ATTACHMENT A – SELECTED PORTIONS OF EPA'S SUMMARIES FOR MEMBRANES-RELATED TECHNOLOGIES

Appendix B – BKT FMX Membrane Technology

1.0 TECHNOLOGY DESCRIPTION

BKT originally started as a company specializing in biological treatment technologies for livestock wastewater but has since developed the FMX system and expanded their applications to the shale gas, food and beverage, biotechnology, and power industries. BKT developed their anti-fouling membrane filtration system in Korea and this system has now been operating in the U.S. for the past ten years.

The FMX membrane system is an advanced membrane filtration system designed for wastewaters containing high total suspended solids (TSS) and total dissolved solids (TDS) and uses vortex-generating blades to minimize fouling of membrane surfaces. Blades are used to generate a vortex that maintains turbulent flows on the membrane surfaces; these eddies serve to reduce deposits on the membrane surface that could lead to fouling or scaling. The blades are made of a lightweight engineered plastic and are resistant to chemicals, corrosion, and heat. The blades are connected to a center drive shaft and positioned between trays of membranes vertically. The center shaft rotates the blades and membranes resulting in the turbulence. Depending on the membrane surface area required, the number of membrane/blade stacks and size of the membrane pores can be customized to meet the desired removals.

The FMX system processes wastewater between 50 and 150 liters per square meter per hour (LMH) (or 30 and 88 gallons per square foot per day (GFD)). Depending on the application, microfiltration, ultrafiltration, or nanofiltration membranes can be used in the system. For FGD wastewater applications, BKT recommends using nanofiltration membranes. The FMX system can be operated in conjunction with a downstream conventional RO system. In this configuration, the FMX system reduces the TDS concentrations and total hardness in the FGD wastewater which prevents scaling in the RO system, while the RO system further treats the permeate to reduce the pollutant concentrations to very low levels prior to discharge.

According to BKT pretreatment prior to entering the FMX system is dependent on the concentration of TSS in the feed. If FGD wastewater undergoes settling (e.g., impoundment, settling tank), only a light particle filter may be needed; however, the FMX cannot receive influent directly from a hydrocyclone. At one half to two percent solids, the concentration is too high for the FMX system and would require either ultrafiltration or a physical/chemical pretreatment system with pH adjustment and coagulation /flocculation to remove solids.

As shown in pilot studies, the FMX system can also be incorporated into an existing treatment train. A treatment system using FMX nanofiltration followed by conventional RO could be used as a single-step treatment process for FGD wastewater. Including pretreatment prior to the FMX system may increase overall process efficiency of the FMX system and help lower the capital and operations and maintenance costs of the FMX portion of the system. Treating FGD wastewater with the FMX system can also be used to achieve significant volume reduction upstream of thermal or brine solidification/encapsulation zero discharge technologies, thereby reducing the size and cost of the thermal or encapsulation equipment. Figure 1 shows an example process flow diagram for FGD wastewater treatment with an FMX system that includes a chemical precipitation pretreatment step using lime addition, the FMX stage, a post-processing RO system, and an evaporator/crystallizer system to handle the concentrate stream.

Industry sources report that the FMX tests summarized in Section 2 demonstrate that anti-fouling technology can enable the use of membrane filtration to treat FGD wastewater and that the FMX/RO treatment train is effective at removing selenium, arsenic, mercury, and nitrate-nitrite to concentrations well below the ELG limitations. These sources also report that the onsite tests demonstrate that the anti-fouling properties of the FMX system enable it to treat FGD wastewater without the need for extensive pretreatment. Additionally, the FMX/RO treatment process has a relatively small footprint and obviates the need for the reaction tanks and much of the other equipment typically included as part of chemical-biological treatment trains.

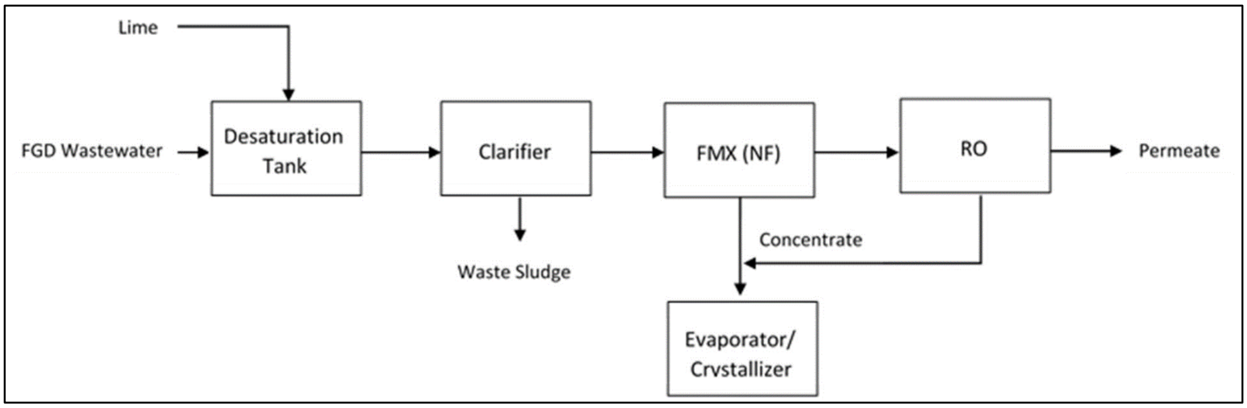

Figure 1. Example Process Flow Diagram for FMX Membrane System with Pretreatment and RO System

Like other membrane systems, the FMX membranes require periodic flushing and chemical cleanings. The FMX system provides the ability to replace membranes without replacing other associated equipment. BKT estimates that the membranes will need to be replaced every one to two years depending on the operation of the system. Chemical cleaning requirements and frequencies for the membranes are variable and dependent on the characteristics of the influent wastewater and treatment system configuration. As demonstrated in one pilot study, permeate from the FMX system treatment process can be further treated and reused to clean the membranes, eliminating the need for implementation of chemical clean-in-place (CIP) procedures. BKT has also indicated that influent characteristics affect the cost of operation of the system, as a high TDS concentration combined with a lower sulfate concentration is less expensive to operate than a lower TDS concentration combined with a higher sulfate concentration due to the impacts on membrane flux.

2.0 TECHNOLOGY STATUS AND PERFORMANCE

BKT has conducted at least six onsite pilot-scale studies for the treatment of FGD wastewater from coal-fired power plants using the FMX system. These pilot tests are summarized below.

2.1 Pilot Study #1

A commercial-scale FMX system was tested for three months at a coal-fired power plant to treat FGD wastewater. The FMX module contained nanofiltration membranes and was used in conjunction with a conventional spiral-wound reverse osmosis membrane. The system was operated in batch mode, with the FMX system receiving untreated FGD wastewater from the plant's FGD storage tank. During each batch, the concentrate from the FMX system was returned to the feed tank and the system continued to process the wastewater until the desired recovery was reached (i.e., 70-80 percent of the feed volume passes through the membrane as permeate).

The permeate from the FMX stage was transferred to the RO stage for further treatment and was able to meet the 2015 ELGs for selenium in FGD wastewater. Other than gravity settling in a surface impoundment, no pretreatment of the wastewater was performed prior to the FMX system. Using the combination of FMX and spiral RO, the treatment train consistently met the discharge limits for FGD wastewater established by the 2015 ELGs (in fact, the effluent concentrations were lower than the limits proposed by EPA in 2013, which were lower than the limits established by the 2015 ELGs). Average pollutant concentrations are shown in Table 1. The pilot test results demonstrated that anti-fouling technology enables the use of membrane filtration to treat FGD wastewater, with no loss of flux and no irreversible fouling or scaling of the membranes over the duration of the study. The pilot test also showed that chemical pretreatment of the wastewater was unnecessary.

Table 1. Pilot Study #1 – Average Pollutant Concentrations[46]

Paramete	Feed	FMX Permeate	RO Permeate
pH	7.2	7.1	6.05
Conductivity (µS/cm)	21,700	13,000	149
Alkalinity (mg/L as CaCO3)	57.6	30	5
Total Dissolved Solids (mg/L)	17,500	8,930	201
Total Suspended Solids (mg/L)	38	19.5	1.5
Total Solids (mg/L)	17,500	8,950	202
Fluorine (mg/L)	7.8	3.35	< 0.039
Chlorine (mg/L)	7,250	4,300	< 28.9
Bromine (mg/L)	59.8	36.2	< 0.283
Nitrate-Nitrite (mg/L as N)	< 27.3	< 17.6	< 0.234
Phosphate (mg/L as P)	< 4.56	< 2.93	< 0.039
Sulfate (mg/L)	1,070	252	< 1.75
Beryllium (µg/L)	< 1.7	< 0.75	< 0.5
Boron (µg/L)	120,000	106,000	39,900
Sodium (µg/L)	32,000	30,200	2,750
Magnesium (µg/L)	661,000	293,000	1,780
Aluminum (µg/L)	867	105	< 135
Silicon (µg/L)	24,700	17,500	< 1220
Potassium (µg/L)	14,600	15,000	< 2780
Calcium (µg/L)	3,540,000	2,120,000	14,100
Titanium (µg/L)	< 32.8	< 3	< 3
Chromium (µg/L)	7.7	< 2	< 2
Manganese (µg/L)	8,750	4,780	31.2
Iron (µg/L)	< 476	< 100	< 100
Cobalt (µg/L)	64.1	31.3	< 0.75

[46] As in the main body of the report, yellow highlights in this and other tables are for pollutants with specified limits in the 2015 ELG Rule. Blue highlights are of additional pollutants that are not included in the 2015 Rule but are important nonetheless.

Table 1. Pilot Study #1 – Average Pollutant Concentrations

Paramete	Feed	FMX Permeate	RO Permeate
Nickel (µg/L)	325	160	< 5
Zinc (µg/L)	1,740	1,250	12.7
Arsenic (µg/L)	< 12.7	< 5.35	< 2
Selenium (µg/L)	219	55.4	< 1
Strontium (µg/L)	1,140	589	4.05
Molybdenum (µg/L)	62.6	15.4	< 0.5
Silver (µg/L)	< 1.5	< 0.5	< 0.5
Cadmium (µg/L)	72.7	56.3	< 0.75
Antimony (µg/L)	7.6	2.65	< 0.5
Barium (µg/L)	496	265	2.4
Tungsten (µg/L)	3.8	1.95	< 0.5
Mercury (µg/L)	2,030	94.7	< 5
Lead (µg/L)	< 2.015	< 0.5	< 0.5
Uranium (µg/L)	24.8	6.08	< 0.5

2.2 Pilot Study #2

BKT conducted a pilot study of the FMX system at a coal-fired power plant, testing two different nanofiltration membranes during the study. Permeate generated from the FMX system was further treated by a conventional RO system.

