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FGD Wastewater Treatment Testing Using a Saltworks Flex EDR Selective (Electrodialysis Reversal System) Technology

2020 TECHNICAL REPORT

FGD Wastewater Treatment Testing Using a Saltworks Flex EDR Selective (Electrodialysis Reversal System) Technology

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ABSTRACT

A 61-day, on-site pilot of Saltworks Technologies Inc.'s *Flex EDR Selective* (electrodialysis reversal system) technology was completed at the Water Research Center (located at Georgia Power's Plant Bowen near Cartersville, Georgia) in collaboration with the Electric Power Research Institute, Southern Company, and U. S. Department of Energy. A unique characteristic of the Flex EDR technology is its ability to selectively remove chloride from a wastewater. In this project, flue gas desulfurization (FGD) wastewater was tested. Because FGD operators often establish limits on chloride concentration levels based on FGD material of construction to initiate purge/blowdown cycles, the Flex EDR technology has the potential to enable higher scrubber water recycling.

The piloted treatment technology demonstrated over a 90% recovery in a system that required a less complex pretreatment often associated with other water treatment approaches. Instead, chloride removal allows for an internal process recycle, which significantly decreases wastewater volume. The resulting products are a low chloride and cleaner water that can be either reused or potentially discharged and a concentrated calcium-chloride-rich brine that is suitable for further volume reduction or direct wastewater encapsulation.

The key results from the testing revealed the following about Flex EDR Selective:

- Averaged a 93% recovery while operating for over 1440 hours with 98% uptime operating continuously on two water sources: (1) FGD wastewater and (2) reverse osmosis concentrated FGD wastewater.
- Selectively removed chloride while rejecting sulfate from entering into the brine.
- Pretreated the wastewater with only lime softening to reduce low-solubility metals, silica, and fluoride, followed by an acid addition to manage carbonate scale potential.
- Reduced the chlorides in both wastewater sources to less than 1500 mg/L.
- Produced a predominantly calcium-chloride brine with an average of 52,400 mg/L total dissolved solids.
- Demonstrated versatility to treat wastewater of different concentrations and water chemistries using the same treatment plant.
- The technology provider estimated a $2/m^3 inlet ($7.6/kgal inlet) total cost of ownership (capital expenditures and operating expenses) for a 1407-m^3/day (256-gpm) plant.

Keywords

Chloride removal
Electrodialysis
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Ion exchange membrane
Monovalent anion selective
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PRIMARY AUDIENCE: Utilities facing water management challenges

KEY RESEARCH QUESTION

This work examined the applicability of the Saltworks Flex EDR technology to treat flue gas desulfurization (FGD) wastewater. Through a 61-day pilot test, the ability of the technology to process the wastewater (allowing the majority of the wastewater to be recycled back to the FGD scrubber and reducing the wastewater volume) was evaluated.

RESEARCH OVERVIEW

The project was an on-site pilot at the Water Research Center at Georgia Power's Plant Bowen and performed in collaboration with the Electric Power Research Institute (EPRI), Southern Company, and the U.S. Department of Energy. The Flex EDR Selective pilot was a fully containerized plant with a capacity of treating 1 to 3 m^3/day of FGD wastewater. A full-scale electrodialysis reversal (EDR) stack was employed in the pilot. The pilot system also included a containerized chemical pretreatment and prefiltration system. The Flex EDR Selective operated reliably for 24/7 for 61 days (1480 hours), treating FGD wastewater from the host site settling basin for the first 945 hours followed by treating a concentrated FGD wastewater that was generated using an on-site membrane system.

KEY FINDINGS

- Saltworks' IonFlux monovalent anion selective ion exchange membrane enables electrodialysis to selectively remove chloride from the wastewater while simultaneously retaining sulfate in the treated water. The result was a treated water with average chloride concentrations less than 1500 mg/L that could be recycled back to the FGD system and a low volume calcium chloride brine stream (average of 52,400 mg/L total dissolved solids) with reduced scaling potential.
- An overall 93% recovery was achieved by Flex EDR Selective operating on the two water sources.
- Both water sources have scaling concentrations of manganese, magnesium hydroxide, calcium fluoride, and/or calcium sulfate. A high pH chemical treatment step with lime was performed to reduce concentrations of low-solubility metals, fluoride, and silica to minimize scaling risk to the downstream Flex EDR Selective plant, and the precipitated solids were removed by a filtration system.

WHY THIS MATTERS

As sites face increasing challenges in managing wastewater streams from a variety of sources, the electric power industry requires effective technologies for managing a wide array of wastewater streams. A primary concern for many utilities is finding a way to eliminate the discharge of wastewater streams and recover water for reuse within the plant. There are many novel options with the potential for eliminating wastewater discharge and recovering water for reuse; however, few field trials have been conducted on challenging wastewater streams that are typical in the energy sector.

HOW TO APPLY RESULTS

An understanding of water treatment technologies and processes is useful for owners and operators of power plants, who are making decisions on future wastewater treatment and disposal methods. The circumstances and economics of each station will be different and might depend on the type of wastewater being considered, wastewater treatment systems in use, potential changes to regulations, and permit limits. The information in this report will assist in understanding strategies and variables to develop portions of the economic analysis.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- *Studies on the Encapsulation of Brine Generated from a Process Using Selective Electrodialysis Reversal*. EPRI, Palo Alto, CA: 2020. 3002019595.
- *Membrane Treatment Guidelines.* EPRI, Palo Alto, CA: 2019. 3002011342.
- *Real-Time Online Membrane Monitor Demonstration*. EPRI, Palo Alto, CA: 2020. 3002019888.
- *Digital Membrane Scale Detection for Self-Cleaning by Adaptive Flow Reversal*. EPRI, Palo Alto, CA: 2016. 3002008517.
- *Vortex-Based Antifouling Membrane System Treating Flue Gas Desulfurization Wastewater*. EPRI, Palo Alto, CA: 2014. 3002002147.

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REPORT SUMMARY

Saltworks Technologies Inc. (Saltworks) completed a 61-day continuous Flex EDR Selective (electrodialysis reversal system) pilot with 98% uptime while demonstrating that 93% of treated flue gas desulfurization (FGD) wastewater could be recycled back to the FGD system and reducing the wastewater volume by 15 times. A $2/m^3 inlet ($7.6/kgal inlet) total cost of ownership (capital expenditures and operating expenses) is estimated, as no soda ash softening is used in the process. The reduced volume concentrated brine reject has a low scaling potential and is suitable for further volume reduction or direct wastewater encapsulation using fly ash and a supplemental chemical binder.

The project was an on-site pilot at the Water Research Center at Georgia Power's Plant Bowen and performed in collaboration with the Electric Power Research Institute (EPRI), Southern Company, and the U.S. Department of Energy. The Flex EDR Selective pilot was a fully containerized plant with a capacity of treating 1 to 3 m^3/day of FGD wastewater (Figure 1). A full scale EDR stack was employed in the pilot. The pilot system also included a containerized chemical pretreatment (no soda ash) and prefiltration system. Pilot testing was completed from March 24, 2019, to May 24, 2019.

Figure 1
Flex EDR Selective Pilot Plants (left) and Flex EDR Selective Stack (right)

The Flex EDR Selective, which leverages 50-year-old electrodialysis technology, aims to selectively remove chloride from FGD wastewater. Chloride concentrations in power plant FGD systems are increased to reduce wastewater treatment volume and subsequent costs; higher chloride concentrations require blowdown. Saltworks' IonFlux monovalent anion selective ion exchange membrane enables electrodialysis to selectively remove chloride from the wastewater while simultaneously retaining sulfate in the treated water. The result was a treated water with average chloride concentrations less than 1500 mg/L that could be recycled back to the FGD system and a low-volume calcium chloride brine stream with reduced scaling potential.

Flex EDR Selective was tested on two different wastewater sources at the Water Research Center: (1) FGD wastewater from the settling basin and (2) vibratory shear-enhanced processing (VSEP) reverse osmosis reject ("VSEP reject"). FGD wastewater had a total dissolved solids (TDS) of 11,000 mg/L while VSEP reject, being brine concentrated by the membrane system, had a TDS of 33,000 mg/L VSEP (three times higher). The raw water chemistry for both is presented in Table 2. The same pilot system treated both feed sources showing the flexibility and robustness of Flex EDR Selective to operate on variable water chemistry.

An overall 93% recovery was achieved by Flex EDR Selective operating on the two water sources. The recoveries operating on the individual water sources are summarized in Table 1. Because the brine concentration is held constant, increasing the inlet TDS results in a reduction in the recovery of the system. As a result, there is a decrease in recovery when switching from FGD wastewater to the more concentrated VSEP reject.

Table 1
Summary of Pilot System Recoveries

Water Source	Recovery	Wastewater Volume Reduction
FGD Wastewater from Settling Basin	95.3%	21.3x
VSEP Reject	81.6%	5.4x
Combined Total	93.2%	14.8x

Both water sources have scaling concentrations of manganese, magnesium hydroxide, calcium fluoride, and/or calcium sulfate. A high pH chemical treatment step with lime was performed to reduce concentrations of low-solubility metals, fluoride, and silica to minimize scaling risk to the downstream Flex EDR Selective plant (Figure 2), and the precipitated solids were removed by a filtration system.

Table 2
Summary of Analytical Results

Water Source:	FGD Wastewater from Reserve Lake Average of All Analytical Data				VSEP Reject Average of All Analytical Data			
Parameter	Raw	Pre-treated Raw	Treated Water	Brine	Raw	Pre-treated Raw	Treated Water	Brine
Units:	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Total Dissolved Solids	10893	10853	7431	129850	32800	31667	4382	146500
Total Suspended Solids	20	30	13	453	82	73	10	131
Total Hardness (as CaCO3)	4750	4895	-	44867	13633	11900	-	40917
Total Organic Carbon	1.88	1.40	7.12	20.2	3.07	2.51	4.46	1.05
Alkalinity (as CaCO3)	37.7	15.4	-	<20	-	-	-	<20
Aluminum (Total)	0.0360	0.0251	-	0.0719	0.0395	0.0223	-	0.0270
Ammonia (as N)	0.31	0.30	0.23	1.77	0.35	0.34	0.20	1.08
Arsenic (Total)	0.02	0.02	-	0.02	0.02	0.02	-	0.02
Barium (Total)	0.145	0.133	-	1.647	0.501	0.469	-	1.65
Boron (Total)	62.3	58.5	-	31.1	100.8	95.0	-	41.9
Bromide	8.95	8.92	3.40	177	19.80	22.20	1.21	105
Calcium (Total)	1547	1927	-	17783	4507	4767	-	16383
Chloride	2532	2770	1564	31200	7220	7323	1240	33883
Fluoride	5.26	1.02	1.07	1.57	13.00	2.93	0.74	1.77
Iron (Total)	0.0596	0.0500	-	0.2998	0.0500	0.0500	-	0.0531
Lithium (Total)	0.0359	0.0364	-	0.0933	0.0786	0.0774	-	0.146
Magnesium (Total)	181	20	-	113	573.3333	1.2933	-	5.71
Manganese (Total)	1.58	0.02	-	0.15	0.21	0.00	-	0.01
Mercury	0.00107	0.00030	0.00020	0.00091	0.01116	0.00122	0.00021	0.00677
Nitrate (as N)	8.2	8.3	2.8	159.3	19.4	18.2	1.5	87.6
Nitrite (as N)	0.304	0.258	0.338	0.913	0.304	0.304	0.304	0.791
Combined Nitrate/Nitrite (as N)	7.175	5.18	2.9	157	-	-	-	-
Phosphate (Ortho)	0.1	0.3	0.1	0.7	0.8	0.7	0.1	1.0
Potassium (Total)	5.12	5.10	-	41.7	12.53	12.43	-	45.3
Selenium (Total)	0.0671	0.0639	-	0.0418	0.2283	0.1940	-	0.139
Silica (Reactive) Total	7.34	0.48	-	1.21	16.00	0.73	-	1.52
Sodium (Total)	17.0	18.4	-	502	28.9	39.3	-	2995
Strontium (Total)	6.64	6.70	-	49.3	16.87	16.17	-	50.5
Sulfate	1137	1319	1317	560	3403	1260	696	534

