JV TASK 126 – MERCURY CONTROL TECHNOLOGIES FOR ELECTRIC UTILITIES BURNING BITUMINOUS COAL

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JV TASK 126 – MERCURY CONTROL TECHNOLOGIES FOR ELECTRIC UTILITIES BURNING BITUMINOUS COAL

ABSTRACT

The EERC developed an applied research consortium project to test cost-effective mercury (Hg) control technologies for utilities burning bituminous coals. The project goal was to test innovative Hg control technologies that have the potential to reduce Hg emissions from bituminous coal-fired power plants by ≥90% at costs of one-half to three-quarters of current estimates for activated carbon injection (ACI). Hg control technology evaluations were performed using the EERC's combustion test facility (CTF). The CTF was fired on pulverized bituminous coals at 550,000 Btu/hr (580 MJ/hr). The CTF was configured with the following air pollution control devices (APCDs): selective catalytic reduction (SCR) unit, electrostatic precipitator (ESP), and wet flue gas desulfurization system (WFDS). The Hg control technologies investigated as part of this project included ACI (three Norit Americas, Inc., and eleven Envergex sorbents), elemental mercury (Hg^0) oxidation catalysts (i.e., the noble metals in Hitachi Zosen, Cormetech, and Hitachi SCR catalysts), sorbent enhancement additives (SEAs) (a proprietary EERC additive, trona, and limestone), and blending with a Powder River Basin (PRB) subbituminous coal. These Hg control technologies were evaluated separately, and many were also tested in combination.

Bituminous coals from the Conesville Coal Preparation Company and Knight Hawk Coal Mine were used to evaluate Hg control. In addition, the Knight Hawk coal was blended with a PRB subbituminous coal from the Antelope Mine. The Conesville, Knight Hawk, and low-sulfur Knight Hawk coals possessed the characteristics of bituminous coals, relatively high chlorine (137–1006 ppm, dry) and sulfur contents (3.31–5.73 wt%, dry), that resulted in a flue gas containing significant proportions of Hg^0 and oxidized mercury (Hg^{2+}). Conversely, the subbituminous Antelope coal had much lower chlorine (6 ppm, dry) and sulfur contents (0.32 wt%, dry) that resulted in a combustion flue gas containing primarily Hg^0.

Continuous mercury monitor (CMM) results were used to evaluate the proportions of gaseous Hg^0 and Hg^{2+} forms in the flue gases and ESP and WFDS Hg removal performances obtained during baseline combustion conditions for the Conesville, Knight Hawk, and low-sulfur Knight Hawk coals. The CMM results obtained during baseline Antelope coal combustion were unreliable and were, therefore, not useful for evaluating Hg^0 and Hg^{2+} or APCD Hg removal performance. Baseline combustion conditions involved tests when no sorbents or SEAs were being injected. Ammonia (NH_3) injection, however, occurred during most of the baseline combustion tests. NH_3 did not significantly affect Hg^0 oxidation or capture in the ESP or WFDS. All three bituminous coal combustion flue gases contained significant proportions of Hg^0 and Hg^{2+}, especially at the SCR inlet or between the catalyst layers. The CMM at the ESP outlet indicated that Hg^0 oxidation occurred downstream from the SCR catalysts. The ESP was ineffective in capturing Hg, but the WFDS was very effective in capturing Hg^{2+} but not Hg^0. Based on the baseline coal combustion results, the primary goal and benefit of injecting sorbents and/or SEAs was to significantly improve ESP Hg capture so that the potential for Hg reemission from the WFDS can be reduced.

The industry standard practice of injecting DARCO® Hg and/or DARCO Hg-LH was performed during combustion of the bituminous coals to enable a comparison for comparability purposes with the alternative technologies that were evaluated. Conesville coal combustion tests indicated that DARCO Hg injection at reasonable rates (i.e., ≤5lb/Macf) improved ESP Hg capture from <10% to about 50%. The WFDS effectively removed Hg from the Conesville coal combustion flue gas (50%-70% Hg removal) at efficiencies of ≥80% because most of the Hg downstream from the Hitachi Zosen and Cormetech catalysts and ESP occurred as Hg^{2+}. The WFDS was not as effective in removing Hg from the Knight Hawk coal combustion flue gas because less Hg^{2+} was present. Injection of DARCO Hg into the Knight Hawk coal combustion flue gas improved ESP Hg removal performance from 15% to 25% to a maximum of 40%. The combination of DARCO Hg and SEA2 injection at 1.2 lb/Macf and 0.6–2.3 ppm, respectively, further improved ESP Hg removal to about 60%. Combining trona injection with low DARCO Hg and SEA2 injection at 1.2 lb/Macf and 0.6 ppm, respectively, significantly improved ESP Hg capture to approximately 70%.

The Envergex E11, E21, and Hg E23 sorbents and DARCO E26 provided ESP Hg capture performance similar to DARCO Hg at an equivalent injection rate. The combination of Envergex E21 at 5 lb/Macf and limestone injection improved ESP Hg removal to about 50%. At very high injection rates of 12 to 48 lb/Macf, Envergex E23, E25, and E27 provided ESP Hg removals ranging from 40% to 80%.

The WFDS was most effective in removing Hg from the low-sulfur Knight Hawk coal combustion flue gas downstream of a Hitachi catalyst. In contrast to the Conesville and Knight Hawk coals, DARCO Hg injection was ineffective in promoting ESP Hg capture from the low-sulfur Knight Hawk coal combustion flue gas. Injection of DARCO Hg-LH into the low-sulfur Knight Hawk coal combustion flue gas, however, enhanced ESP Hg removal to 30%–40%. Injection of Envergex 28 and 30 provided ESP Hg removal efficiencies similar to DARCO Hg-LH at an equivalent injection rate. Coinjection of Envergex 30 at 3 lb/Macf with Envergex 24 significantly improved ESP Hg removal to about 50% but only at a very high Envergex 24 injection rate of 30 lb/Macf. The injection of Envergex 24 alone at 30 lb/Macf provided an ESP Hg removal of 40%. Injection of Envergex 31 at 3 and 5 lb/Macf did not significantly improve ESP Hg removal performance. Coinjection of Envergex 31 at 5 lb/Macf with Envergex 24 at 15 and 30 lb/Macf improved ESP Hg capture to about 30% and 80%, respectively. Relatively high injection rates of Envergex 33 at 16.5 and 33 lb/Macf provided ESP Hg removal efficiencies of 40% and 60%, respectively. Limestone injection in the presence or absence of NH_3 injection did not significantly affect ESP or WFDS Hg removal performance.

Although the CMM results obtained during Antelope–Knight Hawk coal combustion were unreliable, Ontario Hydro Hg measurement results were obtained at the ESP outlet during combustion of the Antelope–Knight Hawk blends at ratios of 90:10 and 80:20. The results indicated that most, ≈90%, of the Hg occurred as Hg^{2+}. ESP Hg removal efficiencies were similar for both blends, with an average of 42%. An increase of 10% in the blend proportion did not significantly affect Hg speciation or capture in the ESP.

Continuous emission monitoring and limited SO_3 analysis results were obtained during Conesville, Knight Hawk, low-sulfur Knight Hawk, and Antelope coal combustion testing of

Hitachi Zosen, Cormetech, and Hitachi catalysts upstream of a WFDS. Limited SO_3 analyses indicated that SO_3 concentrations at the outlets of the SCR catalysts were <1% of the SO_2 exiting the furnace. NH_3 injections combined with the SCR catalysts effectively reduced NO_x emissions by >80%. The WFDS was also effective in reducing SO_2 emissions by >80%.

The deposits produced in the CTF during the Antelope and Antelope–Knight Hawk coal combustion tests were analyzed using a point count technique on a scanning electron microscope (SEM) to evaluate the effects of coal blending on ash deposition and slagging and fouling severity. As expected, based on the Antelope and Knight Hawk coal ash compositions, increased blend ratios of Knight Hawk contributed to increasing hematite (Fe_2O_3) in the coal ash deposits. Predicted slag viscosities for a typical furnace exit gas temperature of 2200° to 2400°F were very high, suggesting that the parent Antelope coal and the Antelope–Knight Hawk coal blends should not pose a slagging problem. The predicted slag viscosities for a given temperature were very similar regardless of blend proportion, suggesting that blending with Knight Hawk coal at ≤30% should not significantly affect slagging propensity.

TABLE OF CONTENTS

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TABLE OF CONTENTS (continued)

LIST OF FIGURES

Continued…

LIST OF FIGURES (continued)

Continued…

LIST OF FIGURES (continued)

Continued…

LIST OF FIGURES (continued)

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LIST OF FIGURES (continued)

LIST OF TABLES

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JV TASK 126 – MERCURY CONTROL TECHNOLOGIES FOR ELECTRIC UTILITIES BURNING BITUMINOUS COAL

EXECUTIVE SUMMARY

The Energy & Environmental Research Center (EERC) developed an applied research consortium project to test cost-effective mercury (Hg) control technologies for utilities burning bituminous coals. The project sponsors included the Illinois Clean Coal Institute (ICCI); Marsulex Environmental; Hitachi Power Systems America, Ltd.; Cormetech Incorporated; American Electric Power; Hitachi Zosen Corporation, and the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL). The project goal was to test innovative Hg control technologies that have the potential to reduce Hg emissions from bituminous coal-fired power plants by ≥90% at costs of one-half to three-quarters of current estimates for activated carbon injection (ACI).

Hg control technology evaluations were performed using the EERC's combustion test facility (CTF), fired on pulverized bituminous coals at 550,000 Btu/hr (580 MJ/hr). The CTF was configured with the following air pollution control devices (APCDs): selective catalytic reduction (SCR), electrostatic precipitator (ESP), and wet flue gas desulfurization system (WFDS). In general, the Hg control technologies investigated as part of this project included ACI, elemental mercury (Hg^0) oxidation catalysts (i.e., the noble metals in Hitachi Zosen, Cormetech, and Hitachi catalysts), sorbent enhancement additives (SEAs), and blending with a Powder River Basin (PRB) subbituminous coal. The Hg control technologies that were evaluated are summarized in Table ES-1.

Bituminous coals from the Conesville Coal Preparation Company and Knight Hawk Coal Mine were used in evaluating Hg control. In addition, the Knight Hawk coal was blended with a PRB subbituminous coal from the Antelope Mine. General information on the test coals is presented in Table ES-2. Proximate, ultimate, Hg, and chlorine analysis results for the coals and coal blends are summarized in Tables ES-3–5. The Conesville, Knight Hawk, and low-sulfur Knight Hawk coals possess the characteristics of bituminous coals; that is, relatively high chlorine and sulfur contents that generally result in a flue gas containing significant proportions of Hg^0 and oxidized mercury (Hg^{2+}). Conversely, the subbituminous Antelope coal has lower chlorine and sulfur contents that generally result in a combustion flue gas containing primarily Hg^0. Estimates of Hg concentrations on a flue gas basis and a heating value basis were calculated according to U.S. Environmental Protection Agency (EPA) Method 19. These values are presented in Tables ES-4 and ES-5.

Continuous mercury monitor (CMM) results were used to evaluate the proportions of gaseous Hg^0 and Hg^{2+} forms in the flue gases and ESP and WFDS Hg removal performances obtained during baseline combustion conditions for the Conesville, Knight Hawk, and low-sulfur Knight Hawk coals. The CMM results obtained during baseline Antelope coal combustion were unreliable and were, therefore, not useful for evaluating Hg^0 and Hg^{2+} or APCD Hg removal performance. Baseline combustion conditions involved tests when no sorbents or SEAs were being injected. Ammonia (NH_3) injection, however, occurred during most of the baseline

Table ES-1. Potential Hg Control Technologies

- Sorbent Injection Technologies
  - NORIT Americas Inc. DARCO® Hg
  - NORIT Americas Inc. DARCO E26
  - NORIT Americas Inc. DARCO Hg-LH
  - Envergex E11
  - Envergex E21
  - Envergex Hg E23
  - Envergex 24
  - Envergex E25
  - Envergex Hg E25
  - Envergex E27
  - Envergex 28
  - Envergex 30
  - Envergex 31
  - Envergex 33
- SEAs
  - SEA 2
  - Limestone
  - Trona
- Hg^0 Oxidation Technologies
  - Hitachi Zosen Catalyst
  - Cormetech Catalyst
  - Hitachi Catalyst
- Coal Pretreatment Processes
  - Blending with PRB Subbituminous Coal

Table ES-2. Coal Information

Organization	Mines or Plant	Seams Mined	Location	Production, tons
Knight Hawk Coal, L.L.C.	Creek Paum, Royal Falcon, Prairie Eagle, and Red Hawk	Herrin No. 6, Springfield No. 5, and Murphysboro	Ava, IL	2,660,234[a]
American Electric Power	Conesville Coal Preparation Company	Lower Freeport	Conesville, OH	4,549,129[b]
Kennecott Energy Company	Antelope	Anderson/Canyon	Douglas, WY	29,682,368[c]

[a] 2007 mine production statistic from *The Illinois Coal Industry*: Report of the Department of Commerce and Economic Opportunity, Office of Coal Development, June 2008, 78 pp.

[b] 2003 coal received by Conesville plant statistic from *Keystone Coal Industry Manual*; Mining Media: Prairieville, LA, 2005.

[c] 2004 mine production statistic from *Keystone Coal Industry Manual*; Mining Media: Prairieville, LA, 2005.

Table ES-3. Proximate and Heating Value Coal Analysis Results

Coal:	Conesville	Knight Hawk	Low-Sulfur Knight Hawk	Antelope
Date(s):	October 7–20, 2008	June 18, 2008	November 12, 2008	June 9, 2008
Proximate Analysis, as-fired, wt%				
Moisture	5.50 ±0.30[a]	8.60	3.20	24.1
Volatile Matter	33.5 ±0.7[a]	33.2	32.6	29.9
Fixed Carbon	45.4 ±0.8[a]	47.9	50.3	40.4
Ash	15.6 ±1.1[a]	10.3	13.9	5.63
Heating Value, Btu/lb	10,795 ±246[a]	11,083	11,385	8719
Proximate Analysis, dry basis, wt%				
Volatile Matter	35.5 ±0.6[a]	36.4	33.7	39.4
Fixed Carbon	48.0 ±0.7[a]	52.3	52.0	53.2
Ash	16.5 ±1.2[a]	11.3	14.4	7.41
Heating Value, Btu/lb	11,422 ±226[a]	12,131	11,764	11,480

[a] Average and ±95% confidence interval based on ten analyses.

Table ES-4. Ultimate, Hg, and Cl Coal Analysis Results

Coal:	Conesville	Knight Hawk	Low-Sulfur Knight Hawk	Antelope
Date(s)	Oct 7–20, 2008	Oct 24–Nov 12, 2008	Feb 24–March 5, 2008	June 25–July 1, 2008
Ultimate Analysis, as-fired, wt%				
Hydrogen	4.32 ±0.15[a]	4.30	4.45	3.46
Carbon	61.6 ±1.4[a]	62.5	67.7	51.8
Nitrogen	1.27 ±0.05[a]	1.39	1.59	0.76
Sulfur	4.80 ±0.07[a]	5.24	3.20	0.25
Oxygen	7.00 ±0.53[a]	7.65	5.93	14.1
Ash	15.6 ±1.1[a]	10.3	13.9	5.63
Ultimate Analysis, dry basis, wt%				
Hydrogen	4.57 ±0.14[a]	4.71	4.60	4.55
Carbon	65.2 ±1.3[a]	68.4	70.0	68.2
Nitrogen	1.34 ±0.05[a]	1.52	1.64	1.00
Sulfur	5.08 ±0.08[a]	5.73	3.31	0.32
Oxygen	7.41 ±0.56[a]	8.37	6.13	18.5
Ash	16.5 ±1.2[a]	11.3	14.4	7.41
Coal Analysis, dry basis, ppm				
Hg	0.168 ±0.007[a]	0.0902±0.0021[b]	0.0804 ±0.0060[d]	0.0595 ±0.0039[e]
Cl	382 ±17[a]	137 ±6[c]	1006 ±34[c]	6
Calculated Flue Gas				
Hg, $\mu g/dNm^3$	19.9	10.4	8.87	7.22
Hg, $lb/10^{12}$	14.7	7.68	6.84	5.18

[a] Average and ±95% confidence interval based on ten analyses.
[b] Average and ±95% confidence interval based on nine analyses
[c] Average and ±95% confidence interval based on four analyses.
[d] Average and ±95% confidence interval based on eleven analyses.
[e] Average and ±95% confidence interval based on seven analyses.

