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Performance Evaluation of a Vibratory Shear Enhanced Processing Membrane System for FGD Wastewater Treatment

2014 TECHNICAL REPORT

Performance Evaluation of a Vibratory Shear Enhanced Processing Membrane System for FGD Wastewater Treatment

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Abstract

Steam electric power generating units are facing with stringent discharge limits for selenium, mercury, arsenic, and nitrite/nitrate in flue gas desulfurization (FGD) wastewater. The purpose of this demonstration project was to evaluate the efficacy of a commercially available technology that could assist power generating units with FGD wastewater treatment.

A pilot Vibratory Shear Enhanced Processing/Spiral Reverse Osmosis (VSEP/RO) System from New Logic Research, Inc., (consisting of a 0.5 gpm [0.11 m^3/h] VSEP pilot unit equipped with an RO membrane and a 2.5 gpm [0.57 m^3/h] spiral RO pilot) was installed at the Water Research Center at Georgia Power's Plant Bowen in Cartersville, Georgia. Contaminant removal efficiencies, flux rate, percent water recovery, and operational parameters (that is, cleaning and fouling) of the VSEP/RO system were evaluated during a three-month test program using gypsum-saturated FGD wastewater.

The VSEP/RO system effectively removed selenium, mercury, arsenic, and nitrate/nitrite from gypsum-saturated FGD wastewater with total dissolved solids (TDS) levels of 7,702–15,672 mg/L (7,710.8–15,689.9 ppm) to levels below the proposed effluent guidelines. The first stage, VSEP pilot unit, removed approximately 94% TDS, while the second stage, Spiral RO pilot unit, removed an additional 5.8% TDS, yielding an overall TDS removal efficiency of 99.8%. The VSEP pilot unit can be operated in two modes: batch concentration mode or single-pass process mode. But regardless of the VSEP pilot unit mode of operation, no irreversible membrane fouling was observed throughout this study; an acidic cleaning of the VSEP pilot unit followed by a basic cleaning successfully restored flux rates to original levels. The addition of anti-scalant (10 mg/L [10 ppm]) to the system improved the water recovery by as much as 30% (from 50% to 80%).

Keywords
Effluent limitation guidelines
Flue gas desulfurization
Reverse osmosis
Vibratory Shear Enhanced Processing Membrane System
Wastewater treatment
Water reuse

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Section 1: Introduction

The use of the Vibratory Shear Enhanced Processing Membrane System (VSEP) from New Logic Research, Inc., (NLR) to remove high total dissolved solids (TDS) from flue gas desulfurization (FGD) wastewater and other power plant waste streams could provide significant cost and energy savings compared to conventional thermal zero liquid discharge (ZLD) technologies. FGD wastewaters may contain up to 10,000 mg/L (10,011.4 ppm) of total suspended solids (TSS) and up to 70,000 mg/L (70,080 ppm) of TDS for those power plants that recirculate or recycle the FGD wastewater in their scrubber systems. The VSEP/Reverse Osmosis (RO) system could be used as a volume reduction step upstream of thermal ZLD technologies to produce highly concentrated wastewater brine, thereby reducing the required capacity, capital, and operational expenditure of the ZLD system.

VSEP is a membrane filtration technology that uses vibration to minimize fouling of the filtration media. The VSEP can generate a clean permeate stream of water and a volume-reduced concentrated waste stream. This project evaluated the effectiveness of a VSEP/RO system to treat FGD wastewater to provide acceptable permeate quality for reuse or discharge. Specifically, the objectives of the project were to:

- Provide performance data on removal efficiencies of the key regulatory constituents of selenium, mercury, arsenic, and nitrite/nitrate as well as of other anions and cations in the wastewater being treated.
- Evaluate operational conditions (that is, cleaning) for minimization of fouling and extended membrane life.
- Determine flux rate and percent water recovery.

Section 2: Background

Membrane-based separations of liquids from solids are common, but many membrane devices have issues with fouling. This long-term loss in throughput capacity is due primarily to the formation of a boundary layer that builds up naturally on the membrane surface during the filtration process. To help minimize this boundary layer buildup, membrane designers have used a method known as *tangential-flow* or *cross-flow filtration* that relies on high-velocity fluid flow pumped across the membrane surface as a means of reducing the boundary layer effect. However, New Logic Research developed an alternative method, called VSEP (Jaffrin, 2008; Shi and Benjamin, 2009; Shi and Benjamin, 2008; Johnson, et al., 2006).

VSEP

NLR has developed an alternative method for producing intense shear waves on the face of a membrane. The technique is called *Vibratory Shear Enhanced Processing* (VSEP) and is applied to a membrane filter pack that consists of leaf elements arrayed as parallel discs and separated by gaskets. See Figure 2-1. Shear cleaning action is created by vigorously vibrating the leaf elements in a direction tangent to the faces of the membranes. The shear waves produced by the membrane's vibration cause solids and foulants to be lifted off the membrane surface and remixed with the bulk material flowing through the membrane stack (Jaffrin, 2008; Shi and Benjamin, 2009; Shi and Benjamin, 2008; Johnson, et al., 2006).

The disk stack is oscillated above a torsion spring that moves the stack back and forth rapidly, approximately 7/8" (2.22 cm). The oscillation produces a shear at the membrane surface of about 150,000 inverse seconds (equivalent to over 200 Gs of force), which is approximately 10 times the shear rate of the best conventional cross-flow systems. More important, the shear in a VSEP system is focused at the membrane surface where it is cost effective and most useful in preventing fouling, while the bulk fluid between the membrane disks moves very little.

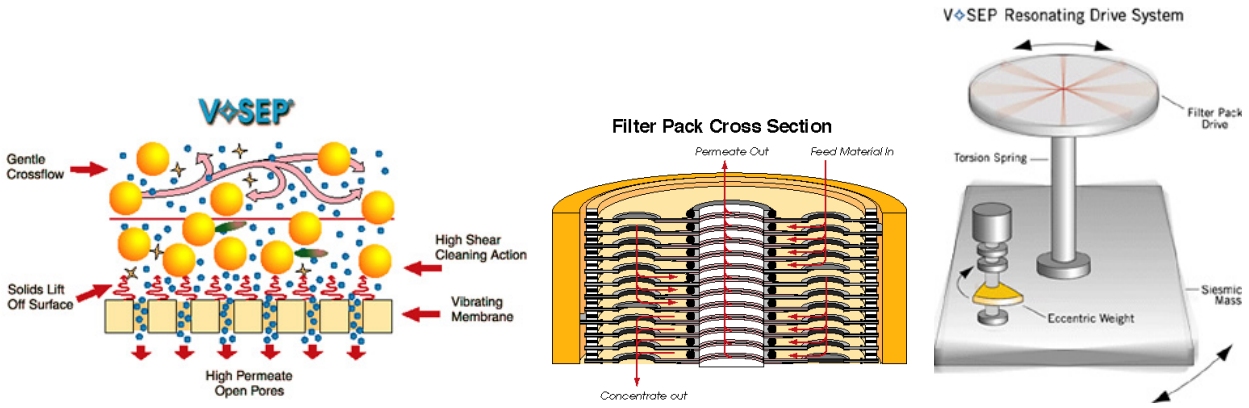


Figure 2-1
VSEP cross flow and filter pack cross section

Section 3: Experimental Plan

In order to evaluate the effectiveness of the VSEP/RO system when applied to power plant FGD wastewater streams, a VSEP pilot (P) unit with 16.9 ft^2 (1.57 m^2) of membrane area and a Spiral RO pilot unit was tested at the Water Research Center (WRC) located at Georgia Power's Plant Bowen over a three-month period. A pressure study was performed to determine the optimal pressure for FGD wastewater treatment. Next, the pre-treatment step was optimized for pH and anti-scalant dosage. Then, the system was operated in batch concentration mode and single-pass process mode to compare the performance of each concentration method. In addition, a high-pressure study was completed to determine the maximum percent water recovery for FGD wastewater.

Equipment and Setup

NLR provided a VSEP membrane filtration P-unit and periphery equipment (auto-LP). The P-unit was installed with a Reverse Osmosis (RO) membrane called Energy-Saving Polyamide (ESPA) from Hydranautics. The auto-LP is an optional unit that connects to the VSEP pilot unit and has a data logger and basic automation that was used for pilot testing. The ESPA membrane was chosen based on previous bench-scale testing at NLR's laboratory. The bench-scale results are presented in Appendix A. A spiral-wound RO membrane unit was installed with the Low Fouling Composite (LFC) membrane from Hydranautics and was used as a polishing stage for the VSEP permeate. Figure 3-1 is a photograph of a VSEP pilot unit that was tested at the WRC. Figure 3-2 shows the Spiral RO System.

Figure 3-1
VSEP pilot unit

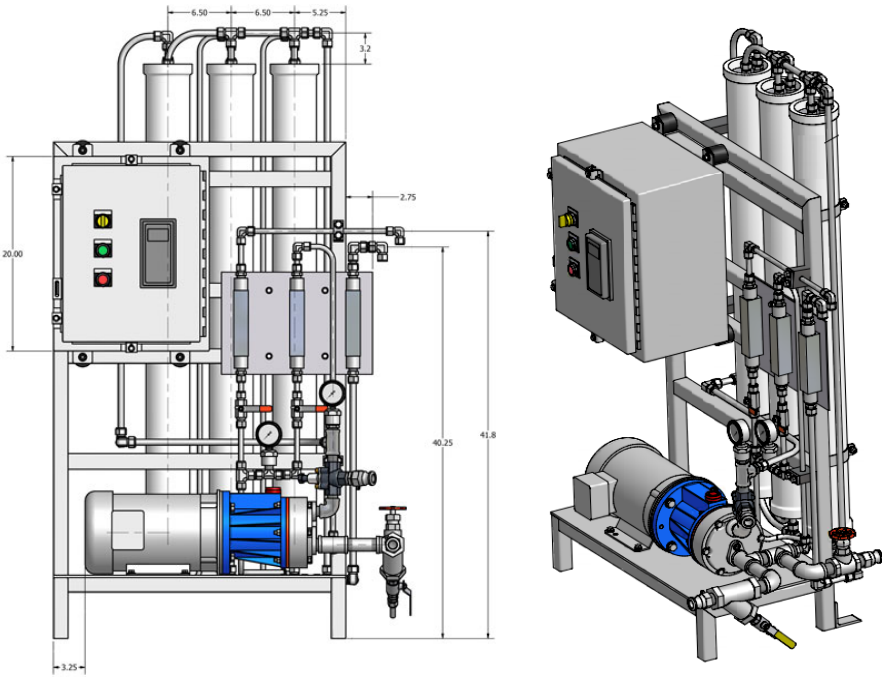


Figure 3-2
Spiral RO System

The VSEP pilot unit can be operated in two modes: batch concentration mode or single-pass process mode. In batch mode, a finite volume of feed is processed with concentrate sent back to the feed tank, while permeate is sent to a separate destination. As the permeate is removed, the feed tank volume is decreased and becomes concentrated until an end point based on permeate flow or another desired set point is reached. The concentrate flow is held constant and maximizes cross flow and, in combination with vibration, will reduce the overall rate of fouling. Batch mode is optimum for maximum volume reduction. The batch mode schematic is shown in Figure 3-3.