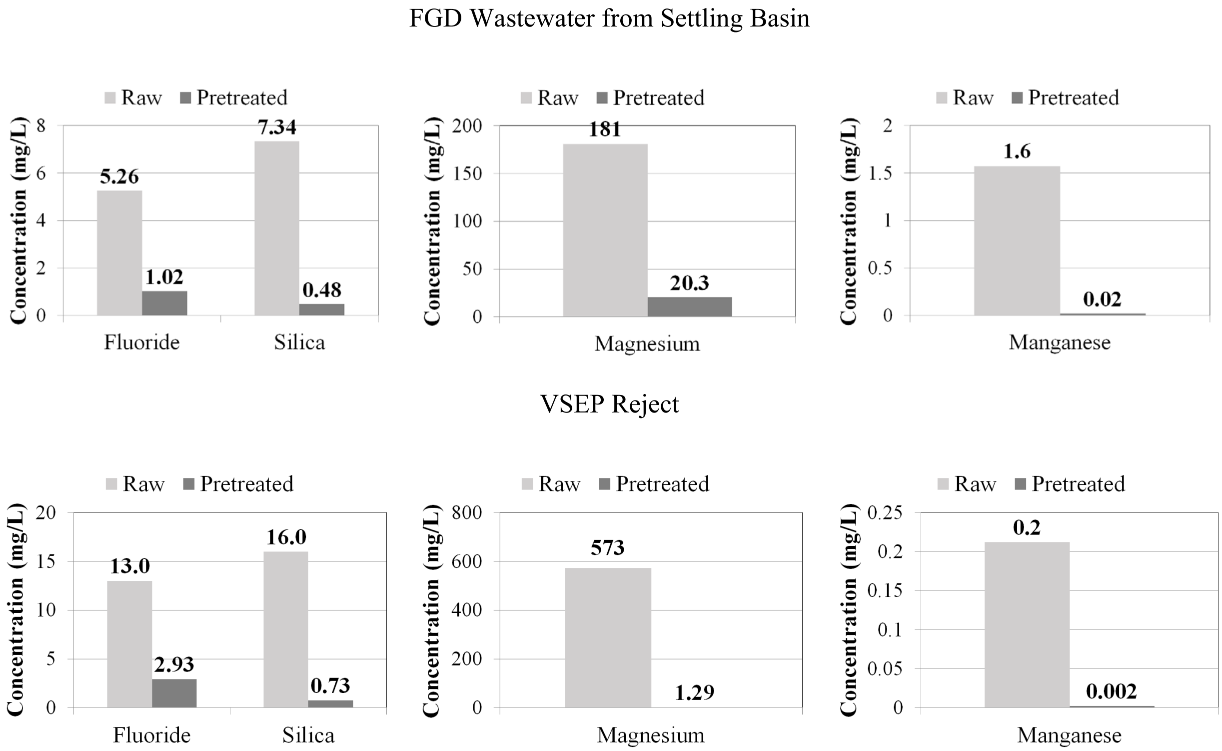

Figure 2
Pretreatment for Metals, Fluoride, and Silica

Flex EDR Selective operated reliably for 24/7 for 61 days (1480 hours), treating FGD wastewater from the host site settling basin for the first 945 hours followed by treating VSEP reject for the remainder of the pilot (Figure 3). The pilot dispatched to the site had a 40-membrane pair Flex EDR Selective stack. This stack over-performed because of better observed flux than the small-scale stack used for the off-site pilot work, and TDS in the FGD wastewater being treated by the system, which was lower than the designed specification.

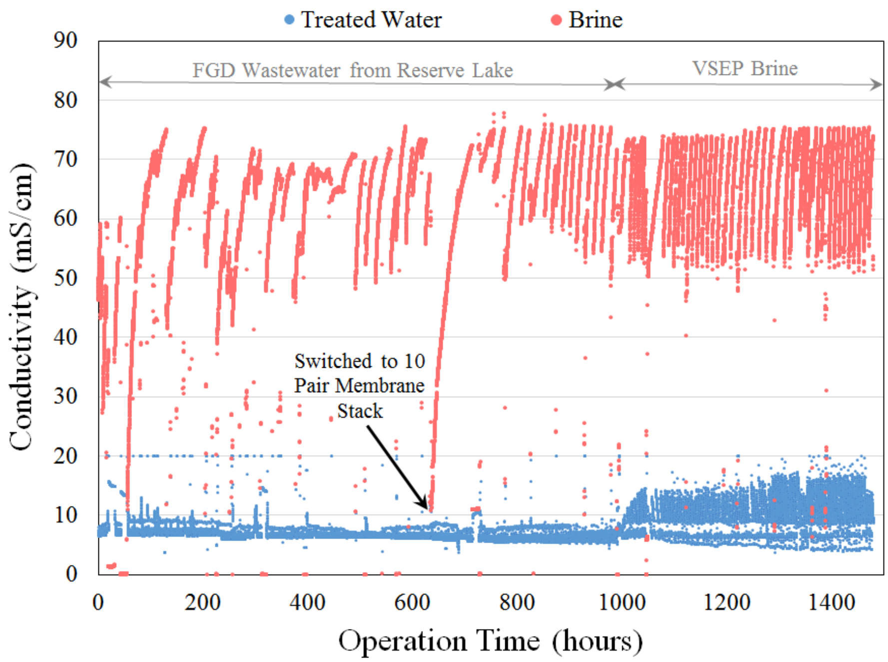

Figure 3
Flex EDR Selective Reliable Operation for 61 Days

As such, the stack operated with a treatment capacity approximately five times higher than the capacity of the pretreatment system. To match the flow of the pretreatment system, the stack was operated at a lower current density, which does not offer optimal cost efficiency. To pilot operating at its ideal cost efficiency, a 10-membrane pair Flex EDR Selective stack was installed. This "thinner" stack was operated at peak energy efficiency to collect data to inform on the full-scale total system economics.

Flex EDR Selective reduced chloride in both water sources down to 1500 mg/L while producing a brine with an average of approximately 52,400 mg/L TDS (see Table 2). The 5.24% concentrated brine is predominately calcium chloride, which has a low risk of scaling (Table 3). This brine could be directly encapsulated with fly ash and other constituents, which was the focus of the studies by EPRI and Golder Associates under this project. Alternatively, the brine could also be sent to a brine concentrator for further volume reduction before encapsulation.

Table 3
Brine Composition as a Percentage of TDS

Chloride	61.5%
Calcium	32.4%
Sodium	3.4%
Nitrate	1.0%
Sulfate	1.0%

The brine water chemistry has low scaling potential due to the performance of Saltworks' IonFlux monovalent anion selective ion exchange membranes. Under an electrical potential, the membranes passed chloride to reduce the concentration to 1500 mg/L while rejecting sulfate from the brine and keeping it in the treated water. The analytical data from the pilot in Figure 4 show that chloride is selectively removed and sulfate is retained in the treated water. The IonFlux monovalent selective anion exchange membrane is not 100% selective, so there is nominal sulfate transport through the membrane. This is more noticeable in the VSEP reject data, as there are three times more chlorides to be removed than the untreated FGD wastewater. Nevertheless, the sulfate in the brine was maintained at around 550 mg/L for the entire pilot, even when operating with the VSEP reject, keeping calcium sulfate under minimal-scaling conditions.

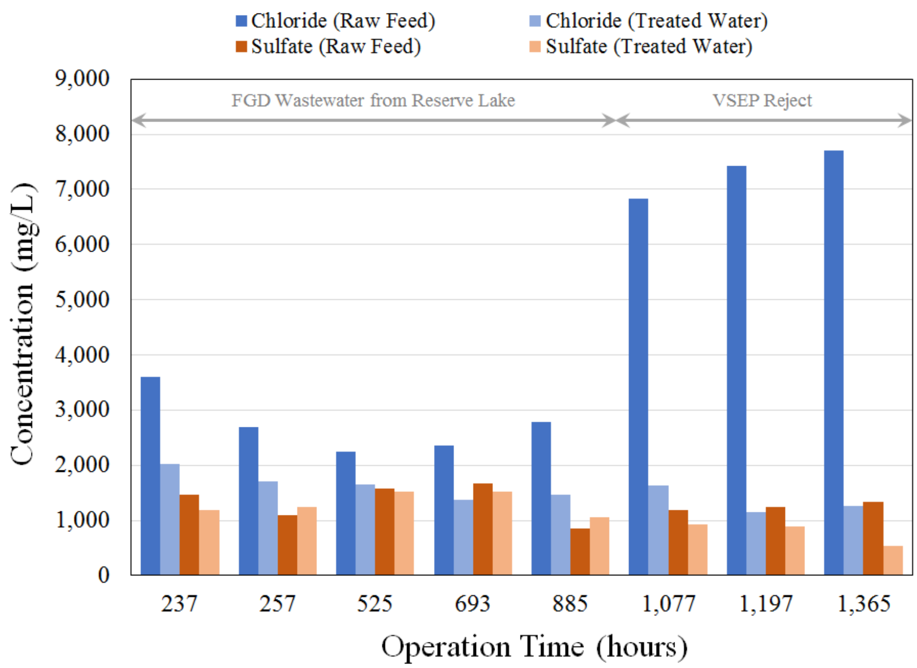

Figure 4
Selective Chloride Removal and Sulfate Rejection

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INTRODUCTION

Power plant wet flue gas desulfurization (FGD) systems, which are used to remove sulfur from the air emissions, create wastewater that requires treatment prior to reuse or discharge. FGD wastewater is generated when chloride concentrations exceed a set concentration generally established to mitigate corrosion in FGD equipment. High chloride concentrations inhibit sulfur absorption from the flue gas and create corrosion concerns with wetted equipment. FGD wastewater characteristics vary widely depending on the facility, fuel source, wet scrubbing method, and FGD system employed. However, many FGD wastewaters are highly scaling and difficult to treat, mainly due to high concentrations of hardness (calcium, magnesium) and sulfate. Many conventional water treatment processes, including most membrane systems, also require chemical softening to remove hardness and ensure reliability.

Increasing the amount of FGD water recycled in the system would reduce wastewater volumes and could be accomplished by directly pulling out excessive chloride from the wastewater prior to it returning back to the FGD absorber. Saltworks' Flex EDR Selective, employing monovalent anion selective anion exchange membranes (mAEM), is applied to remove chloride from FGD wastewater without the need for soda ash softening. The result is a chloride reduced treated water that could be recycled back to the FGD system. At the same time, Flex EDR Selective concentrates the removed chloride and other cations, mainly calcium and magnesium, and produces a low volume brine. The brine, which is predominantly calcium chloride, has a low scaling risk since the majority of the sulfate is retained in the treated water by the highly selective mAEM. Flex EDR Selective builds upon 50-year-old electrodialysis technology and is enabled by Saltworks' advances in monovalent ion exchange membranes. These membranes are manufactured from a ductile and highly conductive ion exchange polymer.

This report summarizes an on-site Flex EDR Selective pilot plant operating on two different sources of FGD wastewater at the Water Research Center at Georgia Power's Plant Bowen near Cartersville, Georgia. The pilot project objectives were to:

- Demonstrate reliable Flex EDR Selective operations under site conditions for 60 days
- Evaluate Flex EDR Selective performance to reduce chloride concentration to less than 1500 mg/L
- Collect data to determine operating expenses (OPEX; energy and chemicals) and capital expenditures (CAPEX; membrane flux) for full-scale plant design and economics

2
TECHNOLOGY OVERVIEW

Saltworks Flex EDR Selective system selectively removes chloride from FGD wastewater. This could enable coal-fired power plants to increase internal recycle rates and decrease wastewater volume. The process is enabled by Saltworks' proprietary IonFlux mAEM that has 98% selectivity for monovalent anions, such as chlorides, while rejecting multivalent anions, such as sulfates.

The Flex EDR Selective technology is based on monovalent electrodialysis reversal. As shown in Figure 2-1, Flex EDR Selective can selectively remove monovalent chlorides while rejecting sulfates from the brine stream. As a result, it produces a brine composed primarily of calcium chloride with low risk of scaling. The lack of sulfates entering the brine (blocked by the mAEM) removes the need for chemical softening upstream.

