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14. ABSTRACT
Applied research was conducted on Counterflow Reverse Osmosis (CFRO), a membrane-based brine concentration/desalination method, with a pilot system constructed, installed and operated at a site in Saudi Arabia for this purpose. The pilot test demonstrated the ability of CFRO technology to reduce desalination costs by maximizing brine concentration and thereby minimizing brine flow with minimal energy. Specifically, the pilot system recovered up to 50% of the fresh water from an existing seawater desalination plant's brine waste stream while meeting the plant's water quality, cost, and energy consumption goals. Operating data collected from the pilot system and presented in this report quantifies performance, serves as proof-of-concept to facilitate commercial adoption of the technology and informs large-scale system design.

15. SUBJECT TERMS
Desalination, brine, brine concentration, reverse osmosis, CFRO

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Counter Flow Reverse Osmosis – Innovative Desalination Technology for Cost Effective Concentrate Management and Reduced Energy Use

Prepared for the Bureau of Reclamation Under Agreement No. R18AC00113

by

Richard Stover, Gradiant Osmotics

Mission Statements

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Disclaimer

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Acknowledgments

The Bureau of Reclamation's Desalination and Water Purification Research and Development Program sponsored this research.

SAWACO Water Desalination Company, established in Saudi Arabia under license by the Ministry of Water, hosted and operated the pilot unit.

Wigen Water Technologies constructed the pilot unit.

Gradiant Osmotics conducted design, procurement, fabrication management, factory acceptance testing, shipment, connection, startup and commissioning, operation management, optimization, and all reporting under this contract.

Acronyms and Abbreviations

CFRO	Counterflow reverse osmosis
CIP	Clean in place
ERD	Energy recovery device
KPI	Key performance parameters
ORP	Oxidation reduction potential
Precon RO	Preconcentrating reverse osmosis system, upstream of a CFRO system
Reclamation	Bureau of Reclamation
RO	Reverse osmosis
SMBS	Sodium metabisulfite
SWRO	Seawater reverse osmosis
TDS	Total dissolved solids

Measurements

°C	degree Centigrade
°F	degree Fahrenheit
μS/cm	micro Siemens per centimeter, a measure of conductivity
bar	unit of pressure
gpm	gallons per minute, a measure of flow rate
kWh/m^3	kilowatt hours per cubic meter of permeate, a measure of specific energy
m^3/d	cubic meters per day, a measure of flow rate
m^3/hr	cubic meters per hour, a measure of flow rate
mg/l	milligram per liter, a measure of concentration
MGD	million gallons per day, a measure of flow rate
mV	millivolts, a measure of oxidation reduction potential
NTU	normal turbidity units, a measure of degree of turbidity
psi	pounds per square inch, a measure of pressure

Metric Conversions

Unit	Metric equivalent
1 gallon	3.785 liters
1 gallon per minute	3.785 liters per minute
1 gallon per minute	0.227 cubic meters per hour
1 gallon per square foot of membrane area per day	40.74 liters per square meter per day
1 inch	2.54 centimeters
1 million gallons per day	3,785 cubic meters per day
1 pound per square inch	6.895 kilopascals
1 pound per square inch	0.0690 bar
1 square foot	0.093 square meters
°F (temperature measurement)	(°F–32) × 0.556 = °C
1 °F (temperature change or difference)	0.556 °C

Table of Contents

Figures

Tables

Executive Summary

Gradiant conducted applied research on counterflow reverse osmosis (CFRO), a membrane-based brine concentration/desalination method. The scope of the project included designing, building, installing and operating a pilot system that uses the technology. Bureau of Reclamation funding was used to offset some of the costs of fabrication, shipping, operation, and maintenance of the pilot system.

This project tested this novel desalination process at a sufficiently large scale to determine the technical, practical, and economic viability of the technology and thereby demonstrate its utility and practicality. Specifically, the pilot test demonstrated the ability of CFRO technology to reduce desalination costs at a seawater desalination plant in Jeddah, Saudi Arabia by maximizing brine concentration, and thereby minimizing brine flow, with minimal energy. Operating data collected from the pilot system are being used to quantify performance, serve as proof-of-concept to facilitate commercial adoption of the technology, and inform large-scale system design.

Site selection and system fabrication, shipment, startup and commissioning were completed in November 2019. The unit has operated continuously from then until July 2021. Operation included performance optimization and durability testing.

Performance data indicated that the pilot met most performance targets, including recovery rate, brine concentration, permeate purity, permeate flow, energy consumption, and uptime, demonstrating that CFRO technology effectively produces drinking water quality permeate from seawater reverse osmosis (SWRO) brine. Continuous automated operation of the pilot unit indicated that the process is reliable, requiring minimal operator engagement. Cost and performance data were extrapolated to full-scale plant size. Lessons learned during the project will benefit future CFRO process deployments.

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1. Introduction

Water scarcity is driving the development of alternative water resources, such as desalination and water reuse. Many industrial processes, including reverse osmosis (RO), the most widely applied treatment method, generate a substantial stream of brine concentrate that represents an environmental hazard and a significant cost. Typically, additional concentration of this brine is not possible with RO equipment due to the required pressures, which exceed equipment limitations. Existing brine concentration technologies require high capital costs and consume significant amounts of energy, and therefore are generally not affordable or practical. Disc tube RO and ultra-high-pressure RO can be operated at pressures of up to 1,800 psi (124 bar), and thereby concentrate up to 120,000 mg/l brine total dissolved solids (TDS), but membrane compaction necessitates a relatively high number of modules for a given flow rate, and the specialty pressure vessels, pumps and energy recovery devices necessary are either very expensive or unavailable.

CFRO is a membrane-based brine concentration process that can achieve brine concentrations of more than 250,000 mg/l TDS at feed pressures of less than 1,200 pounds per square inch (psi) feed pressure. Bench-top test data conducted by Gradiant were used to inform the design of a pilot system and predict its performance. The pilot system constructed to this design performed basically as expected. Its performance showed that the CFRO process could operate at costs comparable to greenfield seawater reverse osmosis (SWRO).

