Cyclone Feed
Flow (gpm)	7-8.5	6-7.5	0.1-0.5	6.0-7.5	1.0.-1.5	3.5-4.0	~1.0	~1.0	2.5-3.0
Pressure (psi)		30-35	30-35			400-600		~1.0	~50
Conductivity (µS/cm)	1,800-3,500	1,800-3,500	1,800-3,500	200-300	9,000-16,500	10,000-18,000	200-1,500	200-1,500	13,000-21,000
TDS	6,300	6,300	3,000	630	12,500	13,800	1,380	1,380	
TSS (g/L)	Nil	Nil	Nil	Nil	<<1	10-15	Nil	Nil	14-21
Calcium (mg/L)	870	870	350	50	1,700	1,900	100	100	
Sulfate (mg/L)	1,800	1,800	730	90	3,600	4,000	200	200	
Sodium (mg/L)	590	590	300	160	1,200	1,300	130	130	
Magnesium (mg/L)	220	220	90	10	440	500	25	25	
Chloride (mg/L)	1,000	1,000	500	250	2,000	2,200	230	230	

EDR/SPARRO PROCESS FLOW DIAGRAM

FIGURE 5

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4.0 SOLIDS ANALYSIS

In order to determine marketability, it is important to gather information on the physical properties and chemical makeup of the solids. Physical and chemical tolerances are application specific for many users and appropriate analysis is required to ensure regulatory compliance. For example, certain particle size distributions may be unacceptable and strictly regulated in the abrasives and sand blasting sectors.

Two solids samples taken from the pilot plant were used for this analysis: the first was collected from the SPARRO cyclone underflow and consists of heavier particulates while the second was collected from the SPARRO cyclone overflow consisting of lighter particulates and smaller crystalline material. For clarification purposes, solids collected from the underflow will be referred to as "underflow" while cyclone overflow will be referred to as "blowdown."

Because the physical and chemical characteristics of the solids generated are influenced by the quality of water being treated and the size of initial "seed" for the slurry, it is important to note the analytical results obtained are meant as an illustration of variation that may be encountered and are not necessarily indicative of the quality of solids generated during full scale operation.

Physical qualification and Chemical analyses of the samples were conducted by Omya, Inc., Florence, VT, USA.

Table 1 and Table 2 present the physical characteristics of the samples. Table 1 lists the values for three general physical characteristics including coefficient of curvature, specific gravity, and moisture content. These samples were collected as a slurry in a five gallon bucket and left to stand unaltered for approximately two weeks. As Table 1 indicates, the solids content of the two samples ranges from 54 to 60%. Depending on the market sector selected, additional drying facilities may be required to alter this solids content further. Table 2 lists the results of the particle size distribution conducted on the two slurry samples including the effective size and uniformity coefficient.

Table 1 General Physical Characteristics of the Samples

Parameter	Underflow	Blowdown
Coefficient of Curvature	2.13	1.65
Specific Gravity, g/cm^3	2.3$^{(1)}$	
Solids Content, %	60.4	54.1

1. This is a literature value for $CaSO_4.2H_2O$

Table 2	Particle Size Distribution	
	Volume Under (%)	
Size (μm)	Underflow	Blowdown
1.0	2.18	7.27
5.0	8.05	28.86
10.0	10.88	46.33
20.0	19.20	78.10
50.0	76.66	100.0
100.0	100.0	100.0
Effective Size, d_{10}=	7.83	1.26
Uniformity Coefficient =	5.08	10.9

To determine the chemical composition of the solids produced, Omya, Inc. performed three tests on each sample: X-ray diffraction (XRD), X-ray fluorescence (XRF), and scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS). XRD, which gives the relative mass of crystalline solids, indicated that both samples contained calcite ($CaCO_3$) and gypsum ($CaSO_4$) in a ratio of about 70% calcite and 30% gypsum. Further testing using XRF and SEM-EDS indicated that both samples contained a majority of calcium sulfate. These results indicate that a significant portion of the calcium sulfate solids are in an amorphous state. The results of the XRF testing are listed in Table 3.

Table 3	XRF Testing Results	
Parameter	% Mass	
	Underflow	Blowdown
CaO	39.8	40.6
MgO	0.53	0.61
Al_2O_3	<0.01	<0.01
Fe_2O_3	<0.01	<0.01
SiO_2	0.12	0.11
K_2O	0.01	0.02
SrO	0.16	0.17
SO_3	31.2	35.2
Loss On Ignition (LOI) at 950 ºC	24.4	27.6

According to the XRF analysis, approximately 65% of the total solids were calcium sulfate (gypsum) and 35% calcium carbonate (limestone). Depending on the market sector selected, this ratio may not be acceptable and a higher concentration of calcium sulfate may be required. In such a case, sulfuric acid may be added to the treatment process to increase the precipitation of calcium sulfate and decrease the precipitation of calcium carbonate.

5.0 POTENTIAL SOLIDS USERS

As part of this market study, a preliminary survey of potential gypsum users was conducted. The survey covered a diverse set of industries that may potentially utilize gypsum in their process. Calcium sulfate (gypsum) is an abundant natural resource used as a raw material in a wide variety of applications including building materials, casting industries, medical applications, and agricultural uses. Various companies were identified and contacted to discuss potential marketability within their respective industries. Detailed contact information for the companies contacted is presented in Appendix A.1.

As a preliminary analysis, many of the companies contacted did not respond to the survey. Of the twelve companies contacted, only four companies expressed interest requesting additional information before any discussion of cost would be considered. Below is a summary of the survey results.

Three market sectors showed interest in gypsum: fertilizer and soil amendment, casting industries, and abrasives and sand blasting. Additionally, gypsum is used in large quantities in building materials such as dry-wall. Companies such as Pabco Gypsum, which mine their own gypsum, may be interested in purchasing the byproduct in order to extend the useful life of their quarries. Further information in this regard is not available.

5.1 Omya, Inc.

Omya is a global producer of industrial minerals and specializes in fillers and pigments derived from calcium carbonate and dolomite. Omya's major markets include paper, polymers, building materials, and life sciences. As a supplier of industrial minerals, Omya took an interest in the pilot project and worked with the project team to test the solids produced from the pilot plant. Their analysis concluded that the solids produced in the pilot study were not a high purity, high quality calcium sulfate product, but a mixture of calcium carbonate and calcium sulfate. While the pilot plant did not produce a high purity product, Omya indicated that there would still be demand for the solids produced in industries with lower purity standards, such as soil amendment.

5.2 Kellogg Garden Products

Kellogg Garden Products is an organic soil amendment and fertilizer manufacturer and has strict regulations regarding the generation of gypsum used in its soil amendment product. While they do use gypsum on a regular basis, the use of chemicals during the formation of gypsum would be strictly prohibited by their regulators. Further information regarding the process would need to be presented to their regulatory committee in order to determine feasibility. However, their contact person, Mr. Godfrey, did indicate that it was highly unlikely that the gypsum byproduct produced from a water treatment desalting operation would be suitable for use in an organic fertilizer product.

5.3 Gro Power

Gro Power is a soil amendment and fertilizer manufacturer. Unlike Kellogg Garden Products, Gro Power is not regulated by chemical formation of gypsum and may have a market for gypsum produced during SPARRO operation. However, in order to determine the marketability, a detailed chemical and physical analysis would need to be conducted on the solids. Possible marketability would include field chemical modification in areas where deicing salts are used on roads. Further analysis would be required to determine ultimate feasibility, but Mr. Anberg of GroPower was confident the gypsum byproduct would be marketable.

5.4 Architectural Cast Inc.

Architectural Cast Inc. is a casting company located in Vernon, CA. Architectural Cast purchases pallets containing 40 sacks of gypsum powder at a time. In a good year, they purchase on average 30-40 pallets or the equivalent of 16-22 tons of gypsum powder. In their industry, they purchase powdered gypsum, add water and pour the cast. Set-up time is critical and cannot be greater than 20 minutes. In order for the gypsum byproduct to be successfully used in this industry, a sample would need to be experimentally tested for performance, uniformity, and usability. Should the gypsum byproduct provide equal or greater performance, casting may be a reliable market.

5.5 Crystal Mark

Crystal Mark is an abrasives and sand blasting company located in Glendale, CA. Crystal Mark specializes in the wholesale of abrasives for various sand blasting enterprises including construction and specialty industries. A potential specialty market may be for gemstone polishing and removal of gypsum and limestone deposits on crystals for resale value. For example, large quartz crystals are often blasted with gypsum powder to remove gypsum deposits before retail at various gem and mineral stores. However, the product must meet several standards.

The gypsum byproduct provided must be in powder form and must be very dry. Additionally, key constituents would need to be identified including hardness, particle size distribution, moisture content of the final dewatered product, and sieve analysis. Particle size distribution is of extreme importance and a detailed analysis must be provided. If more than 1% of the sample is less than 10 micrometers, the gypsum solid cannot be used as a sand blasting abrasive because it can cause severe respiratory distress. The Occupational Safety and Health Administration (OSHA) strictly regulates powders in order to prevent a respiratory illness known as “Black Lung” common in the coal mining industry.

Furthermore, sample consistency is required. In order for the product to prove marketable, the gypsum byproduct must demonstrate consistent physical characteristics and delivery must be reliable. Disruption in a consistent product line would constitute an investment risk Crystal Mark would be hesitant in accepting.

However, should the product meet OSHA requirements, demonstrate appropriate physical characteristics, and prove to be reliable in quality and quantity, gypsum byproduct could definitely be marketable. Crystal Mark typical pays between 20-40 cents/lb for specialty abrasives which would be equivalent to $400-800/ton.

Overall, the abrasives industry appears promising and further investigation should be conducted to determine feasibility if a larger scale EDR/SPARRO installation were to be considered. However, based on the sieve analysis presented in Table 2, neither the underflow or blowdown products would be suitable for use by Crystal Mark without further processing, due to the high concentration of particles less than 10 microns in size.

6.0 PRELIMINARY COST ANALYSIS

During pilot testing, solids production was estimated at 2.4 lb/h (1.07 kg/hr or 56.5 lbs/day). Therefore, in order to maintain the solids concentration within the SPARRO system, 56.5 lbs of solids must be removed from the system each day. The SPARRO pilot was designed to treat 1.3 gpm of concentrate produced by a 8.8 gpm EDR pilot. In order to estimate the disposal costs and solids production, it was assumed that the pilot plant flow ratios of SPARRO to EDR would be maintained. Therefore, for an EDR/SPARRO facility treating 1.0 MGD of concentrate, an accompanying SPARRO facility would be designed to treat 0.3 MGD of EDR concentrate. Maintaining the solids production ratio, the total anticipated solids removed from a 0.3 MGD SPARRO facility would be approximately 4.5 tons/day.

Therefore, in order to conduct a preliminary cost analysis, the following assumptions were made:

- EDR facility design capacity = 1 MGD or 1,120 AF/yr
- SPARRO facility design capacity = 0.30 MGD
- SPARRO Daily dry Solids Production Rate = 4.5 tons/day (1,650 tons/year)
- SPARRO wet solids production rate = 2,750 tons/year (assuming 60% solids)
- Operating Time = 365 days/yr

Three alternatives were evaluated for the disposal of solids. The first alternative considers landfill disposal for all solids. The second considers the sale of a portion of the gypsum solids, and the third considers giving away the solids to a soil amendment company.

6.1 Landfill Disposal

Under this option, solids are considered a waste product that will need to be disposed into a municipal landfill. This means the facility would incur the cost of transportation to the landfill and cost of disposal. However, because a specific location for a potential site has not been identified, it is assumed the hauling costs range between $18/ton to $60/ton depending on the size and loading/unloading conditions. The average cost of landfill disposal for municipal solids and inert waste based on six landfills in the southern California area is approximately $40/ton.

Therefore, a total average unit disposal cost estimate may range between $58/ton and $100/ton, depending on hauling costs. At these unit cost values, the total annual cost for the disposal of the gypsum solids under this option may range between $160,000/yr and $275,000/yr, which translates to a unit water cost range of between $161/AF and $278/AF; in terms of water recovered by the EDR/SPARRO combination.

6.2 Sale of Gypsum Solids

For this alternative, solids are considered a marketable product that could be utilized to off-set some of the treatment cost. Based on discussions with the potential users contacted in this study, the unit price of the solids could be as high as $400-800/ton with hauling costs paid by the user. However, it is unlikely that abrasives and sand blasting industries can handle approximately 1,650 tons/yr of solids. Additionally, Architectural Cast Inc. indicated a peak usage of 16-22 tons/yr. Due to the limited information available, it was assumed that only 10% of the solids generated could be sold at $350/ton, to be conservative and allow for hauling cost, with the remaining 90% sent for landfill disposal.

Therefore, assuming 165 tons/yr is sold at $350/ton while 1,485 tons/yr (2,475 wet tons/year) are disposed of at a cost between $58/ton and $100/ton, the total annual cost of disposal of the solids under this option would range from $85,000/yr to $189,000/yr. This translates to a unit water cost ranging from $86/AF and $191/AF.

6.3 Give Solids Away as Soil Amendment

Under this alternative the solids produced by the SPARRO process would be allowed to drain (to remove as much moisture as possible) and them would be hauled to a soil amendment facility and given away at no cost.

In this case, assuming 2,750 wet tons/year is produced and hauled at $18 and $60/ton the annual disposal cost would be between $49,500 and $165,000 per year, or a unit water cost of between $50/AF and $167/AF.

7.0 SUMMARY & CONCLUSIONS

Gypsum solids are produced during SPARRO operation. A preliminary market analysis has been conducted to determine potential marketability in various industrial sectors. To this effect, solids characterization was conducted and various potential users were contacted to determine interest.

