POWER

FGD WASTEWATER EVAPORATION PILOT PROJECT AT A LARGE POWER PLANT

In the fall of 2015, the U.S. Environmental Protection Agency (EPA) promulgated revised effluent guidelines for steam electric power generating units (EGUs). The 2015 Effluent Limit Guidelines (ELGs) final ruling (1) is now in place. While there is now some uncertainties as to the effective start date for the new guidelines, the tightening discharge limits will certainly impact a number of electric power plants across the United States. Particularly challenging wastewaters in this context include flue gas desulfurization (FGD) purge water and coal combustion residual (CCR) pond waters.

As a result, EGUs face stringent discharge limits for selenium, mercury, arsenic, and nitrite/nitrate in FGD wastewater in the coming years. Table A summarizes FGD wastewater effluent limits under the 2015 regulations.

One of the main methods used to treat these challenging waste streams and addressing the new regulation is volume reduction through evaporation often as part of a zero liquid discharge (ZLD) treatment train.

TABLE A
Effluent Limitations for FGD and Gasification Wastewater

	Existing Source Regulation		New Source Regulation	
Constituent	**30-Day Average**	**Daily Max**	**30-Day Average**	**Daily Max**
Arsenic (As)	8 µg/L	11 µg/L	-	4 µg/L
Mercury (Hg)	356 ng/L	788 ng/L	24 ng/L	39 ng/L
Nitrate/nitrite (as N)	4.4 mg/L	17.0 mg/L	-	-
Selenium (Se)	12 µg/L	23 µg/L	-	5 µg/L
TDS	-	-	24 mg/L	50 mg/L

Evaporation Technology Solutions

Traditional evaporation solutions for treating these wastewaters have often proved to be cost-prohibitive, operationally challenging, and/or resource-intensive for the following reasons:

- High capital cost because of the need for large amounts of exotic materials of construction.
- Scaling in heat exchangers and other process equipment requires excessive downtime for cleanings.
- Pretreatment systems are required to alter water chemistry to reduce maintenance burdens. These may require additional chemicals, processes, and waste disposal.
- Operation is very sensitive to changes in chemistry and requires significant monitoring of chemistry and laboratory resources to limit process downtime because of plant upsets.
- The need to connect an additional piece of large capital equipment (a crystallizer) to the evaporation system in order to achieve ZLD.

The Electric Power Research Institute (EPRI) conducted a study[A] using a different evaporation technology installed at the Water Research Center at Southern Co.'s Plant Bowen, located in Cartersville, GA. The purpose of this project (2) was to evaluate the efficacy of an adiabatic evaporator[B] for FGD wastewater treatment/concentration at a 952-megawatt (MW) coal-fired power plant. (*Editor's note: Through the rest of the text, this technology will be referred to as a concentrator.*) The system used flue gas from the power station as the source of thermal energy for evaporation.

Produced concentrated FGD slurry and other process liquids were analyzed and characteristics of dissolved and suspended constituents were determined for subsequent ZLD-type treatment and possible environmentally acceptable disposal. These pre-full-scale demonstration tests assessed process efficiency, extent of fouling, and performance degradation over an extended period of time.

The study revealed that the adbiatic concentrator technology, which uses a direct contact evaporation process, can be a particularly appealing option for sites implementing a ZLD treatment train and without many of the disadvantages experienced by more traditional technologies. Furthermore, there is potential for producing a concentrated slurry that can be stabilized (or solidified) for disposal without the need to add a crystallizer stage to the process. The study validated that the adiabatic concentrator offered an alternative solution for reducing plant wastewater volumes and facilitating efficient capture and disposal of water contaminants in an environmentally responsible manner.

Project Objectives

The project's objectives were to investigate:

- The concentrator for volume reduction of FGD blowdown wastewater using flue gas from a coal-fired power plant as the source of thermal energy for evaporation.
- Integration of the concentrator process equipment with plant operations and operating profile (e.g., load, temperature, and pressure shifts).

By Benjamin Laurent
(Heartland Water Technology)

- Impact of using flue gas (and fly ash) on the evaporative concentrator system process equipment/operation.
- Feasibility of subsequent ZLD-type treatment of concentrated FGD wastewater residuals, particularly quality produced and potential for environmentally acceptable disposal.