This report is focused on desalination of brine from an existing seawater desalination facility in which the CFRO process showed that it can double a plant's drinking water production without new intake, outfall, or pre-treatment costs or impacts. However, the results have implications for desalination of brine streams and minimization of waste brine flow rates at:

- Other existing seawater desalination facilities,
- New seawater desalination facilities,
- Inland groundwater desalination facilities,
- Industrial and municipal wastewater reuse facilities, and
- Industrial facilities in power, mining, textiles, electronics, pharmaceuticals, and food and beverage sectors.

For most of these applications, the ability to affordably desalinate brine streams means greater water use efficiency, reduced brine disposal costs, or both. This, in turn, can enable water treatment projects that were not previously feasible, provide new sources of fresh water supply and/or reduce environmental impacts associated with brine treatment or disposal.

This report is for water treatment plant planners, stakeholders, and decisionmakers to quickly understand that desalination of brine streams and minimization of waste brine production with this novel membrane-based process is not only feasible but also affordable and practical.

1.1. Project Background

SAWACO, one of Saudi Arabia's largest private potable water suppliers, owns and operates desalination plants that produce more than 30,000 m^3/day of fresh water in the Kingdom's western region. The fresh water they produce is used for everything from domestic consumption to landscaping, irrigation, agriculture, industry, and hospitality. Increased scarcity of freshwater resources and continued economic growth have made it essential to maximize the water production efficiency from the Kingdom's desalination plants.

Despite the critical demand, SAWACO's seawater reverse osmosis (SWRO) desalination plant is unable to produce more fresh water because of natural constraints on its seawater intake and limited pretreatment capacity. SAWACO turned to Gradiant to convert the seawater desalination brine waste stream into feed stock for additional freshwater production with a counterflow RO (CFRO) system. The project began with Gradiant's development of a 50 m^3/day (13,000 gal/day) demonstration unit. The objective of the demonstration project was to efficiently recover fresh water at a 50 percent recovery rate from the plant's brine waste stream while meeting the plant's fresh water quality, cost, and energy consumption goals.

1.2. Problems and Needs

Concentration or desalination of brine is desired in many applications but has not been feasible for both financial and technical reasons. The standard treatment method is thermal brine concentration, such as evaporation with mechanical vapor compression, but the capital cost and energy necessary are prohibitive for most applications. Conventional RO is limited to maximum brine concentrations of about 70,000 mg/l TDS by pressure capacity limits of available RO membranes and equipment. Disc tube RO and ultra-high-pressure RO can be operated at pressures of up to 1,800 psi (124 bar), and thereby concentrate up to 120,000 mg/l brine TDS, but membrane compaction necessitates a relatively large number of modules for a given flow rate, and the specialty pressure vessels, pumps, and energy recovery devices necessary are either very expensive or unavailable. The need for a membrane desalination process that can operate within the pressure capabilities of available membranes and equipment is clear.

2. Technical Approach and Methods

The proposed project included designing and constructing the pilot system, selecting and preparing the test site, installing and starting up the pilot system, and conducting extensive testing over the course of about 18 months. This work is described in detail below.

2.1. Technology

The CFRO process was developed as a non-evaporative, membrane-based means to desalinate hypersaline brines. Like standard RO, it uses hydraulic pressure to drive water across a semi-permeable membrane. Uniquely, a saline sweep solution is applied to the permeate side of the membranes to reduce osmotic resistance, such that feed pressures of 1,200 psi (83 bar) or less are required, even for brine concentrations of up to 260,000 mg/l TDS. Multiple CFRO stages are connected in a cascade, concentrating brine to any desired concentration up to saturation while producing a purified water stream for beneficial use or safe discharge.

2.2. Design of Pilot System

With reference to Figure 1 and Table 1, stream 1 is the brine reject stream from the existing SWRO plant. It is combined with stream 7, the dilute sweep stream from the CFRO membranes, pressurized and fed to the preconcentrating RO (precon RO) unit as stream 2. Permeate exits the precon RO membranes as stream 3. Brine from the precon RO unit is fed directly to the CFRO unit (stream 4) without breaking or boosting pressure. After cascading through multiple CFRO stages, brine from the last CFRO stage is depressurized through an energy recovery device or throttle valve. A portion of the final brine is returned to the CFRO membranes to serve as sweep solution (stream 6). The rest of the brine is disposed of in the plant's brine outfall (stream 5). Because flow through the precon RO membranes is less than that required by the RO membrane manufacturer, a portion of the RO brine is recirculated to the high-pressure pump suction. The CFRO process ultimately produces two product streams: desalinated permeate and concentrated brine.

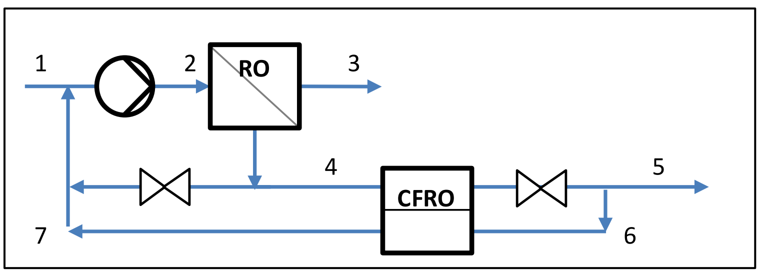

Figure 1. CFRO pilot unit process flow diagram

Table 1. Measurements of flow, pressure, and salinity at the streams shown in Figure 1

Measurement	Stream 1	Stream 2	Stream 3	Stream 4	Stream 5	Stream 6	Stream 7
Flow, m^3/h	1.8	4.3	0.8	2.3	0.9	0.4	1.4
Pressure, bar	1	75	0	70	5	5	1
Salinity, g/l	6.5	6.4	0	9	13.2	13.2	6.3

Flow within a CFRO element is illustrated in Figure 2, provided by the membrane manufacturer. Green arrows depict feed/brine flow. Blue arrows depict sweep solution flow. These are hollow fiber membrane elements, with a plenum in the vessel at each end of the membrane element that the fibers open into. Sweep solution flows inside while feed and brine flow on the outsides of the fibers. The feed and brine flow path is through the center tube, which bridges the low-pressure plenum and is distributed over the length of the fiber bundle, and then exits a side port. The assembly can also be fed from the side and brine will collect in the center tube.

