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Flue Gas Desulfurization Wastewater Treatment in Constructed Wetlands: System Design, Removal Processes, and Treatment Performance

Christopher J. Snider
Burns & McDonnell
Kansas City, MO

Jared Morrison
Westar Energy, Inc.
Topeka, KS

Andrew Rietcheck
Westar Energy, Inc.
Topeka, KS

Dennis Haag
Burns & McDonnell
Kansas City, MO

Maria Squillace
Burns & McDonnell
Kansas City, MO

Katie Bland
Burns & McDonnell
Kansas City, MO

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ABSTRACT

The use of constructed wetland treatment systems (CWTS) in the power generation sector has not yet been well established due to lack of research and project experience. Westar Energy decided to undertake a pilot CWTS project to treat flue gas desulfurization wastewater from the Jeffrey Energy Center located north of St. Marys, Kansas. After 1.5 years of operation the results from the pilot CWTS are considered successful and full scale design is being considered.

INTRODUCTION

Westar Energy, Inc.'s (Westar) Jeffrey Energy Center (JEC) is a coal-fired generating facility composed of three separate 800 MW units. Each unit operates with a flue gas desulfurization (FGD) scrubber to remove sulfur oxides and hydrogen chloride from the exhaust flue gas to meet air emission regulations.

The FGD system produces a slurry mixture by-product high in suspended solids, dissolved solids, nutrients, and metals. The wastewater requires treatment or disposal in accordance with the Kansas Surface Water Quality Standards and Antidegradation policies. In response to these regulations, JEC constructed a wastewater treatment facility to remove suspended solids and mercury. After treatment, the FGD wastewater still contains elevated levels of constituents relative to the Kansas Department of Health and Environment (KDHE) regulations for discharge of industrial wastewater.

Currently, Westar is diluting the FGD wastewater and discharging it to Lost Creek, a tributary to the Kansas River. KDHE, however, is only allowing this to occur until June of 2014; therefore a secondary treatment system is required. A pilot scale constructed wetland treatment system (CWTS) was designed by Burns & McDonnell and constructed by JEC in December 2010 to demonstrate the potential for biological treatment of the FGD wastewater treatment stream. The pilot scale system will assist in making an informed decision regarding the final treatment technology choice for Westar's JEC.

SITE LOCATION AND DESCRIPTION

The JEC site is located seven miles northwest of St. Marys, Kansas. The site is fueled by low-sulfur coal from the Powder River Basin. Construction began in 1974, and unit 1 began operation in 1978, unit 2 in 1980, and unit 3 in 1983. Beginning in 2008, the site began the process of rebuilding the FGD scrubbers at the facility as required by a Regional Haze consent agreement between Westar and KDHE. Figures 1 and 2 show the JEC site and geographic location, respectively.

Figure 1: Westar's Jeffrey Energy Center coal-fired generating facility.

Figure 2: Geographic location of Westar's Jeffrey Energy Center coal-fired generating facility.

ALTERNATIVES EVALUATION

INTRODUCTION–Five technically viable FGD wastewater treatment types were evaluated for implementation at JEC:

1) Underground (injection well) injection
2) Process through falling film evaporators and crystallizer
3) Process through reverse osmosis (RO) and crystallizer
4) Process with falling film evaporators, using the brine to condition fly ash for disposal in an on-site landfill
5) Treatment with sulfate precipitation and CWTS; comingle wetland effluent with cooling tower feed water

The five alternatives were technically evaluated and a 15-year net present value was determined. The least-cost alternative was the CWTS with sulfate precipitation pretreatment.

The injection well option for the JEC site was not preferred due to the uncertainty of the local formations to receive the required flow. System maintenance and economics associated with reverse osmosis and evaporators made them financially unfeasible. The biological treatment through the use of a CWTS with sulfate precipitation was selected as the preferred alternative.

CWTS PILOT DESIGN

The CWTS pilot project receives a 50/50 blend of 18,000 GPD of Kansas River water and 18,000 GPD of FGD effluent. The system exhibits a hydraulic residence time of approximately seven days, and the total wetland area is 2.1 acres. The pilot project was competed in four and a half months, and costs totaled $2.9 million. Kansas State University assisted with the project under a research contract during the operational phase.