Flue Gas as an Energy Source

The concentrator has been used commercially at numerous sites, including a 1,500 MW coal fired power plant in the Midwest, but the EPRI project was unique in that the thermal energy source consisted of flue gas from the plant. Utilizing flue gas heat as an energy source provides several potential benefits over other process configurations:

- Flue gas, being a low-grade and/or waste-heat energy source, may provide a strong economic advantage over other energy sources (e.g., electricity, natural gas, or propane).
- Using the concentrator with flue gas provides a closed-loop vapor stream system integrated upstream of typical traditional emissions controls systems, with no additional air emission points being created.
- Fly ash contained within the flue gas is partially captured by the concentrator and concentrated along with the FGD wastewater, which lends itself to enhancing (and simplifying) downstream solids stabilization processes (fly ash is a typical constituent of solids stabilization processes).
- Residuals from this process could potentially be stabilized and disposed of separately from the majority of coal combustion residual materials.

It was uncertain how fly ash would impact project and equipment performance and operability, including the characteristics of the concentrated slurry. Therefore, risks were identified and managed through several initiatives as noted here:

1. Bench-top testing evaluated ash-settling behavior, ash slurry consistency and characteristics, and efficacy of potential chemical additives (e.g., flocculants, coagulants) on the settling rate of ash.
2. Installation of an optional coarse ash removal system was to be considered if the ash loading on the system degraded performance, this was not required or used.
3. Process equipment and ash loading were carefully monitored through controlled shutdowns.

Integration with Plant Operations

With the use of flue gas to drive evaporation, there is the challenge of integrating the process with plant operations. This challenge is two-fold:

1. Accommodating plant load shifts and associated flue gas operating temperatures and pressures, as well as planned and unplanned outages.
2. Coordinating with plant operations to ensure mutual operation of the concentrator within the plant and providing safe operating environments for equipment and personnel.

The integration of the concentrator within the plant operations is shown in Figure 1. A hot flue gas slipstream from the selective catalytic reduction (SCR) process output (prior to the air preheater) was fed to the concentrator inlet. The concentrator used the flue gas' thermal energy as the evaporative driver for its process, with the concentrator exhaust consisting of cooled (approximately 120 to 140°F), saturated gas returning to the primary duct downstream of the air preheater and upstream of the electrostatic precipitator. This location of the concentrator within the plant process flow not only provided a thermal energy driver, but also a gas flow motive driver by using the pressure drop across the air preheater as a motive force.

TABLE B
Assumption of Operational Energy Balance Analysis

Parameter	Value	Unit
Plant unit capacity	750	MW
System capacity factor	90	%
Plant heat rate	10,000	BTU/kWh
Fuel energy content	13,500	BTU/lb (wet basis)
FGD purge water feedrate	50	gpm
Annual FGD purge water processed	23.6	million gal/year
FGD purge water TDS	25,000	mg/L
Final slurry moisture content	35%	mass percent
Hot flue gas temperature	650	°F

TABLE C
Summary of Operational Energy Results

	Flue Gas	Propane	Natural Gas	Electricity
Annual thermal energy cost*	$495,500	$3,590,400	$784,100	$3,081,700
Normalized energy cost ($/gal feed)	$0.021	$0.152	$0.033	$0.130
Plant heat rate impact (% increase)	0.32%	0.03%	0.03%	1.77%

*Note: Assumes $1.25/gallons (gal) for propane, $3.00/million British thermal units (MMBTU) for natural gas, and $0.03/kilowatt hours (kWh) for electric heat. Costs for flue gas are approximated by converting utilized thermal energy to equivalent electricity produced (using plant heat rate) at a rate of $0.03/kWh, while assuming any thermal sensible heat used by the concentrator below the plant air preheater outlet temperature (e.g., 320°F) is "free" and does not incur a heat rate penalty or energy cost penalty.

Impact on Energy Use

The concentrator uses a thermally-driven adiabatic evaporative process. It is important to understand the operational energy balance and impact on plant heat rate associated with operating a full-scale commercial system. The following analysis presents a conceptual energy balance for a potential full-scale unit driven by flue gas heat. The basis of this analysis is a 50-gallons per minute (gpm) wastewater processing rate basis, yielding a back-end slurry containing 35% water by weight (typical of solidification/stabilization process requirements).

The underlying assumptions of this analysis are presented in Table B. A summary of energy consumption and cost results are shown in Table C. For comparison purposes, the flue gas thermal energy source scenario is compared to the concentrator using propane, natural gas, or electric thermal heat as a thermal energy source for evaporation.