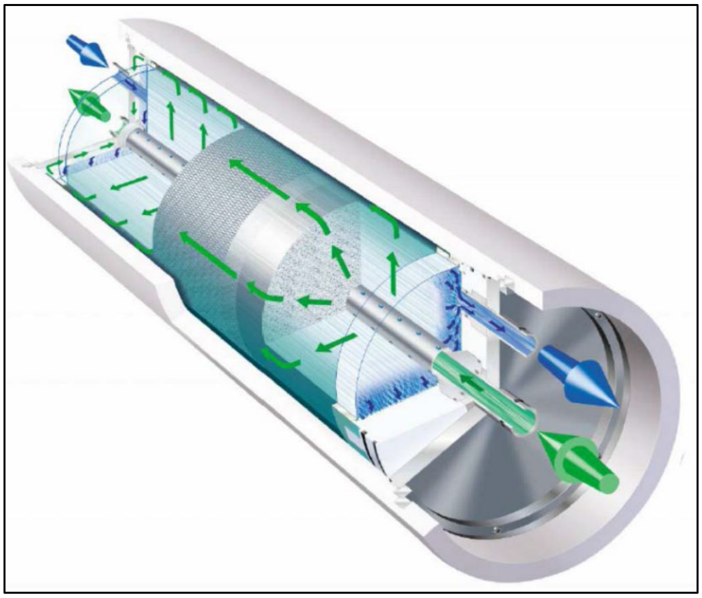

Figure 2. Flow pattern in the CFRO membrane

2.3. Fabrication of Pilot System

Construction of the pilot system was outsourced to Wigen Water Technologies of Minnesota, a reputable design-build firm with extensive experience building conventional RO systems. The pilot system was housed in a climatized 40-foot sea container to facilitate easy transport and rapid deployment. Figure 3, Figure 4, and Figure 5 show the pilot system in the fabrication shop.

Figure 3. CFRO pilot unit in the fabrication shop.

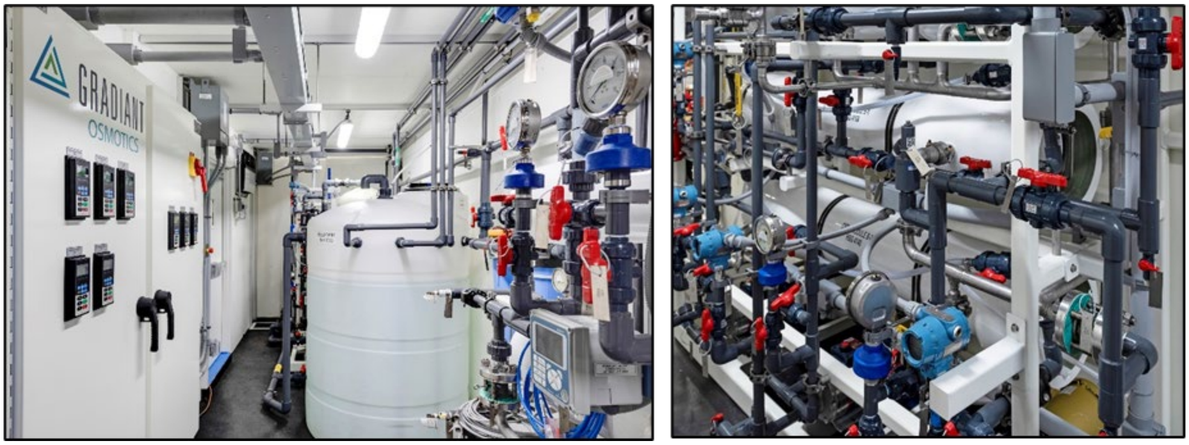

Figure 4. Interior views of CFRO pilot unit

Figure 5. More interior views of the CFRO pilot unit

Upon completion of construction, the pilot system was wet-tested over a full range of flows and pressures at the vendor's facility. Construction and testing were completed, and the unit was shipped in August 2019.

2.4. Pilot Site

2.4.1. Site Selection

Concurrently, a test site was selected. Seawater brine was chosen as the ideal feedstock for this first full-scale demonstration because of its high TDS, low hardness, low fouling potential, and relatively constant composition and temperature. In addition, seawater brine is typically easily accessible, and CFRO brine can be easily returned to the brine line for disposal. Also, seawater desalination plants typically have abundant supplies of electrical power, which Gradiant can tap into to power the pilot. The sites considered were the Claude "Bud" Lewis plant in Carlsbad, California, the Tuas Desalination plant in Singapore, and a seawater RO plant operated by Sawaco in Jeddah, Saudi Arabia.

The Saudi site was chosen as the best option for the sake of project schedule and cost. The plant location is illustrated in Figure 6 and Figure 7. The site is about a 1-hour drive south of Jeddah. It is surrounded by desert that is home to camels.

Figure 6. SAWACO plant site location in western Saudi Arabia

Figure 7. Local fauna

2.4.2. Source Water

Table 2 shows the SAWACO plant's brine composition, which is the feedwater of the pilot unit. Notable is the relatively high concentration of manganese. The source of manganese is a saline groundwater aquifer that flows into the plant's beach well. To mitigate potential manganese scaling, the demonstration unit was equipped with a greensand media filter.

Table 2. Summary of feed water quality data

Parameter	Units	Value
pH @25° C	STD units	7.37
Total dissolved solids	mg/L	69,885
Conductivity	µS/cm	87,700
Temperature	° C	29.5
Total Alkalinity	mg/L as $CaCO_3$	193
Total Hardness	mg/L	3,598
Bicarbonates	mg/L	193
Calcium	mg/L	938
Magnesium	mg/L	2,660
Sodium	mg/L	20,600
Potassium	mg/L	1,340
Iron	mg/L	0.28
Manganese	mg/L	1.7
Silica	mg/L	10.0
Chlorides	mg/L	37,978
Nitrate	mg/L	0.4
Turbidity	NTU	0.58

mg/L = milligrams per liter
NTU = normal turbidity units
µS/cm = micro Siemens per centimeter

2.5. Installation

Pilot deployment and startup were managed by Gradiant's experienced field service team in collaboration with SAWACO managers and operators. Commissioning was completed by end of November 2019. Figure 8 and Figure 9 show some of the installation and commissioning activities.

Figure 8. CFRO pilot unit installation

Figure 9. CFRO pilot unit commissioning

2.6. Operation and Testing

Operation began in December 2019. After steady-state operation, the pilot unit underwent optimization testing. Extended steady-state operation and optimization testing continued through 2020 and 2021.