There are three different cell types operating in the CWTS (Figure 3). These include Free Water Surface (FWS), Vegetated Submerged Bed (VSB), and Vertical Flow Bed (VFB) systems. FWS cells (Figure 3a) function in a manner similar to that of a permanently flooded emergent marsh with shallow water depth and a combination of emergent and rooted aquatic species such as cattail, bulrush, water lily and arrow head. The VSB cells (Figure 3b) function similar to a fully saturated emergent marsh with high ground water levels and plant species such as switch grass, inland salt grass, and sedges. VFB (Figure 3c) cells are similar to VSB cells except incoming water is applied evenly over the surface of the cell, allowing vertical infiltration instead of horizontal flow.

DESIGN SUMMARY – The primary objective of the pilot design CWTS is to demonstrate specific removal ranges for constitutes of concern, adequately represent a full scale CWTS, define full scale capital and operational costs, and evaluate the ability of the vegetation to survive in the FBD/raw water mixture.

<u>Layout Design</u>- The CWTS was constructed with eight (8) wetland cells that were placed into two (2) parallel, side by side, treatment lines. This arrangement, shown in Figure 4, allows the system to remain in operation during maintenance cycles or if a line (side) or treatment unit (cell) should fail. The two treatment lines, A and B, contain 4 cells each.

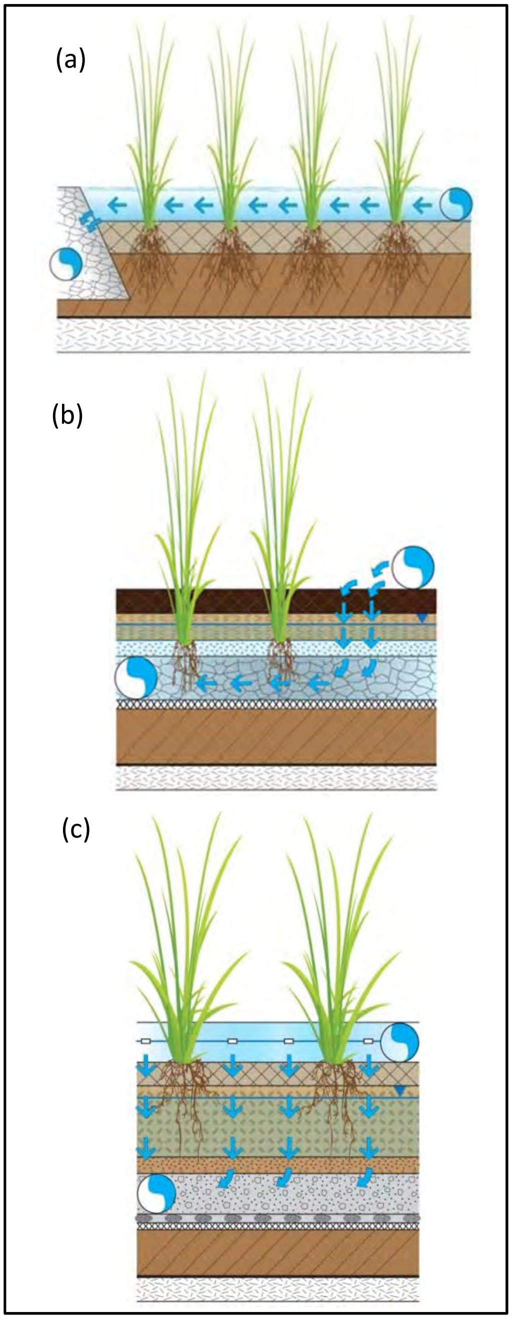

Figure 3: Three wetland cell types used in JEC's wetland system including (a) free water surface (FWS), (b) vegetated submerged bed (VSB), and (c) vertical flow bed (VFB).

Each cell is numbered according to the position within the line. The order of treatment for each line is: FWS A1/B1, VSB A2/B2, VFB A3/B3, and VSB A4/B4.

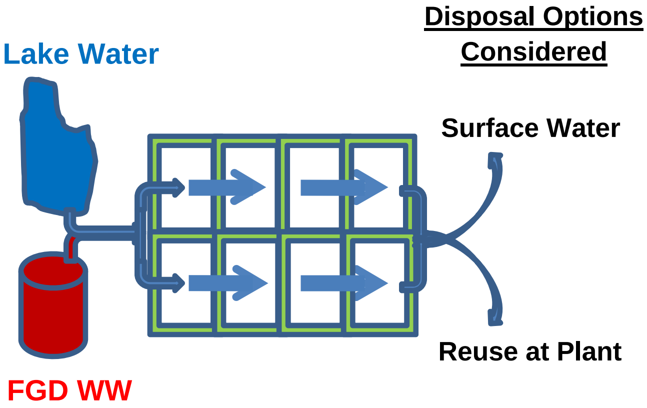

Figure 4: Constructed wetland treatment system train layout with 2 lines, each composed of 4 cells.

