Can a Scale-Resistant, Membrane-Based Solution to Treat FGD Wastewater Meet EPA Guidelines?

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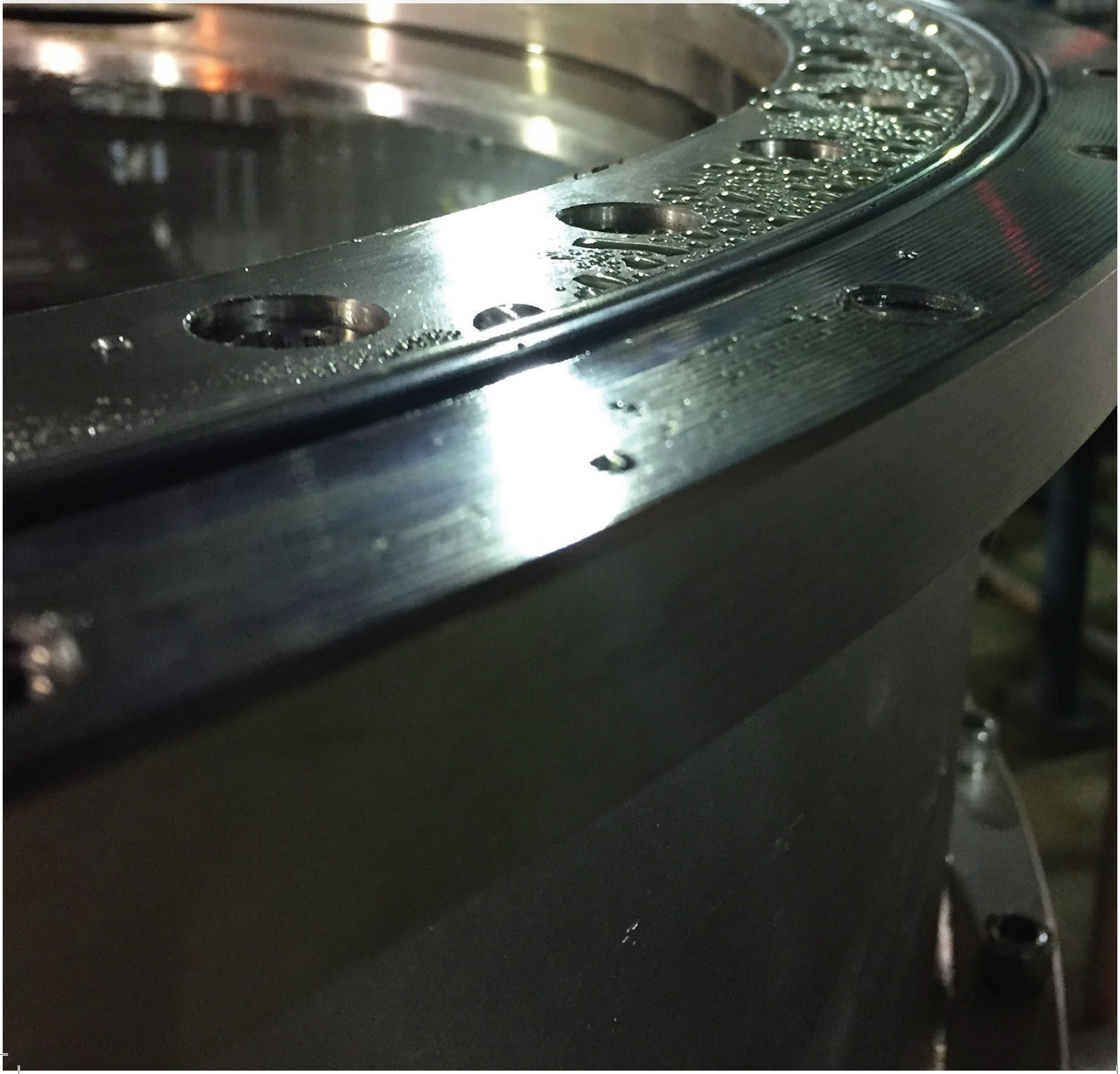


Coal-fired power plants are required by the Clean Air Act to regulate the quantity of sulfur gases emitted by their facilities (1). Generally, sulfurous compounds (e.g., sulfur oxide [SO_X]) are emitted in flue gases as byproducts of coal combustion. To prevent sulfur emissions, power plants employ various technologies to remove SO_X from flue gases in a process called flue gas desulfurization (FGD). This is most commonly achieved using wet scrubbers, wherein stack gases are passed through a liquid slurry of acidified calcium carbonate. This slurry captures gaseous sulfur as liquid calcium sulfate (gypsum), which is precipitated in downstream hydrocyclones.

Following the precipitation of solids, calcium carbonate ($CaCO_3$) is added once again, and the slurry is recycled through the scrubber. As it contacts flue gases, the slurry dissolves not only SO_X but also a range of other compounds, including salts, metals, nitrates, chlorides, and various constituents of the combusted coal (2). The product of this accumulation process is a concentrated liquid that must be purged from the scrubber to avoid corrosion and maintain scrubbing performance (3).

Background

According to the U.S. Environmental Protection Agency's (EPA's) Rule 40 CFR Part 423 (4), this purge stream must be treated prior to discharge to reduce concentrations of at least four key contaminants, including mercury, arsenic, nitrates, and selenium. The limits on these four constituents are described in the EPA's 2015 Effluent Limitation Guidelines (ELG) for FGD wastewater (5). The quantitative discharge limits on these compounds were based on the best available technologies (BATs) at the time of the original EPA study, which were determined to be either a combination of chemical precipitation and biological treatment or the use of evaporators. Evaporators can achieve a higher effluent quality and therefore were assigned tighter effluent limits, but this technology was traditionally too expensive for most plants to operate sustainably, and so the lesser BAT option was provided in the rule.

Table 1 lists the effluent quality limits for the four 2015 ELG contaminants under each of the two treatment options designated by the EPA. Those contaminants are arsenic, mercury, selenium, and nitrogen oxide (NO_X). Local discharge permits granted by state regulators under the National Pollutant Discharge Elimination System (NPDES) may also include additional effluent limits, notably total dissolved solids (TDS). Until recently, the total available treatment options were limited to evaporation, ion exchange, physical/chemical precipitation, and biological treatment. Evaporation equipment and operating costs are comparatively high; therefore, this option is only attractive for small, extremely concentrated streams. Physical/chemical treatment and ion exchange is effective for removing specific contaminants—notably mercury, arsenic, and boron—though these processes are not effective for removal of nitrates or TDS. Biological treatment is effective for removal of selenium and nitrate only (6).