7.1 Solids Analysis

Two samples of solids from the pilot plant were analyzed for physical and chemical constituents. One sample was obtained from the SPARRO cyclone underflow consisting of heavier solids. The other sample was obtained from the overflow consisting of lighter, smaller particles. Both solids samples were mainly comprised of calcium sulfate with some calcium carbonate. The physical analysis of the solids found that the average particle size of the underflow solids was 35 μm and 11 μm for the overflow solids. The chemical analysis concluded that both solids samples were approximately 65% calcium sulfate and 35% calcium carbonate and that a significant portion of the calcium sulfate was in an amorphous state.

7.2 Potential Users

The market survey examined a wide range of applications and markets identifying four primary market sectors. These market sectors include building material manufacturers such as Pabco Gypsum, fertilizer and soil amendments, casting companies, and abrasives and sand blasting.

While building material manufacturers were non-responsive to questions regarding the gypsum byproduct, companies like Pabco Gypsum operate gypsum mines to produce their products. Pabco Gypsum operates a mine in Nevada and may be interested in purchasing SPARRO byproduct gypsum in order to extend the useful life of their quarry. Further investigation would need to be conducted to determine marketability with gypsum building construction manufacturers.

Fertilizer and soil amendment manufacturers showed interest in the gypsum byproduct and indicate a strong marketability in certain sectors. Due to the nature of chemical treatment involved upstream of the SPARRO process, organic fertilizer and soil amendment companies such as Kellogg Garden Products may be unable to utilize the product. However, gypsum is used in a wide variety of soil amendment products and is sold at various home improvement stores to improve clay soils, in arid or coastal regions, or to correct lawn damage caused by salts and winter ice-melting chemicals. Samples would need to be provided to determine user specific application.

Casting companies use large quantities of gypsum on a regular basis. Performance criteria and consistency of quality and quantity are paramount to utilization within the industry. Samples would be required for verification and additional information would need to be obtained to determine application within the industry.

Depending on the particle size distribution, physical characteristics, and consistency in quality, quantity, and delivery, gypsum byproduct could be marketed as an abrasive in specialty markets. However, due to numerous OSHA regulations regarding respiration of fine particulates, a particle size distribution and sieve analysis is critical to determining usability as an abrasive. Additionally, dewatering and drying processes would need to be implemented prior to shipment. Crystal Mark indicated a potential price between 20-40 cents/lb or $400-800/ton assuming marketability, consistency, and acceptability.

7.3 Cost Analysis

The three alternatives for solids disposal were considered: landfill disposal; sale of a portion to a user, and giving the solids away to a soil amendment company. The cost of landfill disposal, including transportation cost was determined to be in the range of $58/ton and $100/ton. For a production capacity of 4.5 tons/day (7.5 wet tons/day), the annual disposal cost could range between $160,000/yr and $275,000/yr which translates to a unit water cost range between $161/AF and $278/AF.

The sale of 10% of the gypsum solids at $350/ton with transportation cost borne by the user could lessen the disposal costs to between $58,000/yr to $189,000/yr. This translates to a unit water cost ranging from $86/AF and $191/AF. If this option is implemented, it represents a reduction in water cost. However, this is a high-level economic analysis based on limited information and further study should be conducted.

The least cost alternative would be to haul the solids to a soil amendment company and give the solids away for free. In this case, the costs would be between $49,500 and $165,000 per year, or between $50/AF and $167/AF when expressing in terms of unit water cost.

7.4 Conclusion

The following conclusions were reached based on the outcome of the preliminary market survey:

1. The market survey suggests a clear market demand for the gypsum solids byproduct.
2. While there are no guarantees that a user will purchase the solids, three companies in three industries expressed strong interest in receiving the solids for various applications.
3. Based on discussions with Crystal Mark, the sale price of solids may range between $400/ton and $800/ton. Transportation costs would be paid by the user.
4. Crystal Mark and Architectural Cast Inc. indicated capacity based on marketability. For analysis purposes, it is assumed approximately 25% utilization within the two industries with 75% disposal requirements.
5. Further testing of actual solids production would be required to determine suitability for each end user.

6. Additional industries may be identified by a more in depth market study and cost estimates should be revised upon further analysis.

Based on the results of the market survey, it is clear that there are multiple viable gypsum solids users. Depending on the quality of the gypsum byproduct from a specific treatment application, it is possible that multiple users could be found to take the byproduct. This approach also helps protect the facility from fluctuations in the market demand of an individual buyer. Ideal buyers are ones that satisfy the following criteria:

1. Buyers are in different industry sectors to protect against fluctuations in the buyer's market.

2. Multiple buyers which increases the potential purchase capacity.

3. Buyers are local to reduce transportation costs and maximize value.

4. Buyers can readily receive truckloads on a routine basis.

5. Buyers produce a wide range of products or sell to a diverse user base.

Potential disadvantages to this approach include higher management costs and potential supply vulnerability due to variable quality and quantity of solids produced. However, increasing utilization reduces disposal costs and increases water cost off-set.

Byproduct that cannot be utilized/sold to an interested industry would need to be disposed of to a local landfill operation. Such disposal costs are around $58/ton today.

Overall, for a groundwater RO desalting operation treating 5-mgd of brackish groundwater with a similar water chemistry to that experienced by the City of Corona, CA, a 1-mgd EDR/SPARRO treatment combination could be applied as a concentrate treatment approach. This combination could be expected to recover an additional 0.83-mgd (929 AFY) of potable water with a value of around $743,000 (based on an average cost of $800/AF which is reasonable for Southern California). This is based on the assumption that the EDR product water will be of a quality suitable for blending with the upstream RO permeate to produce potable water. Brine stream disposal costs would be reduced by approximately 80%, providing additional positive cash flow for the project.

Gypsum solids produced from the SPARRO process would total almost 2,750 wet tons/year in this example. Based on the market analysis presented earlier, it appears that the cost of disposal of the solids could at least be off set by the sale of a portion of the byproduct. In the worst case, landfill disposal would cost around $160,000 per year, and in the best case (assuming that the product is hauled to a soil amendment facility and given away for free), the disposal cost would be less than $100,000 per year. From this example, the value of the recovered water and the benefits derived from reducing the volume of brine for disposal are significant, and substantially more valuable to the economic viability of the project than the value of the solid byproduct.

CONTACT INFORMATION OF POTENTIAL USERS

Table A.1 Contact Information for Potential Byproduct Solids Market Sectors			
Market Sector	**Company**	**Address**	**Contact**
Construction Material Manufacturing	Orco Block	4510 Rutile St. Riverside, CA 92509	Tim Mallis 951-818-6724
Specialty Aggregate Processing	A-1 Grit	1901 Massachusetts Ave. Riverside, CA 92507	Louis Moldina 800-266-4748
Cement Manufacture	Rancho Ready Mix	1150 South Rancho Ave. Colton, CA 92324	951-245-2460
Abrasives and Sand Blasting	Cyrstal Mark	613 Justin Ave. Glendale, CA 91201	Keith Swan 800-659-7926
Building Material	Architectural Cast Inc.	4807 E 49th St. Vernon, CA 90058	Ross Bowen 323-588-2498
Gypsum Mining	Pabco Gypsum	4301 Firestone Blvd. South Gate, CA	702-407-3718
Fertilizer and Soil Amendment	Kellogg Garden Products	8605 Schaefer Ave. Ontario, CA 91761	Andrew Godfrey 800-232-2322
Fertilizer and Soil Amendment	Scott Miracle Gro	915 East Grevillea Ct. Ontario, CA 91761	Matt Grossbauer 909-947-1133
Fertilizer and Soil Amendment	Sun Gro Horticulture	2101 Whisler Rd. McFarland, CA 93250	Shiv Redi 209-602-4771
Fertilizer and Soil Amendment	Gro Power	15065 Telephone Ave. Chino, CA 91710	Jack Anberg 562-754-0415
Biosolids Stabilization	Synago	1800 Bering Dr. #1000 Houston, TX	Lauri Loader 909-322-0388

GE SUMMARY REPORT ON EDR PERFORMANCE

EDR Technology
Pilot Scale Demonstration
U.S. Bureau of Reclamation
Corona, California
FINAL REPORT

Submitted to:

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10540 Talbert Ave, Suite 200 East
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Submitted by:

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July 2013

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Executive Summary

GE Water & Process Technologies conducted a three month pilot study from February to June 2013, utilizing an Electrodialysis Reversal (EDR) membrane system. The study was conducted in Corona, California where the pilot treated the Temescal Desalter's Reverse Osmosis (RO) reject water. The pilot unit was started February 18th 2013 and the optimized test period began March 26th. The study finished June 14th, 2013.

The primary piloting objective was to validate the use of EDR technology to increase the recovery of RO systems. The EDR pilot was first operated in an optimization period for a month. Then it was operated alone for another month to collect baseline EDR performance data. The EDR pilot was then connected to another pilot called a Slurry Precipitation and Recycle Reverse Osmosis (SPARRO) pilot. The SPARRO pilot was used to treat the EDR concentrate stream to increase the recovery of the combined systems. At the end of the study, the SPARRO product water was recycled back to the EDR pilot, where it was added back into the concentrate stream as concentrate make-up, further increasing total system recovery.

The EDR pilot successfully operated at 60% recovery alone and above 90% recovery with the combined RO and SPARRO processes. Three clean-in-place (CIP) events were required throughout the 4 month study to drop pilot pressures. The highly concentrated waste water would minimize disposal volume.

This document provides a summary of the operational and analytical results obtained throughout the pilot study. The following sections highlight the conclusions that can be drawn from the pilot-scale demonstration in Corona.

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1. Introduction

An EDR pilot was established at the Temescal Desalter in Corona, CA to validate the use of EDR technology to increase the recovery of RO systems. The EDR pilot was combined with the Slurry Precipitation and Recycle Reverse Osmosis (SARRO) process to treat RO reject from the existing desalination plant. The main objective was to reduce costs by reducing the amount of concentrate generated and increasing product water production. The purpose of the pilot, by concentrating and maintaining a brine stream that is highly saturated with salts, was to demonstrate the RO and EDR ability to operate at a combined water recovery of greater than 90%.

This document provides a summary of all operational, analytical, membrane integrity results obtained throughout the Corona pilot study. The pilot objectives are stated in Section 2. The basic operating principles of the Electrodialysis Reversal treatment process and the GE Water & Process Technologies pilot are presented in Section 3. Sections 4, 5, 6 and 7 outline the phases of the study, operational results, analytical results, and cleaning results of the EDR unit. Section 8 presents the conclusions after the pilot study.

2. Pilot Objectives

The following were the specific objectives of the Corona, CA pilot study:

- Phase 1:
    - The EDR pilot will be operated alone to treat the RO reject to determine baseline operations for comparison against the EDR/SPARRO process combination. Expected duration of this phase will be one month.
- Phase 2:
    - The SPARRO pilot unit will be integrated into the EDR system concentrate loop. The duration of this phase will be two months.
    - During this phase Carollo will collect samples, take process readings, conduct minor maintenance, and make any necessary adjustments.
    - Determine optimal design parameters to obtain required product water quality and generate stable membrane performance.
    - Determine the maximum recovery while maintaining stable operation.
    - Demonstrate that the EDR Water Treatment System will produce effluent that will meet applicable standards.
    - Determine the chemical consumption requirements for the EDR system.
    - Establish the cleaning (CIP) frequency for the application.
    - At the end of testing the membranes from the SPARRO unit will be sent for a membrane autopsy.
- EDR pilot study will NOT be used to indicate optimum system run lengths between membrane CIP, and optimum chemical usages. An indication of performance can be seen, optimal settings would be developed on a full size EDR system over longer period of operating time.

3. Electrodialysis Reversal Technology

Electrodialysis (ED) is an electrochemical separation process that removes ions and other charged species from water and other fluids. ED uses small quantities of DC voltage electricity to transport these species through membranes composed of ion exchange material to create a separate purified and concentrated stream.

When a DC voltage is applied across a pair of electrodes positive ions, such as sodium, move towards the negatively charged cathode. These are called cations. Negative ions, such as chloride, move towards the positively charged anode, and these are called anions. If membranes are placed between the electrodes, different flow paths are made.

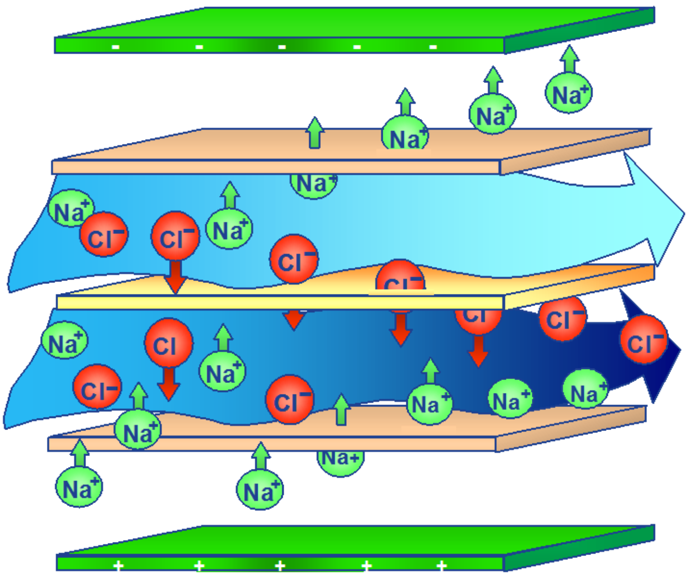

Figure 1: Electrodialysis Process

A membrane permeable to cations only is placed nearest to each of the electrodes. Cations move through the cation-transfer membranes, while anions move through the anion-transfer membrane. Flow spacers are placed between the membranes to support the membranes and create a turbulent flow path. Water flows tangentially across the membranes, not through them. The ions travel through the membranes so that one stream is demineralized as product while the other is concentrated. Since the water does not need to be forced through the membranes, the cost of electrodialysis treatment is only in removing the salt.