2.7. Performance Objectives

The overall performance objective was to continuously and reliably desalinate seawater brine at up to 50 percent recovery with minimal energy consumption. Key performance parameters (KPIs) included energy consumption, permeate production flow rate, conversion/recovery rate, feed pressures and uptime. Clean-in-place (CIP) frequency and efficacy was another key performance parameter.

The following target technical performance criteria were defined for the project.

- Total brine treatment capacity (influent basis) = 50 m^3/d
- Fresh water recovery ratio of 50 percent
- Brine TDS at least 130,000 mg/l
- Permeate TDS less than 400 mg/l
- Specific energy consumption less than 8 kWh/m^3 permeate, normalized to full-scale pump/motor and energy recovery device efficiencies
- Uptime greater than 98 percent

3. Results and Discussion

3.1. Results

The pilot unit operated continuously from December 2019 until July 2021. Inlet flowrate, illustrated in Figure 10, was consistently just above 2 m^3/h and uptime was over 99 percent.

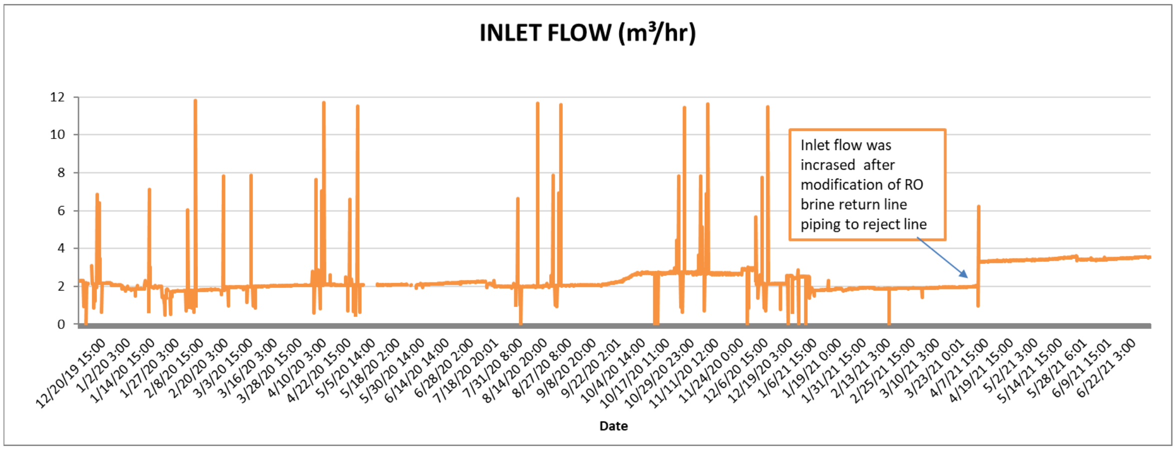

Figure 10. Inlet flow rate

Feedwater salinity, monitored as feedwater conductivity, is presented in Figure 11. Feedwater composition was fairly constant, with a slight long-term downward trend.

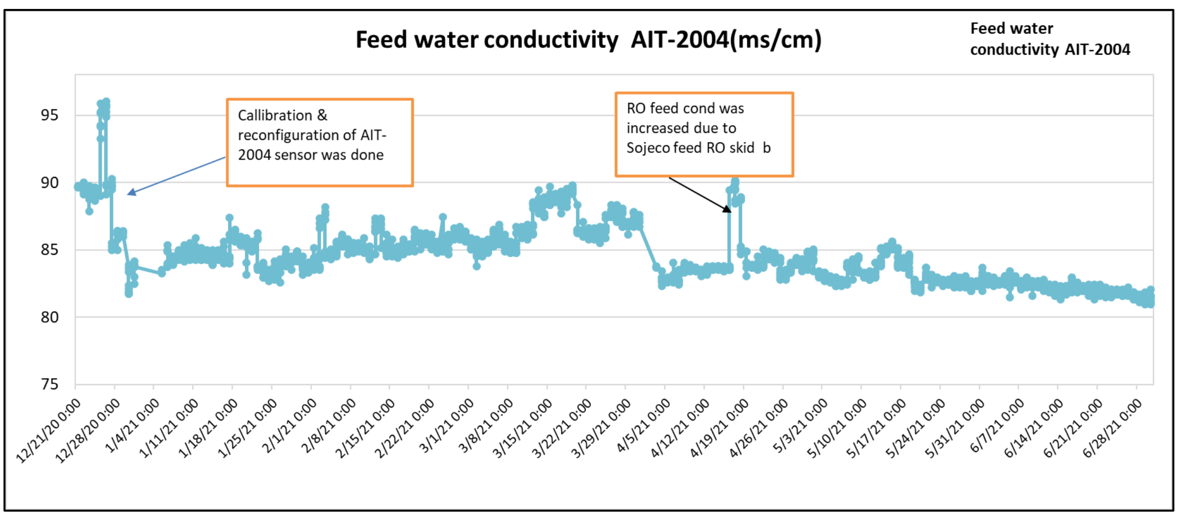

Figure 11. Feedwater conductivity

High-pressure pump discharge pressure is presented in Figure 12. Pressure was fairly constant, with a slight long-term downward trend, corresponding with the feedwater conductivity.