Table 1: 2015 ELG discharge limits for FGD wastewater.*

BAT *Chemical Precipitation + Biological Treatment*			*BADCT* *Evaporation*	
	Daily Max	30-Day Avg.	Daily Max	30-Day Avg.
Arsenic	11 µg/L	8 µg/L	4 µg/L	
Mercury	788 ng/L	356 ng/L	39 ng/L	24 ng/L
Selenium	23 µg/L	12 µg/L	5 µg/L	
NOx	17.0 mg/L	4.4 mg/L		

*Limits as established by the EPA for FGD wastewater.

Membrane Treatment

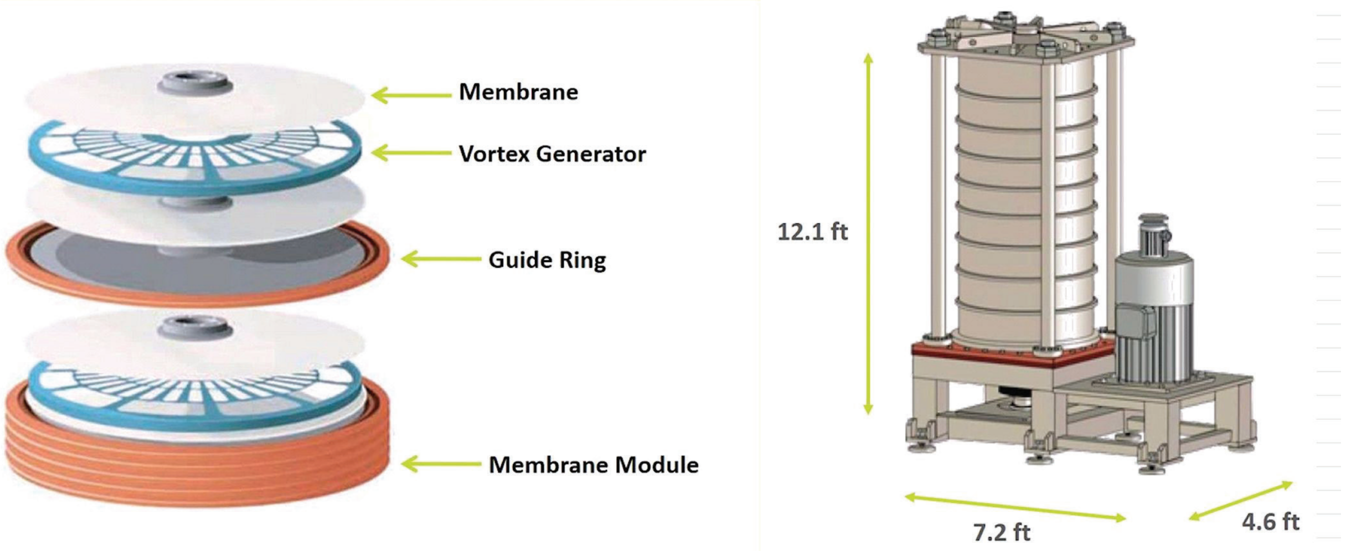
Membrane filtration provides a physical barrier that separates solids from wastewater in a nonspecific manner. This represents a major advantage over other selective treatment methods outlined above, but membrane systems have not traditionally been able to filter FGD wastewaters. The biggest shortcoming of membrane systems is their susceptibility to "plugging" or fouling. This is most commonly seen when treating wastewaters containing suspended solids.

During filtration, the solids form a layer on the membrane, restricting the flow of clean water. Membrane filtration can also remove dissolved solids or salts from water, but when removing salts, a new challenge is faced. When filtrate leaves the system, the retained water becomes concentrated and often surpasses the saturation concentration of lower solubility salts, which results in mineral precipitation and scaling of the membrane surface. This blinds the membrane and makes filtration impossible.

To address these problems, an anti-fouling membrane system[A] (AFMS) has been developed to offer a membrane filtration approach for treating FGD wastewater. This technology is illustrated in Figure 1. The left image in Figure 1 shows how the AFMS integrates crossflow membrane filtration with rotating blades positioned between each membrane to effectively prevent fouling. The righthand image shows how the AFMS system appears.

In the AFMS system, the blades generate a sheer force on the surface of the membrane and prevent surface buildup of suspended solids. Using this technology, the AFMS can filter thicker liquids that are not filterable with traditional membrane systems. Through extensive testing, it was discovered that the same mechanism used to prevent solids buildup in the AFMS also prevents scaling in ionic separation applications. The blades effectively mix the feed solution, preventing the concentration of salts at the membrane surface that form the concentration polarization layer. This not only reduces the potential for scaling but also increases the efficiency of the membrane. Following this discovery, AFMS technology was tested in various ionic separation applications.

Figure 1: Exploded view of membrane module, showing vortex-generating blades (left image) and full-scale AFMS filtration unit with 100 membrane modules (right image).



FGD Wastewater Challenges

FGD wastewater is extremely difficult to treat due to its high salinity and high potential to form scale (4). Various utilities have expressed an interest in evaluating the ability of the AFMS system to remove heavy metals, nitrates, and dissolved solids from FGD wastewater while avoiding scaling, fouling, and other operational challenges of traditional membrane systems. The authors tested FGD effluent from several different coal-fired power plants at a range of scales, from benchtop tests to full-scale system modules.

A number of membranes have been tested for time periods that ranged from several days to more than three months of piloting. The present article describes an onsite demonstration performed at one coal-fired power plant. The plant owners contacted the authors, requesting to evaluate the ability of the AFMS platform to process wastewater from their FGD purge pretreatment process for eventual reuse or discharge under 2015 ELG regulations (5). The goal of the AFMS unit was to remove large fractions of contaminants while protecting downstream reverse osmosis (RO) systems that could effectively meet discharge or reuse quality targets. To determine the feasibility of incorporating AFMS into complete treatment systems capable of meeting both 2015 ELG and TDS permit limitations, analytical results from onsite AFMS trials were used to simulate RO system performance on AFMS effluent.