Table ES-5. Proximate, Heating, Ultimate, and Hg Values for the Antelope–Knight Hawk Coal Blends

Antelope–Knight Hawk Coal Blends:	100%	90%:10%	80%:20%	70%:30%
Date(s):	6/25/08	6/27/08	6/27/08	6/28/08
Proximate Analysis, as-fired, wt%				
Moisture	16.3	18.1	16.6	13.4
Volatile Matter	32.4	31.6	31.9	32.7
Fixed Carbon	43.7	43.2	43.8	45.7
Ash	7.65	7.14	7.69	8.28
Heating Value, Btu/lb	9555	9458	9692	10,094
Ultimate Analysis, as-fired, wt%				
Hydrogen	3.88	3.87	3.98	4.11
Carbon	56.1	55.3	56.1	58.7
Nitrogen	1.08	1.09	1.11	1.19
Sulfur	0.42	0.57	0.90	1.15
Oxygen	14.6	14.0	13.6	13.2
Ash	7.65	7.14	7.69	8.28
Coal Analysis, dry basis, ppm				
Hg	0.0856	0.0608	0.0525	0.0673
Calculated Flue Gas				
Hg, $\mu g/dNm^3$	10.5	7.36	6.33	8.03
Hg, $lb/10^{12}$	7.50	5.26	4.52	5.77

Table ES-6. Summary of Hg Species Proportions (Hg^0 and Hg^{2+}) and APCD Hg Removal Efficiencies Obtained During Baseline Coal Combustion Conditions

	SCR Catalyst, %		ESP Outlet, %		ESP	WFDS Hg
Coal	Hg^0	Hg^{2+}	Hg^0	Hg^{2+}	Removal, %	Removal, %
Conesville	40	60	10	90	<10	>80
Knight Hawk	60	40	20	80	15–25	60–70
Low-Sulfur Knight Hawk	70	30	20	80	<10	85–90

combustion tests. NH_3 did not significantly affect Hg^0 oxidation or capture in the ESP or WFDS. The relative proportions (%) of Hg^0 and Hg^{2+} and APCD Hg removal efficiencies for the baseline coal combustion flue gases are compared in Table ES-6. All three flue gases contained significant proportions of Hg^0 and Hg^{2+}, especially at the SCR inlet or between the catalyst layers. The CMM at the ESP outlet indicated that Hg^0 oxidation occurred downstream from the SCR catalysts. The ESP was ineffective in capturing Hg but the WFDS was very effective in capturing Hg^{2+} but not Hg^0. Based on the results in Table ES-6, the primary goal and benefit of injecting sorbents and/or SEAs is to significantly improve ESP Hg capture so that the potential for Hg reemission from the WFDS can be reduced.

Pilot-scale Hg control technology results are summarized in Table ES-7. The industry standard practice of injecting DARCO Hg and/or DARCO Hg-LH was performed during combustion of the bituminous coals to enable a comparison with the alternative technologies that were evaluated. Conesville coal combustion tests indicated that DARCO Hg injection at reasonable rates improved ESP Hg capture from <10% to about 50%. The WFDS effectively removed Hg from the Conesville coal combustion flue gas at efficiencies of ≥80% because most of the Hg downstream from the Hitachi Zosen and Cormetech catalysts and ESP occurred as Hg^{2+}. The WFDS was not as effective in removing Hg from the Knight Hawk coal combustion flue gas because less Hg^{2+} was present. Injection of DARCO Hg into the Knight Hawk coal combustion flue gas improved ESP Hg removal performance from 15% to 25% to a maximum of 40%. The combination of DARCO Hg and SEA2 injections at 1.2 lb/Macf and 0.6–2.3 ppm, respectively, further improved ESP Hg removal to about 60%. Combining trona injection with low DARCO Hg and SEA2 injection at 1.2 lb/Macf and 0.6 ppm, respectively, significantly improved ESP Hg capture to approximately 70%. Trona injection combined with DARCO Hg injection, however, was not as effective in enhancing ESP Hg capture as injecting DARCO Hg alone. Coinjection of limestone with DARCO Hg did not significantly improve ESP Hg removal performance. The combination of DARCO Hg-LH and trona injection provided ESP Hg removal performance similar to coinjection of DARCO Hg and trona or limestone. The Envergex E11, E21, and Hg E23 sorbents and DARCO E26 provided ESP Hg capture performance similar to DARCO Hg at an equivalent injection rate. The combination of Envergex E21 at 5 lb/Macf and limestone injection improved ESP Hg removal to about 50%. At very high injection rates of 12 to 48 lb/Macf, Envergex E23, E25, and E27 provided ESP Hg removals ranging from 40% to 80%.

The WFDS was most effective in removing Hg from the low-sulfur Knight Hawk coal combustion flue gas downstream of a Hitachi catalyst. In contrast to the Conesville and Knight Hawk coals, DARCO Hg injection was ineffective in promoting ESP Hg capture from the low-sulfur Knight Hawk coal combustion flue gas. Injection of DARCO Hg-LH into the low-sulfur Knight Hawk coal combustion flue gas, however, enhanced ESP Hg removal to 30%–40%. Injection of Envergex 28 and 30 provided ESP Hg removal efficiencies similar to DARCO Hg-LH at an equivalent injection rate. Coinjection of Envergex 30 at 3 lb/Macf with Envergex 24 significantly improved ESP Hg removal to about 50% but only at a very high Envergex 24 injection rate of 30 lb/Macf. The injection of Envergex 24 alone at 30 lb/Macf provided an ESP Hg removal of 40%. Injection of Envergex 31 at 3 and 5 lb/Macf did not significantly improve ESP Hg removal performance. Coinjection of Envergex 31 at 5 lb/Macf with Envergex 24 at 15 and 30 lb/Macf improved ESP Hg capture to about 30% and 80%, respectively. Relatively high injection rates of Envergex 33 at 16.5 and 33 lb/Macf provided ESP Hg removal efficiencies of 40% and 60%, respectively. Limestone injection in the presence or absence of NH_3 injection did not significantly affect ESP or WFDS Hg removal performance.

Although the CMM results obtained during Antelope–Knight Hawk coal combustion were unreliable, Ontario Hydro Hg measurement results were obtained at the ESP outlet during combustion of the Antelope–Knight Hawk blends at ratios of 90:10 and 80:20. The results indicated that most, ≈90%, of the Hg occurred as Hg^{2+}. ESP Hg removal efficiencies were similar for both blends, with an average of 42%. An increase of 10% in the blend proportion did not significantly affect Hg speciation or capture in the ESP.

Presented in Table ES-8 are representative continuous emission monitoring and sulfur trioxide (SO_3) analysis results and APCD NO_x and SO_2 removal efficiencies obtained during Conesville, Knight Hawk, low-sulfur Knight Hawk, and Antelope coal combustion testing of Hitachi Zosen, Cormetech, and Hitachi catalysts upstream of a WFDS. Limited SO_3 analyses indicated that SO_3 concentrations at the outlets of the SCR catalysts were <1% of the sulfur dioxide (SO_2) exiting the furnace. NH_3 injection combined with the SCR catalysts effectively reduced nitrogen oxide (NO_x) emissions by >80%. The WFDS was also effective in reducing SO_2 emissions by >80%.

The deposits produced in the CTF during the Antelope and Antelope–Knight Hawk coal combustion tests were analyzed using a point count technique on an automated scanning electron microscope (ASEM) to evaluate the effects of coal blending on ash deposition and slagging and fouling severity. As expected, based on the Antelope and Knight Hawk coal ash compositions, increased blend ratios of Knight Hawk contribute to increasing hematite (Fe_2O_3) in the coal ash deposits. ASEM analyses indicated that the deposits are composed mostly of a calcium aluminosilicate glass. An iron oxide component, most likely Fe_2O_3, in the deposits gradually increased from 4.0 wt% in the Antelope coal ash deposit to 4.5, 6.0, and 9.6 wt% as the Knight Hawk blend proportions increased by 10%, 20%, and 30%, respectively. Fe_2O_3 is primarily an oxidation product of the relatively large amounts of pyrite (FeS_2) common to U.S. bituminous coals. Predicted slag viscosities for a typical furnace exit gas temperature of 2200° to 2400°F were very high, suggesting that the parent Antelope coal and the Antelope–Knight Hawk coal blends should not pose a slagging problem. The predicted slag viscosities for a given temperature were very similar regardless of blend proportion, suggesting that blending with Knight Hawk coal at ≤30% should not significantly affect slagging propensity.

Table ES-7. Summary of Pilot-Scale Mercury Control Technology Results

Coal	Catalyst	NO_x/NH_3	ESP	WFDS	Sorbent, lb/Macf	SEA, ppm or g/hr	ESP Hg Removal, %	WFDS Hg Removal, %	Total Hg Removal, %
Conesville	Hitachi Zosen	Off	On	Off	NA[a]	NA	14	NA	14
Conesville	Hitachi Zosen	1:1	On	Off	DARCO Hg, 1	NA	47	NA	47
Conesville	Hitachi Zosen	1:1	On	Off	DARCO Hg, 3	NA	38	NA	38
Conesville	Hitachi Zosen	1:1	On	Off	DARCO Hg, 5	NA	54	NA	54
Conesville	Hitachi Zosen	1:1	On	On	NA	NA	9	84	93
Conesville	Cormetech	Off	On	On	NA	NA	<5	82	82
Conesville	Cormetech	1:1	On	On	NA	NA	<5	76	76
Knight Hawk	Cormetech	1:1	On	On	NA	NA	15	64	79
Knight Hawk	Cormetech	1:1	On	On	DARCO Hg, 1	NA	24	58	82
Knight Hawk	Cormetech	1:1	On	On	DARCO Hg, 3	NA	33	49	82
Knight Hawk	Cormetech	1:1	On	On	DARCO Hg, 5	NA	40	38	78
Knight Hawk	Cormetech	1:1	On	On	NA	NA	15	70	85
Knight Hawk	Cormetech	1:1	On	On	DARCO Hg, 1.2	SEA2, 0.6 ppm	57	27	84
Knight Hawk	Cormetech	1:1	On	On	DARCO Hg, 1.2	SEA2, 1.2 ppm	59	27	86
Knight Hawk	Cormetech	1:1	On	On	DARCO Hg, 1.2	SEA2, 2.3 ppm	63	25	88
Knight Hawk	Cormetech	1:1	On	On	NA	NA	57	27	84
Knight Hawk	Cormetech	1:1	On	On	DARCO Hg, 1.2	SEA2, 0.6 ppm; trona, 11.4 g/hr	67	22	89
Knight Hawk	Cormetech	1:1	On	On	DARCO Hg, 1.2	SEA2, 0.6 ppm; trona, 28.4 g/hr	64	24	88
Knight Hawk	Cormetech	1:1	On	On	DARCO Hg, 1.2	SEA2, 0.6 ppm; trona, 56.8 g/hr	67	21	88
Knight Hawk	Cormetech	1:1	On	On	NA	NA	15	64	79
Knight Hawk	Cormetech	1:1	On	On	DARCO Hg, 3	trona, 28 or 57 g/hr	21	58	79
Knight Hawk	Cormetech	1:1	On	On	DARCO Hg, 5	trona, 28 or 57 g/hr	33	46	79
Knight Hawk	Cormetech	1:1	On	On	NA	NA	15	68	83
Knight Hawk	Cormetech	1:1	On	On	NA	Limestone, 57 g/hr	19	63	82
Knight Hawk	Cormetech	1:1	On	On	DARCO Hg, 3	Limestone, 28 g/hr	21	62	83
Knight Hawk	Cormetech	1:1	On	On	DARCO Hg, 3	Limestone, 57 g/hr	25	61	86
Knight Hawk	Cormetech	1:1	On	On	DARCO Hg, 5	Limestone, 28 g/hr	30	54	84
Knight Hawk	Cormetech	1:1	On	On	DARCO Hg, 5	Limestone, 57 g/hr	35	51	86
Knight Hawk	Cormetech	1:1	On	On	NA	NA	14	67	81
Knight Hawk	Cormetech	1:1	On	On	DARCO Hg-LH, 3	Trona, 28 g/hr	27	52	79
Knight Hawk	Cormetech	1:1	On	On	DARCO Hg-LH, 3	Trona, 57 g/hr	29	50	79
Knight Hawk	Cormetech	1:1	On	On	DARCO Hg-LH, 5	Trona, 28 g/hr	32	50	82

[a] Not applicable

Continued…

Table ES-7. Summary of Pilot-Scale Mercury Control Technology Results (continued)

Coal	Catalyst	NOx/NH3	ESP	WFDS	Sorbent, lb/Macf	SEA, ppm or g/hr	ESP Hg Removal, %	WFDS Hg Removal, %	Total Hg Removal, %
Knight Hawk	Cormetech	1:1	On	On	DARCO Hg-LH, 5	Trona, 57 g/hr	35	46	81
Knight Hawk	Cormetech	1:1	On	On	NA	NA	20	62	82
Knight Hawk	Cormetech	1:1	On	On	Envergex E11, 1	NA	26	56	82
Knight Hawk	Cormetech	1:1	On	On	Envergex E11, 3	NA	28	54	82
Knight Hawk	Cormetech	1:1	On	On	Envergex E11, 5	NA	35	46	81
Knight Hawk	Cormetech	1:1	On	On	NA	NA	28	52	80
Knight Hawk	Cormetech	1:1	On	On	Envergex E21, 1	NA	26	54	80
Knight Hawk	Cormetech	1:1	On	On	Envergex E21, 3	NA	34	45	79
Knight Hawk	Cormetech	1:1	On	On	Envergex E21, 5	NA	42	39	81
Knight Hawk	Cormetech	1:1	On	On	NA	NA	27	49	76
Knight Hawk	Cormetech	1:1	On	On	Envergex E21, 3	Limestone, 28 g/hr	38	49	87
Knight Hawk	Cormetech	1:1	On	On	Envergex E21, 3	Limestone, 57 g/hr	41	45	86
Knight Hawk	Cormetech	1:1	On	On	Envergex E21, 5	Limestone, 28 g/hr	48	34	82
Knight Hawk	Cormetech	1:1	On	On	Envergex E21, 5	Limestone, 57 g/hr	47	36	83
Knight Hawk	Cormetech	1:1	On	On	NA	NA	21	65	86
Knight Hawk	Cormetech	1:1	On	On	Envergex Hg E23, 3	NA	24	63	87
Knight Hawk	Cormetech	1:1	On	On	Envergex Hg E23, 6	NA	32	56	88
Knight Hawk	Cormetech	1:1	On	On	Envergex Hg E23, 12	NA	43	46	89
Knight Hawk	Cormetech	1:1	On	On	Envergex Hg E23, 18	NA	50	39	89
Knight Hawk	Cormetech	1:1	On	On	NA	NA	30	42	72
Knight Hawk	Cormetech	1:1	On	On	Envergex E25, 35	NA	78	16	94
Knight Hawk	Cormetech	1:1	On	On	Envergex E25, 48	NA	83	12	95
Knight Hawk	Cormetech	1:1	On	On	NA	NA	30	42	72
Knight Hawk	Cormetech	1:1	On	On	Envergex Hg E25, 18	NA	61	30	91
Knight Hawk	Cormetech	1:1	On	On	Envergex Hg E25, 35	NA	74	18	92
Knight Hawk	Cormetech	1:1	On	On	NA	NA	19	56	75
Knight Hawk	Cormetech	1:1	On	On	DARCO E26, 1	NA	28	45	73
Knight Hawk	Cormetech	1:1	On	On	DARCO E26, 3	NA	34	49	83
Knight Hawk	Cormetech	1:1	On	On	DARCO E26, 5	NA	41	39	80
Knight Hawk	Cormetech	1:1	On	On	NA	NA	30	42	72
Knight Hawk	Cormetech	1:1	On	On	Envergex E27, 18	NA	40	48	88
Knight Hawk	Cormetech	1:1	On	On	Envergex E27, 35	NA	51	39	90
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	NA	NA	<5	85	85

[a] Not applicable

Continued…

Table ES-7. Summary of Pilot-Scale Mercury Control Technology Results (continued)

Coal	Catalyst	NOx/NH3	ESP	WFDS	Sorbent, lb/Macf	SEA, ppm or g/hr	ESP Hg Removal, %	WFDS Hg Removal, %	Total Hg Removal, %
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	DARCO Hg, 3	NA	<5	87	87
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	DARCO Hg, 5	NA	<5	85	85
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	DARCO Hg, 10	NA	<5	82	82
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	NA	NA	<5	87	87
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	DARCO Hg-LH, 3	NA	29	62	91
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	DARCO Hg-LH, 5	NA	33	58	91
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	DARCO Hg-LH, 10	NA	40	50	90
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	NA	NA	<5	90	90
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	Envergex 28, 3	NA	11	85	96
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	Envergex 28, 5	NA	37	58	95
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	NA	NA	14	77	91
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	Envergex 30, 3	NA	23	64	87
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	Envergex 30, 3; Envergex 24, 15	NA	23	58	81
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	Envergex 30, 3; Envergex 24, 30	NA	54	31	85
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	Envergex 24, 30	NA	40	52	92
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	NA	NA	<5	86	86
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	Envergex 31, 3	NA	11	75	86
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	Envergex 31, 5	NA	8	78	86
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	Envergex 31, 5; Envergex 24, 15	NA	28	59	87
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	Envergex 31, 5; Envergex 24, 30	NA	81	9	90
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	NA	NA	7	87	94
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	Envergex 33, 16.5	NA	41	54	95
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	Envergex 33, 33	NA	60	33	93
Low-Sulfur Knight Hawk	Hitachi	Off	On	On	NA	NA	6	83	89
Low-Sulfur Knight Hawk	Hitachi	1:0.8	On	On	NA	Limestone, 11.4 g/hr	<5	85	85
Low-Sulfur Knight Hawk	Hitachi	1:0.8	On	On	NA	Limestone, 28.4 g/hr	<5	83	83
Low-Sulfur Knight Hawk	Hitachi	1:0.8	On	On	NA	Limestone, 56.8 g/hr	<5	82	82
Low-Sulfur Knight Hawk	Hitachi	1:1	On	On	NA	Limestone, 56.8 g/hr	<5	80	80
Low-Sulfur Knight Hawk	Hitachi	Off	On	On	NA	Limestone, 56.8 g/hr	<5	81	81
Low-Sulfur Knight Hawk	Hitachi	1:0.8	On	On	NA	NA	22	70	92
80:20 Antelope–Knight Hawk	Hitachi Zosen	1:1	On	Off	NA	NA	39	NA	39

[a] Not applicable.