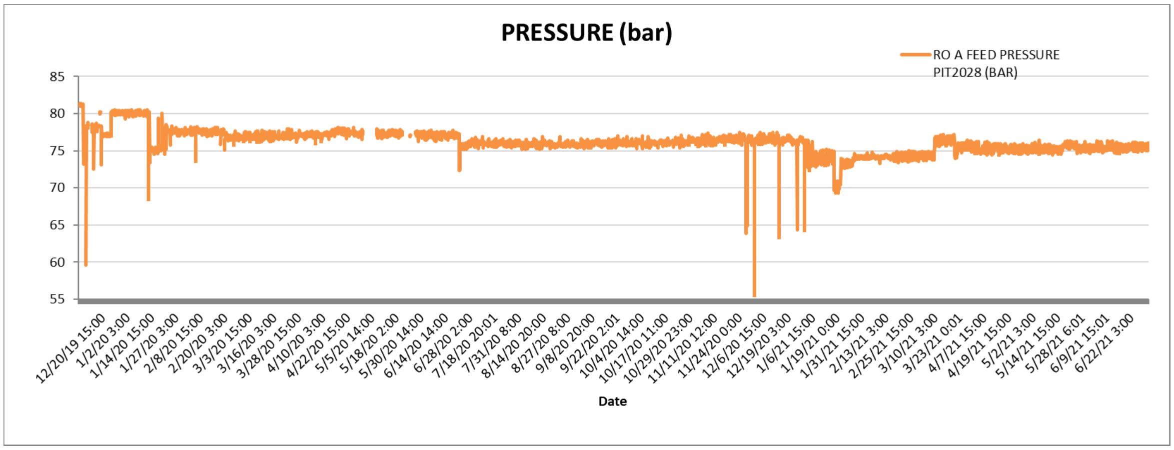

Figure 12. Feed pressure

RO recovery and permeate flow rate are illustrated in Figure 13 and Figure 14. As discussed in the following section, the RO membranes fouled almost immediately upon installation and continued to foul steadily over the first year of operation, resulting in a loss of permeate flow. A 20 percent loss of flux was observed between December and February. Membrane replacement in February did not improve flux because the new membranes fouled as quickly as the original ones. However, once a second set of new membranes were installed and fouling was mitigated in December 2020, recovery and permeate flow increased to meet the KPIs. A CIP in April 2021 also improved recovery and permeate flow rate.

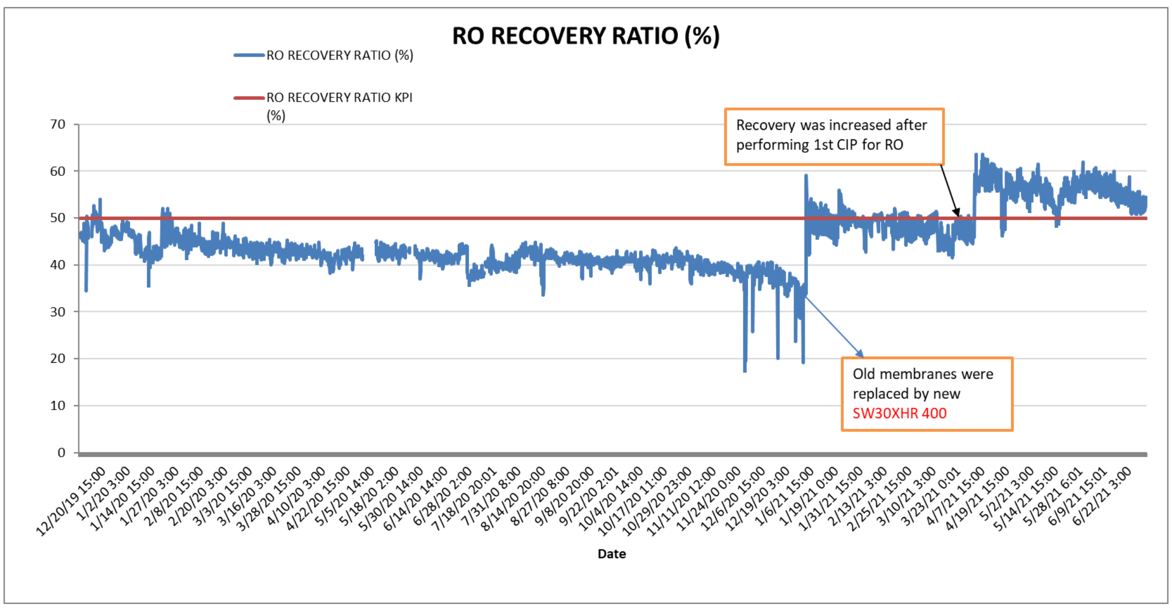

Figure 13. RO recovery rate

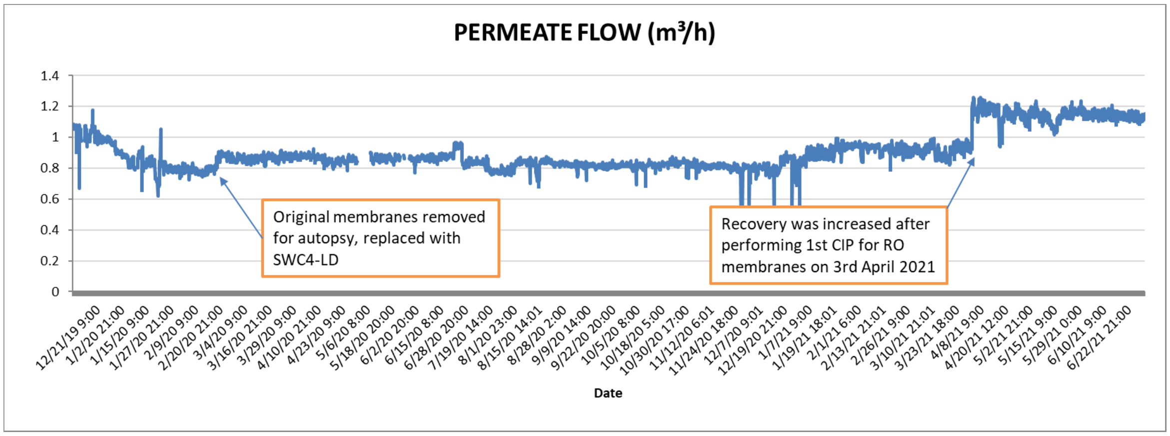

Figure 14. Permeate flow rate

As shown in Figure 15, the permeate TDS using the original membranes (Dupont SWXHR-400i) was initially well below the KPI of 400 mg/l. After the original membranes were replaced and submitted to autopsy in the effort to understand the reduced flow noted above, the new membranes (Hydranautics SWC4-LD) had a lower salt rejection rating than the originals. Higher permeate TDS was expected and was indeed observed to occur between June 2020 and when the membranes were replaced with the same model as the originals in January 2021. However, permeate TDS was not successfully returned to below the KPI of 400 mg/l.