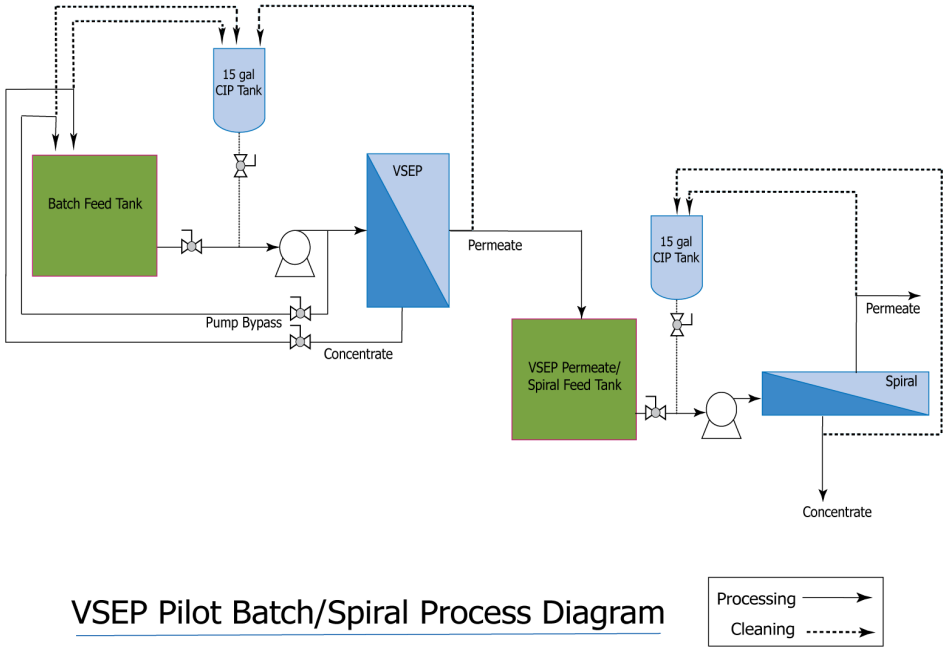


Figure 3-3
Pilot testing batch process flow diagram

In single-pass mode, the feed enters the filter pack and the concentrate valve is closed while permeate is continuously removed to a separate destination. The system totalizes permeate flow and opens the concentrate valve once the calculated total permeate volume required has been achieved, based on input parameters from the user. The concentrate material is purged when the concentrate valve is cycled open. When the valve is closed, the feed is concentrated inside the membrane system in one pass through the membrane. Dead-heading the membrane can limit the recovery and flux of the membrane compared to batch mode. Figure 3-4 presents a process flow diagram for the single-pass mode process.

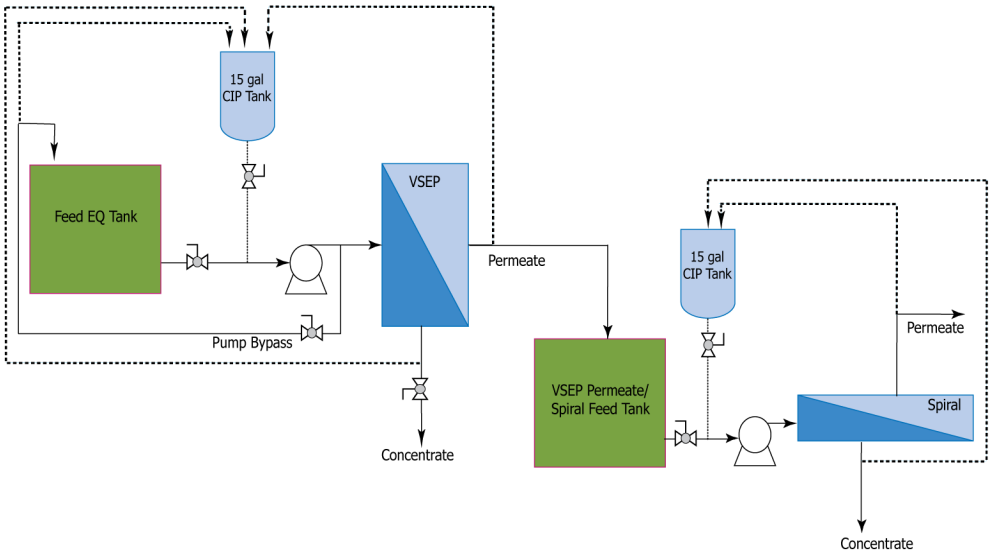


Figure 3-4
Pilot testing single-pass mode process flow diagram

Pressure Study

After the VSEP system operated on feed material and was stable, a pressure study was completed. The flux was recorded at various pressures (that is, 200 psi [1379 kPa], 300 psi [2068 kPa], 400 psi [2758 kPa], 450 psi [3103 kPa], and 500 psi [3447 kPa]). The flux was temperature corrected to 25°C (77°F). The temperature-corrected flux was plotted against pressure (see Figure 4-1).

Pre-Treatment Optimization

The initial feed (FGD wastewater) material was tested in batch mode to establish a baseline for performance without adding anti-scalant or adjusting the feed pH. Next, 10 mg/L (10 ppm) of NLR 759 anti-scalant was added to the feed to increase the flux rate. Finally, the pH of the feed was adjusted to 6.5 in order to further increase the flux rate and optimize the pre-treatment process. Conductivity and pH of feed, VSEP permeate, and VSEP concentrate were measured using composite samples.

Single-Pass Concentration

With the pre-treatment optimized, the system was set up in single-pass concentration for process optimization. The system was set up at 70% recovery and tested at 400 and 500 psi (2758 and 3447 kPa). The system recovery was increased to 75% recovery at 500 psi (3447 kPa) and tested for long-term performance. The system operated 181 hours. The first cleaning was performed based on a timed interval, and afterward, the system operated until permeate decreased to a low-permeate flow set point.

The VSEP permeate and VSEP concentrate were collected in two separate 275 gal (1041 liters) tote bins, and the VSEP permeate was processed with the spiral RO unit after each VSEP run. Three composite samples from feed, VSEP permeate, and VSEP concentrate totes were taken as well as two grab samples from spiral RO permeate and spiral RO concentrate streams. The collected five samples were analyzed for pH, conductivity, TSS, TDS, and nitrate/nitrite. In addition, the processed composite samples (that is, feed, VSEP permeate, VSEP concentrate) and grab samples (that is, spiral RO permeate and spiral RO concentrate) were taken during the 75% recovery run at 500 psi (3447 kPa) and were sent for full characteristics analysis. The full characteristics analysis included pH, conductivity, alkalinity, TSS, TDS, and total solids (TS), anions, ammonium, selenium speciation, dissolved and total metals, and dissolved and total mercury.

High-Pressure Study

To provide an option for higher recovery, a second stage of testing on the VSEP concentrate was conducted at 800 psi (5516 kPa). The concentrate (250 gal [946 L]) from the 75% recovery single-pass run was collected for a high-pressure (that is, 800 psi [5516 kPa]) batch concentration test. The equipment was operated at 500 psi (3447 kPa), 600 psi (4137 kPa), 700 psi (4826 kPa), 800 psi (5516 kPa), 900 psi (6205 kPa), and 1000 psi (6895 kPa). The temperature-corrected flux rates were plotted against pressure.

In the first stage (single-pass concentration at 500 psi [3447 kPa]), the VSEP permeate and VSEP concentrate were collected in two separate totes, and the VSEP permeate was processed with the spiral RO unit after each VSEP run. Three composite samples from feed, VSEP permeate, and VSEP concentrate totes were taken as well as two grab samples from spiral RO permeate and spiral RO concentrate streams.

In the second stage, the collected VSEP concentrate was concentrated further in batch mode at 800 psi (5516 kPa) to maximize the flux and recovery. The material was concentrated until the permeate flow decreased below the flow set point. The VSEP permeate 2 and VSEP concentrate 2 were collected in two separate totes. Two composite samples were taken from VSEP permeate 2 and

VSEP concentrate 2. The VSEP permeate 2 was processed with the spiral RO and produced spiral RO permeate 2 and spiral RO concentrate 2. Two grab samples were taken from the spiral RO permeate and spiral RO concentrate streams.

In total, nine samples were collected and analyzed for pH, conductivity, TSS, and TDS. The permeate samples were analyzed for nitrate/nitrite.

Batch Mode

The VSEP system was tested in batch mode with 10 mg/L (10 ppm) of NLR 759 to compare to the single-pass concentration performance for an economic analysis. A feed tank with 250 gallons (946 L) of feed was processed until the flux rates declined and reached the low-permeate flow set point. The batch was repeated five times with a chemical cleaning between each batch.

Analytical Methods

The analytical methods employed are shown in Table 3-1.

Table 3-1
Analytical methods and procedure details

Parameter	Method	Container	Preservation	Holding Time
Trace metals - total recoverable	EPA 200.8/6020	500 ml HDPE	HNO_3 to pH<2	180 Days
Trace metals - dissolved	EPA 200.8/6020	500 ml HDPE	HNO_3 to pH<2	180 Days
Low-level Hg - total recoverable	EPA 1631e	125 ml glass	BrCl to Color	28 days/ 90 days
Low-level Hg - dissolved	EPA 1631e	125 ml glass	BrCl to Color	28 days/ 90 days
Speciation	UHPLC-ICP-CRC-MS	250 ml HDPE	Cool 4°C	n.a.
Anions	EPA 300.0	1 L HDPE	Cool 4°C	48 hours/ 28 days
Cations	ASTM D6919-09	1 L HDPE	Cool 4°C	28 days
Alkalinity	ASTM D1067-06	1 L HDPE	Cool 4°C	14 days
pH	EPA 150.2	1 L HDPE	None	Immediate
Conductivity	EPA 120.1	1 L HDPE	Cool 4°C	28 days
TS/TSS/TDS	ASTM D5907-03	1 L HDPE	Cool 4°C	7 days

1 L = 0.26 gal
1 ml = 0.00026 gal
°F = (°C x 9/5) + 32

Section 4: Results and Discussions

FGD Wastewater Chemistry

The FGD wastewaters utilized for evaluating the VSEP performance had a TDS content varying between 7,702 mg/L (7,710.8 ppm) and 15,672 mg/L (15,690 ppm) with an average value of 12,536 mg/L (12,550 ppm). The conductivity of the FGD wastewater varied between 11,200 and 17,760 µS/cm with an average conductivity of 15,118 µS/cm.

FGD wastewater is mainly composed of calcium, magnesium, sodium, chloride, and sulfate. Table 4-1 presents ranges for major anion and metal concentrations in FGD wastewater used in this project.

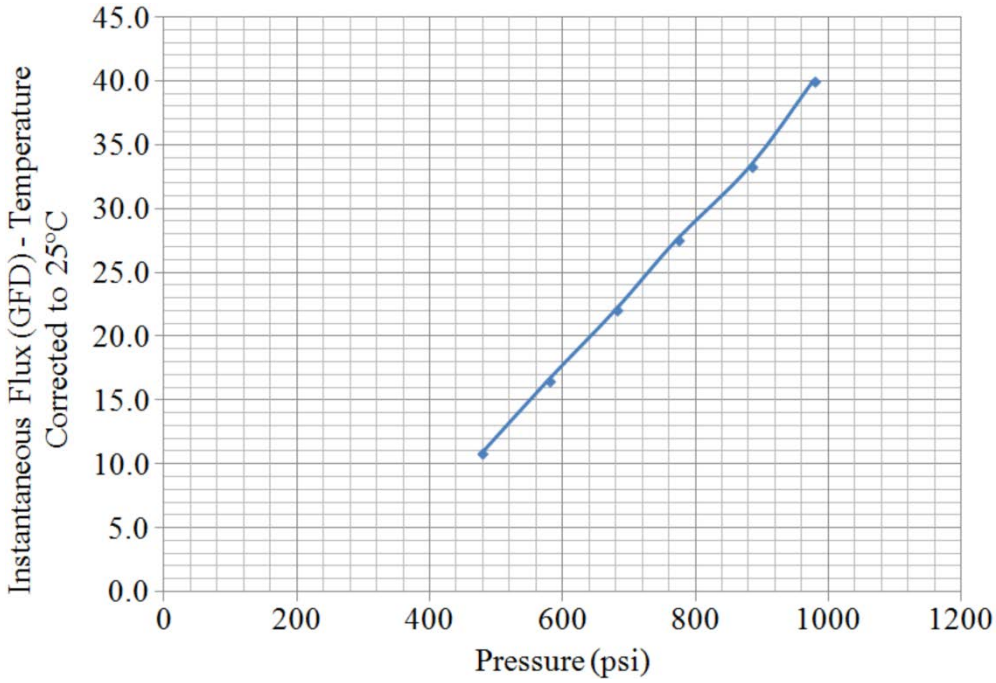
Table 4-1
Major anion and cation concentration ranges in the FGD wastewater

Parameter	Concentration
TDS (mg/L)	7,702–15,672
Selenium (µg/L)	191–273
Mercury (ng/L)	928–1,403
Arsenic (µg/L)	< 5
Nitrate/Nitrate as N (mg/L)	13–24
Chloride (mg/L)	4,106–8,014
Sulfate (mg/L)	1,015–1,444
Calcium (mg/L)	2,096–2,982
Magnesium (mg/L)	383–646
Sodium (mg/L)	23–52

1 mg/L = 1 ppm
1 µg/L = 1 ppb
1 ng/L = 1 ppt

Pressure Study

The relationship between flux and pressure was found to be linear, and 400–500 psi (2,758–3,447 kPa) pressure was chosen for the remainder of the study except for the high-pressure study, which was conducted at 800 psi (5,516 kPa). Figure 4-1 illustrates the results of the pressure study, depicting corrected flux rate versus different operation pressure.