RO is a well-established technology supported by robust simulation software. RO system manufacturers consider simulation projections sufficiently accurate for sizing commercial projects. Therefore, this study assumes that simulation results are sufficiently accurate in predicting contaminant rejection and establishing operating parameters for preliminary reporting. These assumptions would need to be tested in subsequent piloting to verify RO results prior to full-scale installation.

Materials and Methods

To demonstrate the performance of the AFMS system on FGD purge wastewater, a 190-day trial was conducted on site at a large power plant in the southeastern United States. The plant burns eastern bituminous coal and uses FGD wet scrubbers to remove sulfur and other compounds from stack gases. Following precipitation of gypsum and separation using hydrocyclones, the plant passes FGD purge wastewater through a physical/chemical precipitation process to remove mercury. Despite this precipitation process, the plant is not able to meet 2015 ELG limits in its wastewater. For the purpose of this study, the effluent of this precipitation process was tested in the AFMS. A limited analysis of the AFMS feed is described in Table 2. Average pH of influent feed was 7.9.

Table 2: Selective analysis of plant FGD wastewater.

Component	*Feed*
TDS	25,500 mg/L
$CaCO_3$	50 mg/L
Arsenic	10 µg/L
Mercury	50 ng/L
Selenium	200 µg/L
NO_X (aq)	25 mg/L

Prior to arrival on site, membrane selection was performed by testing a 20-liter (L) sample volume of FGD wastewater in a bench-scale AFMS unit at the service company's[B] offices in California. After testing several membranes, a commercially available, flat-sheet polyamide nanofiltration (NF) membrane was selected to maximize flux, rejection, and resilience while minimizing replacement costs.

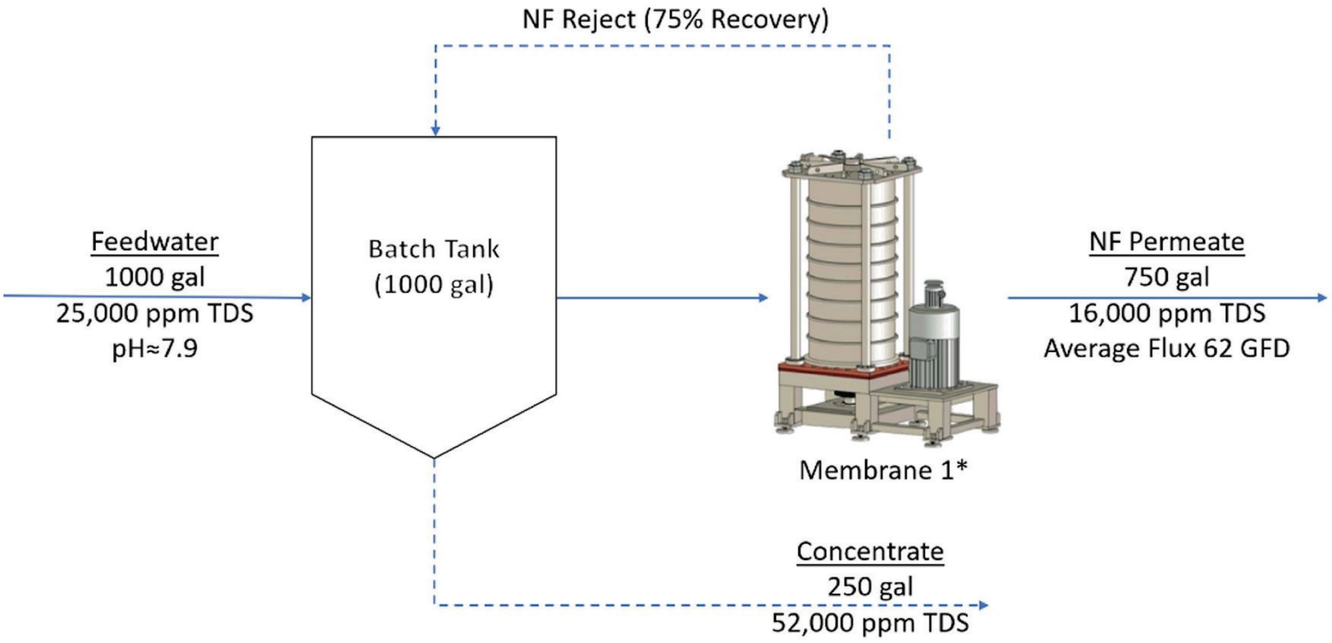
For onsite testing, this membrane was cut to size and installed on specialized membrane trays for loading onto the AFMS housing module. The AFMS unit selected for this study is a full-scale model that can be mounted with up to 100 membrane trays. Twenty trays were used in this study for a total surface area of 16.3 square meters (m^2), with trays stacked vertically to minimize system footprint. Because of FGD wastewater's high chloride content, a stainless steel AFMS model was selected to prevent corrosion. The testing unit was installed on plant property in proximity to the FGD wet scrubber and physical/chemical precipitation systems.

Plant-sourced wastewater was introduced immediately after pretreatment into a 3,800-L batch tank, where it was recycled through the AFMS over multiple filtration cycles to achieve clean water recovery rates of up to 80%. No chemical antiscalants or amendments were ever added to batch feed volumes, and influent pH was not altered. During filtration, AFMS permeate was collected for sampling or discharged to drain while the rejected fraction was returned to the batch tank for recycling. Since the unit was operated in batch mode with fixed influent volumes for each batch, recovery rates could be set by monitoring permeate volumes and stopping the batch once the desired recovery had been reached. A programmable logic controller (PLC) was used to control transmembrane pressure by monitoring and adjusting the feed pumping rate while also maintaining a set backpressure on the permeate drain valve.

The upper and lower limits of achievable membrane flux are generally dependent on feed and membrane characteristics, but instantaneous flux could be adjusted within the available bounds by adjusting transmembrane pressures. Whenever possible, the system attempted to maintain constant pressures and tolerated a gradual and unavoidable reduction in flux as the batch feed became concentrated. Permeate samples were collected for analysis, and excess volumes were sent to drain. A separate tank was used to hold flush water for rinsing the system between batches or for cleaning in place (CIP).