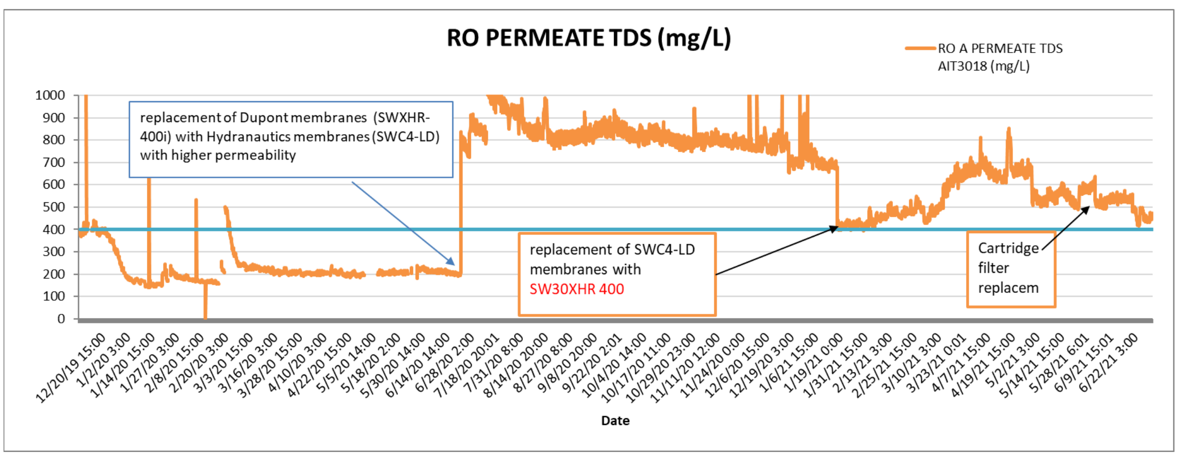

Figure 15. RO permeate TDS

CFRO brine TDS is plotted in Figure 16. Both the original membranes and new membranes installed in January 2021 exhibited a steady decrease in brine TDS.

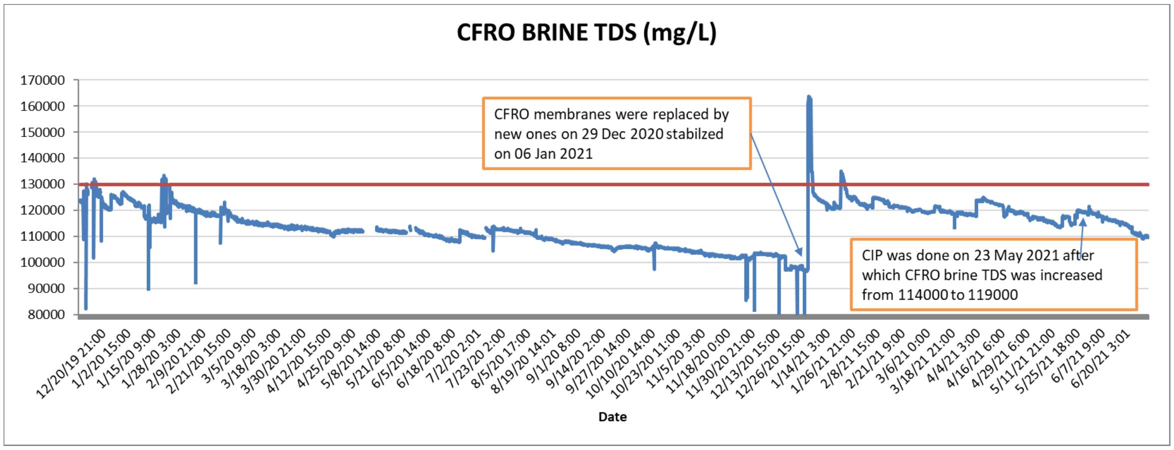

Figure 16. CFRO brine TDS

Specific energy consumption is illustrated in Figure 17. Energy was consumed in the pilot unit primarily by the high-pressure pump, and the rest by the feed-and-sweep pump. In January 2020, 40 percent brine recirculation was applied in the effort to enhance crossflow and thereby mitigate RO membrane fouling. This increased the throughput of the high-pressure pump without increasing permeate flow; therefore, there was an increase in specific energy consumption. Specific energy lowered when RO and CFRO membranes were replaced in January 2021, due to an increase in permeate production with no additional pumping energy. Specific energy decreased again in early April 2021 when the membranes were cleaned.

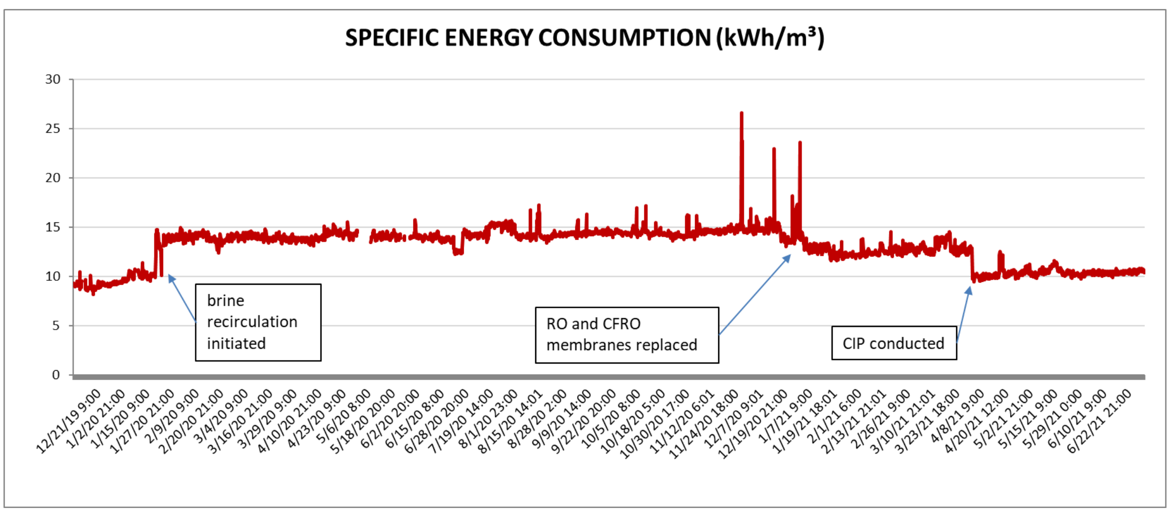

Figure 17. Specific energy consumption

3.2. Analysis

In addition to the performance information presented and described above, autopsies of the original RO and CFRO membranes were conducted. Combined analyses of the performance data and the autopsies are provided below, organized by the types of problems encountered and addressed. Opportunities for full-scale implementation are also assessed.

