

Determination of Trace Element Concentrations at an Eastern Bituminous Coal Plant Employing an SCR and Wet FGD

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PRODUCT DESCRIPTION

Previous sampling has shown that air pollution control devices can have a significant impact on mercury and other trace elements. For example, selective catalytic reduction (SCR) can substantially increase the percentage of oxidized mercury that can then be removed by a wet flue gas desulfurization (FGD) system. The electrostatic precipitator (ESP) also readily captures most of the trace elements of interest. The emission of these trace elements is then directly related to the overall particulate collection efficiency of the ESP. With funding from the Electric Power Research Institute (EPRI), the U.S. Department of Energy, and Center for Air Toxic Metals® (CATM®) Affiliates, a project completed at a power plant burning a bituminous coal provided data on the behavior of a number of trace elements across various pollution control devices including SCR, ESP, and wet FGD. The project focused on the wet FGD system.

Results and Findings

Results showed that with the possible exception of selenium, the trace element emissions at the stack were very low. As expected, the trace element removal across the ESP was very much in line with the particulate collection efficiency. The overall mass balances were generally good, but the mass balances across the wet FGD were more variable. This finding is most likely a result of some of the concentrations being very low and also of the uncertainties in determining flows within a wet FGD.

Challenges and Objectives

As environmental scrutiny of coal-fired power plants increases, trace elements other than mercury may well become of interest. Therefore, there is a need for the plants to understand the behavior of these trace elements across the entire system. To further this goal, specific objectives of this project were to determine the overall behavior of trace elements in the system and provide an overall trace metal balance for the plant. In particular, the project focused on wet FGD. It is clear that understanding the behavior of the various trace elements in a wet FGD system is going to be a challenge, as it is one of the least controlled devices in a power plant. It is often very difficult to obtain the samples that are needed and determine the flow rates of the various inlet and outlet streams.

Applications, Values, and Use

The results from this project will provide insight into the behavior of trace elements in a power plant as well as help to determine what specific trace elements should be more closely scrutinized.

EPRI Perspective

Multimedia trace element characterization—especially for mercury—is of growing power plant concern. This study characterizes multimedia measurements at one bituminous coal-fired power plant with SCR and wet FGD systems. EPRI recently synthesized all the available data for mercury in *Multimedia Mercury Fate at Coal-Fired Power Plants Equipped with SCR and Wet FGD Controls* (1014095, March 2008) and plans to conduct similar analyses for selenium and boron in 2008.

Approach

The project team completed sampling for trace elements across each of the various pollution control devices. This included taking solid samples of the coal and ESP ash, sludge and liquid samples from the each of the inlet and outlet streams of the wet FGD, and flue gas samples at three different locations. The team analyzed each of the samples using the appropriate techniques for a total of 32 different trace, minor, and major elements. Knowing the various flow rates, the team calculated the mass balances for each of the elements.

Keywords

Trace elements

Air toxics

Utilities

Wet flue gas desulfurization

ABSTRACT

The Energy & Environmental Research Center (EERC), in partnership with Babcock & Wilcox (B&W) and with funding from U.S. Department of Energy (DOE), conducting tests to prove that a high level of mercury control (>90%) can be achieved at a power plant burning a high-sulfur eastern bituminous coal.

With funding from the Electric Power Research Institute (EPRI), DOE, and Center for Air Toxic Metals[®] (CATM[®]) Affiliates Program, the EERC completed an additional sampling project to provide data as to the behavior of a number of trace elements across the various pollution control devices, with a special emphasis on the wet flue gas desulfurization (FGD) system.

Results showed that the concentrations of almost all the elements of interest leaving the stack were very low, and a high percentage of the trace elements were captured in the electrostatic precipitator (ESP) (for most, >80%). Although, with a few exceptions, the overall mass balances were generally quite good, the mass balances across the wet FGD were more variable. This is most likely a result of some of the concentrations being very low and also the uncertainties in determining flows within a wet FGD.

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1

INTRODUCTION

The Energy & Environmental Research Center (EERC), in partnership with Babcock & Wilcox (B&W) and with funding from U.S. Department of Energy (DOE), conducted testing to prove that a high level of mercury control (>90%) can be achieved at a power plant burning a high-sulfur eastern bituminous coal. An additional sampling project to provide data regarding a number of trace elements was added to the DOE testing with funding from the Electric Power Research Institute (EPRI), DOE, and Center for Air Toxic Metals[®] (CATM[®]) Affiliates. The trace element testing was conducted over a 5-day period during a 30-day evaluation of B&W's wet flue gas desulfurization (FGD) mercury reemission additive. The additional project was designed to provide data as to the behavior of a number of trace elements across the various pollution control devices with a special emphasis on the wet FGD system.

Previous sampling completed by the EERC and others⁽¹⁻³⁾ has shown that air pollution control devices can have a significant impact on mercury and other trace elements. Selective catalytic reduction (SCR) can substantially increase the percentage of oxidized mercury (Hg^{2+}) which can then be removed by a wet FGD system. Depending on the coal, a percentage of the mercury is also bound with particulate matter and is, therefore, removed by the electrostatic precipitator (ESP). In addition to oxidizing mercury, SCR catalysts will also oxidize SO_2 to SO_3 . As the temperature of the flue gas decreases, the SO_3 reacts with water vapor to form an acid aerosol that is not captured by the FGD. The acid aerosol is both an emission problem and can cause excessive corrosion of ductwork and piping. The ESP also readily captures most of the trace elements of interest. The emission of these trace elements is then directly related to the overall particulate collection efficiency of the ESP. However, in addition to mercury, several trace elements may have a vapor state. These include selenium, subsulfide species of arsenic and nickel, and halogens.

2

PROJECT GOAL AND OBJECTIVE

Specific objectives of the work were as follows:

- Determine the multimedia fate of trace elements in a power plant with an SCR and wet FGD system.
- Determine the mercury speciation and removal across the air pollution control devices.
- Provide an overall trace metal balance for the plant.

3

DESCRIPTION OF POWER PLANT AND TEST UNIT

The power plant that was tested, has three active units. Both the DOE mercury control project and trace element project were conducted on the same unit. The unit is configured as follows:

Coal	Medium- to high-sulfur eastern bituminous.
Boiler	The test unit is a 530-MW wall-fired boiler. However, for this test, only half the flue gas was sampled.
NO _x	Low-NO _x burners and SCR. The SCR has Hitachi plate catalysts.
Particulate	Cold-side ESPs.
SO ₂	Limestone-forced oxidation (LSFO) wet FGD.

Also, the trace element sampling was conducted during a 30-day test of B&W's wet FGD reemission additive, which was added to the FGD slurry to prevent elemental mercury reemission. A schematic of the unit is shown in Figure 3-1.

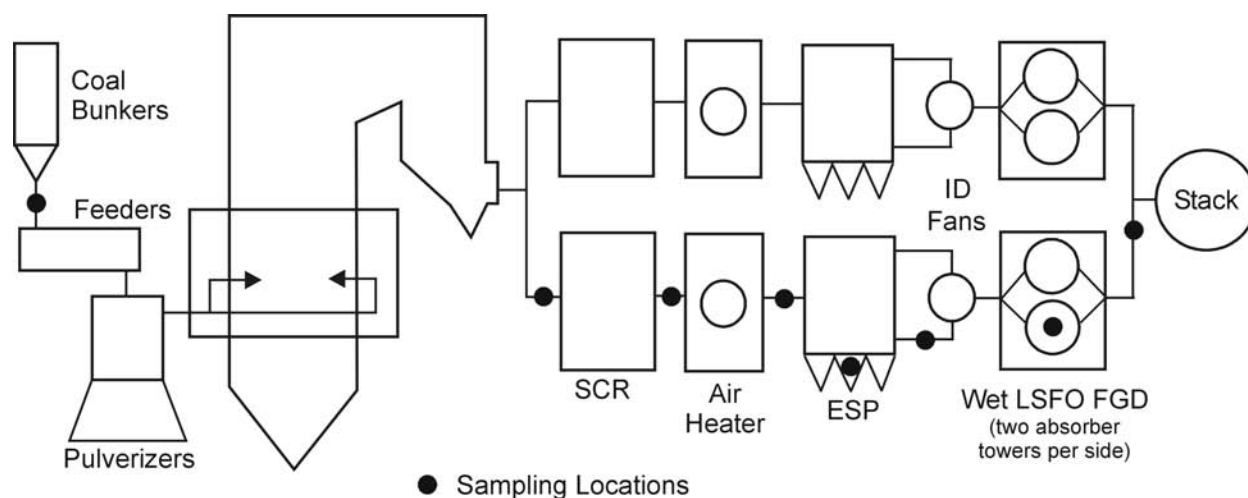


Figure 3-1
Schematic of the Test Unit

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SAMPLING AND ANALYTICAL METHODS

Table 4-1 provides a list of the elements that were of interest for this project. This list includes both major and minor trace elements. For purposes of this report, the term trace elements is used to describe both groups. As shown in Table 4-1, all samples were analyzed using inductively coupled plasma–mass spectroscopy (ICP–MS). The solid samples were also analyzed using XRF (x-ray fluorescence). In addition, all the samples were analyzed for halogen anions, chlorides, fluorides, and bromides using ion chromatography (IC). With the exception of the continuous mercury monitor (CMM) located at the wet FGD outlet, which used cold-vapor atomic fluorescence spectroscopy, all mercury samples were analyzed using cold-vapor atomic adsorption spectroscopy (CVAAS).

Table 4-1
Elements of Interest

Element	Analysis Method
Aluminum (Al)	XRF and ICP–MS
Arsenic (As)	ICP–MS
Antimony (Sb)	ICP–MS
Barium (Ba)	XRF and ICP–MS
Beryllium (Be)	ICP–MS
Boron (B)	ICP–MS
Bromine (Br)	IC
Cadmium (Cd)	ICP–MS
Calcium (Ca)	XRF
Chlorine (Cl)	IC
Cobalt (Co)	ICP–MS
Chromium (Cr)	XRF and ICP–MS
Copper (Cu)	XRF and ICP–MS
Fluorine (F)	IC
Iron (Fe)	XRF and ICP–MS
Lead (Pb)	ICP–MS
Mercury (Hg)	CVAAS
Molybdenum (Mo)	ICP–MS

Table 4-1 (continued)
Elements of Interest

Element	Analysis Method
Nickel (Ni)	XRF and ICP–MS
Magnesium (Mg)	XRF
Manganese (Mn)	XRF and ICP–MS
Phosphorus (P)	XRF
Potassium (K)	XRF
Selenium (Se)	ICP–MS
Silicon (Si)	XRF
Silver (Ag)	ICP–MS
Sodium (Na)	XRF
Strontium (Sr)	XRF and ICP–MS
Thallium (Tl)	ICP–MS
Titanium (Ti)	XRF and ICP–MS
Vanadium (V)	XRF and ICP–MS
Zinc (Zn)	XRF and ICP–MS

The flue gas samples that were collected are shown in Table 4-2 and solid/liquid samples in Table 4-3. The wet FGD samples were filtered in the field, and both the solid and liquid fractions were analyzed. The percent solids in each sample were determined.

Table 4-2
Flue Gas-Sampling Parameters

Sampling Location	Ontario Hydro (OH) Method¹	EPA² Method 29	EPA Method 26A	CMM³	Sorbent Traps^{3,4}
SCR Inlet	3		3		
SCR Outlet	3		3		
ESP Inlet		3	3		
ESP Outlet		3	3	1	4
Wet FGD Outlet		3	3	1	4

¹ ASTM International D6784-02.

² U.S. Environmental Protection Agency.

³ Part of the DOE program.

⁴ Sorbent traps were used as specified in EPA Method 30B.

Table 4-3
Analysis Completed on Solid and Liquid Samples

	Hg	Halogen Anions	Trace Elements ¹	Major Elements ²	Proximate	Ultimate	LOI ³ Carbon
<i>Solid Samples</i>							
Coal	X	X	X	X	X	X	
ESP Hopper Ash	X	X	X	X			X
Limestone	X	X	X	X			
Gypsum	X	X	X	X			
FGD Sludge Solids	X	X	X	X			
<i>Liquid Samples</i>							
Reaction Tank	X	X	X	X			
Hydroclone Overflow	X	X	X	X			
Hydroclone underflow	X	X	X	X			
Cake Wash	X	X	X	X			
<i>Sample Filters</i>							
OH Method	X	X					
EPA Method 29	X		X	X			
EPA Method 26A		X					
<i>Sorbent Traps</i>	X						

¹ Trace elements include Ag, Ba, Cd, Cr, Cu, Ni, Pb, Zn, Sb, Be, Se, Sr, Co, Mo, Tl, and Ti.

² Major elements include Ca, Na, Si, Al, Fe, Mg, K, P, Cr, V, Ni, Zn, and Mn.

³ Loss on ignition.

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RESULTS AND DISCUSSIONS

Flue Gas Sampling

Particulate Sampling

Although not a compliance-type sample (the duct was not traversed, and the condensable fraction was not measured), dust loading was measured as part of the mercury and trace element sampling that was conducted. The results are shown in Table 5-1. It should be noted that the OH samples were conducted earlier under the DOE project, compared to the EPA Method 29 samples which were part of the trace element study. Between the two sampling times, there appeared to be a change in coal. The ash content was considerably higher in the coal fired, 12.5% compared to 9.5%. As can be seen in Table 5-1, the overall particulate removal was high, >99.9%, but the removal across the ESP was rather low.

Table 5-1
Particulate Removal

Sample	ESP Inlet, gr/dscf	ESP Outlet, gr/dscf	FGD Outlet, gr/dscf	ESP Removal, %	Total Removal, ^a %
OH ^b	3.8543	—	0.0428	—	99.89
OH ^b	2.6887	—	0.0242	—	99.10
OH ^b	3.3292	—	0.0006	—	99.98
OH ^b	2.9187	—	0.0020	—	99.93
Method 29 ^c	1.8785	0.1846	0.0030	90.17	99.84
Method 29 ^c	1.7534	0.0806	0.0001	95.40	99.99
Method 29 ^c	2.2855	0.0740	0.0001	96.75	99.99

a Total removal is defined from the ESP inlet to the FGD outlet.

b Samples taken during 6/25/07 to 6/27/07.

c Samples taken during 9/25/07 to 9/28/07.

Mercury

OH sampling was conducted across the SCR to quantify changes to mercury speciation. The speciated mercury values are provided in Table 5-2, and the data are presented graphically in Figure 5-1. As indicated in Figure 5-1, the proportions of Hg^{2+} and particulate-bound mercury did increase across the SCR, while the total mercury content remained consistent. Total mercury concentrations agreed fairly well with values calculated from the coal feed. The actual sampling results for the wet chemistry methods (OH, EPA Method 29, and EPA Method 26A) measurements are present in Appendix A – C.