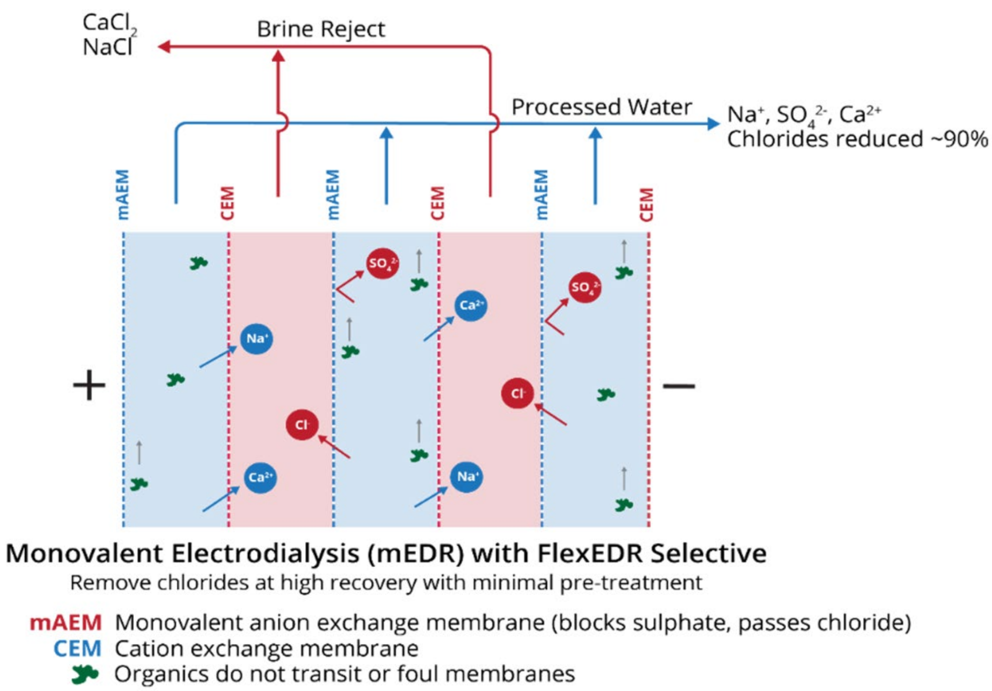

Figure 2-1
Simplified Flex EDR Selective Diagram

Flex EDR Selective improves upon electrodialysis with patented and patent pending improvements, as described in the following:

- **Saltworks' IonFlux membranes.** New generation, fouling tolerant, highly conductive, and ductile ion exchange membranes that increase membrane reliability and reduce energy requirements over competing membrane products. Saltworks offers membranes with a broad chemical tolerance (pH 1–13) and two types tuned to either transport multivalent ions rapidly (for softening applications) or transport monovalent ions preferentially (for ion separation). For this pilot project, mAEM was used for specific chloride removal from the FGD wastewater.
- **Electrode hardness blocker.** Proprietary system that prevents calcium fouling of electrodes (Figure 2-2), removes the need for chemical (acid) dosing electrolyte streams, and improves health and safety by eliminating the risk of chlorine gas production.

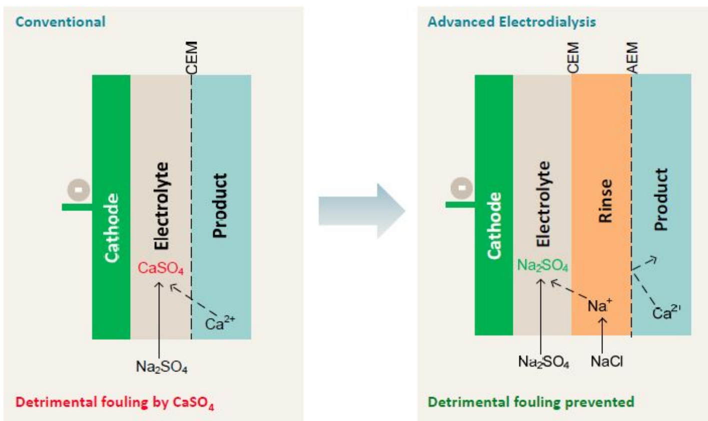

Figure 2-2
Saltworks' Patented NaCl Rinse System to Prevent Electrode Fouling

- **Mechanical design.** Plate and frame stack that allows modularity for ease of service and expansion, and a positive hydraulic seal that reduces intercompartmental leakages.

Full-scale plants can be implemented, as the foundation technology (electrodialysis) is not new and production systems are in place in the Saltworks' facility, as shown in Figure 2-3.

Figure 2-3
Full-Scale Production of Electrodialysis Stacks and Membrane

3
FLEX EDR SELECTIVE PILOT PLANT OVERVIEW

The Flex EDR Selective pilot plant, with a capacity of treating 1 to 3 m^3/day FGD wastewater, was tested for 61 days from March 24, 2019, to May 24, 2019. The pilot plant train consisted of two systems, pretreatment and Flex EDR Selective, in two ISO 40-foot (12-m) containers, as shown in Figure 3-1 and Figure 3-2. The plants were fully automated for 24/7 operation and had full data acquisition (DAQ) functionality. The Flex EDR Selective pilot plant was used to complete duration and performance testing under field conditions for forming the design basis of a larger scale plant.

Figure 3-1
Flex EDR Selective with Pretreatment Pilot Plants (left) and Flex EDR Selective Stack and Control System (right)

Figure 3-2
Pretreatment Lime Dosing System (left) and Filter System (right)

The simplified process flow diagram for the pilot is shown in Figure 3-3.

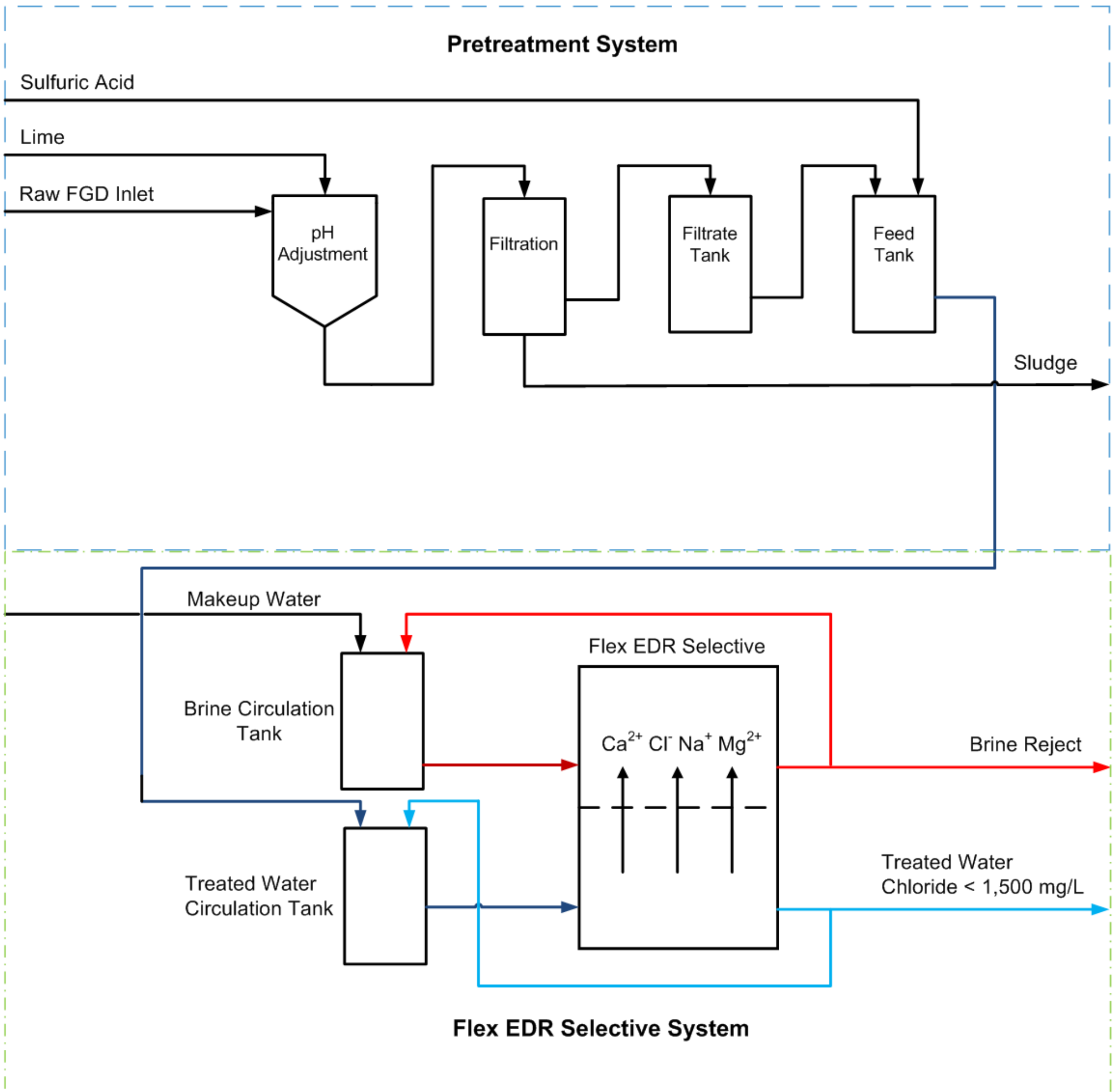

Figure 3-3
Simplified Process Flow Diagram for Flex EDR Selective with Pretreatment

3.1 Pretreatment

Pretreatment was completed to remove low-solubility ions, such as manganese, fluoride, and silica, that can potentially create scaling compounds by Flex EDR Selective as the brine is concentrated. Metals and fluoride can be removed by raising the pH to 11 with lime. At the elevated pH, these are precipitated, reducing their concentrations to less than 10 mg/L. Through co-precipitation and adsorption mechanisms, silica is also removed in the process. No soda ash is required to reduce calcium concentrations. Flex EDR Selective rejects sulfate from entering the brine and concentrating, so there is low calcium sulfate scaling potential. The solids are removed by a filter system.

Prior to entering the Flex EDR Selective plant, the pretreated feed is acidified to pH 3 with sulfuric acid. The main purpose of reducing the pH to 3 is to mitigate any carbonate scaling risk. Lime and sulfuric acid for pH adjustments are the only chemicals used for pretreatment.

3.2 Flex EDR Selective Pilot

The core of the pilot plant is Saltworks' Flex EDR Selective system. The pilot operates at capacities of 1 to 3 m^3/day depending on the inlet total dissolved solids (TDS) concentration. The Flex EDR Selective system is equipped with Saltworks' EDR stacks consisting of pairs of IonFlux cation exchange membrane and IonFlux mAEM.

The Flex EDR Selective pilot is configured as a semi-batch process but it emulates the continuous process that would be employed for a full-scale plant. As shown in the simplified process flow diagram (Figure 3-4), Flex EDR Selective "pumps" ions (chloride and cations) from the treated water stream into the brine stream. As a batch process, the treated water stream continuously circulates through the stack until the desired chloride concentration (1500 mg/L) is reached and is then discharged. The chloride concentration is determined based on a conductivity correlation that was predetermined through an off-site pilot with representative FGD wastewater from the site. When treated water is discharged, its tank is refilled with more pretreated feed. The brine is concentrated to a determined conductivity (~52,400 mg/L TDS) and then a portion is discharged. Utility water is used as a brine circulation tank makeup water.