3.2.1. Iodine Fouling

RO membrane autopsy revealed iodine fouling, which is an unusual phenomenon, but consistent with the observed combination of flux loss and permeate TDS decrease starting shortly after startup. Due to covid-19 pandemic-related delays, shipment of the membranes for autopsy and the autopsy itself took extra time, such that the results were not received for 4 months after the membranes were removed. As a result, the replacement membranes suffered iodine fouling as well. Once iodine fouling was identified, it was easily mitigated by reducing the oxidation reduction potential (ORP) of the demonstration unit's feed stream by dosing with sodium metabisulfite (SMBS), starting in July 2020. However, because iodine fouling is permanent, improved membrane performance was not realized until the RO and CFRO membranes were replaced in January 2021.

3.2.2. Manganese Fouling

The risk of manganese fouling on-site was well known in advance, as evidenced by years of struggle with the mineral in the upstream seawater desalination plant. Although the pilot was equipped with a greensand media specifically to control manganese, the media was apparently overwhelmed with manganese and became ineffective after a few months. See Figure 18 below, which shows manganese precipitation on cartridge filters and in the feed tank. Manganese was also noted in both the RO and CFRO membrane autopsies.

Figure 18. Manganese fouling

The primary strategy for mitigating manganese fouling was to prevent it from entering the pilot system. To achieve this, Gradiant worked extensively with SAWACO engineers and staff to clean equipment and improve water handling in the seawater desalination plant. Mitigation measures included emptying and cleaning manganese out of feed and break tanks, equipping tanks with downcomers to prevent oxidation of manganese during fluid transfer, SMBS dosing to keep manganese in a soluble reduced state, and monitoring and controlling ORP at key points throughout the process. However, there were still places in both the main plant and the pilot plant where process water was unavoidably exposed to air and, therefore, the risk of manganese oxidation and precipitation remained.

3.2.3. Membrane Compaction

Both the RO and CFRO membrane autopsies indicated flux loss due to membrane compaction. Typically, membrane compaction is the result of high-pressure operation, high-temperature operation, or when approaching end of life. Pressure was well-controlled in the process to levels below the manufacturers' recommended maximums, and the duration of the pilot operation was far less than expected life. Pilot feedwater temperature ranged from 33 to 35° Centigrade, which is below maximum limits recommended by the manufacturers. Therefore, we concluded that pressure, temperature, and age could not have been the causes of compaction. However, the combination of iodine fouling, which tends to plug membranes, pressure and temperature likely caused premature compaction. Therefore, mitigating iodine fouling will likely slow compaction in future operations.

3.2.4. Energy Consumption

Brine recirculation will not be required in a full-scale system, eliminating the associated energy loss. A full-scale system will also use an energy recovery device (ERD) instead of a throttle valve at the discharge of the CFRO cascade. The ERD will transfer brine pressure to the precon RO feed (stream 2 in Figure 1 above), thereby reducing the duty of the high-pressure pump and reducing energy consumption. Unfortunately, the demonstration unit flow rates were too low for operation without brine recirculation or with an energy recovery device.

Pilot unit flow, pressure, efficiencies, and computed energy consumption, which matched measured energy consumption, are given in Table 3. These data clearly indicate that the majority of the energy consumed by the process was by the high-pressure pump. High-pressure pump energy included the energy required to re-pressurize brine diverted to the feed tank for brine recirculation.

Table 3. Pump flows, pressure, efficiencies, and energy requirements

Parameter	Units	Component			
		Feed Pump	Sweep Pump 1	HP Pump	Total
Flow	m^3/h	4.5	0.8	4.5	0.86
Pressure	bar	1.0	12.0	78.0	-
Efficiency	N/A	65%	79%	79%	-
Energy	kW	0.19	0.29	12.18	12.66
Specific Energy	kWh/m^3	-	-	-	14.76

HP = high pressure
m^3/h = cubic meters per hour
kW = kilowatts
kWh/m^3 = kilowatt-hours per cubic meter of permeate

In a full-scale implementation of the CFRO process, energy recovery devices and large centrifugal pumps will be employed. Also, brine recirculation will not be necessary with full-size RO membrane arrays. To account for these differences, the following changes were made to the computation of energy consumption:

- Pumps – Demonstration unit pump and motor efficiencies were replaced with realistic full-scale device efficiencies.
- Energy Recovery – The energy-saving performance of an isobaric ERD array was taken into account, the primary benefit being an indirect reduction in high-pressure pump flow and energy consumption. For a CFRO system operating at 50 percent recovery, approximately half of the high-pressure membrane feed would come from the high-pressure pump, and the rest would come from the ERD. Operation of the ERD in a CRFO system requires use of a circulation pump and an additional sweep pump.
- Brine Recirculation – Brine recirculation was eliminated in the normalization calculation since it will not be necessary in a full-scale system.
- Flows - Pilot flow rates were retained in the normalized calculations to enable easy comparison with the measured pilot data.

Normalized energy performance is presented in Table 4. The largest reduction in energy consumption is due to reduced flow through the high-pressure pump, which is partly the result of supplying some of the high-pressure flow with the ERD and partly by eliminating brine recirculation. The normalized data include an added circulation pump, necessary for ERD operation, and a second sweep pump to repressurize CFRO brine depressurized through ERD. Despite the additional components, normalized specific energy consumption is 55 percent less than measured in the pilot.

Table 4. Normalized pump flows, pressure, efficiencies, and energy requirements

Parameter	Units	Component					
		Feed Pump	Sweep Pump 1	HP Pump	Circulation Pump	Sweep Pump 2	Total
Flow	m^3/h	4.5	0.8	1.6	1.6	0.4	0.86
Pressure	bar	1.0	12.0	78.0	10.0	12.0	-
Efficiency	N/A	65%	75%	75%	70%	75%	-
Energy	kW	0.19	0.29	4.47	0.63	0.17	5.75
Specific Energy	kWh/m^3	-	-	-	-	-	6.69

Normalized energy consumption was plotted as a function of date in Figure 19. These data indicate normalized specific energy consumption of between 6.0 and 7.0 kWh/m^3 (23 and 27 kWh/1,000 gal) can be expected for a full-scale system.