Table 5-2
OH Results across the SCR during the Long-Term Mercury Test

Sample	SCR Inlet (dry and 3% O_2), $\mu\text{g}/\text{m}^3$				SCR Outlet (dry and 3% O_2), $\mu\text{g}/\text{m}^3$			
	$\text{Hg}(\text{p})$	Hg^{2+}	Hg^0	$\text{Hg}(\text{total})$	$\text{Hg}(\text{p})$	Hg^{2+}	Hg^0	$\text{Hg}(\text{total})$
9/25/07	0.27	9.79	5.89	15.95	1.29	13.49	2.31	17.08
9/26/07 (1)	0.24	6.80	6.19	13.24	0.89	11.17	1.92	13.98
9/26/07 (2)	0.20	4.79	5.80	10.79	0.60	9.95	1.12	11.68

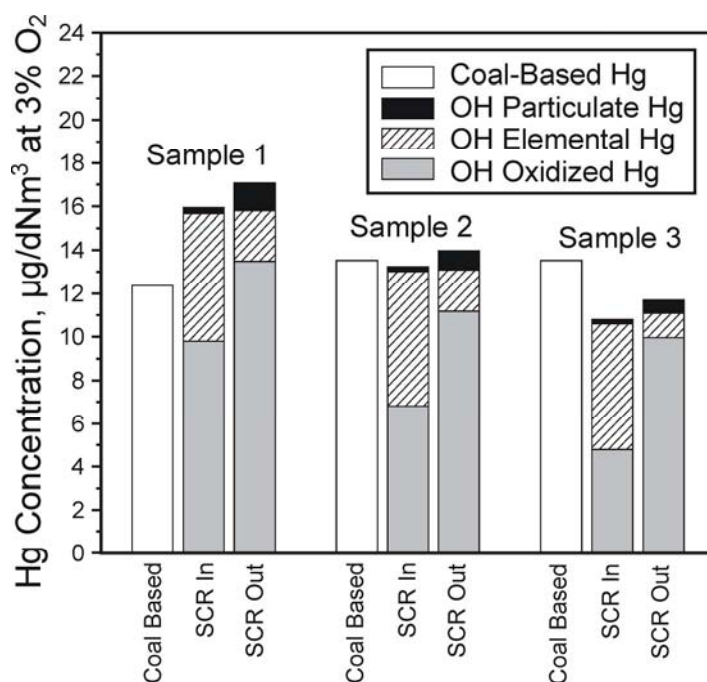


Figure 5-1
Comparison of Mercury Speciation at the SCR Inlet and Outlet during the Longer-Term Test

CMM data were collected at the ESP outlet and the FGD outlet as part of the DOE field test. Hourly averaged data for the entire long-term test are plotted in Figure 5-2, along with the calculated mercury removal between the ESP outlet and FGD outlet. EPA Method 30B samples were also taken periodically at both locations to confirm the total gas-phase mercury concentrations reported by the CMMs. A summary of EPA Method 30B sampling results and the corresponding averaged CMM data are provided in Table 5-3. There was very good agreement between the CMMs and the sorbent traps.

Halogens

Gas-phase halogen measurements using EPA Method 26A were conducted at five locations: the SCR inlet and outlet, the ESP inlet and outlet, and the FGD outlet. Chloride, fluoride, and bromide flue gas concentrations are summarized in Table 5-4. Chlorides and fluorides were detected at all locations upstream of the FGD, with both species effectively removed by the wet FGD. Bromides were not detected in significant quantities at any sampling location.

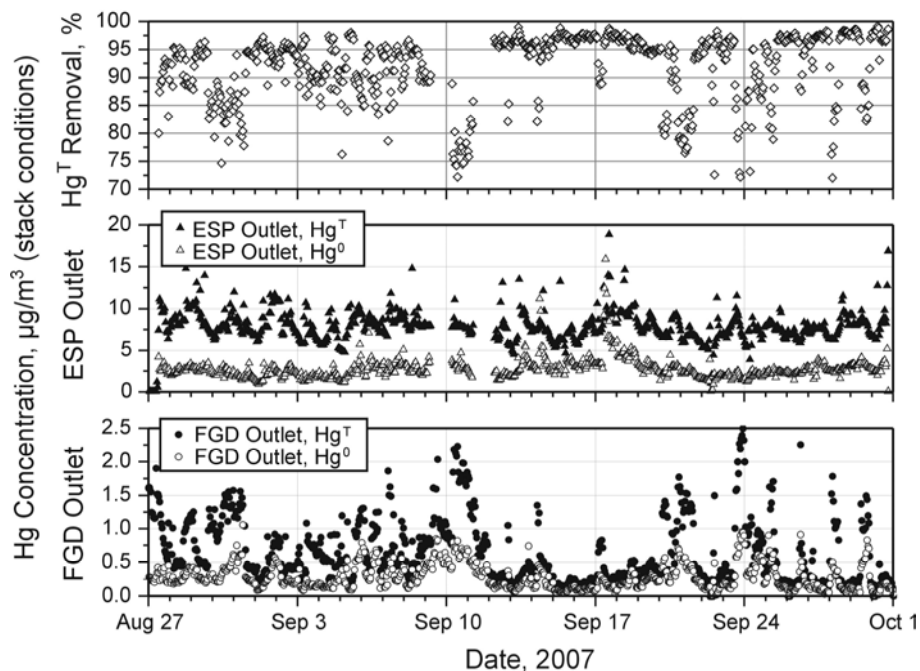


Figure 5-2
Hourly Averaged CMM-Based Mercury Removal (ESP Outlet to FGD Outlet) and CMM Data during the Long-Term Test

Table 5-3
Longer-Term Mercury-Sampling Summary

Date	ESP Outlet Hg, $\mu\text{g}/\text{dNm}^3$ at 3% O_2		FGD Outlet Hg, $\mu\text{g}/\text{dNm}^3$ at 3% O_2		Hg Removal, %	
	Method 30B	CMM Average	Method 30B	CMM Average	Method 30B	CMM
8/28/07	12.01	12.09	0.64	0.73	94.7	93.9
8/28/07	11.91	11.19	1.53	1.47	87.1	86.9
8/29/07	12.50	12.65	1.08	0.74	91.3	94.2
8/29/07	10.84	10.95	0.61	0.68	94.4	93.8
9/24/07	11.31	9.85	1.37	1.12	87.9	88.6
9/26/07	10.12	9.97	0.34	0.24	96.6	96.9
9/27/07	11.14	10.05	0.45	0.29	95.9	97.1
9/27/07	12.04	10.29	0.37	0.27	96.9	97.4

Flue Gas Trace Element Sampling

Gas-phase trace element sampling was performed using EPA Method 29 at three locations: the ESP inlet and outlet and the FGD outlet. Three samples were collected at each location, and each sample was analyzed for the 23 trace elements of interest (previously shown in Table 4-1).

Averages for each set of three samples are presented in Table 5-5. The total element concentrations presented in Table 5-5 include gas-phase and particulate-bound species; the percentage of each element detected as a particulate is indicated. All of these elements with the exception of boron, mercury, and selenium, were removed at >80% by the ESP, with most being over 90%. The total removal (across ESP and wet FGD) was nearly 100% for almost all the elements. In general, the removal of most trace elements by the ESP was similar to particulate collection efficiency. The glaring exception was selenium, however, the flue gas measurements of selenium are in question since the selenium analyses of the coal and the FGD solid and liquid streams suggest that the selenium entering the system was captured by the wet FGD.

Solids and Liquid Sampling

As previously presented in Table 4-3, samples were collected from the following process streams: coal into the system, ESP ash out, gypsum out, limestone in, gypsum cake wash water out, and FGD hydroclone streams—reaction tank in, underflow out, and overflow out. Three samples of each stream were analyzed.

Table 5-4
Halogen-Sampling Results (based on 3% O₂)

Sample Location/Date	Chloride Conc., ppm	Fluoride Conc., ppm	Bromide Conc., ppm
SCR Inlet Avg.	75.2	18.0	<0.4
1	29.6	5.3	<0.4
2	121.4	29.3	<0.4
3	74.6	19.5	<0.4
SCR Outlet Avg.	117.8	17.7	<0.2
1	142.1	27.8	<0.3
2	121.8	24.3	<0.2
3	89.4	4.0	<0.2
ESP Inlet Avg.	117.8	17.3	<0.5
1	100.9	14.4	<0.6
2	120.8	13.5	<0.5
3	118.2	24.1	<0.4
ESP Outlet Avg.	121.5	21.6	<0.3
1	129.0	22.5	<0.3
2	117.4	20.2	<0.3
3	132.4	22.0	<0.3
FGD Outlet Avg.	1.5	<1.1	<0.3
1	1.2	<1.0	<0.3
2	1.0	<1.0	<0.3
3	2.2	<1.4	<0.4

Table 5-5
Average Flue Gas Concentrations for Selected Elements (3% O₂)

Element	ESP Inlet		ESP Outlet		Wet FGD Outlet		Across ESP	Total
	Total Conc., µg/dNm ³	Particulate-Bound, %	Total Conc., µg/dNm ³	Particulate-Bound, %	Total Conc., µg/dNm ³	Particulate-Bound, %		
Ag	5.14	100	0.392	100	0.0261	5.8	92.4	99.5
Al	557,000	99.6	37,700	96.2	967	39.3	93.2	99.8
As	429	99.6	71.1	91.4	6.07	100	83.4	98.6
B	14,400	54.7	6680	8.7	1380	5.6	53.6	90.4
Ba	5950	99.2	651	95.5	73.4	97.9	89.1	98.8
Be	48.4	99.0	3.80	85.8	0.267	58.6	92.1	99.4
Cd	61.8	99.5	9.17	90.4	1.37	96.7	85.2	97.8
Co	161	99.8	10.4	96.4	0.0777	86.0	93.5	100.0
Cr	1170	99.6	104	91.3	5.74	65.1	91.1	99.5
Cu	405	97.3	42.8	72.8	0.950	91.5	89.4	99.8
Fe	605,000	99.9	31,000	98.9	377	100	94.9	99.9
Hg	11.1	2.5	12.4	0.1	0.650	1.5	-11.7	94.1
Mn	1580	99.0	102	91.5	7.02	38.2	93.5	99.6
Mo	385	99.4	55.7	87.4	7.61	96.2	85.5	98.0
Ni	554	99.6	42.5	91.2	1.45	65.3	92.3	99.7
Pb	327	99.7	35.9	95.2	0.865	100	89.0	99.7
Sb	45.4	99.7	6.09	94.9	0.790	100	86.6	98.3
Se	76.7*	71.7	328*	4.4	88.8*	27.6	-327.6	-15.8
Sr	1340	98.1	91.8	93.3	5.55	53.9	93.1	99.6
Ti	29,100	99.8	1910	97.9	35.4	93.9	93.4	99.9
Tl	65.6	99.6	9.65	90.2	1.46	100	85.3	97.8
V	1850	99.3	178	88.2	12.9	92.8	90.4	99.3
Zn	2510	93.9	452	61.5	32.9	49.9	82.0	98.7

*The flue gas measurements of selenium are in question based on an overall mass balance. Refer to the text for discussion.

Coal and ESP Hopper Ash

The coal feed data corresponding to the sampling days are presented in Table 5-6. The coal sampled during the long-term test had somewhat higher moisture and lower ash content than the coal sampled during the baseline and parametric phases of the DOE test.

The average LOI for the ESP hopper ash during the trace element sampling was determined to be 1.49%. The trace element analysis for the coal and ESP hopper ash is provided in Table 5-7. All the coal and ash data are presented in Appendix B.

Wet FGD Samples

In addition to the coal and ESP hopper ash samples, major and trace element analyses were conducted on three samples of each of the following wet FGD process streams: gypsum out, limestone in, gypsum cake wash water out, and FGD thickener streams—reaction tank in, underflow out, and overflow out. Results are present in Tables 5-8 and 5-9. As shown in Table 5-8, each of the samples from wet FGD hydroclone streams were subdivided into solid and liquid fractions and analyzed separately. The solid portion was analyzed using both ICP–MS and XRF and the liquid portions using only ICP–MS. The wet FGD slurry data is provided in Appendix E.

Table 5-6
Coal Data during Trace Element Sampling*

Sample Date	1	2	3	4	Average	Earlier Average
Proximate Analysis						
Moisture, %	12.2	11.1	8.5	8.6	10.1	3.63
Volatile Matter, %	35.15	34.72	35.55	35.44	35.22	33.94
Fixed Carbon, %	43.64	44.68	45.03	44.61	44.49	45.23
Ash, %	9.00	9.50	10.92	11.36	10.20	13.19
Ultimate Analysis						
Hydrogen, %	5.65	5.31	5.31	5.33	5.40	4.76
Carbon, %	70.77	65.47	69.98	73.04	69.82	70.69
Nitrogen, %	1.30	1.38	1.38	1.17	1.31	1.36
Sulfur, %	2.83	3.20	3.42	3.03	3.12	2.98
Oxygen, %	10.44	15.15	9.00	6.07	10.17	7.03
Heating Value, Btu/lb	11,041	11,215	11,442	11,314	11,253	11,799

*All values on an as-received basis.

Table 5-7
Coal and ESP Ash Major and Trace Element Concentrations

Analyzed Using ICP–MS			Analyzed Using XRF		
Element	Dry Coal, ppm	ESP Ash, ppm	Element/Oxides	Dry Coal, %	ESP Ash, %
Ag	0.103	1.10	Al ₂ O ₃	2.39	17.4
Al	9980	102,000	BaO	0.0102	0.0967
As	6.57	53.5	CaO	0.470	4.00
B	80.1	1410	Cr	0.00817	0.0667
Ba	103	892	Cu	0.00117	0.0100
Be	1.35	10.8	Fe ₂ O ₃	2.00	18.1
Cd	0.437	6.70	K ₂ O	0.309	2.49
Co	4.18	34.8	MgO	0.186	1.28
Cr	21.6	190	MnO	0.00619	0.0500
Cu	15.6	78.5	Na ₂ O	0.0784	0.597
Fe	13,400	141,000	NiO	0.00158	0.0133
Hg	0.114	0.0226	P ₂ O ₅	0.0237	0.237
Mn	30.0	318	SiO ₂	5.63	44.5
Mo	6.12	60.8	SO ₃	0.435	1.19
Ni	11.5	113	SrO	0.00350	0.0300
Pb	5.73	57.3	TiO ₂	0.105	0.903
Sb	0.846	6.75	V ₂ O ₅	0.00825	0.0733
Se	2.33	4.94	Zn	0.00430	0.0367
Sr	24.6	221	Sum	11.67 ¹	91.07
Ti	503	4550			
Tl	1.01	8.33			
V	43.4	379			
Zn	51.0	397			
F	130	30.0			
Cl	1020	20.8			
Br	7.81	0			

¹The corresponding average dry ash content for the coal was 11.68%.