Table ES-8. Representative Continuous Emission Monitoring Results Obtained During Conesville, Knight Hawk, and Low-Sulfur Knight Hawk Coal Combustion Testing of Hitachi Zosen, Cormetech, and Hitachi Catalysts and a WFDS

Coal	Catalyst	NO_x/NH^3	WFDS	Furnace NO_x, ppmv	SCR Outlet NO_x, ppmv	SCR NO_x Removal, %	Furnace SO_2, ppmv	SCR Inlet SO_3, ppmv	SCR Outlet SO_3, ppmv	WFDS Outlet SO_2, ppmv	WFDS SO_2 Removal, %
Low-Sulfur Knight Hawk	Hitachi	Off	On	On	NA	Limestone, 56.8 g/hr	18	73	91		
90:10 Antelope–Knight Hawk	Hitachi Zosen	1:1	On	Off	NA	NA	46	NA	46		
Conesville	Hitachi Zosen	Off	Off	407	402	1	3444	NA[a]	NA	3289	4
Conesville	Hitachi Zosen	1:1	On	493	37	92	3689	NA	20.4 ±1.3[b]	184	95
Conesville	Cormetech	Off	Off	491	484	1	3775	NA	NA	3721	1
Conesville	Cormetech	1:1	Off	507	93	82	3839	NA	NA	3815	1
Conesville	Cormetech	1:1	On	491	63	87	3868	NA	NA	243	94
Knight Hawk	Cormetech	Off	On	452	412	9	3513	NA	NA	30	99
Knight Hawk	Cormetech	1:1	On	353	30	91	3400	NA	NA	218	94
Knight Hawk	Cormetech	1:2	On	352	49	86	3319	NA	NA	274	92
Low-Sulfur Knight Hawk	Hitachi	Off	On	335	310	7	1999	NA	NA	44	98
Low-Sulfur Knight Hawk	Hitachi	1:1	On	451	72	84	2118	<1	14.1[c]	401	81
80:20 Antelope–Knight Hawk	Hitachi Zosen	1:1	Off	361	16	96	820	NA	NA	812	<1
70:30 Antelope–Knight Hawk	Hitachi Zosen	1:1	Off	427	15	96	1032	NA	NA	1014	2

[a] Not analyzed.

[b] Average and 95% confidence interval based on four SO_3 analyses.

[c] Average based on duplicate SO_3 analyses.

JV TASK 126 – MERCURY CONTROL TECHNOLOGIES FOR ELECTRIC UTILITIES BURNING BITUMINOUS COAL

INTRODUCTION AND BACKGROUND

The EERC developed a practically oriented, applied research consortium project to test cost-effective Hg control technologies for utilities burning bituminous coals. Based on health and emission data, the U.S. Environmental Protection Agency (EPA) has decided to regulate Hg from utility power plants. Effective approaches have been identified and tested for selected low-rank subbituminous and lignite coals (1, 2). However, the capability to achieve high Hg removal efficiencies (>80%) for high-rank bituminous coals remains a challenge. In general, successful Hg control approaches have included the use of oxidizing agents or sorbent enhancement additives (SEAs) alone or in combination with ACI as well as chemically and/or physically enhanced sorbents. For high-rank coals, recent data indicate that it is difficult to achieve high capture efficiencies at low cost (i.e., at low sorbent injection rates) (3, 4).

This research consortium project focused on providing detailed information on the control of Hg emissions in bituminous coal-fired power plants using existing or future APCDs, including SCR, a WFDS, and an ESP for nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate control, respectively. The project goal was to test innovative Hg control technologies that could potentially reduce Hg emissions from bituminous-fired power plants by ≥90% at costs of one-half to three-quarters of current estimates (e.g., DOE 2005 baseline cost estimate is $60,000/lb of Hg removed). Testing was performed using the EERC's combustion test facility (CTF). Pulverized bituminous coals were fired in the CTF at 580 MJ/hr (550,000 Btu/hr) to produce particulate-laden flue gas streams. The CTF was configured with various APCDs to simulate configurations of interest to the project sponsors. The APCDs tested included an ESP, SCR system, and a WFDS. Hg removal technologies investigated as part of this project included ACI, inorganic sorbent injection, Hg^0 oxidation catalysts (i.e., the noble metals in Hitachi Zosen, Cormetech, and Hitachi SCR catalysts), SEA injection, and coal blending with an alkaline-earth metal-rich subbituminous coal.

Mercury Regulations

In December 2000, EPA decided that the regulation of Hg from coal-fired electric utility steam-generating units was appropriate and necessary under Section 112 of the Clean Air Act (5). EPA determined that Hg emissions from power plants pose significant hazards to public health and must be reduced. The EPA *Mercury Study Report to Congress* (6) and the *Utility Hazardous Air Pollutant Report to Congress* (7) both identified coal-fired boilers as the largest single category of atmospheric Hg emissions in the United States, accounting for about one-third of the total anthropogenic emissions.

On March 15, 2005, EPA issued the first-ever federal rule, the Clean Air Mercury Rule (CAMR), to permanently cap and reduce Hg emissions from coal-fired power plants (a power plant is defined as an electrical generating facility that provides >25 MW_e). The rule is a market-based cap-and-trade program (Section 111 of the Clean Air Act) that is similar to the program in place for sulfur dioxide (SO_2). The rule was to be administered in two phases. The first phase placed a cap of 38 tons of Hg beginning in 2010. The second phase set a final cap of 15 tons by 2018. Currently, the estimate of Hg emitted from coal-fired power plants is 48 tons; therefore, the 2010 and 2018 reductions are 21% and 69%, respectively.

With the implementation in March 2005 of the Clear Air Interstate Rule (CAIR) to reduce emissions of SO_2 and NO_x in the eastern 28 states, it was expected that the initial phase of CAMR would be met as a cobenefit from the additional wet scrubbers and SCR systems that are being installed. However, a cap of 15 tons will require additional Hg-specific controls at many power plants.

In addition to CAMR, EPA published a final agency action that reversed the regulatory finding that it issued in December 2000. On February 8, 2008, the U.S. Court of Appeals for the District of Columbia Circuit issued an opinion in a case initiated by 15 states and other groups challenging CAMR and EPA's decision to "delist" mercury as a hazardous air pollutant. The court held that EPA's reversal of the December 2000 regulatory finding was unlawful and vacated both the reversal and CAMR and sent CAMR back to EPA for reconsideration.

On July 11, 2008, the U.S. Court of Appeals for the District of Columbia Circuit vacated CAIR, but then on December 23, 2008, the same court sent CAIR back to EPA to repair flaws that led the court to vacate the rule in July. The court gave no timetable for the flaws to be repaired; however, it did not intend to grant an indefinite stay to its decision.

A house Hg bill (H.R. 821) was introduced and supported by the new administration on February 3, 2009, to stop EPA's repair efforts of CAIR and to return to the more rigorous Hg emission standards required under Clean Air Act Section 112; thus it is likely that EPA will develop a maximum achievable control technology (MACT) standard, which would require every oil- and coal-based power plant to install Hg-specific controls. New EPA rulemaking could take several years to finalize.

Mercury Is a Health Concern

Mercury is a neurological toxin that can cause impairment of mental, sensory, and motor functions in humans, particularly in developing fetuses and children. A congressionally mandated reassessment of the toxicological effects of Hg issued by the National Research Council (5) in August 2000 reaffirmed EPA's low Hg exposure reference dose of 0.1 μg/kg per day as the scientifically justifiable level for the protection of child-bearing women, based on quantifiable findings for low-dose exposure in a large-study population in the Faroe Islands. Prompted by these health concerns, Hg is the chemical contaminant responsible, at least in part, for the issuance of approximately 2000 fish consumption advisories. Almost 68% of all advisories issued in the United States are a result of Hg contamination in fish and shellfish. Freshwater lake advisories have more than doubled in the last 5 years, resulting in over 40 states that have issued fish advisories because of Hg. Furthermore, the Food and Drug Administration (FDA) issued an advisory limiting consumption of certain ocean fish. However, FDA intends to revise the advisory by recommending that pregnant women should eat more not less fish during pregnancy. This is based on studies that have uniformly shown that increasing the maternal consumption of ocean fish has beneficial effects on child development outcomes. These effects may be because the relatively low methylmercury contents of ocean fish are not substantial enough to compromise the beneficial effects of the selenium that is abundantly present (8–12).

Mercury Control Challenge for Bituminous Coals

Mercury emissions from utilities burning U.S. coals were determined through EPA's Information Collection Request (ICR) (13), which mandated Hg and Cl analyses on coal shipped to units larger than 25 MW_e during 1999 and emission testing on 84 units selected to represent different categories of air pollution control equipment and coal rank. As shown in Table 1, bituminous coals from the eastern United States, on average, contain significantly higher concentrations of Hg, Cl, and S than subbituminous coals from the western United States. Based on the ICR data, Powder River Basin (PRB) coals produce as much as 6 lb Hg/10^{12} Btu compared to 8 lb Hg/10^{12} Btu for North Dakota lignites, 6.5 lb Hg/10^{12} Btu for Illinois Basin bituminous coals, 9.5 lb Hg/10^{12} Btu for Appalachian bituminous coals, and 12.5 lb Hg/10^{12} Btu for Gulf Coast lignites (13).

The chemical and mineralogical composition of coal has major effects on the quantity and chemical forms of Hg in the flue gas and, as a result, the effectiveness of APCDs to remove Hg from flue gas. Coals containing greater than about 200 ppm Cl produce flue gas that is dominated by the more easily removable mercuric compounds (Hg^{2+}), most likely mercuric chloride ($HgCl_2$). Appalachian and Illinois Basin bituminous coals generally have >200 ppm chlorine. Conversely, low-chlorine (<50 ppm) subbituminous and lignite coal combustion flue gases contain predominantly Hg^0, which is substantially more difficult to remove than Hg^{2+} (14). Additionally, the abundance of calcium in subbituminous coal fly ashes may reduce the oxidizing effect of the already-low chlorine content by reactively scavenging chlorine species (Cl, HCl, and Cl_2) from the combustion flue gas.

Table 1. Average Coal Compositions and Heating Values from a Select Group of ICR Data, on a dry basis

Parameter	Eastern Bituminous	Western Subbituminous
Hg, ppm	0.126	0.068
Cl, ppm	1064	124
S, wt%	1.67	0.48
Ash, wt%	11.65	7.92
Ca, ppm	2700	14,000
HHV,[a] Btu/lb	12,900	9300
Moisture, wt%	2.5	19.4

[a] Higher heating value.

Initial testing of Hg control technologies indicated that the major challenge was associated with western subbituminous and lignite coals because Hg^0 was generally the dominant species in their combustion flue gases (15, 16). As a result of these initial findings, significant research, development, and testing efforts were focused on the development of Hg^0 oxidation additives and SEAs specifically for low-rank coals. Recent testing at power plants firing low-rank coals has shown that Hg^0 oxidation and SEAs have successfully attained removal efficiencies above 85% to 90% during short-term testing (1 month) using 1 to 3 lb/Macf ACI (17). Conversely, only 50% to 80% removals were obtained during ACI at 5 to 7 lb/Macf into bituminous coal combustion flue gases (13, 14).

Mercury Control Options

Options for controlling Hg emissions are being investigated that have the potential to attain >90% removal of Hg from flue gas. An overview of methods being considered is shown in Figure 1. An investigation of Hg control technology options for coal-fired power plants must consider coal properties, firing conditions, and existing and future APCDs. The options for controlling Hg emissions include coal cleaning, combustion operation modification, chemical addition for oxidizing Hg^0, sorbent injection upstream of APCDs, Hg^0 oxidation catalysts, SCR catalysts, and sorbent beds.

Numerous evaluations of potential Hg sorbents have demonstrated that the chemical speciation of Hg controls its capture mechanism and ultimate environmental fate. ACI is the most tested technology available for capturing Hg. ACs have the potential to effectively adsorb Hg^0 and Hg^{2+}, depending on the carbon characteristics and flue gas composition (18). Most AC research has been performed in fixed-bed reactors that simulate relatively long residence time (gas–solid contact times of minutes or hours). This is representative of the Hg captured by fabric filters (FFs) (19–21). However, it is important to investigate short-residence-time (seconds), in-flight Hg capture because most of the coal-burning boilers in the United States employ cold-side ESPs (CS-ESPs) for controlling particulate matter (PM) emissions.

The projected annual cost for ACI into a duct is significant. Carbon-to-Hg weight ratios of 3000–18,000 lb C injected/lb Hg in flue gas have been estimated to achieve 90% Hg removal from a coal combustion flue gas containing 10 $\mu g/Nm^3$ of Hg (22). More efficient C-based sorbents are required to enable lower C-to-Hg weight ratios to be used, thus reducing costs. The Hg reactivity and capacity of C have been improved by chemically treating the C before or after it is injected.

Hg^0 oxidation technologies being investigated for lignite and subbituminous coals include catalysis, chemical additives, and cofiring fuels. The catalysts that have been tested include metal-impregnated, oxide-impregnated, noble metal, and SCR catalysts for NO_x reduction. The chemical additives tested are generally halogen-containing salts. The cofired fuels tested contained oxidizing agents (18).

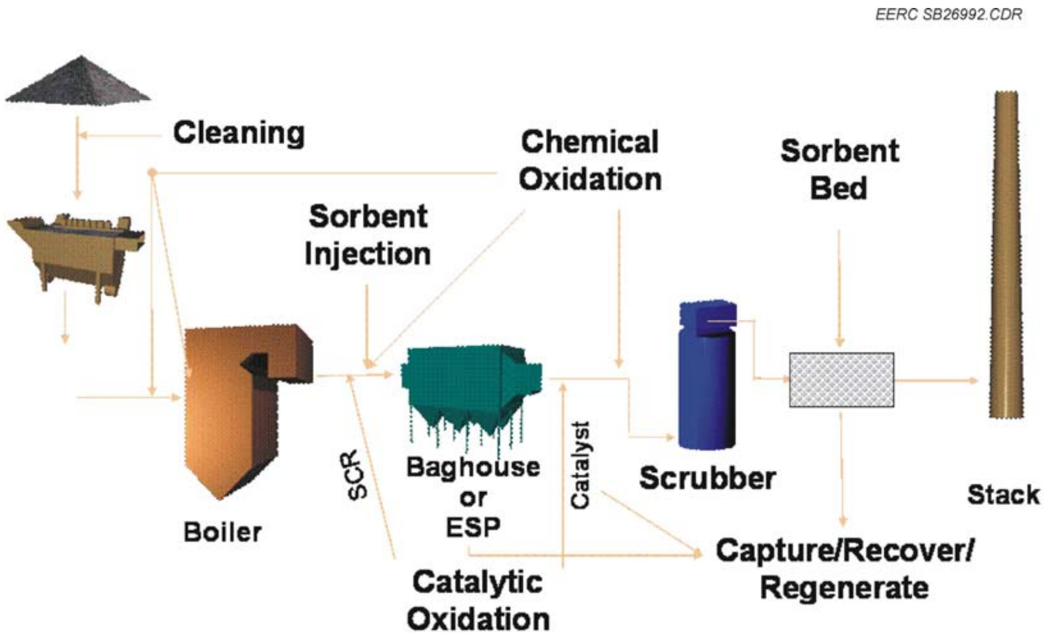


Figure 1. Options for controlling coal combustion Hg emissions.

Mercury speciation sampling has been performed upstream and downstream of SCR catalysts at power plants firing bituminous and subbituminous coals (23). Test results indicated evidence of Hg^0 oxidation across SCR catalysts when bituminous coals were fired. However, when subbituminous coal was fired, the results indicated limited Hg^0 oxidation, and more testing needs to be performed on low-rank coals. The capability of SCR systems to promote Hg^0 oxidation is coal-specific and probably related to the Cl, S, and Ca contents of the coal as well as temperature and specific operation of the SCR catalyst, including space velocity.

ESP Testing

Figure 2 shows results obtained from the DOE Phase II Hg control field tests conducted on several plants with various types of Hg control technologies. These technologies included ACI, enhanced carbon injection, and SEA injection combined with ACI. The best methods include SEA2 combined with ACI and enhanced carbons for low-rank coals. Results for high-rank coals indicate relatively high injection rates in order to attain higher removal rates that are 2 to 4 times higher than that attained for low-rank coals. Figure 3 shows that over 7 lb/Macf of carbon is required to achieve 80% control for an eastern bituminous coal fired in a pulverized coal (pc)-fired unit equipped with an ESP. Table 2 shows additional data indicating that high ACI rates are required for effectively capturing Hg. The effect of sulfur compounds in the flue gas on Hg capture are obtained from testing performed at Mississippi Power Plant Daniel, which is equipped with an ESP. With no SO_3 injection upstream of the ESP, 82% and 70% of the Hg in the flue gas was removed at carbon injection rates of 10 and 6 lb/Macf, respectively. With 20 ppm sulfur trioxide (SO_3) in the flue gas, the performance was much poorer, 58% and 42%

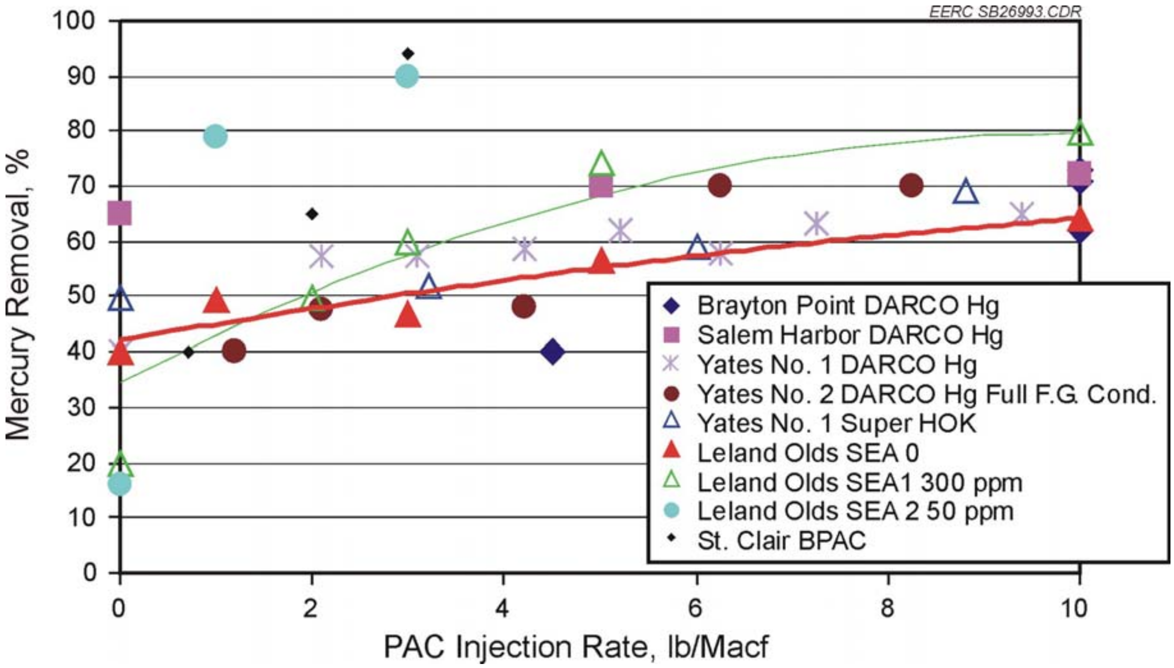


Figure 2. Hg removal percentages across the ESP during full-scale testing supported by DOE (Leland Olds – lignite-fired, St. Clair – subbituminous-fired, Brayton Point – bituminous-fired, Yates – bituminous-fired, Salem Harbor – bituminous-fired) (PAC = powdered activated carbon).