Electrodialysis Reversal (EDR) is a continuous self-cleaning electrodialysis process by means of periodic reversal of the DC polarity, thereby switching the concentrating and diluting flow streams. A membrane stack is assembled by compiling multiple EDR membrane cell pairs between two identical electrodes which act as both cathode and anode during the reversal cycle. An EDR cell pair contains an Anion Exchange Membrane, a concentrating spacer, a Cation Exchange Membrane and a diluting spacer. An EDR stack can contain between 500 and 600 cell pairs.

Figure 2: EDR Membrane Cell Pair and Full EDR Membrane Stack

3.1 EDR Treatment Process

In the EDR treatment process there are 3 main streams: feed water, concentrate and product. The feed water is pumped through a feed pump and then through the membrane stacks to make desalinated product. The concentrate is pumped through the concentrate pump to make ion saturated concentrate. The flow of feed water and concentrate through the stack is essentially equal. Most of the concentrate leaving the stack is recycled through the concentrate pump so that a high recovery can be achieved. However, in order to prevent the concentrate from becoming too concentrated, which could result in salts precipitating or forming a scale on the membranes, a small amount of concentrate is wasted. This quantity is made up with fresh water from the feed stream. Figure 3 depicts the flow streams for the EDR process.

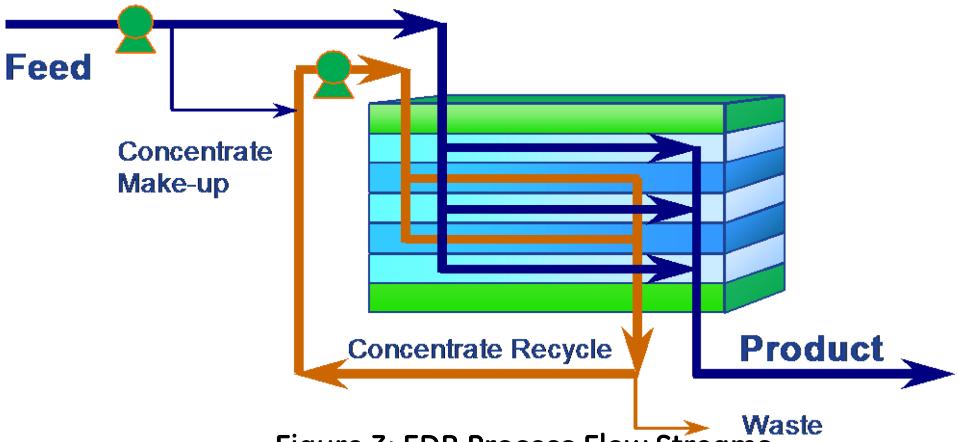

Figure 3: EDR Process Flow Streams

The electrical polarity, and thus the demineralized and concentrate flow passages are automatically reversed two to four times every hour. This results in a reversal of direction of ion movement, which provides "electrical flushing" of scale forming ions and colloidal matter from the membrane surfaces. This "electrical flushing" controls scaling and fouling of membranes and can eliminate the need for extensive pre-treatment of the feed water and also reduces the need of chemical cleaning.

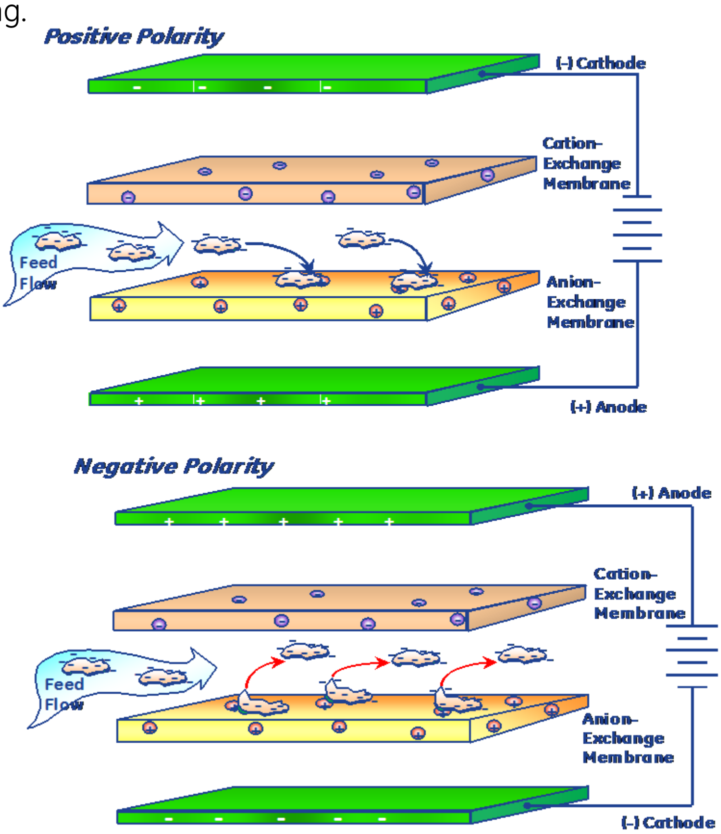

Figure 4: EDR Polarity Reversal Effect on Colloidal Matter

The alternating exposure of membrane surfaces to the product and concentrate streams provides a self-cleaning capability that enables desalting of scaling or fouling waters. At reversal, automatically operated valves switch the two inlet and outlet streams so that the incoming feed water flows into the new demineralizing compartments and the recycled concentrate stream flows into the new concentrating compartments. The effect of this reversal is that the concentrate stream remaining in the stack whose salinity is higher than the feed water, must now be desalted. This creates a brief period of time in which the demineralized stream (product water) salinity is higher than the specified level. This slug of water is known as off-spec product. Conductivity controlled valves shunt the product to waste until specifications are met.

The manner in which the membrane stack array is arranged is called staging. The purpose of staging is to provide sufficient membrane area and retention time to remove a specified fraction of salt from the demineralized stream. Staging is the process of adding additional passes through an EDR stack for each increment of water processed. The ultimate goal of staging is to increase product water purity. In larger systems, additional stages are created by simply adding more stacks in series to achieve the desired water purity.

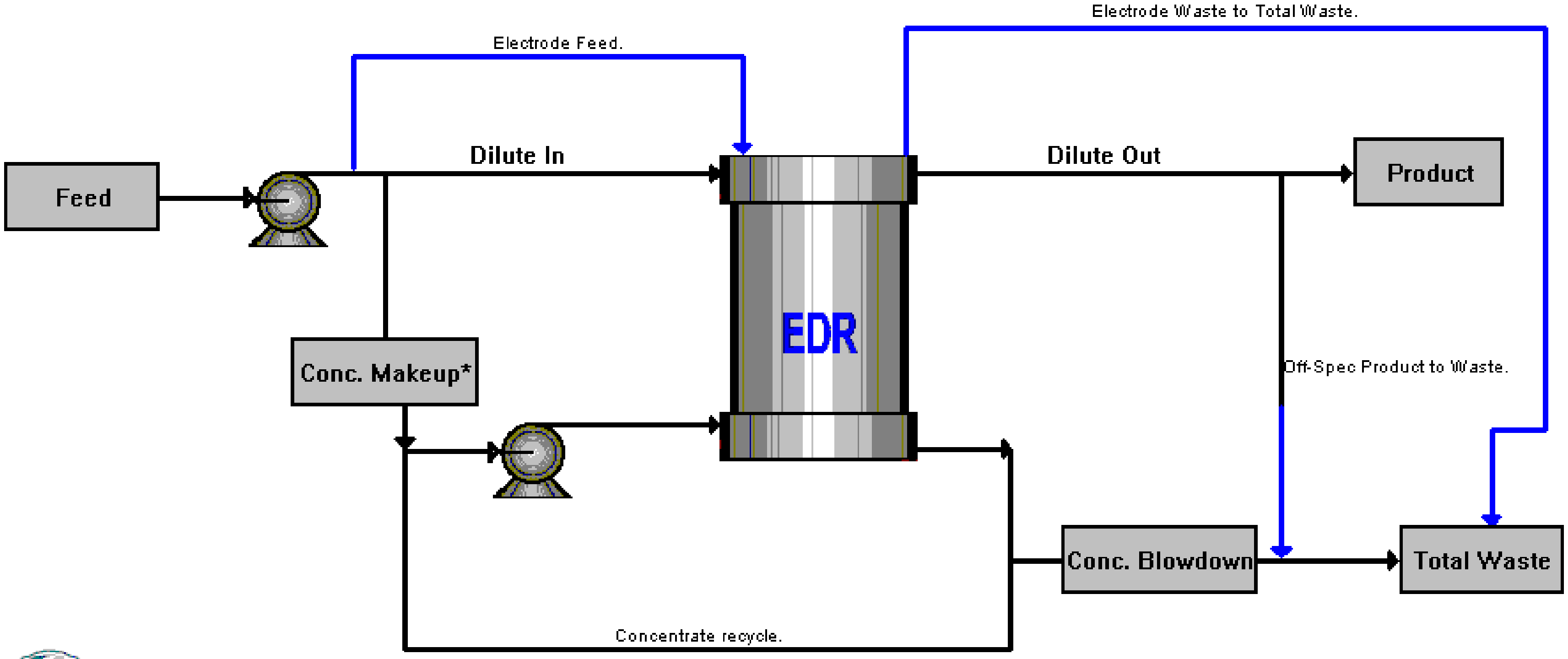

Figure 5: EDR Process Flow Diagram

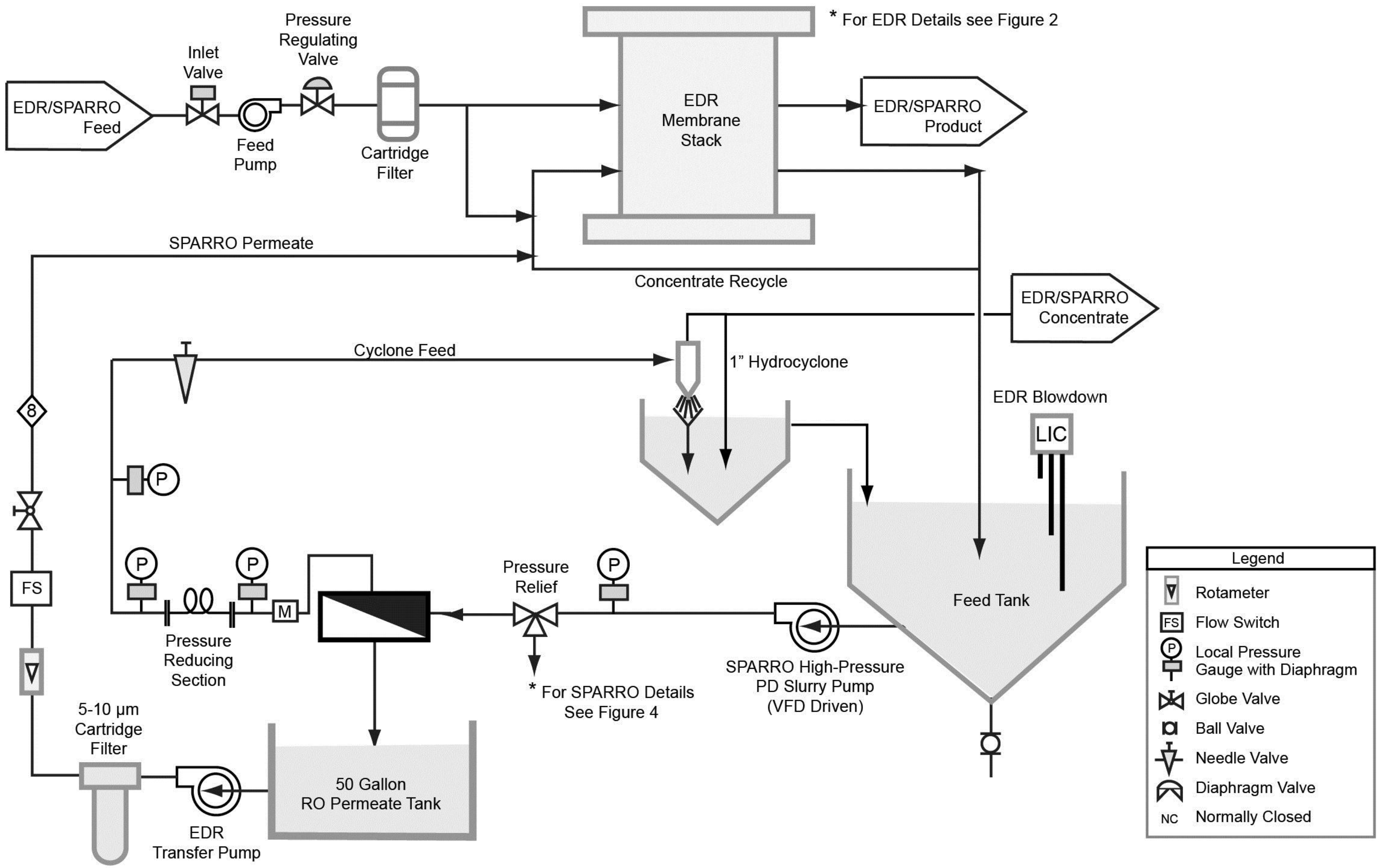

Figure 6: EDR and SPARRO Combined Process Flow Diagram

4. Pilot Study Process and Equipment Description

4.1 Pilot Study Process

4.1.1 Water Quality

This pilot study was conducted at the Temescal Desalter using RO reject water as feed water for the EDR pilot. The quality of this reject water, shown below in Table 1, was used to determine the EDR design in the WATSYS. Also shown in this table are predicted values for product water, concentrate blowdown, and waste. These measurements were taken before the study began.