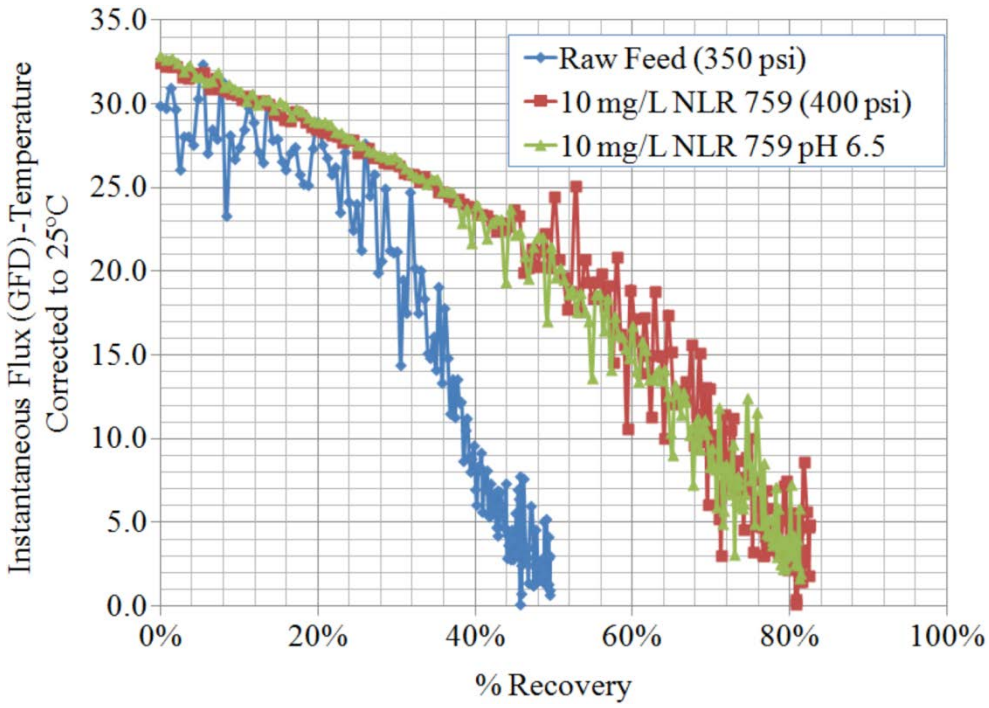


1 GFD = 1.70 LMH
1 psi = 6.9 kPa
°F = (°C x 9/5) + 32

Figure 4-1
Pressure study – temperature corrected flux rate vs. pressure

Pre-Treatment Optimization

The first batch ended at 50% water recovery, and to increase flux rate of the system, 10 mg/L (10 ppm) of NLR 759 anti-scalant was added to the feed. The addition of the NLR 759 improved the performance to achieve 80% water recovery. Adjusting the pH of the feed can increase the solubility of common foulants and further improve performance, but in this case, decreasing the feed pH to 6.5 did not show an improvement from adding anti-scalant alone. The addition of 10 mg/L (10 ppm) of NLR 759 was used for the remainder of tests. The results are shown in Figure 4-2 and Tables 4-2 and 4-3. The flux rate increased from 11.6 gallons per ft^2 per day (GFD) (19.7 liters per m^2 per hour [LMH]) to 14.8 GFD (25.2 LMH) when 10 mg/L (10 ppm) of antiscalant was added. Adjusting the feed pH to 6.5 and adding 10 mg/L (10 ppm) of antiscalant resulted in a negligible (0.2 GFD [0.34 LMH]) flux rate increase.



1 mg/L = 1 ppm
1 psi = 6.9 kPa
°F = (°C x 9/5) + 32
1 GFD = 1.70 LMH

Figure 4-2
Batch concentration pre-treatment comparison study

Table 4-2
Batch concentration pre-treatment performance summary

Pre-treatment	Pressure	Initial Flux*	Ending Flux*	Average Flux*	% Recovery	Run Time (Minutes)
None	350 psi (2,413 kPa)	29.9 GFD (50.9 LMH)	3.0 GFD (5.1 LMH)	11.6 GFD (19.7 LMH)	50%	900
10 mg/L NLR 759	400 psi (2,758 kPa)	32.4 GFD (55.1 LMH)	4.9 GFD (8.33 LMH)	14.8 GFD (25.2 LMH)	82.5%	1015
10 mg/L NLR 759 + pH 6.5	400 psi (2,758 kPa)	32.9 GFD (56.0 LMH)	2.0 GFD (3.4 LMH)	15 GFD (25.5 LMH)	81.4%	980

*Flux rates are corrected to 25°C (77°F).
1 mg/L = 1 ppm

Table 4-3
Batch concentration pre-treatment analytical summary

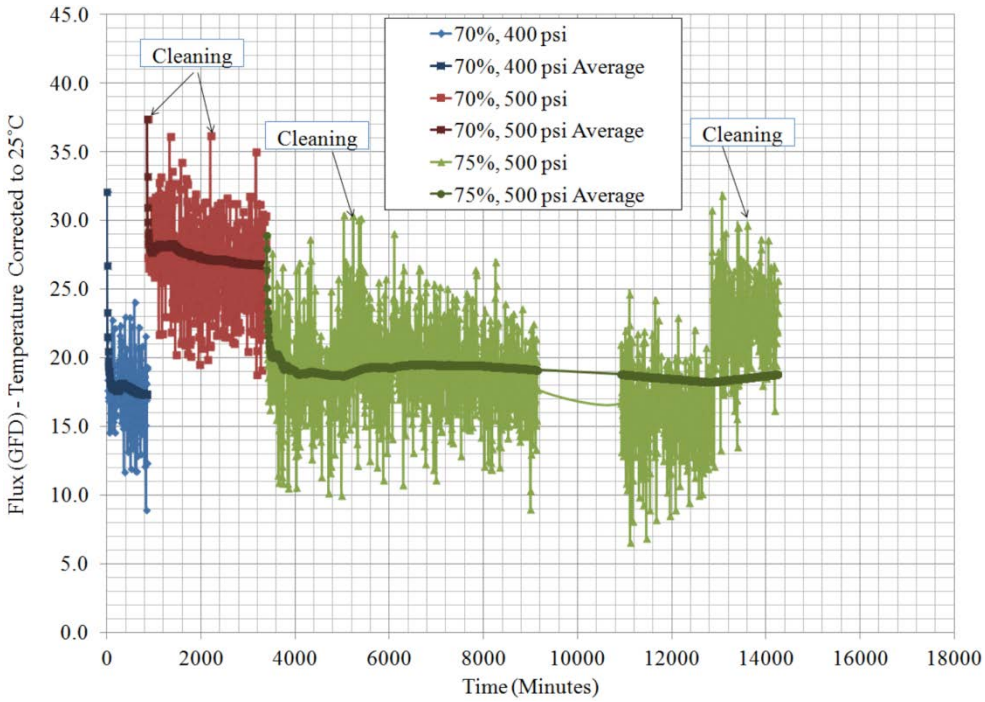
Pre-treatment	pH			Conductivity		
	Feed	Permeate	Concentrate	Feed	Permeate	Concentrate
None	7.15	6.88	7.24	16,720 µS/cm	539 µS/cm	28,900 µS/cm
10 mg/L NLR 759	6.78	6.44	7.32	16,630 µS/cm	880 µS/cm	61,800 µS/cm
10 mg/L NLR 759 + pH 6.0	6.48	6.18	6.83	16,630 µS/cm	930 µS/cm	62,200 µS/cm

*Recorded in the field with a portable meter
1 mg/L = 1 ppm

Single-Pass Concentration

Processing FGD wastewater through VSEP modules equipped with RO followed by spiral-wound RO membranes (VSEP/RO) yielded an effluent that met the proposed effluent limitation guidelines for selenium, arsenic, mercury, and nitrate/nitrite. The VSEP/RO system was very effective in removing dissolved solids, and the overall TDS and conductivity were reduced 99.8%. No membrane fouling was observed. An acidic and basic cleaning restored the membrane flux rate and the system's efficiency in removing contaminants of interest. In single-pass concentration, the water recovery of 75% and flux rate of 18.8 GFD [32.0 LMH] was achieved at 500 psi (3,447 kPa) operating pressure. In this process, 10 mg/L (10 ppm) of anti-scalant (NLR 759) was added to initial feed.

Figure 4-3 presents the temperature-corrected flux rate versus time. After approximately 67 hours of operation and seven cleaning procedures, the RO membrane used in the VSEP pilot unit was conditioned and stabilized. The cleaning effectively recovered the permeate flow rate and showed long-term performance stability during eight single-pass operation events. During each event, the VSEP pilot unit was operated until a low-level set point permeate flow rate was achieved. At this point, a cleaning was performed to restore the flux rate. Table 4-4 summarizes the flux rates achieved at different conditions.



1 psi = 6.9 kPa
°F = (°C x 9/5) + 32
1 GFD = 1.70 LMH

Figure 4-3
Single-pass concentration corrected flux rates

Table 4-4
Single-pass flux rate summary

% Recovery	Pre-Treatment	Pressure	Average Flux*	Run Time
70%	10 mg/L NLR 759	400 psi (2,758 kPa)	17.3 GFD (29.4 LMH)	14 hours
70%	10 mg/L NLR 759	500 psi (3,447 kPa)	26.8 GFD (45.6 LMH)	42 hours
75%	10 mg/L NLR 759	500 psi (3,447 kPa)	18.8 GFD (32.0 LMH)	181 hours

*Flux rates are temperature corrected to 25°C (77°F).
1 mg/L = 1 ppm

The VSEP pilot (alone) reduced about 95.1% of the TDS in the FGD wastewater, and overall, 99.8% TDS removal was achieved in the VSEP/RO system's effluent. Table 4-5 shows average values of basic water characteristics measured in this study. Eight sets of samples were collected during the single-pass test events. The results from eight measurements were averaged and are

shown in Table 4-4. The detailed analytical results for TSS, pH, conductivity, TDS, and nitrate/nitrite for each sample are presented in Appendix B. The VSEP permeate and Spiral RO permeate were very clear with non-detectable TSS.

Table 4-5
Single-pass analytical summary – basic characteristics

Parameters	TSS (mg/L)	pH	Conductivity (µS/cm)	TDS (mg/L)	Nitrate/Nitrite (mg/L)
Initial feed (average*)	94	7.26	17,300	14,901	n.a.**
VSEP permeate (average*)	n.d. (<1)	6.31	688	754	0.47
Spiral RO permeate (average*)	n.d. (<1)	6.71	24	26	0.04
VSEP concentrate (average*)	407	7.01	62,288	66,164	n.a.**
Spiral RO concentrate (average*)	3	6.02	1,906	1,514	n.a.**

1 mg/L = 1 ppm
* Average of eight measurement for eight different samples.
** These samples were not measured for nitrate/nitrite.

Selenium, arsenic, mercury, and nitrate/nitrite in the Spiral RO permeate were comfortably below the proposed effluent guidelines as shown in Table 4-6. The full analytical characteristics are presented in Appendix C.