Table 5-8
Trace Element Concentrations in Wet FGD Samples

Element	Gypsum (dry), ppm	Limestone, ppm	Underflow Avg. Solids: 29.7%		Overflow Avg. Solids: 4.94%		Reaction Tank Avg. Solids: 11.7%		Cake Wash Avg. Solids: 0.267%	
			Solids, ppm	Liquids, µg/L ¹	Solids, ppm	Liquids, µg/L ¹	Solids, ppm	Liquids, µg/L ¹	Solids, ppm	Liquids, µg/L ¹
Ag	0	0	0	0.160	0	0.430	0.820	0.315	0	0
Al	2920	782	1730	647	7560	3270	2920	4830	10,700	768
As	1.65	0	0.475	0	5.21	0	1.70	0	5.3	3.67
B	800	915	0	57,200	0	62,200	556	51,600	631	44,500
Ba	25.1	19.4	37.3	104	99.9	147	38.9	149	103	92.6
Be	0	0	0	3.14	0.54	4.50	0	4.00	0.63	2.28
Cd	0	0	0	40.5	0	66.9	0	56.7	1.09	19.3
Co	2.46	4.25	1.8	9.72	2.94	17.3	2.11	13.8	3.08	7.50
Cr	31.4	4.00	39.3	9.78	186	13.9	55.1	10.0	149	9.05
Cu	5.16	3.11	3.53	7.67	11.2	26.2	4.62	21.8	11.5	10.1
Fe	2220	1070	1330	0	5200	0	1920	0	6790	0
Hg	0.270	0	0.38	1.72	0.683	82.6	0.303	59.7	0.041	0.300
Mn	56.0	74.6	40.9	1980	104	4530	33.7	3260	83.5	920
Mo	1.95	0	1.23	59.7	5.56	11.2	2.24	15.6	4.49	89.1
Ni	20.9	34.6	17.4	182	23.3	326	18.8	252	19.4	106
Pb	4.15	0	0.702	0	4.75	0	1.5	0	6.73	0
Sb	0	0	0	4.48	1.1	3.86	0	4.76	1	4.56

¹ Halogen liquid values are given in mg/L.

² Only two of the three measurements are used in these average values.

Table 5-8 (continued)
Trace Element Concentrations in Wet FGD Samples

Element	Gypsum (dry), ppm	Limestone, ppm	Underflow Avg. Solids: 29.7%		Overflow Avg. Solids: 4.94%		Reaction Tank Avg. Solids: 11.7%		Cake Wash Avg. Solids: 0.267%	
			Solids, ppm	Liquids, µg/L ¹	Solids, ppm	Liquids, µg/L ¹	Solids, ppm	Liquids, µg/L ¹	Solids, ppm	Liquids, µg/L ¹
Se	2.92	0	2.8	960	5.22	1220	3.17	893	5.72	667
Sr	531	759	477	8730	533	8430	522	7630	297	7380
Ti	239	1.54	214	5.40	875	8.40	293	8.32	438	3.63
Tl	0	0	0	12.2	0	10.5	0	13.4	1.03	11.2
V	12.0	4.86	8.93	22.1	40.5	20.3	14.3	16.4	33.6	27.4
Zn	30.8	11.2	21	206	44.2	1530	17.8	1450	65.9	34.1
F	323	0	541	15.2 ¹	1080 ²	17.7 ¹	526	17.7 ¹	0	8.40 ¹
Cl	65.0	46.4	0	2200 ¹	171	1950 ^{1,2}	0	1810 ¹	0	287 ¹
Br	0	0	0.714	9.58 ¹	3.63	9.26 ¹	1.51	8.43 ¹	0	1.00 ¹

¹ Halogen liquid values are given in mg/L.

² Only two of the three measurements are used in these average values.

Table 5-9
XRF Analysis of Wet FGD Solids for Major Elements

Element/Oxides	Gypsum, %	Limestone, %	FGD Hydroclone Flows, Solids Fraction			EPA M29 ¹ Filter, %
			Underflow, %	Overflow, %	Reaction Tank, %	
Al ₂ O ₃	1.00	0.900	1.13	2.80	1.37	19.6
BaO	0.0133	0	0.0100	0.0200	0.0133	0.140
CaO	42.2	52.7	41.2	37.9	41.1	4.47
Cr	0.110	0.100	0.110	0.127	0.110	0.0800
Cu	0	0	0	0	0	0.0100
Fe ₂ O ₃	0	0	0	0.543	0	16.8
K ₂ O	0.117	0.103	0.127	0.483	0.177	3.19
MgO	0.507	1.28	0.577	1.00	0.617	1.47
MnO	0.0133	0.0200	0.0100	0.0267	0.0100	0.0600
Na ₂ O	0.0867	0.0733	0.0800	0.110	0.0900	0.660
NiO	0	0	0	0.00667	0	0.0200
P ₂ O ₅	0.0300	0.0333	0.0400	0.0900	0.0433	0.390
SiO ₂	4.37	3.57	5.20	10.5	5.57	49.3
SO ₃	51.4	0	51.3	46.1	50.6	1.71
SrO	0.0600	0.0700	0.0600	0.0633	0.0600	0.0400
TiO ₂	0.0667	0.0600	0.0700	0.140	0.0767	0.990
V ₂ O ₅	0	0	0	0	0	0.0800
Zn	0	0	0	0.00667	0	0.0500
Sum	99.97 ²	58.91 ³	99.91 ²	99.92 ²	99.84 ²	99.06

¹ ESP outlet sampling location.

² The primary solid constituent of these samples was gypsum, CaSO₄ · 2H₂O; however, the excellent closure with CaSO₄ (CaO + SO₃) alone indicates that the water of hydration was not present in these samples and that the gypsum was dehydrated during sample processing.

³ The primary constituent of limestone is CaCO₃; however, CO₂ was not quantified by XRF. When a stoichiometric amount of CO₂ was added (41.4%), the average closure for these samples became 100.37% and the active ingredient, CaCO₃, comprised 94.2% of the sample.

It should be noted that in Table 5-8 the solid samples were never completely separated from the liquid phase, i.e., the solids retained some percentage of moisture. This implies that some of the detected elemental concentrations in the solid fraction were due to this residual liquid. To account for this, a calculated concentration based on the residual moisture content was subtracted from the total concentration present in the solid sample according to Equation 5-1.

$$X_{\text{solid}} = X_{\text{solid as determined}} - X_{\text{liquid}} \left(\frac{\gamma}{1 - \gamma} \right) \quad \text{Eq. 5-1}$$

where X_{solid} is the concentration of element X in the solid fraction, $X_{\text{solid as determined}}$ is the measured concentration in the solid fraction that includes the contribution from the residual liquid, X_{liquid} is the measured elemental concentration in the liquid fraction, and γ is the residual moisture content of the filtered solid fraction.

Mass Balance

To determine the fate of trace elements, the mass flow rate for each element of interest was estimated at several points throughout the unit. For this exercise, the flows were simplified according to the schematic shown in Figure 5-3. Concentration data from the flue gas sampling (Tables 5-4 and 5-7) and the analysis of physical samples (Tables 5-7–5-9) were scaled by the appropriate process flow rate within the plant. Estimates for the magnitude of the key process streams are presented in Table 5-10. The mass flow rate for each element of interest was estimated at 12 locations within the system schematic presented in Figure 5-3. Results of these calculations are provided in Table 5-11. The locations where mass flow rates have been computed are divided into three categories: process inputs, process outputs, and intermediate streams. Details regarding the calculation of these primary flows through the unit are provided in Appendix F, sample calculation.

Mass balances were calculated across the test unit to provide a check of the elemental mass flow rates. The mass balance calculations accounted for the following input and output streams (unless otherwise noted):

Process inputs:

- Coal feed to boiler
- Limestone supply to wet FGD

Process outputs:

- Flue gas out from the FGD
- Collected ESP ash
- Gypsum product out
- Chlorides blowdown
- Discarded cake wash water

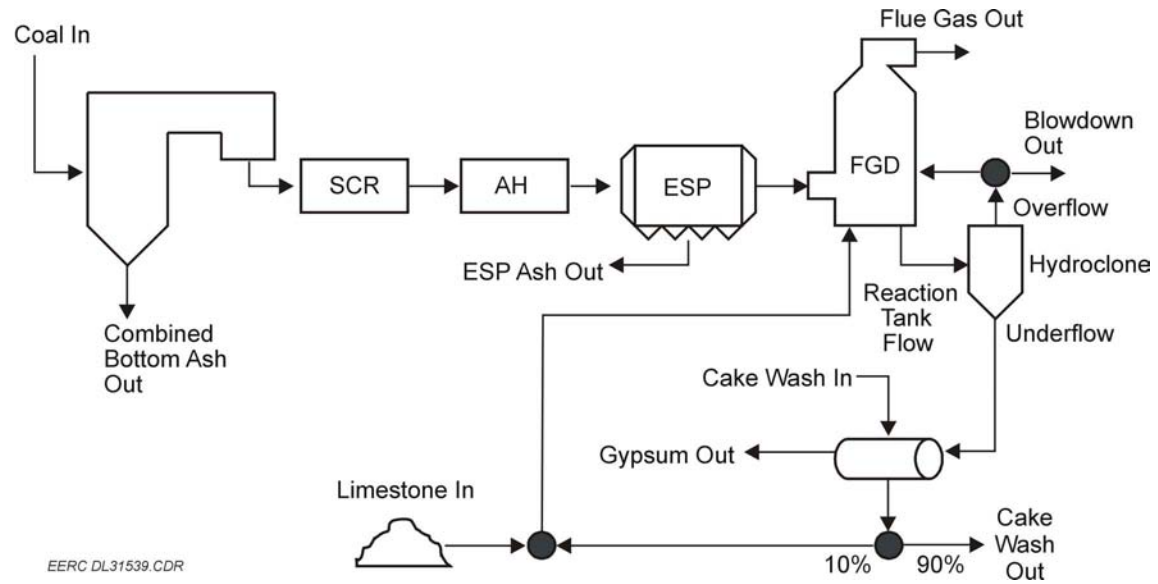


Figure 5-3
Simplified Schematic of the Test Unit

Table 5-10
Primary Material Stream Flow Rates for Mass Balance Calculations

Material Stream	Flow Rate
Coal Feed In (dry)	326,000 lb/hr
Flue Gas Flow Rate	524 x 10 ⁵ dscf/hr at 3% O ₂
ESP Ash Out	29,400 lb/hr
Limestone In	37,600 lb/hr
Gypsum Out	57,100 lb/hr
Reaction Tank Flow to Hydroclone	Solids: 84,000 lb/hr Liquids: 701,000 lb/hr
Underflow from Hydroclone	Solids: 57,100 lb/hr Liquids: 139,000 lb/hr
Overflow from Hydroclone	Solids: 28,200 lb/hr Liquids: 561,000 lb/hr
Blowdown Out (overflow composition)	Solids: 1270 lb/hr Liquids: 25,400 lb/hr
Cake Wash Water Out	Solids: 2530 lb/hr Liquids: 947,000 lb/hr

Table 5-11
Estimated Elemental Concentrations of Process Streams

	Process Input, lb/hr		Process Output, lb/hr					Intermediate Streams, lb/hr				
	Coal	Limestone	ESP Ash	FGD Outlet (stack)	Gypsum	Blowdown	Cake Wash	ESP Inlet	ESP Outlet	Reaction Tank Flow	Overflow	Underflow
Ag	0.0336	0	0.0323	0.0000853	0	0.0000109	0	0.0168	0.00128	0.0691	0.000241	0.0000222
Al	3250	29.4	3010	3.16	167	9.68	27.9	1820	123	248	215	99
As	2.14	0	1.57	0.0198	0.0941	0.00661	0.0169	1.4	0.233	0.143	0.147	0.0271
B	26.1	34.4	41.4	4.51	45.7	1.58	43.7	47.2	21.8	82.9	34.9	7.95
Ba	33.5	0.73	26.2	0.24	1.43	0.131	0.347	19.4	2.13	3.37	2.9	2.14
Be	0.439	0	0.318	0.000874	0	0.0008	0.00375	0.158	0.0124	0.0028	0.0177	0.000436
Cd	0.143	0	0.197	0.00447	0	0.0017	0.0211	0.202	0.03	0.0397	0.0375	0.00563
Co	1.36	0.16	1.02	0.000254	0.14	0.00417	0.0149	0.527	0.0342	0.187	0.0925	0.104
Cr	7.05	0.15	5.58	0.0188	1.8	0.237	0.386	3.83	0.34	4.63	5.25	2.24
Cu	5.09	0.117	2.31	0.00311	0.295	0.0149	0.0386	1.32	0.14	0.403	0.332	0.203
Fe	4360	40.1	4150	1.23	126	6.61	17.2	1980	102	161	147	75.7
Hg	0.0373	0	0.00126	0.00213	0.0154	0.00296	0.000388	0.0364	0.0406	0.0673	0.0656	0.022
Mn	9.79	2.8	9.35	0.0229	3.2	0.247	1.08	5.16	0.333	5.11	5.47	2.61
Mo	2	0	1.79	0.0249	0.112	0.00735	0.0957	1.26	0.182	0.199	0.163	0.0785
Ni	3.75	1.3	3.33	0.00474	1.2	0.0379	0.15	1.81	0.139	1.76	0.841	1.02
Pb	1.87	0	1.68	0.00283	0.237	0.00603	0.017	1.07	0.117	0.126	0.134	0.0401

Table 5-11 (continued)
Estimated Elemental Concentrations of Process Streams

	Process Input, lb/hr		Process Output, lb/hr					Intermediate Streams, lb/hr				
	Coal	Limestone	ESP Ash	FGD Outlet (stack)	Gypsum	Blowdown	Cake Wash	ESP Inlet	ESP Outlet	Reaction Tank Flow	Overflow	Underflow
Sb	0.276	0	0.199	0.00258	0	0.00149	0.00685	0.148	0.0199	0.00334	0.0331	0.000623
Se	0.759	0	0.145	0.29	0.167	0.0375	0.646	0.251	1.07	0.892	0.83	0.293
Sr	8.01	28.5	6.5	0.0182	30.3	0.891	7.74	4.37	0.3	49.2	19.8	28.5
Ti	164	0.0579	134	0.116	13.6	1.11	1.11	95	6.24	24.6	24.7	12.2
Tl	0.328	0	0.245	0.00479	0	0.000267	0.0132	0.214	0.0316	0.0094	0.00591	0.0017
V	14.1	0.183	11.1	0.0422	0.686	0.0519	0.111	6.05	0.581	1.21	1.15	0.513
Zn	16.6	0.419	11.7	0.108	1.76	0.0949	0.199	8.21	1.48	2.51	2.1	1.23
F	42.4	0	0.882	0	18.5	1.82	7.95	44.8	55.7	56.6	40.4	33
Cl	333	1.75	0.613	8.75	3.71	49.7	272	549	609	1270	1100	306
Br	2.55	0	0	0	0	0.24	0.947	0	0	6.04	5.3	1.37

The general formula used to compute the closure of each mass balance is provided as Equation 5-2.

$$\text{Closure} = \frac{\text{Element content of process output streams}}{\text{Element content of process input streams}} \times 100 \% \quad \text{Eq. 5-2}$$

Mass Balance around Entire System (Coal to Stack)

Table 5-12 presents three total mass balance scenarios. The equations for calculating the mass balance for each scenario are shown in Equations 5-3 – 5-5, respectively. In each equation, X is the mass flow rate for the trace element of interest for each of the processes. Scenario 1 (Equation 5-3) is the simplest, as it assumes nothing beyond the calculated process inputs and outputs of Table 5-11. However, inorganic residuals from the coal also leave the system from the boiler and at various heat exchanger dust collection hoppers before the ESP. These streams are collectively represented by the bottom ash stream in Figure 5-3. No analysis was performed on this stream, but it is responsible for element content leaving the system.