Water flushes and CIP cycles were also performed automatically using PLC controls at established intervals. CIP cycles were initially performed every five batches as a precaution against membrane fouling, but as membrane performance was observed to remain steady, the number of batches between CIP cycles was gradually increased until CIPs were eliminated approximately halfway into the study. The final 96,000 gallons were treated with only hot water flushes between batches. The demonstration process flow is illustrated in Figure 2.

Figure 2: Process flow of FGD wastewater test.



Following testing with the selected "optimal" nanofiltration membrane, a second, tighter nanofiltration membrane with pores roughly half the size of the first membrane was also tested for a total of 70 batches (70,000 L). This membrane was tested to evaluate the ability of the AFMS system to meet stricter discharge targets through improved rejection. If tighter nanofiltration membranes were able to meet 2015 ELG targets alone, downstream RO polishing would become unnecessary. Performance comparisons between the looser optimal membrane and tighter membrane are presented in Table 3.

Table 3: Comparison of ion-specific removal performance and flux between two nanofiltration membranes.

Component	*Testing Method*	*Tight Membrane*	*Optimal Membrane*
Mercury	EPA 245.1	97%	94%
Arsenic	EPA 200.8	92%	80%
Lead	EPA 200.8	90%	90%
Selenium	EPA 200.8	82%	61%
Thallium	EPA 200.8	70%	10%
TOC	SM5310C/EPA 9060A	70%	67%
CaCO3	SM23208	68%	53%
Sulfate	EPA 300.0	65%	66%
Phosphorus	EPA 365.1	63%	42%
Magnesium	EPA 200.7	58%	36%
Manganese	EPA 200.8	58%	35%
Nitrite + Nitrate	EPA 353.7	58%	35%
Calcium	EPA 200.7	55%	31%
Bromide	EPA 300.0	54%	33%
Chloride	EPA 300.0	52%	38%
Strontium	EPA 200.7	51%	34%
Boron	EPA 200.7	33%	11%
TDS	SM2540C	52%	34%
Flux	Observed	26.7 LMH	104 LMH

Concentrate and permeate grab samples were collected from one batch on each of 10 different days (roughly one week apart) during testing of the optimal membrane and nine days during testing of the tighter membrane. Samples were collected, processed, and shipped to a certified analytical laboratory by the power plant staff. Removal data were averaged over all samples for each membrane.

To simulate the performance of RO systems in processing AFMS effluent, membrane projection software[C] was used to run RO filtration projections. Several configurations of RO were simulated, and a three-stage, single-pass RO was found most suitable for maximizing recovery, while meeting permeate water quality limits. The simulation was set at an ambient water temperature of 77 °F (25 °C) and average membrane age of 2 years. Feed pH was set to 7.5 and reduced to 4.3 by (in-simulation) addition of acid to minimize scaling potential. The maximum AFMS permeate concentration values were taken from empirical AFMS results and used to produce conservative RO projections. Since the RO system would be fed with permeate from the upstream AFMS (NF permeate), the RO feed was categorized as RO permeate in the projections. This increased the allowable operational envelope for the simulation. Nevertheless, due to the feed's industrial origins, average permeate flux was conservatively restricted to <25.5 liters per square meter per hour (LMH).

Since membrane-manufacturer simulations limit salt oversaturation to well below the maximum salt concentration suggested by manufacturers of antiscalant treatments, additional projections were run using a projection software[D] that evaluates membrane scaling potential. It was hoped that this software would reflect the full capabilities of modern antiscalant treatments and allow the simulation to run at higher recoveries than the membrane optimization softwareC projection. In total, four separate RO projections were evaluated. Apart from recovery, all other input parameters were set equivalently across all four projections (summarized in Table 4).

Table 4: RO simulation parameters used in study.

RO Operating Parameters	
Recovery (%)	70–81
Average permeate flux (LMH)	23.1
Maximum operating pressure (psig)	368
Average element age (years)	2
Salt passage increase (%/year)	6
Flux decline (%/year)	10
Feed water temperature (°C)	25
RO system configuration	1 pass, 3 stage

Performance Projections

Here are some projections based on these software programs:

1. Projection A: Membrane performance software using 70% recovery.

2. Projection Ai: Antiscalant software projection using 70% recovery (mirroring Projection A).

3. Projection Aii: Antiscalant software projection using 76% recovery (maximum recovery that did not output any hydraulic warnings).

4. Projection Aiii: Antiscalant software projection using the maximum possible 81% recovery (outputs hydraulic warnings for low concentrate flow, which can be easily resolved by recirculating the concentrate).

Results

Over roughly 190 days, a total of 253 batches of 1,000 L each were processed through the AFMS system on site at the power plant. Of these, 184 batches were first processed using the "optimal" (looser) membrane and 69 batches were subsequently run on the tighter membrane. Recovery values were initially set at 60% and gradually increased until the maximum tested recovery value of 80%. As can be seen in Figure 3, most of the optimal membrane trial was conducted at 75% recovery. This value was chosen as an optimal recovery point that balanced flux, rejection, and the ability of the membranes to be easily cleaned between batches.

Over the course of six months, no significant mechanical failures were encountered, and the physical integrity of the membranes was maintained, as evidenced by consistent trans-membrane pressures and relatively stable rejection values over the course of the study. Over the course of six months, total solids rejection did decline from roughly 50% to roughly 35% in the optimal membrane (Figure 4), likely due to the use of tap water for system flushes. Tap water contains significant levels of free chlorine, which oxidizes and degrades polyamide membranes. For this reason, tap water should be avoided when flushing polyamide membranes.

Figure 3: Established recovery values and subsequent membrane flux over the course of the study.