Table 1: Water Quality

Parameter	Units	Raw Water Value	Product	Concentrate BD	Waste
Calcium	mg/l	720.0	94.9	2160.8	1657.7
Magnesium	mg/l	180.0	28.2	530.4	407.8
Sodium	mg/l	566.4	149.6	1534.2	1191.7
Potassium	mg/l	0.0	0.0	0.0	0.0
Strontium	mg/l	0.0	0.0	0.0	0.0
Barium	mg/l	0.0	0.0	0.0	0.0
Ammonia	mg/l	0.0	0.0	0.0	0.0
Bicarbonate	mg/l	1340.0	446.7	3424.1	2679.9
Sulphate	mg/l	1400.0	138.1	4303.9	3292.9
Chloride	mg/l	860.0	119.5	2567.3	1970.8
Fluoride	mg/l	0.0	0.0	0.0	0.0
Nitrate	mg/l	0.0	0.0	0.0	0.0
Total PO4	mg/l	0.0	0.0	0.0	0.0
HPO4	mg/l	0.0	0.0	0.0	0.0
H2PO4	mg/l	0.0	0.0	0.0	0.0
Silica	mgl	150.0	150.0	150.0	150.0
CO2	mgl	273.58	273.58	275.30	276.82
Carbonate	mgl	0.49	0.05	3.19	1.94
Total Hardness	CaCO3	2536.5	352.5	7571.9	5812.7
TDS	mg/l	5216.9	1126.9	14673.8	11352.7
Conductivity	uS/cm	5763.7	1333.8	14453.1	11516.2
pH		6.90	6.42	7.30	7.20

Throughout the course of this study, water samples were taken for: feed water, product water, and concentrate blowdown. These samples were sent out to a third party laboratory for analysis. Some simple tests and measurements were also performed on-site.

4.1.2 Description of Phases

The Corona pilot study was divided into three main phases: Phase I, Phase II, and Phase III. Each phase represented a run with specific operating conditions. A WATSYS was developed to outline preliminary operating parameters for each phase, shown below in Table 2. The operating conditions for all phases are discussed in detail in this section.

Table 2: Preliminary Operating Conditions

Parameter	Phase I	Phase II	Phase IIIa	Phase IIIb
Description	EDR optimization (operating alone)	EDR operating alone	EDR operating with SPARRO	EDR operating with SPARRO at lower flow
Dates	Feb 18 - March 15	March 26 – April 17	April 17 – May 28	May 29 – June 12
Duration	4 weeks	3 weeks	6 weeks	2 weeks
Applied Voltage	56 V / 47 V	56 V / 47 V	56 V / 47 V	54 V / 45 V
Current	23.9 A / 13.6 A	23.9 A / 13.6 A	23.9 A / 13.6 A	22.4 A / 12.5 A
Cycle Time	15 min	15 min	15 min	15 min
Dilute Flow Rate	7.9 gpm	7.1 gpm	7.1 gpm	6.5 gpm
Product Flow Rate	7.5 gpm	6.8 gpm	6.8 gpm	6.2 gpm
Concentrate Make-up Flow	2.7 gpm	2.5 gpm	2.5 gpm (1.7 gpm with SPARRO product recycled)	2.3 gpm (1.5 gpm with SPARRO product recycled)
Concentrate Blowdown Flow	3.1 gpm	2.8 gpm	2.8 gpm	2.6 gpm
Recovery	60% (92% combined with RO)	60% (92% combined with RO)	60% (93% with RO and SPARRO recycle)	60% (93% with RO and SPARRO recycle)
ECIP Chemicals	1/3 gal HCl (18%) every 8 hrs	1/3 gal HCl (18%) every 8 hrs	1/3 gal HCl (18%) every 8 hrs	1/3 gal HCl (18%) every 8 hrs
Clean in Place (CIP)	In between phases (ie. monthly).			

In Phase I the WATSYS design operating parameters were adjusted to optimize the EDR pilot performance and recovery.

Phase II of the pilot study involved the EDR pilot operating as a stand-alone process under the optimized conditions from Phase I, treating RO reject water from the Temescal Desalter. The purpose of this phase was to establish a baseline with which to compare results of the EDR operating in conjunction with the SPARRO system.

During Phase IIIa the EDR pilot continued to operate under the same condition as it did in Phase II. The only difference was that during this phase the SPARRO was operating and processing the EDR reject as feed water. The SPARRO was returning product water back to the EDR as concentrate make-up for periods of a couple of days at a time. During the periods in which the SPARRO was returning product water to the EDR, the make-up flow from the EDR feed water was reduced by 0.8 gpm, as a result.

Phase IIIb was introduced as an extension of Phase IIIa with reduced flow. A new WATSYS design analysis was run with reduced flows since the feed and concentrate pumps were running above 90%. At the beginning of the study the pumps were running at a lower pump speed. These pump speeds likely increased due to the higher pressures that resulted from scale deposits on the inside of the pipes as shown in Figure 7.

Figure 7: Scale Deposits in Concentrate Piping

From the beginning of Phase II, the pilot was run continuously for three and a half months with only a few minor shut-downs.

4.2 Pilot Equipment Description

GE W&PT supplied the EDR pilot unit to demonstrate treated water quality and to collect operational data for full-scale design. During the study GE W&PT used one membrane stack with two electrical phases, four hydraulic stages, and a total of 160 cell pairs. The unit is automated with all the necessary components to perform operating procedures used by full-scale EDR treatment plants.

The pilot operated in auto mode with the SCADA system. The service person was required to replace cartridge filters located on the EDR pilot before the EDR stacks depending on fouling. Also it was necessary to clean membranes during the pilot study in auto or manual mode.

Table 3: Electrical Requirements

Electrical Requirements	
# of Lines	1
# of Stages	2 electrical, 4 hydraulic
Cell pairs	35/45 // 35/45
Applied Voltage (V)	56/47
Current (Amps)	23.9/13.6
Surge (Amps)	34.7/39.1

5. Discussion – Operational Results and Membrane Performance

The following section provides graphs and explanation of operational results from Phase II and Phase III.

5.1 Pressure

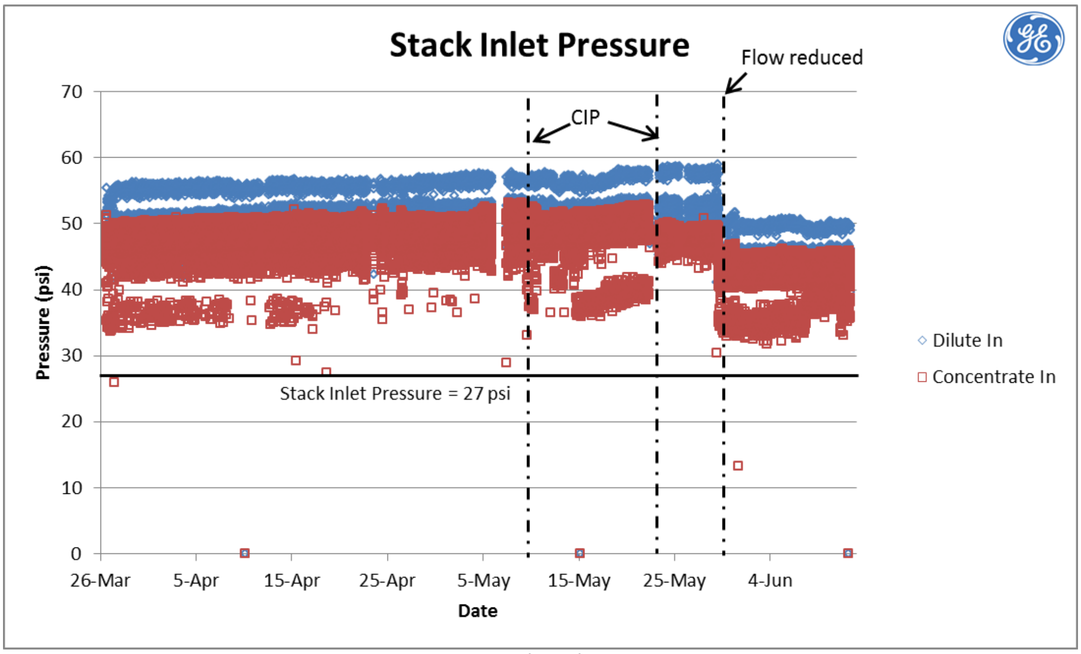

Figure 8: Stack Inlet Pressure

Figure 8 shows the stack inlet pressures in both the dilute and concentrate streams. Figure 9 shows the stack outlet pressures in dilute and concentrate streams. In both figures the dilute streams are represented by blue dots while the concentrate streams are represented with red dots. The WATSYS design program predicts the stack pressures based on system flows and the number of cell pairs. The predicted stack inlet and outlet pressures are shown on the graphs above with a black line.

The stack inlet pressures are expected to remain constant throughout the pilot operation. Any increase of these pressures indicates the precipitation of organic or inorganic components or deposition of solids in the membrane stack or in the downstream piping. Only a slight increase of pressure was observed on the stack inlet and these pressures dropped back down after cleaning (CIP).

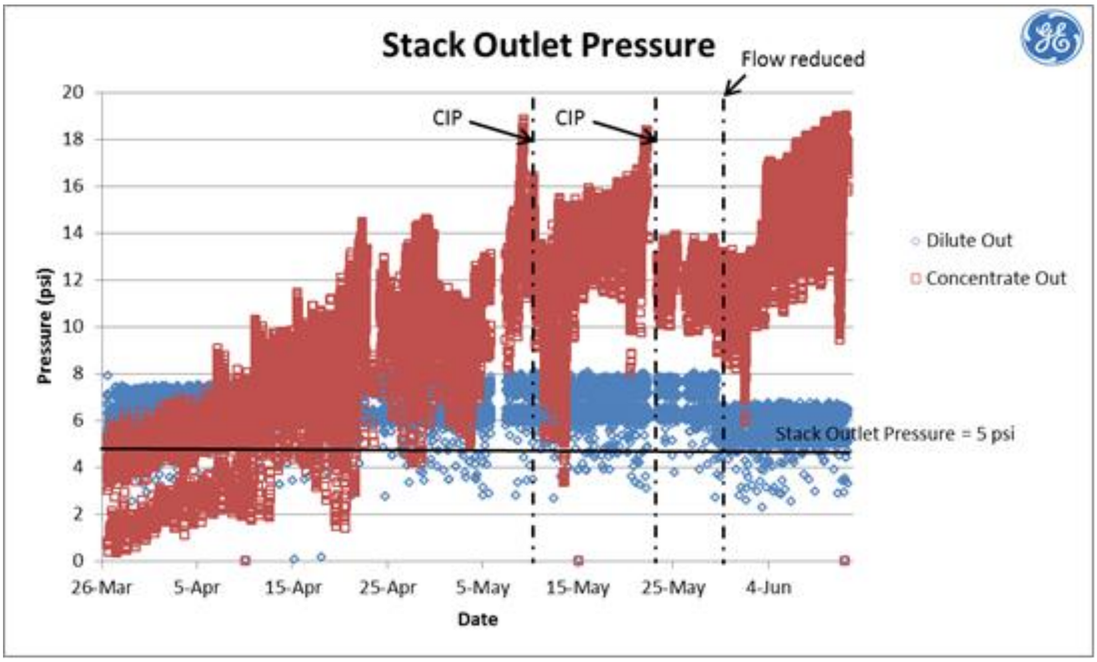

Figure 9: Stack Outlet Pressure

On the outlet side of the stack, the increase in concentrate stream pressure was quite drastic. However, it is likely that the pressure transmitter was reading a higher value than the actual pressure in the concentrate line. This was probably due to scaling on the pressure transmitter sensor, depicted below in Figure 10. As further proof of this faulty reading, it was noted at one point in the study that the pressure transmitter was reading 8 psi when the pilot was off (the pressure in that line should have been reading zero). Additionally, if the pressure on the outlet side of the stack were increasing, a corresponding rise in stack inlet pressure would also be expected, which was not observed in this case.

Figure 10: Inside of Concentrate Outlet Pressure Transmitter

The differential pressures between the dilute and concentrate streams are shown in Figure 11 below. The differential pressure at the stack inlet is shown in purple, while the differential pressure at the stack outlet is in green. It is common practice to maintain slightly higher pressure on the dilute stream compared to the concentrate stream of the EDR process. This insures that if there are any physical leaks, the product streams will leak into the concentrate stream to prevent the concentrate from contaminating the product stream. In this graph, positive differential pressures indicate that the dilute stream pressure is higher than the concentrate stream pressure, as desired. The inlet differential pressure was well maintained above zero throughout the pilot. The outlet differential pressure dropped down below zero due to the false high pressure readings for the concentrate outlet stream pressure.