Based on these assumptions and the described configuration, the following conclusions may be drawn:

1. A 50-gpm concentrator system would consume approximately 4% of the flue gas of a 750-MW plant, as well as use 4% of the plant's fly ash within the final slurry stream (this does not include any supplemental fly ash that may be used in final stabilization).
2. The resulting slurry output would equate to a net 90% volume reduction for the flue gas scenario, based on the incoming 50-gpm FGD purge water input. The natural gas, propane, and electricity scenarios could achieve greater (e.g., 97%) volume reduction as they do not inherently introduce fly ash into the system.

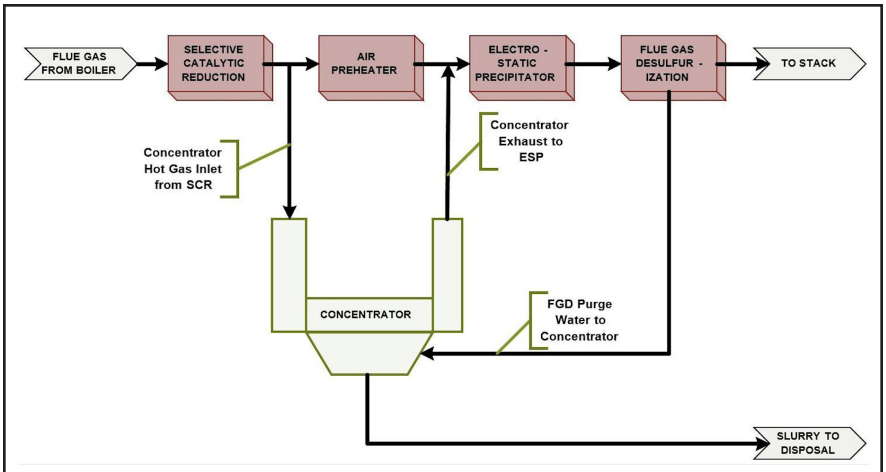


Figure 1. Schematic of process as installed within a coal-fired power plant.

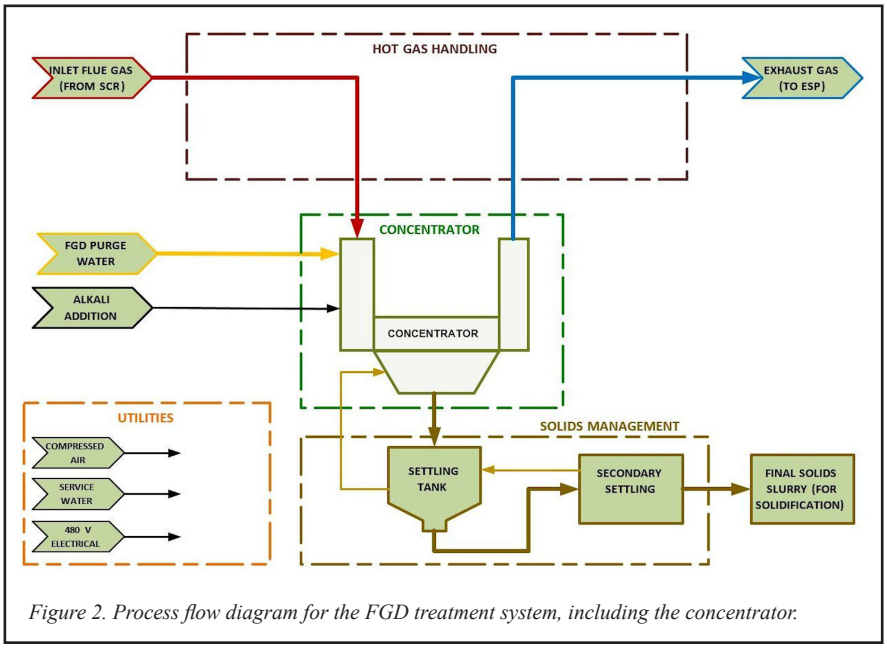


Figure 2. Process flow diagram for the FGD treatment system, including the concentrator.

Project Implementation

Key Equipment

The concentrator[B] used in the EPRI Project consisted of a skid-mounted unit containing the following key pieces of equipment:

- A pilot-scale concentrator, rated at 1,000 gallons per day (gpd) processing rate, including a high-alloy evaporation zone, fiberglass concentrator body, vapor/liquid entrainment separator, induced draft fan, and recycle pump.
- A cone-bottom settling tank with purge valve for collecting solids/precipitates.
- Interconnecting piping, process instrumentation, valves, and other components.
- A fully automatic programmable logic controller (PLC) control system, including process controls, safety alarms, data loggers, and human-machine interface (HMI).