Both pretreated FGD wastewater, which had been injected with a polymer for coagulation in a clarifier, and untreated FGD wastewater were tested as influent streams to the FMX system. Based on the results of the study, BKT determined that polymers have the potential to coat the membranes and, thereby, decrease the performance of the FMX system. Table 2 presents the average pollutant concentrations feed, FMX permeate, and RO permeate.

Table 2. Average Pollutant Concentrations in the Feed and Permeate for FMX Nanofiltration and RO During Pilot Study #2

Parameter	Feed	FMX Permeate	RO Permeate
Arsenic (Total, µg/L)	2.21	1.14	0.673
Mercury (Total, ng/L)	77.4	7.18	0.81
Selenium (Total, µg/L)	275	96.7	2.13

2.3 Pilot Study #3

BKT conducted an 8-month pilot test of the FMX system using a commercial-scale unit with nanofiltration membranes at a coal-fired power plant. The pilot system treated FGD wastewater in 1,000-gallon batches. Effluent from chemical precipitation treatment was transferred to a feed tank at the head of the FMX system. Wastewater from the feed tank was fed to the FMX nanofiltration system. Permeate from the pilot system was returned to the equalization tank at the front end of the plant's existing full-scale FGD wastewater treatment system; concentrate (i.e., membrane reject) was transferred back to the feed tank. A polishing RO unit was not used in this test to further treat the FMX permeate. Plant staff reported that the permeate from the FMX nanofiltration system was pure enough for reuse in the FGD system. The wastewater was treated in two to three batches per day and the system was drained and flushed with hot water at the end of each day and at the end of each batch cycle. A clean-in-place (CIP) procedure was conducted once per month using hydrochloric acid and sodium hydroxide.

The FMX concentrate was collected so that it could be used to evaluate encapsulation processes. The primary goal of the study was to produce enough brine that could be used to test various cement recipes and evaluate whether the FMX system could be operated as a closed-loop system. Additionally, plant staff determined that the FMX permeate would be fit for reuse in the FGD system and that the closed-loop system recovered 80 percent of the influent wastewater. This means that the volume of wastewater ultimately requiring additional disposal or management (e.g., encapsulation, crystallization, underground injection) was reduced to 20 percent of the original volume. Table 3 presents the average pollutant concentrations measured at the influent and effluent of the FMX system during the testing. Since a polishing RO unit was not included during this test, the data in Table 3 does not show the effluent quality following combined FMX and RO treatment.

Table 3. Average Pollutant Concentrations in the Feed and Permeate for FMX Nanofiltration During Pilot Test #3

Paramete	Feed	FMX Permeate
Arsenic (Total, µg/L)	10	2
Mercury (Total, ng/L)	50	3
Selenium (Total, µg/L)	200	69

The plant intended to conduct an encapsulation study using brine from the FMX nanofiltration system and the plant's fly ash. The encapsulation study had not yet been conducted at the time EPA obtained information about this test.

2.4 Pilot Study #4

An FMX system with nanofiltration membranes was used for over a year to treat FGD wastewater at a coal-fired power plant. FGD wastewater was transferred directly from the plant's existing holding ponds to the FMX system without any additional pretreatment. Permeate from the FMX system was recirculated back to the holding ponds. The system was set up to treat one batch per day at an 80 percent water recovery rate. During testing, a CIP procedure was performed once per month using the FMX system permeate. Table 4 presents the average pollutant concentrations in the FMX feed and permeate for data collected over approximately six months. Since a polishing RO unit was not included for this pilot test, the data in Table 4 does not show the effluent quality following combined FMX and RO treatment.

Table 4. Pilot Study #4 – Average Pollutant Concentrations

Paramete	Feed	FMX Permeate
Total Suspended Solids (mg/L)	1,360	<10
Total Dissolved Solids (mg/L)	25,400	5,230
Bromide (mg/L)	73	15
Nitrate (as N, mg/L)	27.8	6
Calcium (Dissolved, µg/L)	5,620,000	1,297,000
Arsenic (Total, µg/L)	<5.5	<5.5
Mercury (Total, ng/L)	1,610	334
Selenium (Total, µg/L)	423	30.4

2.5 Pilot Study #5

BKT conducted a 3-month pilot study of the FMX system at a coal-fired power plant. Wastewater from the plant's FGD holding pond was transferred to a feed tank prior to treatment through the FMX system. Permeate from the FMX system was further treated using a conventional RO system and the FMX system concentrate was transferred back to the FGD holding pond.

Based on the results of the study, BKT determined that increasing the speed of the FMX system blades increases flux and reduces the rate of flux decline as more permeate is produced. BKT also determined that introducing an anti-scalant to the feed water reduces the change in flux, which successively reduces CIP needs and increases membrane lifespan. Table 5 presents the average pollutant concentrations in the treatment system influent, the FMX permeate, and the RO permeate.

Table 5. Average Pollutant Concentrations in the Feed and Permeate for FMX Nanofiltration and RO During Pilot Study #5

Paramete	Feed	FMX Permeate	RO Permeate
Total Dissolved Solids (mg/L)	3,890	1,860	192
Sulfate, mg/L	2,380	929	20
Arsenic (Total), ug/L	11.1	8.46	6.09
Mercury (Total), ng/L	240	16.6	< 5
Selenium (Total), ug/L	1,930	726	6.84
Nitrate-Nitrite	5.6	5.6	1.25

2.6 Pilot Study #6

BKT conducted a pilot study of a 400 gallon per minute (GPM) FMX system in 2018 at a large coal-fired power plant in the Southeastern U.S. The FMX system was set up to be able to function in either a batch or a single pass (SP) mode. Wastewater was drawn from the plant's FGD holding ponds and sent through the FMX system; batch tests were performed with approximately 1,000 gallons of feed. Effluent from the FMX system was also intermittently sent through a RO system in order to assess the performance of a treatment strategy combining the two methods.

BKT found that operating in batch mode results in the lowest operating and maintenance costs, as compared to continuous, single-pass operation and would therefore be the most advantageous operation mode for steam electric plants. BKT also found that combining the FMX system with an RO system resulted in continuous flow rates through the RO membranes, suggesting that FMX treatment successfully prevented scaling. Table 6 presents the average pollutant concentrations in the treatment system influent, the FMX permeate, and the RO permeate over the course of two months of operation.

Table 6. Average Pollutant Concentrations in the Feed and Permeate for FMX Nanofiltration and RO During Pilot Study #6

Paramete	Feed	FMX Permeate	RO Permeate
TSS (ppm)	14.4	0.00	0.00
Alkalinity (ppm)	40.3	34.4	-
Chloride (ppm)	227	209	11.3
Nitrate (ppm)	19.0	19.2	3.5
Sulfate (ppm)	2,350	1,115	12
Phosphate (ppm)	≤ 0.25	≤ 0.25	≤ 0.25
Sodium (ppm)	59	43	4.11
Magnesium (ppm)	231	117	0.84
Aluminum (ppb)	108	≤ 107	≤ 107
Silica (ppm)	15	12	1.07
Calcium (ppm)	501	246	≤ 2.11
Iron (ppb)	166	116	107
Arsenic (ppb)	≤ 8.1	≤ 6.69	≤ 5.73
Selenium (ppb)	2,062	974	8.44
NO2+NO3 as N (ppm)	5.54	5.66	1.17
Total Mercury (ppb)	151	≤ 10.2	≤ 12.3
TDS (ppm)	3,995	2,193	224

Note: Underlined average pollutant concentration values include samples below the detection limit.

Appendix I – KLeenWater Technology

1.0 TECHNOLOGY DESCRIPTION

KLeeNwater is a joint venture between ProChem, Inc. and Environmental Energy Services Corporation (EES). KLeeNwater offers three trade-marked technologies for FGD wastewater treatment applications: ProChem's I-MICRO, I-PRO, and B-PRO. I-MICRO is a microfiltration membrane with chemical addition, and I-PRO and B-PRO are reverse osmosis (RO) membranes. The typical application for FGD wastewater treatment consists of pretreatment to reduce the amount of suspended solids in the wastewater (using either I-MICRO microfiltration/chemical pretreatment, or physical/chemical pretreatment), followed by the I-PRO and B-PRO RO membranes.

Scale forming ions, including calcium, magnesium, and sulfates, are targeted during pretreatment. When microfiltration is incorporated into the treatment train, KLeeNwater uses ProChem's ceramic microfiltration/chemical pretreatment system (I-MICRO). I-MICRO is designed to remove total suspended solids (TSS) from wastewater containing up to 4 percent (40,000 parts per million) TSS. Solids that are removed from the wastewater by the I-MICRO membrane are typically sent to a filter press. Where chemical precipitation is used for TSS removal in place of the I-MICRO system, KLeeNwater includes a sand filtration system upstream of the I-PRO (downstream of chemical precipitation). After TSS removal with either the I-MICRO or chemical precipitation, KLeeNwater also implements cartridge filters to further protect the I-PRO/B-PRO membranes. Cartridge filter effluent is sent to the I-PRO system for further removal of contaminants, including arsenic, mercury, selenium, nitrates/nitrites, boron, bromides, and chlorides.

I-PRO is designed to handle high concentrations of total dissolved solids (TDS). The technology has a TDS influent limit of 5,000 to 45,000 milligrams per liter (mg/L) and a flow rate range of 15 of 350 gallons per minute (GPM). Multiple membrane systems can be installed in parallel to accommodate larger flows.

KLeeNwater offers its brackish water reverse osmosis system (B-PRO) for further removal of TDS from I-PRO permeate. This polishing step is not needed in all industrial wastewater applications. B-PRO has a TDS limit of 10 to 5,000 mg/L and a flow rate range of 10 to 350 GPM. For both I-PRO and B-PRO, higher flow rates would be managed using additional membrane modules.

Like other membrane systems, KLeeNwater RO membranes require flushing and chemical cleaning. In pilot studies, flushes using system permeate were performed approximately once a day and chemical cleanings were performed approximately once a week. KLeeNwater estimates the membranes will need to be replaced quarterly.