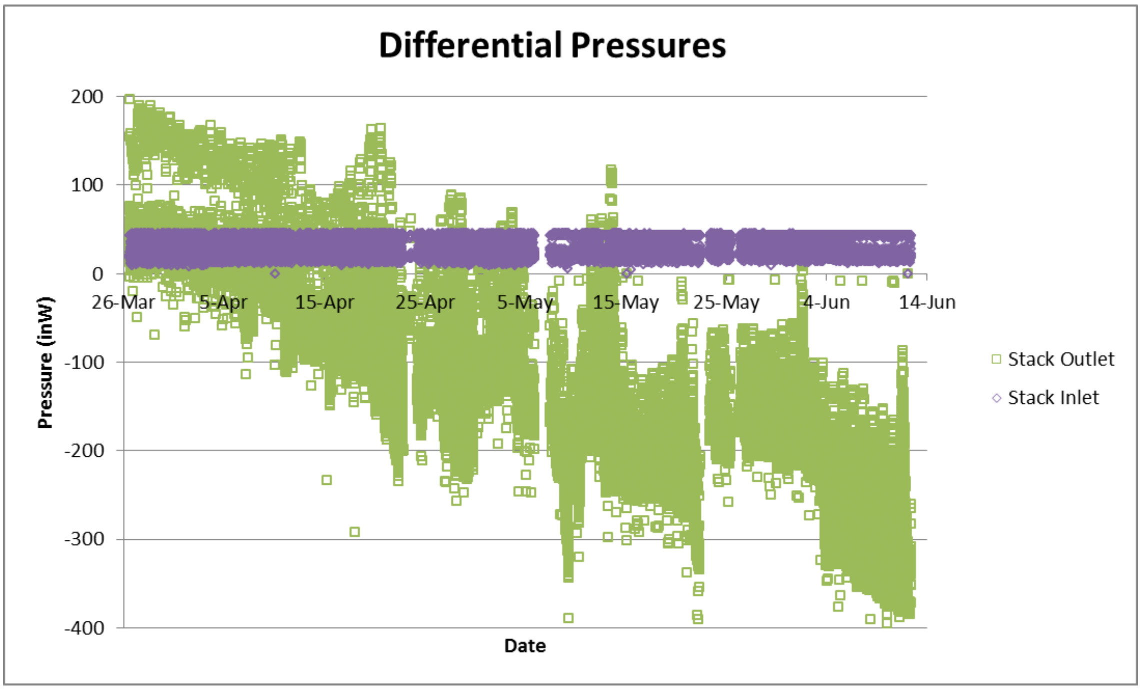

Figure 11: Differential Pressures Between Dilute and Concentrate Streams

The final pressure measured was the pressure across the cartridge filter, shown below in Figure 12. The pressure transmitters from which this differential pressure is measured are directly on either side of the cartridge filter. The purpose of the 10 micron cartridge filter is to prevent any larger particles from damaging the membrane stack.

Theoretically, a pressure drop of 15 psi across the cartridge filter indicates that significant fouling has occurred and the filter should be replaced. Over the course of this study there was minimal increase in the pressure drop across the cartridge filter, showing only a slight spike in pressure April 27. The difference in pressure did not exceed the threshold of 15 psi, however the filter was still replaced on May 5 with a smaller pore size filter (1 micron) to help protect the membranes in the downstream SPARRO process.

The cartridge filter was removed at the beginning of the testing period, after the one month optimization phase (Phase I) and did not show significant fouling. Figure 13 below shows the filter on March 26.

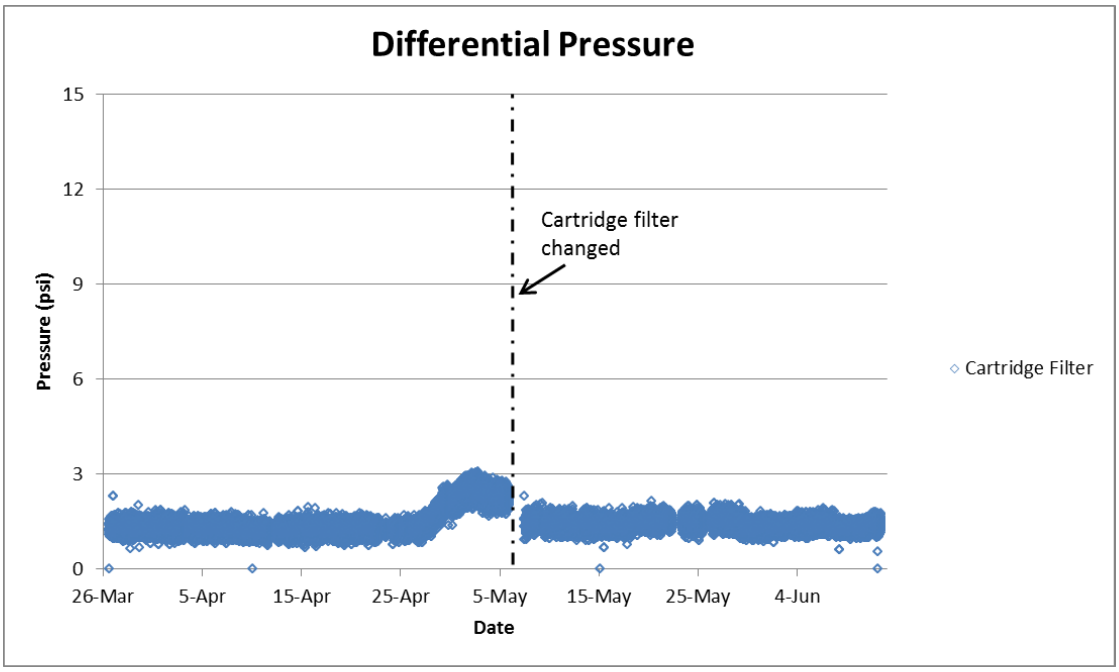

Figure 12: Cartridge Filter Pressure

Figure 13: Used Cartridge Filter (March 26)

5.2 Flow Rates

The EDR pilot system flows are represented in Figure 14 and Figure 15 below. The red dots indicate the dilute-out flow from the EDR pilot which was initially set to 6.8 gpm and later reduced to 6.2 gpm. The dilute-out flow represents product water and off-spec water. The concentrate blow-down flow is show in green on the graph below. This flow was set to 2.8 gpm and adjusted to 2.6 gpm later. Both flows mentioned above are controlled by either pump or valve PID loops and therefore remain constant at the set value throughout the study.

The concentrate make-up flow is plotted in blue below in Figure 14. The WATSYS predicted value for this flow was 2.5 gpm and was later reduced to 2.3 gpm. Occasionally the product water from the SPARRO pilot was recycled back into this stream, reducing the amount of make-up flow required from the EDR feed by about 1 gpm. This change is reflected on the graph below by the boxes labeled "SPARRO on".

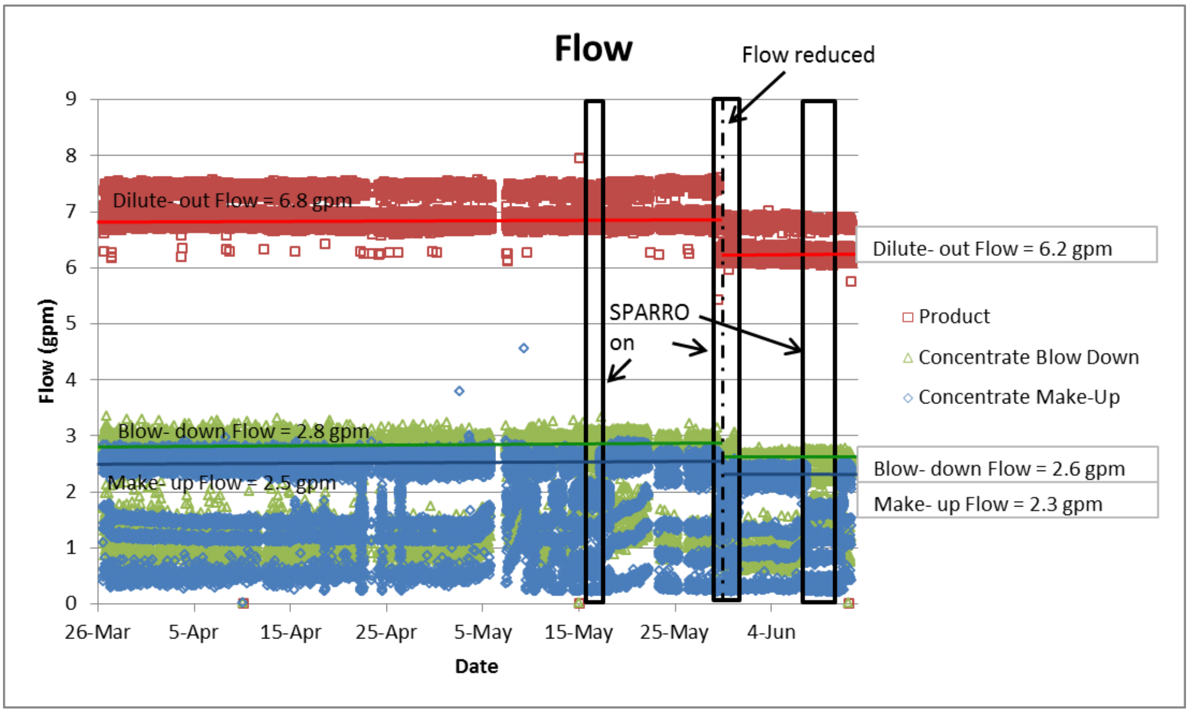

Figure 14: EDR Pilot Flow Rates

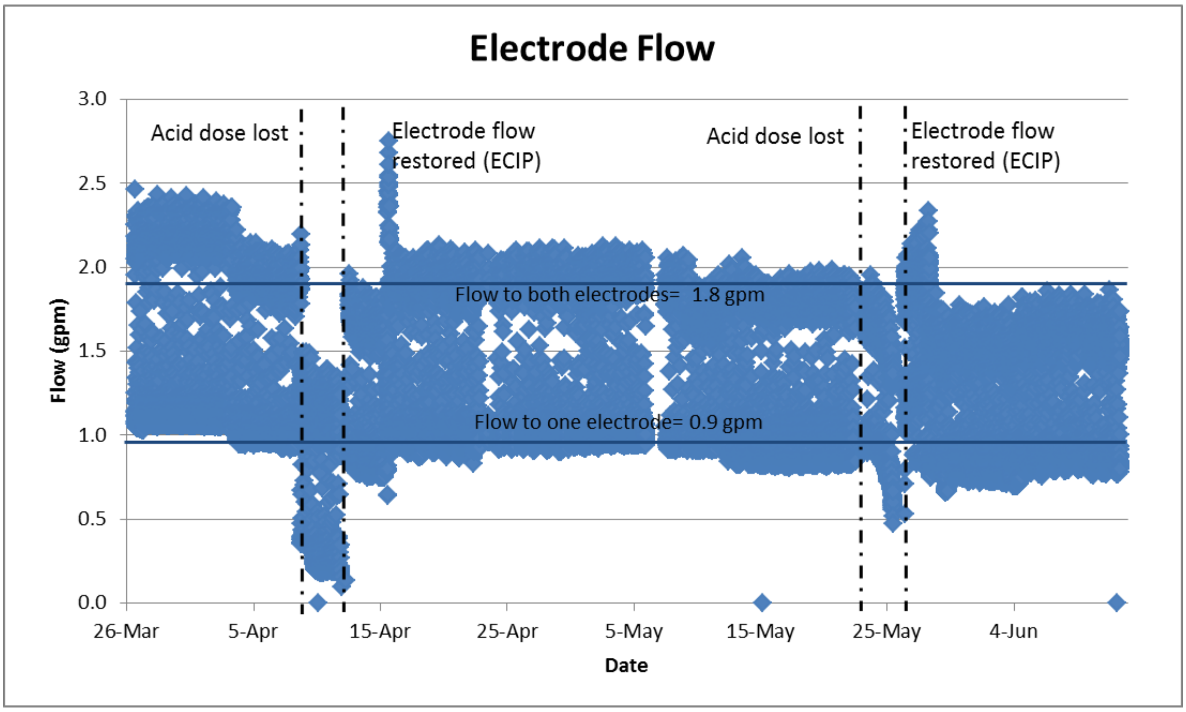

Figure 15: Electrode Flow Rates

The flow to the electrodes was recorded, shown above in Figure 15. During regular operations the flow to one electrodes stays on while the flow to the other electrode bumps on and off intermittently. This flow acts as a continuous cleaning mechanism for any gases or particles that build up on the electrode surfaces during operations. Additionally, an electrode clean-in-place (ECIP), during which hydrochloric acid is dosed into this stream, occurs every 8 hours to improve the cleaning process. This flow cannot be allowed to drop below 0.5 gpm because at this point the self cleaning mechanism becomes ineffective and scale can build up quickly on electrode surfaces.

The reccomended WATSYS design values for the electrode flow was 0.9 gpm to one electrode and 1.8 gpm when both electrodes flows turned on. These flows are marked on the graph above. Due to difficulties keeping acid docing pumps primed, the electrode flow both showed significant scaling twice over the course of the study. Once the ECIP's stopped occuring, scale built up quickly blocking electrode flow paths and reducing the flow below the 0.5 gpm limit. The first time this happened the stack was taken apart and the electrode flow spacer was cleared out to clear out the scale build-up. Figure 16 below shows the white scale that was built up in the electrode flow spacer.