In addition to the concentrator, the balance of system equipment included:

1. Inlet hot gas and outlet cool gas actuated dampers controlling gas flow between the primary plant ductwork and the concentrator and integrated into the PLC system.
2. Alkali (e.g., sodium hydroxide, lime), chemical metering pump, and associated interconnection fittings for optional pH control of the concentrator's circulating fluid.
3. Self-dumping hopper for secondary settling of collected solids and storage of generated solids.

Process Flow Description

The project process flow (see Figure 2) included the following steps:

1. Hot flue gas is allowed to enter the system by opening the actuated inlet hot gas damper and drawing flue gas (downstream of the SCR) into the concentrator system; simultaneously, the actuated exhaust gas damper is opened, allowing cool, saturated gas to exit the concentrator and return to the plant primary duct upstream of the electrostatic precipitator.
2. If needed, the hot flue gas is bypassed

TABLE D
Physical Composition of Brine Slurry

Parameter	Value	Unit
TDS of liquid phase	194,620	mg/kg
TSS of brine slurry	862,700	mg/kg
Density of liquid phase	1.242	kg/L
Density of brine slurry	1.652	kg/L

TABLE E
S/S Mixtures

Mix No.	Brine Slurry (%)	CFA (%)	PC (%)	FS (%)
1	75	15	10	0
2	70	20	10	0
3	75	20	5	0
4	70	25	5	0
5	75	8.5	10	6.5
6	70	13.5	10	6.5

through a coarse ash separator to minimize ash loading to the system; ash is collected in a self-dumping hopper for disposal (this system was not used during this test).

3. FGD wastewater is fed to the concentrator evaporation zone where it is mixed with the inlet hot flue gas; a recycle pump within the concentrator continuously recirculates the fluid within the concentrator and through the evaporation zone to ensure constant mixing, optimal evaporation, and avoid settling within the concentrator.

4. An induced-draft fan draws flue gas through the system and exhausts cooled, saturated gas into the exhaust ductwork.

5. A purge stream from the recycle pump flows into a cone-bottom settling tank, where collected solids settle and are discharged to a secondary settling hopper.

6. Decant from the primary settling tank as well as the secondary settling hopper are returned to the concentrator for further processing.

7. An optional metering pump injects alkali material into the system to maintain a desired pH.

Water Chemistry

As water chemistry can vary considerably from wastewater type and from plant to plant, understanding and monitoring chemistry through the test was important for several reasons as noted here:

- Predicting process performance (e.g., cycles of concentration, volume reduction) based on influent chemistry and evaporation rates.
- Tracking process performance through an initial cycling up period as well as optimizing steady state operation based on process performance for a given key variable (e.g., total circulating solids within the concentrator).
- Monitoring concentrations of key species of interest (e.g., selenium) within the system, including concentration within the concentrator solids/slurry output.

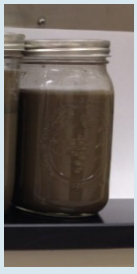
Operation

During the course of the pilot test, the concentrator was operated in a 24/7 mode for the 14-day trial.

Sampling and Analysis

As part of determining operational performance and optimizing key process parameters, a robust sampling and analysis plan was designed and implemented as part of the pilot test. Liquid and solid

TABLE F
Summary of Concentrator Performance, During Steady-State Operation

	Infeed FGD Purge Water	Process Circulation	Settling Tank Discharge	Secondary Settling
Total solids	~3.5%	30-40%	50-60%	70-80%
TDS	~3.5%	30-35%	~10%	<10%
Specific gravity	1.0	1.2	~1.5	> 1.5
Calcium (mg/L)	~6,500	~55,000	~55,000	>60,000
Sodium (mg/L)	~120	>30,000	>20,000	>25,000
Chlorides (mg/L)	~15,000	>210,000	>230,000	>250,000
Sulfates (mg/L)	~1,000	~350	~300	N/A
Visual Observation				

samples were collected from designated sample ports at periodic intervals and analyzed. Additionally, samples were periodically collected for field monitoring of specific gravity (an indirect indicator of solids concentration), pH, and solids settling behavior. Sampling locations included the following:

- Inlet FGD wastewater from plant to the concentrator infeed tank.
- Circulating process fluid within the concentrator.
- Slurry effluent from the primary cone-bottom settling tank.
- Final slurry from the decant hopper.