Table 4-6
Single-pass analytical summary – full characteristics

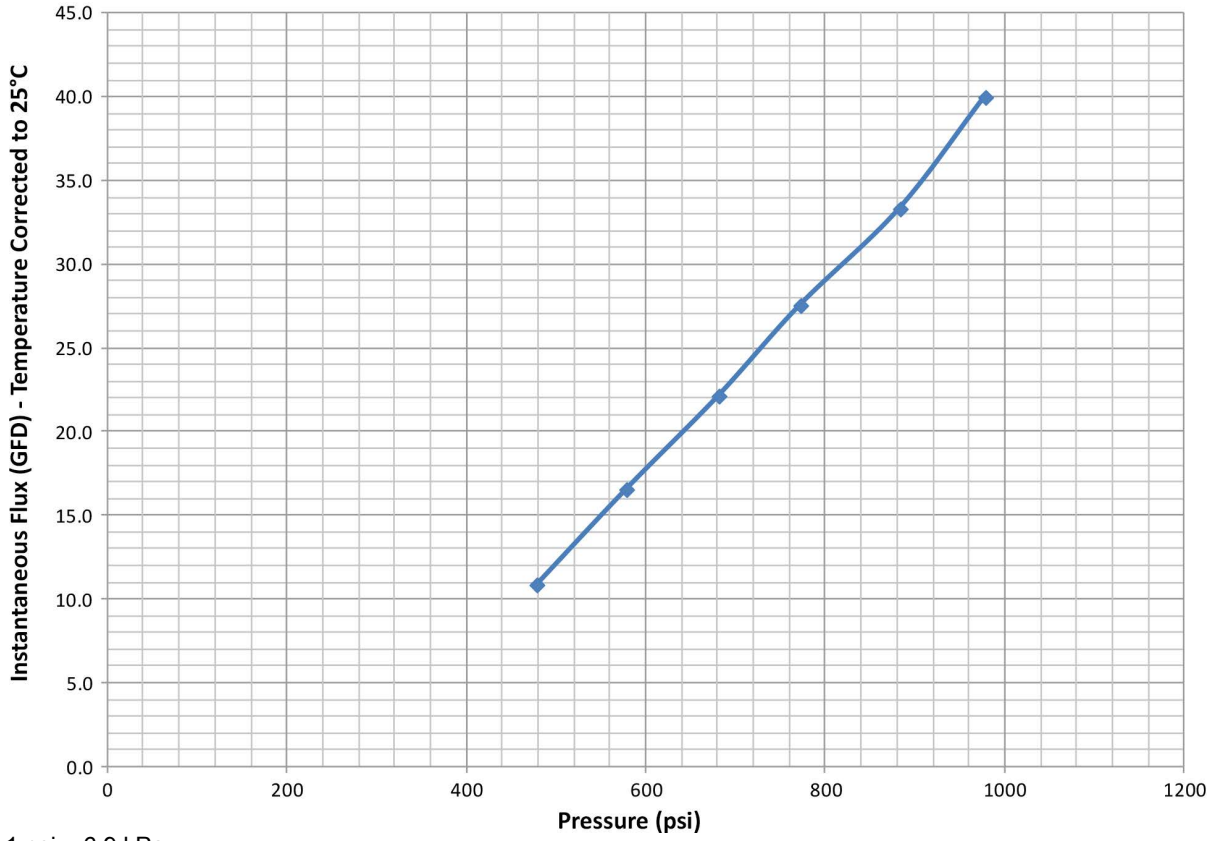
Parameter	Feed (FGD Wastewater)	VSEP Permeate	Spiral RO Permeate	Limits	% Removal Efficiency
Selenium (µg/L)	191	1.5	n.d. (<1)	10	>99.9%
Mercury (ng/L)	1,403	35.35	11.03	119	99.2%
Arsenic (µg/L)	n.d. (< 5)	n.d. (<1)	n.d. (<1)	6	>80.0%
Nitrate/Nitrate as N (mg/L)	23.74	0.60	0.04	0.13	99.8%
Chloride (mg/L)	8,014.4	254.3	n.d. (<25)	-	>99.7%
Sulfate (mg/L)	1,443.7	n.d. (<25)	n.d. (<25)	-	>98.3%
Calcium (mg/L)	2,982.5	72.7	n.d. (<2)	-	>99.9%
Magnesium (mg/L)	646.3	12.5	n.d. (<0.05)	-	>99.99%
Sodium (mg/L)	52.1	12.5	2.5	-	95.2%

1 µg/L = 1 ppb
1 mg/L = 1 ppm

High-Pressure Study

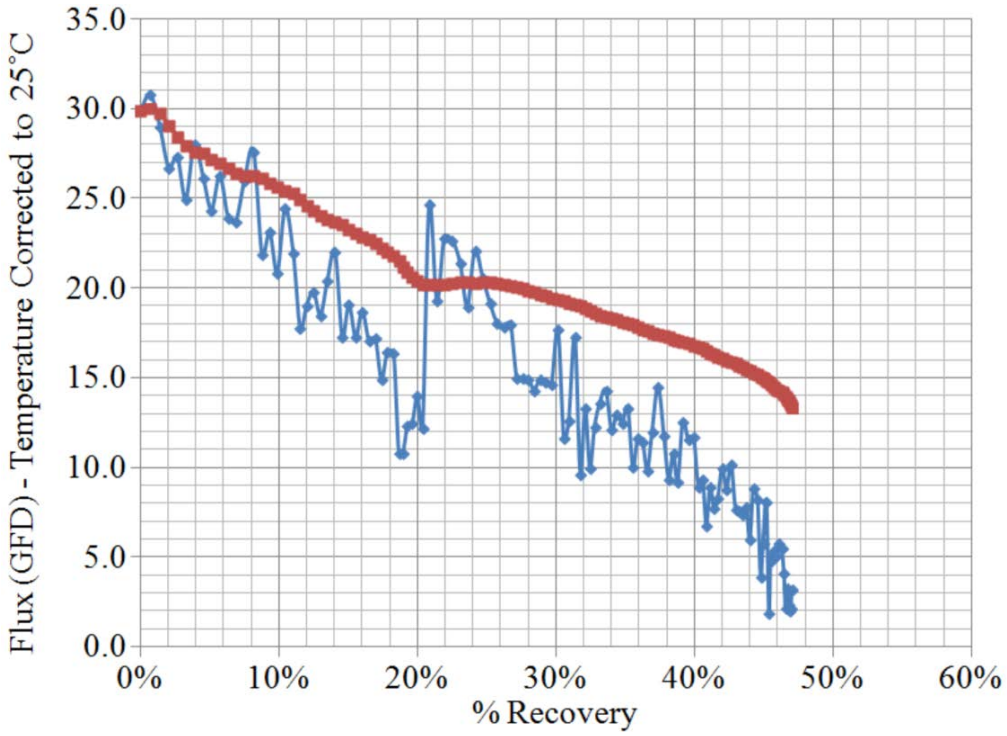
The VSEP concentrate can be further processed using the VSEP pilot unit at a higher pressure to achieve greater water recovery. In a single-pass operation, 75% water recovery was achieved at 500 psi (3,447 kPa). When the VSEP concentrate was further processed through the VSEP pilot unit at 800 psi (5,516 kPa), an overall water recovery of 86.8% was achieved.

The standard full-scale VSEP system is capable of operating at 550 psi (3,792 kPa) (and a high-pressure system is available for specific applications that can be operated at pressures up to 1,000 psi (6,895 kPa). To overcome osmotic pressure in the high TDS concentrate, a pressure study was conducted with the VSEP pilot system. The relationship between pressure and permeate flux was found to be linear, and the results are shown in Figure 4-4. The operating pressure chosen for the second stage of the VSEP high-pressure study was 800 psi (5,516 kPa). At this pressure, the VSEP system was able to achieve 47% recovery, yielding an overall system recovery of 86.8% (75% + 0.47 × 25%) of the permeate. The average flux rate for the stage 2 process was 13.4 GFD (22.8 LMH). The results are shown in Figure 4-5 and Tables 4-7 and 4-8.



1 psi = 6.9 kPa
°F = (°C x 9/5) + 32
1 GFD = 1.70 LMH

Figure 4-4
Stage 2 pressure study for 500–1,000 psi (3,447–6,895 kPa)



°F = (°C x 9/5) + 32
1 GFD = 1.70 LMH

Figure 4-5
High-pressure stage 2 batch concentration

Table 4-7
Performance summary at 80% recovery

Pre-treatment	Pressure	Initial Flux*	Ending Flux*	Average Flux*	% Recovery	Spiral %Recovery**	Run Time (Minutes)
None	800 psi (5,516 kPa)	29.9 GFD (50.9 LMH)	3.2 GFD (5.44 LMH)	13.4 GFD (22.8 LMH)	47%	79%	585

*Flux rates are temperature corrected to 25°C (77°F).
** At 150 psi (1034 kPa)
1 GFD = 1.70 LMH

The VSEP permeate and Spiral RO permeate qualities obtained from the high-pressure study were comparable to those obtained in the single-pass studies. The VSEP permeate TDS in the high-pressure study was 838 mg/L (839 ppm), and this value was in the VSEP permeate TDS range (342–1,020 mg/L [342.4–1,021.2 ppm]) achieved in the single-pass study. The Spiral RO polished the VSEP permeate and produced high-quality water with a TDS of 40 mg/L (40 ppm).

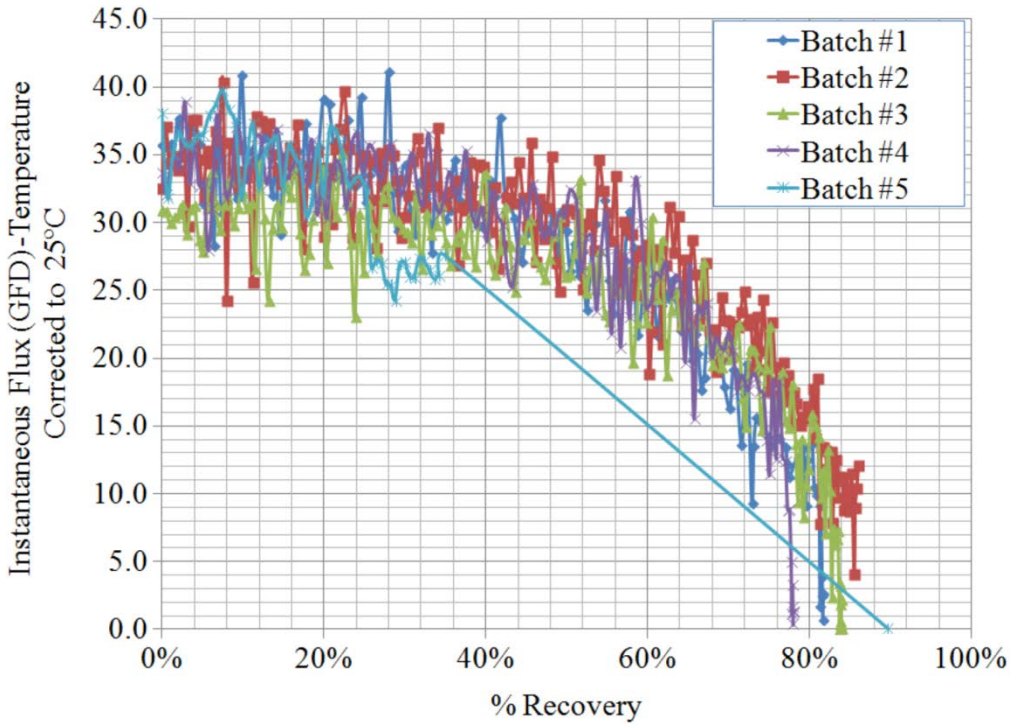
Table 4-8
Single-pass analytical summary – basic characteristics

Parameters	TSS (mg/L)	pH	Conductivity (µS/cm)	TDS (mg/L)	Nitrate/Nitrite (mg/L)
Initial feed	482	6.99	59,700	54,196	n.a.*
VSEP permeate	n.d. (<1)	6.51	1,587	838	1.00
Spiral RO permeate	n.d. (<1)	6.87	35.7	40.0	0.08
VSEP concentrate	1,086	6.75	89,700	88,828	n.a.*
Spiral RO concentrate	10	6.09	4,280	3,210	n.a.*

1 mg/L = 1 ppm
*These samples were not measured for nitrate/nitrite.