I-PRO or B-PRO concentrate can be managed using a variety of approaches, including thermal or brine solidification processes to achieve zero liquid discharge. Encapsulation or solidification of the liquid waste generated from the treatment technology can be done to achieve zero liquid discharge. KLeeNwater has tested different mixtures (e.g., fly ash, lime, superabsorbent polymer) in an effort to improve wastewater treatment and disposal practices to achieve encapsulation of the concentrate produced from the technology.

2.0 TECHNOLOGY STATUS AND PERFORMANCE

The KLeeNwater system has been tested at coal-fired power plants in both laboratory- and pilot- scale studies. KLeeNwater has conducted at least 23 laboratory-scale studies treating wastewater from coal-fired power plants. At least two of the laboratory-scale studies involved treatment of FGD wastewater. EPA has reviewed data for four onsite pilot-scale studies with KLeeNwater at steam electric power plants for FGD wastewater treatment, which consistently show pollutant concentrations in the membrane permeate lower than the limits established by the 2015 ELGs. All pilot systems included I-MICRO, followed by the I-PRO and B-PRO and were operated using a flow rate of approximately five GPM.

2.1 Pilot Studies #1 and #2

KLeeNwater conducted a 5-week pilot study at a utility to test the membrane technology and confirm the results of a previous bench-scale study. The FGD wastewater used as influent to the pilot had a chlorides concentration of 14,300 ppm and TDS concentration of 29,700 ppm.

The pilot treatment system included physical/chemical treatment, I-MICRO, I-PRO, and B-PRO The effluent from the pilot system consistently met ELG and state regulations and the permeate was considered suitable for re-use within the plant or discharge. The encapsulation tests also met regulatory requirements for leachability.

The pilot system was operated using a different pretreatment strategy during each week of the pilot to evaluate the chemical consumption, system performance, and overall costs of the treatment system. KLeeNwater determined that the optimal pretreatment design was to use an aluminum-based coagulant and proprietary scale inhibitor formulation prior to the RO. This specific test was conducted during Week 4 and repeated during Week 5 to confirm the results.

The water recovery data from the Week 4 and 5 trials was consistent, even appearing in line with the recovery achieved in bench-scale laboratory trials. Table 1 lists the data obtained from the pilot study.

Table 1. Pilot Test #1 - Average Results

Paramete	FGD Purge	Final Effluent
Arsenic (µg/L)	14.5	1.2
Nitrate-Nitrite as N (mg/L)	70.4	0.16
Selenium (µg/L)	563	2.7
TDS (mg/L)	27,900	86.8

The second pilot study was conducted to validate the results of the first pilot study and to refine the pretreatment process. KLeeNwater successfully validated the results of the first study and further optimized the system's pretreatment in the second study.

2.2 Pilot Study #3

KLeeNwater conducted a six-week pilot-scale study at a coal-fired power plant to treat FGD wastewater. With the exception of a 5-day period, the system operated 7 days per week during the first shift (demonstrating the ability of the system to handle demands due to load cycling). During the 5-day period, the system was operated 24 hours per day to demonstrate continuous operation.

The FGD wastewater used as influent to the pilot had a chlorides concentration of 865 ppm and TDS concentration of 4,340 ppm. The RO system performed achieved an average water recovery of greater than 90 percent. The pilot unit provided 5 GPM of treated water that met the 2015 ELG requirements. Table 2 lists the data obtained from the pilot study.

Table 2. Pilot Test #3 - Average Results

Paramete	Pretreatment Influent	Final Effluent

Arsenic (µg/L)	158	5.0
Mercury (ng/L)	53,900	9.7
Nitrate-Nitrite as N (mg/L)	5.15	0.40
Selenium (µg/L)	809	9.5
TDS (mg/L)	4,580	90.2

2.3 Pilot Study #4

KLeeNwater conducted a pilot study for 10 weeks, operating continuously, at a coal-fired power plant to treat FGD wastewater. The test objectives were to confirm results of a previous bench- scale test, meet ELGs while reducing I-PRO concentrate volume, assess B-PRO for water reuse applications, compare pretreatment programs, and demonstrate long-term feasibility of the technology. The treatment train consisted of chemical pretreatment followed by clarification, microfiltration (I-Micro), and a two-stage RO system (I-PRO/B-PRO). The system yielded on average 85.4 percent recovery. The highest recovery rate achieved was 93 percent while running untreated FGD wastewater through the treatment train; the lowest recovery rate was 69 percent when brine was recycled back to the EQ tanks and no FGD wastewater was added to the EQ tanks. Discharge consistently met ELG regulations when the B-PRO system was operated; otherwise, B-PRO permeate was of sufficient quality for reuse as scrubber make-up water. Table 3 lists the data obtained from the pilot study.

Table 3. Pilot Test #4 - Average Results

Parameter	Feed Tank Effluent	Final Effluent
Arsenic (µg/L)	18.5	5.0
Mercury (ng/L)	636	0.5
Nitrate-Nitrite as N (mg/L)	294	1.19
Selenium (µg/L)	561	5.0
TDS (mg/L)	19,200	67.1

2.4 Concentrate Management Pilot Testing

As part of KLeeNwater's pilot tests, the company looks at options to manage the concentrate (i.e., membrane reject stream) generated from the treatment of FGD wastewater. Four concentrate management technologies have been evaluated in different pilot studies to assess their performance in encapsulating concentrate. These include:

- Wetting fly ash with concentrate (fly ash wetting).
- Wetting FGD gypsum with concentrate (gypsum wetting).
- Wetting fly ash samples with lime and concentrate (hydrated lime encapsulation).
- Adding super absorbent polymer and lime with concentrate (super absorbent polymer encapsulation).

Based on the results of the pilot studies, KLeeNwater states that their treatment technology produces a concentrate that can be encapsulated using these different approaches and achieve compliance with toxicity characteristic leaching procedure (TCLP) testing.

Appendix K – New Logic Membrane Technology

1.0 TECHNOLOGY DESCRIPTION

The first industrial application of New Logic's VSEP technology was for dewatering kaolin clay for coal mining facilities. Since then, New Logic has expanded the use of the VSEP to other industries, including petrochemical, automotive, food and beverage, pulp and paper, and power generation.

The VSEP system is a new generation membrane filtration system designed for wastewaters containing high total suspended solids (TSS) and total dissolved solids (TDS) and uses vibratory movement to reduce fouling on the membrane surface. The technology works by spinning an eccentric weight bearing, which induces a vibratory action that is translated to the torsion spring and on to the filter pack drive (i.e., the membrane). The filter then oscillates 54 times per second up to an amplitude of ¾ of an inch. The shear created by the rapid change in direction makes it difficult for foulants to attach to the membranes. However, clean water may still pass through the membrane pores.

Early applications of VSEP were configured with microfiltration and ultrafiltration membranes, which mainly removed suspended solids and large organics. Today, New Logic also produces fully-automated VSEP systems configured with reverse osmosis (RO) membranes. The RO membranes can separate difficult to treat feed streams including those with high levels of suspended and dissolved solids, oils, metals, and organics. New Logic also provides spiral- wound RO membranes that can be used independently or in conjunction with VSEP. Figure 1 shows an example of a process flow diagram for a combination VSEP and spiral RO treatment system for FGD wastewater. The concentrate from stage one (VSEP) can be disposed of using a variety of onsite and offsite techniques, including thermal treatment, solidification (also referred to as encapsulation), and underground disposal. The concentrate from stage two (RO reject) would typically be combined with the feed entering the VSEP membrane (stage one).

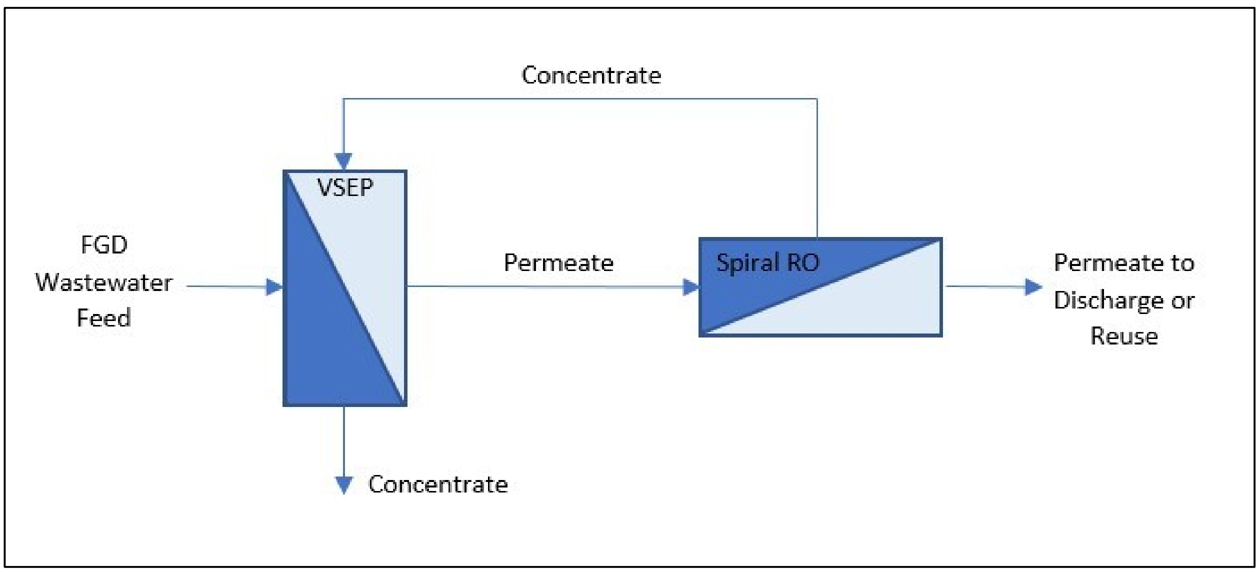

Figure 1. Example Two-Stage VSEP System Process Flow Diagram

Another potential configuration would be a three-stage system with two VSEP RO membrane units followed by a conventional spiral RO membrane to polish the VSEP permeate, as shown in Figure 2. This configuration consists of a low-pressure (500 psi) VSEP RO membrane and a high-pressure (1,000 psi) VSEP RO membrane. Concentrate from the low-pressure VSEP is transferred to a high-pressure VSEP stage, with the permeate from the two VSEP stages becoming the influent to the spiral RO membrane. According to New Logic, the number of VSEP/RO stages is determined by the TDS or osmotic pressure limitations and the desired amount of water recovery (or to reduce the volume of reject requiring disposal).