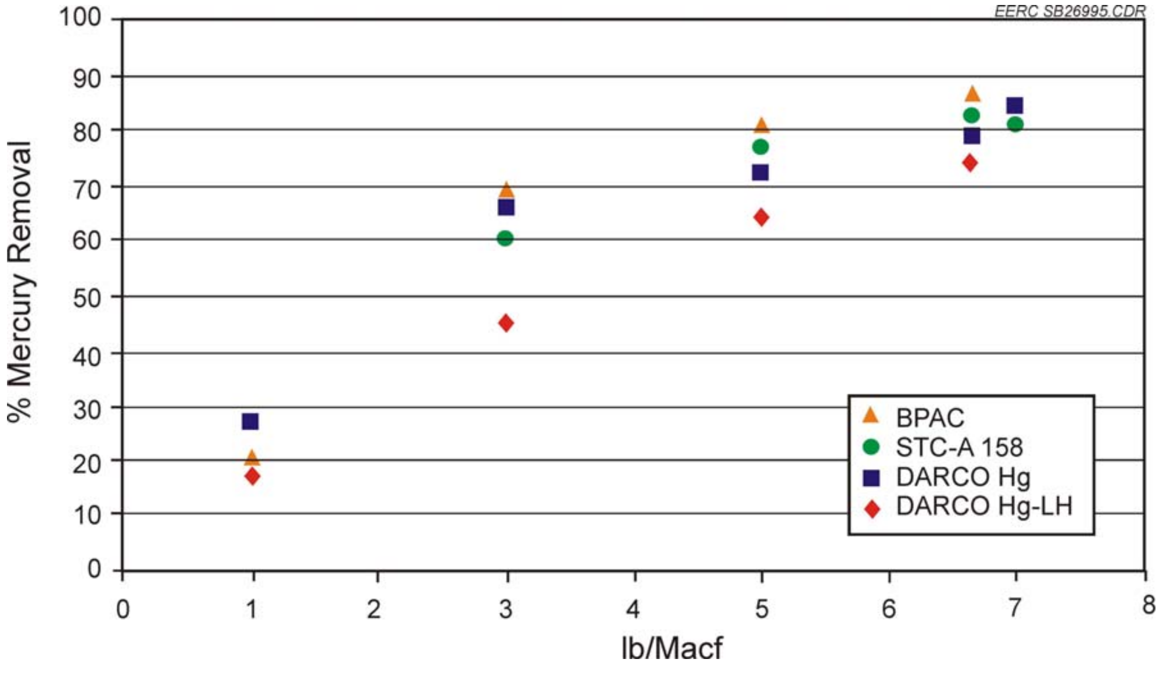


Figure 3. Results of testing at Duke Power's Allen Station (pc with ESP only) (24).

Table 2. Summary of Mercury Control Data for Bituminous, Subbituminous, and Lignitic Coals (4)

Coal	PM Unit	Hg Removal	lb/MMacf	Plant	Utility	Data
Bitum. Low-S	CS-ESP	85%	5.0	Allen	Duke	Apogee/ST
Bitum. High-S	CS-ESP	70%	4.0	Lausche	OhioU	SorbTech
Bitum. High SO_3	CS-ESP	NA[a]	4.0	Merrimack	PSNH	SorbTech
Bitum. Low-S	HS-ESP[c]	80%[b]	6.4	Cliffside	Duke	SorbTech
Bitum. Low-S	HS-ESP	50%	5.0	Buck	Duke	SorbTech
Subbitum. Blend	CS-ESP	90%	3.0	St. Clair	Detroit Ed.	SorbTech
Subbituminous	CS-ESP	90+%	3.0	St. Clair	Detroit Ed.	SorbTech
Subbituminous	CS-ESP	90%	3.2	Stanton 1	GRE[d]	EERC/URS
Lignite	SDA[e]/FF	95%	1.5	Stanton 10	GRE	EERC/URS
Lignite	CS-ESP[f]	70%	1.5	Stanton 10	GRE	EERC/URS

[a] Public Service of New Hampshire (PSNH) has not yet publicly released these data.
[b] When under low-load conditions at this plant.
[c] Hot-side ESP.
[d] Great River Energy.
[e] Spray dryer absorber.
[f] Actually, the in-flight Hg removal across the SDA.

removal with injection rates of 10 and 6 lb/Macf, respectively. More effective methods are, therefore, required for Hg removal with bituminous coals.

ESP–FF Testing

EERC pilot- and full-scale ESP and ESP–FF (TOXECON®) Hg removal efficiencies for bituminous coal are compared to Fort Union lignite and subbituminous coal removal efficiencies in Figure 4 as a result of ACI. As indicated in Figure 4, coal type (i.e., composition) was an important parameter that affected the Hg removal efficiency of a control device. During the pilot-scale lignite and utility-scale eastern bituminous coal tests, Hg removal efficiencies increased with increasing ACI rates. Conversely, Hg removal efficiencies were never greater than 70%, regardless of the ACI rate into the PRB subbituminous coal combustion flue gas.

Dry and Wet Scrubber Testing

Pilot- and full-scale testing have been conducted on dry and wet scrubbers. A significant amount of testing has been conducted on lower-rank coals. The results of recent testing conducted as part of the DOE Phase II program for subbituminous- and lignite-fired

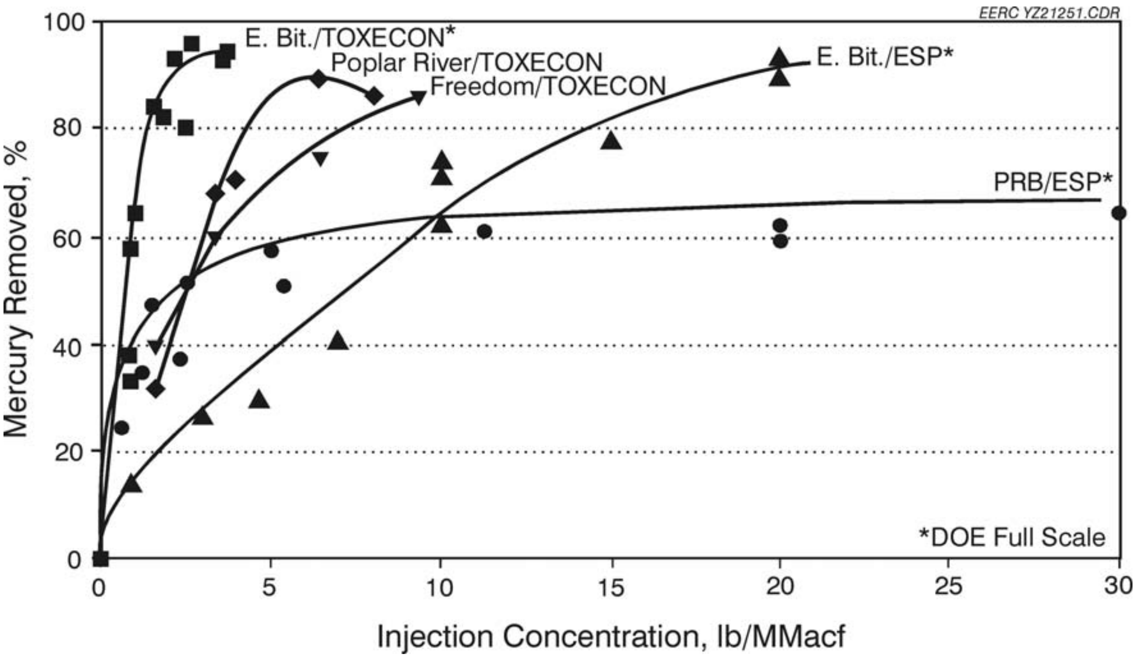


Figure 4. Pilot-scale ESP–FF (22) and full-scale TOXECON and ESP (25) Hg removal efficiencies as a function of ACI rate.

systems equipped with SDA–FF are illustrated in Figure 5. Based on these results, the most effective methods for mercury control are SEA combined with ACI and enhanced ACI. The results of the ICR for mercury control without the addition of mercury control technologies are shown in Figure 6, indicating high removal rates were obtained for a bituminous-fired plant equipped with a dry scrubber. Figure 7 shows ICR results for a wet scrubber. With a wet scrubber alone, native capture of mercury from bituminous coals averaged around 80%. But with an SCR in the air pollution control train, additional oxidation of the mercury results in higher removals with a downstream wet scrubber (typically greater than 90%).

Coal Blending

Most of the PRB subbituminous coals produce ashes that are rich in alkaline-earth metals, mainly calcium and magnesium. These metals are reactive with SO_3, thus subbituminous coal ashes reactively scavenge SO_3 from flue gas to form sulfate compounds. The blending of a PRB subbituminous coal with a bituminous coal should promote SO_3 capture, thereby reducing the adverse effects of SO_3 on Hg adsorption on AC. The higher halogen contents of bituminous coals should also be beneficial in promoting Hg^0 oxidation, thus enhancing Hg capture in existing APCDs.

Mercury Reduction Technologies

Table 3 summarizes the potential Hg reduction technologies evaluated during the consortium research project. These technologies are described in the subsequent subsections of this report.

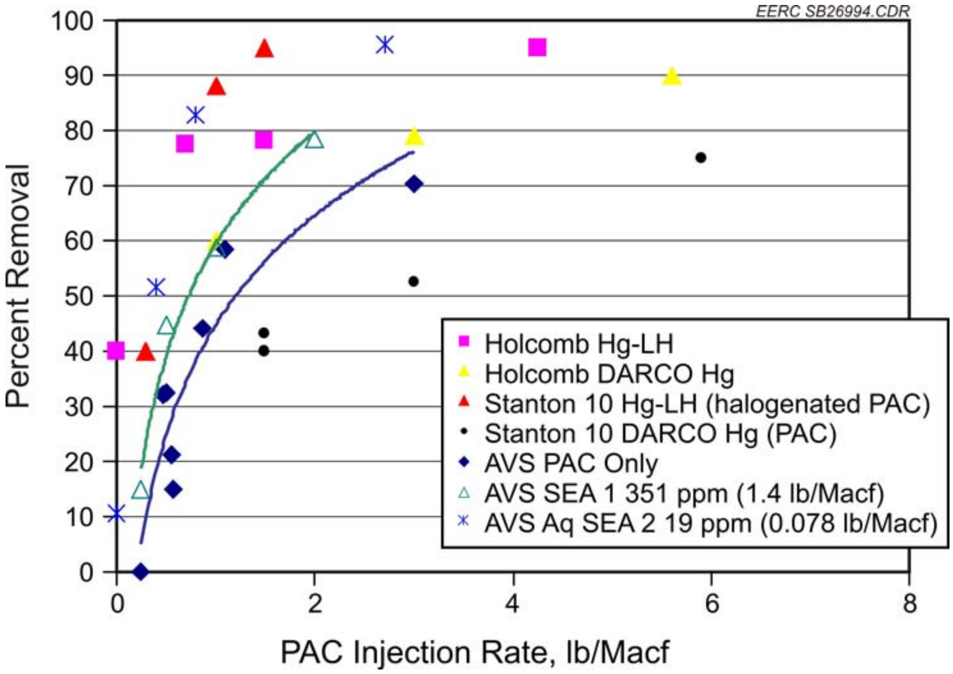


Figure 5. Percent removal achieved in Phase II DOE field testing with SDA–FF using sorbents and SEA.

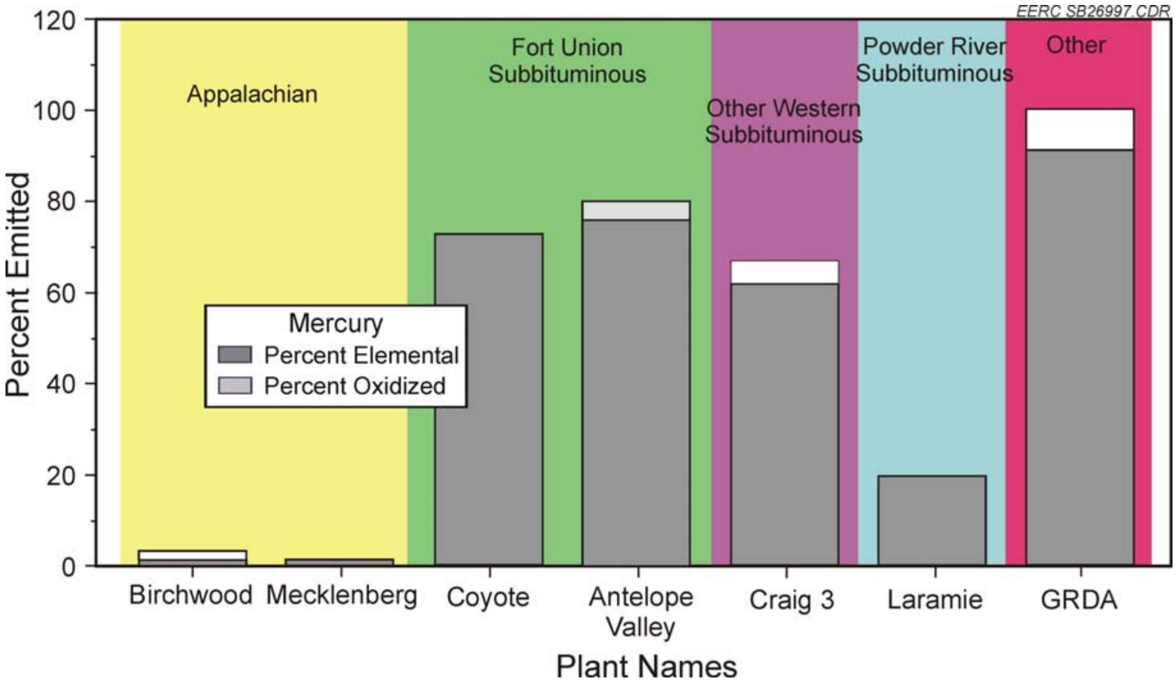


Figure 6. Percent mercury emitted from dry scrubbers based on ICR data.

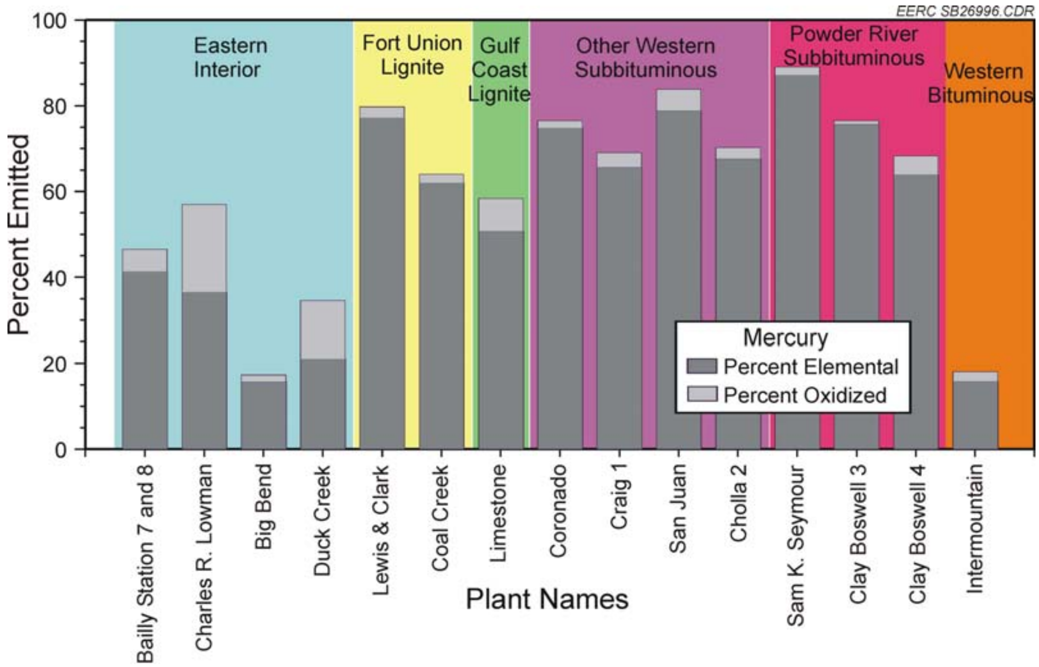


Figure 7. Percent mercury emitted from wet scrubbers based on ICR data.