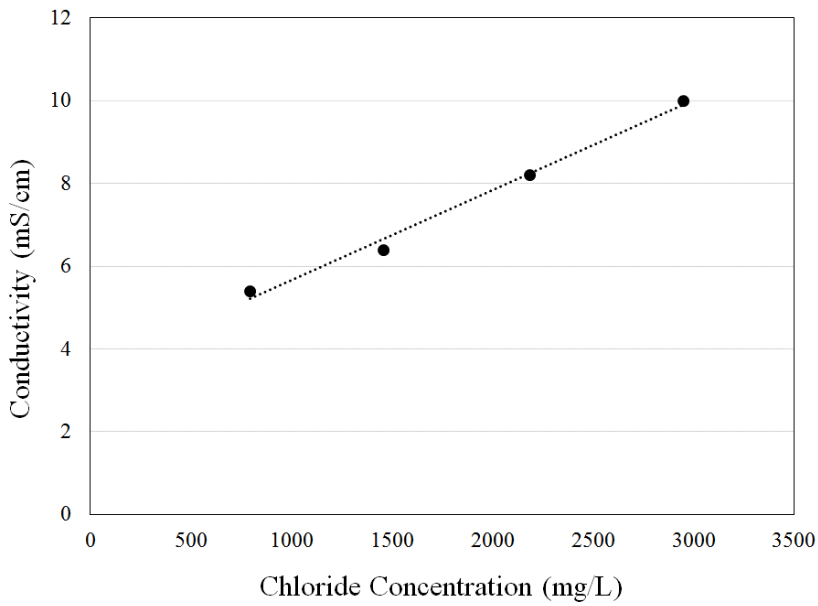

Figure 3-4
Chloride Conductivity Correlation

4
PILOT TEST RESULTS

The Flex EDR Selective pilot plant reliably operated for 61 days, 24/7, including weekends and unattended overnights. The key results from the testing describe Flex EDR Selective, as follows:

- Potential for cost savings through selective chloride removal and recycle versus more costly and complex complete treatment systems
- Averaged 93% recovery while operating for over 1440 hours with 98% uptime operating continuously on two water sources: (1) FGD wastewater from settling basin (untreated) and (2) reverse osmosis brine VSEP reject
- Selectively removed chloride while rejecting sulfate from entering into the brine, eliminating the need for soda ash softening
- Pretreated the wastewater with only lime softening to remove low-solubility metals, silica, and fluoride followed by acid addition to manage carbonate scale potential
- Reduced the chloride concentration in both wastewater sources to less than 1500 mg/L for consideration of recycling back to the FGD system
- Produced a predominantly calcium chloride brine with an average of 52,400 mg/L TDS (The brine has low scaling potential and could be solidified by fly ash and supplementary binder or further volume reducing, using a thermal brine concentrator.)
- Demonstrated versatility to treat wastewater of different concentrations and water chemistries with the same treatment plant
- Estimated a $2/m^3 inlet ($7.6/kgal inlet) total cost of ownership (CAPEX and OPEX) for a 1407-m^3/day (256-gpm) plant, which could be 50% the cost of soda ash softening followed by membrane concentration.

4.1 Pilot Test Wastewater Sources

Two water sources were tested during the pilot: (1) FGD wastewater (untreated) and (2) VSEP reject. The VSEP reject, being brine concentrated by a VSEP membrane system, had a TDS of 22,000 mg/L higher (three times) than the untreated FGD wastewater (33,000 mg/L VSEP brine vs. 11,000 mg/L FGD wastewater). The detailed water chemistry for both is presented in Table 4-1.

Table 4-1
Summary of Analytical Results for Flex EDR Selective Raw Feedwater

Date Sampled	3/27/2019	4/3/2019	4/8/2019	4/15/2019	4/22/2019	4/30/2019	5/8/2019	5/13/2019	5/20/2019
Operation Time (Hours)	69	237	357	525	693	885	1077	1197	1365
Parameter	Raw FGD Wastewater from Reserve Lake					Raw VSEP Reject			
Units	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Total Dissolved Solids	7860	12100	11800	10100	12300	11200	29900	35300	33200
Total Suspended Solids	8	12	16	29	26	28	101	77	67
Total Hardness (as CaCO3)	5130	4610	5130	4090	4640	4900	13600	13200	14100
Total Hardness Dissolved (as CaCO3)	5009	4523	5038	4460	4580	4990	13100	13000	14400
Total Organic Carbon	1.62	1.7	1.75	1.92	2.17	2.14	2.37	2.81	4.04
Alkalinity (as CaCO3)	46.2	43.8	42.8	42.2	41.3	<20	<20	<20	<20
Aluminum (Total)	0.027	0.0365	0.0217	0.0385	0.0606	0.0319	0.0229	0.024	0.0715
Aluminum (Dissolved)	0.02	0.0346	0.02	0.0242	0.0412	0.02	0.02	0.02	0.0605
Ammonia (as N)	0.321	0.35	0.3	0.28	0.346	0.24	0.41	0.26	0.37
Ammonia (as N 4500 NH3, ESL)	0.316	0.275	0.353	0.415	0.365	-	-	-	-
Arsenic (Total)	0.00248	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Arsenic (Dissolved)	0.00272	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Barium (Total)	0.127	0.124	0.121	0.145	0.171	0.179	0.47	0.48	0.554
Barium (Dissolved)	0.124	0.124	0.13	0.149	0.174	0.187	0.482	0.504	0.585
Boron (Total)	66.3	62.7	67.1	54.9	60.9	62.0	99.3	96.1	107
Boron (Dissolved)	67.8	61.9	66	57	62.1	62.6	95.9	96.6	108
Bromide	12.3	10.8	11.3	9.84	8.95	0.50	16.8	18.7	23.9
Calcium (Total)	1660	1500	1670	1310	1520	1620	4520	4380	4620
Calcium (Dissolved)	1620	1470	1640	1460	1500	1650	4380	4310	4700
Chloride	2830	2420	2670	2240	2490	2540	6890	7160	7610
Fluoride	5.5	5.3	5.88	4.27	5.75	4.87	11.1	11.7	16.2
Iron (Total)	0.05	0.05	0.05	0.0609	0.0802	0.0667	0.05	0.05	0.05
Iron (Dissolved)	0.05	0.05	0.05	0.05	0.0732	0.055	0.05	0.05	0.05
Lithium (Total)	0.0347	0.0287	0.029	0.0431	0.0391	0.0409	0.0774	0.0749	0.0836
Lithium (Dissolved)	0.0344	0.0294	0.0321	0.0454	0.0408	0.043	0.0764	0.0823	0.0901
Magnesium (Total)	239	210	233	198	205	0.0409	556	540	624
Magnesium (Dissolved)	234	207	229	197	203	0.043	534	533	647
Manganese (Total)	1.41	1.38	1.72	1.53	1.97	1.44	0.238	0.0598	0.339
Manganese (Dissolved)	1.34	1.4	1.79	2.04	1.99	1.39	0.226	0.0693	0.322
Mercury	0.000919	0.00065	0.000265	0.000576	0.0002	0.00382	0.0182	0.00207	0.0132
Nitrate (as N)	8.98	7.91	8.18	7.35	8.3	8.3	18.4	19.7	20
Nitrite (as N)	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304
Combined Nitrate/Nitrite (as N)	8.7	7.9	7	5.1	-	-	-	-	-
Phosphate (Ortho)	0.1	0.1	0.1	0.1	0.1	0.1	1.0	0.37	1
Potassium (Total)	5.66	4.92	5.37	4.61	5.15	4.98	13.2	13	11.4
Potassium (Dissolved)	5.3	5.07	5.42	4.39	5.13	5.2	13.2	13.2	12
Selenium (Total)	0.0759	0.0641	0.0562	0.0603	0.0686	0.0776	0.204	0.223	0.258
Selenium (Dissolved)	0.0812	0.0718	0.0634	5.84	0.0762	6.23	0.221	0.24	0.274
Silica (Reactive) Total	6.75	7.24	6.61	8.41	8	7.04	14.1	15.8	18.1
Silica (Reactive) Dissolved	7.09	6.52	7.05	7.37	8.05	7.38	14.6	15.2	17.5
Sodium (Total)	19.4	15.3	15.8	20.9	15.7	14.9	30.2	28.5	28
Sodium (Dissolved)	18.4	15.7	15.2	24.6	15.9	14.9	30.3	28.5	29.6
Strontium (Total)	7.71	6.69	7.41	5.84	5.94	6.23	16.5	15.7	18.4
Strontium (Dissolved)	7.38	6.77	7.28	5.75	5.94	6.26	16.4	15.7	18.7
Sulfate	1100	930	1040	1320	1300	1130	3290	3250	3670

The data presented in the proceeding sections highlight the pilot system effectiveness in reducing chloride concentrations in both tested water sources. Flex EDR Selective reduced the chloride concentrations to 1500 mg/L even in the VSEP reject, where its chloride concentration was 4700 mg/L higher than that in the FGD wastewater. Also, the VSEP reject had calcium sulfate concentrations that were supersaturated (see Section 4.2 for further discussion). For full-scale implementations, the range of possible water chemistries to be treated should be considered in the engineering design.

The pilot dispatched to site a 40-membrane pair Flex EDR Selective stack. The stack was sized based on off-site pilot testing on an FGD wastewater that had higher TDS concentrations than those for the on-site pilot. As well, the pilot stack had a better performance than the small-scale stack used for the off-site pilot work. This resulted in the Flex EDR Selective pilot capacity of 16 m^3/day. An oversized stack means that the Flex EDR Selective pilot can either treat a higher volume of water at the same TDS concentration or a lower volume of water at a higher TDS concentration. However, the pretreatment system had only a capacity of 3 m^3/day and could not keep up with providing sufficient pretreated feedwater (that is, 16 m^3/day). The VSEP reject, with high TDS concentrations, was not yet available. As such, to match the capacity of the pretreatment system, the Flex EDR Selective stack was subsequently operated at a lower current density. Flex EDR Selective can operate at any current density; however, operating at a lower current density would not offer cost efficiency.

To test operating at optimal energy efficiency, a 10-membrane pair Flex EDR Selective stack was installed. This "thinner" stack was operated at optimal energy efficiency to collect data to inform on the full-scale total system economics. The size of the stack does not influence the water recovery, chloride reduction performance, or brine concentration. The different scenarios of water sources and stack sizes during the pilot test are summarized in Table 4-2.

Table 4-2
Summary of Water Source and Stack Size Testing Scenarios

Operating Time	Stack Size	Water Source
0 to 660 hours	40 membrane pairs	FGD wastewater (untreated)
660 to 995 hours	10 membrane pairs	FGD wastewater (untreated)
995 to 1480 hours	10 membrane pairs	VSEP reject

4.2 Pretreatment Results

The pretreatment system was effective in reducing low-solubility metals, silica, and fluoride in the Flex EDR Selective feed, eliminating scaling potential from these constituents. No soda ash was used—only lime and sulfuric acid to adjust the pH (see Section 3.1 for pretreatment overview). Table 4-3 summarizes the scaling potential of the raw water and after pretreatment. The detailed analytical results for the average of all raw and pretreated water are presented in Table 4-4.

Table 4-3
Scaling Potential Before and After Pretreatment**

	FGD Wastewater (Untreated)	VSEP Reject
Raw	• Manganese, magnesium hydroxide, and calcium fluoride are at or near scaling limits. • Calcium sulfate is within ~65% of its scaling limit.*	• Calcium fluoride is at scaling concentrations • Calcium sulfate is over its solubility limit (supersaturation).* • Barium sulfate is within ~35% of its scaling limit.
After pretreatment	• Manganese, magnesium hydroxide, and calcium fluoride no longer have scaling potential. • Calcium sulfate is within ~70% of its scaling limit.*	• Calcium fluoride no longer has scaling potential. • Calcium sulfate is within ~70% of its scaling limit.* • Barium sulfate is within ~35% of its scaling limit.

* Flex EDR Selective rejects sulfates from entering into the brine and concentrating. Hence, pretreatment for calcium is not required (that is, no soda ash softening).

** Both raw water sources have scaling potential from CaCO3. Pretreatment also includes reducing the pH of the feed to the Flex EDR Selective to pH 3, removing alkalinity from the water and CaCO3 scaling potential.