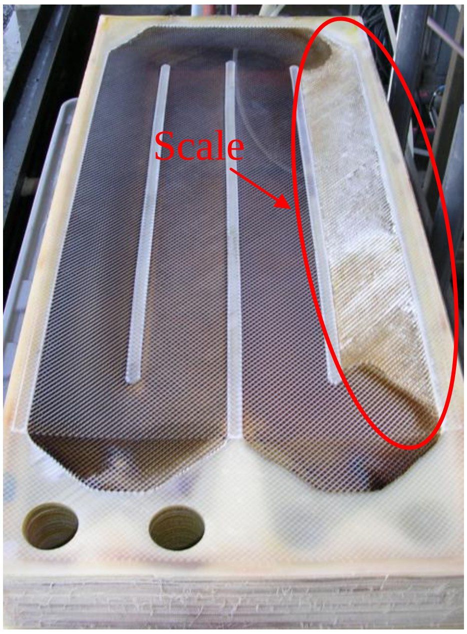

Figure 16: Electrode Flow Spacer Scale Build-up

5.3 Voltage and Current of Electrical Stages

Figure 17 shows the EDR pilot voltage, while Figure 18 shows current in the two electrical stages throughout the study. The EDR pilot was comprised of only one stack and 4 hydraulic stages; consisting of a total of 160 cell pairs. A cell pair consists of an anion membrane with a spacer and a cation membrane with a spacer.

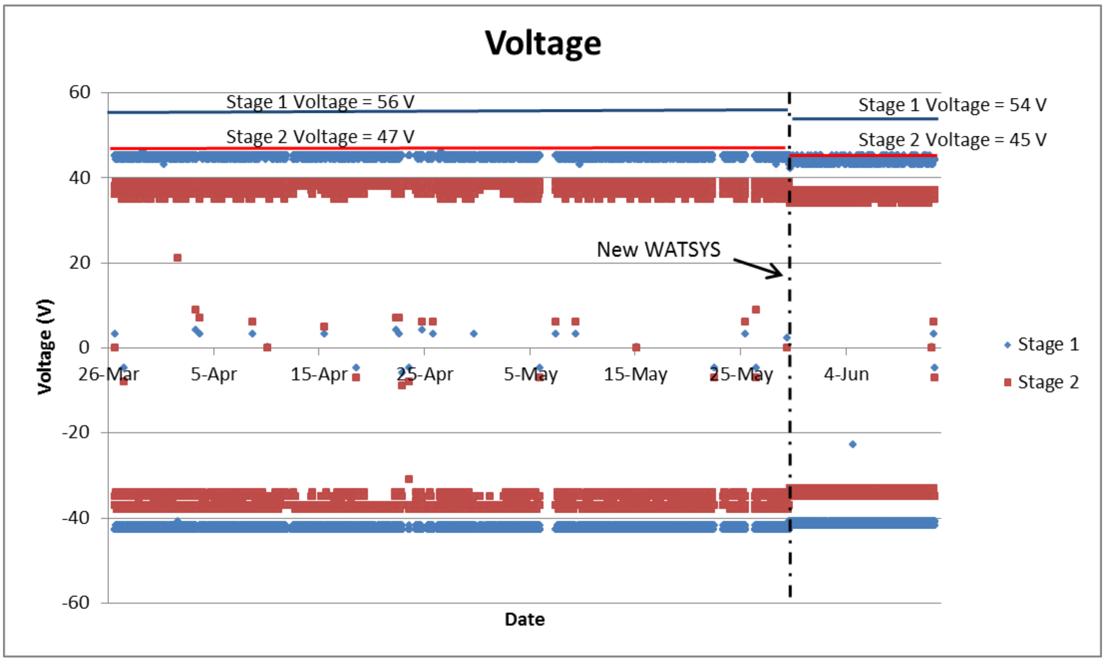

Figure 17: EDR Pilot Voltage

The transport of ions is driven by the applied electrical DC voltage. The higher this voltage, the higher the DC current is, and the greater amount of ions removed from the product water. However, the voltage cannot be increased infinitely. Extreme voltage causes polarization which leads to electrochemically induced scaling and fouling.

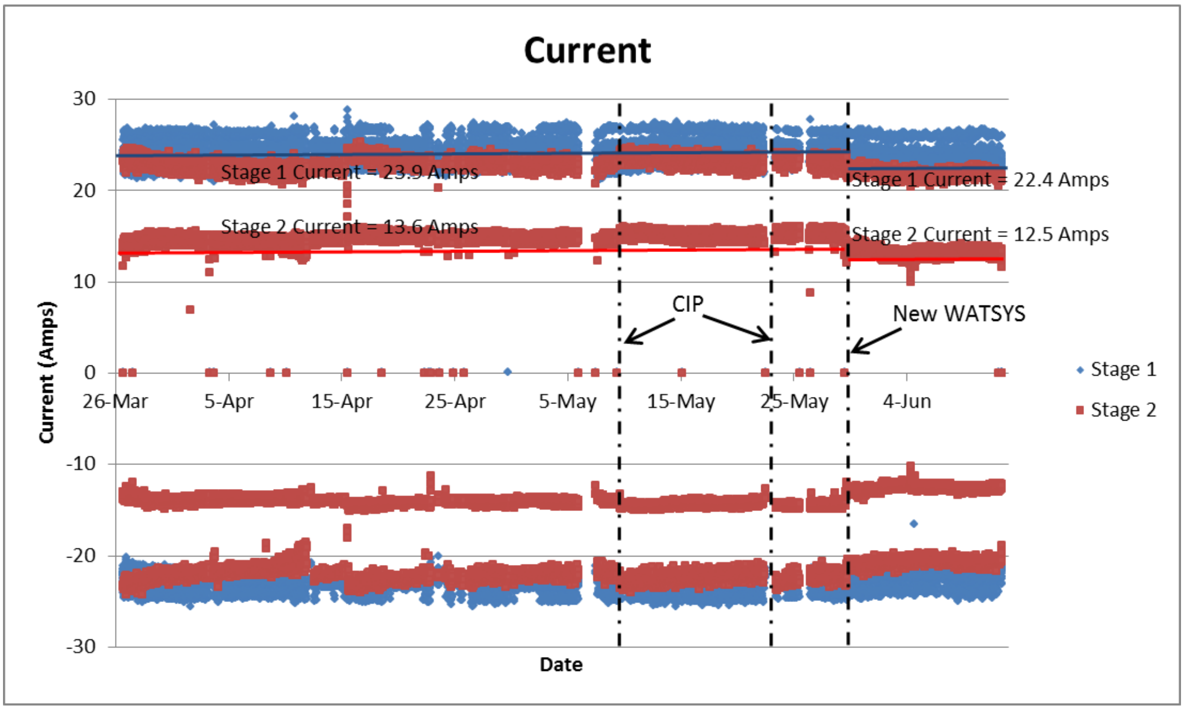

Figure 18: EDR Pilot Current

Current is the transport of ionized salts in the EDR desalination process. Analogous to electricity, changes in current are related to changes in electrical resistance. An important aspect of piloting is observation of development of electrical resistance (drop in current) from fouling. Foulants can deposit on the membrane surface as ions are transported through the membranes. Accumulation of deposits leads to increase in electrical resistance which is observed as a drop in current and a loss in product quality (less current transports less ionized salts). Accordingly, an increasing amount of voltage must be applied to induce the same current.

Since the current is what causes the removal of ions, the voltage should be adjusted accordingly to reach the suggested design current. The WATSYS design recommended currents and voltages are labeled on the graphs above. The graph in Figure 18 above shows that the currents remained relatively constant throughout the course of the study. This means there has been no evidence of membrane fouling effecting current, electrical resistance or product quality. Any slight drop in current that was observed during operations was recovered with CIP's (marked on the graph).

6. Discussion – Water Quality Results

The EDR pilot operated onsite from January to June. The intention of the customer was to treat the Temescal Desalter RO's reject with the EDR and SPARRO pilots to remove salts and other ions. The analytical results which are presented by the following graphs show the effectiveness of the EDR system at removing certain ions.

As it can be seen from the analytical results below, the EDR pilot showed consistent ion removal and product water quality.

6.1 Conductivity

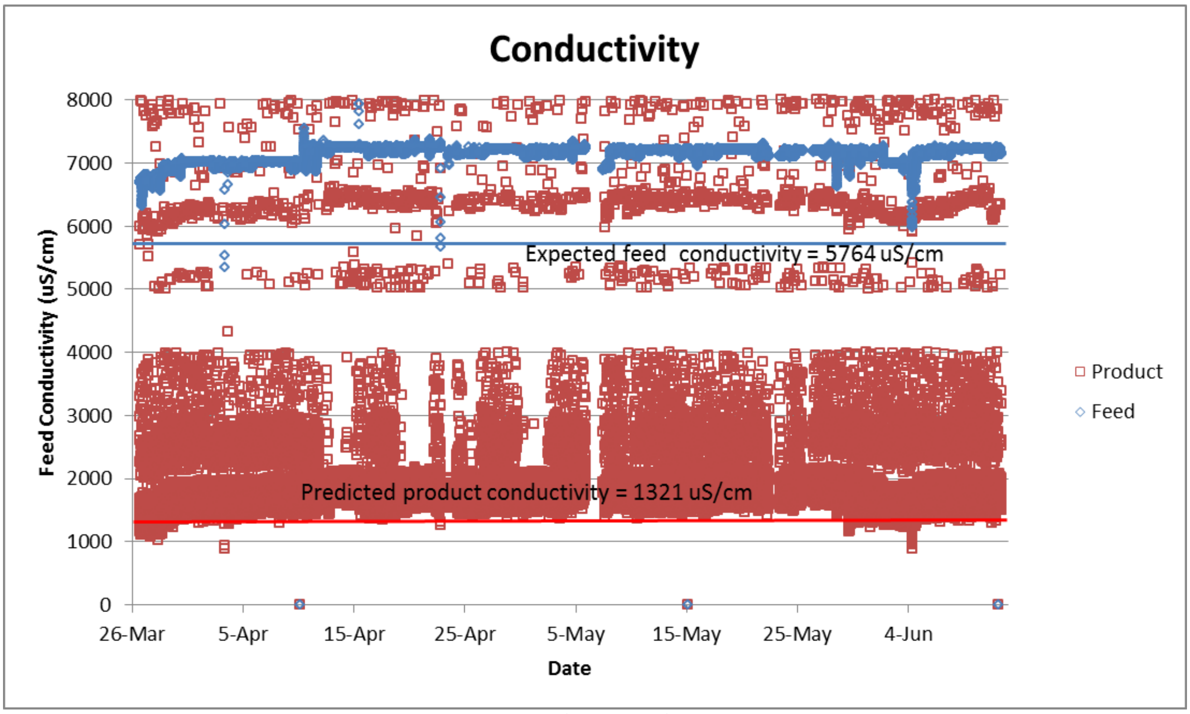

Figure 19: EDR Pilot Conductivity

In Figure 19, the blue dots show the conductivity of the feed water. The conductivity of the EDR product is shown by the dark blue dots. During the pilot study, the feed conductivity was stable around 7000 uS/cm. The product water conductivity varied from 1500 – 2000 uS/cm. The EDR system has therefore consistently produced product water of conductivity just above the predicted level of 1321 uS/cm. There are some anomalies in the product water conductivity shown in the figure above. These anomalies are attributed to times when the conductivity was recorded immediately after a polarity reversal, when the water would have been redirected to off-spec. It is important to note that at conductivities above 3000 uS/cm the water was automatically treated as off-spec and redirected into the waste stream to ensure constant low conductivities in the product water.

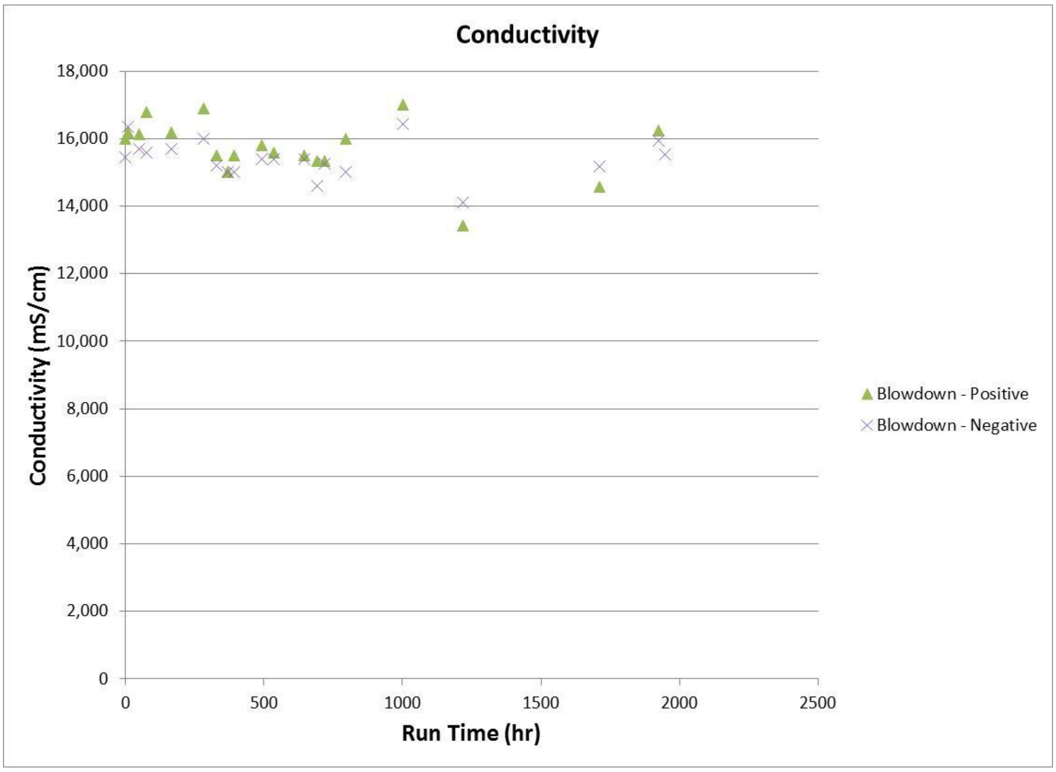

Figure 20: EDR Pilot Concentrate Conductivity

Concentrate conductivity is an important measure of overall recovery that can be achieved in a full scale EDR plant. According to the WATSYS design the target conductivity of the concentrate water coming out of the stack was 14,669uS/cm. It proved difficult to monitor concentrate stream conductivity due to the highly scaling nature of the water and scale deposits on the probes. Concentrate stream conductivity was measured manually and was found to be in the range of 15,000 – 17,000 uS/cm as shown above in Figure 20.