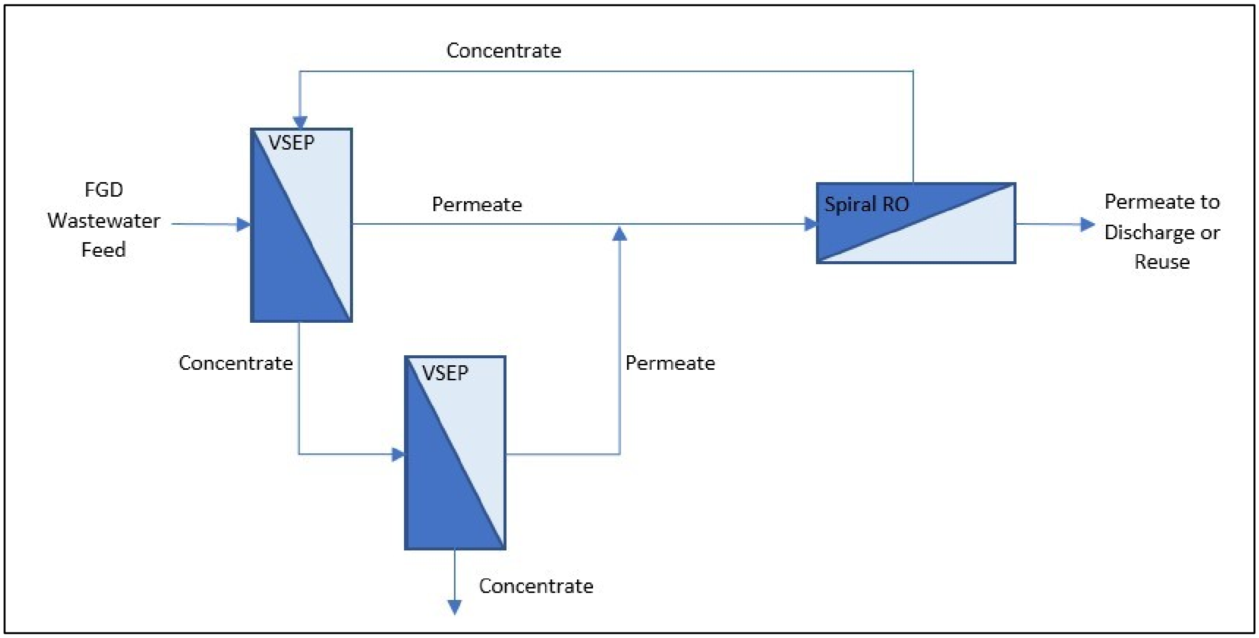

Figure 2. Example Three-Stage VSEP System Process Flow Diagram

New Logic's VSEP modules are available in several sizes. The largest VSEP module currently offered by New Logic is 1,400 ft^2. The capacity of a single 1,400 ft^2 VSEP module will depend on the TDS of the feed, temperature, and recovery rate. But assuming an average flux rate of 18 gallons per square foot per day, which could be considered a typical range, the single module could produce 18,000 gallons per day (GPD) [12.5 GPM] of permeate. Modules of VSEPs can be operated in parallel to meet any flow rate requirements.

Concentration of TSS is not a limiting factor for the VSEP/RO system; however, particle size is. Large particles, those greater than 100 micrometers (μm) in diameter, can cause damage to pumps, valves, and the membrane. Pretreatment of the raw feed water prior to the VSEP/RO technology is necessary for FGD wastewater treatment applications. The raw feed water should be strained or passed through a settling tank to remove grit and large particles, and also treated such that the influent TDS does not exceed 100,000 ppm. As designed, the typical VSEP/RO system includes a basket strainer, but this is not meant as a pretreatment step; it is a secondary measure for large particles or items that may be accidentally dropped (e.g., screwdrivers). It should not be the sole form of pretreatment if the wastewater does contain particles larger than 100 microns. Another pretreatment step that needs to be considered is chemical addition to remove free chlorine and other oxidants. Dechlorination of the feed may be necessary because chlorine damages the polyamide membranes used in the VSEP system, which would result in a lower membrane rejection rate.

Like other membrane systems, the VSEP membranes require periodic flushing and chemical cleanings. These cleanings occur anywhere from once a day to once a month, with once or twice a week being the average. New Logic estimates that the membranes will need to be replaced every one to two years.

Industry sources report that the VSEP tests summarized in Section 2 demonstrate that anti- fouling technology can enable the use of membrane filtration to treat FGD wastewater and that the VSEP/RO treatment train is effective at removing selenium, arsenic, mercury, and nitrate- nitrite to concentrations well below the ELG limitations. These sources also report that the onsite tests demonstrate that the anti-fouling properties of the VSEP system enable it to treat FGD wastewater without the need for extensive pretreatment. Additionally, the VSEP/RO treatment process has a relatively small footprint and obviates the need for the reaction tanks and much of the other equipment typically included as part of chemical-biological treatment trains. Treating FGD wastewater with the VSEP/RO system can achieve significant volume reduction upstream of thermal or encapsulation zero discharge technologies, thereby reducing the size and cost of the thermal/encapsulation equipment.

2.0 TECHNOLOGY STATUS AND PERFORMANCE

New Logic has conducted several on-site, pilot-scale studies for the treatment of wastewater from power plants using the VSEP system. Table 1 provides a summary of several pilots conducted to treat FGD wastewater and fly ash leachate. With the exception of one pilot study where the wastewater was pretreated by softening with lime and soda ash, New Logic confirmed that there was no pretreatment prior to the VSEP system. New Logic also confirmed that all studies included spiral RO polishing in the treatment train.

Table 1. Summary of New Logic Pilot-Scale Studies

Location	Date	Application	Pilot Feed Rate	Water Recover	Feed TDS	Concentrate TDS (mg/L)
Pilot Study #1	6/29/09 - 8/14/09	FGD Wastewater	30.0	67.0%	41,200	93,000
Pilot Study #2	10/16/13 - 1/15/14	FGD Wastewater	25.5	83.2%	17,500	63,500
Pilot Study #3	1/10/15 - 1/20/15	FGD Wastewater	24.8	73.0%	24,600	105,200
Pilot Study #4	6/8/15 - 7/17/15	FGD Wastewater	21.6	75.0%	16,000	59,000
Pilot Study #5	5/17/16 - 6/8/16	FGD Wastewater	24.3	78.8%	4,000	14,200
Pilot Study #6	3/1/18 - 3/15/18	Fly Ash Leachate	27.9	93.0%	7,700	57,000
Pilot Study #7	6/2018 – 10/2018	Surface Impoundment Effluent, including FGD	Specific details unknown.			
Pilot Study #8	9/26/18 - 10/10/18	FGD Wastewater	29.5	55.0%	46,800	75,500

EPA has additional details on three of the on-site, pilot-scale studies for the treatment of FGD wastewater listed in Table 1: Pilot Study #2, #4, and #7. New Logic also provided further information on full-scale VSEP systems installed to treat cooling tower blowdown. The details of these three FGD wastewater pilots and cooling tower blowdown applications are presented
further in the subsections below.

2.1 Pilot Study #2

A commercial-scale two-stage VSEP/RO system was tested for three months at a coal-fired power plant to treat FGD wastewater. During the study, the VSEP system was operated in both a batch mode and a single-pass mode, with the VSEP system receiving untreated FGD wastewater from the plant's feed tank. The source of wastewater for the feed tank was the plant's FGD settling pond. Other than gravity settling in a surface impoundment, no pretreatment of the wastewater was performed prior to the VSEP system. During batch mode, a finite volume of FGD wastewater is processed through the system. The permeate was transferred away from the system, while the concentrate stream was recycled back to the feed tank for reprocessing. As the batch continued, the feed to the VSEP system became more concentrated and continued operating until a specified end point was reached, such as a target permeate flow rate. Batch operation such as this can be used to maximize the amount of water recovery, which has the effect of minimizing the volume of concentrate requiring disposal or further treatment. During single-pass mode, the feed enters the VSEP system while the concentrate valve is closed. As the permeate is processed through the system, the concentrate valve is opened when the desired permeate volume has been achieved.

The concentrated wastewater (membrane reject) is purged from the system when the concentrate valve is opened. During the study, in both modes of operation, the VSEP permeate was transferred to a conventional spiral RO for polishing. Using the combination of VSEP and spiral RO, the treatment train consistently met the discharge limits for FGD wastewater established by the 2015 ELGs (in fact, the effluent concentrations were lower than the limits proposed by EPA in 2013, which were lower than the limits established by the 2015 ELGs). The pilot test results demonstrated that anti-fouling technology enables the use of membrane filtration to treat FGD wastewater, with no loss of flux and no irreversible fouling or scaling of the membranes over the duration of the study. The pilot test also showed that chemical pretreatment of the wastewater was unnecessary, although addition of anti-scalant can increase water recovery rates. Table 2 presents the average pollutant concentrations in the influent, the VSEP permeate, and the spiral RO permeate when the system was operated in a single-pass mode. Table 3 presents the average pollutant concentrations in the influent, the VSEP permeate, and the spiral RO permeate when the system was operated in a batch mode.