Sorbent Injection Technologies: NORIT Americas Inc. DARCO® and Envergex

NORIT Americas Inc. DARCO Hg and DARCO Hg-LH are lignite-based PACs manufactured specifically for the removal of Hg from flue gas. DARCO Hg-LH is an impregnated lignite-based activated carbon that is designed for capturing Hg from halogen-lean flue gas. The DARCO E26 is a lignite-based activated carbon that was treated with an Envergex proprietary process. General properties and characteristics of the DARCO sorbents are presented in Table 4. Properties of the Envergex sorbents are unavailable because they are proprietary and confidential**.**

SEAs: SEA2, Limestone, and Trona

SEA2 is the EERC's proprietary additive that has been used in many pilot- and full-scale demonstrations of enhanced Hg control. This powdered additive was vaporized and injected using a tube furnace. SEA2 promotes Hg^0 oxidation and capture on sorbents, including the unburned carbon in fly ash.

Efforts to remove NO_x through the use of SCR systems have resulted in increased SO_3 concentrations in flue gas. In addition, when WFDSs are used for sulfur control, particularly with high-sulfur fuels, significant levels of sulfuric acid (H_2SO_4) mist tend to pass through the system and result in stack opacity issues. Increased corrosion has been identified as another potential problem with increased SO_3 in flue gas. SO_3 also hinders the performance of ACI for capturing Hg. Limestone, consisting mainly of calcite ($CaCO_3$), or trona, a hydrated sodium bicarbonate carbonate ($Na_3[HCO_3][CO_3]\ 2H_2O$) mineral, was injected into the flue gas during testing to capture SO_3 and potentially improve ACI performance.

Table 3. Potential Hg Control Technologies

- Sorbent Injection Technologies
  - NORIT Americas Inc. DARCO® Hg
  - NORIT Americas Inc. DARCO E26
  - NORIT Americas Inc. DARCO Hg-LH
  - Envergex E11
  - Envergex E21
  - Envergex Hg E23
  - Envergex 24
  - Envergex E25
  - Envergex Hg E25
  - Envergex E27
  - Envergex 28
  - Envergex 30
  - Envergex 31
  - Envergex 33
- SEAs
  - SEA 2
  - Limestone
  - Trona
- Hg^0 Oxidation Technologies
  - Hitachi Zosen Catalyst
  - Cormetech Catalyst
  - Hitachi Catalyst
- Coal Pretreatment Processes
  - Blending with PRB Subbituminous Coal

Table 4. Specifications of Norit Carbons (26)

Parameter	DARCO Hg	DARCO Hg-LH
Moisture, wt%, maximum	80	70
−325 (45 μm) mesh, wt%, minimum	95	95
Iodine Number, mg/g	550	500
Sulfur, wt%	1.2	1.2
Bulk Density, tamped, g/mL (lb/ft^3)	0.51 (32)	0.60 (37)
Surface Area, m^2/g	600	550
Ignition Temperature, °C	≥ 400	≥ 400

Hg^0 Oxidation Technologies: Hitachi Zosen, Cormetech, and Hitachi SCR Technologies

The noble metals contained in the catalysts used in SCR technologies may promote Hg^0 oxidation and capture in APCDs. Thus catalysts supplied by Hitachi Zosen, Cormetech and Hitachi were tested as potential multipollutant control technologies for reducing NO_x and Hg emissions.

Coal Pretreatment Process: Blending with Subbituminous Coal

PRB subbituminous coals generally produce ashes that are rich in alkaline-earth metals, primarily calcium and magnesium. These metals are reactive with SO_3, thus subbituminous coal ashes reactively scavenge SO_3 from flue gas to form sulfate compounds. The blending of a PRB subbituminous coal with a bituminous coal should promote SO_3 capture, thereby reducing the adverse effects of SO_3 on Hg adsorption on AC. The higher halogen contents of bituminous coals should also be beneficial in promoting Hg^0 oxidation, thus enhancing Hg capture in existing APCDs.

OBJECTIVES

The overall goal is to evaluate and identify advanced innovative mercury (Hg) control technologies that will reduce Hg emissions from bituminous-fired power plants by ≥90% at costs of one-half to three-quarters of current estimates associated with activated carbon injection (ACI); the U.S. Department of Energy's (DOE's) 2005 baseline cost estimate is $60,000/lb of Hg removed. The specific objectives are focused on determining the feasibility of the following technologies: elemental mercury (Hg^0) oxidation catalysts for improving Hg capture in a wet scrubber, incorporation of additives and technologies that enhance Hg sorbent effectiveness in an electrostatic precipitator (ESP) and ESP–wet flue gas desulfurization system (WFDS) configuration. In addition, an objective was to examine and overcome the deleterious effect of coal sulfur on Hg capture. The potential beneficial effect of blending an alkaline-earth metal-rich subbituminous coal with a bituminous coal on Hg capture was also evaluated.The project work plan consisted of five tasks to achieve the objectives:

- Task 1 – Kickoff Meeting and Needs Assessment
- Task 2 – Pilot-Scale Test System Setup and Shakedown
- Task 3 – Weeklong Test Campaigns
  - Task 3a – Mercury Control Enhancement for Systems Equipped with Particulate Control Devices and Scrubbers
  - Task 3b – Mercury Control Enhancement in Multipollutant Control Systems
    - ♦ Plants with selective catalytic reduction (SCR) units

- Task 4 – Blending Tests
  - Task 4a – Setup and Shakedown for Blending Tests
  - Task 4b – Parametric Tests
- Task 5 – Reporting and Management

Task 1 consisted of an assessment of client fuels, system configurations, and existing air pollution control devices (APCDs) and a determination of coals and APCD configurations to be tested. A detailed work plan was developed based on client needs expressed at a project kickoff meeting held at the Energy & Environmental Research Center (EERC) on March 27, 2007.

In Task 2, pilot-scale WFD and SCR systems were designed and constructed to be used for pilot-scale coal combustion testing. Shakedown testing of the SCR and WFDS involved firing natural gas in a pilot-scale combustion system. A week of shakedown tests with high-sulfur (>2%) coal were also performed.

During Task 3, various Hg control technologies were evaluated over several weeks using different configurations involving the ESP, WFDS, and SCR. Task 4 involved an evaluation of coal blending as a Hg control strategy. Task 5 involved the preparation of monthly and quarterly progress reports and a final technical report for project sponsors and participants.

EXPERIMENTAL PROCEDURES

Description of Pilot-Scale Test Facilities

Combustion Test Facility

An isometric drawing of the EERC's CTF is shown in Figure 8. The furnace capacity is approximately 100 lb/hr (750,000 Btu/hr) depending on the heat content of the fuel. The combustion chamber is 30 inches in diameter, 8 feet high, and refractory-lined and has been used for combustion testing of fuels of all rank. The furnace can be configured in many different arrangements, and the graphic shows a second probe bank used for low-temperature ash-fouling evaluations. This section was replaced by a series of water-cooled, refractory-lined heat exchangers for the tests reported here.

The furnace exit gas temperature (FEGT) was maintained between 1900° and 2150°F. Two Type S thermocouples, located at the top of the combustion chamber, were used to monitor the FEGT. They are situated 180° apart at the midpoint of the transition from vertical to horizontal flow. Excess air levels were controlled manually by adjusting valves on the primary and secondary airstreams. The distribution was about 15% primary and 85% secondary.

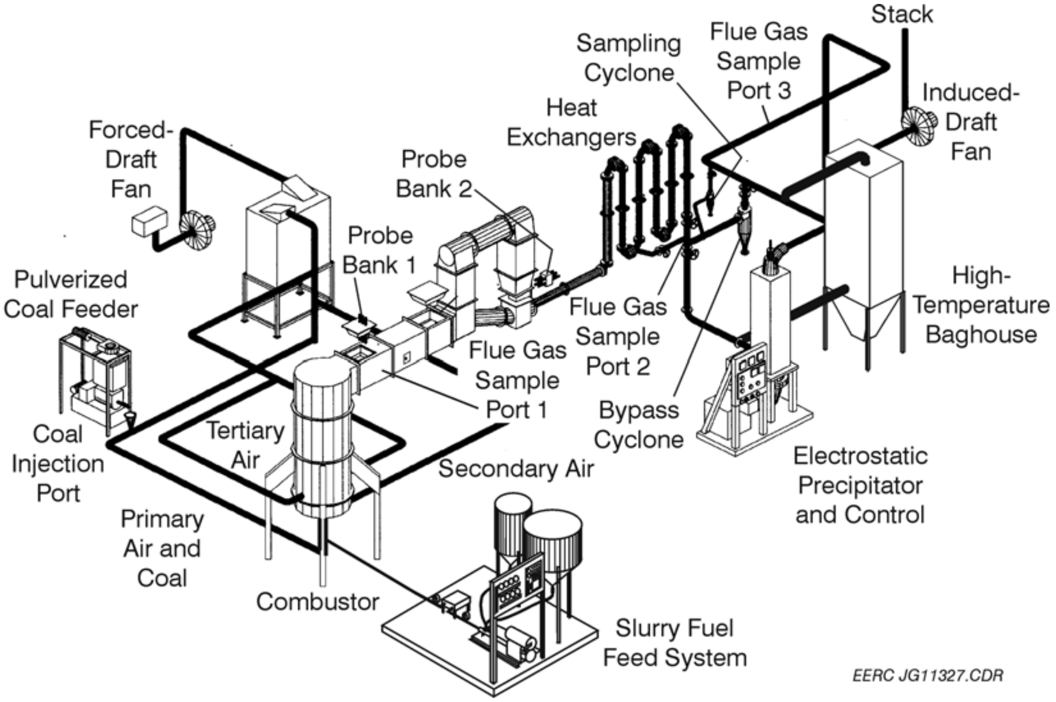


Figure 8. The CTF, with its auxiliary systems, provides a controlled environment for combustion tests.

Conesville, Knight Hawk, and low-sulfur Knight Hawk bituminous coals and the Knight Hawk–subbituminous Antelope coal blends were pulverized remotely in a hammer mill pulverizer, targeted to a size of 70% less than 200 mesh. They were then charged to a microprocessor-controlled weight loss feeder from a transport hopper. Combustion air was preheated by an electric air heater. The pulverized coals were screw-fed by the gravimetric feeder into the throat of a venturi section in the primary air line to the burner. Heated secondary air was introduced through an adjustable-swirl burner, which uses only primary and secondary air. Flue gas passed through the furnace into a 10-inch-square duct that was also refractory-lined. After exiting the duct, the flue gas passed through a series of water-cooled, refractory-lined heat exchangers and a series of air-cooled heat exchangers before being discharged through an ESP or ESP–WFDS.

Electrostatic Precipitator

A single-wire, tubular ESP, shown in Figure 9, was used for testing. A flue gas flow velocity through the ESP of 5 ft/min (1.52 m/min) and a plate spacing of 11 in. provide a specific collection area of 125 ft^2/1000 acfm (11.6 m^2/28.32 acmm) at 300°F (149°C). The ESP has an electrically isolated plate that is grounded through an ammeter, thus enabling continual monitoring of the actual plate current to ensure consistent ESP operation. The tubular plate is suspended by a load cell which is used to monitor rapping efficiency. In addition, sight ports are located on top of the ESP to enable online inspections of electrode alignment, sparking, rapping, and dust buildup on the plate. The ESP was operated at 40–60 kV and a corona current of 4.0 mA. The ESP was thoroughly cleaned between tests so that all tests began on the same basis.

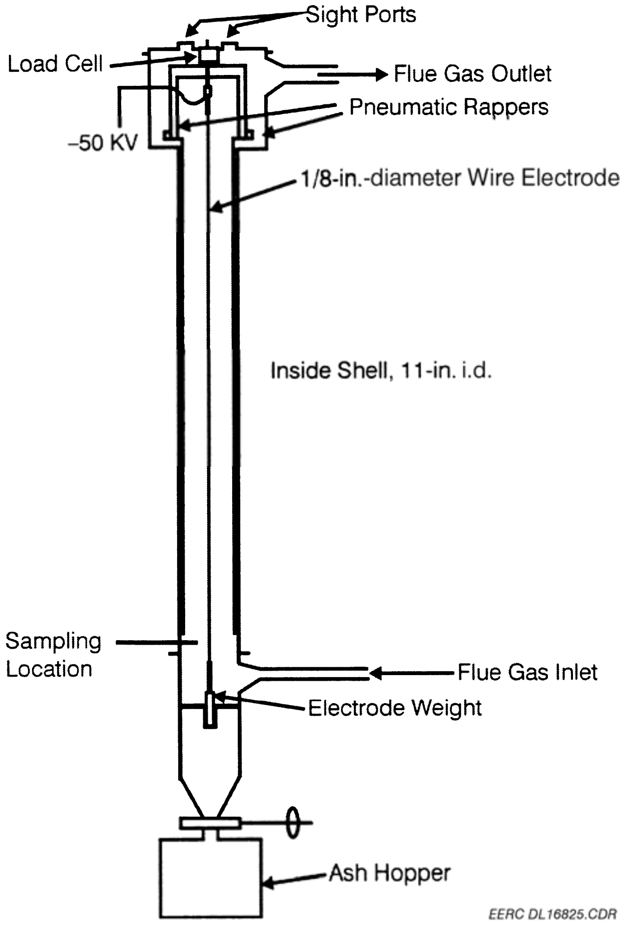


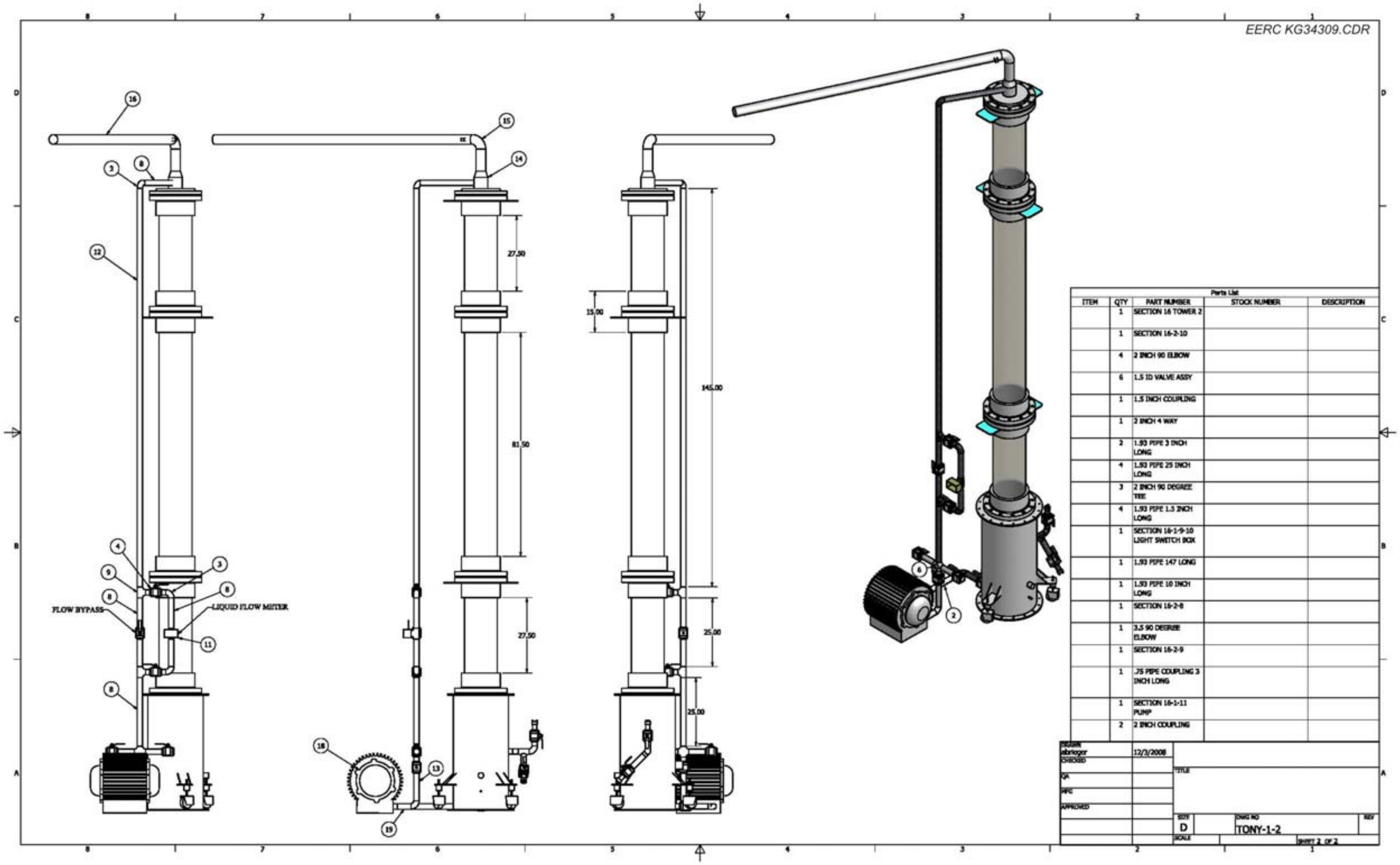
Figure 9. Schematic of the pilot-scale ESP.

Wet Flue Gas Desulfurization System

The pilot-scale WFDS is shown schematically in Figure 10. The column is 7 inches in diameter, with a height of approximately 20 feet. The scrubber is equipped with packing to ensure that the scrubber solutions do not simply run down the walls of the scrubber. The column is made of plastic material, while the spray nozzles are made from stainless steel.

Gas Analyses

Two banks of Rosemount NGA gas analyzers were used to monitor O_2, CO, CO_2, and NO_x concentrations. SO_2 was monitored by analyzers manufactured by Ametek. The analyzers were located at the furnace exit and the particulate control device exit. The gas analyses were reported on a dry basis. Baldwin Environmental manufactures the flue gas conditioners used to remove water vapor from each gas sample. The flue gas constituents were constantly monitored and recorded by the CTF's data acquisition system.