Table 5-12
Mass Balance Closure Values for Selected Elements of Interest

Element	Scenario 1 (no bottom ash assumed) Closure, %	Scenario 2 (calculated bottom ash¹) Closure, %	Scenario 3 (calculated bottom ash with underflow²) Closure, %	Trace Element Removal (coal to stack), %
Ag	96.3	116	116	99.75
Al	98	116	113	99.90
As	79.9	94.5	90.6	99.07
B	226	240	104	82.72
Ba	83	98.4	99.4	99.28
Be	73.6	88.1	87.3	99.81
Cd	157	185	174	99.87
Co	77.6	91	87.7	99.89
Cr	111	127	128	99.73
Cu	51.1	59.9	57.4	99.94
Fe	97.7	117	115	99.97
Hg	59.4	60.1	76.5	94.29
Mn	110	125	112	99.77
Mo	102	119	113	98.76

Table 5-12 (continued)
Mass Balance Closure Values for Selected Elements of Interest

Element	Scenario 1 (no bottom ash assumed) Closure, %	Scenario 2 (calculated bottom ash ¹) Closure, %	Scenario 3 (calculated bottom ash with underflow ²) Closure, %	Trace Element Removal (coal to stack), %
Ni	93.4	107	100	99.87
Pb	104	122	111	99.85
Sb	75.9	90.3	88.1	99.06
Se	170	173	103	61.79
Sr	124	128	101	99.77
Ti	91.4	108	106	99.93
Tl	80.3	95.3	91.7	98.54
V	83.9	99.4	97.4	99.70
Zn	81.1	94.8	90.5	99.35
F	68.7	69.1	84.1	100.0
Cl ³	100	100	99.9	97.37
Br	46.6	46.6	58.1	100.0

¹ The bottom ash flow calculation assumes that there is approximately a 80%–20% split between fly ash and bottom ash. The composition of the bottom ash was assumed to be equal to that of the ESP ash.

² This closure calculation includes the same bottom ash assumption as described in Note 1 but replaces the gypsum and cake wash outlet streams with the mass flow rates equivalent to 100% of the hydroclone underflow solids stream and 90% of the underflow liquids.

³ A mass balance for chlorides was used to estimate the magnitude of the blowdown stream; therefore, closure for the no-bottom ash calculation was artificially imposed to be 100%.

$$Closure, \% = \frac{X_{ESPAsh} + X_{Stack} + X_{Gypsum} + X_{CakeWashOut} + X_{Blowdown}}{X_{Coal} + X_{Limestone}} \times 100 \quad \text{Eq. 5-3}$$

$$Closure, \% = \frac{X_{ESPAsh} + X_{Stack} + X_{Gypsum} + X_{CakeWashOut} + X_{Blowdown} + X_{BottomAsh}}{X_{Coal} + X_{Limestone}} \times 100 \quad \text{Eq. 5-4}$$

$$Closure, \% = \frac{X_{ESPAsh} + X_{Stack} + (X_{UnderflowSolids} + 0.9X_{UnderflowLiquids}) + X_{Blowdown} + X_{BottomAsh}}{X_{Coal} + X_{Limestone}} \times 100 \quad \text{Eq. 5-5}$$

To account for this outlet, Scenario 2 in Table 5-12 assumes that a fraction (20%) of the ash entering with the coal was removed as bottom ash, and this stream was added as a process output in Scenario 2 as is shown in Equation 5-4. Because of the lack of a better estimate, the composition of the bottom ash stream was assumed to be the same as the ESP ash.

The third mass balance (Equation 5-5) scenario in Table 5-12 uses the same assumptions regarding bottom ash as the second scenario, but it eliminates the unknowns associated with the cake wash water inlet to the system.

A significant amount of liquid enters the system as the gypsum cake wash water. The cake wash water is supplied from the cooling tower blowdown stream for Units 3 and 4. For the mass balance calculations, the trace element content of this stream was considered negligible and was assumed to be zero for the elements of interest. However, this may not be a valid assumption for constituents that can concentrate in the cooling tower water such as chlorides. If there were significant chloride levels in the wash water, then the magnitude of the cake wash outlet stream would be underestimated and would bias all of the elemental mass flow rates at this location. To minimize this unknown, the process output streams of gypsum production and the cake wash water outlet were replaced in the third scenario by the hydroclone underflow stream. It should be noted that, in Figure 5-3, the underflow stream is almost totally discarded from the system, either in the form of gypsum or liquid diluted with cake wash water. With a couple of exceptions, the mass balances shown in Table 5-12 appear to be reasonable. Cadmium was somewhat high, and copper and bromine were low.

As shown in Table 5-12 the actual amount of each of these trace elements leaving the stack is very low. With the exception of selenium and boron, the removal across the combination of ESP and wet FGD was >90% and for most >99%.

Mass Balance across the ESP

For most of the elements of interest, the removal across the ESP was >80%, as shown in Figure 5-4, which is the ESP removal for each element based on the measured concentration entering with the coal and that was detected leaving in the ESP ash. The exceptions were the halogens, mercury, selenium, and copper. Copper is an anomaly as the mass balance was also very low, as shown in Table 5-12. It may have been a result of how the ESP ash was sampled. Only the ash from the first field was collected. The overall collection efficiency of the ESP for all of the trace elements might have been a bit higher if all the field samples were collected and apportioned. These results based on the coal input were very similar to those obtained based on the flue gas measurements previously shown in Table 5-5.

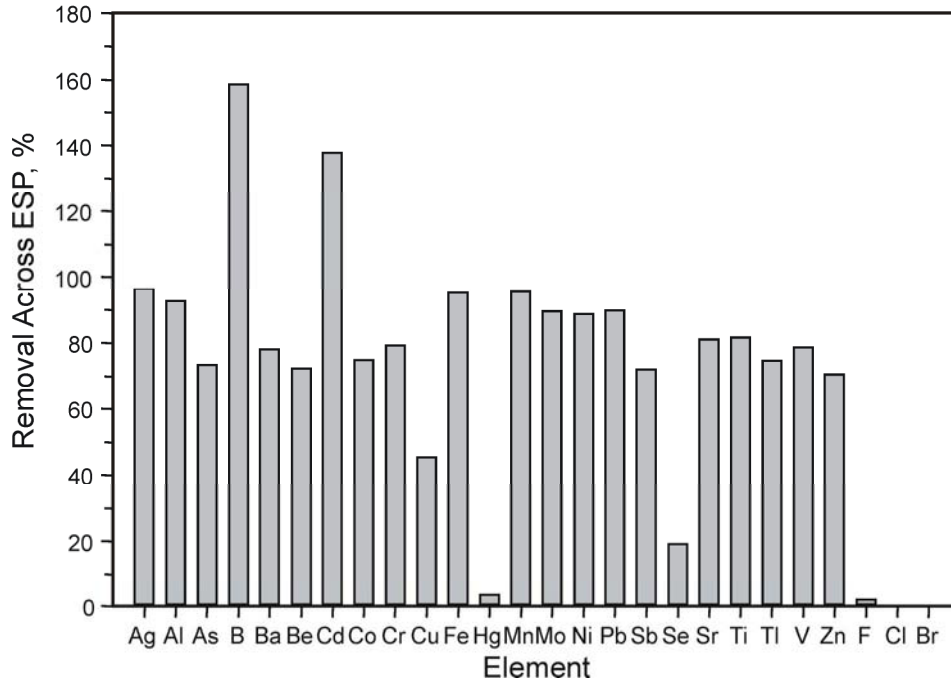


Figure 5-4
Trace Element Removal across the ESP, based on Coal and ESP Ash Sampling

Mass Balance around Wet FGD

A mass balance for the elements of interest was completed around the scrubber, and the results are shown in Table 5-13. The mass balance was again calculated in two ways as shown in Equations 5-6 and 5-7. The first method (Equation 6) used the sum of the concentrations of trace elements from the cake wash and gypsum and flue gas as the total outlet concentration. The second method (Equation 5-7) used the hydroclone underflow concentration as a replacement for the cake wash and gypsum in an effort to minimize the unknown magnitude of cake wash water into the system. There does not appear to be any consistent pattern, and which calculation gives better results depends on the element of interest.

$$Closure, \% = \frac{X_{Stack} + X_{Gypsum} + X_{CakeWashOut} + X_{Blowdown}}{X_{Flue\ Gas\ ESP\ Out} + X_{Limestone}} \times 100 \quad \text{Eq. 5-6}$$

$$Closure, \% = \frac{X_{Stack} + X_{Underflow\ Total} + X_{Blowdown}}{X_{Flue\ Gas\ ESP\ Out} + X_{Limestone}} \times 100 \quad \text{Eq. 5-7}$$

Table 5-13
Flow Stream Values and Mass Balances for the FGD System

Element	Inlet, lb/hr		Outlet, lb/hr					Mass Balance, %	
	Flue Gas ¹	Limestone	Flue Gas ²	Blowdown	Gypsum	Cake Wash	Underflow	Gypsum + Cake Wash ³	Underflow ⁴
Ag	0.00128	0	0.0000853	0.0000109	0	0	0.0000222	7.51	9.25
Al	123	29.4	3.16	9.68	167	27.9	99	136	73.2
As	0.233	0	0.0198	0.00661	0.0941	0.0169	0.0271	59.1	23
B	21.8	34.4	4.51	1.58	45.7	43.7	7.95	170	24.9
Ba	2.13	0.73	0.24	0.131	1.43	0.347	2.14	75.3	88
Be	0.0124	0	0.000874	0.0008	0	0.00375	0.000436	43.6	17
Cd	0.03	0	0.00447	0.0017	0	0.0211	0.00563	90.8	39.4
Co	0.0342	0.16	0.000254	0.00417	0.14	0.0149	0.104	82.1	55.8
Cr	0.34	0.15	0.0188	0.237	1.8	0.386	2.24	496	509
Cu	0.14	0.117	0.00311	0.0149	0.295	0.0386	0.203	137	85.9
Fe	102	40.1	1.23	6.61	126	17.2	75.7	107	59
Hg	0.0406	0	0.00213	0.00296	0.0154	0.000388	0.022	51.6	66.7
Mn	0.333	2.8	0.0229	0.247	3.2	1.08	2.61	145	91.9
Mo	0.182	0	0.0249	0.00735	0.112	0.0957	0.0785	131	60.7
Ni	0.139	1.3	0.00474	0.0379	1.2	0.15	1.02	96.3	73.8
Pb	0.117	0	0.00283	0.00603	0.237	0.017	0.0401	224	41.7
Sb	0.0199	0	0.00258	0.00149	0	0.00685	0.000623	54.8	23.6
Se	1.07	0	0.29	0.0375	0.167	0.646	0.293	106	57.9

¹ Flue gas concentration was measured at the ESP outlet/FGD inlet location.

² Flue gas concentration was measured at the FGD outlet location.

³ Closure was computed using the flow rates computed for the gypsum and cake wash outlet streams.

⁴ Closure was computed by replacing the gypsum and cake wash streams with the underflow flow rate.

Table 5-13 (continued)
Flow Stream Values and Mass Balances for the FGD System

Element	Inlet, lb/hr		Outlet, lb/hr					Mass Balance, %	
	Flue Gas ¹	Limestone	Flue Gas ²	Blowdown	Gypsum	Cake Wash	Underflow	Gypsum + Cake Wash ³	Underflow ⁴
Sr	0.3	28.5	0.0182	0.891	30.3	7.74	28.5	135	102
Ti	6.24	0.0579	0.116	1.11	13.6	1.11	12.2	254	213
Tl	0.0316	0	0.00479	0.000267	0	0.0132	0.0017	57.9	21.4
V	0.581	0.183	0.0422	0.0519	0.686	0.111	0.513	117	79.5
Zn	1.48	0.419	0.108	0.0949	1.76	0.199	1.23	114	75.3
F	55.7	0	0	1.82	18.5	7.95	33	50.7	62.5
Cl	609	1.75	8.75	49.7	3.71	272	306	54.7	59.6
Br	0	0	0	0.24	0	0.947	1.37	0	0

¹ Flue gas concentration was measured at the ESP outlet/FGD inlet location.

² Flue gas concentration was measured at the FGD outlet location.

³ Closure was computed using the flow rates computed for the gypsum and cake wash outlet streams.

⁴ Closure was computed by replacing the gypsum and cake wash streams with the underflow flow rate.