Table 2. Average Pollutant Concentrations for VSEP Pilot Operating in Single-Pass Mode During Pilot Study #2

Paramete	Feed	VSEP Permeat	Spiral RO
Alkalinity (mg/L)	56.3	10.8	10.8
TDS (mg/L)	17,400	813	352
TSS (mg/L)	106	2	< 1

Table 2. Average Pollutant Concentrations for VSEP Pilot Operating in Single-Pass Mode During Pilot Study #2

Paramete	Feed	VSEP Permeat	Spiral RO
Total Solids (mg/L)	17,600	815	353
Fluoride (mg/L)	9.46	< 1.30	< 1.30
Chloride (mg/L)	8,010	254	< 25
Nitrite (mg/L)	4.58	< 1.30	< 1.30
Bromide (mg/L)	61.0	< 3.26	< 3.26
Nitrate (mg/L)	19.2	< 6.51	< 6.51
Nitrate-Nitrite (mg/L)	23.7	0.45	0.07
Phosphate (mg/L)	< 1.30	< 1.30	< 1.30
Sulfate (mg/L)	1,440	< 25	< 25
Beryllium (µg/L)	< 2.5	0.67	< 0.5
Boron (µg/L)	155,000	109,000	81,200
Sodium (µg/L)	52,100	15,900	2,480
Magnesium (µg/L)	646,000	12,500	< 50
Aluminum (µg/L)	< 1,000	< 200	< 200
Silicon (µg/L)	20,900	1,010	< 1,000
Potassium (µg/L)	20,050	10,300	< 2,000
Calcium (µg/L)	2,980,000	72,700	< 2,000
Titanium (µg/L)	21.4	< 2	< 2
Vanadium (µg/L)	< 50	< 10	< 10
Chromium (µg/L)	< 10	< 2	< 2
Manganese (µg/L)	6,430	134	< 4
Iron (µg/L)	< 500	< 100	< 100
Cobalt (µg/L)	34.6	< 0.5	< 0.5
Nickel (µg/L)	178	< 5	< 5
Copper (µg/L)	< 25	< 5	< 5
Zinc (µg/L)	2,010	47.9	< 10
Arsenic (µg/L)	< 5	< 1	< 1
Selenium (µg/L)	191	1.54	< 1
Strontium (µg/L)	912	22.8	< 0.5
Molybdenum (µg/L)	64.6	0.52	< 0.5
Silver (µg/L)	< 2.5	< 0.5	< 0.5
Cadmium (µg/L)	74.2	1.61	< 0.5
Antimony (µg/L)	5.24	< 0.5	< 0.5
Barium (µg/L)	404	11.0	< 0.5
Tungsten (µg/L)	< 2.5	< 0.5	< 0.5
Mercury (ng/L)	1,400	35.4	11.0

Table 2. Average Pollutant Concentrations for VSEP Pilot Operating in Single-Pass Mode During Pilot Study #2

Paramete	Feed	VSEP Permeat	Spiral RO
Thallium (µg/L)	8.12	9.76	1.19
Lead (µg/L)	< 2.5	< 0.5	< 0.5
Uranium (µg/L)	23.1	< 0.5	< 0.5

Table 3. Average Pollutant Concentrations for VSEP Pilot Operating in Batch Mode During Pilot Study #2

Paramete	Feed	VSEP Permeat	Spiral RO
Alkalinity (mg/L)	55.0	10.0	10.0
TDS (mg/L)	9,820	544	< 1
TSS (mg/L)	58	< 1	< 1
Total Solids (mg/L)	9,880	544	< 1
Fluoride (mg/L)	6.3	< 1.30	< 0.260
Chloride (mg/L)	4,110	183	< 5
Nitrite (mg/L)	< 5.21	< 1.30	0.5
Bromide (mg/L)	23.3	5.8	< 0.651
Nitrate (mg/L)	< 26.0	< 6.51	< 1.30
Nitrate-Nitrite (mg/L)	13.1	0.75	0.04
Phosphate (mg/L)	< 5.21	< 1.30	< 0.260
Sulfate (mg/L)	1,010	< 25	< 5
Ammonium (µg/L)	< 40	< 20	0.109
Beryllium (µg/L)	0.72	< 20	< 0.5
Boron (µg/L)	97,900	< 0.5	32,400
Sodium (µg/L)	24,800	54,100	881
Magnesium (µg/L)	375,000	5,260	139
Aluminum (µg/L)	< 400	14,000	< 400
Silicon (µg/L)	17,400	< 400	< 1,000
Potassium (µg/L)	13,800	1,000	< 2,000
Calcium (µg/L)	2,120,000	4,650	< 2,000
Titanium (µg/L)	6.08	86,100	< 1
Vanadium (µg/L)	< 10	< 1	< 10
Chromium (µg/L)	< 2	16.2	< 2
Manganese (µg/L)	5,110	< 2	< 2
Iron (µg/L)	< 100	181	< 100
Cobalt (µg/L)	36.4	< 100	< 0.5
Nickel (µg/L)	177	1.32	< 5

Table 3. Average Pollutant Concentrations for VSEP Pilot Operating in Batch Mode During Pilot Study #2

Paramete	Feed	VSEP Permeat	Spiral RO
Copper (µg/L)	10.8	6.61	< 5
Zinc (µg/L)	1,160	< 5	< 5
Arsenic (µg/L)	2.03	42.9	< 1
Selenium (µg/L)	267	< 1	< 1
Strontium (µg/L)	633	4.24	< 0.5
Molybdenum (µg/L)	31.3	24.7	< 0.5
Silver (µg/L)	< 0.5	0.54	< 0.5
Cadmium (µg/L)	54.4	< 0.5	< 0.5
Antimony (µg/L)	5.02	1.33	< 0.5
Barium (µg/L)	288	< 0.5	< 1
Tungsten (µg/L)	0.65	11.4	< 0.5
Mercury (ng/L)	833	< 0.5	<10
Thallium (µg/L)	6.20	10.3	0.88
Lead (µg/L)	< 0.5	5.46	< 0.5
Uranium (µg/L)	15.1	< 0.5	< 0.5

2.2 Pilot Study #4

New Logic conducted a pilot study at a coal-fired power plant to test the performance of its VSEP system at treating FGD wastewater at a power plant. During the study, the VSEP system was primarily tested in the single-pass mode, but the percent recovery and the use of an anti- scalant pretreatment were varied to find the optimal performance for the system. Additionally, the VSEP permeate was fed through a spiral-wound RO system to improve the quality of the discharge. Three single-pass runs were conducted at 50 percent recovery, and four single-pass runs were conducted at 75 percent recovery. Initial testing demonstrated that anti-scalant typically increased throughput rates, so the majority of testing was performed with anti-scalant. Results from the 50 percent recovery runs are presented in Table 4, and results from the 75 percent recovery runs are presented in Table 5.

Table 4. Single-Pass Pollutant Concentrations Under 50% Permeate Recovery Rate During Pilot Study #4

Run Permeate Recovery Rate	Parameter	Feed	VSEP Permeat	Spiral RO Permeat
50	Mercury (total, ng/L)	110	1.7	0.28[a]
	Arsenic (total, µg/L)	2.5[a]	ND	ND

Table 4. Single-Pass Pollutant Concentrations Under 50% Permeate Recovery Rate During Pilot Study #4

Run Permeate Recovery Rate	Parameter	Feed	VSEP Permeat	Spiral RO
	Cadmium (total, µg/L)	ND	ND	ND
	Chromium (total, µg/L)	ND	ND	ND
	Copper (total, µg/L)	ND	ND	ND
	Selenium (total, µg/L)	280	6.3	2.3[a]
	Zinc (total, µg/L)	ND	ND	ND
	Nitrate (as N; mg/L)	6.4	0.51	0.02[a]
	TDS (mg/L)	13,000	540	51
	TSS (mg/L)	31	ND	1.6[a]
50	Mercury (total, ng/L)	190	3.5	1.8
	Arsenic (total, µg/L)	2.5[a]	ND	ND
	Cadmium (total, µg/L)	ND	ND	ND
	Chromium (total, µg/L)	ND	ND	ND
	Copper (total, µg/L)	2.2[a]	ND	ND
	Selenium (total, µg/L)	340	6.4	2.8[a]
	Zinc (total, µg/L)	ND	ND	ND
	Nitrate (as N; mg/L)	6.1	1.3	ND
	TDS (mg/L)	16,000	750	230
	TSS (mg/L)	97	1.6[a]	2[a]
50	Mercury (total, ng/L)	69	1.3	1.9
	Arsenic (total, µg/L)	3[a]	ND	ND
	Cadmium (total, µg/L)	ND	ND	ND
	Chromium (total, µg/L)	ND	ND	ND
	Copper (total, µg/L)	1.9[a]	ND	ND
	Selenium (total, µg/L)	240	3.4[a]	1.6[a]
	Zinc (total, µg/L)	ND	ND	ND
	Nitrate (as N; mg/L)	17	1	0.18
	TDS (mg/L)	16,000	620	150

Table 4. Single-Pass Pollutant Concentrations Under 50% Permeate Recovery Rate During Pilot Study #4

Run Permeate Recovery Rate	Parameter	Feed	VSEP Permeate	Spiral RO
	TSS (mg/L)	29	1.6[a]	6.4

a – Measurement below the quantitation limit, but above the method detection limit.

Table 5. Single-Pass Pollutant Concentrations Under 75% Permeate Recovery Rate During Pilot Study #4

Run Permeate Recovery Rate	Parameter	Feed	VSEP Permeate	Spiral RO
75	Mercury (total, ng/L)	150	4.2	0.24[a]
	Arsenic (total, µg/L)	1.9[a]	ND	ND
	Cadmium (total, µg/L)	ND	ND	ND
	Chromium (total, µg/L)	ND	ND	ND
	Copper (total, µg/L)	1.4[a]	ND	2.9[a]
	Selenium (total, µg/L)	330	11	3.9[a]
	Zinc (total, µg/L)	ND	ND	ND
	Nitrate (as N; mg/L)	15	3.2	0.025[a]
	TDS (mg/L)	16,000	1,000	240
	TSS (mg/L)	63	1.6[a]	ND
75	Mercury (total, ng/L)	180	2.6	0.44[a]
	Arsenic (total, µg/L)	2[a]	ND	ND
	Cadmium (total, µg/L)	ND	ND	ND
	Chromium (total, µg/L)	ND	ND	ND
	Copper (total, µg/L)	1.7[a]	ND	ND
	Selenium (total, µg/L)	320	10	5
	Zinc (total, µg/L)	ND	ND	ND
	Nitrate (as N; mg/L)	16	2.6	0.06[a]
	TDS (mg/L)	15,000	1,200	260
	TSS (mg/L)	36	3.2[a]	2.8[a]
75	Mercury (total, ng/L)	100	6.5	1.2
	Arsenic (total, µg/L)	1.9[a]	ND	ND
	Cadmium (total, µg/L)	ND	ND	ND

Table 5. Single-Pass Pollutant Concentrations Under 75% Permeate Recovery Rate During Pilot Study #4

Run Permeate Recovery Rate	Parameter	Feed	VSEP Permeate	Spiral RO
	Chromium (total, µg/L)	ND	ND	ND
	Copper (total, µg/L)	ND	ND	1.7[a]
	Selenium (total, µg/L)	250	7.9	5
	Zinc (total, µg/L)	ND	ND	ND
	Nitrate (as N; mg/L)	17	1.1	0.13
	TDS (mg/L)	16,000	1,100	100
	TSS (mg/L)	170	5.6	7.6
75	Mercury (total, ng/L)	54	2.6	0.82
	Arsenic (total, µg/L)	2.3[a]	ND	ND
	Cadmium (total, µg/L)	ND	ND	ND
	Chromium (total, µg/L)	ND	ND	ND
	Copper (total, µg/L)	ND	ND	ND
	Selenium (total, µg/L)	250	10	3.2[a]
	Zinc (total, µg/L)	ND	ND	ND
	Nitrate (as N; mg/L)	16	3.7	0.23
	TDS (mg/L)	16,000	2,000	110
	TSS (mg/L)	71	2.8[a]	1.6[a]

a – Measurement below the quantitation limit, but above the method detection limit.