ITEM	QTY	PART NUMBER	STOCK NUMBER	DESCRIPTION
	1	SECTION 16 TOWER 2		
	1	SECTION 16-2-10		
	4	2 INCH 90 ELBOW		
	6	1.5 ID VALVE ASSY		
	1	1.5 INCH COUPLING		
	1	2 INCH 4 WAY		
	2	1.93 PIPE 3 INCH LONG		
	4	1.93 PIPE 25 INCH LONG		
	3	2 INCH 90 DEGREE TEE		
	4	1.93 PIPE 1.5 INCH LONG		
	1	SECTION 16-1-9-10 LIGHT SWITCH BOX		
	1	1.93 PIPE 147 LONG		
	1	1.93 PIPE 10 INCH LONG		
	1	SECTION 16-2-8		
	1	3.5 90 DEGREE ELBOW		
	1	SECTION 16-2-9		
	1	.75 PIPE COUPLING 3 INCH LONG		
	1	SECTION 16-1-11 PUMP		
	2	2 INCH COUPLING		

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SHEET 2 OF 2

Figure 10. Schematic of the pilot-scale WFDS system.

Sampling, Analyses, and Data Reduction

Continuous Mercury Sampling and Analysis

Continuous mercury monitors (CMMs) were used for determining Hg^0 and total gaseous Hg concentrations. The majority of the measurements were made with Tekran analyzers. Tekran Model 2537A atomic fluorescence-based Hg vapor analyzers were used in conjunction with PS Analytical S235C400 wet-chemistry conversion units. The S235C400 uses two separate liquid flow paths, one to continuously reduce Hg^{2+} to Hg^0, resulting in a total gaseous Hg sample, and the other to continuously scrub out Hg^{2+}, resulting in an Hg^0 sample. The S235C400 also uses a Peltier thermoelectric cooler module to cool and dry the sample gases prior to analysis. The Tekran instrument traps the Hg vapor from the conditioned sample onto a cartridge containing an ultrapure gold sorbent. The amalgamated Hg is then thermally desorbed and detected using atomic fluorescence spectrometry. A dual-cartridge design allows alternate sampling and desorption, resulting in continuous measurement of the sample stream. The Model 2537A allows two methods of calibration: manual injection or automatic permeation source. Permeation source calibration was used to calibrate the instrument daily. Manual injection calibration on both cartridges was performed for verification. The Tekran instrument can measure either Hg or Hg^0, with one analysis point being obtained approximately every 2.5 minutes.

Ontario Hydro (OH) Method and Mercury Analysis

ASTM International Method D6784-02 (Standard Test Method for Elemental, Oxidized, Particle-Bound, and Total Mercury in Flue Gas Generated from Coal-Fired Stationary Sources – Ontario Hydro Method) was used during Antelope–Knight Hawk coal combustion tests. Samples were withdrawn from the flue gas stream isokinetically through a probe/filter system maintained at 120°C or the flue gas temperature, whichever was greater, followed by a series of impinger solutions in an ice bath. Particle-bound mercury was collected on a quartz filter in the front half of the sampling train. Hg^{2+} was collected in impingers containing a chilled aqueous potassium chloride solution. Hg^0 was collected in subsequent impingers (one impinger containing a chilled aqueous acidic solution of hydrogen peroxide and three impingers containing chilled aqueous acidic solutions of potassium permanganate). Samples were recovered and sent to the lab for analysis. The OH samples were typically prepared and analyzed the same day of collection or the following day. Mercury was determined by cold-vapor atomic absorption spectroscopy (CVAAS) using a CETAC M6000A automated Hg analyzer. Results were initially reported in µg/L and then converted to µg/dscm.

Mercury Analyses of Combustion Residues

The particle-bound Hg and Hg in combustion residues were determined using ASTM Method D6414-01 (Standard Test Method for Total Mercury in Coal and Coal Combustion Residues by Acid Extraction or Wet Oxidation/Cold-Vapor Atomic Absorption). Samples were heated in a hot-water bath at 80°C with a mixture of nitric and hydrochloric acids. After digestion, the solutions were cooled, diluted to a known volume, filtered, and analyzed by CVAA using a CETAC M6000A Hg analyzer. Mercury concentrations were reported as µg/g on a dry basis.

Coal Analyses

All coals were pulverized to a standard combustion grind (i.e., 70%–80% of the coal particles <75 µm) for analysis and combustion testing purposes. Hourly samples of each coal were collected during testing. During multiple days of testing for a given coal, daily samples were combined to provide a representative composite sample for analysis. Proximate and ultimate analyses were conducted on the composite coal samples using ASTM Methods D3172, D5142, and D3176. A Mitsubishi Model TOX-100 total chlorine analyzer was used to perform the recently validated ASTM Method D6721-01 (Standard Test Method for Determination of Chlorine in Coal by Oxidative Hydrolysis Microcoulometry). Coal Hg contents were determined using CVAAS according to EPA Method 245.1 and EPA SW-846 Method 7470.

Test Coals

Three bituminous coals were supplied by Knight Hawk Coal, L.L.C., and American Electric Power, and a PRB subbituminous coal was supplied by Kennecott Energy Company for Hg control testing purposes. General information on the three coals is presented in Table 5.

Overview of Pilot-Scale Testing

Conesville Bituminous Coal Combustion Testing of a Hitachi Zosen Catalyst, ESP, and WFDS System

Table 6 presents the initial test matrix involving the combustion of Conesville bituminous coal in the CTF with the Hitachi Zosen catalyst, an ESP, and a WFDS installed. Baseline testing was performed to provide information on Hg control without the use of additives or sorbents. The industry standard of injecting DARCO Hg was performed so that test results could be compared to other pilot- and full-scale studies. As part of the test matrix in Table 6, CMM results were obtained at the inlet to the SCR or in between the three catalyst layers. CMM results were also obtained at the ESP outlet and WFDS outlet.

Table 5. Coal Information

Organization	Mines or Plant	Seams Mined	Location	Production, tons
Knight Hawk Coal, L.L.C.	Creek Paum, Royal Falcon, Prairie Eagle, and Red Hawk	Herrin No. 6, Springfield No. 5, and Murphysboro	Ava, IL	2,660,234[a]
American Electric Power	Conesville Coal Preparation Company	Lower Freeport	Conesville, OH	4,549,129[b]
Kennecott Energy Company	Antelope	Anderson/Canyon	Douglas, WY	29,682,368[c]

[a] 2007 mine production statistic from *The Illinois Coal Industry*; Report of the Department of Commerce and Economic Opportunity, Office of Coal Development, June 2008, 78 pp.

[b] 2003 coal received by Conesville plant statistic from *Keystone Coal Industry Manual*; Mining Media: Prairieville, LA, 2005.

[c] 2004 mine production statistic from *Keystone Coal Industry Manual*; Mining Media: Prairieville, LA, 2005.

Table 6. Test Matrix Involving Conesville Bituminous Coal Combustion, a Hitachi Zosen Catalyst, ESP, and WFDS

Date	Duration, hr	ESP	WFDS	NH_3, ppmv	Sorbent, lb/MMacf
10/6/08	0.78	On	On	18	
10/6/08	0.67	On	On		
10/6/08	0.22	On	On	423	
10/6/08	2.42	On	On	373	
10/7/08	4.47	On	On	468	
10/7/08	0.53	On	Off	423	
10/7/08	3.92	On	Off	473	
10/8/08	0.92	On	Off	473	
10/8/08	0.65	On	Off	448	
10/8/08	0.63	On	Off	448	DARCO Hg, 1
10/8/08	0.98	On	Off	448	DARCO Hg, 3
10/8/08	0.40	On	Off	473	DARCO Hg, 5
10/8/08	0.83	On	On	473	
10/10/08	1.00	On	On		
10/10/08	1.00	On	On	428	
10/10/08	0.48	On	On	448	
10/10/08	1.00	On	On	448	
10/13/08	0.70	On	On	398	
10/13/08	0.57	On	On	410	
10/13/08	0.87	On	On	410	
10/13/08	0.40	On	Off	410	
10/14/08	2.98	On	Off	433	
10/14/08	0.33	On	On	440	
10/14/08	1.75	Off	On	440	
10/15/08	0.97	On	On	448	
10/15/08	2.10	On	On	448	
10/15/08	2.03	On	On	448	
10/16/08	0.63	On	On	440	
10/16/08	0.77	On	On	440	
10/16/08	0.88	On	On	440	
10/16/08	2.50	On	On	440	
10/16/08	1.27	On	On	440	
10/17/08	4.78	On	On	428	
10/20/08	2.40	On	On	436	
10/20/08	0.55	On	On	387	
10/20/08	1.20	On	On	344	
10/20/08	1.35	On	On	473	
10/20/08	0.48	On	On		
10/20/08	0.88	On	On	492	
10/21/08	0.55	On	On		
10/21/08	1.12	On	On	410	
10/21/08	1.35	On	On	410	
10/21/08	0.97	On	On		
10/21/08	1.32	On	On	410	
10/21/08	0.72	On	On	410	
10/21/08	0.87	On	On	528	

Conesville or Knight Hawk Bituminous Coal Combustion Testing of a Cormetech Catalyst, ESP, and WFDS

Table 7 summarizes the test matrix involving sorbent and/or SEA injection into the CTF equipped with Cormetech catalyst, ESP, and WFDS. On October 23, 2008, Conesville coal was burned in the CTF, and then beginning on October 24, 2008, the Knight Hawk coal was burned in the CTF.

Low-Sulfur Knight Hawk Bituminous Coal Combustion Testing of Hitachi Catalyst, ESP, and WFDS

Shown schematically in Figure 11 are the APCD configuration and injection and sampling locations that were used during the combustion of low-sulfur Knight Hawk coal. CMM measurements were performed at Locations 1 (SCR inlet), 4 (SCR outlet), 5 (ESP inlet), 6 (ESP outlet), and 7 (scrubber outlet). SO_3 sampling was performed at Locations 1 (SCR inlet) and 4 (SCR outlet). Depending on injection requirements, either or both injection locations indicated in Figure 11 were used. The ESP depicted in Figure 11 is larger than the ESP used during the previous pilot-scale testing of Hg control technologies. The newly constructed ESP accommodates the full flue gas flow, whereas the older ESP treated about half of the flue gas flow stream. Summarized in Table 8 is the testing matrix involving the APCD configuration indicated in Figure 11 and low-sulfur Knight Hawk coal combustion.

Antelope–Knight Hawk Coal Blend Combustion Testing of Hitachi Zosen Catalyst, ESP, and WFDS

The Antelope coal was blended with Knight Hawk coal at blend ratios of 90:10, 80:20, and 70:30 on a dry-heating-value basis to evaluate the effects of coal blending on Hg emission control.

RESULTS AND DISCUSSION

Task 1 – Kickoff Meeting and Needs Assessment

A detailed work plan described in Tables 6–8 was developed based on client needs expressed at a project kickoff meeting held at the EERC on March 27, 2007.

Task 2 – Pilot-Scale Test System Setup and Shakedown

The existing pilot-scale combustion system was modified to accommodate a WFDS and SCR. A WFDS was designed with input from the project sponsors and built. The WFDS is presented schematically in Figure 10. The WFDS column is 7 inches in diameter, with a height of approximately 20 feet. The scrubber is equipped with packing to ensure that the scrubber solutions do not simply run down the walls of the scrubber. The column is made of plastic material, while the spray nozzles are made from stainless steel.

Table 7. Test Matrix Involving Conesville or Knight Hawk Bituminous Coal Combustion, a Cormetech Catalyst, an ESP, and a WFDS

Date	Duration, hr	ESP	WFDS	NH_3, ppmv	Sorbent, lb/MMacf	SEAs, ppm or g/hr
10/23/08	0.80	On	On			
10/23/08	1.03	On	On	550		
10/23/08	0.55	On	On	550		
10/23/08	0.80	On	On			
10/24/08	0.63	On	On			
10/24/08	1.67	On	On	450		
10/24/08	2.38	On	On	450		
10/24/08	0.57	On	On	450		
10/27/08	3.75	On	On	495		
10/27/08	1.83	On	On	450		
10/28/08	1.13	On	On			
10/28/08	1.05	On	On	425		
10/28/08	0.65	On	On	425	DARCO Hg, 1	
10/28/08	0.15	On	On	350	DARCO Hg, 1	
10/28/08	0.80	On	On	350	DARCO Hg, 3	
10/28/08	0.95	On	On	350	DARCO Hg, 5	
10/28/08	0.72	On	On	350		
10/28/08	0.42	On	On	350	DARCO Hg, 1	
10/28/08	1.60	On	On	350	DARCO Hg, 3	
10/28/08	1.12	On	On	350	DARCO Hg, 5	
10/29/08	0.40	On	Off			
10/29/08	1.52	On	On	430		
10/29/08	0.80	On	On	430	Envergex E11, 1	
10/29/08	1.60	Off	On	430	Envergex E11, 3	
10/29/08	0.87	On	On	430	Envergex E11, 5	
10/29/08	0.80	On	On	430		
10/29/08	1.18	On	On	430	Envergex E21, 1	
10/29/08	1.20	On	On	430	Envergex E21, 3	
10/29/08	1.12	On	On	430	Envergex E21, 5	
10/30/08	1.75	On	On			
10/30/08	2.23	On	On	350		
10/30/08	1.12	On	On	350	DARCO Hg, 1.2	SEA, 0.6
10/30/08	0.63	On	On	350	DARCO Hg, 1.2	SEA, 1.2
10/30/08	0.55	On	On	350	DARCO Hg, 1.2	SEA, 2.3
10/30/08	0.80	On	On	350	DARCO Hg, 1.2	SEA, 0.6
10/30/08	0.72	On	On	350	DARCO Hg, 1.2	SEA, 0.6; trona, 11.4
10/30/08	0.80	On	On	350	DARCO Hg, 1.2	SEA, 0.6; trona, 28.4
10/30/08	0.72	On	On	350	DARCO Hg, 1.2	SEA, 0.6; trona, 56.8
11/3/08	1.05	On	On			
11/3/08	2.48	On	On	360		
11/3/08	0.95	On	On	360		
11/3/08	0.55	On	On	360		
11/3/08	1.12	On	On	360	DARCO E26, 1	
11/3/08	0.72	On	On	360	DARCO E26, 3	
11/3/08	1.18	On	On	385	DARCO E26, 5	
11/4/08	0.97	On	On	375		

Continued…

Table 7. Test Matrix Involving Conesville or Knight Hawk Bituminous Coal Combustion, a Cormetech Catalyst, an ESP, and a WFDS (continued)

Date	Duration, hr	ESP	WFDS	NH_3, ppmv	Sorbent, lb/MMacf	SEAs, ppm or g/hr
11/4/08	2.38	On	On	350		Trona, 11.4
11/4/08	0.73	On	On	350		Trona, 28.4
11/4/08	0.65	On	On	350		Trona, 56.8
11/4/08	0.72	On	On	350		
11/4/08	0.72	On	On	350	DARCO Hg, 3	Trona, 28.4
11/4/08	0.88	On	On	350	DARCO Hg, 3	Trona, 56.8
11/4/08	0.88	On	On	488	DARCO Hg, 5	Trona, 28.4
11/4/08	0.72	On	On	350	DARCO Hg, 5	Trona, 28.4
11/5/08	0.72	On	On			
11/5/08	1.20	On	On	420		
11/5/08	1.35	On	On	420	DARCO Hg-LH, 3	Trona, 28.4
11/5/08	1.43	On	On	420	DARCO Hg-LH, 3	Trona, 56.8
11/5/08	1.03	On	On	420	DARCO Hg-LH, 5	Trona, 28.4
11/5/08	0.63	On	On	440	DARCO Hg-LH, 5	Trona, 56.8
11/10/08	1.52	On	On			
11/10/08	2.00	On	On	325		
11/10/08	0.78	On	On	325		Limestone, 56.8
11/10/08	1.52	On	On	325		
11/10/08	1.35	On	On	325	DARCO Hg, 3	Limestone, 28.4
11/10/08	1.12	On	On	325	DARCO Hg, 3	Limestone, 56.8
11/10/08	0.48	On	On	325	DARCO Hg, 5	Limestone, 28.4
11/10/08	0.65	On	On	325	DARCO Hg, 5	Limestone, 56.8
11/11/08	1.28	On	On	340		
11/11/08	1.83	On	On	325	Envergex E21, 3	Limestone, 28.4
11/11/08	1.55	On	On	325	Envergex E21, 3	Limestone, 56.8
11/11/08	0.88	On	On	325	Envergex E21, 5	Limestone, 28.4
11/11/08	1.12	On	On	325	Envergex E21, 5	Limestone, 56.8
11/12/08	1.83	On	On	300		
11/12/08	1.12	On	On	300	Envergex Hg E23, 3	
11/12/08	1.77	On	On	300	Envergex Hg E23, 6	
11/12/08	0.78	On	On	300	Envergex Hg E23, 12	
11/12/08	1.12	On	On	300	Envergex Hg E23, 18	
11/13/08	1.12	On	On	300		
11/13/08	0.23	On	On	300		
11/13/08	1.35	On	On	380	Envergex E25, 35	
11/13/08	0.48	On	On	380	Envergex E25, 48	
11/13/08	1.83	On	On	380		
11/13/08	0.80	On	On	380	Envergex E27, 18,	
11/13/08	0.95	On	On	380	Envergex E27, 35	
11/13/08	0.63	On	On	380		
11/13/08	0.57	On	On	380	Envergex Hg E25, 18	
11/13/08	0.65	On	On	380	Envergex Hg E25,	

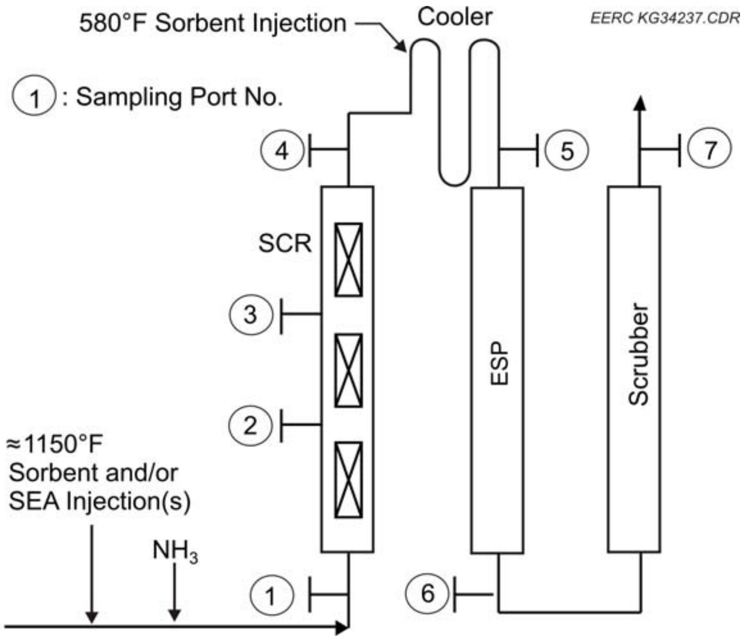

Figure 11. Schematic of the APCD configuration and sampling and injection locations during low-sulfur Knight Hawk bituminous coal combustion testing of a Hitachi catalyst, an ESP, and a WFDS.