Another dimension regarding the fate of trace elements is provided by a detailed look at the distribution of the elements within the wet FGD circuit. Mass flow data were estimated across the hydroclone, which is the key intermediate component of the scrubber system. Table 5-14 summarizes the flows into the hydroclone (from the reaction tank) and out of the hydroclone (overflow and underflow streams). Each flow is further subdivided to show the association of elements with either the solid or liquid phases. A mass balance closure (Equation 5-8) value across the wet FGD is also provided in Table 5-14. Although, the mass balance closures for the various trace metals are in general reasonable, in most cases the mass balance is >100%. This indicates that there is either an overestimation of the concentration of the trace element at the scrubber outlet or an underestimation of the inlet.

$$Closure, \% = \frac{X_{Overflow\ Total} + X_{Underflow\ Total}}{X_{Reaction\ Tank\ Total}} \times 100 \quad \text{Eq. 5-8}$$

Table 5-14
Summary of Trace Element Flows through the FGD

Element	Reaction Tank In		Overflow Out		Underflow Out		Closure, %
	Solids, lb/hr	Liquids, lb/hr	Solids, lb/hr	Liquids, lb/hr	Solids, lb/hr	Liquids, lb/hr	
Ag	0.0689	0.000221	0	0.000241	0	0.0000222	0.381
Al	245	3.39	213	1.83	98.9	0.0899	126
As	0.143	0	0.147	0	0.0271	0	122
B	46.7	36.2	0	34.9	0	7.95	51.6
Ba	3.26	0.104	2.82	0.0827	2.13	0.0145	150
Be	0	0.0028	0.0152	0.00252	0	0.000436	648
Cd	0	0.0397	0	0.0375	0	0.00563	109
Co	0.177	0.00971	0.0828	0.00973	0.103	0.00135	105
Cr	4.63	0.00701	5.25	0.0078	2.24	0.00136	162
Cu	0.388	0.0153	0.317	0.0147	0.202	0.00107	133
Fe	161	0	147	0	75.7	0	138
Hg	0.0255	0.0418	0.0193	0.0463	0.0217	0.000239	130
Mn	2.83	2.29	2.92	2.54	2.34	0.276	158
Mo	0.188	0.0109	0.157	0.00628	0.0702	0.00829	121
Ni	1.58	0.177	0.657	0.183	0.996	0.0252	106
Pb	0.126	0	0.134	0	0.0401	0	138

Table 5-14 (continued)
Summary of Trace Element Flows through the FGD

Element	Reaction Tank In		Overflow Out		Underflow Out		Liquids, lb/hr
	Solids, lb/hr	Liquids, lb/hr	Solids, lb/hr	Liquids, lb/hr	Element	Solids, lb/hr	
Sb	0	0.00334	0.031	0.00217	0	0.000623	1010
Se	0.267	0.626	0.147	0.682	0.16	0.133	126
Sr	43.8	5.35	15	4.73	27.3	1.21	98
Ti	24.6	0.00583	24.7	0.00471	12.2	0.000751	150
Tl	0	0.0094	0	0.00591	0	0.0017	80.9
V	1.2	0.0115	1.14	0.0114	0.51	0.00308	137
Zn	1.49	1.02	1.25	0.857	1.2	0.0286	133
F	44.2	12.4	30.5	9.9	30.9	2.11	130
Cl	0	1270	4.81	1090	0	306	110
Br	0.127	5.91	0.102	5.19	0.0408	1.33	110

6

QUALITY CONTROL/QUALITY ASSURANCE (QA/QC)

A quality management system, authorized and supported by EERC managers, is in effect and governs all programs within the organization. Additionally, the CATM Program at the EERC has a Quality Management Plan (QMP) in effect that addresses trace metal emission research at the EERC. The QMP has been reviewed and accepted by EPA. It was the intent of this project to follow the Quality Manual, the QMP, and all revisions. The QA/QC for this project can be divided into the QA/QC for the sampling and that designed to ensure quality data from the laboratory doing the analysis.

Sampling QA/QC

The most important QA/QC that the EERC has is that the personnel who perform the sampling and analysis are highly trained in the procedures. In the field, the sampling procedures followed as closely as possible those outlined in EPA Method 29. The sampling boxes used were all calibrated prior to going into the field according to the *Quality Assurance Handbook for Air Pollution Measurement Systems: Volume III. Stationary Source Specific Methods*. As this project was piggybacked with a separate project and because of constraints at the plant, it was agreed prior to conducting the test that the sampling would be done at a single point rather than traversing the duct.

Prior to beginning the testing, all glassware and sample containers were cleaned and labeled according to the specification outline in EPA Method 29 and the OH method. Chain-of-custody procedures were also followed.

For the EPA Method 29 samples, field blanks were done each day. A field blank consists of a sample train that is set up as if to be used for sampling. The field blank is then torn down and the solutions prepared and analyzed like all other Method 29 samples. In addition, filter blanks were also submitted for analysis. The EPA Method 29 field blank results are shown in Table 6-1. With the exception of boron and aluminum, all the blanks were low. The high reading for boron may be a result of the type of glassware and filters used for the sampling.

The wet FGD samples were collected and filtered in accordance with the EPRI report entitled “*Sampling and Analytical Plan Guidance for Water Characterization of Coal-Fired Steam Electric Utility Facilities*” (4). As such, all the samples were filtered in the field and preserved using nitric acid.

QA/QC Procedures for ICP–MS and ICP–AES Analysis of Samples

Both ICP–MS and inductively coupled plasma atomic emission spectrometry (ICP–AES) were used for the trace element analysis of the various sample types. The following ASTM and EPA methods were employed for the preparation and analysis of the different samples: EPA Method SW846 3052 (Microwave Assisted Acid Digestion of Siliceous and Organically Based Matrices), SW-846 6020A (ICP–MS), and ASTM Method D6357 (Standard Test Method for Determination of Trace Elements in Coal, Coke, and Combustion Residues from Coal Utilization Processes by ICP–AES, ICP–MS, and Graphite Furnace Atomic Absorption Spectrometry). The methods of analysis chosen for each sample type depended on the required detection limits, sample matrix, and analytes of interest. The following QA/QC parameters apply to both analytical techniques.

The instruments were calibrated with a blank and a minimum of three standards which were prepared from commercially available stock standards traceable to the National Institute of Standards and Technology (NIST). The blank and standard diluent were 1% v/v HNO₃ prepared from concentrated trace metal-grade acid and ASTM Type I water. After calibration, an initial calibration verification (ICV) standard was run, which required a reading of 95%–105% of the actual value, or the instrument was recalibrated. The ICV was prepared from a separate source than the calibration standards. Calibration standards and ICVs were prepared daily.

A minimum of one sample out of every ten or one sample from each batch was analyzed in triplicate to determine instrument precision. Acceptable precision limits are <10% relative standard deviation (RSD). All sample replicates for this project were within the acceptable limits of <10% RSD. Analyte spikes of known concentrations were prepared for each sample matrix and analyzed at the same frequency to confirm analyte recovery from a particular matrix. The amount of analyte added was approximately equal to the amount found in the sample. The solution used for spiking was prepared from a separate stock than the calibration standards. Recovery of the added spike was calculated as follows:

$$\% \text{ Recovery} = \frac{[(\text{Sample} + \text{Spike}) - (\text{Sample})]}{(\text{Spike})} \times 100\% \quad \text{Eq. 6-1}$$

Acceptable ranges for analyte recovery are 85%–115% for samples reading above the method detection limit (MDL) and 50%–150% for samples reading below the MDL. All matrix spikes for this project were within the acceptable limits.

A continuing calibration verification (CCV) standard, prepared at a concentration equivalent to the midpoint range of the calibration curve, was run every ten samples and at the end of every run to check the slope of the calibration curve. The CCV must read 90%–110% of the true value or the instrument was recalibrated and the samples since the last acceptable CCV were reanalyzed.

Estimated MDLs for ICP–MS and ICP–AES, along with isotopes and wavelengths used for the elements of interest, are presented in Table 6-1. MDLs may vary by sample matrix and dilution volumes. Not all samples were analyzed by both instruments, but typically the samples were analyzed by ICP–AES first and the results evaluated. Samples with analytes falling below the MDL of ICP–AES were reanalyzed using ICP–MS, if it was determined that better detection could be achieved. Aluminum, barium, iron, strontium, and titanium were analyzed by ICP–AES and not ICP–MS because the concentrations were above the MDL of this instrument, and some of these elements were also analyzed by XRF spectrometry.

Table 6-1
Field Blanks for EPA Method 29 Samples

Element	MC2-D1-FB, µg/L	MC2-D2-FB, µg/L	MC2-D3-FB, µg/L	MC2-D4-FB, µg/L	45-mm Filter, µg	Thimble Filter, µg
Ag	<0.1	<0.1	<0.1	<0.1	<0.03	<0.03
Al	784	266	790	644	211	49.9
As	<10	<10	<10	<10	<0.05	<0.05
B	2060	1190	2120	1224	104	53.7
Ba	<1	<1	<1	<1	2.90	1.50
Be	0.12	0.12	0.11	0.11	<0.03	<0.03
Cd	<0.1	<0.1	<0.1	<0.1	<0.03	<0.03
Co	<0.2	<0.2	<0.2	<0.2	<0.05	<0.05
Cr	1.92	0.84	1.78	1.89	6.93	0.84
Cu	<0.2	2.94	<0.2	<0.2	<0.05	<0.05
Fe	<50	<50	<50	<50	44	11.0
Mn	2.25	6.75	1.04	0.27	1.00	0.90
Hg	–	–	–	–	0.138	<0.001
Mo	0.315	0.325	0.250	0.255	21.6	2.48
Ni	0.1	0.1	0.26	0.1	0.99	<0.05
Pb	<0.2	<0.2	<0.2	<0.2	<0.05	<0.05
Sb	<0.2	<0.2	<0.2	<0.2	<0.05	<0.05
Se	0.815	9.27	0.31	0.51	<0.05	<0.05
Sr	0.9	1.16	1.24	0.85	0.90	0.20
Ti	1.28	3.56	2.15	1.69	3.40	0.90
Tl	<0.2	<0.2	<0.2	<0.2	<0.05	<0.05
V	0.1	0.34	0.1	0.15	0.30	0.20
Zn	6.61	6.22	12.1	2.80	3.30	0.90

Method blanks and control samples were digested and analyzed along with the project samples to evaluate possible contamination and method accuracy. The control samples were purchased standard reference materials from NIST (1633b fly ash and 1632b coal). Acceptable recovery limits for control samples as indicated in SW-846 6020A are 80%–120% of the certified value. The determined values for these reference materials by either ICP–MS or ICP–AES are presented in Table 6-2. Not all analytes in these reference materials have certified values. Some elements are designated as noncertified or informational, because the full certification process was not completed. These values are indicated in Table 6-3. The determined values for all the analytes measured in the 1633b fly ash were within the acceptable limits; however, a few of 1632b coal parameters were outside of these limits. Antimony and nickel were slightly high at 142% and 133% recovery, respectively, while barium and strontium were low, with recoveries of 78% and 70%, respectively. It should be noted that antimony and strontium are noncertified parameters in the NIST coal, and strontium and barium were also analyzed by XRF spectrometry for the project coals, which showed very comparable results between the two techniques.

Table 6-2
Measuring Parameters for ICP–MS and ICP–AES

Element	ICP–MS		ICP–AES	
	Isotope	MDL, µg/L	Wavelength, nm	MDL, µg/L
Al	NA ¹	NA	308.215	200
As	⁷⁵ As	0.5	189.041	150
Sb	¹²¹ Sb	0.2	217.581	200
Ba	NA	NA	455.403	1
Be	⁹ Be	0.1	313.042	2
Cd	¹¹⁴ Cd	0.1	226.502	20
Co	⁵⁹ Co	0.1	228.618	50
Cr	⁵² Cr	0.05	206.149	50
Cu	⁶³ Cu	0.1	324.754	20
Fe	NA	NA	259.940	50
Pb	²⁰⁸ Pb	0.1	220.353	200
Mo	⁹⁸ Mo	0.2	202.030	50
Ni	⁶⁰ Ni	0.2	231.604	100
Mn	⁵⁵ Mn	0.1	257.610	50
Se	⁷⁸ Se	0.2	196.026	300
Ag	¹⁰⁷ Ag	0.1	328.068	50
Sr	NA	NA	407.771	1.0

¹ Not applicable.

Table 6-2 (continued)
Measuring Parameters for ICP–MS and ICP–AES

Element	ICP–MS		ICP–AES	
	Isotope	MDL, µg/L	Element	Isotope
Tl	²⁰⁵ Tl	0.2	190.801	200
Ti	NA	NA	334.941	20
V	⁵¹ V	0.1	292.401	20
Zn	⁶⁶ Zn	0.2	206.200	10

¹ Not applicable.

Table 6-3
Recovery of Standard Reference Materials

Element	NIST 1633b Fly Ash			NIST 1632b Coal		
	Reference Value, µg/g dry	Determined, µg/g dry	Recovery, %	Reference Value, µg/g dry	Determined, µg/g dry	Recovery, %
Al	150,500	138,300	92	8550	7270	85
As	136.2	163	120	3.72	4.06	109
Sb	6 ¹	5.2	87	0.24 ¹	0.34	142
Ba	709	696	98	67.5	52.5	78
Be	NA ²	NA	NA	NA	NA	NA
Cd	0.784	0.94	120	0.0573	0.050	87
Co	50 ¹	48.8	98	2.29	2.08	91
Cr	198.2	186	94	11 ¹	12.0	108
Cu	112.8	117	104	6.28	5.33	85
Fe	77,800	76,800	99	7590	6190	82
Pb	68.2	67.9	100	3.67	3.36	92
Mo	NA	NA	NA	0.9 ¹	0.85	95
Ni	120.6	118	98	6.10	8.09	133
Mn	131.8	130	99	12.4	10.9	88
Se	10.26	11.6	113	1.29	1.35	105
Ag	NA	NA	NA	NA	NA	NA
Sr	1041	1070	103	102 ¹	71.2	70

¹ Noncertified value.

² Not available.

Table 6-3 (continued)
Recovery of Standard Reference Materials

Element	NIST 1633b Fly Ash			NIST 1632b Coal		
	Reference Value, µg/g dry	Determined, µg/g dry	Recovery %	Reference Value, µg/g dry	Determined, µg/g dry	Recovery %
Tl	5.9 ¹	5.72	97	NA	NA	NA
Ti	7910	6970	88	454	401	88
V	295.7	295	100	14 ¹	11.3	81
Zn	210 ¹	209	100	11.89	10.0	87

¹ Noncertified value.

² Not available.

7

CONCLUSIONS

The concentrations of almost all of the elements of interest leaving the stack were very low. The only possible exception was selenium, but the flue gas selenium measurements are in question since the overall mass balance for selenium suggests that it was effectively removed across the wet FGD.

A high percentage of the trace elements were captured in the ESP (for most, >80%).