Batch Mode

Processing FGD wastewater with TDS levels of 7,702–9,824 mg/L (7,710.8–9,835.2 ppm) through the VSEP/RO system yielded a final effluent that met the proposed effluent limitation guidelines for selenium, arsenic, mercury, and nitrate/nitrite. In batch mode, the average performance of the system was 25.5 GFD (43.4 kPa) and 83.2% recovery at 500 psi (3,447 kPa) at 25°C (77°F). The batch mode flux rate (25.5 GFD [43.4 kPa]) and respective water recovery (83.2%) were higher than those (18.8 GFD [32.0 kPa] and 75%) achieved in single-pass concentration at 500 psi (3,447 kPa). No membrane fouling was observed. An acidic and basic cleaning restored membrane flux rate and efficiency in removing contaminants of interest. The flux rate results are shown in Figure 4-6 and Tables 4-9, 4-10, and 4-11. In this process, 10 mg/L (10 ppm) of anti-scalant (NLR 759) was added to the initial feed, and the test was repeated five times. The system was intermittently operated for 80 hours and consistently achieved low-level TDS in permeates.



°F = (°C x 9/5) + 32
1 GFD = 1.70 LMH

Figure 4-6
Batch mode corrected flux rates

The cleaning of the VSEP system effectively recovered permeate flow and showed long-term performance stability during five batch mode operation events. In each event, the VSEP pilot unit was operated until a low-level permeate flow rate was achieved. At this point, a cleaning was performed to restore the flux rate. Table 4-9 summarizes the flux rate achieved at different conditions.

Table 4-9
Batch concentration performance summary

Batch	Pre-treatment	Pressure	Initial Flux*	Ending Flux*	Average Flux*	% Recovery	Spiral % Recovery	Run Time (Minutes)
#1	10 mg/L NLR 759	500 psi (3,447 kPa)	35.7 GFD (60.7 LMH)	0.2 GFD (0.34 LMH)	24.0 GFD (40.8 LMH)	82%	75%	925
#2	10 mg/L NLR 759	500 psi (3,447 kPa)	32.6 GFD (55.4 LMH)	1.8 GFD (3.06 LMH)	21.2 GFD (36.1 LMH)	88.7%	71.4%	1230
#3	10 mg/L NLR 759	500 psi (3,447 kPa)	30.9 GFD (52.6 LMH)	0.1 GFD (0.17 LMH)	22.2 GFD (37.8 LMH)	84%	75%	830
#4	10 mg/L NLR 759	500 psi (3,447 kPa)	33.7 GFD (57.3 LMH)	1.4 GFD (2.38 LMH)	26.0 GFD (44.2 LMH)	78%	76.9%	690
#5	10 mg/L NLR 759	500 psi (3,447 kPa)	38.1 GFD (64.8 LMH)	0.1 GFD (0.17 LMH)	15.3 GFD (26.0 LMH)	89.6%	76%	1100

*Flux rates are temperature corrected to 25°C (77°F).
1 mg/L = 1 ppm
1 GFD = 1.70 LMH

The VSEP/RO system was very effective in removing dissolved solids. The overall TDS and conductivity were reduced 99.9%. The first-stage VSEP pilot unit removed 91.6% of TDS, while the second stage Spiral RO pilot unit removed an additional 8.3% of TDS, yielding an overall TDS removal efficiency of 99.9%. Permeates were very clear with non-detectable TSS levels (<1 mg/L [<1 ppm]). The basic characteristics for all five events and respective samples are presented in Appendix D.

Table 4-10
Batch mode analytical summary – basic characteristics

Parameters	TSS (mg/L)	pH	Conductivity (µS/cm)	TDS (mg/L)	Nitrate/Nitrite (mg/L)
Initial feed (average*)	86	7.28	11,628	8,752	n.a.*
VSEP permeate (average*)	n.d. (<1)	6.64	737	736	0.73
Spiral RO permeate (average*)	n.d. (<1)	6.71	14	12	0.05
VSEP concentrate (average*)	438	7.09	55,980	46,909	n.a.*
Spiral RO concentrate (average*)	4	6.37	1,560	1,168	n.a.*

*These samples were not measured for nitrate/nitrite.
1 mg/L = 1 ppm

Selenium, arsenic, mercury, and nitrate/nitrite in the Spiral RO permeate were below the proposed effluent guidelines as shown in Table 4-11. Nitrate/nitrite levels are typically a concern when using conventional RO systems. Although the first-stage VSEP pilot unit alone did not satisfy the proposed regulatory limits, the second stage Spiral RO was able to successfully reduce nitrate/nitrite levels below the proposed limits. The full characteristics of five samples (that is, initial feed, VSEP permeate, VSEP concentrate, Spiral RO permeate, and Spiral RO concentrate) for Batch #3 are presented in Appendix E.

Table 4-11
Batch mode analytical summary – full characteristics

Parameter	Feed (FGD Wastewater)	VSEP Permeate	Spiral RO Permeate	Limits	% Removal Efficiency
Selenium (µg/L)	273	4.4	n.d. (<1)	10	>99.6%
Mercury (ng/L)	928	93.85	n.d. (<10)	119	>98.9%
Arsenic (µg/L)	3.01	n.d. (<1)	n.d. (<1)	6	>66.8%
Nitrate/Nitrate as N (mg/L)	13.12	0.75	0.04	0.13	99.7%
Chloride (mg/L)	4,106.8	183.3	n.d. (<5)	-	>99.9%
Sulfate (mg/L)	1,014.7	n.d. (<25)	n.d. (<5)	-	>99.5%
Calcium (mg/L)	2,096.7	86.7	n.d. (<2)	-	>99.9%
Magnesium (mg/L)	382.6	14.7	0.15	-	99.96%
Sodium (mg/L)	23.3	0.8	0.8	-	96.5%

1 µg/L = 1 ppb
1 mg/L = 1 ppm

Cleaning Results

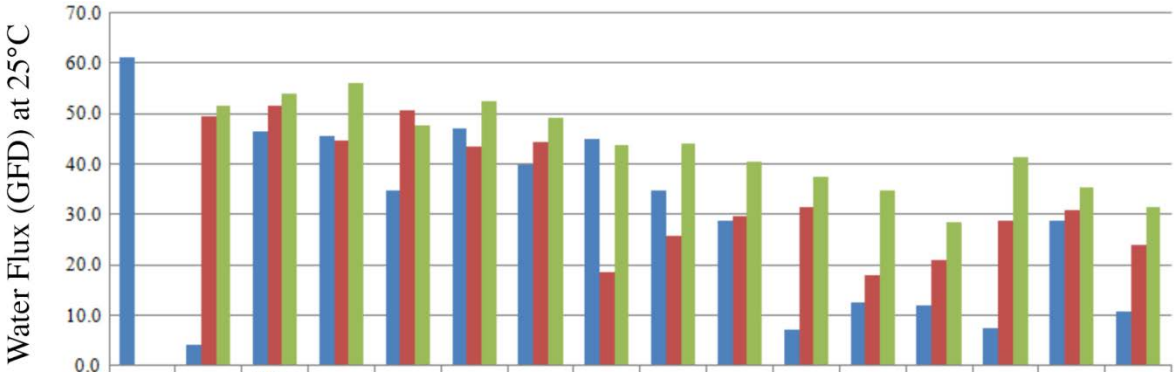
The cleaning effectively restored permeate flow and showed long-term performance stability. Chemical cleaning of the membrane was performed to restore the flux. The VSEP technology can prevent colloidal fouling of the membrane and can reduce the polarization of rejected materials at the membrane surface, but it cannot prevent the chemical bonding type of fouling that will occur with all membranes. For this reason, chemical cleaners are used to solubilize the foulants and restore the membrane performance. During chemical cleaning, cleaners are re-circulated through the membrane system and then flushed out. Multiple cleaning cycles are used if required.

When a new membrane is exposed to feed material, the membrane will take time to become conditioned. Once the membrane is conditioned, a new baseline can be established for measuring a successful cleaning. It can take many cleaning cycles to establish a conditioned membrane and determine the optimum cleaning method. The success of a cleaning depends on material concentration and cleaning conditions. Hot water and cleaners at the proper pH value are essential to successfully recover membrane flux. After multiple cleaning variations, acidic NLR 404 followed by a basic NLR 505 cleaning was found to successfully recover flux.

NLR 404 is an acidic liquid cleaner designed to provide rapid mineral scale cleaning of a wide range of RO, nanofiltration (NF), and ultrafiltration (UF) membranes. It removes metallic salts such as iron, aluminum, barium and strontium sulfate, calcium sulfate, and calcium carbonate, as well as dyes and polymers.

NLR 505 is a caustic liquid membrane cleaner designed to provide superior and rapid soil-removal properties. It contains a combination of ingredients that provide cleaning actions including lifting, dispersing, emulsifying, sequestering, dissolving, and suspending. It removes biological and organic materials, silt, particulates, colloids, silica, and emulsified oil from a wide range of RO, NF, UF, and microfiltration membranes.

The results are shown in Figure 4-7. The system was initially tested on clean water to obtain the water flux for the new membrane. This value is used as a reference for cleanings. After approximately 67 hours of operation and seven cleaning events, the RO membrane used in the VSEP pilot unit was conditioned and stabilized. Once the filter pack condition was verified, the system was operated on feed material to begin process variable optimization.



	New	After Batch #1 10/18	After Conc-entr-ation Study 10/21	After Batch #2 10/22	After Batch #3 10/23	After 70% Run 10/24	After 70% Run 10/25	After 75% Run 11/5	After 75% Run 11/14	After 75% Run 11/25	After High Pres-sure Batch	After Batch #1	After Batch #2	After Batch #3	After Batch #4	After Batch #5
Water Flush	61.2	4.3	46.5	45.7	34.9	47.2	40.0	45.1	34.9	28.9	7.2	12.7	12.0	7.3	28.7	10.9
NLR 404		49.6	51.5	44.8	50.7	43.6	44.3	18.6	25.7	29.7	31.6	17.9	21.0	28.7	31.0	24
NLR 505		51.5	54.1	56.2	47.7	52.4	49.1	43.9	44.1	40.5	37.6	34.9	28.4	41.5	35.4	31.6

°F = (°C x 9/5) + 32
1 GFD = 1.70 LMH

Figure 4-7
Cleaning study

Summary of Results

Table 4-12 is a summary of pilot test results recommended for full-scale design. The batch concentration mode resulted in a higher flux rate and a higher water recovery at the same operating pressure of 500 psi (3,447 kPa). The batch concentration setup requires larger feed holding tanks, and thus, a larger footprint than single-pass. Although batch concentration is more effective than single-pass, in some locations space is limited. Therefore, an economic feasibility study should be conducted on a case-by-case basis to quantify and identify all benefits expected and their associated costs.

Table 4-12
Design recommendations

Mode of Operation	Batch Concentration	Single Pass
Membrane	ESPA	ESPA
Average flux rate	25.5 GFD (43.4 LMH)	18.8 GFD (32.0 LMH)
Maximum percent recovery	83.2%	75%
Pressure	500 psi (3,447 kPa)	500 psi (3447 kPa)
Temperature	25°C (77°F)	25°C (77°F)
Pre-treatment	10 mg/L (10 ppm) NLR 759	10 mg/L (10 ppm) NLR 759
Cleaning chemicals	NLR 404/505	NLR 404/505
Cleaning frequency	~Every batch	~two/week

System Sizing Estimate

The following example illustrates how to calculate the expected flow rate of a single module using a membrane surface area of 1400 ft^2 (130 m^2) and the flux rate determined in this research. Currently, the largest commercially available VSEP module can accommodate 1400 ft^2 (130 m^2) of membrane and provide a batch concentration flux rate of 25.5 GFD (43.4 LMH). Cleaning requirements consume two hours per day, thereby leaving 22 hours per day for filtration/operation. The permeate recovery will be 83.2% of the initial feed volume. A 30% safety factor is considered for sizing purposes. In summary, 19.1 GPM (4.34 m^3/h) and 16.3 GPM (3.7 m^3/h) permeate can be produced in batch mode and single-pass using a VSEP module with 1400 ft^2 (130 m^2) of membrane surface.