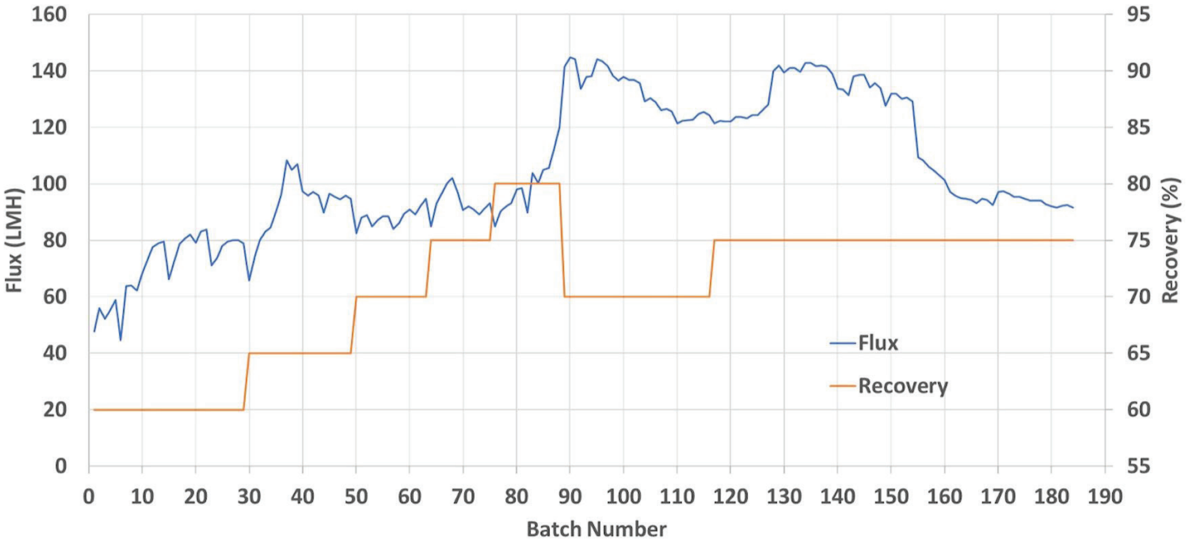
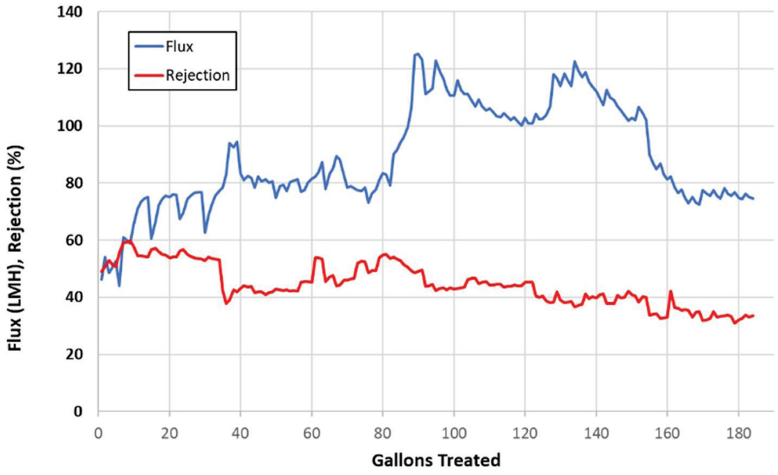


Figure 4: Flux and TDS rejection over the course of the study.



Membrane flux values varied widely over the course of the study, from 44 to 125 LMH on the optimal membrane to 20 to 47 LMH on the tighter membrane. A comparison of ion-specific removal performance and membrane flux between the two membranes is shown in Table 3. While the tighter membrane did achieve improvements in rejection from 3% to 23% (depending on the constituent), because of the significant (>70%) reduction in average flux demonstrated by this membrane, it was decided that the looser optimal membrane is more cost-effective for this application. The remainder of this article will focus on results obtained from the optimal (looser) membrane.

Flux rates were generally high at the beginning of a batch and then declined over the course of each batch as the feed became concentrated in the batch tank. This occurs as increasing trans-membrane concentration gradients create higher osmotic pressures, which must be overcome by the AFMS system in order to pass water through the membrane. At the conclusion of each batch, hot water flushes were sufficient to recover membrane flux and rejection levels in preparation for the next batch.

Overall, day-to-day changes in influent concentration (salt content) and composition also affected flux, with flux dropping with increasing TDS overall. Figure 5 demonstrates the temporal variations in both membrane flux and influent conductivity, a proxy for concentration of dissolved influent salts. A linear regression of membrane flux and percent rejection demonstrates that almost half of all variation in rejection can be explained by changes in flux. In this study, higher flux (which also correlated to less concentrated influent) resulted in lower rejection as a percent of TDS (Figure 6).

Figure 5: Feed conductivity (an indication of feed concentration and membrane flux.