Wastewater and dilution water are pumped from the existing FGD solids removal plant to a splitter box on the east side of the CWTS where water is divided between FWS cells A1 and B1. These cells are used for mixing wastewater and dilution water as well as initial treatment of constituents, in particular salts. Water is gravity fed from cells A1/B1 to VSB cells A2/B2.The effluent from these cells flows into an irrigation lift station to enable the equal distribution of water over the VFB wetland in cells A3/B3. Effluent from the VFB cells is gravity fed to the final VSB cells in A4/B4. The fully treated water is transported out of the system through an effluent lift station to a temporary surface water discharge point.

Piping Design- The FWS and VSB wetland cells contain 6-inch gated PVC pipes at the east side of each cell that distribute water by gravity into the cells. In each wetland cell the wastewater flows west towards 6-inch perforated high-density polyethylene (HDPE) drain pipe that is contained within a crushed limestone rock gravel envelope. The VFB wetland cells contain a solid 6-inch PVC header that manifolds into a series of three 6-inch gated UV-stabilized PVC pipes spaced evenly across the surface of the cells. Even flow distribution across each wetland surface is ensured though the use of adjustable gates on the header pipes. The water infiltrates vertically through engineered soil to a series of 6-inch perforated HDPE drain pipe and crushed limestone gravel bedding in the bottom of each cell. AgriDrain water control structures are positioned at the outlet of each wetland, allowing for the precise control of the water level within each cell.

Plant and Soil Design- Engineered soils were used for six out of the eight cells in the system. The VFB and VSB bed soil was created and composed of 25% native top soil, 10% native clay, 40% fine sand, and 25% organic matter. Five tons per acre of moldy hay was tilled into the VSB and VFB cells. A liquid bacteria mixture containing VermaPlex, SOS Biological and Fulvic Acid extract was introduced into the eight cells in the CWTS.

In the FWS cells (A1/B1) plant materials were planted within a 6 inch layer of topsoil placed on top of a protective liner cover soil. The topsoil and cattails were obtained from an adjacent natural wetland near the CWTS. Additional emergent and rooted aquatic plants were planted within each FWS cell.

In the VSB cells (A2/B2/A4/B4) plant materials were planted within a 6 inch layer topsoil place on top of the following subgrade: 6 inches engineered soil, 3 inches sand filter material; non-woven geotextile fabric; 9 inches crushed limestone rock; non-woven geotextile fabric; 12 inches of protective cover soil; and 60 mil liner.

The VFB cells (A3/B3) had plant materials placed within a 6 inch layer of topsoil placed on top of the following subgrade: 24 inches engineered soil; 3 inches sand filter material; non-woven geotextile fabric; 9 inches crushed limestone rock; non-woven geotextile fabric; 12 inches of protective cover soil; and 60 mil liner.

SAMPLING, OPERATION, AND MAINTENANCE

The pilot evaluation includes a comprehensive sampling program, including regular water, soil, and vegetation monitoring. The program is designed to evaluate the overall system, as well as individual cell and line performance. A 4 month period starting in January 2011 allowed the wetland to develop for current treatment. Water samples were collected from the CWTS inlet and outlet, and between each wetland cell from May-July 2011. From July 2011- May 2012, samples were taken primarily from the inlet and outlet only. Water samples were collected bi-weekly through early spring 2011 and weekly thereafter. Vegetation and soil samples were also collected and tested several times during the growing season.

PIILOT CWTS PERFORMANCE

After approximately 1.5 years of operation, JEC Pilot CWTS has achieved various levels of performance for treatment of target constituents. The following information concerning results pertains to data collection, validation, and evaluation for the period of May 2011-July 2012.

WATER TREATMENT EFFICIENCY- The removal efficiency of the CWTS was determined for all analytes by comparison of the average concentration in the effluent to the average concentration in the influent. The average influent concentration was calculated from the results of 49 sampling events from May 12, 2011 through July 10, 2012, and average effluent concentration from 51 sampling events between April 12, 2011- July 10, 2012. Note, when calculating averages and in the case of a non-detect result, the detection limit was used to calculate the numerical average. The following criteria were used in the evaluation of removal efficiency:

- Effective constituent removal was categorized by a removal efficiency greater than 20%
- Ineffective constituent removal was categorized by a removal efficiency of 0%
- Percent removal between 0% and 20% indicated little or no removal efficiency and provided inconclusive results

Overall, 19 constituents showed effective removal efficiency, 11 constituents showed ineffective removal efficiency, and 15 constituents showed little or no removal. The following sections summarize these results. Removal efficiencies, influent and effluent concentrations, and KDHE surface water standards are included in Appendix A.