Table 4-4
Comparison of Averaged Raw and Pretreated Raw Analytical Data

Parameter	Data are an Average of All Available Analytical Results					
	Raw FGD Wastewater from Reserve Lake	Pre-treat Raw FGD Wastewater from Reserve Lake	Reduction	Raw VSEP Reject	Pre-treat Raw VSEP Reject	Reduction
Units	mg/L	mg/L	%	mg/L	mg/L	%
Total Dissolved Solids	10893	10853	0.4%	32800	31667	3.5%
Total Suspended Solids	20	30	-48.7%	82	73	10.6%
Total Hardness (as CaCO3)	4750	4895	-3.1%	13633	11900	12.7%
Total Organic Carbon	1.88	1.40	25.6%	3.07	2.51	18.4%
Aluminum (Total)	0.0360	0.0251	30.3%	0.0395	0.0223	43.4%
Ammonia (as N)	0.31	0.30	0.6%	0.35	0.34	2.9%
Arsenic (Total)	0.017	0.017	-.07%	0.020	0.020	0.0%
Barium (Total)	0.145	0.133	7.7%	0.501	0.469	6.4%
Boron (Total)	62.3	58.5	6.1%	101	95	5.7%
Bromide	8.95	8.92	0.3%	19.8	22.2	-12.1%
Calcium (Total)	1547	1927	-24.6%	4507	4767	-5.8%
Chloride	2532	2770	-9.4%	7220	7323	-1.4%
Fluoride	5.26	1.02	80.6%	13.0	2.9	77.5%
Iron (Total)	0.0596	0.0500	16.2%	0.0500	0.0500	0.0%
Lithium (Total)	0.0359	0.0364	-1.2%	0.0786	0.0774	1.6%
Magnesium (Total)	181	20	88.7%	573	1.3	99.8%
Manganese (Total)	1.58	0.02	98.7%	0.21	0.0022	99.0%
Mercury	0.00107	0.00030	72.4%	0.01116	0.00122	89.1%
Nitrate (as N)	8.2	8.3	-1.2%	19.4	18.2	6.2%
Nitrite (as N)	0.304	0.258	15.0%	0.304	0.304	0.0%
Phosphate (Ortho)	0.1	0.26	-158.3%	0.79	0.7	11.4%
Potassium (Total)	5.12	5.10	0.2%	12.5	12.4	0.8%
Selenium (Total)	0.0671	0.0639	4.7%	0.228	0.194	15.0%
Silica (Reactive) Total	7.34	0.48	93.5%	16.0	0.7	95.4%
Sodium (Total)	17.0	18.4	-8.1%	28.9	39.3	-36.0%
Strontium (Total)	6.64	6.70	-0.9%	16.9	16.2	4.2%
Sulfate	1137	1319	-16.1%	3403	1260	63.0%

The data from Table 4-4 show the following:

- Fluoride, silica, magnesium, and manganese were all reduced by at least 77%.
- Mercury and aluminum were also reduced, albeit their concentrations were not high in the raw.
- The sulfate in the VSEP reject was reduced 63% as the calcium in the lime caused precipitation of calcium sulfate.
- Lime pretreatment also reduced organics up to 25%.
- Calcium concentrations increased after pretreatment due to the lime addition.

Solids were removed by a filter system. The filtrate was pH adjusted with sulfuric acid to reduce the pH to 3 as described in Section 3.1. The pH data from the pilot are summarized in Figure 4-1. The pH of the Flex EDR Selective feed (pretreated raw), treated water, and brine are all around pH 3 or lower. It is noted that the brine pH is around 2 due to Flex EDR Selective's concentration of protons (H^+) in the brine, which reduces the pH.

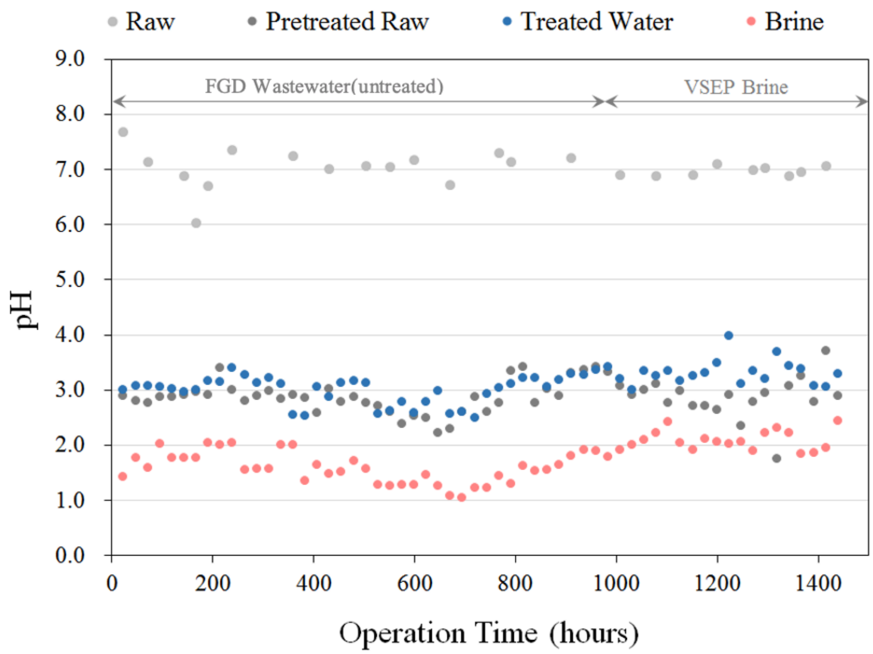

Figure 4-1
Summary of pH Data from the Flex EDR Pilot

The full analytical data are included in Table 4-5.

Table 4-5
Summary of Analytical Results of Flex EDR Selective Pretreated Raw

Date Sampled	3/27/2019	4/3/2019	4/8/2019	4/15/2019	4/22/2019	4/30/2019	5/8/2019	5/13/2019	5/20/2019
Operation Time (Hours)	69	237	357	525	693	885	1077	1197	1365
Parameter	Pretreated Raw FGD Wastewater (Untreated)					Pretreated Raw VSEP Reject			
Units	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Total Dissolved Solids	8420	10100	12000	10200	12000	12400	26900	35500	32600
Total Suspended Solids	35	32	24	21	32	33	61	77	81
Total Hardness (as CaCO3)	5370	4920	5340	4170	4440	5130	11300	11700	12700
Total Hardness Dissolved (as CaCO3)	5364	4820	5285	4400	4510	5210	10900	11900	12800
Total Organic Carbon	1.14	1.26	1.17	1.42	1.88	1.54	2.11	2.51	2.9
Alkalinity (as CaCO3)	<20	<20	42.4	<20	<20	<20	-	-	-
Aluminum (Total)	0.0274	0.0238	0.02	0.0384	0.0211	0.02	0.02	0.02	0.027
Aluminum (Dissolved)	0.0253	0.552	0.02	0.0567	0.02	0.02	0.02	0.02	0.02
Ammonia (as N)	0.321	0.39	0.31	0.26	0.305	0.24	0.4	0.24	0.37
Ammonia (as N 4500 NH3, ESL)	0.421	0.468	0.322	0.484	0.371	-	-	-	-
Arsenic (Total)	0.00316	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Arsenic (Dissolved)	0.00314	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Barium (Total)	0.128	0.115	0.11	0.133	0.148	0.166	0.428	0.454	0.525
Barium (Dissolved)	0.13	0.112	0.118	0.139	0.152	0.175	0.43	0.49	0.532
Boron (Total)	64.2	59.3	62.3	51.5	56.5	57.4	93.1	91	101
Boron (Dissolved)	63.5	59.5	61.5	51.2	56.2	57.7	90.2	91.2	99.1
Bromide	12.4	11.6	11.6	9.31	8.12	0.5	19.2	21.2	26.2
Calcium (Total)	2080	1940	2090	1640	1760	2050	4530	4700	5070
Calcium (Dissolved)	2080	1900	2070	1730	1790	2080	4380	4770	5110
Chloride	2950	3600	2690	2240	2350	2790	6830	7430	7710
Fluoride	0.939	0.921	1.03	0.6	1.36	1.28	2.63	2.41	3.75
Iron (Total)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Iron (Dissolved)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Lithium (Total)	0.0344	0.03	0.029	0.0447	0.0395	0.0405	0.0761	0.0778	0.0782
Lithium (Dissolved)	0.0359	0.0299	0.0315	0.0484	0.0415	0.0441	0.0763	0.0839	0.0771
Magnesium (Total)	41.9	18.5	28.9	19.1	10.6	3.07	1.06	1.69	1.13
Magnesium (Dissolved)	39.9	18.4	28.3	18.5	10.6	3.24	1.07	1.87	1.15
Manganese (Total)	0.0884	0.00893	0.00253	0.00576	0.0112	0.00536	0.0025	0.002	0.002
Manganese (Dissolved)	0.0896	0.0101	0.00286	0.00558	0.0115	0.00472	0.002	0.002	0.002
Mercury	0.0002	0.0002	0.0002	0.0002	0.0002	0.000776	0.00157	0.00137	0.000718
Nitrate (as N)	9.19	8.62	8.39	7.21	7.73	8.48	17.9	19.1	17.5
Nitrite (as N)	0.0304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304
Combined Nitrate/Nitrite (as N)	0.0152	8.5	7	5.2	-	-	-	-	-
Phosphate (Ortho)	0.1	0.15	0.1	0.1	0.1	1.0	1	0.1	1
Potassium (Total)	5.54	5.13	5.43	4.47	4.99	5.06	12.3	13.5	11.5
Potassium (Dissolved)	5.35	5.15	5.55	4.48	5.19	5.46	12.1	13.5	12.5
Selenium (Total)	0.073	0.0662	0.0596	0.0619	0.0635	0.0594	0.158	0.191	0.233
Selenium (Dissolved)	0.0789	0.0716	0.0607	0.0571	0.0683	0.0718	0.171	0.214	0.236
Silica (Reactive) Total	0.906	0.435	0.255	0.33	0.441	0.502	0.648	0.673	0.874
Silica (Reactive) Dissolved	0.961	0.397	0.288	0.384	0.382	0.546	0.726	0.735	0.918
Sodium (Total)	19.3	16.3	16.3	22	21.8	14.6	28.9	29.7	59.3
Sodium (Dissolved)	18.8	17.2	15.4	26.9	22.3	15.4	29	29.5	57.8
Strontium (Total)	7.73	7.1	7.66	5.81	5.73	6.16	14.5	15.8	18.2
Strontium (Dissolved)	7.49	7.12	7.55	5.57	5.78	6.48	14.5	15.7	17.9
Sulfate	1260	1460	1100	1580	1670	846	1190	1250	1340

4.3 Flex EDR Selective Pilot Results

4.3.1 Reliable Continuous Operation

The Flex EDR Selective pilot operated 24/7 for 61 days on two different FGD wastewater sources. The plant DAQ for the treated water and brine conductivities are plotted in Figure 4-2. The data show reliable operation with highly scaling waters due to:

- Flex EDR Selective's mAEM blocking sulfate from entering into the brine and concentrating, drastically reducing the potential for $CaSO_4$ scaling.
- Production of a predominantly $CaCl_2$ brine that has low scaling potential.
- Pretreatment reduced low-solubility metals, fluoride, and silica that could cause scaling, noting that the pretreatment does not use soda ash softening.
- Clean-in-Place (CIP) to prevent any scaling or fouling from becoming irreversible.
- Diligent Flex EDR Selective plant operations through daily checks and data review to identify any early deviations to the expected plant performance.
- The organics concentration in the wastewater was low with total organic carbons (TOC) being less than 5 mg/L; hence, fouling potential was minimal.