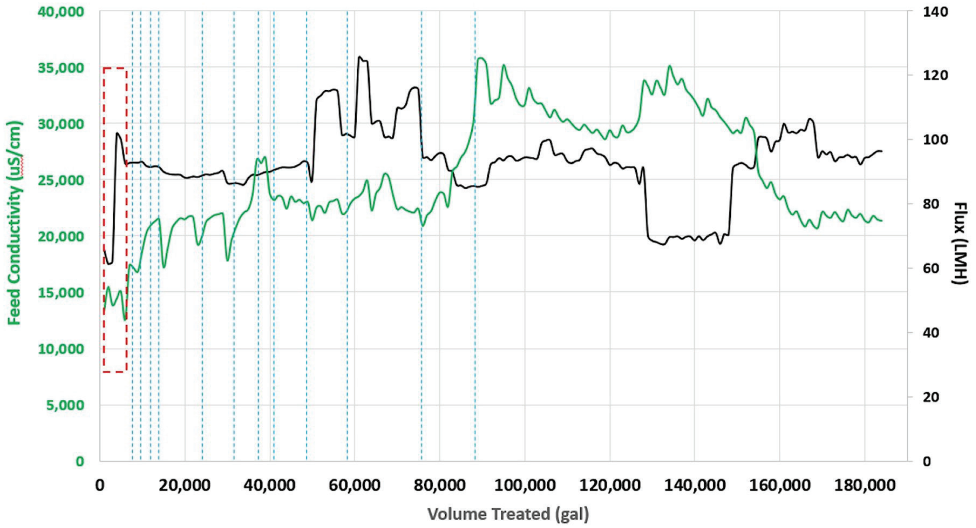
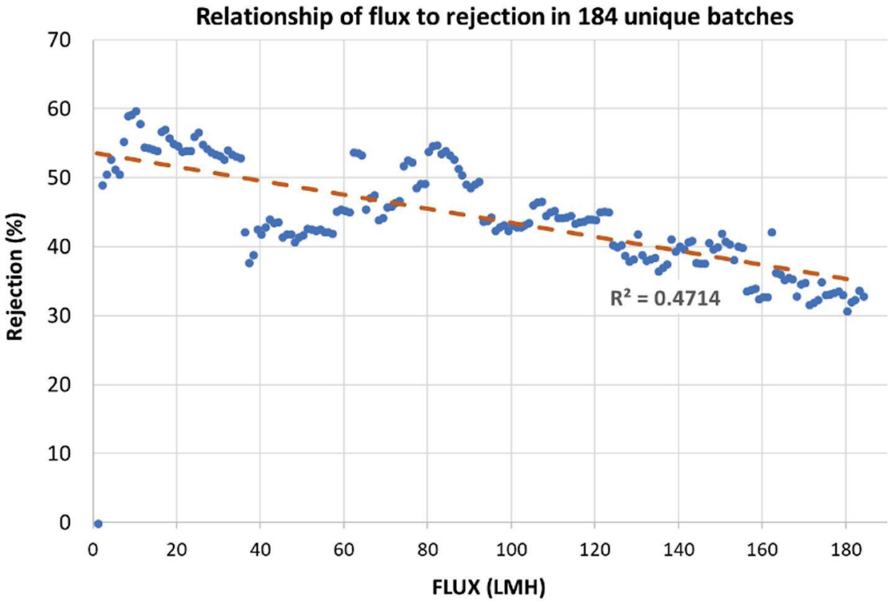
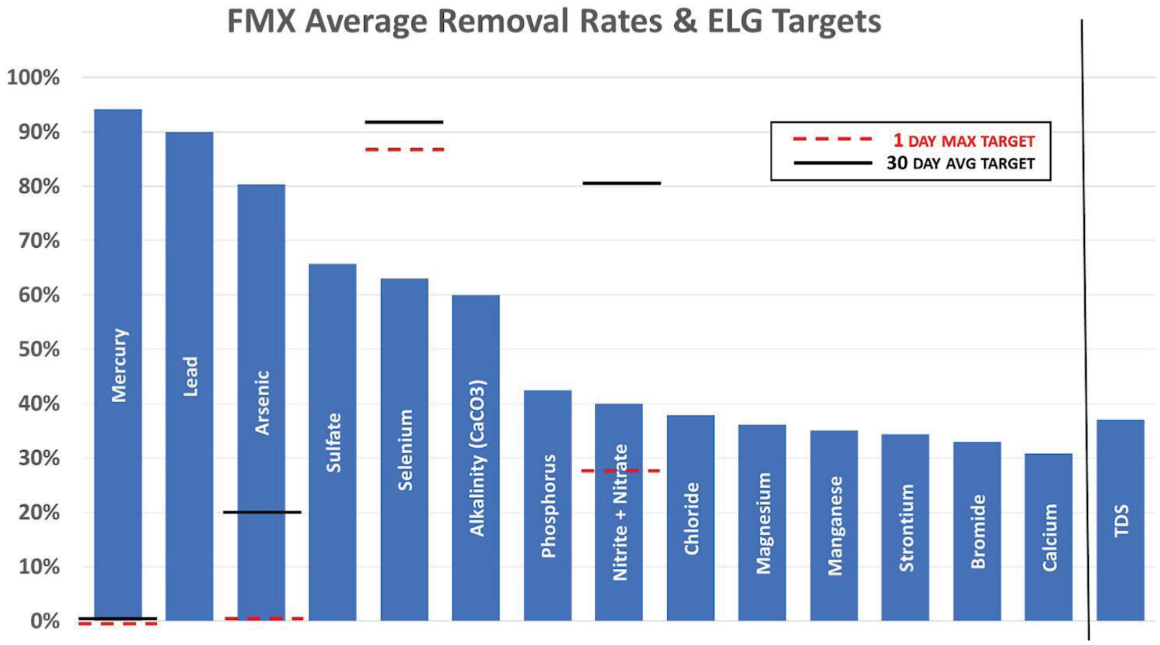


Figure 6: Linear regression comparing membrane flux with salt rejection as a percentage of TDS.



Using a commercially available nanofiltration membrane, the AFMS demonstrated average ELG constituent removal rates from 40% to 94%. Rejection rates were ion dependent and varied over the course of the study with variances in flux, clean water recovery rate and other factors. Average removal for each 2015 ELG constituent are shown in Figure 7. Empirical concentrations of ions in AFMS effluent were privileged by the utility and could only be reported on a relative basis in this paper. The number of data points available for each ion (N=10) were limited by the high cost of frequent sampling and laboratory analysis. Establishing high-resolution time-courses of rejection for each ion was prohibitively expensive; therefore, rejections of ELG constituents are assumed to vary proportionally to the ability of the AFMS membrane to reject dissolved solids in general.

Figure 7: Average removal per constituent over the course of the study. Dashed lines represent the removal threshold necessary to meet the EPA 2015 ELG maximum one-day discharge target, and solid black lines represent the threshold for meeting the limit on 30-day average values.



Results from the membrane maker's RO projection software[C] (A) showed a feedwater sulfate rejection of 99.04%. As discussed, sulfate rejection is used as a proxy for selenate rejection in this study. Given a selenium feedwater concentration of 292 parts per billion (ppb), permeate selenium was therefore projected at 2.79 ppb. At such low concentrations, it is important to have a large safety margin. Allowing for a safety factor of 1.8 (80% margin), a permeate selenium of 5.0 ppb could be guaranteed (<5 ppb EPA limit). Conversely, the antiscalant treatment manufacturer's software program[D] projections predicted even higher sulfate rejections, meaning selenium permeate concentrations are predicted to be even lower.

The RO maker's software[C] (Projection A) predicted a nitrate (NO_3^-) permeate concentration of 17.8 parts per million (ppm). The EPA limit is 4.4 ppm NO_3^-N, or 19.5 ppm NO_3^-. The antiscalant treatment company's software[D] projected for permeate nitrate levels that were similar.

Since the feed pH was significantly lowered (to 4.3) to minimize scaling potential (in Projection A), a small dose of sodium hydroxide was added to the permeate to bring the pH up to neutral. Adding caustic to the permeate had minimal impact on permeate TDS, which remained below 600 ppm. Removal rates for a range of non-ELG-regulated ions are presented in Table 5.

Table 5: Projected RO removal performance for various non-ELG components.