2.3 Pilot Study #7

New Logic conducted a pilot study at a power plant to test the performance of the VSEP system at reducing the volume of water stored in a surface impoundment containing FGD wastewater. The plant operates with zero discharge and its storage ponds were beginning to reach a level that could potentially cause issues at the plant. Therefore, the plant was looking for a technology that would allow them to reuse water internally to reduce the amount of raw water entering the plant and reduce the volume of stored water in the ponds. The tested system incorporated five VSEP nanofiltration membrane modules. The addition of spiral RO treatment downstream of the VSEP modules was not tested as part of the original pilot test but was determined to be a viable option for further polishing monovalent ions. The goal of the study was to identify the optimum system operation that allowed for the highest recovery achievable in which the required cleanings were at least five days apart. The pilot test found that 75 percent recovery at 210 psi reduced the conductivity of the feed water from approximately 5,000 µS/cm to 1,400 µS/cm in the permeate.

Concentrate from the system averaged approximately 10,500 µS/cm and was routed to one of the on-site evaporation ponds.

2.4 Cooling Tower Blowdown VSEP Installations

New Logic has installed four full-scale VSEP installations to treat cooling tower blowdown. Table 6 provides a summary of these installations including system design flowrate, permeate destination, and concentration destination.

Table 6. Summary of Cooling Tower Blowdown VSEP Installations

Project	Feed Material	Design Flow Rate	Permeate Destination	Concentrate Destination
ExxonMobil King Ranch Gas Plant	Cooling Tower Blowdown	161	Reuse as boiler feed and/or cooling tower makeup	Saltwater disposal
Burney Forest Power	Cooling Tower Blowdown	35	Reuse as cooling tower	Brine hauling
Calpine Pastoria	Cooling Tower Blowdown	60	Reuse as cooling tower	Brine concentrator
Talen Energy	Cooling Tower Blowdown and Groundwater	167	Reuse as cooling tower	Scrubber slurry pit

Appendix L – Oasys Forward Osmosis Technology

1.0 TECHNOLOGY DESCRIPTION

Forward osmosis (FO) is a membrane-based process utilizing a draw solution as a high osmotic potential agent to capture fresh water from a saline or contaminated feed stream. FO is driven by an osmotic pressure gradient across a semi-permeable membrane to attain spontaneous and preferential diffusion of water molecules from a wastewater feed into a draw solution. The draw solution pulls out the clean water from the wastewater feed stream and becomes diluted as it flows through the FO membrane system. The result of the FO separation is a highly concentrated wastestream (i.e., brine stream) and a diluted draw solution stream. The diluted draw solution stream is subsequently processed and recycled to re-concentrate the draw solution to full strength for reuse in the FO system and to recover the final high-quality product water.

Oasys has developed a high recovery FO technology platform, the MBC system, which combines a specialized draw solution technology, a highly efficient draw recovery system, and a proprietary FO membrane. Oasys has two MBC system technologies, the ClearFlo MBC system and the ClearFlo Edge MBC system. The ClearFlo MBC can treat influent total dissolved solids (TDS) concentrations of up to 150,000 ppm. Oasys manufactures the ClearFlo MBC Edge for smaller desalination applications, with influent streams containing up to 50,000 ppm TDS.

1.1 FGD Wastewater Treatment – ClearFlo MBC

Oasys developed the ClearFlo MBC system by combining optimization of membrane and draw solution interaction, innovation in draw solution recovery, and refinements to system controls architecture to improve process performance and economics. The Oasys FO membrane is a thin- foam composite (TFC) with a thin polyamide backbone. Treatment only requires one pass through the membrane unit. The MBC utilizes a high osmotic draw solution (6,000 psi) that is highly soluble. The solution contains ammonia carbamate, formed by dissolving ammonia and carbon dioxide gases in water.

Two streams are fed into the FO membrane unit: influent wastewater and the concentrated draw solution (CDS) in a countercurrent orientation. Two streams also leave the FO membrane unit: the diluted draw solution (DDS) and the concentrated brine solution. The DDS is sent to a recovery unit where clean water is stripped and discharged for reuse. The draw solution is thermolytic—as heat is added, the ammonia and carbon dioxide evaporate from solution, leaving behind clean water. The ratio of ammonium salts to other components in the dilute and concentrated draw solution naturally buffers the solution and maintains pH between 9.8 and 10.3. No additional pH control by chemical addition is required, other than making sure the salt ratios are in range. The ammonia and carbon dioxide gases formed in the recovery unit are sent to a condenser absorber (a simple distillation column) for recovery.

The ClearFlow MBC system is operated at atmospheric pressure. The difference between the effective feed pressure of the CDS and the effective draw pressure of the DDS is the driving force for FO. Unlike the conventional reverse osmosis (RO) where the differential osmotic pressure generally decreases as the water flows through the membrane column, FO can maintain an approximately constant differential osmotic pressure through the membrane column. The draw solution is concentrated and polarized at the feed and becomes more dilute as water is naturally pulled from the wastewater to the other side of the membrane, thus creating a concentrated brine solution.

The draw solution system is considered a closed loop. A minimal amount of draw solution does pass into the brine. Over time, makeup draw solution is required due to some loss into the brine and losses due to upsets and sample collection. Draw solution that passes into the brine is stripped out in a brine stripper column, ensuring that draw solution is lost at a very slow rate. Energy used to heat the thermolytic draw solution can be recovered.

RO is sometimes used to pre-concentrate influent that enters the FO membrane. By pre- concentrating the wastewater, the FO system can be smaller and more economical.

Upon exiting the FO unit, the brine concentrate has a TDS concentration of 250,000 ppm or higher. Brine concentrate may then be fed into a crystallizer, a spray dryer, or mixed with fly ash and lime to manufacture a solid for disposal. Oasys does not provide evaporation, crystallizing, or spray drying equipment.

2.0 TECHNOLOGY STATUS AND PERFORMANCE

Oasys has installed two full-scale systems for the treatment of FGD wastewater internationally and has conducted one pilot studies in the U.S.

2.1 Changxing Power Station – China

In 2015, Oasys installed a full-scale treatment system at the coal-fired Huaneng Changxing Power Plant the world's first FO-based ZLD solution. The station includes twin 660 MW steam generators and flue gas pollution controls including wet limestone slurry FGD units by Wuhan Kaidi. The treatment train consists of a solids contact clarifier, filter press, multi-media filtration, and weak acid cation (WAC) ion exchange polishing as pretreatment, then into the ClearFlo MBC system (RO pre-concentration and the FO trains). The concentrated brine is then sent to a crystallizer.

The treatment system is designed to handle approximately 160,000 gallons per day. The incoming FGD wastewater has a TDS concentration of 25,000 ppm. Since operation began, the system has consistently achieved product water with a TDS concentration in the range of 35 to 50 ppm.

The FO system at Changxing was designed to treat wastestreams that were pretreated for mineral hardness removal and concentrated using a RO membrane system. Operations have found the FGD wastewater to be generally at a much lower TDS than the design envelope of 25,000 to 40,000 ppm. The low salinity of the raw water leads to a higher total water recovery through the RO and FO systems. The raw feed is rich in sulfate, which is typical of most FGD blowdown. The combination of these factors requires the removal of mineral hardness for extensive water recovery in the RO and FO systems prior to being fed to the crystallizer. Table 1 presents water quality data for the FO system at Changxing.

Table 1. Water Quality of Major Streams of the FO System in Changxing, China

Analyte	Raw FGD Wastewate	Pretreated MBC Feed	FO Fee	MBC Brine/ Crystallizer	MBC Product
pH	9.4-10.2	9.5-11.0	9.5-11.6	9.5-9.8	9.9-10.9
Na (mg/L)	1,400-2,000	3,460-6,800	14,000-21,000	57,000-85,000	8.7-19.2
Ca (mg/L)	60-600	< 5.0	< 5.0	< 5.0	< 0.05
Mg (mg/L)	150-650	< 5.0	< 5.0	< 5.0	< 0.05
SiO_2 (mg/L)	10-80	5-37	26-137	200-300	< 0.10
Cl (mg/L)	1,700-3,000	2,600-4,800	8,000-16,000	37,000-59,000	5.5-15.2
SO_4 (mg/L)	1,500-3,500	1,500-3,500	8,000-15,000	33,000-45,000	0.3-1.1
HCO_3	40-120	210-620	1,000-3,300	7,300-20,800	3.0-10.1
CO_3 (mg/L)	15-45	390-805	2,000-4,200	1,300-6,200	5.5-11.0

TDS (mg/L)	6,500-11,500	8,700-16,000	43,000-64,500	155,000-220,000	36-49

Note: Raw water contains 0.0025 mg/L arsenic, 0.044 mg/L selenium, 19.4 mg/L nitrate nitrogen, and 0.1 mg/L nitrite nitrogen. Mercury was not detected, with a detection limit of 0.0002 mg/L. The product water from the RO and system contains < 0.001 mg/L arsenic, 0.0026 mg/L selenium, 7.3 mg/L nitrate nitrogen, and 0.06 mg/L nitrite nitrogen. Mercury was not detected, with a detection limit of 0.0002 mg/L.

2.2 Shanxi Lujin Wangqu Power Station, Lucheng City, China

At the Shanxi Lujin Wangqu Power Plant, Oasys installed a full-scale MBC system to treat FGD wastewater at a feed rate of 79,000 gallons per day. Pretreatment prior to entering the MBC system consists of softening, multimedia filtration, and weak acid cation exchange. The treatment system was installed in mid-2017. The final brine is combined with bottom ash and fly ash for landfill disposal but is not completely encapsulated. Product water is used as make-up water to an offsite denim plant.