Example Calculation

Gallons of permeate produced per day = 1400 ft^2 (130 m^2) × (25.5 GFD) × (22/24 hrs/day operation) = 32,725 GPD (123.8 m^3/day)

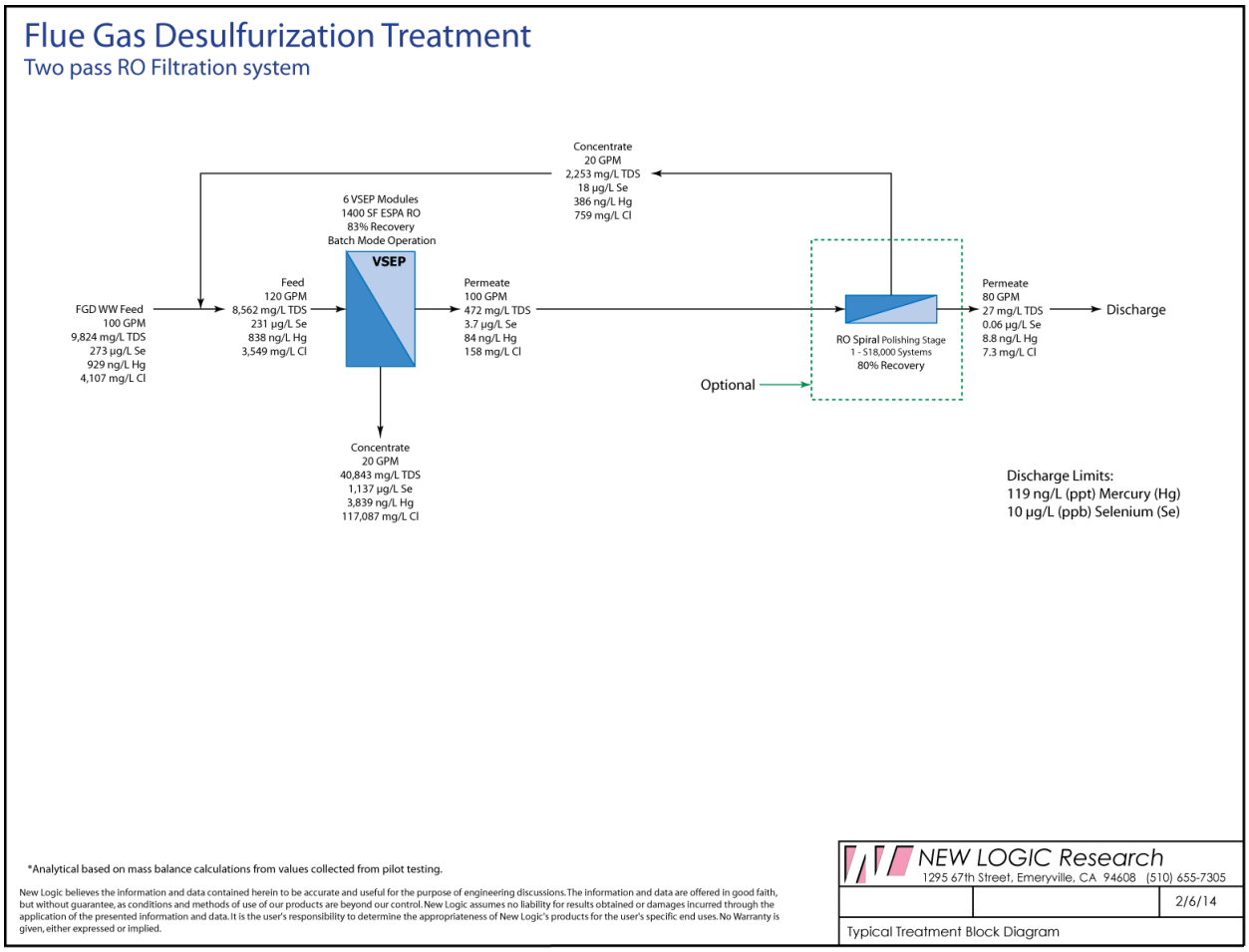
Membrane flux rates have the units of gallons per square foot per day (GFD). To convert flow rates in units of GFD to gallons per minute (gpm), the following equation was used:

Feed processed per minute = 32,725 GPD ÷ (83.2% recovery) ÷ (1440 min/day) = 27.3 gpm

27.3 gpm × 0.7(30% safety factor) = 19.1 gpm per 1400 ft^2 module (4.34 m^3/h per 130 m^2 module)

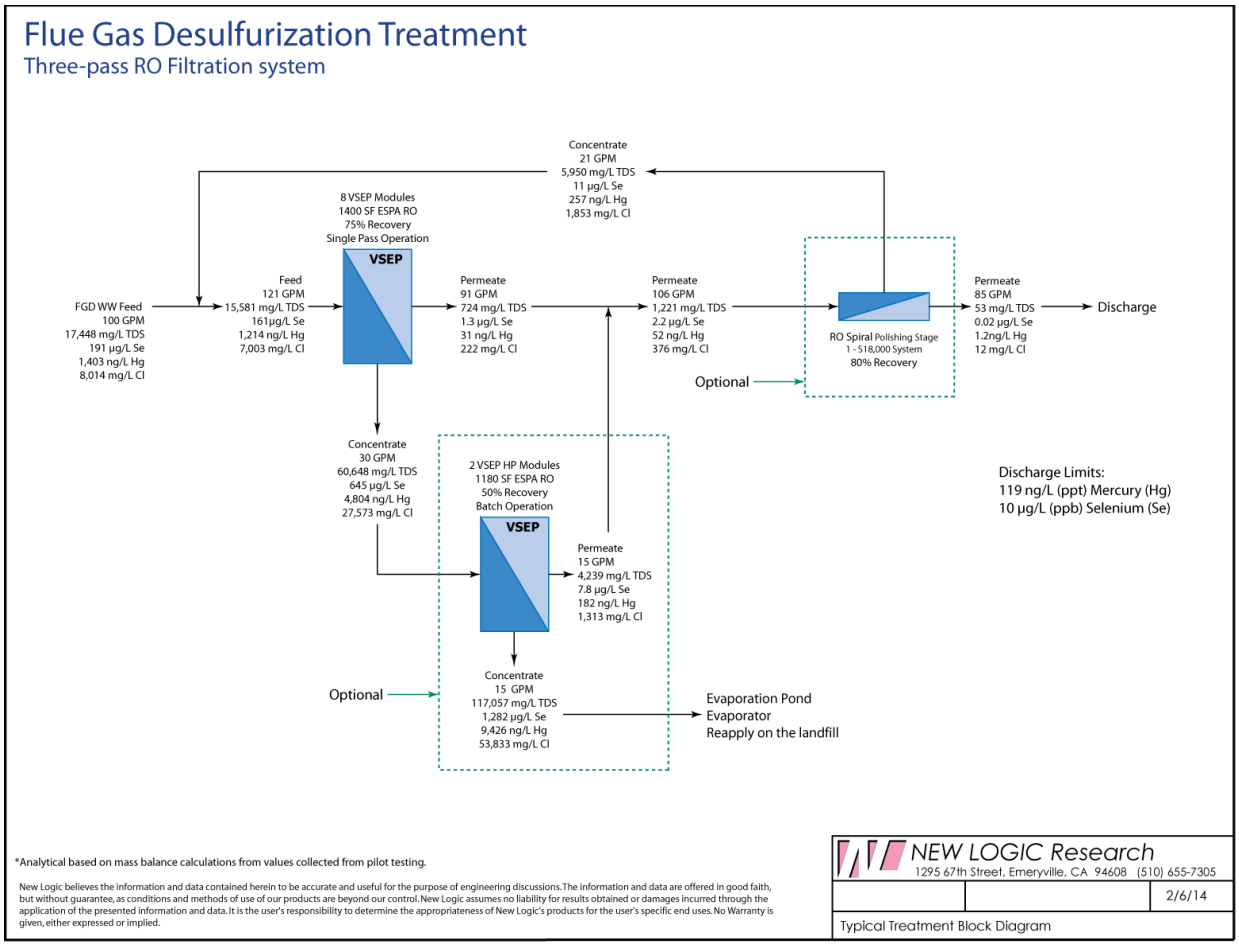
Based on these test results, two system configurations could be considered for a FGD application. The flow diagrams shown in Figure 4-8 illustrates a 100 GPM (22.7 m^3/h) (feed) system, a two-stage system using a VSEP/RO system in the first stage followed by a spiral RO system. Figure 4-9 presents as a three-stage system that includes the addition of a VSEP high-pressure concentration stage

to the previous system. The two-stage system is sized for batch mode of operation, which would require two feed tanks for batch operations, each having a minimum of a 4-hour retention capacity (that is, 24,000 gal [90.8 m^3] for 100 GPM [22.7 m^3/h]). One feed tank would be used for processing, while the other is either being filled or emptied. This arrangement would not be practical for a large system capacity, since the batch tanks would become very large. In those cases, the use of the three-stage system as illustrated in the second process flow diagram would be preferable.



1 GPM = 3.785 LPM
1 ng/L = 1 ppt
1 µg/L = 1 ppb
1 mg/L = 1 ppm

Figure 4-8
Two-pass RO filtration system



1 GPM = 3.785 LPM

1 ng/L = 1 ppt

1 µg/L = 1 ppb

1 mg/L = 1 ppm

Figure 4-9
Three-pass RO filtration system

Table 4-13 shows the estimated operating costs for each stage. Increasing the system capacity would be a ratio of the size shown for each arrangement, and the system operating cost should remain about the same for a larger system.

Table 4-13
Estimated system operating cost (Opex)

Stage	Stage 1	Stage 2	Concentration Stage	Total
Two-pass RO filtration system	$4.35/1,000 gal	$0.33/1,000 gal	-	$4.86/1,000 gal
Three-pass RO filtration system	$5.64/1,000 gal	$0.33/1,000 gal	$6.60/1,000 gal	$12.57/1,000 gal

1 gal = 3.785 L
$/1000 gal of feed includes electrical power, membrane replacement, and membrane cleaning requirements.

Examples of full-scale units are presented in Figure 4-10.

Figure 4-10
Full-scale VSEP/RO systems

Section 5: Conclusions

A pilot VSEP/RO system (consisting of a 0.5 GPM [0.11 m^3/h] VSEP and a 2.5 GPM [0.57 m^3/h] Spiral RO pilot unit) was installed at the WRC at Georgia Power's Plant Bowen in Cartersville, Georgia. Contaminant removal efficiencies, flux rate, percent of water recovery, and operational parameters (that is, cleaning and fouling) of the VSEP/RO system were evaluated during a three-month test program using gypsum-saturated FGD wastewater.

The two-stage VSEP/RO system was very effective in removing selenium, arsenic, mercury, and nitrate/nitrite to below proposed effluent limitation guidelines. The first stage, VSEP pilot unit, removed approximately 94% TDS, while the second stage, Spiral RO pilot unit, removed an additional 5.8% TDS, yielding an overall TDS removal efficiency of 99.8%. The first-stage VSEP pilot unit independently removed mercury, selenium, and arsenic to below the proposed effluent limitation guidelines. However, it was incapable of meeting the nitrate/nitrite limit (0.13 mg/L) in VSEP permeates. The nitrate/nitrite concentrations in the VSEP permeate were between 0.40 mg/L (0.401 ppm) and 0.75 mg/L (0.751 ppm), which were above 0.13 mg/L (0.13 ppm). The stage-two Spiral RO unit was essential in polishing the effluent nitrate/nitrite to 0.03–0.07 mg/L (0.03–0.07 ppm), which was below the 0.13 mg/L (0.13 ppm) limit. In summary, the VSEP pilot unit essentially removed the majority of the contaminants of concern and TDS, while the Spiral RO functioned as a safeguard against contaminant leakage and a polishing step for nitrate/nitrite.