Metals- CWTS influent and effluent were monitored for a total of 22 metals. Nine metals had good removal efficiency: aluminum, barium, boron, chromium, iron, mercury, molybdenum, selenium, and vanadium. Of these metals, aluminum, mercury, and selenium exhibited very good removal efficiencies at 89%, 81%, and 90%, respectively. Additionally, barium and chromium had effluent concentrations below or equal to the minimum KDHE surface water standard.

Six metals had poor removal efficiency: arsenic, cadmium, cobalt, manganese, nickel, and zinc. The concentrations of these analytes increased, thus, it is likely that some of these analytes were involved in ion exchange processes within the system. Arsenic, nickel, and zinc effluent concentrations were below or equal to the minimum KDHE surface water standards. The cadmium effluent concentration was below the Agriculture Irrigation and Domestic Water Supply standards, but not the Aquatic Life standard. Cobalt and manganese do not have available KDHE surface water standards.

The remaining seven metals (Be, Cu, Pb, Ag, Na, Sn, Sb) showed little or no percent removal (0-20%). However, the majority of these metals have effluent concentrations below or equal to the available KDHE surface water standards.

Halogens- Samples for anionic halogens, chloride and fluoride, were analyzed. Chloride showed little to no removal efficiency (3%) and an effluent concentration above the KDHE surface water standard. However, fluoride exhibited very good removal efficiency (83%).

Water Quality Parameters- Twenty-one water quality parameters were monitored. Nine of these parameters experienced good removal efficiency: ammonia, chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), magnesium, nitrate as N, nitrite as N, potassium, total suspended solids (TSS), and total organic carbon (TOC). Nitrate as N showed an effective removal efficiency of 88%. Six water quality parameters showed poor removal efficiency: alkalinity as CaCO3, biological oxygen demand (BOD), calcium, hardness, and phosphorus. The remaining seven water quality parameters had little or no removal. Effluent concentrations of sulfate were above the KDHE surface water standard; however, the effluent concentration of nitrate as N was below the minimum KDHE surface water standards.

WATER MASS LOAD REDUCTION- The mass load reduction estimates for water were calculated by determining the total volume of influent and effluent water in the CWTS and applying the average constituent concentrations of the influent and effluent water samples. With the exception of mercury and selenium, most reported concentrations for elements in water samples were above detection limits. The high detection limit for most mercury and some selenium effluent samples was a factor in most water testing results. However, since detection limits were adjusted with each sample and testing event, they may provide a trend for the concentrations of these elements. The analytical testing results for water provide an accurate estimate of the mass (kg) removed by the CWTS for the major constituents of concern.

Table 1 provides the estimate of the mass removed in water for data collection through May 2012. Generally, both treatment lines performed with similar removal results, and no major trends were observed between individual cells. The total estimated influent mass load minus the total estimated effluent mass load of each major constituent found in the water samples showed a load reduction for all constituents including the following reduction percentages: 93% fluoride; 92% selenium; 83% mercury; 42% boron; 5% sulfate; and 2% chloride.

Table 1: Constituent mass removal (kg) in water.

Constituent	Water			
	Influent	Effluent	Total Removed	Percent Removal
Boron	114.87	66.81	48.06	42
Mercury	0.0378	0.0063	0.0315	83
Selenium	4.59	0.38	4.21	92
Fluoride	388.48	28.36	360.12	93
Chloride	19,095	18,656	439	2
Sulfate	77,532	73,868	3,664	5

As the constituent is removed from the water, that mass is attenuated in soil. One concern with the accumulation of constituent mass in soil is that the soil concentration could significantly increase and pose an environmental threat or trigger a regulatory requirement. Soil sample results were compared with risk screening levels specified in the Kansas Department of Health and Environment (KDHE)/ Bureau of Environmental Remediation (BER) risk-based levels for constituents in soil (Kansas Department of Health and Environment, 2010). Mercury and selenium have determined risk levels and are presented in Table 2. Both contaminants are well below the acceptable level for industrial soils.

Table 2: Average soil concentration and KDHE risk-based levels.

Average Concentration[1]				
Constituent	Units	Top Soil[2]	Engineered Soil[2]	KDHE Tier 2 Risk-Based Level[3]
Mercury	mg/kg	0.078	0.045	66200
Selenium	mg/kg	1.990	2.047	10200

[1] Average concentration calculated using all available data. In the case of a non-detect value, the laboratory's practical quantitation limit (PQL) was used to calculate the numerical average.