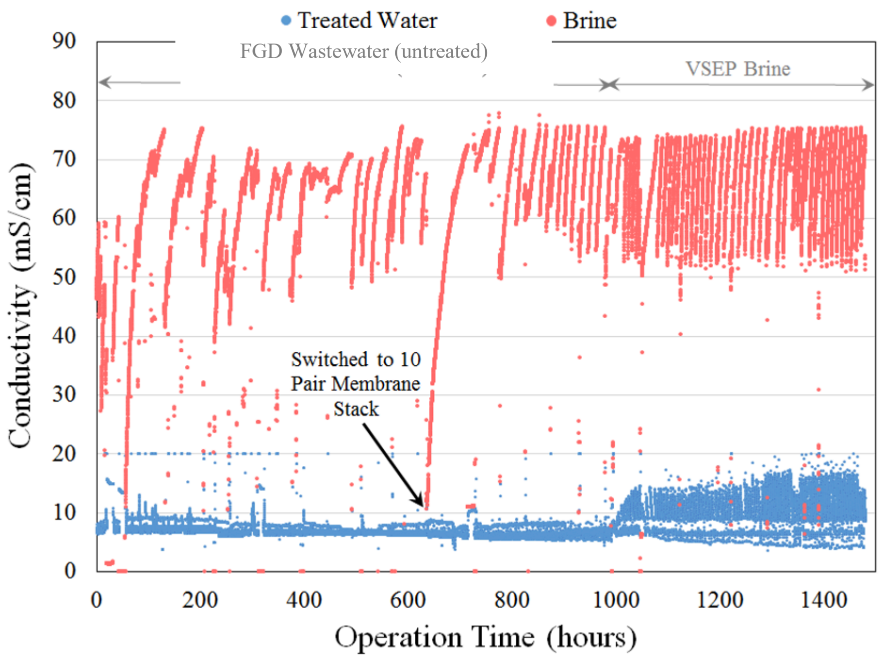

Figure 4-2
Flex EDR Selective Treated Water and Concentrated Brine Conductivities

EDR stack reversals were not used, as the above methods were effective in maintaining reliable plant operations. Antiscalants were also not used for the same reasons as above, and none were identified to be effective at a pH less than 3.

Stack resistance data confirmed that the Flex EDR Selective membranes remained free of scaling throughout the pilot. Inorganic scaling and organic fouling impact membrane performance and system reliability. The two wastewater sources tested had minimal organics with TOC ≤ 4 mg/L (see Table 4-1), so fouling is not expected. The main scalant that could impact performance would be calcium sulfate since others were removed by the pretreatment system (see Section 4.2).

The pilot's DAQ system recorded the Flex EDR Selective stack resistance. The data are summarized in Figure 4-3. The resistance data showed no indications of membrane scaling, staying steady throughout. The variability in resistance is due to changes in concentration, temperature effects, and as the current changes. Unlike static resistors, resistance in an EDR stack is dynamic. As a boundary layer is desalted or reduced in size, resistance changes. The higher resistance at the beginning of the pilot to 660 hours was due to the thicker stack with more compartments (see Section 4.1).

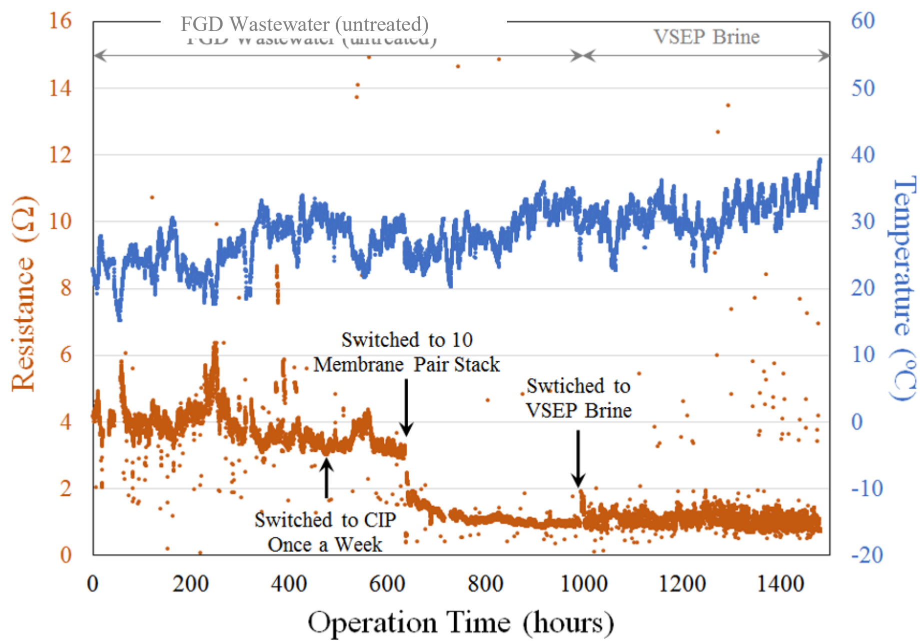

Figure 4-3
Flex EDR Selective Stack Resistance

The membranes were maintained, descaled, and cleaned by the plant's automated water flushes and CIP operations. Saltworks previously completed an off-site small-scale pilot to optimize the cleaning process and controls. Based on these test results, a water flush, and CIP recipe, frequency and procedure were established. The CIP solution was a 1% NaCl, which provides a conductive cleaning solution to remove any scale on the membranes. The automated cleaning process consisted of a 15-minute water flush followed by a 15-minute CIP solution on an every-two-day frequency. During the cleaning, the stack polarity was reversed to assist in an ionic "back flush" of any scalants into the CIP solution. The stack polarity was not reversed during normal operations, as explained earlier.

The cleaning processes maintained membrane performance throughout the pilot. At 489 hours, the frequency of CIP was reduced from every two days to once a week; the water flush was still maintained at every two days. The Flex EDR Selective maintained performance even at the decreased CIP frequency.

4.3.2 Recovery

The total plant recovery was 93.2% from treating 86.7 m^3 of both wastewater sources. Flex EDR Selective demonstrated potential to enable recycling over 90% of the FGD wastewater for internal power plant reuse while reducing the wastewater volume by 15 times. The high recovery is achieved without the need for soda ash softening or a thermal system. The recovery was determined by the inlet and outlet volume data measured during the pilot test and calculated by Equation 4-1:

$$\textbf{Recovery}\ (\%) = \frac{\textbf{Volume of Treated Water x 100}}{(\textbf{Volume of Raw+ Volume of Brine Makeup Water})} \qquad \textbf{Eq. 4-1}$$

The pilot recovery data are summarized in Table 4-6.

Table 4-6
Flex EDR Selective Pilot Water Balance and Recovery

	FGD Wastewater	VSEP Reject	Total
Raw In (m^3)	73.7	13.0	86.7
Brine Makeup Water In (m^3)	0.58	0.35	0.93
Treated Water Out (m^3)	70.8	10.9	81.7
Brine Out (m^3)	1.4	2.0	3.4
Recovery	**95.3%**	**81.6%**	**93.2%**
Wastewater Volume Reduction	**21.3x**	**5.4x**	**14.8x**
Water Retained in Plant (m^3)	-	-	3.0
In-Retained-Out Differential (m^3)	-	-	-0.5
Water Balance Difference (%)	-	-	-0.5%

The data show that a higher recovery of 95.3% was achieved on FGD wastewater (untreated) compared to the 81.6% on VSEP reject. Per mass balance mathematics, as inlet TDS increase for a set brine concentration TDS, the recovery decreases. The concentrated brine produced by both wastewater sources averaged 52,400 mg/L TDS.

Water balance data for the pilot were less than 1% difference (see Table 4-6). The volume data were based on the pilot's DAQ data from flow totalizers. The discrepancies between in and out are due to volume removal from the plant for analytical testing (that is, samples) not included in the water balance and expected measurement errors.

4.3.3 Flex EDR Selective Treated Water (Chloride Reduction)

Flex EDR Selective was effective in consistently reducing chloride concentrations in the two FGD wastewater sources down to 1500 mg/L. To confirm chloride reduction, samples of the raw wastewater and treated water were submitted to an analytical laboratory for a detailed chemistry characterization. The analytical results for chloride are summarized in Table 4-7. In addition to analytical lab checks, on-site pilot grab samples were performed to estimate the chloride concentration using an electrical conductivity Hach probe and the chloride/conductivity correlation seen in Figure 3-4. The data show the reduction of chloride to 1500 mg/L for both wastewater sources with VSEP reject having a greater chloride removal due to its higher initial chloride concentration. The samples from April 3, April 8, and May 8 had chloride concentrations higher than 1500 mg/L in the treated water. This was due to the original chloride goal range of 1500 to 2000 mg/L, which was subsequently revised to aim for the 1500 mg/L chloride goal and the tuning of the conductivity versus chloride concentrations correlation for plant operations. Once tuned and the goal clarified to the site operations team, the plant discharged the treated water, based on the correct conductivity correlating to a chloride concentration of 1500 mg/L. The full analytical data for the treated water are summarized in Table 4-8.

Table 4-7
Analytical Data for Chloride Concentration

Date	Hours of Operation	Feed Source	Chloride Concentration (mg/L)		Percent Removal
			Raw Feed	Treated Water	
April 3, 2019	237	FGD Wastewater	3,600	2,030	43.6%
April 8, 2019	257		2,690	1,710	36.4%
April 15, 2019	525		2,240	1,650	26.3%
April 22, 2019	693		2,350	1,380	41.3%
April 30, 2019	885		2,790	1,460	47.7%
May 8, 2019	1,077	VSEP Reject	6,830	1,630	76.1%
May 13, 2019	1,197		7,430	1,150	84.5%
May 20, 2019	1,365		7,710	1,260	83.7%

Table 4-8
Summary of Analytical Results for Flex EDR Selective Treated Water

Date Sampled	4/3/2019	4/4/2019	4/8/2019	4/11/2019	4/15/2019	4/18/2019	4/22/2019	4/24/2019	4/30/2019	5/8/2019	5/9/2019	5/13/2019	5/16/2019	5/20/2019	5/23/2019
Operation Time (Hours)	**237**	**261**	**357**	**429**	**525**	**597**	**693**	**741**	**885**	**1077**	**1101**	**1197**	**1269**	**1365**	**1437**
Parameter	**Treated Water FGD Wastewater (Untreated)**									**Treated Water VSEP Reject**					
Units	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**
Total Dissolved Solids	7570	6140	7960	7720	7620	7740	7460	7660	7010	7160	5290	4460	2710	3290	3380
Total Suspended Solids	9	9	12	12	15	22	13	8	20	23	8	8	5	5	8
Total Hardness Dissolved (as CaCO3)	2861	3121	3499	3590	3510	3790	3080	3080	3180	2830	2230	1470	1140	807	725
Total Organic Carbon	2.98	40.4	4.16	4.74	2.01	1.98	3.03	2.55	2.19	4.69	4.29	4.38	4.69	4.35	4.34
Alkalinity (as CaCO3)	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
Aluminum (Dissolved)	0.0837	0.0218	0.147	0.0902	0.02	0.02	0.0501	0.0206	0.02	0.02	0.02	0.02	0.02	0.027	0.02
Ammonia (as N)	0.23	0.25	0.22	0.22	0.23	0.3	0.231	0.22	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Ammonia (as N 4500 NH3, ESL)	0.183	0.155	0.285	0.306	0.423	0.297	0.229	-	-	-	-	-	-	-	-
Boron (Dissolved)	53.1	56.8	58.5	55.3	49.9	58.9	55.8	54	57	84	80.3	85.1	84.3	87.1	83.3
Bromide	3.49	3.53	4.61	4.25	5.2	4.2	2.47	2.15	0.716	0.733	2.22	0.682	0.915	1.51	1.21
Calcium (Dissolved)	1120	1220	1380	1420	1380	1500	1220	1220	1270	1130	891	587	458	323	290
Chloride	2030	1510	1710	1430	1650	1550	1380	1360	1460	1630	1370	1150	810	1260	1220
Fluoride	0.83	0.872	1.11	0.821	0.642	1.25	1.39	1.45	1.29	1.14	0.5	1.11	0.621	0.597	0.5
Manganese (Dissolved)	0.0255	0.00343	0.00446	0.0054	0.00447	0.00406	0.0132	0.00383	0.00286	0.00208	0.002	0.002	0.002	0.002	0.002
Mercury	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.000242	0.0002	0.0002	0.0002	0.0002	0.0002
Nitrate (as N)	2.41	2.61	3.13	-	3.67	3.57	2.26	2.4	2.47	2.4	1.86	1.11	0.735	1.52	1.21
Nitrite (as N)	0.304	0.304	0.304	0.609	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304	0.304
Combined Nitrate/Nitrite (as N)	2.9	2.8	2.7	3.6	2.5	-	-	-	-	-	-	-	-	-	-
Phosphate (Ortho)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Strontium (Dissolved)	4.35	4.94	4.89	4.16	4.32	4.32	4.2	4.15	4.16	3.76	3.08	2.37	0.825	0.887	0.969
Sulfate	1190	1330	1240	1050	1520	1470	1530	1460	1060	930	825	883	614	530	391

The chloride concentrations from the pilot grab samples are summarized in Figure 4-4.