2.3 Water Research Center Pilot Study for FGD Wastewater Treatment

Oasys deployed the ClearFlo MBC technology at the Water Research Center (WRC) at Georgia Power's Plant Bowen Power Station from September to October 2016. The two-month pilot study tested a sidestream of FGD pond effluent and verified MBC system performance, reliability, and safety. Oasys operated a 6-9 gallon per minute system consisting of a physical/chemical treatment system to reduce hardness, metals, silica, and solids (pH adjustment, chemical softening, microfiltration, ion exchange, antiscalant) prior to the MBC system (RO, single-pass FO units, and draw recovery system).

The FO units operated as a single-pass operation and did not require cleaning throughout the duration of the study, which totaled more than 300 hours of continuous operation. Untreated FGD wastewater TDS concentrations ranged from 12,000 to 20,000 ppm and 90-95 percent of the raw water was recovered for potential reuse or discharge with a TDS concentration of less than 250 ppm. Brine concentrate had TDS concentrations of up to 300,000 ppm. Table 2 presents performance data from the WRC pilot study.

Table 2. Summary of Performance Data from WRC Pilot Study

Analyte	Raw FGD Water	MBC Feed Water	MBC Product Water
		Data Based on Oasys Demonstration Pilot	
Arsenic (ppb)	33	29	ND (<5)
Mercury (ppt)	2,920	ND (<200)	ND (<200)
Selenium (ppb)	313	250	3.4
Nitrate-Nitrite (ppm-N)	15	13	0.9
TDS (ppm)	13,300	14,600	<250
Boron (ppm)	187	159	4.4

Appendix M – Purestream Membrane Technology

1.0 TECHNOLOGY DESCRIPTION

Purestream is a water services company formed in 2010 with a specialty in developing brine concentration and desalination technology for water reuse in power plants. Purestream's AVARA uses advanced mechanical vapor recompression to remove pollutants from wastewater and generates a reusable distillate stream and concentrated brine stream from wastewater. It can be used in municipal, commercial, and industrial wastewater treatment systems but is intended for power plant waste streams. It is designed as a modular system that could be used in the field to minimize wastewater, reducing or even eliminating the need to transport, treat, or dispose of wastewater elsewhere.

Each commercial AVARA module has a capacity of 35 gallons per minute (GPM), is skid- mounted (50 feet by 12 feet) and can easily be installed. The modular system, after being purchased or leased from Purestream, can be built in 180 days and is deployable within two days of on-site delivery; assembly only requires electrical and plumbing connections be established. Multiple 35 GPM units can operate together to create a larger capacity system. Each self- contained unit can be placed on-site on individual skids (one unit and ancillary equipment per skid) or equipment can be reconfigured (e.g., all compressors on one skid, all heat exchangers on one skid, etc.) for flexible installation. Purestream asserts that if pH, scaling potential, and solids are monitored and kept within an acceptable range, there are not any additional factors that would preclude installation of the system in any plant design. Influent concentrations are typically monitored and controlled at the feed tank prior to the heat exchanger. Figure 1 shows a process flow diagram for a typical AVARA system.

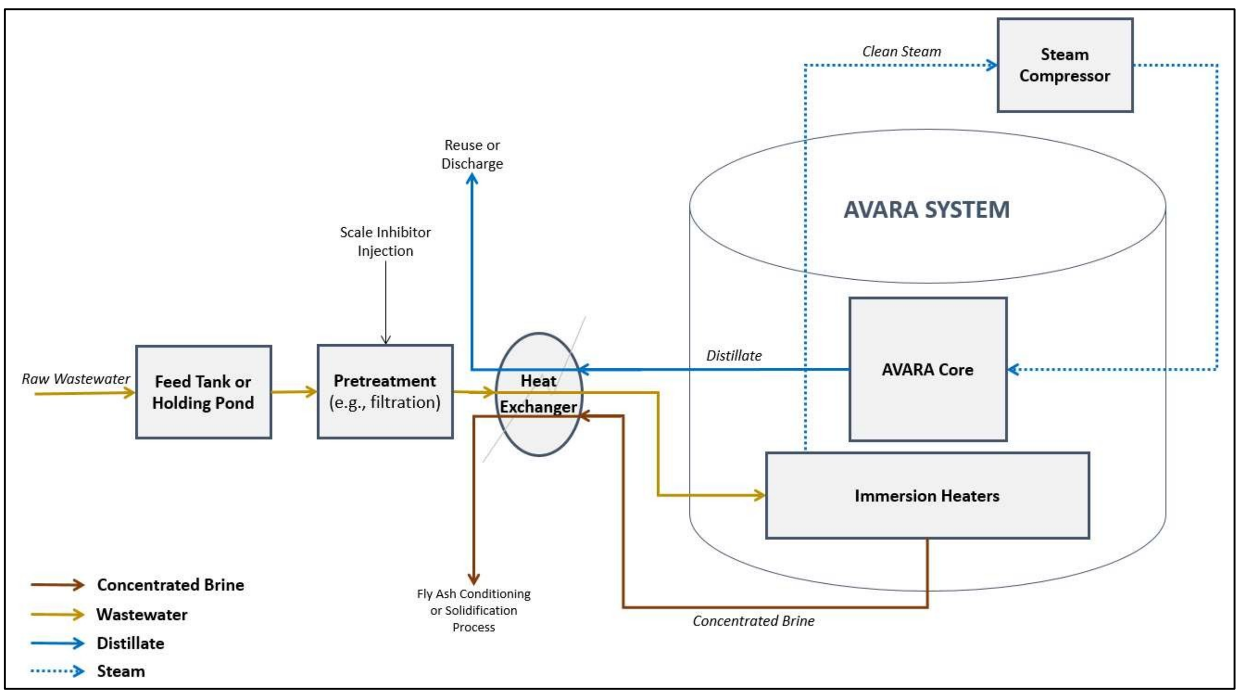

Figure 1. Process Flow Diagram for AVARA Mechanical Vapor Recompression System

FGD wastewater is pumped from a holding pond or tank through an influent filtration system to remove suspended solids; a scale inhibitor is added at the filtration system. To facilitate evaporation, wastewater is initially heated by immersion heaters to the desired temperature. As the wastewater inside the tank boils, steam vents from the top of the tank and passes through a steam compressor, which pushes the steam inside the AVARA cores; the cores are a proprietary design in vertical plate orientation. Heat transfers from steam inside the cores to the brine in the tank, while the steam condenses inside the cores and becomes the "clean" distillate stream. This distillate stream can be discharged or returned to the plant for beneficial reuse; it has a total dissolved solids (TDS) concentration below 300 parts per million (ppm). As wastewater evaporates and steam is generated, the TDS in the brine remaining in the tank becomes concentrated. Once the brine reaches a predetermined TDS set point concentration, not to exceed 200,000 ppm, brine is discharged from the tank in a continuous stream through hydrocyclones. Heat exchangers recover and transfer energy from the hot brine and distillate streams to preheat influent entering the AVARA tank, reducing reliance on the immersion heaters. The concentrated brine may be combined with fly ash for disposal in a landfill or may be used as an ingredient for a solidification process (also referred to as brine encapsulation).

In most FGD wastewater applications, raw FGD wastewater with a total suspended solids (TSS) concentration below 30 ppm can be pumped directly into the AVARA system. Wastewater with higher TSS concentrations may require clarification to lower this influent TSS concentration. However, a settling tank often provides sufficient pretreatment. Chemical addition may also be required to maintain the necessary pH between 5.5 and 6.5. Crystal inhibitors and antiscalants are also added to maintain optimal conditions and to mitigate scaling. The bubbles generated by the boiling liquid create turbulence, which also helps mitigate scaling on the immersed cores. Transducers create ultrasonic bubbles and turbulence in the tank that also prevent scale from building up on the cores. Water circulation within the tank also reduces scaling. The submerged core design leaves little potential for oxidation, so equipment corrosion is typically not an issue.

Conventional reverse osmosis (RO) technology may be used to preconcentrate FGD wastewater prior to the AVARA. This could be a cost-effective zero discharge technology when implemented with brine encapsulation.

The AVARA's modular design allows for simple and quick core replacements and repairs. The cores can be considered akin to cartridges that can be removed and replaced with minimal system downtime. When removed, the cores can be serviced offline (i.e., mechanical or chemical cleaning) without affecting running operation of the system. AVARA can be kept in standby mode during shut-down periods of less than a week. In standby mode, burners are lowered to keep wastewater warm and prevent solids from precipitating. For extended shut-down periods, the system is purged, flushed, and residual steam is blown out. The small volumes of steam released from the vents are not typically scrubbed because this is an infrequent process. The AVARA system is marketed as a turn-key technology that includes operation and service (i.e., Purestream is contracted to operate the system for the facility). The longest system operating in the field has been running intermittently for three years.

The AVARA system typically requires on-site operators, but the system can be managed remotely with proper process controls. One operator can run up to five AVARA modules. When scale builds up and cleaning is required in a multi-unit fleet, one unit can be shut down for cleaning while the others continue operating. Based on a pilot-scale study treating FGD wastewater, Purestream estimates the system can operate a year or more before cleaning to remove scale is required. In testing and full-scale implementation to date, cores have been pressure washed to remove scale and have not required chemical cleaning.

2.0 TECHNOLOGY STATUS AND PERFORMANCE

In 2015, Purestream, in conjunction with the Electric Power Research Institute (EPRI), began exploring the potential for AVARA to manage wastewater from coal-fired power plants. Since that time, Purestream has been piloting AVARA with EPRI and three coal-fired power plants to treat FGD wastewater and other waste streams. In 2017, Purestream conducted another AVARA pilot-scale study to treat FGD wastewater at a coal-fired power plant in Northern Indiana. Each of these pilot-scale studies is summarized in Table 1.