Solidification and Stabilization

Following the conclusion of the pilot test, preliminary solidification/stabilization (S/S) experiments were conducted using the concentrator's brine slurry. Six different recipes/mixtures were prepared with varied concentrations of brine slurry, coal fly ash (CFA), and Portland cement (PC). In some cases, Iron (II) Sulfate Heptahydrate ($FeSO_4 \cdot 7H_2O$) (FS) was used as an additive to enhance immobilization of heavy metals as described in the S/S Materials and Methods sections below.

Table D shows physical properties of the brine slurry utilized in the S/S experiments.

When the concentrator brine slurry was allowed to settle, a thick layer of settled solids (suspended solids when the brine slurry is agitated) formed with a liquid phase supernatant on top. The liquid phase included water and dissolved solids. A significant portion of the settled solids was CFA, but also included precipitates such as sodium sulfate, and gypsum, among others.

Selenium speciation for the liquid phase of the brine slurry was determined by sampling and analyzing the supernatant (after a long period of settling). The supernatant was analyzed, using an ion exchange-inductively coupled plasma-mass spectrometry (IX-ICP-MS) method.

Six S/S solids were produced by mixing the four main components— brine slurry, CFA, PC, and FS in varying ratios. Table E shows the mass ratios of the components in each mixture. In addition to the mixtures shown in Table E, some mixtures were prepared using quicklime (QL) instead of PC. However, the QL S/S samples did not appear to set up well. Only the PC S/S samples were included in the analysis. The S/S mixtures prepared with QL were not comprehensive and more research is needed on the QL S/S of the brine slurry.

The brine slurry, CFA, and PC were simultaneously added to a bench-top stainless steel mixer and homogenized for approximately 2 minutes. If FS was used in the mixture, FS was added after two minutes of initial mixing. The mixture was then homogenized for 18 additional minutes. The resulting S/S slurry was then poured into plastic concrete forms. The S/S slurry was allowed to cure for seven days in a humid environment.

Toxicity Characteristic Leaching Procedure (TCLP) tests were conducted per EPA Method 1311 to evaluate the leachability of the S/S solids. The samples were digested per EPA Method 3051, and analyzed per EPA Method 6020a for metals and per EPA Method 7473 for mercury. The produced S/S solids were also digested per EPA Method 3051, and analyzed in the same manner.

Results and Discussion

Liquid Volume Reduction

The pilot test was conducted in 24/7 operation for a period of approximately 14 days from Sept. 17 to Oct. 2, 2014, with a total of approximately 10,000 gallons of FGD wastewater being processed through the concentrator. The concentrator achieved a net volume reduction of

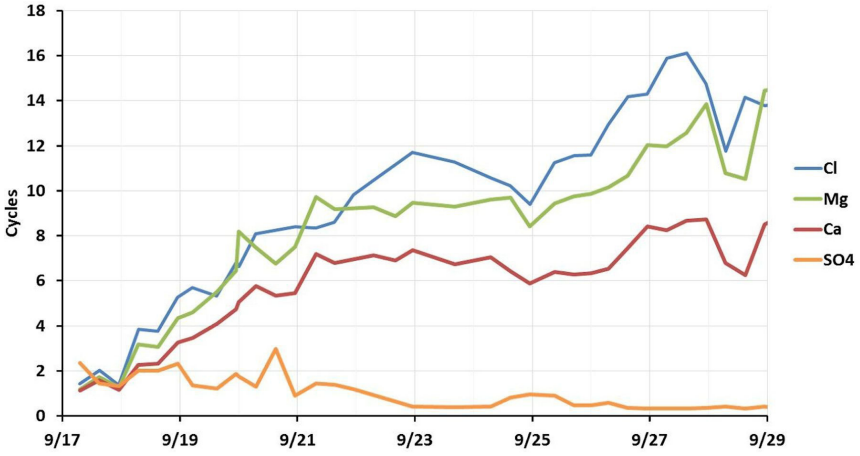


Figure 3. Daily changes in cycles of concentration for Cl, Mg, Ca, and SO4 in the concentrator.