[2] Soil samples collected on January 7, April 26, June 2, August 4, October 11, November 8, and December 6, 2011

[3] KDHE Tier 2 Risk-Based Levels (KDHE 2010)

Selenium (Se) levels were measured at the influent and effluent of CWTS (Table 3). Selenite (Se(IV), SeO_3^{2-}) and selenate (Se(VI), SeO_4^{2-}) were the two dominant species of dissolved selenium. Compared to selenite, selenate had a higher initial concentration and was reduced to a lower level in the effluent. Selenate was expected to have the highest concentration because it is the most mobile and thus bioavailable of the Se species (Reddy & Vance, 1995). The sulfate concentration in the wetland was relatively high (≈2.0 g L^{-1}) therefore SRB was expected to be active in the organically rich sediment. Microbial growth experiments have demonstrated that selenate is reduced in the presence of high sulfate concentrations and that reduction is biologically mediated (Baldwin & Hodaly, 2003) (Tomei et al, 1995).

Table 1: Selenium speciation results.

SELENIUM SPECIATION RESULTS
Applied Speciation and Consulting, LLC

Date	Sample ID	Se(IV) (ug/L)	Se(VI) (ug/L)		SeCN (ug/L)	
3/28/2012	Influent	3.70	30.47		0.30	U
	Effluent	3.04	0.24	U	0.30	U
6/12/2012	Influent	5.36	60.69		0.30	U
	Effluent	0.12	0.06	U	0.30	U

Notes:
Se = Selenium
Se(IV) = Selenite
Se(VI) = Selenate
SeCN = Selenocyanate
U = Compound not detected
ug/L = micrograms per liter

After approximately 1.5 years of operation, JEC Pilot CWTS has achieved various levels of performance for treatment of target constituents. Current data and studies performed during 2011-2012 indicate that the Pilot CWTS is operating effectively to remove several major constituents, including boron, selenium, mercury, and fluoride. The system has not been effective in removing salts including chloride and sulfate. The high level of salts in the CWTS effluent has led to the conclusion that an irrigation land application system would require too many acres and therefore would probably not be economically feasible. Therefore, other wastewater effluent alternatives are being pursued. The feasibly of implementing a full scale CWTS is currently being evaluated, and preliminary design details are presented in the following section.

FULL SCALE CONSTRUCTED WETLAND TREATMENT SYSTEM

To evaluate the feasibility of a full scale CWTS, CORMIX and plant water balance modeling were conducted as well as column studies and an ecological risk assessment (ERA). Two options are being evaluated for disposal of the CWTS effluent: use of the CWTS effluent as cooling tower makeup and discharge of the effluent to the facility's raw water makeup lake.

CORMIX & PLANT WATER BLANCE MODELING RESULTS- CORMIX is a mixing zone model for environmental impact assessment of regulatory mixing zones resulting from continuous point source discharges. The CORMIX model and plant water balance models were used extensively in evaluating the full scale CWTS for the JEC site. The CORMIX model, combined with the revised plant water balance, has enabled the prediction of the water quality at various points in the plant processes, and enabled the use of these predictions in order to understand how these affect the plant discharge to the Kansas River and associated NPDES permitting. Through this analysis, it was determined that JEC can meet Kansas surface water standards through the CWTS treatment.

Through the use of the CORMIX model, it was concluded that for JEC to meet surface water discharge standards the cooling towers should be operated at six cycles of concentration and a ten inch diameter pipeline would be required for discharge to the Kansas River. Through iterative use of the two models, this was determined to be the best case scenario for JEC to meet the discharge limits while operating within a range of data that included average and maximum constituent levels. This manner of operation provides optimal mixing in the river.

COLUMN STUDIES- Kansas State University (KSU) was contracted to perform bench scale tests for the full-scale CWTS. Various column studies have also been conducted to support the CWTS pilot and full scale conceptual design.

The column studies involved two primary tasks to measure the soils ability to remove major constituents: 1) establish breakthrough curves for soil removal performance; and 2) determine the constituent concentrations in two types of soils. The concentrations of various elements were measured at the entrance and outlet of each column. Breakthrough curves were created for selenium, as well as several other elements by plotting the influent and effluent concentrations against soil pore-volumes. Selenium did not appear to breakthrough in any of the columns during the 100 day experiment, indicating both engineered soil and topsoil effectively attenuated Selenium within the soil mass during the 100 day column study period.