With a few exceptions (copper, cadmium, bromine), the overall mass balances were generally quite good, even given the uncertainties of the bottom ash.

The mass balances across the wet FGD were more variable. This is most likely a result of some of the concentrations being very low and also the uncertainties in determining flows within a wet FGD.

A high percentage of the trace elements in the wet FGD solutions were associated with the solids.

8

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4. *Analytical Plan Guidance for Water Characterization of Coal-Fired Steam Electric Utility Facilities*; EPRI: Palo Alto, CA, 2007; 1014946.

A

WET-CHEMISTRY METHOD SAMPLING DATA ONTARIO HYDRO METHOD

Table A-1
Earlier Ontario Hydro Method Sampling Data

Earlier Ontario Hydro Method Sampling Data								
Sample Date	Location	Mercury Concentrations, µg/dNm³ 3% O₂				Dust Loading, gr/dscf, 3% O₂	O₂, % dry	H₂O, %
		Particulate	Oxidized	Elemental	Total			
Baseline Sampling								
1	ESP Inlet	0.08	19.32	1.50	20.90	3.8543	6	10.1
2	ESP Inlet	0.04	13.27	0.21	13.52	2.6887	5.9	9.6
3	ESP Inlet	0.04	12.71	0.49	13.24	3.3292	5.9	9.9
4	ESP Inlet	0.03	12.11	0.24	12.38	2.9187	5.7	10
1	FGD Outlet	0.04	0.68	1.80	2.52	0.0428	7.3	16.6
2	FGD Outlet	0.05	0.60	1.13	1.78	0.0242	6.7	16.2
3	FGD Outlet	0.00	0.55	1.28	1.83	0.0006	6.7	16.7
4	FGD Outlet	0.01	0.42	1.38	1.81	0.0020	6.3	16.7

B

**WET-CHEMISTRY METHOD SAMPLING DATA EPA
METHOD 26A**

Table B-1
EPA Method 26A Results

Location	Stack Press., in H ₂ O	Stack Temp., °F	Gas vol., dry scf	Moisture, %	Dust Loading, gr/scf	O ₂ , %	CO ₂ , %	Chloride ppm		Fluoride ppm		Bromide ppm	
								H ₂ SO ₄	NaOH	H ₂ SO ₄	NaOH	H ₂ SO ₄	NaOH
SCR-In	-7.5	640	21.048	9.9	0.7702	5.8	13.4	23.4	1.6	4.5	<0.5	<0.3	<0.1
SCR-Out	-5.5	644	19.243	10.6	6.7255	5.2	14.0	121.0	3.7	24.4	<0.6	<0.3	<0.1
SCR-In	-7.5	633	20.648	10.1	1.7036	5.8	1.4	99.8	2.8	24.8	<0.5	<0.3	<0.1
SCR-Out	-6.0	642	22.935	10.4	4.9394	5.2	14.0	105.6	1.3	21.4	<0.5	<0.2	<0.1
ESP-In	-7.7	322	10.830	12.0	0.3310	5.5	13.8	86.9	<0.6	12.4	<1.0	<0.5	<0.2
ESP-Out	15.8	345	24.203	10.3	0.1553	6.9	12.5	101.1	<0.2	17.6	<0.5	<0.2	<0.1
FGD-Out	2.6	130	25.185	17.3	0.0019	6.9	12.3	0.9	<0.2	<0.8	<0.4	<0.2	<0.1
ESP-In	-7.7	323	14.682	11.2	1.9801	5.5	13.8	103.6	0.4	11.6	<0.8	<0.4	<0.2
ESP-Out	15.8	345	24.258	10.4	0.0997	6.9	12.5	91.2	0.4	15.8	<0.5	<0.2	<0.1
FGD-Out	2.6	129	25.241	17.2	0.0013	6.9	12.3	0.5	0.2	<0.8	<0.4	<0.2	<0.1
SCR-In	-7.5	635	20.751	10.1	0.8844	5.8	13.4	62.0	1.0	16.4	<0.5	<0.3	<0.1
SCR-Out	-5.5	643	22.041	10.6	4.9985	5.6	13.6	75.9	0.6	3.4	<0.5	<0.2	<0.1
ESP-In	-7.7	312	16.029	10.4	2.1265	6.1	12.8	97.1	0.7	19.9	<0.7	<0.3	<0.2
ESP-Out	15.8	345	24.224	9.3	0.0624	7.3	12.1	99.5	0.6	16.7	<0.5	<0.2	<0.1
FGD-Out	2.6	127	19.712	16.1	0.0005	6.2	12.9	1.2	0.6	<1.1	<0.6	<0.3	<0.1

C

**WET-CHEMISTRY METHOD SAMPLING DATA EPA
METHOD 29**

Table C-1
EPA Method 29 Results (Elements Ag, Al, As, B, Ba, Be, Cd, Co, Cr, Cu, and Fe)

Sample ID	Elements										
	Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe
D2-ESPin											
Probe Rinse (250mL), µg/L	0.00	9660	16.00	4580	175.80	1.04	1.64	1.69	16.86	14.29	2330
H ₂ O ₂ (500mL), µg/L	0.00	782	0.00	7400	1.68	0.42	0.00	0.00	1.31	11.22	0
KMnO ₄ (500mL), µg/L											
Filter, µg/g	1.31	121411	114.38	2500	1709.65	11.10	13.45	36.25	283.48	97.75	130647
D2-ESPout											
Probe Rinse (250mL), µg/L	0.00	4300	30.00	1440	185.30	1.10	3.32	1.49	25.24	11.69	1690
H ₂ O ₂ (500mL), µg/L	0.00	992	0.00	11020	0.00	0.67	0.14	0.00	9.64	18.14	0
KMnO ₄ (500mL), µg/L											
Filter, µg/g	1.65	131298	265.75	2413	2495.16	13.86	28.08	43.56	318.80	129.63	124031
D2-FGDout	0.00	736	0.00	1250	8.50	0.12	0.13	0.15	0.56	0.00	0
Probe Rinse (250mL), µg/L	0.00	714	0.00	1644	0.00	0.11	0.00	0.00	0.83	0.00	0
H ₂ O ₂ (500mL), µg/L											
KMnO ₄ (500mL), µg/L											
Filter, µg/g	0.01	390	11.40	60	125.00	0.52	1.75	0.22	4.29	2.15	448
D4-ESPin	0.00	3680	0.00	1946	110.70	0.47	0.89	0.62	9.89	3.42	856
Probe Rinse (250mL), µg/L	0.00	964	0.00	6740	0.00	0.37	0.00	0.00	1.17	15.31	85
H ₂ O ₂ (500mL), µg/L											
KMnO ₄ (500mL), µg/L											
Filter, µg/g	1.23	121933	71.49	660	1624.14	10.01	12.39	31.72	270.85	88.91	129784
D4-ESPout	0.00		0.00		0.00			0.00			0
Probe Rinse (250mL), µg/L	0.00		0.00		0.00						0
H ₂ O ₂ (500mL), µg/L											

Table C-1 (continued)
EPA Method 29 Results (Elements Ag, Al, As, B, Ba, Be, Cd, Co, Cr, Cu, and Fe)

Sample ID	Elements										
	Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe
KMnO ₄ (500mL), µg/L											
Filter, µg/g	0.18	29500	22.10	347	586.00	1.95	4.14	3.97	78.00	14.54	21800
D4-FGDout	0.00	574	0.00	1098	2.42	0.11	0.00	0.00	0.00	0.80	0
Probe Rinse (250mL), µg/L	0.00	708	0.00	1462	0.00	0.11	0.00	0.00	2.46	0.00	0
H ₂ O ₂ (500mL), µg/L											
KMnO ₄ (500mL), µg/L											
Filter, µg/g	0.00	316	1.48	84	62.50	0.00	0.90	0.00	2.87	0.00	293
D5-ESPin	0.00	2080	0.00	2540	114.70	0.23	0.00	0.19	7.21	0.26	73
Probe Rinse (250mL), µg/L	0.00	928	0.00	9120	1.67	0.38	0.00	0.00	1.00	11.80	0
H ₂ O ₂ (500mL), µg/L											
KMnO ₄ (500mL), µg/L											
Filter, µg/g	0.93	124878	96.15	1966	734.15	10.73	14.73	38.24	229.27	77.41	140000
D5-ESPout	0.00	5800	40.00	1844	155.90	1.59	6.01	2.09	44.13	14.84	2270
Probe Rinse (250mL), µg/L	0.00	1110	0.00	12400	0.00	0.59	0.00	0.00	4.96	16.58	0
H ₂ O ₂ (500mL), µg/L											
KMnO ₄ (500mL), µg/L											
Filter, µg/g	0.28	22300	24.90	351	224.0	1.85	8.05		67.40	22.11	16800
D5-FGDout	0.22	548	0.00	1208	2.42	0.14	0.32	0.00	6.08	0.00	0
Probe Rinse (250mL), µg/L	0.00	720	0.00	1868	1.85	0.17	0.00	0.00	2.94	0.00	0
H ₂ O ₂ (500mL), µg/L											
KMnO ₄ (500mL), µg/L											
Filter, µg/g	0.00	302	4.58	55	20.00	0.00	0.97	0.00	2.88	0.50	276

Table C-2
EPA Method 29 Results (Elements Hg, Mn, Mo, Ni, Pb, Sb, Se, Sr, Ti, Tl, V, and Zn)

Sample ID	Elements											
	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sr	Ti	Tl	V	Zn
D2-ESPin												
Probe Rinse (250mL), µg/L	0.00	64.69	12.98	7.33	7.09	0.98	9.26	101.70	247	1.45	31.02	49.16
H ₂ O ₂ (500mL), µg/L	11.70	5.18	0.50	0.69	0.00	0.00	24.82	1.48	12	0.00	10.80	179.60
KMnO ₄ (500mL), µg/L	1.22											
Filter, µg/g	0.10	327.75	79.93	124.21	74.12	8.70	16.66	323.89	6247	14.90	365.73	492.22
D2-ESPout												
Probe Rinse (250mL), µg/L	0.00	25.80	24.01	7.77	7.73	1.14	705.00	27.32	162	3.07	51.22	109.90
H ₂ O ₂ (500mL), µg/L	23.40	3.38	0.52	0.55	0.00	0.00	217.50	1.28	15	0.00	15.48	288.90
KMnO ₄ (500mL), µg/L	1.00											
Filter, µg/g	0.07	351.26	135.54	154.87	126.60	17.71	18.05	351.26	6977	31.81	525.68	835.76
D2-FGDout	0.00	4.87	0.23	1.00	0.00	0.00	5.27	6.99	4	0.00	0.00	42.60
Probe Rinse (250mL), µg/L	0.22	3.37	0.34	0.00	0.00	0.00	191.00	1.33	3	0.00	1.29	44.80
H ₂ O ₂ (500mL), µg/L	1.25											
KMnO ₄ (500mL), µg/L												
Filter, µg/g	0.01	2.20	7.78	0.86	1.79	1.12	25.48	3.90	40	2.04	14.90	16.10
D4-ESPin	0.00	32.68	5.52	4.36	2.56	0.38	7.84	43.93	91	0.66	11.06	30.57
Probe Rinse (250mL), µg/L	17.60	6.81	0.41	0.24	0.00	0.00	38.89	2.00	12	0.00	12.00	233.20
H ₂ O ₂ (500mL), µg/L	0.80											
KMnO ₄ (500mL), µg/L												
Filter, µg/g	0.05	323.85	72.08	111.95	55.03	6.21	9.72	336.11	6133	12.37	318.94	451.42
D4-ESPout	0.00	5.57	0.32	3.35	0.28	0.00	850.00	3.29	0	0.00	0.61	43.01
Probe Rinse (250mL), µg/L	25.70	9.23	0.52	0.71	0.00	0.00	268.50	1.48	13	0.00	0.99	0.00

Table C-2 (continued)
EPA Method 29 Results (Elements Hg, Mn, Mo, Ni, Pb, Sb, Se, Sr, Ti, Tl, V, and Zn)

Sample ID	Elements											
	Hg	Mn	Mo	Ni	Pb	Sb	Se	Sr	Ti	Tl	V	Zn
H ₂ O ₂ (500mL), µg/L	0.85											
KMnO ₄ (500mL), µg/L												
Filter, µg/g	0.01	65.50	26.48	17.54	13.30	1.99	14.84	67.10	1430	3.79	103.00	210.00
D4-FGDout	0.00	2.10	0.00	0.00	0.00	0.00	16.78	4.82	1	0.00	0.43	8.97
Probe Rinse (250mL), µg/L	0.19	0.20	0.25	0.35	0.00	0.00	80.00	1.51	3	0.00	0.99	0.00
H ₂ O ₂ (500mL), µg/L	0.55											
KMnO ₄ (500mL), µg/L												
Filter, µg/g	0.01	1.90	5.49	0.00	0.00	0.00	19.99	2.50	25	0.81	6.10	8.70
D5-ESPin	0.00	19.20	0.42	4.44	0.00	0.00	4.85	55.34	34	0.00	1.95	9.89
Probe Rinse (250mL), µg/L	14.70	1.18	0.34	0.00	0.00	0.00	19.22	1.76	9	0.00	9.36	201.00
H ₂ O ₂ (500mL), µg/L	0.55											
KMnO ₄ (500mL), µg/L												
Filter, µg/g	0.04	378.05	98.83	128.88	84.20	14.05	10.39	229.27	6805	15.76	509.76	602.44
D5-ESPout	0.00	39.36	51.70	23.83	11.75	2.34	890.00	32.54	220	7.51	103.30	163.50
Probe Rinse (250mL), µg/L	22.70	2.57	0.55	2.25	0.00	0.00	165.50	1.41	13	0.00	12.36	271.60
H ₂ O ₂ (500mL), µg/L	0.55											
KMnO ₄ (500mL), µg/L												
Filter, µg/g	0.01	60.80	56.50	30.44	32.30	7.09	18.71	39.70	1150	8.06	133.00	249.00
D5-FGDout	0.00	4.73	0.87	3.19	0.00	0.00	4.48	4.82	1	0.00	2.47	11.89
Probe Rinse (250mL), µg/L	0.22	11.99	0.35	0.00	0.00	0.00	75.00	2.25	2	0.00	0.78	19.44
H ₂ O ₂ (500mL), µg/L	0.85											
KMnO ₄ (500mL), µg/L												
Filter, µg/g	0.01	2.80	6.17	1.54	0.74	1.02	19.61	1.80	25	1.18	11.20	18.00