The VSEP pilot unit can be operated in two modes: batch concentration mode or single-pass process mode. In batch concentration mode, a finite volume of feed is processed with the concentrate sent back to the feed tank, while permeate is sent to a separate holding tank. In single-pass process mode, the feed enters the VSEP pilot unit and is then separated into a permeate stream and a concentrate.

The VSEP system can be designed, built, and operated for operation pressures of up to 1000 psi (6,895 kPa). Pressure studies were conducted to determine the optimal operation pressures. In these studies, the relationship between flux and pressure was found to be linear in the range of 200–1,000 psi (1,379–6,895 kPa), and 500 psi (3,447 kPa) was chosen for batch concentration and single-pass process operations. The high-pressure study was conducted at 800 psi (5,516 kPa) pressure.

The addition of 10 mg/L (10 ppm) anti-scalant improved the batch concentration water recovery from 50% to 80%. Also, the flux rate increased from 11.6 GFD (19.7 LMH) to 14.8 GFD (25.2 LMH) when 10 mg/L (10 ppm) of anti-scalant was added. However, decreasing the feed pH to 6.5 did not show an improvement from adding anti-scalant alone.

In both modes of operation (single-pass and batch concentration), no irreversible membrane fouling, no irregular transmembrane pressure (TMP) increase was observed throughout the project. An acidic cleaning followed by a basic cleaning successfully restored the flux rates. It appears that the VSEP membrane vibration design/mechanism dramatically decreased and prevented the fouling typically seen in standard membrane systems.

Operation of the VSEP system in batch concentration mode resulted in a higher flux rate (25.5 GFD [43.4 LMH]) and percent water recovery (83.2%) than those (18.8 GFD [32.0 LMH] and 75%) achieved in single-pass mode. The batch concentration mode setup required larger feed holding tanks and a larger footprint than the single-pass mode setup. Although the batch concentration mode is more effective than single-pass mode, in some locations space could be a limiting factor. Therefore, an economic feasibility study should be conducted on a case-by-case basis to identify and quantify all expected benefits and associated costs.

In single-pass mode, the VSEP concentrate can be further processed using another VSEP unit operating at a higher pressure to achieve greater water recovery. In a single-pass mode operation, a 75% water recovery was achieved at 500 psi. When the VSEP concentrate was reprocessed through the VSEP unit at 800 psi (5,516 kPa), the system was able to achieve an additional 47% recovery. This resulted in an overall water recovery of 86.8% (75% + 0.47 × 25%). The average flux rate for the high-pressure concentration process was 13.4 GFD (22.8 LMH).

Based on these test results, two system configurations could be considered for a FGD application: (1) a two-stage system using a VSEP equipped with RO membrane in the first stage operating in batch concentration mode followed by a Spiral RO system, and (2) a three-stage system using a VSEP equipped with RO membrane in the first stage operating in single-pass mode, followed by a spiral RO system, and a VSEP high-pressure concentration stage to process VSEP concentrate at a high pressure. The two-stage system is sized for batch mode of operation, which would require two feed tanks for batch operations, each having a minimum of 4-hour retention capacity (that is, 24,000 gal [90.8 m^3] for 100 GPM [22.7 m^3/h]). One feed tank would be processing while the other is being either filled or emptied. This arrangement would not be practical for a large system capacity since the batch tanks would become very large. In those cases, the use of the three-stage system would be preferable.

Section 6: References

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Section 7: Glossary

average flux: The time-weighted average flow rate per membrane surface area that is measured over a particular concentration range.

batch concentration: The machine configuration where a fixed amount of feed slurry is progressively concentrated by removal of permeate from the system. The concentrate from the system is returned to the feed tank.

concentrate: The part of the fluid solution that does not permeate through the membrane.

concentration factor: The ratio of feed flow rate to the concentrate flow rate.

feed: Also called *feed slurry*. The raw solution that is offered for filtration. It typically has suspended solids, bacteria, or molecules that are to be segregated from a clear filtrate and reduced in size, making a concentrate solution of feed slurry.

filter pack: The filtering module, which contains the membrane and the layers and is housed in a fiberglass enclosure.

fouling: The accumulation of materials on the membrane surface or structure, which results in a decrease in flux.

flux: Not the same as flow rate. A measurement of the volume of fluid that passes through the membrane during a certain time interval for a set area of membrane, that is, GFD (LMH).

instantaneous flux: Flux measured at a given moment in time.

L mode: The configuration where a single piece of membrane is used and supported by clamshells on a Series L or LP Machine. This also means that the feed slurry enters the filter pack from below, and the permeate exits from the top.

line out study: The procedure of measuring the membrane flux over time in order to determine eventual stability.

microfiltration: The filtration of particles suspended in solution that are ≥ 0.1 µm (500,000 Daltons) in size or weight.

micron: A unit of measurement. 1 micron is equal to one-millionth of a meter (10^6). 1 micron also equals 12,000 mesh (0.0000394"). The limit of human visibility is 40 microns.

molecular weight: The number that expresses the average mass of the molecules of a compound to the mass of an atom of carbon-12 at a value of exactly 12.

nanofiltration: Filtration of particles suspended in solution that are ≥ 0.01 µm (1000 Daltons) in size or weight.

optimum pressure: The value of the maximum pressure above which that pressure is detrimental to performance.

P mode: The configuration where 19 layers of membrane are used as a filter pack on a Series LP machine. This also means that the feed slurry enters the filter pack from the top, and permeate also exits from the top. The actuated valve is typically used in P Mode.

percent recovery: The ratio of permeate flow rate to the feed flow rate.

permeate: Also called *filtrate*. It is the part of the solution that can or is allowed to filter through the membrane. The particle size of solids still suspended is determined by the pore size of the discriminating membrane.

retentate: The part of the solution that is rejected by the membrane pores. Also known as *concentrate*.

reverse osmosis: Filtration of particles suspended in solution that are ≥ 0.001 µm (100 Daltons) in size or weight.

ultrafiltration: Filtration of particles suspended in solution that are 0.01–0.1 µm (1000–500,000 Daltons) in size or weight.

Appendix A: Preliminary Results of Bench Testing

Initial testing of the VESP modules followed by spiral-wound RO membranes treating a sample of FGD wastewater showed that the overall TDS and conductivity were reduced 98%. Specific metals such as selenium (primarily selenate), mercury, and arsenic showed results close to 99% removal. Nitrite and nitrate reductions were approximately 95%. Anions (chloride and sulfate) and cations (sodium, calcium, and magnesium) removal were in the 99% range. Table A-1 shows the preliminary results of the two-stage bench-scale testing.

Table A-1
Preliminary results of the two-stage bench-scale testing

Parameter	Feed (FGD Wastewater)	VSEP Permeate	Removal Efficiency (%)	Spiral Wound RO Membrane - Permeate	Removal Efficiency (%)
Selenium (µg/L)	1,262	n.d. (<1.0)	>99.9	n.d. (<1.0)	>99.9
Mercury (ng/L)	15,124	192.40	98.7	12.01	99.9
Arsenic (µg/L)	4.02	n.d. (<1.0)	>75.1	n.d. (<1.0)	>75.1
Nitrate/Nitrate as N (mg/L)	14.69	0.92	93.7	0.61	95.8
Chloride (mg/L)	4,136.7	39.9	99.0	n.d. (<1.0)	>99.9
Sulfate (mg/L)	1,207.7	n.d. (<1.0)	>99.9	n.d. (<1.0)	>99.9
Bromide (mg/L)	31.0	0.3	99.1	n.d. (<0.125)	99.6
Fluoride (mg/L)	8.5	0.1	99.3	0.1	99.1
Calcium (mg/L)	2,226.8	13.3	99.4	n.d. (<2)	>99.9
Magnesium (mg/L)	346.5	1.2	99.7	n.d. (<0.050)	>99.9
Sodium (mg/L)	20.7	4.3	79.3	0.7	96.8
Boron (mg/L)	96.3	40.7	57.7	28.5	70.4

1 ng/L = 1 ppt
1 µg/L = 1 ppb
1 mg/L = 1 ppm

Appendix B: Single-Pass Concentration

Table B-1
Field analytical measurements for single-pass concentration trials

Parameters	TSS (mg/L)	pH	Conductivity (µS/cm)	TDS (mg/L)	Nitrate/Nitrite (mg/L)
Initial feed SP#1	62	7.35	18,110	15,087	n.a.
VSEP permeate SP#1	n.d. (<1)	6.29	720	743	0.60
Spiral RO permeate SP#1	n.d. (<1)	6.69	34.8	33	0.04
VSEP concentrate SP#1	266	6.98	62,900	66,659	n.a.
Spiral RO concentrate SP#1	2	6.27	1,942	1,575	n.a.
Initial feed SP#2	80	7.23	17,890	14,773	n.a.
VSEP permeate SP#2	n.d. (<1)	6.23	842	921	0.55
Spiral RO permeate SP#2	n.d. (<1)	6.49	14.88	17	0.07
VSEP concentrate SP#2	373	7.01	62,800	69,626	n.a.
Spiral RO concentrate SP#2	n.d. (<1)	6.16	1,569	1,475	n.a.
Initial feed SP#3	79	7.18	17,910	15,283	n.a.
VSEP permeate SP#3	n.d. (<1)	6.23	746	937	0.45
Spiral RO permeate SP#3	n.d. (<1)	6.63	52.6	43	0.05
VSEP concentrate SP#3	381	6.97	63,300	67,107	n.a.
Spiral RO concentrate SP#3	n.d. (<1)	5.82	2,490	2,003	n.a.
Initial feed SP#4	81	7.25	17,820	15,715	n.a.
VSEP permeate SP#4	n.d. (<1)	6.24	699	1,020	0.45
Spiral RO permeate SP#4	n.d. (<1)	6.53	17.5	8	0.06
VSEP concentrate SP#4	441	7	63,700	71,437	n.a.
Spiral RO concentrate SP#4	n.d. (<1)	5.88	1879	1,534	n.a.
Initial feed SP#5	75	7.21	17,920	15,308	n.a.
VSEP permeate SP#5	n.d. (<1)	6.35	709	849	0.40
Spiral RO permeate SP#5	n.d. (<1)	6.79	21.3	31	0.04
VSEP concentrate SP#5	351	7.08	63,200	69,161	n.a.

Table B-1 (continued)
Field analytical measurements for single-pass concentration trials

Parameters	TSS (mg/L)	pH	Conductivity (µS/cm)	TDS (mg/L)	Nitrate/Nitrite (mg/L)
Spiral RO concentrate SP#5	n.d. (<1)	5.91	2,510	2,155	n.a.
Initial feed SP#6	126	7.28	17,760	15,672	n.a.
VSEP permeate SP#6	n.d. (<1)	6.2	679	714	0.50
Spiral RO permeate SP#6	n.d. (<1)	6.68	16.9	24	0.03
VSEP concentrate SP#6	410	6.97	63,400	64,094	n.a.
Spiral RO concentrate SP#6	14	5.95	2,028	1,218	n.a.
Initial feed SP#7	118	7.3	15,720	14,574	n.a.
VSEP permeate SP#7	n.d. (<5)	6.45	580	510	0.40
Spiral RO permeate SP#7	n.d. (<5)	6.99	14.09	20	0.02
VSEP concentrate SP#7	514	7.02	59,400	60,870	n.a.
Spiral RO concentrate SP#7	6	6.07	1,664	1,150	n.a.
Initial feed SP#8	130	7.28	15,270	12,794	n.a.
VSEP permeate SP#8	n.d. (<5)	6.52	525	342	0.40
Spiral RO permeate SP#8	n.d. (<5)	6.9	17.59	28	0.08
VSEP concentrate SP#8	520	7.06	59,600	60,354	n.a.
Spiral RO concentrate SP#8	6	6.12	1,167	1,002	n.a.