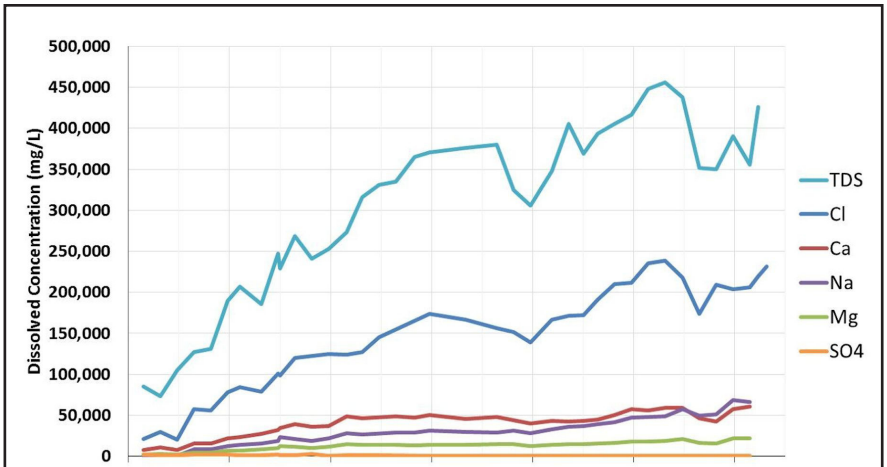


Figure 4. Daily changes in dissolved concentrations of TDS, Cl, Ca, Na, Mg, and SO4.

TABLE G
Maximum RCRA Metal TCLP Concentrations for Class D Waste

RCRA Metal	TCLP Limit (µg/L)
Arsenic (As)	5,000
Barium (Ba)	100,000
Cadmium (Cd)	1,000
Chromium (Cr)	5,000
Lead (Pb)	5,000
Mercury (Hg)	100
Selenium (Se)	1,000
Silver (Ag)	5,000

approximately 90% to 95%, representing an approximate 10 to 15 net cycles of concentration of key species within the concentrator before approaching steady state operation. Figures 3 and 4 show the cycling up process of key species within the concentrator.

A summary of concentrator performance, during steady state operation, is presented in Table F. Figures 3 and 4 show chronological changes in the concentration of various cation, anion, and trace metal species. Cycles of concentration were determined by comparing the concentrations of the infeed FGD water and the process circulation or sump recycle feedwater.

Based on these results, the following observations and conclusions were made:

1. The concentrator discharge yielded a slurry that was 50% to 60% total solids; after secondary settling and decanting, this increased to 70% to 80% solids. The slurry was composed of concentrated brine, salt precipitates, and collected fly ash.
2. At the average processing rate of about 750 gpd, the concentrator required about 10 days to reach steady-state operation; it ran at steady state for about 3 days before a planned system purge diluted slurry concentrations for the remainder of the run.
3. At steady-state operation, total dissolved solids (TDS) levels within the process circulation or sump recycle feedwater were approximately 400,000 to 450,000 milligrams per liter (mg/L), with chlorides at 200,000 to 250,000 mg/L (or approximately 12 to 16 cycles of concentration).
4. Sulfate levels decreased over time, suggesting that sulfates were precipitating as sodium sulfate and/or calcium sulfate as sodium and calcium levels increased.

Plant Operation Integration

The concentrator demonstrated successful integration with operation of the plant during the EPRI Project. This included continued coordination with plant operations managers during equipment start-up, shutdown, and operation, as well as equipment lock-out/tag-out procedures. In addition, training sessions were conducted to establish protocols for operators to open and close plant-side dampers (thus accessing the hot flue gas) while plant operators were provided a means to safely shut down the concentrator if the need ever arose.

From an equipment-operations perspective, there were many challenges and unknowns regarding how the concentrator would respond to changing flue gas temperatures and pressures associated with daily and weekly plant load shifts. The actual temperatures and pressures experienced by the concentrator were unknown until commissioning, because of the length of duct between the SCR outlet and the concentrator. The concentrator achieved the following:

1. The concentrator operated successfully under various transient and steady state plant operating conditions, including wide temperature and pressure swings during evening and morning load shifting, with the only noticeable downside being that evaporation rates dropped with decreasing plant power output.
2. It was able to successfully operate at inlet flue gas temperatures ranging from 375 to 500°F, well below the design or expected temperature of 650°F (lower temperatures were experienced due to heat losses and/or leaks in the long inlet flue gas ductwork).

The concentrator was able to maintain a steady gas flow and pressure drop across the concentrator to support stable and steady state operation, especially during periods of transient plant operation (load swings) with the use of a variable frequency drive (VFD) on the induced draft fan.

Fly Ash Handling and Behavior

Fly ash within the flue gas was captured by the concentrator circulating fluid and collected in the cone-bottom settling tank along with the concentrated brine and precipitated salts. The following observations were made:

1. While minor accumulation of fly ash was observed in various points of the concentrator (e.g., low velocity corners), no major build-up or other detrimental impacts of fly ash were observed.
2. It appeared that collected fly ash in the concentrator easily moved through the system and appears to provide a net benefit in facilitating solids formation (seed), settling, and management.