Table C-3
MM29 Sampling Parameters

Sample I.D.	Test Length	Sample Port	Sampler	Test Time (min.)	Stack Press (in H ₂ O)	Stack Temp (°F)	ΔP Pitot (in H ₂ O)	Noz. Dia. (in.)	Gas Meter Vol. (cf)	Total Dust (g)	Vm Std. SCF	% H ₂ O (in flue gas)	% ISO	DCL (grains/SCF)	DCL (grams/SCM)	% Eff.	O ₂ %	CO ₂ %
D2-ESPIN-M29-1	120	ESPIN-center	DAVE	120	-7.7	324	0.6	0.158	31.944	3.07897	29.370	11.2	100.1	1.6176	3.7011		5.5	13.8
D2-ESPOUT-M29-1	120	ESPOUT	KEN	120	15.8	345	1.1	0.169	50.765	0.45267	48.299	10.4	99.5	0.1446	0.3309	90.1725	6.9	12.5
D2-FGDOUT-M29-1	120	FGDOUT	C. EKEN	120	2.6	129	1.8	0.147	53.242	0.00760	49.996	16.7	97.4	0.0023	0.0054		6.9	12.3
D4-ESPIN-M29-1	120	ESPIN	DAVE W.	120	-7.7	312	0.4	0.177	34.081	3.00859	31.984	10.3	99.2	1.4514	3.3208		6.1	12.8
D4-ESPOUT-M29-1	120	ESPOUT	KEN	120	15.8	345	1.1	0.169	49.918	0.19306	48.550	9.4	99.3	0.0614	0.1404	95.4023	7.3	12.1
D4-FGDOUT-M29-1	120	FGDOUT	C. EKEN	120	2.6	128	1.5	0.136	41.071	0.00009	39.818	16.2	100.8	0.0000	0.0001		7.9	11.6
D5-ESPIN-M29-1	105	ESPIN	DAVE	105	-7.7	314	0.4	0.177	29.671	3.52342	27.986	10.1	96.8	1.9426	4.4448		5.7	13.3
D5-ESPOUT-M29-1	105	ESPOUT	KEN	105	15.8	345	1.1	0.169	43.162	0.15024	42.070	9.4	98.0	0.0551	0.1261	96.7613	7.6	11.7
D5-FGDOUT-M29-1	105	FGDOUT	CRAIG	105	2.6	126	1.5	0.136	36.325	0.00002	34.834	15.6	98.7	0.0000	0.0000		7.4	12.1

D

COAL AND ASH DATA

Table D-1
Parametric Testing Coal Data*

Sample	1	2	3	4	5	6	7	8	9	10	11
Hg, ppm (dry)	0.0934	0.0896	0.0704	0.0707	0.0869	0.0944	0.096	0.0961	0.1	0.081	0.087
Cl, ppm (dry)	1210	1510	1230	1320	1180	1620	425	1620	1500	1570	1500
Proximate Analysis											
Moisture, %	3.6	2.6	4.2	3.4	3.4	2.9	5.2	2.9	3	3	2.7
Volatile Matter, %	35.08	36.01	36.02	36.72	33.54	34.07	34.3	35.63	35.45	35.31	34.98
Fixed Carbon, %	48.77	49.37	49.06	48.69	48.02	47.64	48.44	48.7	48.99	49.18	48.52
Ash, %	12.55	12.02	10.73	11.19	15.04	15.39	12.06	12.76	12.55	12.51	13.79
Ultimate Analysis											
Hydrogen, %	4.91	4.93	5.15	4.94	4.8	4.71	4.86	5.02	4.83	4.75	3.89
Carbon, %	67.23	69	67.71	68.04	72.25	70.79	73.79	74.09	74.19	74.12	74.61
Nitrogen, %	1.59	1.6	1.69	1.68	1.3	1.37	1.52	1.44	1.43	1.4	1.32
Sulfur, %	2.78	2.95	2.65	2.8	2.98	3.08	2.66	3.08	3.16	2.97	3.01
Oxygen, %	10.94	9.5	12.08	11.34	3.63	4.66	5.11	3.61	3.84	4.25	3.38
Heating Value, Btu/lb	12371	12684	12213	12488	11479	11719	11572	12107	12109	12059	11987

*All values on an as-received basis unless otherwise indicated.

Table D-2
Long-Term Testing Coal Data*

Sample	1	2	3	4	5	6	7	8	9	10	11	12
Hg, ppm (dry)	0.0997	0.0933	0.0923	0.0875	0.0832	0.0816	0.0796	0.0868	0.08	0.0897	0.0857	0.0982
Cl, ppm (dry)	1100	881	835	1190	1160	1120	1230	1140	1070	1140	1170	1540
Proximate Analysis												
Moisture, %	10.3	8.6	9.4	10.8	10.7	9.2	11.7	11.2	10.3	10.2	10.4	9.5
Volatile Matter, %	33.98	35.69	36.05	33.72	34.48	35.63	36.05	35.96	37.24	36.56	35.34	35.1
Fixed Carbon, %	43.55	45.03	44.64	44.62	44.41	45.04	43.79	44.61	44.93	44.09	45.84	45.54
Ash, %	12.17	10.68	9.91	10.86	10.42	10.13	8.46	8.24	7.53	9.15	8.43	9.85
Ultimate Analysis												
Hydrogen, %	5.38	5.48	5.49	5.61	5.58	5.53	5.76	5.7	5.76	5.54	5.71	5.63
Carbon, %	61.53	65.54	64.91	64.03	63.63	64.65	64.19	64.67	66.28	63.97	64.78	65.53
Nitrogen, %	1.49	1.55	1.54	1.53	1.54	1.54	1.59	1.56	1.61	1.53	1.58	1.56
Sulfur, %	2.87	3.3	3.13	3.15	3.07	3.01	2.85	2.96	3.04	3.23	3.02	3.09
Oxygen, %	16.57	13.44	15.02	14.81	15.76	15.14	17.15	16.86	15.78	16.58	16.48	14.34
Heating Value, Btu/lb	10701	11304	11327	10971	11053	11208	11109	11295	11576	11268	11468	11412

*All values on an as-received basis unless otherwise indicated.

Table D-2 (continued)
Long-Term Testing Coal Data*

Sample	13	14	15	16	17	18	19	20	21	22	23	24
Hg, ppm (dry)	0.116	0.0881	0.0944	0.0917	0.0818	0.0811	0.0711	0.0732	0.107	0.116	0.153	0.14
Cl, ppm (dry)	1320	1320	1490	1540	1820	1840	1990	956	943	1400	246	732
Proximate Analysis												
Moisture, %	9.2	8.7	9.4	8.9	10.7	11.7	11.5	8.8	9.4	9.1	12.8	11.4
Volatile Matter, %	35.21	35.87	36.09	36.8	36.89	36.98	37.03	38.4	37.03	37.01	37.08	36.85
Fixed Carbon, %	45.42	45.63	45.55	45.59	45.49	44.47	44.66	44.89	43.41	43.64	41.38	42.01
Ash, %	10.18	9.81	8.97	8.71	6.92	6.85	6.81	7.91	10.16	10.25	8.73	9.73
Ultimate Analysis												
Hydrogen, %	5.53	5.54	5.6	5.58	5.78	5.71	5.6	5.66	5.47	5.31	5.59	5.55
Carbon, %	65.28	65.83	66.13	66.31	66.17	68.28	67.35	69.64	72.41	67.33	69.26	67.56
Nitrogen, %	1.55	1.55	1.58	8.71	1.58	1.24	1.13	1.67	1.2	1.16	1.32	1.45
Sulfur, %	3.35	3.06	2.96	2.97	2.99	3.15	2.9	3.04	2.88	2.96	3.03	3.24
Oxygen, %	14.11	14.21	14.77	7.72	16.56	14.77	16.21	12.09	7.88	12.99	12.07	12.47
Heating Value, Btu/lb	11373	11909	11531	11667	11596	11391	11436	11733	11283	11526	10758	10960

*All values on an as-received basis unless otherwise indicated.

Table D-2 (continued)
Long-Term Testing Coal Data*

Sample	25	26	27	28	29	30	31	32	33	34	Long Term Ave.
Hg, ppm (dry)	0.102	0.11	0.0899	0.117	0.127	0.122	0.0944	0.111	0.152	0.114	0.1003
Cl, ppm (dry)	1340	1230	953	806	992	1310	762	1280	1040	1050	1175
Proximate Analysis											
Moisture, %	9.5	8.5	10.1	12.2	11.1	8.5	8.6	9.7	10.8	10.3	10.09
Volatile Matter, %	35.11	36.32	35.32	35.15	34.72	35.55	35.44	34.64	34.17	35.13	35.84
Fixed Carbon, %	44.95	46.19	44.71	43.64	44.68	45.03	44.61	43.78	43.21	43.53	44.49
Ash, %	10.44	9	9.87	9	9.5	10.92	11.36	11.88	11.81	11.05	9.58
Ultimate Analysis											
Hydrogen, %	5.24	5.39	5.49	5.65	5.31	5.31	5.33	5.33	5.32	5.38	5.52
Carbon, %	65.51	67.65	70.54	70.77	65.47	69.98	73.04	67.69	64.19	65.02	66.62
Nitrogen, %	1.29	1.26	1.17	1.3	1.38	1.38	1.17	1.19	1.16	1.37	1.63
Sulfur, %	3.21	3.03	3.07	2.83	3.2	3.42	3.03	2.95	3.43	2.99	3.07
Oxygen, %	14.32	13.67	9.87	10.44	15.15	9	6.07	10.96	14.09	14.2	13.58
Heating Value, Btu/lb	11263	11779	11321	11041	11215	11442	11314	11203	10864	11120	11306

Note: all values on an as-received basis unless otherwise indicated.

Table D-3
ESP Ash Data for Parametric and Long-Term Testing

Sample	Hg, ppm(m)	LOI¹, %
Parametric Testing		
1	0.0607	1.08
2	0.0678	1.69
3	0.036	1.6
4	0.0611	1.32
5	0.0575	0.81
6	0.0585	0.9
7	0.0651	0.95
8	0.092	1.75
9	0.0942	1.02
10	0.0669	0.93
11	0.0465	0.97
Long-Term Testing		
1	0.0099	0.99
2	0.025	1
3	0.02	0.8
4	0.015	0.71
5	0.005	0.48
6	0.005	0.69
7	0.0099	0.64
8	0.0099	0.74
9	0.025	1.38
10	0.015	0.72
11	0.014	0.36
12	0.01	0.69
13	0.03	0.8
14	0.045	2.55
15	0.02	0.66
16	0.0	0.5
17	0.0099	0.44
18	0.005	0.61

Table D-3 (continued)
ESP Ash Data for Parametric and Long-Term Testing

Sample	Hg, ppm(m)	LOI¹, %
Long-Term Testing (continued)		
19	0.01	0.46
20	0.029	0.72
21	0.02	0.67
22	0.019	0.66
23	0.025	0.8
24	0.02	0.7
25	0.02	0.61
26	0.044	1.42
27	0.044	1.38
28	0.045	1.72
29	0.0546	1.52
30	0.04	1.42
31	0.044	1.39
32	0.035	1.33
33	0.0099	0.69
34	0.0099	0.61
Long-Term Average	0.0226	0.908

¹ Loss on ignition.

E

WET FGD SLURRY DATA

Table E-1
Parametric and Long-Term Thickener Underflow Data

Sample	Solids Fraction, %	Hg in Solids, ppm(m)	Hg in Liquids, ppm(m)
Parametric Testing			
1	9.11	0.353	0.06
2	24.4	0.188	0.0182
3	30.5	0.256	0.0101
4	24.9	0.245	0.002
5	32	0.233	0.0001
Long-Term Testing			
1	31.4	0.263	0.0112
2	29.9	0.29	0.00045
3	27.9	0.284	0.001
4	20.7	0.296	0.0015
5	26.7	0.293	0.00035
6	24.9	0.35	0.00045
7	29	0.33	0.0003
8	21.7	0.3	0.00085
9	24	0.234	0.00065
10	28.8	0.302	0.00095
11	28.8	0.305	0.00035
12	35.5	0.316	0.0005
13	35.4	0.765	0.0005
14	34	0.258	0.001
15	28.6	0.18	0.0478
16	26.5	0.283	0.0005
17	26.8	0.279	0.0002
18	28.9	0.358	0.0002

Table E-1 (continued)
Parametric and Long-Term Thickener Underflow Data

Sample	Solids Fraction, %	Hg in Solids, ppm(m)	Hg in Liquids, ppm(m)
Long-Term Testing (continued)			
19	33.9	0.282	0.0005
20	29	0.41	0.0002
21	29.5	0.391	0.005
22	29	0.336	0.0005
23	32.2	0.367	0.00015
24	30.7	0.291	0.01
25	34.3	0.289	0.0292
26	29	0.336	0.0005
27	30.7	0.283	0.0002
28	25.9	0.261	0.03
29	27.3	0.473	0.0045
30	24	0.24	0.0005
31	29.9	0.327	0.0003
32	31.9	0.343	0.00035
33	33.1	0.271	0.0002
34	30.7	0.251	0.00005

Table E-2
Parametric and Long-Term Thickener Overflow Data

Sample	Solids Fraction, %	Hg in Solids, ppm(m)	Hg in Liquids, ppm(m)
Parametric Testing			
1	3.98	0.493	0.045
2	0.83	0.576	0.0348
3	11.7	0.677	0.0139
4	1.6	1.59	0.0139
5	3.03	0.882	0.0026
Long-Term Testing			
1	3.89	1.47	0.0055
2	3.08	1.83	0.00275
3	2.89	1.65	0.011
4	2.96	2.25	0.00275
5	3.01	1.42	0.0015
6	0.79	2.18	0.0045
7	2.5	1.54	0.00065
8	3.24	2.15	0.0018
9	2.52	1.69	0.00015
10	4.09	1.68	0.00875
11	2.09	3.31	0.0275
12	6.95	1.71	0.0025
13	5.58	0.309	0.0782
14	8.41	0.27	0.0725
15	4.25	0.338	0.0901
16	4.56	0.386	0.103
17	3.81	0.555	0.0722
18	5.06	0.481	0.108
19	4.69	0.75	0.0545
20	5.11	0.869	0.0512
21	4.3	0.672	0.0932
22	4.85	1.3	0.086
23	5.71	1.94	0.0165