Based upon the results obtained by the column studies, the following recommendations were developed for a full scale CWTS:

- Design for removal of metals with selenium as primary target constituent
- Design for selenium accumulation in soil to a minimum of 7 mg/kg dry soil mass
- Design wetland cell for total saturation and maximum reduction conditions
- Design a minimum of two wetland cells in series, with the second cell for polishing
- Use native topsoil or amended native soil
- Consider using two tiered wetland cell with upper "normal" wetland soil as insulation blanket that receives diluted FGD or raw water, and lower "buried" 100 percent saturated wetland soil (topsoil) that receives nondiluted FGD waste water
- Consider inflow at bottom of wetland cell to maintain maximum saturated conditions

FULL SCALE CWTS DESIGN- Following the completion of the CORMIX modeling, water balance, and bench-scale column studies, design criteria for the CWTS were developed. This included details regarding constituents of concern such as CORMIX predicted discharge limits, CWTS influent design flow quality, and maximum case cooling tower blowdown discharge based on worst case quality from the makeup lake (raw source) and CWTS effluent.

ERA & Two Tier VFB- An ecological risk assessment (ERA) was recommended to be conducted to evaluate potential ecological risks. The purpose of the ERA is to evaluate the likelihood of adverse ecological effects as a result of the site-specific constituent concentrations in environmental media. The majority of the risks associated with this site are associated with ingestion of invertebrates. In response to these results, a two tier VFB cell was designed for the full scale CWTS treatment system to prevent wildlife contact with concentrated FGD wastewater (Figure 5).

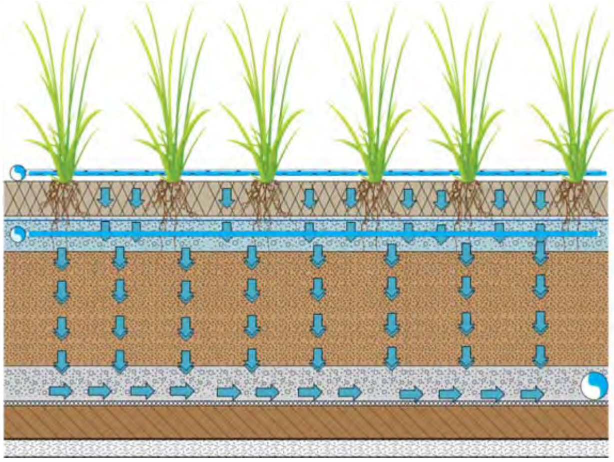

Figure 5: Two tier VFB cell design for full Scale CWTS treatment system.

The two tier VFB consists of two soil layers for treatment, an upper layer and a lower layer. The upper soil layer is a shallow depth soil mass designed primarily as a thermal insulation and cover layer for the lower soil layer. The upper layer will receive intermittent flows to maintain good wet prairie/wetland type and will serve as a cover over the lower soil layer to mitigate ecological risk. The lower soil layer is a much thicker soil mass that is designed to attenuate constituents in a reducing environment and will serve to perform the majority of constituent removal. The FGD influent from an equalization storage pond will be discharged directly to top or bottom of the lower soil layer through a gravel and pipe distribution system. Treated water will be discharged from the lower soil layer at the bottom of the cell through gravel and pipe collection system as in the current pilot system. Discharges will be conveyed in pipes to the single tier VFB located downstream.

Key Full Scale Design Components- An influent flow 161 gpm (approximately 0.7 acre foot of flow per day) has been used to size the wetland treatment system. In addition, treatment capacity is sized for maximum flow of 244 gpm for short periods following large rainfall events and/or when the equalization pond requires dewatering or lowering. The average concentration of major constituents in FGD wastewater without pretreatment was used for CWTS influent conceptual design. This data has been collected since March 2011 during operation of the pilot wetland system. Mass balance removal estimates have been prepared for the pilot CWTS system and by column studies performed by KSU. Although estimates have been prepared for all major constituents, with the exception of sulfate, selenium was determined to be the most important constituent on which to base design of the full scale CWTS.

The full scale CWTS is designed to reach a target final concentration of 7.0 mg/kg selenium in dry soil. This was derived by comparing the results of the column studies and pilot system with proven published removal of 10.0 mg/kg. Using a 7.0 mg/kg and 15 year life, the full scale CWTS would require approximately 95 acre feet of treatment soil. Appendix B summarizes the full scale wetland sizing.