6.2 Temperature

The EDR membranes can stand the maximum temperature of 100˚F. However this should not be the temperature of influent water because the temperature in the stack tends to increase during treatment. Feed water temperature was recorded remotely and is shown in the graph above. The water temperature remained constant between 73 and 75°C throughout the study.

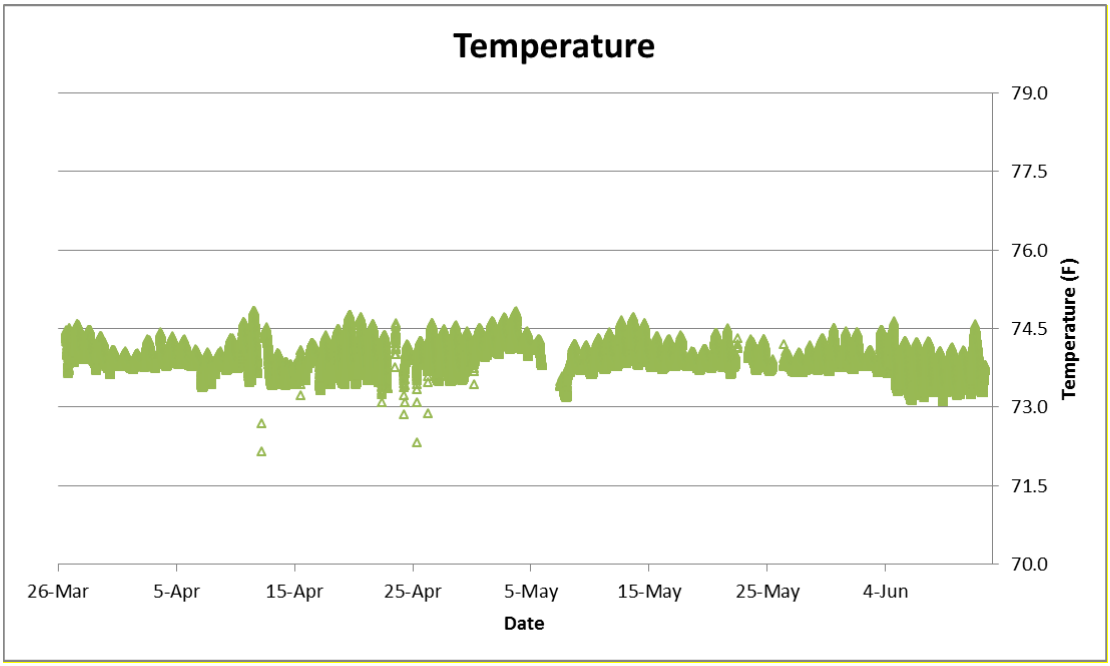

Figure 21: EDR Pilot Temperature

6.3 pH

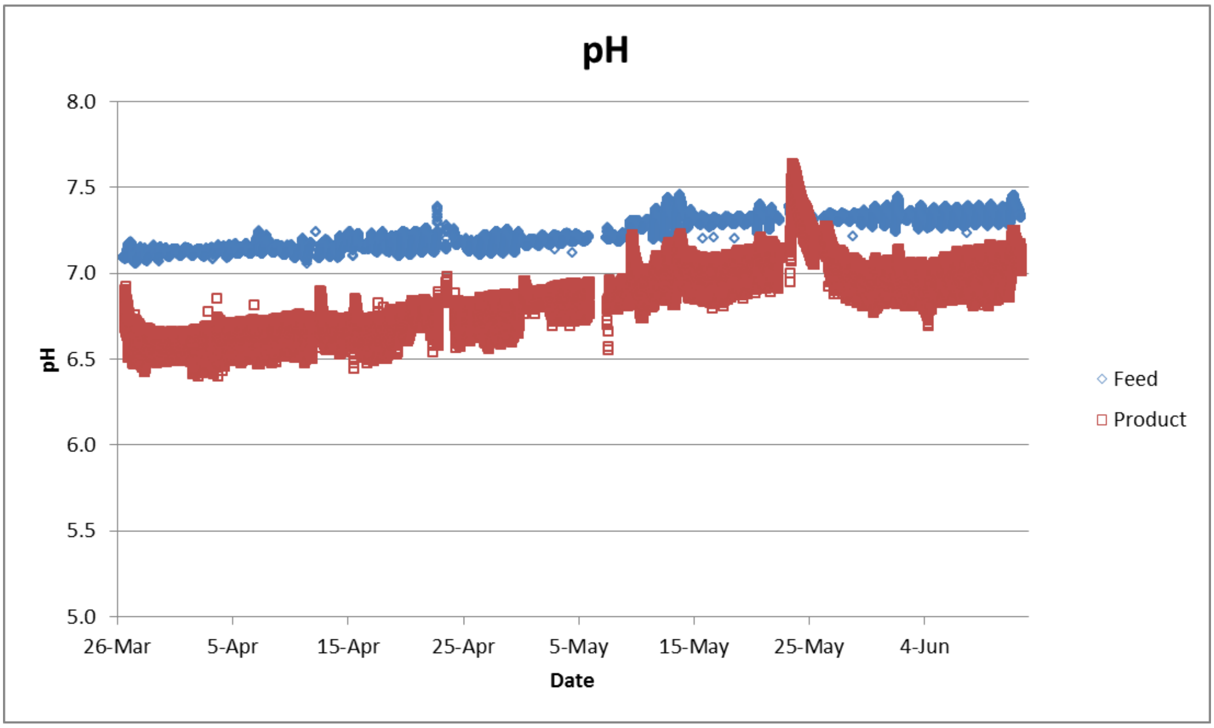

Figure 22: EDR Pilot pH

The blue dots in Figure 22 are EDR feed pH which was between 7 and 7.5 throughout the entire pilot study. The product pH, shown in red, was between 6.5 and 7.5. Both the feed and product pH remained consistent throughout the study.

In order to operate the EDR process smoothly it is necessary to dose hydrochloric acid (HCl) into the electrode feed periodically and the concentrate stream continuously for control of calcium carbonate scaling. This dosing would have decreased concentrate stream pH. The highly concentrated EDR concentrate stream pH was not recorded accurately due to scale deposits on the probe. Handheld readings for all three streams were taken and are graphed below.

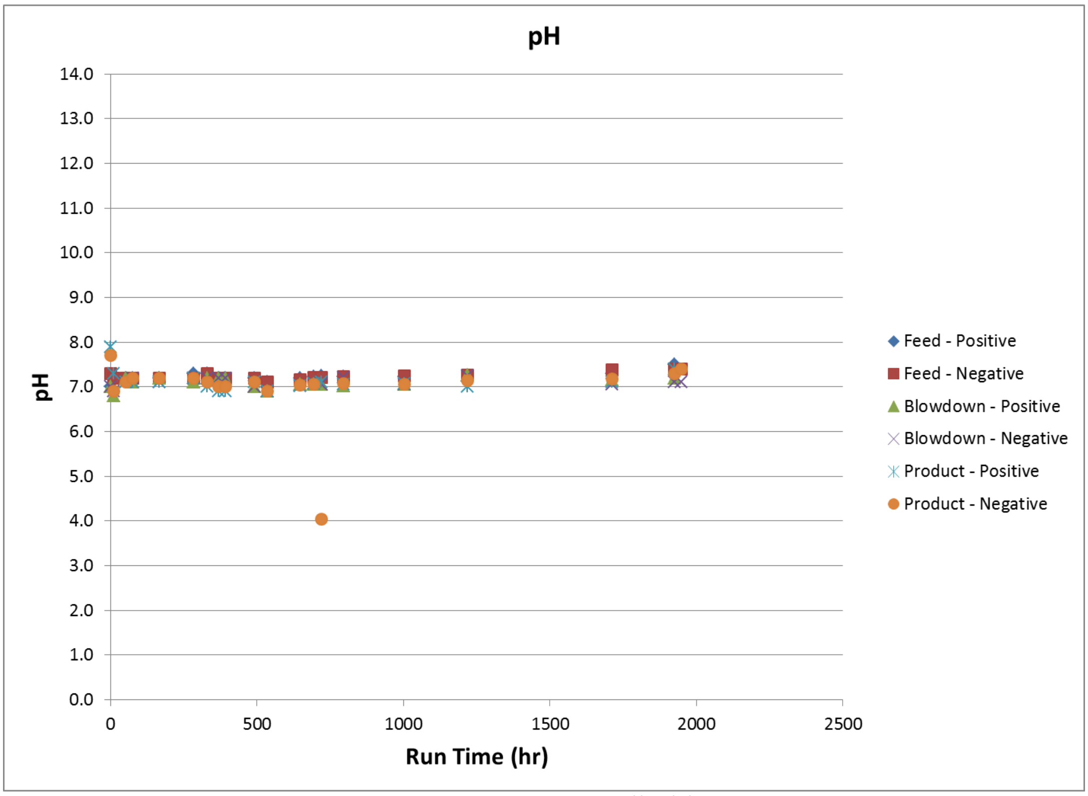

Figure 23: EDR Handheld pH

7. Cleaning

The main purpose of a clean-in-place (CIP) for an EDR system is to remove organic and inorganic foulants/scalants from the surface of the membranes, membrane spacers and piping. The results of a successful CIP will show restored pressures and/or current. It is typical in a full scale system to perform CIP's on a regular basis as preventative maintenance. For this pilot study three CIP's were performed on an "as needed" basis. The main goal of these CIP's in was to reduce stack outlet pressures. The results for the CIP's are shown in the graphs below in terms of stack outlet pressure. No significant change in current or stack inlet pressures were observed during operation or as a result of a CIP.