Table E-2 (continued)
Parametric and Long-Term Thickener Overflow Data

Sample	Solids Fraction, %	Hg in Solids, ppm(m)	Hg in Liquids, ppm(m)
Long-Term Testing (continued)			
24	4.09	0.609	0.0912
25	3.69	0.694	0.0975
26	4.57	0.613	0.0455
27	4.65	0.792	0.0752
28	13.1	0.38	0.0815
29	4.85	0.427	0.0705
30	5.15	0.961	0.0218
31	6.84	0.843	0.05825
32	3.12	0.917	0.119
33	10.8	0.649	0.0492
34	7.32	1.39	0.00015

Table E-3
Parametric and Long-Term Thickener Reaction Tank Inlet Flow Data

Sample	Solids Fraction, %	Hg in Solids, ppm(m)	Hg in Liquids, ppm(m)
Parametric Testing			
1	8.22	0.362	0.0562
2	2.68	0.387	0.0416
3	9.12	0.339	0.0542
4	8.76	0.457	0.0169
5	7.89	0.567	0.0024
Long-Term Testing			
1	13.3	0.363	0.03
2	9.56	0.681	0.00085
3	10.5	0.663	0.00525
4	6.25	0.69	0.008
5	7.54	0.636	0.00105
6	7.93	0.757	0.00195
7	7.03	0.722	0.00065
8	6.37	0.599	0.00215
9	6.96	0.708	0.0003
10	9.59	0.704	0.002
11	10.7	7.74	0.00225
12	13.4	0.498	0.0522
13	13.6	0.313	0.0742
14	12.5	0.222	0.081
15	11.6	0.147	0.0782
16	11.7	0.542	0.00275
17	11.5	0.503	0.0135
18	11.5	0.321	0.0692
19	9.71	0.56	0.0262
20	12.2	0.515	0.0515
21	12.9	0.205	0.0728
22	11.5	0.726	0.0142

Table E-3 (continued)
Parametric and Long-Term Thickener Reaction Tank Inlet Flow Data

Sample	Solids Fraction, %	Hg in Solids, ppm(m)	Hg in Liquids, ppm(m)
Long-Term Testing (continued)			
23	12.4	0.816	0.0225
24	13.6	0.195	0.077
25	12.7	0.244	0.09
26	11.1	0.33	0.0468
27	11.7	0.41	0.017
28	6.41	0.151	0.0688
29	11	0.221	0.07175
30	9.05	0.446	0.0242
31	11.6	0.532	0.0285
32	12.3	0.235	0.07875
33	12.3	0.898	0.0002
34	10.8	0.769	0.00005

F

SAMPLING CALCULATIONS

This appendix describes the assumptions used to calculate the baseline and long-term mercury mass balances. The data used in the example calculations correspond to the long-term test mass balance. The baseline mass balance used the same methodology.

Coal In

Coal feed rate during sampling was recorded in a plant-provided data file:

- Average coal feed rate, 9/24/07-9/28/07: 362,707 lb/hr
- Average coal moisture: 10.1%
- Computed dry coal feed: 326,000 lb/hr

Flue Gas Flow

The average flue gas-flow rate was calculated from the Fd factor computed from the coal ultimate analysis.

Coal Fd factor: 11,007 dscf/MBtu

Coal heating value: 11,253 Btu/lb (as-received)

Flow Determination:

362,707 lb coal	11,253 Btu	11,007 dscf	(21-0) % (Zero excess O ₂)
hr	lb coal	1,000,000 Btu	(21-3) % (3% excess O ₂)

$$= 524 \times 10^5 \text{ dscf/hr at 3\% O}_2$$

ESP Ash Out

The quantity of ash produced by Unit 4 is estimated using the measured ash content and the recorded coal feed rate. The amount of the total ash reaching the ESP is assumed to be 80% with the remaining 20% distributed as bottom ash.

Average coal ash content: 10.2% (as received)

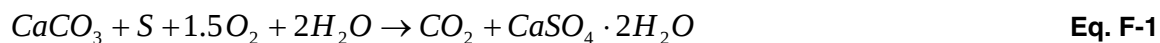
Percentage of ash that reaches the ESP as fly ash: 80%

ESP collection efficiency: 99.5%

362,707 lb coal	0.102 lb ash	0.8 ESP ash	0.995 captured ESP ash
hr	lb coal	total ash	total ESP ash
= 29,400 lb/hr			

Limestone In

The limestone consumption rate was not directly measured; therefore, the rate was estimated by calculating the steady state amount of limestone needed to neutralize the sulfur present in the coal according the overall reaction in Equation F-1.



XRF analysis of the limestone samples indicated that they were approximately 94% calcium carbonate (CaCO_3). Therefore, for every pound of sulfur entering with the coal, there are approximately $(1)100.09/32.06 = 3.12$ pounds of calcium carbonate consumed for neutralization or $3.12/0.94 = 3.32$ pounds of the tested limestone.

Coal sulfur content: 3.12 % (as received)

362,707 lb coal	3.12 lb S	3.32 lb limestone
hr	100 lb coal	1 lb S
= 37,600 lb limestone/hr		

Gypsum Out

Gypsum production rate was not recorded, instead an estimate of the rate was prepared based on the required stoichiometry of Equation F-1. The molar ratio between sulfur in the coal and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is 1:1. Assuming that approximately 94% of the sulfur in the coal was captured and converted to gypsum, then for every pound of sulfur entering the coal, there were $(0.94)172.17/32.06 = 5.05$ pounds of gypsum produced.

362,707 lb coal	3.12 lb S	5.05 lb gypsum
hr	100 lb coal	1 lb S

$$= 57,100 \text{ lb gypsum/hr}$$

The gypsum samples gathered from the plant were composed of gypsum from four individual scrubber units (presumably the two sides of Unit 4 and the two sides of Unit 3) not just the test side of Unit 4. Therefore, any change in gypsum composition because of the control technology was diluted by these other gypsum streams.

Underflow

To define the magnitude of this stream, the percentage of solids present in the underflow were assumed to equal the rate of gypsum production.

Long-term underflow solids: 29.1 %

Underflow solids = 57,100 lb/hr

Underflow liquids:

$$\frac{57,100(1-0.291)}{0.291}$$

$$= 139,000 \text{ lb/hr}$$

Blowdown Outlet Flow

No indication of blowdown flow was provided. Instead, an estimate was based on a chloride mass balance of the entire plant. The extensive chloride data needed for a mass balance were collected under the related trace element sampling that was performed during the long-term test. The needed chloride flow data from that project are provided below.

Chloride Flow Data

Entering in coal: 333 lb Cl/hr

Entering with limestone: 1.75 lb Cl/hr

Leaving with ESP ash: 0.613 lb Cl/hr

Leaving in the flue gas: 8.75 lb Cl/hr

Leaving with gypsum: 3.71 lb Cl/hr

Leaving with cake wash: 272 lb Cl/hr

The difference of approximately 49.7 lb Cl/hr was assumed to be removed with the blowdown stream. The blowdown stream has the same composition as the thickener overflow stream.

Averaged blowdown (overflow) solids: 4.78%

Averaged chloride content of blowdown (overflow) liquids: 1950 ppm

Averaged chloride content of blowdown (overflow) solids: 171 ppm

The chloride mass balance is summarized by Equation B-2 below.

$$\frac{(1 - 0.0478)1950\dot{m}_{\text{Blowdown}} + (0.0478)171\dot{m}_{\text{Blowdown}}}{1,000,000} = 49.7 \text{ lbCl} / \text{hr} \quad \text{Eq. F-2}$$

Which results in a total blowdown flow of 26,700 lb/hr. Solving for the solid and liquid mass flow rates of the blowdown stream results in:

Blowdown solids = $(0.0478)26,600 = 1270 \text{ lb/hr}$

Blowdown liquids = $(1 - 0.0478)26,600 = 25,400 \text{ lb/hr}$

Coal-Based Flue Gas Production (Fd Factor)

Fd = Heat input of fuel, dry basis, dscf/10⁶ Btu

Fd (dscf/10⁶ Btu) =

$$10^6 \times \frac{3.64 \times (\%H_2 - 0.111 \times \%H_2O) + 1.53 \times (\%C) + 0.57 \times (\%S) + 0.14 \times (\%N_2) - 0.46 \times (\%O_2 - 0.899 \times \%H_2O)}{HV}$$

Example:

Fd (dscf/10⁶ Btu) =

$$10^6 \times \frac{3.64 \times (4.76 - 0.111 \times 4.3) + 1.53 \times 74.7 + 0.57 \times 2.94 + 0.14 \times 1.44 - 0.46 \times (4.06 - 0.899 \times 4.3)}{11817}$$

Fd = 11,142 dscf/10⁶ Btu

Where:

%(H₂, C, S, N₂, O₂, H₂O) = Percent (H₂, C, S, N₂, O₂, H₂O) by weight

HV = Heating value (Btu/lb)

Coal-Based Flue Gas Mercury Concentration

Hg_(FGB) = Hg, flue gas basis, µg/Nm³ at 3% O₂

$$Hg_{(FGB)} (\mu g/Nm^3) = Hg_{(dry)} \times 10^6 \times \left(1 - \frac{\%H_2O}{100}\right) \times 453.6 \times \left(\frac{18}{21 \times HV \times F_d \times 0.02832}\right)$$

Example:

$$Hg_{(FGB)} = 0.0833 \times 10^6 \times \left(1 - \frac{4.3}{100}\right) \times 453.6 \times \left(\frac{18}{21 \times 11817 \times 11142 \times 0.02832}\right)$$

$$Hg_{(FGB)} = 8.31 \mu g/dNm^3 \text{ at } 3\% O_2$$

Where:

Hg_(dry) = Mercury measured in coal, dry basis (ppm)

Mercury Concentration, Heating Value Basis

$$Hg_{(HVB)} = \text{Hg, heating value basis, lb/TBtu}$$

$$Hg_{(HVB)} \text{ (lb/TBtu)} = \frac{Hg_{(dry)} \times 10^6}{HV} \times \left(1 - \frac{\%H_2O}{100}\right)$$

Example:

$$Hg_{(HVB)} \text{ (lb/TBtu)} = \frac{0.0833 \times 10^6}{11817} \times \left(1 - \frac{4.3}{100}\right)$$

$$Hg_{(HVB)} = 6.75 \text{ lb/TBtu}$$

Coal to FGD Outlet Mercury Removal

$$\text{Hg Removal (coal to FGD outlet), \%} = \frac{Hg_{(FGB)} - Hg_{FGD \text{ Out}}}{Hg_{(FGB)}} \times 100\%$$

Example:

$$\text{Hg Removal (coal to FGD outlet), \%} = \frac{8.31 - 2.52}{8.31} \times 100\%$$

$$\text{Hg Removal (coal to FGD outlet), \%} = 69.8 \%$$

Where:

$$Hg_{(FGD \text{ Out})} = \text{Hg concentration at FGD Outlet, } \mu\text{g/dNm}^3 \text{ at } 3\% \text{ O}_2$$

ESP Inlet to FGD Outlet Mercury Removal

$$\text{Hg Removal (ESP Inlet to FGD outlet), \%} = \frac{Hg_{(ESP)} - Hg_{FGD \text{ Out}}}{Hg_{(ESP)}} \times 100\%$$

Example:

$$\text{Hg Removal (ESP Inlet to FGD outlet), \%} = \frac{20.90 - 2.52}{20.90} \times 100\%$$

$$\text{Hg Removal (ESP Inlet to FGD outlet), \%} = 88.0\%$$

Where:

$$Hg_{(ESP)} = \text{Hg concentration at ESP Inlet, } \mu\text{g/dNm}^3 \text{ at } 3\% \text{ O}_2$$

Particulate Removal Efficiency

$$\text{Particulate Removal (ESP Inlet to FGD outlet), \%} = \frac{P_{(ESP \text{ In})} - P_{FGD \text{ Out}}}{P_{(ESP \text{ In})}} \times 100\%$$

Example:

$$\text{Particulate Removal (ESP Inlet to FGD outlet), \%} = \frac{3.8543 - 0.0428}{0.0428} \times 100\%$$

$$\text{Particulate Removal (ESP Inlet to FGD outlet), \%} = 98.89\%$$

Where:

$$P_{(ESP \text{ In})} = \text{Dust loading at ESP Inlet, gr/dscf at } 3\% \text{ O}_2$$

$$P_{(FGD \text{ Out})} = \text{Dust loading at FGD Outlet, gr/dscf at } 3\% \text{ O}_2$$

Conversion of Mercury Concentrations to Stack Conditions

$$Hg_{(Stack)} = \text{Mercury concentration reported at stack conditions, } \mu\text{g/m}^3$$

$$Hg_{(Stack)} = Hg_{(dry, 3\%)} \times \left(1 - \frac{\%H_2O}{100}\right) \times \frac{21 - \%O_2}{18}$$

Example:

$$Hg_{(Stack)} = 2.52 \times \left(1 - \frac{16.6}{100}\right) \times \frac{21 - 7.3}{18}$$

$$Hg_{(Stack)} = 1.59 \mu\text{g/m}^3$$

Where:

$$Hg_{(dry, 3\%)} = \text{Hg concentration reported on a dry basis at } 3\% \text{ O}_2, \mu\text{g/dNm}^3 \text{ at } 3\% \text{ O}_2$$

$$\%H_2O = \text{Flue gas moisture concentration, volume \%}$$

$$\%O_2 = \text{Flue gas oxygen concentration, volume \%}$$

Mercury Mass Flow Rates

Liquid and solid streams:

m_{Hg} = Mass flow rate of mercury, lb/hr

$$m_{\text{Hg}} = \frac{\text{Hg}_{\text{Concentration}} \times m_{\text{Stream}}}{10^6}$$

Example:

$$m_{\text{Hg}} = \frac{0.0845 \times 417,000}{10^6}$$

$$m_{\text{Hg}} = 0.0353 \text{ lb/hr}$$

Where:

$\text{Hg}_{\text{Concentration}}$ = Mercury concentration of the liquid or solid stream of interest, ppm(m)

m_{Stream} = Mass flow rate of the liquid or solid stream of interest (details in Appendix B), lb/hr

Flue gas stream:

$$m_{\text{Hg}} = \frac{\text{Hg}_{(\text{dry}, 3\%)}}{10^6 \times 454 \times 3.28^3} \times \frac{\text{CoalFeed} \times \text{HV} \times \text{Fd}}{10^6} \times \frac{21}{18}$$

Example:

$$m_{\text{Hg}} = \frac{1.99}{10^6 \times 454 \times 3.28^3} \times \frac{417,000 \times 11799 \times 10523}{10^6} \times \frac{21}{18}$$

$$m_{\text{Hg}} = 0.00787 \text{ lb/hr}$$

Where:

Coal Feed = Mass flow rate of coal feed (dry basis), lb/hr

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