The major components of conceptual design for the full scale CWTS include the following:

- FGD wastewater and raw water influent lines
- 4 acre equalization pond with +-30 acre feet storage
- CWTS influent pump station (from pond to mixing/distribution structure)
- CWTS Distribution structure (influent mixing, metering, and control structures for raw water
  water and FGD wastewater)
- Parallel CWTS cells including
  - A total of 13.4 acres: Two-Tier VFB Cells
  - A total of 4.2 acres: Single-Tier VFB Cells
- CWTS effluent discharge structure and gravity line to Makeup Lake
- CWTS effluent pump station (required if effluent goes to cooling towers)

- Access road and miscellaneous facilities

Implications for Other Water Streams- As discharge regulations evolve over time, regulators and owners continuously seek reliable water treatment technologies that can meet project objectives in a cost efficient manner. The pilot CWTS at JEC has demonstrated that CWTS technology could be effective at treating coal pile runoff. Typical coal pile runoff contains dissolved metals such as Al, Cr, Fe, Hg, Pb, and Se (Ibeanusi, Phinney, & Thompson, 2003) (Swift, 1985). (Zielinski, Otton, & Johnson, 2001)The CWTS removed many of these metals with effective removal efficiencies (Table 4).

Table 2: Typical coal pile runoff parameters and concentrations, and CWTS % reduction

Parameter	Coal Pile Runoff Concentration Range (mg/L)[1]	CWTS % Reduction[2]
Fe	1.7-480	48
Al	22-60	89
As	0.006-1.5	-6
Hg	0.46-0.1	81
Se	0.006-0.47	90
Cr	0.1-0.13	70
Zn	1.1-3.7	-1
Pb	0.007-1.3	12
Cu	0.4-0.53	13

[1] Concentration ranges were selected by using highest and lowest concentrations found in literature (Ibeanusi, Phinney & Thompson, 2003), (Swift, 1985), (Zielinski, Otton & Johnson, 2001)

[2] Percent removal from pilot scale CWTS. Negative removal efficiencies are due to the natural occurrence of metals in soil, and concentrations are low. The arsenic and lead effluent concentrations in the CWTS meet the drinking water MCL. See Appendix A for CWTS water quality data.

CONCLUSIONS

The Pilot CWTS at JEC has demonstrated that the technology is viable for lower chloride FGD wastewater polishing, when coupled with effluent reuse at the plant.

The constituent mass removal levels reached percentages as high as 90%, while maintaining soil concentrations well below the KDHE industrial risk-based levels. While the use of CWTS is widespread in other applications, it has not yet been widely applied in the coal-fired power generation market sector.

The use of constructed wetlands to treat FGD wastewater is a relatively new technology in the coal-fired power generation sector. The results achieved in this project indicate that CWTS may be a technology that could be considered in certain situations. Limitations exist in the technology. For example, CWTS require a large area (many acres) and sites in northern climates can be problematic. A high chloride concentration in FGD wastewater is another limiting factor as the chloride is toxic to vegetation at certain concentrations.

Innovative design in the CWTS can reduce ecological exposure to problematic constituents when the wastewater is applied to the wetland subsurface where mercury and selenium can be isolated from wildlife.

CWTS are a passive treatment technology and have low operation and maintenance costs. At the JEC Pilot Project, nine metals exhibited effective removal efficiency: aluminum, barium, boron, chromium, iron, mercury, molybdenum, selenium, and vanadium. Of these metals, aluminum, mercury, and selenium exhibited very good removal efficiencies at 89%, 81%, and 90%, respectively.