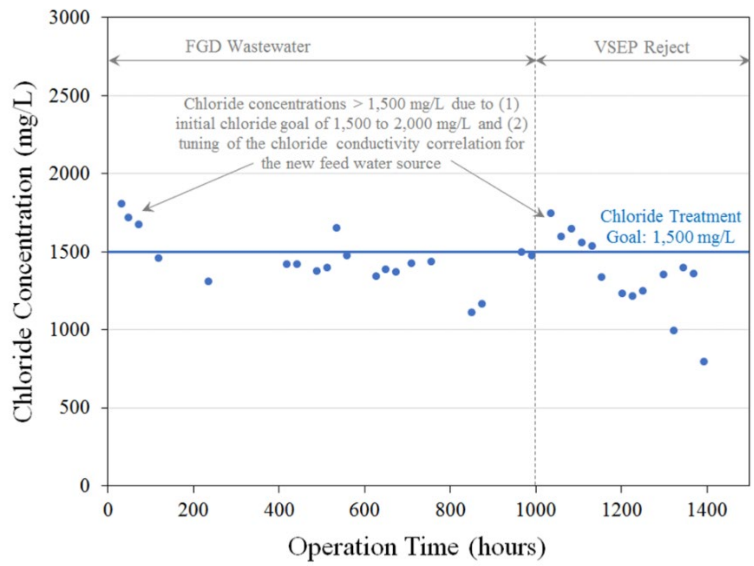

Figure 4-4
Chloride Concentrations in Treated Water from Pilot Grab Samples

4.3.4 Selective Chloride Separation

Flex EDR Selective reduced chloride in the FGD wastewater while rejecting sulfates from entering into the brine. Analytical data for both chloride and sulfate concentrations are presented in Figure 4-5. It should be noted that the sulfate concentration for the raw feed in the graph is from the pretreated samples; unlike chloride, sulfate concentrations in the water were affected by pretreatment. The high pH adjustment step of lime dosing results in sulfate precipitation as calcium sulfate. The subsequent low pH adjustment step of sulfuric acid dosing added sulfate back into the water. Therefore, in Figure 4-5 below, the raw pretreated water data were used for comparison with the treated water sulfate concentration.

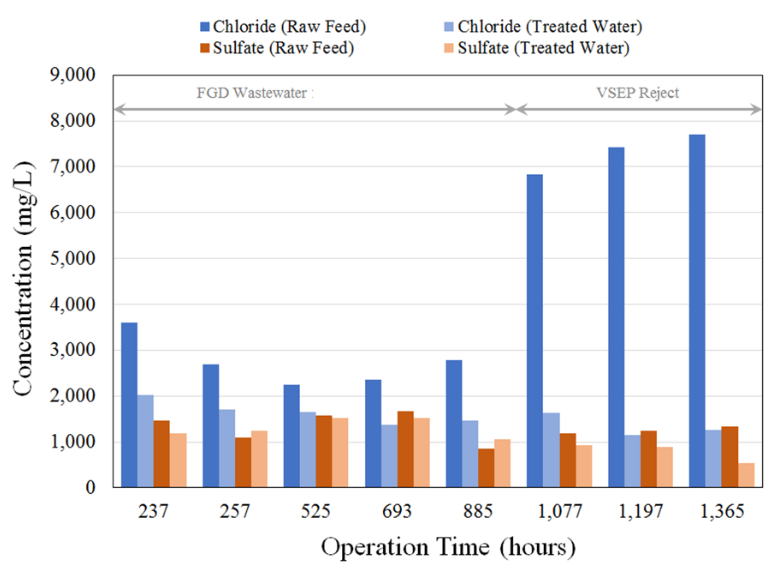

Figure 4-5
Chloride Removal with Sulfate Rejection

The data show that, for the FGD wastewater (untreated) feed, sulfate was rejected by Flex EDR Selective. Chloride concentration results clearly show a reduction, whereas the sulfate concentration difference between the feed and treated water was ±25% (no clear reduction trend). For the VSEP reject feed source, chloride results also clearly show a reduction in concentration. However, sulfate shows a slight concentration reduction from feed to treated water. This is expected as the VSEP reject has two to three times higher chloride concentration in the feed. Since the IonFlux mAEM is not 100% selective (that is, some sulfate passes through), there will be some reduction in sulfate concentration in the treated water. This is more noticeable when there is a larger chloride mass reduction required (that is, VSEP reject) to reach the treated water target of 1500 mg/L.

4.3.5 Flex EDR Selective Brine

The Flex EDR Selective pilot produced a minimal-scaling concentrated brine with an average TDS of approximately 52,400 mg/L. The brine consists of predominantly calcium chloride, as shown in Table 4-9. Calcium and chloride comprised 93.9% of the brine TDS. Nitrate, sodium, and sulfate represented 4.4%, and the remaining 0.7% were other ions and metals.

Table 4-9
Brine Composition as a Percentage of TDS

Chloride	61.5%
Calcium	32.4%
Sodium	3.4%
Nitrate	1.0%
Sulfate	1.0%

Sulfate was present in the brine throughout the pilot, but the average concentration was ~550 mg/L, which keeps calcium sulfate in solution. The mAEM and the proprietary sulfate removal system were effective in preventing sulfates from concentrating in the brine. The detailed analytical results for the brine are summarized in Table 4-10.

Table 4-10
Summary of Analytical Results for Flex EDR Selective Brine

Date Sampled	4/1/2019	4/2/2019	4/16/2019	4/19/2019	4/24/2019	4/29/2019	5/8/2019	5/9/2019	5/14/2019	5/16/2019	5/20/2019	5/23/2019
Operation Time (Hours)	189	213	549	621	741	861	1077	1101	1221	1269	1365	1473
Parameter	Brine FGD Wastewater (Untreated)						Brine VSEP Reject					
Units	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L			
Total Dissolved Solids	131000	118000	88100	140000	170000	132000	146000	142000	158000	142000	121000	170000
Total Suspended Solids	5	204	256	238	223	1790	5	495	5	248	5	30
Total Hardness (as CaCO3)	39900	42600	42500	48100	47800	48300	49500	50200	40200	39200	33700	32700
Total Hardness Dissolved (as CaCO3)	40677	43395	41300	48100	47800	48300	49200	48200	40500	38700	36500	33500
Total Organic Carbon	2.19	84.4	10	10	9.38	5	0.826	0.773	1.1	1.16	1.08	1.37
Alkalinity (as CaCO3)	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
Aluminum (Total)	0.158	0.141	0.0388	0.02	0.044	0.0294	0.02	0.0252	0.0249	0.02	0.0499	0.0218
Aluminum (Dissolved)	0.157	0.142	0.0406	0.02	0.0323	0.0216	0.0207	0.02	0.02	0.02	0.0448	0.02
Ammonia (as N)	1.7	1.5	1.6	1.9	2.2	1.7	1.2	1.1	1	0.96	1.1	1.1
Ammonia (as N 4500 NH3, ESL)	1.36	1.65	1.66	1.92	-	-	-	-	-	-	-	-
Arsenic (Total)	0.02	0.02	-	0.0214	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Arsenic (Dissolved)	0.02	0.02	2.59	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Barium (Total)	1.55	1.76	2.59	1.5	1.21	1.27	2.04	1.91	1.42	1.34	1.61	1.56
Barium (Dissolved)	1.57	1.78	2.51	1.6	1.27	1.3	2.05	1.88	1.41	1.36	1.69	1.61
Boron (Total)	30.5	32.9	33.1	40.4	25.1	24.5	38.9	31.1	40.9	48.1	45.9	46.7
Boron (Dissolved)	31.5	33.4	31.5	40.5	25.7	24.6	38.7	30.7	40.4	48.7	49.3	46.4
Bromide	166	194	238	211	160	91.5	119	115	103	104	98	89
Calcium (Total)	15700	16800	16800	19100	19000	19300	19800	20100	16100	15700	13500	13100
Calcium (Dissolved)	16000	17100	16300	19100	19000	19300	19700	19300	16200	15500	14600	13400
Chloride	36500	15400	32900	32800	35100	34500	36800	34700	33300	34000	32700	31800
Fluoride	1.5	1.5	1.5	1.5	1.89	1.5	2.07	1.13	1.5	1.57	2.56	1.81
Iron (Total)	0.05	0.0601	1.5	0.05	0.0702	0.0687	0.0556	0.05	0.05	0.05	0.0631	0.05
Iron (Dissolved)	0.0527	0.0563	1.5	0.05	0.0705	0.0654	0.0562	0.05	0.05	0.05	0.0608	0.05
Lithium (Total)	0.0416	0.0524	0.0975	0.157	0.106	0.105	0.133	0.134	0.142	0.148	0.148	0.168
Lithium (Dissolved)	0.0414	0.0519	0.0969	0.156	0.108	0.104	0.127	0.13	0.137	0.152	0.158	0.166
Magnesium (Total)	174	166	136	92	80	27.2	8.49	6.36	6.38	5.4	4.08	3.54
Magnesium (Dissolved)	176	169	134	95.9	79.5	27.3	8.47	6.28	6.45	5.46	5.05	3.53
Manganese (Total)	0.563	0.0801	0.045	0.047	0.107	0.071	0.0295	0.0157	0.00304	0.004	0.00762	0.00683
Manganese (Dissolved)	0.569	0.0876	0.041	0.0432	0.109	0.0657	0.0274	0.0173	0.00312	0.00352	0.00706	0.00654
Mercury	0.000484	0.0002	0.0002	0.0002	0.000861	0.0035	0.0133	0.0107	0.00611	0.00476	0.00353	0.00219
Nitrate (as N)	134	151	198	172	152	149	119	101	86.3	81.9	73.6	63.5
Nitrite (as N)	0.913	0.913	0.913	0.913	0.913	0.913	0.913	0.304	0.913	-	0.913	0.913
Combined Nitrate/Nitrite (as N)	150	120	200	-	-	-	-	-	-	-	-	-
Phosphate (Ortho)	0.31	0.1	1	1	1	1	1	1	1	1	1	1
Potassium (Total)	34.7	56.7	35.4	52.7	38.3	32.4	49.7	52.1	43	42.1	39.4	45.7
Potassium (Dissolved)	35.4	58.3	37.7	52.4	38.3	32.9	49.3	50.1	42.9	42.3	45.8	45.6
Selenium (Total)	0.0455	0.0512	-	0.0374	0.0464	0.0284	0.0728	0.0743	0.147	0.188	0.179	0.173
Selenium (Dissolved)	0.0518	0.0532	-	0.051	0.0514	0.0305	0.0872	0.0842	0.172	0.199	0.187	0.196
Silica (Reactive) Total	1.07	1.28	1.27	0.567	1.39	1.66	1.29	1.59	1.64	1.64	1.46	1.52
Silica (Reactive) Dissolved	1.07	1.26	1.62	0.591	1.22	1.75	1.25	1.62	1.64	1.74	1.52	2.00
Sodium (Total)	1090	871	128	191	463	267	540	692	3100	3930	4540	5170
Sodium (Dissolved)	1170	880	124	196	469	270	530	658	3190	3850	4770	5270
Strontium (Total)	53.4	47.3	41.1	43.4	56.4	53.9	54.8	57.3	54.2	49.4	44.1	43
Strontium (Dissolved)	53.7	47.7	39.5	44	56.2	54.5	54.9	56.8	53.8	50	45.7	42.9
Sulfate	479	434	548	812	612	473	473	425	566	670	578	492

The scaling analysis shows that the brine is minimal-scaling. Calcium sulfate is < 55% of the solubility limit at these high brine concentrations. Barium sulfate and strontium sulfate solubility limits are 10 times higher in concentrated calcium chloride[1] than in the raw FGD wastewater. Hence, their concentrations in the brine are less than 10% of their solubility limit. All other potential scalants were removed by the pretreatment system.

The data in Table 4-10 also showed that total suspended solids (TSS) were present in some of the brine samples. It is unknown why TSS are present. All samples submitted to the laboratory had no observable turbidity or solids (suspended or settled). Further investigation is required to identify an explanation.