SO_2 Absorption and pH

During initial operation of the concentrator, a larger-than-expected decrease in the process fluid pH was observed (i.e., pH < 1). This could be attributed to the following:

- To compensate for lower-than-expected hot flue gas temperatures at the process inlet, higher-than-planned gas flowrates through the concentrator were required to maintain evaporation rates.
- Increasing the flue gas flowrate through the concentrator exacerbated the accumulation of acid gases in the downstream process waters.

To address the potential concern with operating at a low pH, lab titration tests were conducted. With the resulting data, calculations were performed to define and implement process fluid pH control via metering/dosing of 25% sodium hydroxide. Sodium hydroxide was used as it was readily available on-site and able to be introduced into the concentrator with minimal process equipment changes.

However, the long-term goal, should pH control be deemed necessary, would be to transition from NaOH addition to lime addition (e.g., quicklime, hydrated lime, or limestone slurry). A forced outage on the plant prematurely ceased operation of the concentrator on Oct. 2, 2014, (one week earlier than planned), and this test with hydrated lime did not occur during the initial trial run.

Operation and Cleaning

During the 14-day, 24/7 runtime, the concentrator experienced 93% runtime and 98% availability factors, with 5%

discretionary downtime for equipment inspection and process/performance evaluation. Additionally, the following observations were made regarding ease of operation:

1. The concentrator's instrumentation and integrated PLC system demonstrated automatic monitoring control of process parameters including liquid levels, FGD wastewater feedrates, temperatures, and pressures.
2. Operator labor was required for maintaining solids levels (i.e., % total solids [TS]) in the concentrator as well as performing manual purges of the cone-bottom settling tank; however, these processes could also be automated.
3. Build-up of ash and salt film was observed within the concentrator; however, these build-ups occurred primarily within the mist-eliminating sections of the concentrator, which was easily accessible for maintenance and cleaning. No build-up or scale was observed in places such as process piping and instrumentation.
4. Solids build-up was easily removed with periodic cleaning using a high-pressure power washer. No cleaning chemicals (e.g., acid cleaning) or special equipment/processes were required for maintenance.

Solidification and Stabilization

Table G shows the maximum TCLP concentrations for the Resource Conservation and Recovery Act (RCRA) metals, which include arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver. TCLP concentrations for these metals must be below the values shown in Table G for a material to be considered Class D waste (non-hazardous).

For all S/S recipes used, of the RCRA metals, selenium concentrations were closest to the Table G limits with values from 233 to 486 micrograms per liter (µg/L) (23% to 48% of the RCRA limit). Mercury TCLP concentrations varied from 1.1 to 3.5 µg/L, which was much less than the Table G limits. The results achieved during the pilot included:

1. Relatively low leaching (~<50%) for selenium, mercury, arsenic, cadmium, chromium, barium, lead, silver, nickel, copper, iron, zinc, strontium, and uranium.
2. A large amount of leaching (>50%) was seen in the results for boron, calcium, magnesium, and sodium.

Selenium Retention

The positive selenium results (leaching of 26.1% to 50.1%) indicate that most of the selenium in the brine slurry (liquid phase + suspended solids) is in the selenite (+IV) form.

Increasing the PC content of the S/S mixture from 5% to 10% enhanced the immobilization of selenium, mercury, arsenic, and others. In fact, selenium leaching decreased from 47% to 50% to 26% to 29% when the PC was increased to 10%.

Issues not Evaluated

It should be noted that the impact of injecting saturated flue gas from this concentrator back into the flue gas ducting was not evaluated in this pilot test.

Conclusions

Based on the EPRI pilot test, collected data and analysis, the following conclusions can be made:

1. The concentrator showed the ability to treat and concentrate FGD wastewater, resulting in a net water volume reduction of 90% to 95% with TDS levels over 400,000 mg/L in the circulating fluid, and yielding a slurry containing 70% to 80% total solids.
2. The concentrator was able to use flue gas heat as an energy source to drive its evaporative process. Fly ash within the flue gas provided a net benefit to the system by aiding in the management and stabilization of precipitated salts from the concentrated brine.
3. The concentrator showed reliable operations (93% uptime), and ease of cleaning and maintenance.
4. The EPRI study validated the feasibility of subsequent ZLD-type treatment of the concentrated FGD wastewater slurry/residuals.
5. Solidification / stabilization of the brine slurry with Portland cement produced solids with significant to excellent immobilization of metals. Selenium was significantly stabilized due to being present primarily as selenite (+IV) as opposed to selenate (+VI) in the brine slurry. Mercury and arsenic were essentially immobilized.
6. The TCLP concentrations for all produced solids in the project were below the maximum RCRA metal TCLP concentrations for Class D waste.
7. Increasing the PC concentration in the S/S mixtures enhanced the immobilization of selenium, mercury, arsenic, chromium, copper, and uranium.