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APPENDIX A

CWTS INFUENT AND EFFLUENT WATER QUALITY DATA AND KDHE SURFACE WATER QUALITY STANDARD

Constituent	KDHE Surface Water Standards (mg/L)			Average Influent Concentration[4,6] (mg/L)	Average Effluent Concentration[5,6] (mg/L)	Percent Reduction (%)
	Agriculture Irrigation[1]	Domestic Water Supply[2]	Aquatic Life Chronic[3]			
Alkalinity, as $CaCO_3$	-	-	-	144	309	-114
Aluminum	-	-	-	0.617	0.068	89
Ammonia	-	-	3.51	**1.396**	**0.514**	63
Antimony	-	0.006	0.03	0.007	0.007	4
Arsenic	0.1	0.01	0.15	**0.008**	**0.008**	-6
Barium	-	1	-	**0.102**	**0.067**	35
Beryllium	-	0.004	-	**0.001**	**0.001**	0
BOD	-	-	-	5.125	5.348	-4
Boron	0.75	-	-	3.593	2.424	33
Cadmium	0.01	0.005	0.003	**0.001**	**0.002**	-87
Calcium	-	-	-	341	494	-45
Chemical Oxygen Demand	-	-	-	97	55	44
Chloride	-	250	-	557	541	3
Chromium	0.1	0.1	0.04	**0.017**	**0.005**	70
Cobalt	-	-	-	0.002	0.009	-436
Copper	0.2	1.3	0.1355	**0.008**	**0.007**	13
Fluoride	1	2	-	10.785	1.794	83
Hardness	-	-	-	2257	2291	-2
Iron	-	-	-	1.181	0.617	48
Kjeldahl Nitrogen, as N	-	-	-	4.867	3.461	29
Lead	5	0.015	0.1714	**0.004**	**0.003**	12
Magnesium	-	-	-	374	289	23
Manganese	-	-	-	1.441	3.966	-175
Mercury	-	0.00014	0.00077	0.00108	0.00020	81
Molybdenum	-	-	-	0.035	0.013	62
Nickel	0.2	0.61	0.7378	**0.005**	**0.006**	-22
Nitrate, as N	-	10	-	33.313	**3.883**	88
Nitrite, as N	-	-	-	1.733	0.406	77
pH (std. units)	-	-	6.5 - 8.5	**8.426**	**7.330**	13
Phosphorus	-	-	-	0.204	0.533	-161
Potassium	-	-	-	62.4	31.5	50
Selenium	0.02	0.17	0.005	0.111	0.011	90
Silver	-	0.05	-	**0.001**	**0.001**	0
Sodium	-	-	-	418	410	2
Total Solids	-	-	-	5521	4558	17
Total Dissolved Solids	-	-	-	4645	4201	10
Total Suspended Solids	-	-	-	19.350	6.783	65
Specific Conductance (umhos/cm)	-	-	-	5464	5223	4
Sulfate	-	250	-	2281	2163	5
Sulfide	-	-	-	0.100	0.100	0
Thallium	-	0.002	0.04	0.002	0.002	7
Tin	-	-	-	0.006	0.006	0
Total Organic Carbon	-	-	-	26.712	18.900	29
Vanadium	-	-	-	0.007	0.005	22
Zinc	2	7.4	1.702	**0.022**	**0.022**	-1

Bold numbers indicate that the constituent concentration is less than or equal to the minimum KDHE standard available

[1] KDHE Surface Water Agriculture Irrigation Limit

[2] KDHE Surface Water Domestic Water Supply Limit

[3] KDHE Surface Water Aquatic Life Chronic Limit

[4] Influent calculated as average of available results from 49 sampling events May 12, 2011 – July 10, 2012

[5] Effluent calculated as average of available lift station results from 51 sampling events April 12, 2011 – July 10, 2012

[6] When calculating averages and in the case of a non-detect, the laboratory practical quantitation limit (PQL) was used to calculate the numerical average

APPENDIX B

CWTS DESIGN AND ANALYSIS SUMMARY

System	Duration	Selenium Load from FGDWW	Selenium Retained in Soil (%)	Actual* or Planned Retained Selenium (mg/kg in dry soil)	Soil Mass (actual* or planned)
Column Study[1]	100 days	0.445 mg	0.445 mg (100%)	2.45*	0.1854 kg*
Column Study[2]	365 days	1.624 mg	1.624 mg (100%)	8.9	0.7416 kg*
Pilot System[3]	1 Year	5.46 kg	4.94 kg (90%)	1.26*	3,926,000 kg*
Pilot System[4]	4 Years	21.8 kg	19.63 kg (90%)	5.0	3,926,000 kg*
Full Scale[5]	15 Years	1095 kg	986 kg (90%)	7.0	140,786,000 kg

[1] Selenium retained in bottom ¼ of soil column with total soil dry weight of 0.7416 kg per column, or 0.1854 kg used

[2] Estimated life of column for remaining ¾ column volume for 365 days and planned rate of 8.9 (3.65 X 2.45 mg/kg)

[3] Pilot volume is 2.65 acre feet of treatment soil with soil dry weight bulk density of 1.2 g/cm^3; minimum retained due to small load, non-saturated soil condition, and 90 percent removal efficiency

[4] Pilot life: same annual load, adjustment in saturation, and estimated improved soil retain rate of 5.0 mg/kg soil

[5] Full Scale: assumed Selenium load of 0.227 mg/l at 161 gpm = 877,591 lpd, 0.2 kg/d, and 73 kg/yr; 90% removal efficiency, and minimum 95 acre feet treatment soil with soil dry weight bulk density of 1.2 g/cm^3, 100 % saturation, subsurface injection, and estimated soil retain rate of 7.0 mg/kg soil