1 mg/L = 1 ppm

Appendix C: Single-Pass Complete Analytical Summary

Table C-1
Comprehensive analytical measurements for single-pass concentration trials

Analysis	Unit	11/07/13					Discharge Limits
		Feed	Permeate	Concentrate	Permeate	Concentrate	
pH	-	7.1	6.2	7.0	6.4	5.7	
Conductivity	µS/cm	18,400	800	60,100	23	2,600	
Alkalinity	mg/L	56.3	10.8	198.9	10.8	9.0	
TDS	mg/L	17,448	813	63,544	352	2,202	
TSS	mg/L	106	2	229	< 1	1	
TS	mg/L	17,554	815	63,773	353	2,203	
F^-	mg/L	9.46	< 1.302	31.38	< 1.302	< 1.302	
Cl^-	mg/L	8,014.44	254.34	27,905.2	< 25	960.23	
NO^{2-}	mg/L	4.58	< 1.302	< 5.208	< 1.302	< 1.302	
Br^-	mg/L	60.97	< 3.257	194.22	< 3.257	7.87	
NO^{3-}	mg/L	19.16	< 6.51	56.59	< 6.51	< 6.51	
NO^3/NO^{2-}	mg/L	23.74	0.45	n.a.	0.07	n.a.	0.13
PO_4^{3-}	mg/L	<1.302	< 1.302	< 5.208	< 1.302	< 1.302	
SO_4^{2-}	mg/L	1,443.73	< 25	3,439.27	< 25	53.81	
Se(IV)	µg/L	84.5	< 1	84.5	< 1	1.135	
Se(VI)	µg/L	471.6	1.3	471.6	< 1	5.3	
Li^+	mg/L	<0.25	< 0.25	< 0.25	< 0.25	< 0.25	
Na^+	mg/L	47.39	15.49	140.46	1.96	62.46	
NH^{4+}	mg/L	<2	< 2	< 2	< 2	6.12	
K^+	mg/L	13.79	7.92	31.61	< 1	30.81	

Table C-1 (continued)
Comprehensive analytical measurements for single-pass concentration trials

Analysis	Unit	11/07/13					Discharge Limits
		Feed	Permeate	Concentrate	Permeate	Concentrate	
Mg^{2+}	mg/L	621.4	7.17	2,698.56	< 1	36.1	
Ca^{2+}	mg/L	3,065.37	73.41	11,076.8	< 5	294.7	
9 Be	µg/L	< 2.5	0.67	< 2.5	< 0.5	< 2.5	
11 B	µg/L	155,277.54	108,829.65	266,557.84	81,226.35	194,269.02	
23 Na	µg/L	52,105.13	15,896.01	127,675.70	2,481.64	56,973.60	
24 Mg	µg/L	646,265.69	12,520.24	2,201,336.57	< 50	45,856.31	
27 Al	µg/L	< 1000	< 200	1,135.95	< 200	< 1000	
28 Si	µg/L	2,0870.37	1,010.48	67,508.73	< 1,000	< 5000	
39 K	µg/L	20,545.75	10,269.31	37,872.64	< 2,000	36,320.14	
44 Ca	µg/L	2,982,467.46	72,659.99	10,740,036.83	< 2,000	267,501.54	
47 Ti	µg/L	21.42	< 2	47.38	< 2	< 10	
51 V	µg/L	< 50	< 10	< 50	< 10	< 50	
52 Cr	µg/L	< 10	< 2	< 10	< 2	< 10	
55 Mn	µg/L	6,433.88	133.53	22,804.14	< 4	515.93	
56 Fe	µg/L	< 500	< 100	997.43	< 100	< 500	
59 Co	µg/L	34.58	< 0.5	119.79	< 0.5	2.67	
60 Ni	µg/L	178.49	< 5	621.45	< 5	29.73	
63 Cu	µg/L	< 25	< 5	67.92	< 5	< 25	
66 Zn	µg/L	2,009.89	47.87	6,762.76	< 10	153.03	
75 As	µg/L	< 5	< 1	9.28	< 1	< 5	6

Table C-1 (continued)
Comprehensive analytical measurements for single-pass concentration trials

Analysis	Unit	11/07/13					Discharge Limits
		Feed	Permeate	Concentrate	Permeate	Concentrate	
78 Se	µg/L	190.67	1.54	694.03	< 1	6.00	10
88 Sr	µg/L	912.30	22.82	3,493.54	< 0.5	84.01	
95 Mo	µg/L	64.58	0.52	246.33	< 0.5	< 2.5	
107 Ag	µg/L	< 2.5	< 0.5	< 2.5	< 0.5	< 2.5	
111 Cd	µg/L	74.18	1.61	287.47	< 0.5	5.81	
121 Sb	µg/L	5.24	< 0.5	22.04	< 0.5	< 2.5	
137 Ba	µg/L	403.58	11.00	1,606.60	< 0.5	42.43	
182 W	µg/L	< 2.5	< 0.5	< 2.5	< 0.5	< 2.5	
200 Hg	ng/L	1,402.87	35.35	2,716.93	11.03	29.76	119
205 Tl	µg/L	8.12	9.76	2.80	1.19	33.10	
208 Pb	µg/L	< 2.5	< 0.5	3.25	< 0.5	< 2.5	
238 U	µg/L	23.05	< 0.5	89.07	< 0.5	< 2.5	

1 mg/L = 1 ppm
1 µg/L = 1 ppb

Appendix D: Batch Mode

Table D-1
Field analytical measurements for batch mode trials

Parameters	TSS (mg/L)	pH	Conductivity (µS/cm)	TDS (mg/L)	Nitrate/Nitrite (mg/L)
Initial feed B#1	58	7.37	11,200	7,702	n.a.
VSEP permeate B#1	0	6.73	501	818	0.60
Spiral RO permeate B#1	0	6.48	10.95	10	0.06
VSEP concentrate B#1	304	6.93	49,600	39,990	n.a.
Spiral RO concentrate B#1	0	6.22	1,123	628	n.a.
Initial feed B#2	66	7.39	10,640	7,824	n.a.
VSEP permeate B#2	0	6.97	810	644	0.74
Spiral RO permeate B#2	0	7.23	14.27	16	0.03
VSEP concentrate B#2	350	7.26	67,500	66,102	n.a.
Spiral RO concentrate B#2	6	6.54	1,362	1,076	n.a.
Initial feed B#3	58	7.28	12,280	9,824	n.a.
VSEP permeate B#3	0	6.48	664	544	0.75
Spiral RO permeate B#3	0	6.48	10.49	0	0.04
VSEP concentrate B#3	289	7	55,000	43,167	n.a.
Spiral RO concentrate B#3	0	6.26	1,592	1,326	n.a.
Initial feed B#4	148	7.15	12,330	8,928	n.a.
VSEP permeate B#4	0	6.24	563	630	0.75
Spiral RO permeate B#4	0	6.33	19.16	20	0.05
VSEP concentrate B#4	748	6.95	49,500	40,088	n.a.
Spiral RO concentrate B#4	16	6.25	1,504	1,186	n.a.
Initial feed B#5	98	7.19	11,690	9,484	n.a.
VSEP permeate B#5	0	6.76	1,146	1,042	0.80
Spiral RO permeate B#5	0	7.02	16.98	14	0.05
VSEP concentrate B#5	500	7.3	58,300	45,198	n.a.
Spiral RO concentrate B#5	0	6.58	2,221	1,624	n.a.

1 mg/L = 1 ppm

Appendix E: Batch #3 Complete Analytical Summary

Table E-1
Comprehensive analytical measurements for batch mode trial #3

Analysis	Unit						Discharge Limits
		Feed	Permeate	Concentrate	Permeate	Concentrate	
pH	-	7.10	6.3	7.0	6.4	6.5	
Conductivity	µS/cm	12,740	681.0	53,600.0	30.9 µS/cm	1,734 µS/cm	
Alkalinity	mg/L	55.0	10.0	200.2	10.0	10.0	
TDS	mg/L	9,824	544	43,167	< 1	1,326	
TSS	mg/L	58	< 1	289	< 1	< 1	
TS	mg/L	9,883	544	43,456	< 1	1,326	
F^-	mg/L	6.3	< 1.302	31.1	< 0.2604	< 1.302	
Cl^-	mg/L	4,106.8	183.3	23,116.4	< 5	474.9	
NO^{2-}	mg/L	< 5.208	< 1.302	29.4	0.5	< 1.302	
Br^-	mg/L	23.3	5.8	102.8	< 0.6514	7.2	
NO^{3-}	mg/L	< 26.04	< 6.51	< 130.2	< 1.302	< 6.51	
NO^{3-}/ NO^{2-}	mg/L	13.12	0.75	n.a.	0.04	n.a.	0.13
PO_4^{3-}	mg/L	< 5.208	< 1.302	< 26.04	< 0.2604	< 1.302	
SO_4^{2-}	mg/L	1,014.7	< 25	913.2	< 5	38.4	
Se(IV)	µg/L	109	2.048	129.122	1.536	2.141	
Se(VI)	µg/L	128.5	2.6	870.6	< 0.5	6.7	
NH^{4+}	µg/L	<40	< 20	< 8	0.1086	< 2	
9 Be	µg/L	0.72	< 20	1.78	< 0.5	< 0.5	
11 B	µg/L	97,930.07	< 0.5	278,696.20	32,429.52	89,237.19	
23 Na	µg/L	24,778.11	54,135.23	117,966.50	881.28	11,808.55	
24 Mg	µg/L	374,545.91	5,262.95	2,072,446.65	139.05	35,030.03	

Table E-1 (continued)
Comprehensive analytical measurements for batch mode trial #3

Analysis	Unit						Discharge Limits
		Feed	Permeate	Concentrate	Permeate	Concentrate	
27 Al	µg/L	< 400	14,017.38	< 400	< 400	< 400	
28 Si	µg/L	17,407.79	< 400	79,941.37	< 1000	2,459.52	
39 K	µg/L	13,848.02	1,001.23	57,869.58	< 2000	10,775.46	
44 Ca	µg/L	2,117,791.02	4,648.31	9,689,112.00	< 2000	217,610.83	
47 Ti	µg/L	6.08	86,054.49	2.22	< 1	< 1	
51 V	µg/L	< 10	< 1	< 10	< 10	12.33	
52 Cr	µg/L	< 2	16.22	< 2	< 2	< 2	
55 Mn	µg/L	5,114.13	< 2	27,724.27	< 2	463.01	
56 Fe	µg/L	< 100	181.32	< 100	< 100	< 100	
59 Co	µg/L	36.40	< 100	196.10	< 0.5	3.38	
60 Ni	µg/L	177.13	1.32	915.60	< 5	37.38	
63 Cu	µg/L	10.80	6.61	82.85	< 5	< 5	
66 Zn	µg/L	1,157.27	< 5	6,443.25	< 5	110.03	
75 As	µg/L	2.03	42.85	10.81	< 1	< 1	6
78 Se	µg/L	267.39	< 1	1,665.16	< 1	10.88	10
88 Sr	µg/L	632.80	4.24	3,332.40	< 0.5	60.63	
95 Mo	µg/L	31.32	24.73	186.27	< 0.5	1.84	
107 Ag	µg/L	< 0.5	0.54	< 0.5	< 0.5	< 0.5	
111 Cd	µg/L	54.35	< 0.5	366.71	< 0.5	3.81	
121 Sb	µg/L	5.02	1.33	28.30	< 0.5	< 0.5	
137 Ba	µg/L	288.10	< 0.5	1,691.99	< 1	30.02	
182 W	µg/L	0.65	11.35	3.84	< 0.5	< 0.5	
200 Hg	ng/L	832.55	< 0.5	322.92	<10	11.81	119
205 Tl	µg/L	6.20	10.33	9.61	0.88	11.67	
208 Pb	µg/L	< 0.5	5.46	0.68	< 0.5	< 0.5	
238 U	µg/L	15.13	< 0.5	87.37	< 0.5	< 0.5	

1 mg/L = 1 ppm
1 µg/L = 1 ppb

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