In addition to the unknown TSS in the brine analytical work, the analytical data in Table 4-10 also showed a large disparity between the lab analyzed TDS and the summation of dissolved ions. In some cases, this difference was as high as 150% between the measured and calculated values. After additional X-ray diffraction analysis by the third-party analytical lab, it was determined that, when using the Environmental Protection Agency's Method SM2540C to measure TDS, the evaporated calcium chloride salts rehydrated from the anhydrous form to the dihydrate and tetrahydrate forms between removal from the desiccator and the final weighing. This speciation change led to artificially high measured TDS values in the lab results and should be considered when analyzing the lab results. Because of this, it is recommended by the analytical lab that the calculated TDS determined by the summation of dissolved ions be used as a more accurate measure of the sample TDS.

4.3.6 Current Limit Test

An important operating parameter for Flex EDR is current; this is the current applied to the electrodes. The operating current induces the transport of salt ions across the membranes inside the Flex EDR stack. Higher currents increase salt flux and thereby, reduce membrane area requirements. However, there is a current limit. At this limit, concentration polarization can occur: ions are not able to transport fast enough to the membrane surface, resulting in localized splitting of water into H^+ and OH^- ions. This is in inefficient use of power.

The current limit is determined by measuring the current at increasing voltages of a specific concentration of the FGD wastewater and at maximum brine concentration. The inflection points at which the current no longer increases with an increasing voltage is the current limit.

For stack operation, the operating current is recommended to be set at 80% of the current limit. The current limit is highly dependent on process conditions such as temperature, flow rates, and the conductivity of the "treated water" and "brine." This information informs of operating parameter on a full-scale stack. Since the current is independent of the stack size, the current limit test was conducted with the 10-membrane pair stack. Figure 4-6 is a summary of the current limit tests completed at different "treated water" conductivities and at the highest brine concentration.

[1] Davis and Collins (1971). *Solubility of Barium and Strontium Sulfates in Strong Electrolyte Solutions*. Environmental Science & Technology. Volume 5, Number 10, Pages 1039–1043.

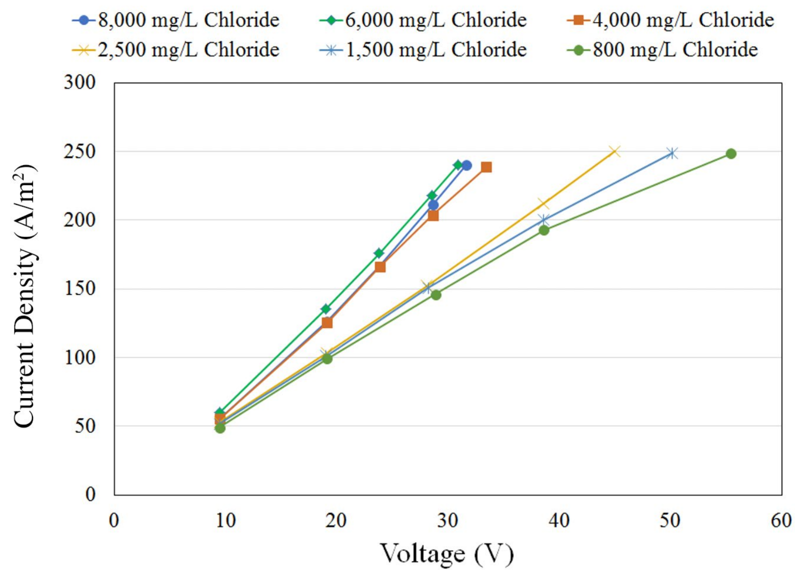

Figure 4-6
Current Limit Test Results

The results show that there is no current limit in the current range tested for treated water chloride concentration above 2500 mg/L, while the current limit is 200 A/m2 when chloride is reduced to 1,500 mg/L. Reducing chloride concentration further to 800 mg/L results in a lower current limit of 150 A/m^2. The current density is proportional to how fast the salt is removed from water—fluxed across the ion exchange membranes. The higher the current density that can be applied, the less membrane area and number of stacks are required for a certain water capacity. The data suggest that if a chloride concentration much lower than 1500 mg/L is required, then additional stacks operating at lower current densities with more membrane area to compensate for the lower flux are required. A current limit of 200 A/m^2 was used for full-scale economics to reduce chlorides to 1500 mg/L, since plant operators confirmed that a chloride goal of 1500 to 2000 mg/L for internal recycle is appropriate. Therefore, it is not economically worthwhile to desalt below 1500 mg/L chlorides.

4.4 Chemicals Consumption

Chemicals used during the pilot were tracked to determine consumption. The chemicals used in the pilot were:

- Pretreatment
  - Lime: pH adjustment to increase the pH to approximately 11 for mercury, manganese, fluoride, and silica removal
  - Sulfuric acid: pH adjustment to decrease the pH to approximately 3 to inhibit carbonation scaling
- Flex EDR Selective
  - NaCl: Flex EDR Selective electrode hardness blocker rinse solution and CIP solution
  - Na_2SO_4: Flex EDR Selective electrolyte
  - Biocide: Prevent biological growth

See Section 2 for an overview of the electrode hardness blocker to protect the Flex EDR electrodes. The chemicals consumption during the pilot are summarized in Table 4-11.

Table 4-11
Pilot Chemicals Consumption

Process Unit	Chemicals	FGD Wastewater (untreated)	VSEP Reject
Pretreatment	Lime (kg/m^3)	1.1	3.6
	98% H_2SO_4 (kg/m^3)	0.16	0.77
Flex EDR Selective	NaCl (kg/m^3)	0.32	0.51
	Na_2SO_4 (kg/m^3)	0.13	0.19
	Biocide (kg/m^3)	0.001	0.001

5
ECONOMICS

An economic analysis of two full-scale plants was completed by the technology provider. The analysis is based on water chemistry of two representative FGD wastewater samples received previously during off-site pilot testing (Table 5-1).

Table 5-1
Design Basis Water Chemistry

Parameter	FGD Wastewater Chemistry #1	FGD Wastewater Chemistry #2
Units:	mg/L	mg/L
pH	7.00	7.02
Total Dissolved Solids	14300	8280
Total Hardness (as CaCO3)	9590	5920
Total Organic Carbon	-	6
Alkalinity (as CaCO3)	60	48
Aluminum	0.032	<0.25
Antimony	<0.0025	<0.025
Arsenic	0.002	<0.005
Barium	0.502	0.276
Beryllium	<0.00025	<0.0025
Bicarbonate (as CaCO3)	60	48
Boron	181	94.7
Bromide	27.4	14.1
Cadmium	0.0829	0.0434
Calcium	2730	1840
Carbonate (as CaCO3)	<1	<1
Chloride	5990	3380
Chromium	0.0054	<0.025
Cobalt	0.00225	0.0028
Copper	0.0032	<0.025
Fluoride	8.6	5.5
Hydroxide (as CaCO3)	<1	<1
Iron	<0.02	<0.1
Lead	<0.00025	<0.0025

Parameter	FGD Wastewater Chemistry #1	FGD Wastewater Chemistry #2
Units:	mg/L	mg/L
Lithium	0.123	0.058
Magnesium	674	322
Manganese	2.97	1.69
Mercury	0.0016	0.0091
Molybdenum	0.0462	0.016
Nickel	0.29	0.14
Nitrate (as N)	19.8	10.6
Nitrite (as N)	<0.05	<0.05
Nitrate + Nitrite (as N)	19.8	10.6
Phosphorus	18	1.5
Potassium	17.9	7
Selenium	0.12	0.071
Silica (Reactive)	31.2	16.8
Silicon	13.4	7
Silver	<0.001	<0.010
Sodium	91	28
Strontium	15.3	10.6
Sulfate	1290	1090
Thallium	0.0035	0.0028
Tin	<0.00025	<0.0025
Titanium	<0.005	<0.05
Uranium	0.0412	0.0343
Vanadium	<0.005	<0.05
Zinc	1.36	0.87

Flex EDR Selective economics for a full-scale 258-gpm (1407-m^3/day) plant are presented in Table 5-2. Two scenarios are presented for treating the two FGD wastewater source: Chemistry #1 at 8380 mg/L TDS and Chemistry #2 at 14,300 mg/L TDS. The economic analysis excludes installation, brine management, disposal, and labor. Capitalization is assumed for 20 years, 8% interest, and 90% uptime. Labor projected to be one full-time equivalent with electrical and mechanical maintenance as required.

Table 5-2
Summary of Full-Scale Plant Economic Analysis (±40% and all in USD)

		Flex EDR Selective Chemistry #1 @ 8280 mg/L TDS	Flex EDR Selective Chemistry #2 @ 14,300 mg/L TDS
Total Plant Inlet Flow (FGD + Makeup Water)	GPM	258	258
	m^3/day	1,407	1,407
FGD Wastewater Inlet Flow	GPM	250	250
	m^3/day	1,361	1,361
FGD Wastewater Inlet TDS	mg/L	8,280	14,300
Reject Brine Flow	GPM	5	17
	m^3/day	28	91
Reject Brine Outlet TDS	mg/L	130,000	130,000
Treated Water Flow	GPM	253	241
	m^3/day	1,379	1,316
Treated Water Discharge TDS	mg/L	6,210	6,210
Treated Water Discharge Chlorides	mg/L	1,500	1,500
Membrane System Treated Water Recovery	%	98.0%	93.6%
Capitol Cost[1]	**$**	**$1,843,792**	**$5,064,691**
	$/$m^3$ inlet	**$0.42**	**$1.15**
Lime	$/$m^3$ inlet	$ 0.57	$ 0.83
Soda Ash (Na_2CO_3)	$/$m^3$ inlet	$ -	$ -
Hydrochloric Acid (31% HCl)	$/$m^3$ inlet	$ 0.24	$ 0.36
Biocide	$/$m^3$ inlet	$0.002	$0.002
Sodium Chloride (NaCl)	$/$m^3$ inlet	$0.21	$0.27
Sodium Sulphate (Na_2SO_4)	$/$m^3$ inlet	$0.06	$0.06
Total Chemical Cost	**$/yr**	**$486,406**	**$680,592**
	$/$m^3$ inlet	**$1.09**	**$1.52**
Energy Requirement[2]	kWh/m^3 inlet	8.03	25.84
Energy Requirement	kW	455	1,465
Energy Cost	**$/yr**	**$215,312**	**$693,037**
	$/$m^3$ inlet	**$0.48**	**$1.55**
Membrane Replacement	**$/yr**	**$45,048**	**$97,671**
	$/$m^3$ inlet	**$0.10**	**$0.22**
Annual Operating Cost[2]	**$/yr**	**$746,765**	**$1,471,300**
	$/$m^3$ inlet	**$1.67**	**$3.29**
Total Cost of Ownership (excludes install, labor)	**$/$m^3$ inlet**	**$2.09**	**$4.45**
	$/kgal	**$7.92**	**$16.84**

1: Excludes install, brine management, disposal. Capitalization assume 20 years, 8% interest, 90% uptime.

2: Excludes labor and disposal costs. Labor projected to be 1 FTE + Electrical/Mechanical maintenance as required.

A
DATA COLLECTION

Data from the pilot test were captured with the intent of providing sufficient data for the design and costing of a full-scale plant. Three types of data were collected during the bench testing: DAQ, manual measurements, and analytical.

A.1 Data Acquisition (DAQ)

The pilot plant comes complete with a 24/7 DAQ system from all electronic transmitters in the plant to record the key operating parameters at every minute frequency. Daily plots of conductivity, tank level, and stack resistance were performed.

A.2 Manual Measurements

Manual measurements are performed daily per manual data sheet to inform pilot performance, sensor calibration, mass, and volume balance.

A.3 Analytical

Analytical data are representative of samples collected at specific sampling ports within the pilot plant and analyzed for specific parameters. There are two types of analytical data that were collected during the testing program. These are described below.

Bench top. These analyses were completed at the pilot as a screen for key parameters of interest. Saltworks completed analyses for total solids and conductivity.

Laboratory. Outside lab analyses using an independent third-party laboratory were used for full characterization of the water. Samples were collected, stored, and transported to the laboratory, as per the laboratory recommended procedures.

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