Table 1. Pilot Scale AVARA Treatment Systems

Pilot Number/Plant	Test Duration and/or Test	Treatment Train	Treated Water	Recovery Rate
Pilot #1 – Springerville Plant (Arizona)	February – September 2016	Storage pond, settling pits, Induced Gas Flotation (IGF), 35	Cooling tower Blowdown	86%
Pilot #2 – Plant Bowen (Georgia)	May – October	3-GPM AVARA	FGD wastewater and brine	-
Pilot #3 – Merom Generating Station (Indiana)	October – December 2016	35-GPM AVARA	FGD wastewater	82.5%
Pilot #4 – Plant in Northern Indiana	July – September 2017	Chemical precipitation (first three quarters of study), 35- GPM AVARA	Pond effluent containing leachate and FGD wastewater	91%

Appendix N – Saltworks Technology

1.0 TECHNOLOGY DESCRIPTION

Headquartered in British Columbia, Canada, Saltworks Technologies (STI) was founded in 2008. STI specializes in technological applications for treating high saline, highly variable wastewater. Specific to FGD wastewater, STI markets two products, the Flex Electrodialysis Reversal (EDR) Selective (previously the Salt Splitter) and SaltMaker zero liquid discharge (ZLD) wastewater treatment technologies.

The Flex EDR Selective is a hybrid technology built around two common desalination technologies: electrodialysis (ED) and reverse osmosis (RO). The ED system operates upstream of the RO which improves RO reliability by reducing the scaling potential and allowing the RO to operate at a lower pressure. ED is used to electrochemically soften wastewater. The electrochemical process uses monoselective ion exchange membranes to selectively remove chlorides from wastewater. Compared to the traditional softening processes, which involve addition of soda ash, the Flex EDR Selective achieves lower volumes of brine exiting the RO system.

The Flex EDR Selective converts calcium sulfate ($CaSO_4$) to non-scaling sodium sulfate (Na_2SO_4) and calcium chloride ($CaCl_2$). Sodium sulfate and calcium chloride are much more soluble in water than calcium sulfate. Sodium chloride (NaCl) must be added to some FGD wastewater to prevent scaling and allow the ED process to function as designed and maintain the chemistry charge balance in the water. The amount of NaCl required varies by influent chemistry and depends on the concentrations of calcium, sulfate, sodium, and chloride. The Flex EDR Selective technology generates a RO permeate stream, that can be discharged or reused, and two concentrated brine streams, one rich in sodium sulfate and another rich in calcium chloride. Lower TDS concentrations in the untreated wastewater result in higher recovery of water in the RO permeate. The two brine streams can achieve a TDS concentration of 200,000 milligrams per liter (mg/L). Reject from the RO system is recycled back to the Flex EDR Selective feed and reprocessed through the system. Sulfates and multi-valent anions do not pass through the Flex EDR Selective ion exchange membranes and thus are recycled back to the FGD scrubber. Arsenate and selenite also do not pass through the ion exchange membranes.

FGD wastewater requires additional treatment to remove heavy metals and silica. For these pollutants, which cannot be effectively removed by the RO, the pH of the incoming wastewater is raised to 10.5 in order to precipitate out these pollutants prior to the Flex EDR Selective system. When treating FGD wastewater, the treated chloride-reduced wastewater is recycled back to the FGD scrubber. The technology also produces a non-scaling brine, predominantly calcium, sodium, and chloride.

The concentrated brine streams can be sent to a traditional crystallizer, to produce solids that can be landfilled as part of a ZLD configuration, or to STI's SaltMaker technology. STI markets their SaltMaker technology as an alternative to traditional crystallizers or vapor compression systems. It uses humidification and dehumidification systems to evaporate the water. The technology can produce more concentrated brine streams or achieve true ZLD and generate solids. SaltMaker technology operates at temperatures below 95 degree Celsius and can use low-pressure steam as the thermal energy source. Because the system reuses thermal energy, it uses 20-25% of the energy of typical single effect evaporation systems that are open to atmosphere. In part, due to its self-cleaning functionalities, STI claims their SaltMaker technology is more robust, is less likely to foul, and experience lower rates of shutdown as compared to traditional vapor compression systems.

Pilot-scale and bench-scale testing has shown the system can successfully treat FGD wastewater. In 2017, a pilot-scale demonstration in China operated for 90 days and treated 50 gallons of wastewater per day. The system included pretreatment to removed silica, transitional metals and ultra/microfiltration. The incoming FGD wastewater had a total dissolved solids concentration of 19,300 mg/l and the system achieved a RO recovery rate of approximately 91-92%; brine (combined flow of both streams) volume was around 8-9%.

In April and May 2018, STI also conducted a second pilot study in collaboration with the United States Department of Energy, the Electric Power Research Institute, and Southern Company, treating FGD wastewater continuously for 60 days to selectively remove chlorides so the wastewater can be reused within the scrubber system.

Appendix S – DuPont Technologies

1.0 TECHNOLOGY DESCRIPTION

DuPont markets a combination of two technologies to treat FGD wastewater: minimal liquid discharge (MLD) membrane filtration and zero liquid discharge (ZLD) thermal treatment.

- MLD – Includes chemical precipitation, ultrafiltration, ion exchange softening, and combinations of reverse osmosis (RO), forward osmosis (FO), and/or nanofiltration (NF).
- ZLD – Includes pretreatment, which could be MLD, followed by a brine concentrator and crystallizer.

When combined with a ZLD thermal treatment technology, MLD systems can be more affordable and reduce landfill waste. The MLD-ZLD water reuse process begins with pretreatment using UF to remove suspended solids followed by ion exchange or microfiltration softening to remove scaling potential. After pretreatment, a combination of primary RO, secondary RO, ultra-high-pressure RO or FO, and/or selective NF generates permeate and a purified sodium chloride brine. The brine is further treated through the ZLD portion of the system, using the brine concentrator and crystallizer. Permeate from the MLD system can be reused.

Pretreatment requirements vary based on the wastewater influent quality. In general, system operation increases in efficiency with greater softening. With DuPont's RO systems, it is ideal to remove close to 100 percent of hardness prior to RO. Instead of a secondary or more robust precipitation softening step, weak acid cation (WAC) exchange is used to ensure a plant can achieve the desired recovery level. The ion exchange regeneration waste can be sent back to a lime and soda softening process for further treatment.

RO treatment is limited by osmotic pressure of the water and the designed pressure limits of the RO system and membrane module. Standard RO systems can be operated up to 1,200 pounds per square inch (psi). When applying 1,200 psi pressure to an RO membrane, water will stop permeating through the membrane when the water osmotic strength approaches 1,200 psi. Depending on the compositions of salts, the maximum concentration of salt achieved by a system operating at 1,200 psi will be approximately eight to 10 percent. For example, sodium chloride has a higher osmotic strength than sodium sulfate and will reach the maximum osmotic strength at a lower concentration than sodium sulfate. Ultra-high-pressure RO systems are designed to operate up to 1,740 psi, producing salt concentrations between 10 to 20 percent depending on the salt composition.

A four-stage, single-pass RO system, using an ultra-high-pressure RO as the final stage, can achieve up to 95 percent water recovery, with booster pumps used between stages to increase pressure. DuPont recommends operating membranes below 35 degrees Celsius to optimize permeate quality such that permeate is suitable for reuse without needing a second pass of RO treatment.

2.0 TECHNOLOGY STATUS AND PERFORMANCE

DuPont has installed nine MLD-ZLD systems for FGD wastewater treatment at power plants in China since 2015, shown in Table 1. Detailed information on two of these installations were provided by DuPont, described in Sections 2.1 and 2.2 below.

Table 1. DuPont MLD-ZLD Installations in China

Plant Number	Commission Date	Capacity (cubic meters per
Plant #1	2015	22

Plant #2	2017	36
Plant #3	2018	25
Plant #4	2018	10
Plant #5	2018	15
Plant #6	2018	40
Plant #7	2018	40
Plant #8	2018	6
Plant #9	2019	100

2.1 Changxing Power Plant – China

The ZLD water treatment system at the Changxing Power Plant in Zhejiang Province, China treats FGD wastewater and cooling tower blowdown using lime soda softening to remove most of the hardness, WAC exchange to remove any remaining hardness, two-pass RO to preconcentrate the brine, FO, and a brine concentrator/crystallizer. Recovered water from the treatment train is reused as boiler make-up water. Since operation began in May 2015, the plant has achieved between 70 to 75 percent water recovery. This plant uses two seawater RO systems that produce a concentrate TDS of 60,000 mg/L. Salts generated by the crystallizer, up to 10,000 metric tons per year, are sold to the local chemical industry.

2.2 Hanchuan Power Plant – China

At the Hanchuan Power Plant in Hubei Province, China, DuPont implemented an FGD wastewater treatment system consisting of tubular microfiltration (MF) softening, NF, two-pass RO (seawater and brackish water systems), high-pressure RO, and ZLD technologies that generate industrial grade salt, shown in Figure 1 below. Final disposal of the salt product is unknown. Laboratory studies have demonstrated that NF concentrate contains sodium sulfate with some sodium chloride, and the permeate mostly consists of sodium chloride (98.5 percent). This treatment train was originally a pilot study that experienced stable operation for over two months and led to full scale implementation, beginning operation in late 2016.

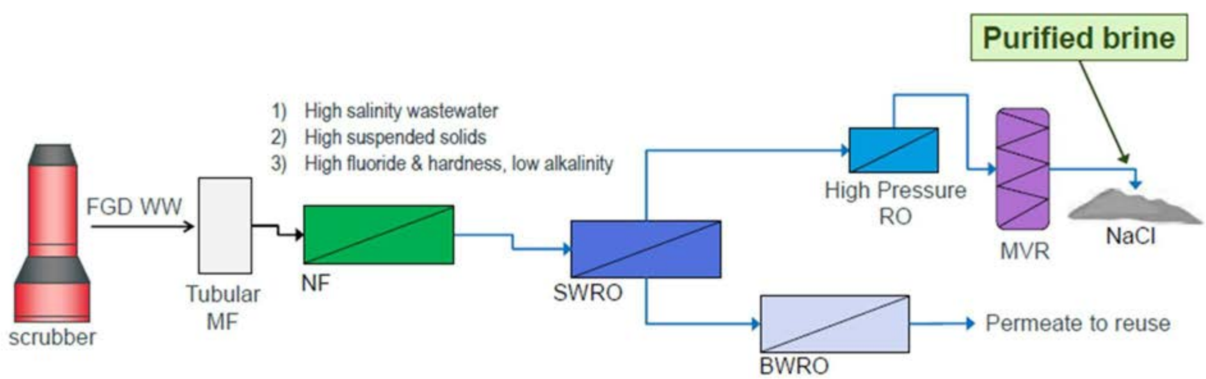

Figure 1. Hanchuan Power Plant FGD Wastewater Treatment System