A pilot-scale SCR reactor was installed on the combustion system ahead of the ESP. The SCR was designed and built for a face velocity of 5 m/s and an operating temperature of 600° to 800°F. The reactor consists of two or three catalyst layers, with ammonia injection available between the layers. External heaters ensure that the flue gas temperature can be maintained. Sampling ports are available at the inlet, outlet, and between catalyst layers to facilitate gas sampling. The pilot-scale WFD and SCR systems were shaken down during subsequent weeklong testing campaigns described in Tables 6–8.

Task 3 – Weeklong Test Campaigns

Coals

Coal proximate, ultimate, Hg, Cl, and ash elemental oxide analysis results are presented in Tables 9–11. The Conesville, Knight Hawk, and low-sulfur Knight Hawk coals possess the characteristics of bituminous coals; that is, relatively high chlorine and sulfur but low alkaline-earth metal contents that generally result in a flue gas containing significant proportions of Hg^0 and Hg^{2+}. Conversely, the subbituminous Antelope coal has lower chlorine and sulfur but higher alkaline-earth metal contents that result in a combustion flue gas that generally contains primarily Hg^0. Estimates of mercury concentrations on a flue gas basis and a heating value basis were calculated according to EPA Method 19. These values are presented in Table 10.

Table 8. Test Matrix Involving Low-Sulfur Knight Hawk Bituminous Coal Combustion, a Hitachi Catalyst, an ESP, and a WFDS

Date	Duration, hr	ESP	WFDS	NO_x/NH_3	Sorbent, lb/Macf Location 1	Sorbent, lb/Macf Location 2	SEA, g/hr
2/23/09	2.35	Off	On	Off			
2/24/09	0.43	On	On	1:1			
2/24/09	0.58	On	On	1:1		DARCO Hg, 3	
2/24/09	0.45	On	On	1:1		DARCO Hg, 5	
2/24/09	0.55	On	On	1:1		DARCO Hg, 10	
2/25/09	0.55	On	On	1:1			
2/25/09	0.37	On	On	1:1		DARCO Hg-LH, 3	
2/25/09	0.48	On	On	1:1		DARCO Hg-LH, 5	
2/25/09	0.48	On	On	1:1		DARCO Hg-LH, 10	
2/25/09	1.30	On	On	1:1			
2/25/09	0.45	On	On	1:1		Envergex 31, 3	
2/25/09	0.50	On	On	1:1		Envergex 31, 5	
2/25/09	0.45	On	On	1:1	Envergex 24, 15	Envergex 31	
2/25/09	0.90	On	On	1:1	Envergex 24, 30	Envergex 31	
2/25/09	0.07	On	On	1:1	Envergex 24, 30		
2/25/09	0.85	On	On	1:1			
2/25/09	0.50	On	On	1:1		Envergex 30, 3	
2/25/09	0.23	On	On	1:1	Envergex 24, 15	Envergex 30, 3	
2/25/09	0.32	On	On	1:1	Envergex 24, 30	Envergex 30, 3	
2/25/09	0.37	On	On	1:1	Envergex 24, 30		
2/26/09	0.60	On	On	Off			
2/26/09	0.27	On	On	1:1			
2/26/09	0.23	On	On	1:1	Envergex 28, 3		
2/26/09	2.13	On	On	1:1			
2/26/09	0.50	On	On	1:1			
2/26/09	0.53	On	On	1:1		Envergex 28, 3	
2/26/09	0.92	On	On	1:1			
2/26/09	0.42	On	On	1:1		Envergex 28, 5	
2/26/09	0.33	On	On	1:1	Envergex 33, 16.5		
2/26/09	0.40	On	On	1:1	Envergex 33, 33		
2/26/09	0.30	On	On	1:1			
2/26/09	0.20	On	On	1:1			
2/26/09	0.57	On	On	1:1	Envergex 33, 33		
2/26/09	0.18	On	On	1:1			
2/27/09	1.13	On	On	Off			
2/27/09	1.12	On	On	1:1			
2/27/09	1.05	On	On	1:0.8			
2/27/09	1.02	On	On	1:0.4			
2/27/09	0.20	On	On	1:0.4			
3/4/09	8.0	On	On	Off			
3/4/09	1.10	On	On	1:0.8			Limestone, 11.4
3/4/09	1.23	On	On	1:0.8			Limestone, 28.4
3/4/09	1.03	On	On	1:0.8			Limestone, 56.8
3/4/09	1.03	On	On	1:1			Limestone, 56.8
3/4/09	0.98	On	On	Off			Limestone, 56.8
3/5/09	1.51	On	On	1:0.8			
3/5/09	2.04	On	On	Off			Limestone, 56.8

Table 9. Proximate and Heating Value Coal Analysis Results

Coal:	Conesville	Knight Hawk	Low-Sulfur Knight Hawk	Antelope
Date(s):	Oct. 7–20, 2008	June 18, 2008	Nov. 12, 2008	June 9, 2008
Proximate Analysis, as-fired, wt%				
Moisture	5.50 ±0.30[a]	8.60	3.20	24.1
Volatile Matter	33.5 ±0.7[a]	33.2	32.6	29.9
Fixed Carbon	45.4 ±0.8[a]	47.9	50.3	40.4
Ash	15.6 ±1.1[a]	10.3	13.9	5.63
Heating Value, Btu/lb	10,795 ±246[a]	11,083	11,385	8719
Proximate Analysis, dry basis, wt%				
Volatile Matter	35.5 ±0.6[a]	36.4	33.7	39.4
Fixed Carbon	48.0 ±0.7[a]	52.3	52.0	53.2
Ash	16.5 ±1.2[a]	11.3	14.4	7.41
Heating Value, Btu/lb	11,422 ±226[a]	12,131	11,764	11,480

[a] Average and ±95% confidence interval based on ten analyses.

Table 10. Ultimate, Hg, and Cl Coal Analysis Results

Coal:	Conesville	Knight Hawk	Low-Sulfur Knight Hawk	Antelope
Date(s):	October 7–20, 2008	Oct 24-Nov 12, 2008	Feb 24–March 5, 2008	June 25–July 1, 2008
Ultimate Analysis, as-fired, wt%				
Hydrogen	4.32 ±0.15[a]	4.30	4.45	3.46
Carbon	61.6 ±1.4[a]	62.5	67.7	51.8
Nitrogen	1.27 ±0.05[a]	1.39	1.59	0.76
Sulfur	4.80 ±0.07[a]	5.24	3.20	0.25
Oxygen	7.00 ±0.53[a]	7.65	5.93	14.1
Ash	15.6 ±1.1 [a]	10.3	13.9	5.63
Ultimate Analysis, dry basis, wt%				
Hydrogen	4.57 ±0.14[a]	4.71	4.60	4.55
Carbon	65.2 ±1.3[a]	68.4	70.0	68.2
Nitrogen	1.34 ±0.05[a]	1.52	1.64	1.00
Sulfur	5.08 ±0.08[a]	5.73	3.31	0.32
Oxygen	7.41 ±0.56[a]	8.37	6.13	18.5
Ash	16.5 ±1.2[a]	11.3	14.4	7.41
Coal Analysis, dry basis, ppm				
Hg	0.168 ±0.007[a]	0.0902±0.0021[b]	0.0804 ±0.0060[d]	0.0595 ±0.0039[e]
Cl	382 ±17[a]	137 ±6[c]	1006 ±34[c]	6
Calculated Flue Gas				
Hg, μg/dNm^3	19.9	10.4	8.87	7.22
Hg, lb/10^{12}	14.7	7.68	6.84	5.18

[a] Average and ±95% confidence interval based on ten analyses.
[b] Average and ±95% confidence interval based on nine analyses
[c] Average and ±95% confidence interval based on four analyses.
[d] Average and ±95% confidence interval based on eleven analyses.
[e] Average and ±95% confidence interval based on seven analyses.

Table 11. Coal Ash Chemical Compositions, elemental oxide, wt%

Coal: Date(s):	Conesville Oct. 7–20, 2008	Knight Hawk June 18, 2008	Low-Sulfur Knight Hawk Nov. 12, 2008	Antelope June 9, 2008
SiO_2	44.6 ±0.5[a]	44.4	53.3	36.8
Al_2O_3	26.4 ±0.2[a]	21.4	25.2	16.9
Fe_2O_3	22.2 ±0.8[a]	27.8	13.7	6.08
TiO_2	0.78 ±0.01[a]	0.64	0.88	0.98
P_2O_5	0.31 ±0.00[a]	0.16	0.20	2.09
CaO	1.23 ±0.03[a]	1.50	1.70	17.3
MgO	1.09 ±0.03[a]	0.96	1.13	5.72
Na_2O	0.20 ±0.03[a]	0.14	0.39	2.11
K_2O	1.89 ±0.08[a]	1.36	2.27	0.54
SO_3	1.15 ±0.17[a]	1.57	1.20	10.5
Total	99.9	99.9	100.0	99.0

[a] Average and ±95% confidence interval based on ten analyses.

Presented in Table 12 are the proximate, ultimate, and Hg analysis results for Antelope and Knight Hawk coal blends. As expected, increasing blend proportions of Knight Hawk coal result in increasing sulfur concentrations.

Testing Involving Conesville Bituminous Coal Combustion and an Installed ESP, Hitachi Zosen Catalyst, and WFDS System

During baseline Conesville coal combustion, CMM measurements at the SCR inlet averaged 15.4 µg/dNm^3, which is 23% less than what was expected based on the coal Hg and calculated flue gas Hg results presented in Table 10. Presented in Figure 12 are the average CMM results obtained at the ESP outlet during baseline Conesville combustion and DARCO Hg injection conditions described in Table 6. The baseline Conesville coal combustion flue gas contained approximately equal proportions of $Hg^0$and Hg^{2+}, whereas most of the Hg was present as Hg^{2+} during DARCO Hg injections. Even though DARCO Hg injections were effective in oxidizing Hg^0, they only improved ESP Hg capture by about 30% to 40%, as indicated in Figure 13. The WFDS probably captured most of the Hg^{2+}, but the CMM at the WFDS outlet was not functioning properly and, thus, no measurement results were obtained.

As indicated in Table 6, many variables were tested during the combustion of Conesville bituminous coal. A statistical analysis of the average valid CMM results for the various test conditions indicated, however, that total Hg and Hg^0 concentrations varied insignificantly for a given measurement location, as shown in Figure 14. Similar to the baseline Conesville coal combustion test, the total Hg CMM results from the SCR catalyst locations were biased on average 22% low relative to the coal calculated flue gas Hg value that is represented by an oval in Figure 14. The higher total Hg concentrations obtained at the ESP outlet are also evidence for a negative bias in the CMM results obtained at the SCR catalyst locations. The average relative proportions of the Hg^0 and Hg^{2+} species measured at each CMM sampling location are presented in Figure 15. Downstream from the SCR catalyst, most of the Hg^0 was oxidized to Hg^{2+} and then

Table 12. Proximate, Heating, Ultimate, and Hg Values for the Antelope−Knight Hawk Coal Blends

Antelope: Knight–Hawk Coal Blends: Date(s):	100% 6/25/08	90%:10% 6/27/08	80%:20% 6/27/08	70%:30% 6/28/08
Proximate Analysis, as-fired, wt%				
Moisture	16.3	18.1	16.6	13.4
Volatile Matter	32.4	31.6	31.9	32.7
Fixed Carbon	43.7	43.2	43.8	45.7
Ash	7.65	7.14	7.69	8.28
Heating Value, Btu/lb	9555	9458	9692	10,094
Ultimate Analysis, as-fired, wt%				
Hydrogen	3.88	3.87	3.98	4.11
Carbon	56.1	55.3	56.1	58.7
Nitrogen	1.08	1.09	1.11	1.19
Sulfur	0.42	0.57	0.90	1.15
Oxygen	14.6	14.0	13.6	13.2
Ash	7.65	7.14	7.69	8.28
Coal Analysis, dry basis, ppm				
Hg	0.0856	0.0608	0.0525	0.0673
Calculated Flue Gas				
Hg, µg/dNm^3	10.5	7.36	6.33	8.03
Hg, lb/10^{12}	7.50	5.26	4.52	5.77

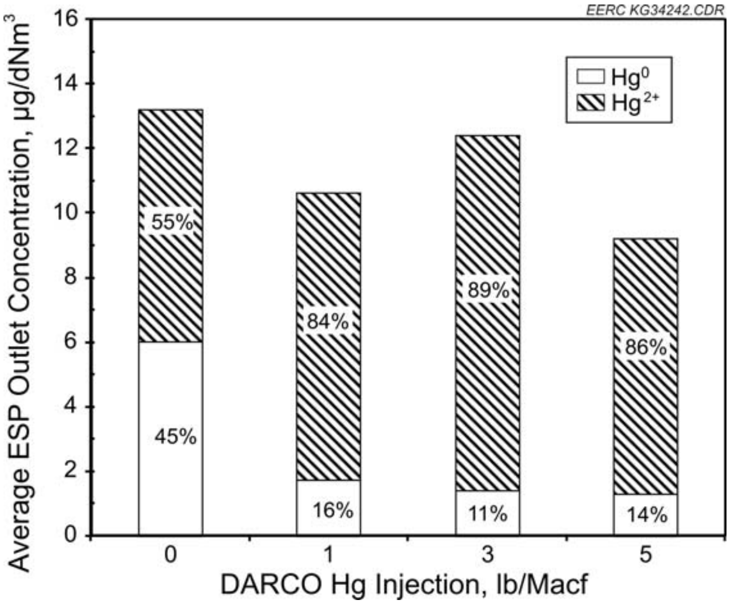

Figure 12. Average ESP outlet CMM results obtained during baseline Conesville combustion and DARCO Hg injection conditions. The relative proportions (%) of Hg^0 and Hg^{2+} are indicated within each of the bars.

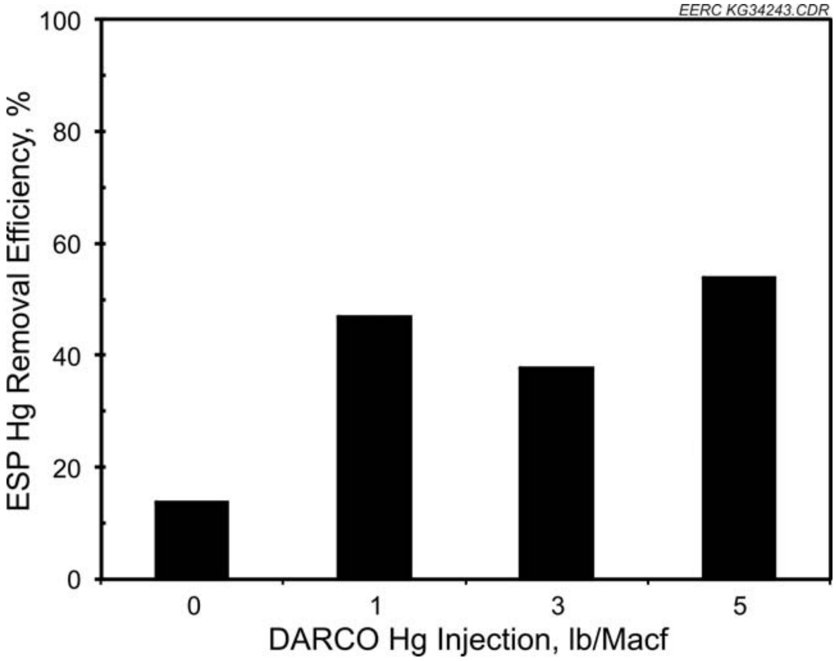

Figure 13. Average ESP Hg removal efficiencies obtained during baseline Conesville combustion and DARCO Hg injection conditions.