Parameter	*Feed Concentration (mg/L)*	*Permeate Concentration (from Projection A) (mg/L)*	*% Removal (ref to feed)*
Calcium	2,440	82.5	96.6
Magnesium	684	23.1	96.6
Sodium	72	11.1	84.6
Potassium	42	7.9	81.2
Ammonia (NH_4^+)	1	0.189	81.1
Barium	0.53	0.018	96.6
Strontium	8	0.27	96.6
Iron	1	0.034	96.6
Manganese	5.6	0.189	96.6
Copper	0.5	0.017	96.6
Carbonate	0.18	0.505	NA
Bicarbonate	30	0.032	99.9
Sulfate	740	7.07	99.0
Chloride	5,820	220.4	96.2
Fluoride	8.5	0.632	92.6
Nitrate	97	17.8	81.6
Phosphate	0.17	0.002	98.8
Silica (SiO_2)	28.5	0.49	98.3
Boron	249	167.8	32.6
Bromide	81	3.96	95.1
TDS	10,308	544.2	94.7

Although 70% recovery presets in Projection A resulted in warning outputs for oversaturation on calcium fluoride (CaF_2), Projections Ai, Aii, and Aiii suggest that antiscalant addition should be able to prevent scaling, even up to 81% recovery (Aiii).

Discussion

The AFMS was able to effectively filter FGD wastewater in this study without significant scaling or fouling challenges, and without pH adjustment or the addition of chemical antiscalants. FGD effluent was successfully processed daily for more than six months, suggesting that the AFMS can manage the full gamut of variation in effluent quality that similar power plants produce. It is important to note that the AFMS in this case did benefit from some level of physical/chemical pretreatment of FGD effluent, and studies are currently underway processing FGD effluent without any pretreatment. Nevertheless, without the AFMS's vortex generating blades, these results would likely not have been achievable using standard nanofiltration techniques.

This assertion is supported by anecdotal accounts from operators who turned off blade rotation for short periods during the start of batches, which resulted in immediate reductions in membrane flux of roughly one third. AFMS filtration performance was generally consistent between batches given similar influent concentrations, but varied together with influent characteristics. Some decline in rejection performance over time can also likely be attributed to oxidative damage from free chlorine in tap water used for system flushing. This use of chlorinated flux water represents a clear case of operator error and should be avoided in future trials. Nevertheless, the ability of the AFMS to recover membrane flux with only water flushes between batches suggests that the membrane did not experience significant scaling despite processing feed concentrations of up to 54,000 ppm TDS and 1,200 ppm sulfates.

In this study, the use of physical/chemical pretreatment obviated the rejection of mercury by the membrane, since mercury levels in AFMS influent already met the BAT 2015 ELG targets for both daily maximums and 30-day averages. Similarly, influent arsenic concentrations were already below the daily maximum 2015 ELG limit, though arsenic levels exceeded the 30-day average limits. AFMS treatment alone was able to reduce arsenic to below the 30-day average limit as well as reduce nitrate and nitrite below the daily maximum limit as listed in the 2015 ELGs. While AFMS treatment reduced nitrates and nitrate by an average of 40%, and selenium by an average of 63%, these reductions were not sufficient to meet the 30-day average limit on NO_3/NO_2 or either the daily or monthly limits on selenium. To meet these targets, using this membrane under these influent conditions, downstream polishing by RO membranes would be required.

Treatment of raw FGD effluent using RO would be expensive, inefficient, and difficult due to significant scaling and fouling, which would reduce membrane flux (requiring a larger system), reduce membrane lifespan (increasing replacement costs), increase the use of CIP chemicals (increasing costs) and reduce clean-water recovery (increasing brine production). In this study, the AFMS was able to reduce scaling constituents such as sulfate, calcium, magnesium, cobalt carbonate ($CoCO_3$), and bromide by 66%, 31%, 36%, 53%, and 33%, respectfully. These reductions in the scaling potential of FGD effluent protect RO membranes in downstream polishing, rendering the complete process more reliable and economical.

In addition, AFMS removed 34% of TDS, with a 38% reduction in chlorides. These reductions would improve membrane flux and reduce cleaning frequencies of downstream RO, further improving the economics of treatment. Even for constituents that may require RO polishing to meet 2015 ELG limits, AFMS treatment does significantly reduce the concentration of these ions, allowing for downsizing of RO systems and a greater margin of safety to ensure that RO system effluents are never in violation of permits. Thus, AFMS and RO treatment are maximally effective and optimally priced when deployed together in series.

Permeate from downstream RO in this study was projected to achieve a TDS level of roughly 600 ppm. This salt concentration is likely too high for reuse as boiler makeup in most boiler systems, but significant other reuse opportunities are available. Specifically, FGD scrubbers lose water, both to evaporation and to purged scrubber effluent. AFMS-RO permeate in this study would be sufficiently low in both TDS and ELG constituents to be reused as clean water makeup to FGD scrubbers without significant corrosion or fouling concerns, and without up-concentrating 2015 ELG constituents. The permeate could also be used for CIP or other reuse applications.

In this study, the AFMS unit alone was able to consistently maintain 75% recovery of permeate from FGD wastewater, with maximum 80% recovery. Subsequent simulations suggest that a consistent recovery of 70–81%

is possible through downstream RO. Together, these two recoveries combine for a total treatment system clean water recovery of 52.5% to 64.8%. This means that the volume of FGD wastewater that must be treated in evaporators could potentially be reduced by >60% using AFMS and RO in series.

As with any membrane system, the AFMS will produce a concentrated brine solution that must be disposed of. Current brine disposal methods for brines containing hazardous heavy metals typically include some form of evaporation. Readily available evaporation technologies typically carry a capital cost of roughly five times the AFMS and RO equipment cost for the same throughput. Therefore, an optimized combination of AFMS/RO and evaporation technologies would be the most economically attractive solution to manage waste brines. Because of the much higher price per gallon of evaporation technologies (both in Capex and Opex), any reduction in concentrate production by AFMS has a disproportionately high impact on the overall treatment system cost. Effectively, this means that maximizing AFMS recovery is the most meaningful method of reducing system costs.