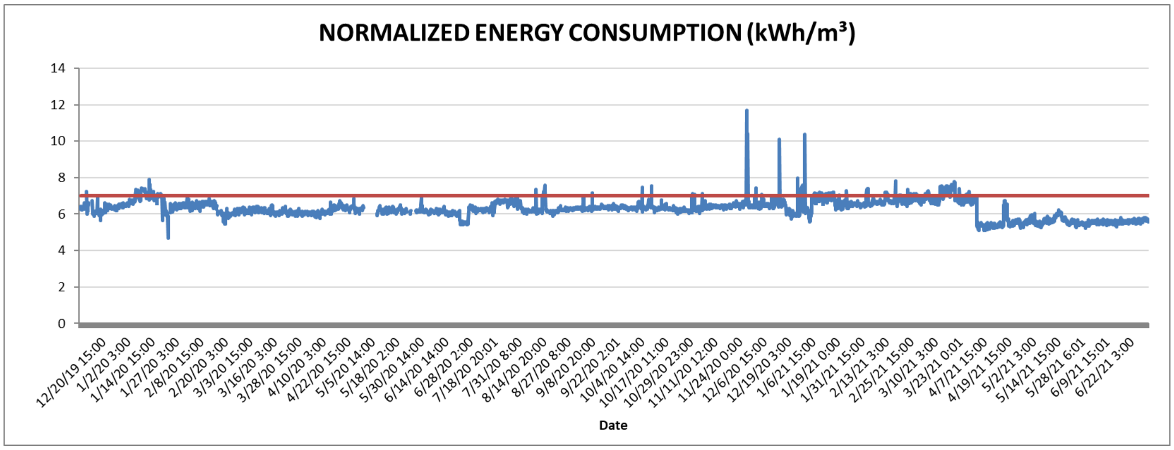

Figure 19. Normalized specific energy consumption

3.2.5. Full-Scale Implementation

As a result of the demonstration project's success, a full scale CFRO plant for producing 5,000 m^3/d (19 million gallons/day) of permeate is being considered for the SAWACO site. To support consideration of this project, energy consumption, capital cost, and total cost were estimated as a function of brine TDS and presented in Figure 20. The following assumptions were made:

- Energy tariff: $0.048/kWh
- Cost amortization period: 25 years
- Interest rate: 5 percent
- Inflation rate: 5 percent
- Isobaric energy recovery
- Fouling will be mitigated in a full-scale system

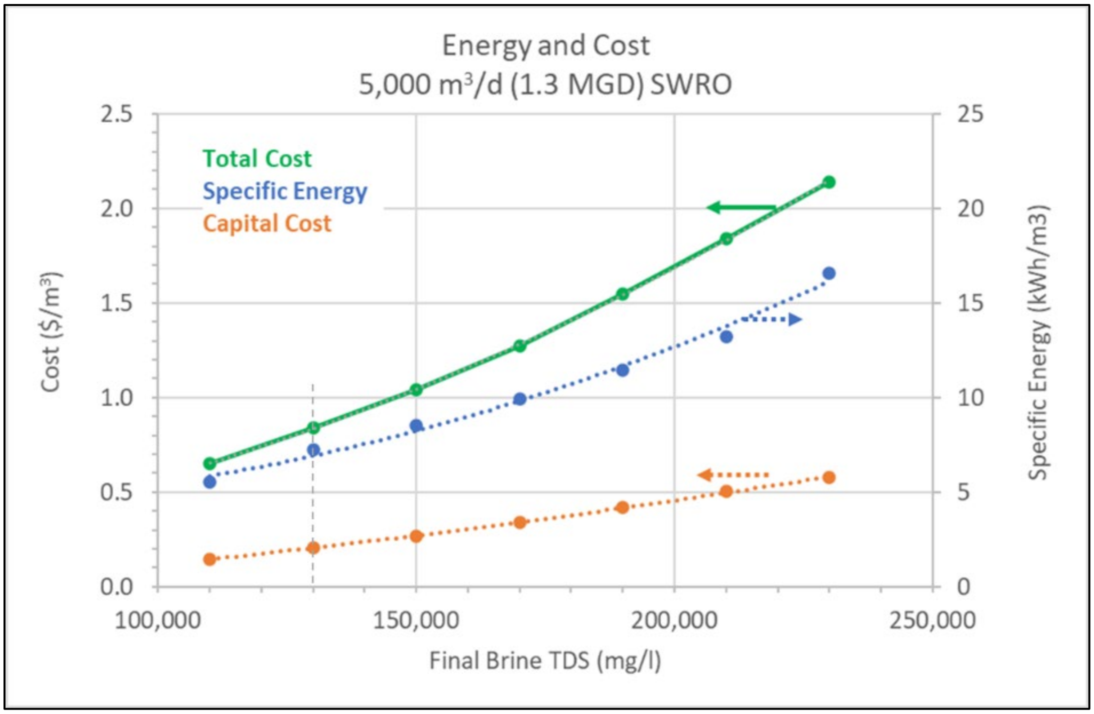

Figure 20. Projected costs and energy requirements for a full-scale CFRO plant

For a CFRO plant operating at 50 percent recovery from a 65,000 mg/l TDS feed stream, producing a 130,000 mg/l brine stream, the cost of water production is anticipated to be less than $0.90/m^3 ($3.40/1,000 gal) of permeate, which is less than the cost would be for water produced with a new SWRO installation at the site.

4. Conclusions

4.1. Conclusions

CFRO system performance information presented in this report shows that seawater brine can be desalinated at 50 percent recovery with feed pressures of less than 80 bar (1,160 psi), producing a final brine of up to 130,000 mg/l TDS and permeate with less than 300 mg/l TDS, using less than 7 kWh per m^3 of permeate (27 kWh/1000gallons) energy. These results demonstrate that CFRO is a reliable, cost-effective, and energy-efficient membrane brine desalination method.

4.2. Challenges

Membrane fouling by manganese and iodine is a unique and specific challenge at the SAWACO site. These fouling mechanisms were not sufficiently addressed in the pilot system design. Response to their detection was slow and limited, such that some KPIs could not be met by the pilot. However, these issues can be simply addressed in the design of a full-scale system by implementing SMBS dosing, monitoring ORP, and limiting air exposure.

4.3. Recommended Next Steps

It is recommended that the CFRO process be deployed for large-scale seawater brine desalination. The CFRO process should also be tested on municipal and industrial brine streams that are too saline for treatment with conventional RO and for sites that cannot afford thermal brine treatment.