Acknowledgements

The project was funded by EPRI and conducted at the Water Research Center at Georgia Power's Plant Bowen. Considerable support in preparing for and executing the project, as well as providing analysis and feedback on project results was provided by EPRI, Southern Co., Georgia Power's Plant Bowen, and Southern Research.

References

1. EPA "Steam Electric Power Generating Effluent Guidelines— 2015 Final Rule. (n.d.), U.S. Environmental Protection Agency, Washington, D.C., available at https://www.epa.gov/eg/steam-electric-power-generating-effluent-guidelines-2015-final-rule (accessed May 25, 2016).
2. EPRI "Demonstration Development Project: Feasibility of an Adiabatic Evaporator for Flue Gas Desulfurization Wastewater Zero Liquid Discharge Treatment Using Flue Gas Heat", Report No. 3002002148, Breckenridge, R., project manager, Electric Power Research Institute, Palo Alto, CA (May 2015).

Bibliography

3. Batchelor, B. "Overview of Waste Stabilization with Cement", *Waste Management*, 26, pp. 689-698 (2006).
4. Connor, J. R.; Hoeffner, S. L. "A Critical Review of Stabilization/Solidification Technology". *Critical Reviews in Environmental Science and Technology 28(4)*, pp. 397-462 (1996).
5. Keller, I.R.B. "The Immobilisation of Heavy Metals and Metalloids in Cement Stabilised Wastes: A Study Focusing on the Selenium Oxyanions SeO_3^{2-} and SeO_4^{2-}", Swiss Federal Institute of Technology, Zurich, Switzerland (2002).
6. Moon, D.H.; Grubb, D.G.; Reilly, T.L. "Stabilization/Solidification of Selenium-Impacted Soils Using Portland Cement and Cement Kiln Dust". *Journal of Hazardous Materials*, 168, pp. 944-951 (2009).
7. Solem-Tishmack, J.K.; McCarthy, G.J. "High-Calcium Combustion By-Products: Engineering Properties, Ettringite Formation, and Potential Application in Solidification and Stabilization of Selenium and Boron", *Cement and Concrete Research*, 25, pp. 658-670 (1995).

Endnotes

[A]The project was reported on in EPRI Report No. 3002002148. The project was funded by EPRI and conducted at the Water Research Center at Georgia Power's Plant Bowen.

[B]The adiabatic evaporator used for FGD wastewater treatment/concentration in the text was a Heartland LM-HT® Concentrator™, which is made by Heartland Water Technology, Inc., Hudson, MA. In the article, it is referred to as a "concentrator".

Author Benjamin Laurent is a senior process engineer with Heartland Water Technology. He has been with the company for 4 years and has more than 10 years of experience in processing engineering and project management. His work includes project conceptualization and development, benchtop and pilot testing, material and energy balance development, and support of project execution through commissioning. Mr. Laurent holds a BS in chemical engineering from the University of Wisconsin—Madison.

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Glossary of Abbreviations

CCR: coal combustion residual
CFA: coal fly ash
EGUs: electric power generating units
ELG: Effluent Limit Guidelines
EPA: U.S. Environmental Protection Agency (headquarters in Washington, DC)
EPRI: Electric Power Research Institute (headquarters in Palo Alto, CA)
FGD: flue gas desulfurization
gpm: gallons per minute
HMI: human-machine interface
$FeSO_4 \cdot 7H_2O$: Iron (II) Sulfate Heptahydrate or FS
IX-ICP-MS: ion exchange-inductively coupled plasma-mass spectrometry
mg/L: milligrams per liter
MW: megawatt
PC: Portland cement
PLC: programmable logic controller
QA: quality assurance
QL: quicklime
RCRA: Resource Conservation and Recovery Act
S/S: solidification/stabilization between "RCRA" and "SCR"
SCR: selective catalytic reduction
TCLP: Toxicity Characteristic Leaching Procedure
TDS: total dissolved solids
TS: total solids
VFD: variable frequency drive
ZLD: zero liquid discharge
µg/L: micrograms per liter