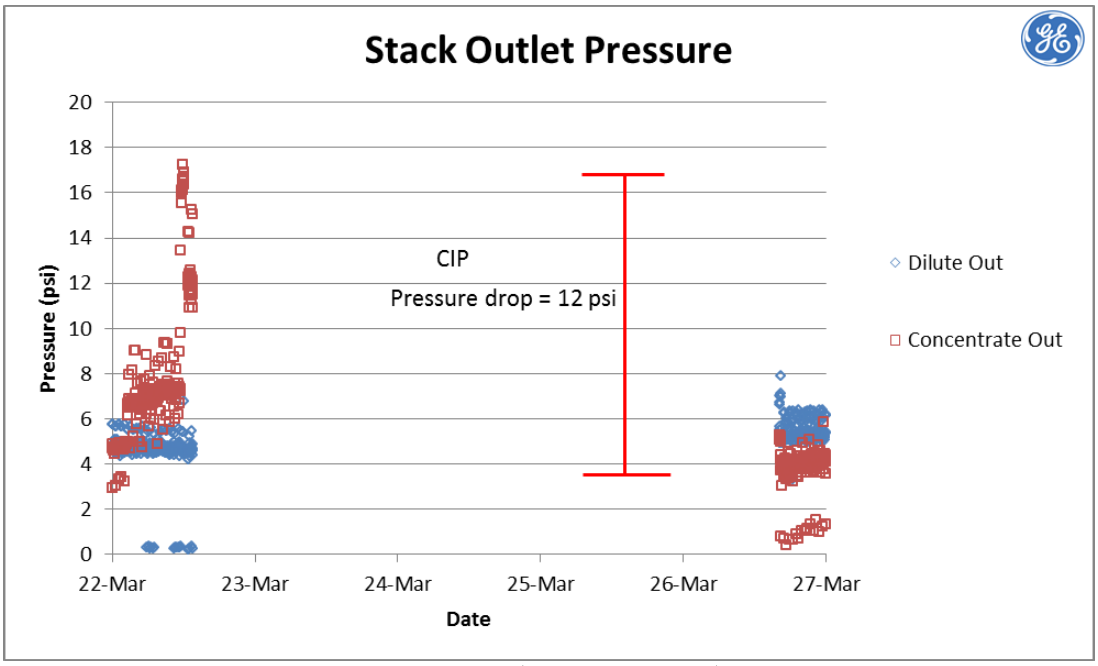

Figure 24: Phase I CIP Results

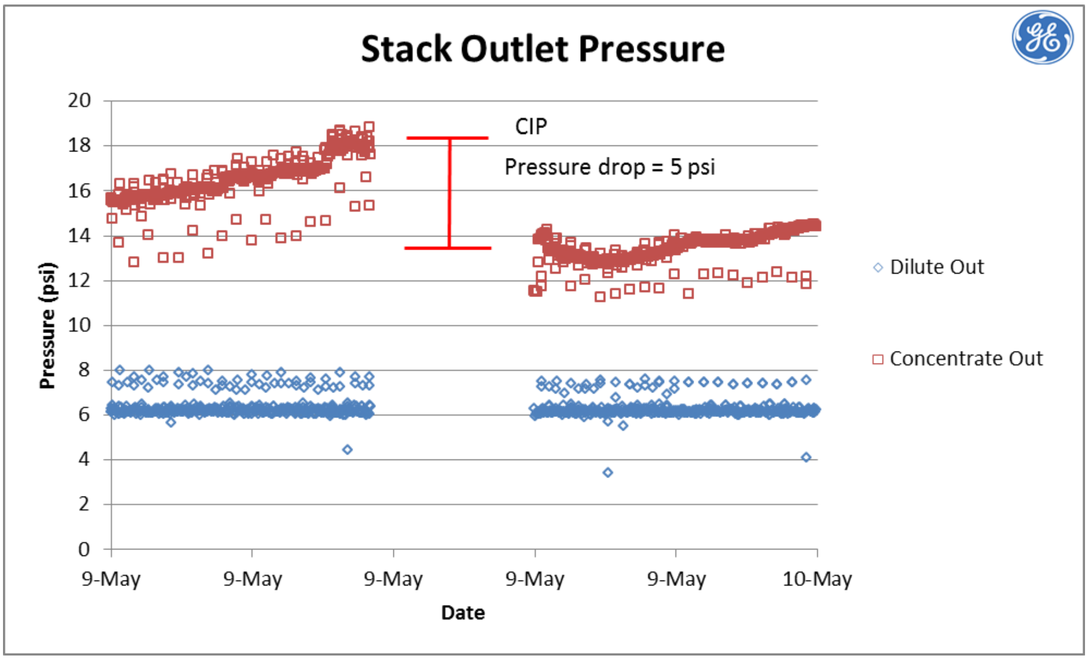

Figure 25: Phase IIIa CIP Results

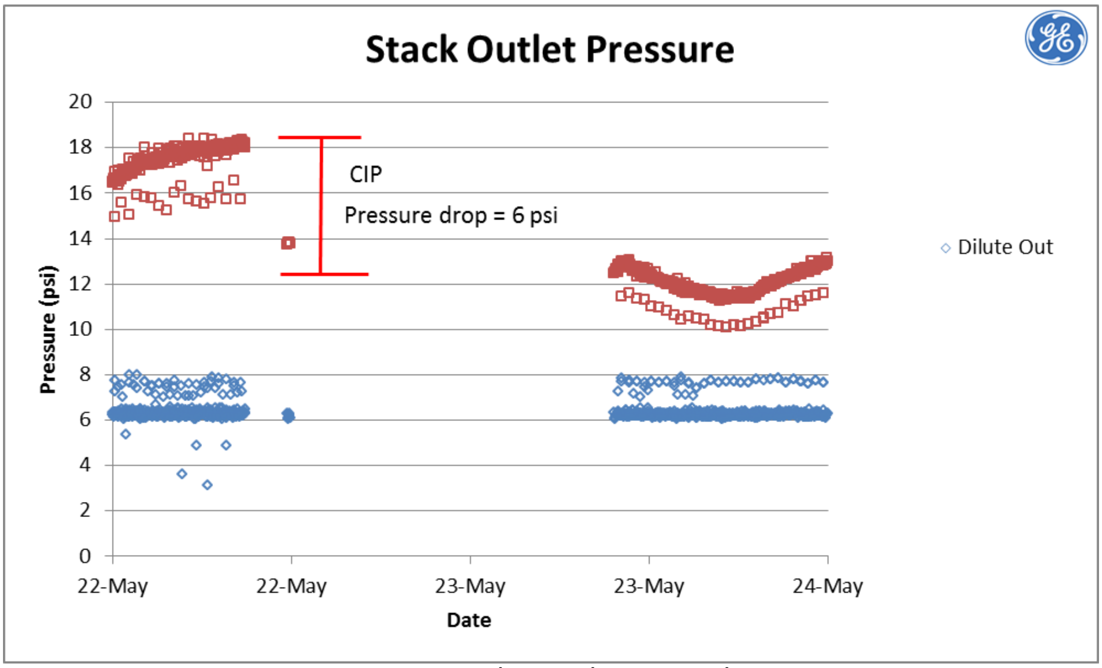

Figure 26: Phase IIIb CIP Results

Overall, the CIP's performed proved to be effective in reducing the stack outlet pressure.

8. Conclusions

The following section highlights the conclusions that can be drawn from the EDR pilot study in Corona, CA.

- Stable EDR membrane performance was demonstrated throughout the pilot study. The inlet pressure did not increase significantly, nor did the current drop, indicating that little fouling occurred. The product water conductivity remained stable between 1500 and 2000 uS/cm, just above the predicted level. Optimal design parameters were determined in Phase I.
- The EDR pilot operated at a recovery of 60% alone. The total system recovery when combined with the RO system was 92%. This total system recovery was further increased to 93% in Phase III, with the addition of the SPARRO pilot.
- An electrode clean in place (ECIP) was performed every 8 hours of operation using an 18% HCl solution. Hydrochloric acid and antiscalant were also dosed into the concentrate stream to control scaling. The pilot study does not indicate optimum chemical usages for a full scale EDR system.
- The clean-in-place (CIP) process was performed three times during the pilot study. The CIP proved effective at reducing the stack outlet pressure. The pilot study does not indicate optimum system run lengths between CIP for a full scale EDR system.

EDR Water Treatment System showed stable operating conditions and product water quality at a system recovery of 60%. This means that an EDR system is suitable to treat the Temescal Desalter RO reject water to improve total system recovery. The overall system recovery that was demonstrated was at 93%.

Appendix C

DETAILED COST ESTIMATE

Carollo Engineers...Working Wonders With Water™

USBR EDR/SPARRO PILOT

Cost Constants:

-	Hydrochloric Acid ($/lb)		$0.11	
-	Antiscalant ($/lb)		$1.00	
-	Sulfuric Acid ($/lb)		$0.08	
-	SPARRO Cleaning Chemicals ($/lb)		$3.50	
-	EDR Membrane Replacement Cost ($/1000 gal)		$0.20	
-	SPARRO Membrane Replacement Cost ($/1000 gal)		$0.95	Assume 2 year membrane life
-	Cost of Sludge Disposal, ($/t)		$55.00	From Market Survey
-	Electrical Power ($/kWh)		$0.13	
-	EDR/SPARRO Building sq ft est., sq ft/mgd		3000.00	
-	EDR Building Cost, $/sq ft		$250.00	

EDR/SPARRO Facility Flowrates Treating 1 mgd of RO concentrate

-	EDR Feed Flow (gpm)		694	
-	EDR Feed Flow (mgd)		1.00	
-	EDR Product Flow (gpm)	83%	576	EDR/SPARRO Recovery at 83% per Pilot Study
-	EDR Product Flow (mgd)		0.83	
-	EDR Product Flow (AF/yr)		929	
-	EDR Blowdown (gpm)	63%	257	EDR Recovery at 63% per pilot study
-	EDR Blowdown (mgd)		0.37	
-	SPARRO Feed Flow (gpm)		295	EDR Blowdown plus Off-Spec Product
-	SPARRO Feed Flow (mgd)		0.42	
-	SPARRO Product Flow (gpm)	60%	177	SPARRO Recovery at 60% per pilot study
-	SPARRO Product Flow (mgd)		0.25	
-	SPARRO Concentrate (gpm)		118	
-	SPARRO Concentrate (mgd)		0.17	

EDR/SPARRO Desalination Facilities O&M Costs

<u>Electrodialysis Reversal</u>		
<u>EDR Power Cost</u>		
<u>EDR Feed Pump</u>		
- Average flowrate, (gpm)	694	
- Average delivery head, (psig)	50	Average Pressure during pilot
- Pump motor efficiency, %	95%	
- Pump efficiency, %	70%	
- Average pump power, Hp	28.9	
- Average pump power, kW	21.6	
- Electrical Cost for this Pump, $/year	**$25,852**	
<u>EDR Concentrate Loop Pump</u>		
- Average flowrate, (gpm)	694	
- Average delivery head, (psig)	50	Average Pressure during pilot
- Pump motor efficiency, %	95%	
- Pump efficiency, %	70%	
- Average pump power, Hp	28.9	
- Average pump power, kW	21.6	
- Electrical Cost for this Pump, $/year	**$25,852**	
Membrane Stack Power		
- Product Flowrate (gpm)	576	
- Membrane Stack Power (kWh/kgal)	6.6	From EDR Model
- Average power, kW/yr	1,998,190	
- Electrical Cost, $/year	**$259,765**	
<u>Chemicals (Antiscalant, cleaning solution etc):</u>		
- Hydrochloric Acid Addition		
- Usage (lb/day)	710	Estimated from EDR model and Pilot data
- Annual Cost ($/yr)	$28,507	
- Antiscalant Addition		
- Dose (mg/L)	20	From Pilot Study
- Usage (lb/day)	62	
- Annual Cost ($/yr)	$22,494	
- Annual Cost for RO Chemicals ($)	**$56,101**	Added 10% for Cartridge Filters
<u>Membrane Replacement and Parts:</u>		
- Annual Cost for Membranes ($)	**$60,551**	
<u>EDR O&M costs, $/yr</u>	**$428,121**	

SPARRO

SPARRO Power

SPARRO Feed Pump		Extrapolated from vendor information
- Average flowrate, (gpm)	295	
- Average delivery head, (psig)	400	From Pilot Study
- Pump motor efficiency, %	95%	
- Pump efficiency, %	65%	
- Average pump power, Hp	105.9	
- Average pump power, kW	79.0	
- Electrical Cost for this Pump, $/year	**$94,659**	
SPARRO Permeate Pump		
- Average flowrate, (gpm)	177	
- Average delivery head, (psig)	15	From Pilot Study
- Pump motor efficiency, %	95%	
- Pump efficiency, %	70%	
- Average pump power, Hp	2.2	
- Average pump power, kW	1.6	
- Electrical Cost for this Pump, $/year	**$1,978**	
SPARRO Tank Mixing		
- Pump motor efficiency, %	95%	
- Total Mixer power, Hp	10.0	
- Average pump power, kW	7.5	
- Electrical Cost for this Pump, $/year	**$8,939**	
Chemicals (Acid, cleaning solution etc):		
- Sulfuric Acid Addition		
- Dose (mg/L)	1250	Estimated based on EDR/SPARRO operating data.
- Usage (lb/day)	4424	
- Annual Cost ($/yr)	$129,190	
- Cleaning Chemicals		
- Usage (lb/yr)	5,400	Estimated as 4 chemical cleans per year
- Annual Cost ($/yr)	**$18,900**	
Membrane Replacement and Parts:		
- Annual Cost for Membranes ($)	**$88,365**	
SPARRO O&M costs, $/yr	**$342,031**	

Sludge disposal Costs			
-	Disposal Costs ($/AF)	$100	From Market Survey assuming giving solids away
-	Annual Cost of Disposal, $/yr	**$92,870**	
-	Labor and Staffing Cost		
	- Labor Cost per Hour ($/hr including benefits)	$48	
	- Total hours per year - Labor, hr	2,190	Assumes 6hr per day 365 days per year
	- Total Labor Costs per year, $/yr	**$104,573**	

-	Electrical Costs, $/yr	$417,045
-	Chemical Costs, $/yr	$199,091
-	Sludge Disposal, $/yr	$92,870
-	Membrane and Media Replacement, $/yr	$148,916
-	Labor and Staffing Costs, $/yr	$104,573
-	**Total O&M Cost, $/yr**	**$962,495**

EDR/SPARRO Desalination Facilities Capital Costs

Electrodialysis Reversal			
-	EDR System, $	$1,400,000	Quote from GE.
-	Installed Cost Factor	1.3	Estimated from GE quote
-	EDR System Installed Cost, $	**$1,820,000**	Includes installation, Electrical, and I&C. Does not include engineering and design costs.
SPARRO			
-	BC System, $	$1,800,000	Estimated from Pilot Quote
-	Installed Cost Factor	1.5	Installation factor
-	BC System Installed Cost, $	**$2,700,000**	Cost for total system installed.
Chemical Systems			
-	EDR Anti-Scalant System, $	$50,000	
-	Hydrochloric Acid System, $	$50,000	
-	Sulfuric Acid System, $	$50,000	
-	Chemical Systems Installed Cost, $	**$150,000**	
Buildings			
-	EDR Building, $	$622,102	1500 sq ft/mgd and $250/sq ft
-	Chemical Building, $	$225,000	1500 sq ft at $150/sq ft
-	Buildings Installed Cost, $	**$847,102**	

Subtotal Treatment systems, $		$4,520,000	
Subtotal Buildings and Storage, $		$847,102	
Subtotal Installed Cost, $		$5,367,102	
Subtotal for Electical est., $		$2,700,000	Some Equipment estimates include electrical
Subtotal for Instrumentation est., $		$2,700,000	Some Equipment Estimates include instrumentaion
Electrical, $	18%	$486,000	
Instrumentation, $	10%	$270,000	
Interconnecting Pipework, $	5%	$226,000	10% of treatment systems. Does not include buildings, Feed Tanks, and ponds.
Site Work, Civil	5%	$226,000	
Total Direct Cost, $		$6,575,102	
- Contingency	20%	$1,315,020	
Total Equipment Cost, $		$7,890,122	
- General Conditions	5%	$394,506	
- Contractor OH&P	12%	$946,815	
- Escalation to Mid-Point (%/year)	0%	$0	
- Sales Tax	8.75%	$287,661	
- Bid Market Allowance	0%	$0	
Total Estimated Construction Cost, $		**$9,519,103**	
- Engineering	0%	$0	
- Legal and Admin	0%	$0	
Estimated Project Cost ($)		**$9,519,103**	
Annual Cost of Capital:			
- Average Annual Interest Rate (%)		6%	
- Loan Period (years)		20	
- Annual Payment ($)		**$829,919**	
- Annual Payment ($/AF)		**$893.64**	
Summary:			
Capital Costs:			
- Project Cost		$9,519,103	
- Annual Cost		$829,919	
Operating Costs:			
- Chemicals, Power, Disposal		$962,495	
- Total Annual Operating Costs		**$962,495**	
Total Annual Costs		**$1,792,413**	
- $/AF		$1,930	