There are two primary methods for improving AFMS recovery. The first and most simple method is to increase the concentration factor of the FGD wastewater by increasing the number of recycling passes that the FGD wastewater makes between the membranes and batch tank. The tradeoff in this method is that beyond a certain point, each additional pass (and increase in concentration) will reduce the flux through the membrane, requiring a larger AFMS. In previous testing, the service companyB tested up to a recovery rate of only 80%. Additional pilot testing at higher concentration factors would be valuable for reducing overall system costs, so long as increased AFMS costs resulting from flux reduction are offset by lower brine evaporation costs. Improving recovery rates by 5–10% may prove highly beneficial, but cost studies cannot be made prior to empirical validation of flux. Additional long-term case studies focusing on recovery rates of more than 80% or 90% will need to be performed before the optimal system cost can be determined.

The second method for achieving improved recovery rates is to reduce the scaling potential or concentration of the FGD wastewater. This involves reducing the quantity of certain dissolved ions in the FGD purge, specifically including chlorides, barium, calcium, and sulfate. Burning “cleaner” coal sources would reduce FGD treatment costs by reducing both the quantity of sulfur that must be scrubbed (and therefore the FGD purge volume), as well as increasing the achievable concentration factor by reducing chloride and other non-sulfurous TDS content in the FGD stream. Any significant reduction in bulk TDS would significantly improve the achievable concentration factor and therefore the recovery rate of the AFMS process.

Closing Thoughts

In considering cost-effective strategies for disposing of FGD scrubber effluent, an optimized configuration of AFMS, RO, and evaporation systems designed to produce recycled scrubber water and concentrated brine represents a new and competitive solution for steam-electric generation wastewater management. This combination of technologies is dramatically cheaper than evaporation alone and is one of only a few technologies that can achieve effluent qualities that can meet any NPDES permit restriction, as well as the EPA’s effluent limitation guidelines.

Membrane filtration can remove total dissolved solids better than any biological, chemical, or physical treatment apart from evaporation, but it is difficult to implement without effective antiscaling systems in place. The AFMS’s ability to prevent scaling without the addition of antiscalant chemicals was demonstrated effectively in this study. AFMS also reduced the concentration of all 2015 ELG constituents, in some cases meeting targets, but was unable to guarantee selenium and nitrate adherence. Downstream of the AFMS, a three-stage, single-pass conventional spiral-wound RO system was simulated to ensure adherence to EPA’s effluent limits for FGD wastewater. RO simulations confirmed that all 2015 ELG limits (including for selenium and nitrate) could easily be met with the addition of downstream RO. These projections suggest that RO can recover 70–81% of RO influent (53–65% of FGD wastewater) as clean water, providing significant opportunities for reuse.

Specifically, RO permeate is suggested for reuse in FGD scrubbers. Onsite pilots of RO systems are necessary for confirmation of maximum recovery values and final permeate water quality. Additional studies are currently underway to confirm the performance of RO systems placed downstream of protective AFMS units in achieving 2015 EPA ELG/NPDES targets at a reasonable operating cost.

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Endnotes

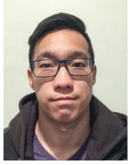
[A] The AFMS (anti-fouling membrane system) mentioned in the text is a treatment system developed by Tomorrow Water (BKT), Anaheim, CA. AFMS is trademarked and sold as "FMX."

[B] The testing referred to in the text was performed on site at a power plant using fresh influent pulled directly from the phys/chem process. The testing system used was a full-size, commercially available FMX unit loaded with 20 membranes.

[C] IMSDesign is the membrane projection software mentioned in the text. The software has been developed by Hydranautics.

[D] PROTON® is an antiscalant projection software offered by American Water Chemicals, which is based in Plant City, FL.

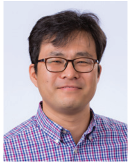
Jon Liberzon is vice president at Tomorrow Water (BKT), where he is focused on novel water treatment technologies, including anti-fouling membranes, municipal primary filtration, and ammonia removal. Previously, Mr. Liberzon worked on projects for AB InBev, the World Bank, DFAT, and IsraAid. From 2012–2017, he was director of water technologies at Algal Scientific, where he commercialized a novel biological process for organics and nitrogen recovery. He also served as technology development manager at Aquanos, a startup firm focused on photosynthetic aeration for municipal wastewater treatment. He holds a master's degree in agricultural engineering from the Technion Institute and a bachelor's degree from the University of Michigan.



Jonathan Chen studied chemical engineering at San Jose State University. Before joining BKT, he was involved with process design and engineering for NASA's Project O.M.E.G.A. and conducted undergraduate research for atomic-layer deposition on magnesium alloys for corrosion inhibition at Boise State University. Incorporating his knowledge of engineering and electronics, Mr. Chen built and programmed a control system for BKT's in-house unit. In his free time, he likes to incorporate his engineering knowledge into all aspects of his life to provide efficient solutions for everyday problems.

Tzu Lung Lin is specialized in applying membrane technology in high-solid, high-viscosity, and high-density solid–liquid separations. He has more than 20 years of engineering and process experience with proprietary membrane filtration technologies. This background has enabled him to help clients with difficult separation applications.

Arnab Hanra has 19 years of experience in detailed design of water and wastewater facilities and has worked in consulting and EPC environments. His technology focus is primarily on microfiltration/ultrafiltration and nanofiltration/reverse osmosis membranes, as well as a wide range of associated pre- and post-treatment technologies. Mr. Hanra has worked on diverse projects ranging from generation of high-purity water for industrial uses to zero-liquid-discharge design in treatment and reuse of RO concentrate for potable use.



Chunwoo Lee has more than 15 years of professional experience in the water and wastewater treatment industry. As the director of engineering at SafBon Water Technology, he is responsible for the review and complete engineering execution of all engineered proposals and project engineering for seawater desalination and advanced water and wastewater treatment projects.

Jaeho Ho, Ph.D., is an environmental engineer with 15 years of industrial experience in research and development and process engineering for water and wastewater treatment systems, including membrane (MF/UF/MBR) technologies, mining/FGD wastewater treatment, and water reuse/advanced oxidation process (AOP). His expertise is in process design and modeling of biological wastewater treatment systems, including activated sludge processes and membrane bioreactor (MBR). He also focusses on the innovative technologies to reduce and recover energy from wastewater, including anaerobic membrane bioreactor (AnMBR) and temperature-phased anaerobic digester (TPAD).

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