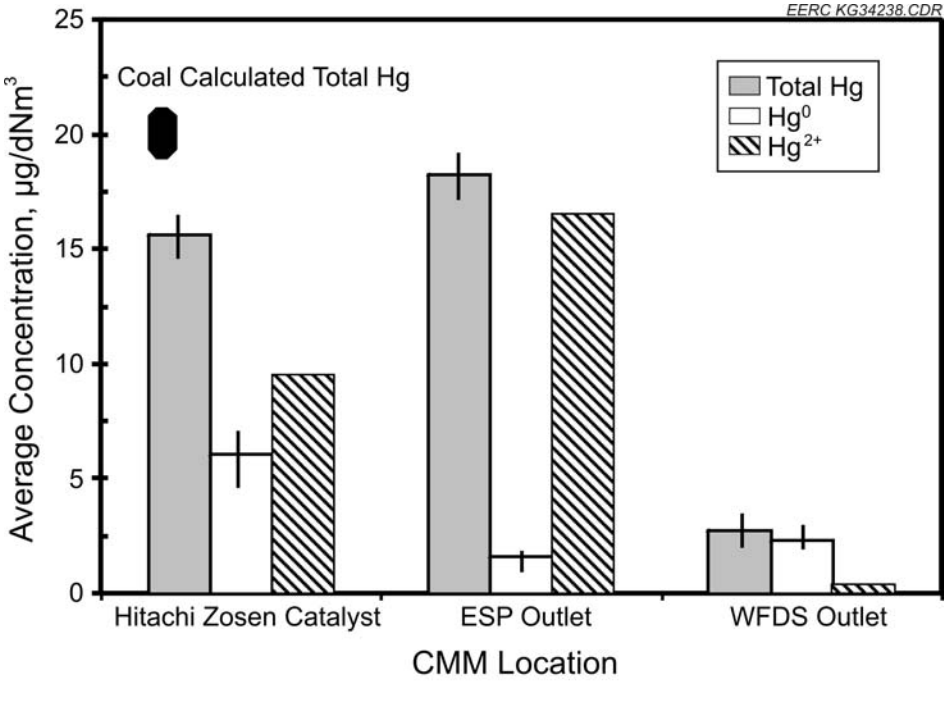

Figure 14. Statistical summary of the CMM results obtained from various levels within the Hitachi Zosen catalyst layers and ESP and WFDS outlets during Conesville coal combustion. Error bars represent 95% confidence intervals. The 95% confidence interval for the calculated flue gas Hg value is equivalent to the length of the oval symbol.

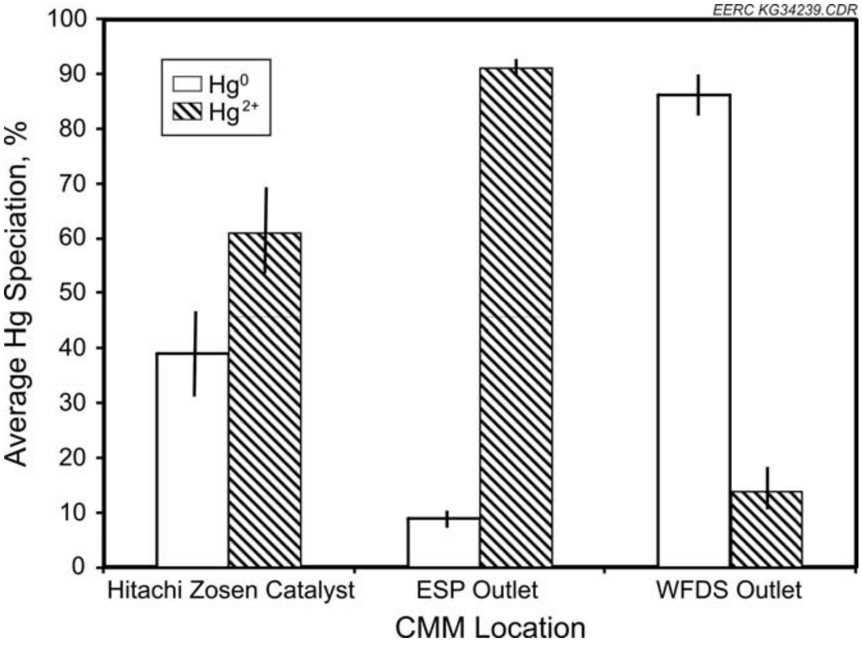

Figure 15. Relative proportions of Hg^0 and Hg^{2+} measured between the Hitachi Zosen catalyst layers and ESP and WFDS outlet locations during Conesville coal combustion. Error bars represent 95% confidence intervals.

captured mainly by the WFDS. Mostly Hg^0 exited the WFDS. The ESP and WFDS Hg removal efficiencies are compared in Figure 16. The Hg removal efficiencies for the ESP were calculated from the average expected (i.e., calculated) flue gas Hg concentration presented in Figure 14 because of the negative bias in Hg CMM results obtained from the SCR catalyst locations. The ESP was ineffective in capturing Hg but the WFDS captured >80% of the Hg.

Representative continuous emission-monitoring results and APCD performance efficiencies obtained during baseline Conesville coal combustion and NH_3 injection testing are presented in Table 13. SO_3 concentrations were very low at the SCR outlet. As indicated in Table 13, NH_3 injection with a Hitachi Zosen catalyst and the WFDS were very effective in controlling NO_x and SO_2 emissions, respectively.

Conesville or Knight Hawk Bituminous Coal Combustion Testing of a Cormetech Catalyst, an ESP, and a WFDS

Presented in Figure 17 are average CMM results obtained during the combustion of Conesville coal in the CTF equipped with a Cormetech catalyst, an ESP, and a WFDS. The results in Figure 17 compare very similarly to those obtained when the Hitachi Zosen catalyst was installed in the CTF, as indicated in Figure 14. In addition, the Hg speciation results and Hg removal efficiencies presented in Figures 18 and 19, respectively, are very similar to those obtained when the Hitachi Zosen catalyst was installed, as indicated in Figures 15 and 16.

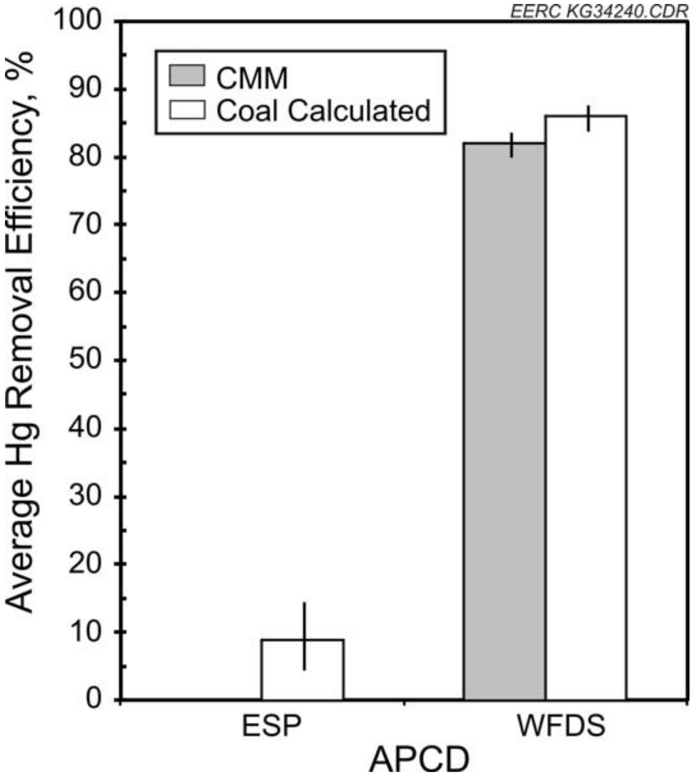

Figure 16. Comparison of the average ESP and WFDS Hg capture efficiencies obtained during Conesville coal combustion in the CTF equipped with a Hitachi Zosen catalyst. Error bars represent 95% confidence intervals.

Table 13. Representative Continuous Emission-Monitoring Results Obtained During Conesville Coal Combustion Testing of a Hitachi Zosen Catalyst and WFDS

NO_x/NH_3	WFDS	Furnace NO_x, ppmv	SCR Outlet NO_x, ppmv	SCR NO_x Removal, %	Furnace SO_2, ppmv	SCR Outlet SO_3, ppmv	WFDS Outlet SO_2, ppmv	WFDS SO_2 Removal, %
Off	Off	407	402	1	3444	NA[a]	3289	4
1:1	On	493	37	92	3689	20.4 ±1.3[a]	184	95

[a] Not analyzed.

[b] 95% confidence interval based on four measurements.

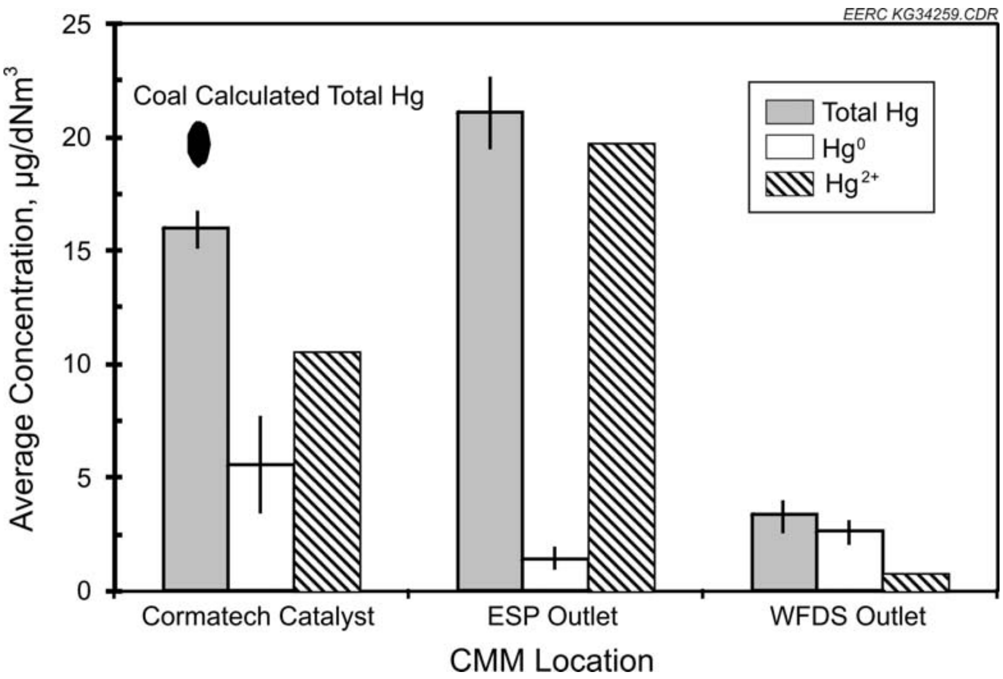

Figure 17. Statistical summary of the CMM results obtained between the second and third Cormetech catalyst layers and ESP and WFDS outlets during Conesville coal combustion. Error bars represent 95% confidence intervals. The 95% confidence interval for the calculated flue gas Hg value is equivalent to the length of the oval symbol.

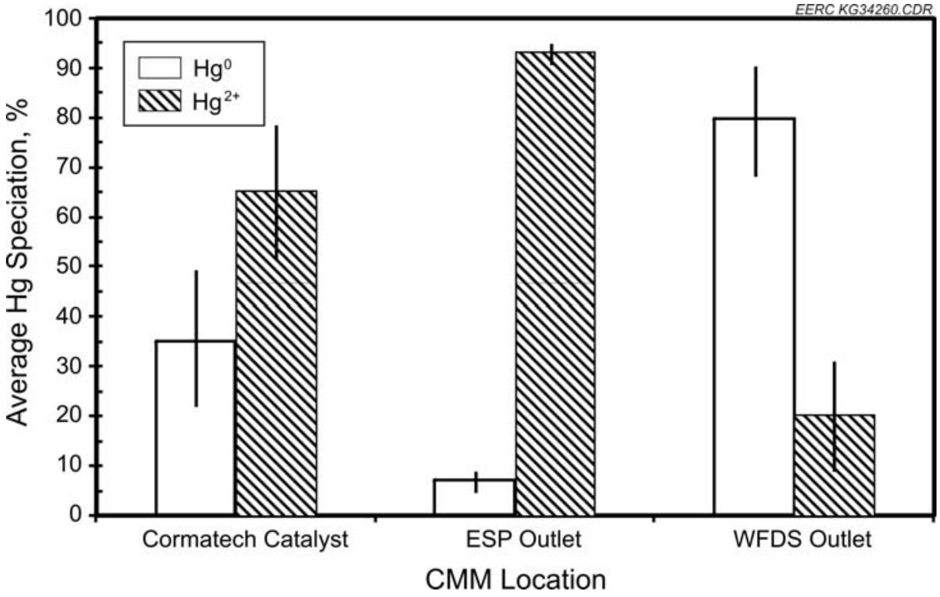

Figure 18. Relative proportions of Hg^0 and Hg^{2+} measured between the second and third Cormetech catalyst layers and ESP and WFDS outlets during Conesville coal combustion. Error bars represent 95% confidence intervals.

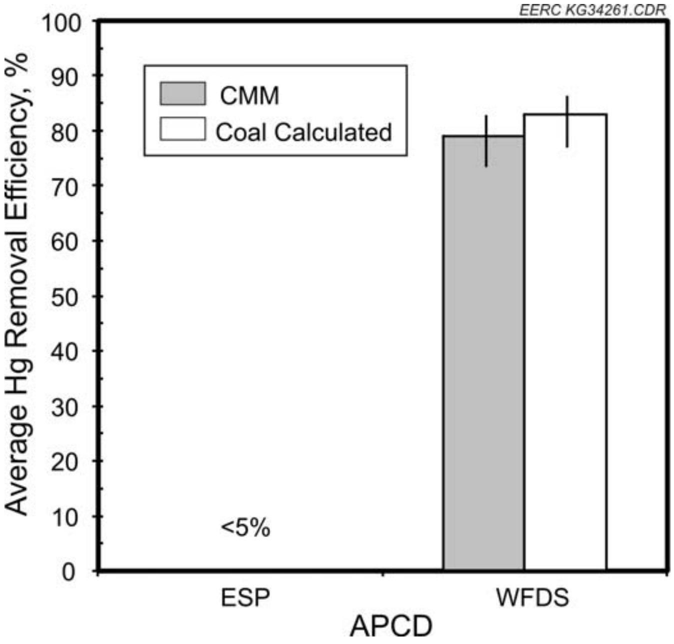

Figure 19. Comparison of the average ESP and WFDS Hg capture efficiencies obtained during Conesville coal combustion in the CTF equipped with a Cormetech catalyst. Error bars represent 95% confidence intervals.

Summarized in Table 14 are representative NO_x and SO_2 concentrations and Cormetech SCR catalyst NO_x and WFDS SO_2 removal efficiencies obtained during the Conesville coal combustion tests. As indicated in Table 14, NH_3 injection with the Cormetech SCR catalyst and the WFDS were very effective in removing NO_x and SO_2, respectively.

Average CMM and Hg removal efficiency results obtained during baseline Knight Hawk coal combustion testing are presented in Figures 20–22. As expected based on the coal Hg and Cl analysis results in Table 10, the Hg content and proportion of Hg^{2+} in the Knight Hawk coal combustion flue gas are much less relative to the Conesville coal combustion flue gas. The calculated total Hg concentration of the Knight Hawk coal combustion flue gas presented in Table 10 is 14% higher than the average CMM results obtained at the SCR and ESP locations, as indicated in Figure 20. Similar to the Hitachi Zosen catalyst, the oxidation of Hg^0 occurs downstream of the Cormetech catalyst and most of the Hg^{2+} is captured in the WFDS.

Table 14. Average Continuous Emission-Monitoring Results Obtained During Conesville Coal Combustion Testing of a Cormetech Catalyst and WFDS

NO_x/NH_3	WFDS	Furnace NO_x, ppmv	SCR Outlet NO_x, ppmv	SCR NO_x Removal, %	Furnace SO_2, ppmv	WFDS Outlet SO_2, ppmv	WFDS SO_2 Removal, %
Off	Off	491	484	1	3775	3721	1
1:1	Off	507	93	82	3839	3815	1
1:1	On	491	63	87	3868	243	94

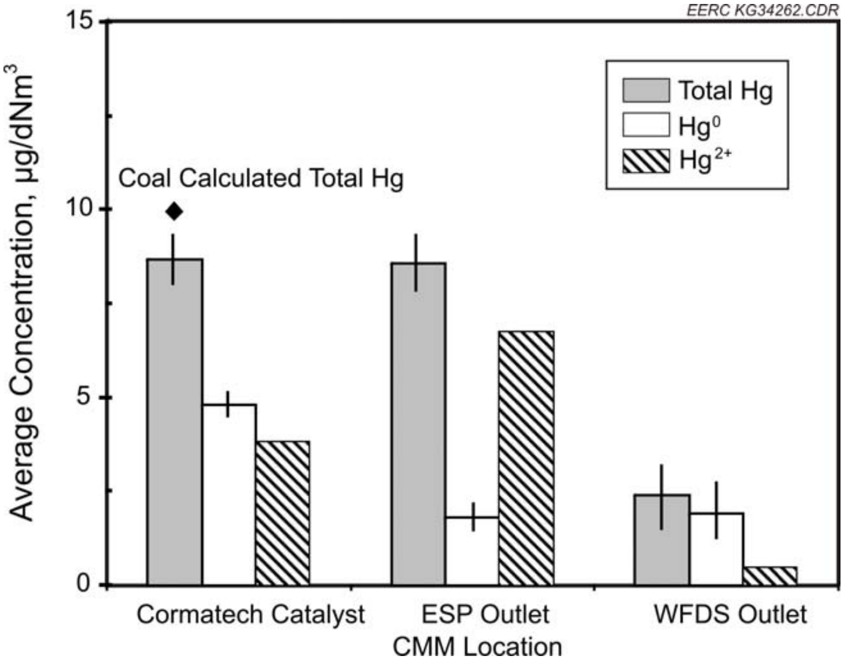

Figure 20. Statistical summary of the CMM results obtained at the inlet to the Cormetech catalyst and between the first and second catalyst layers and from the ESP and WFDS outlets during baseline Knight Hawk coal combustion. Error bars represent 95% confidence intervals.

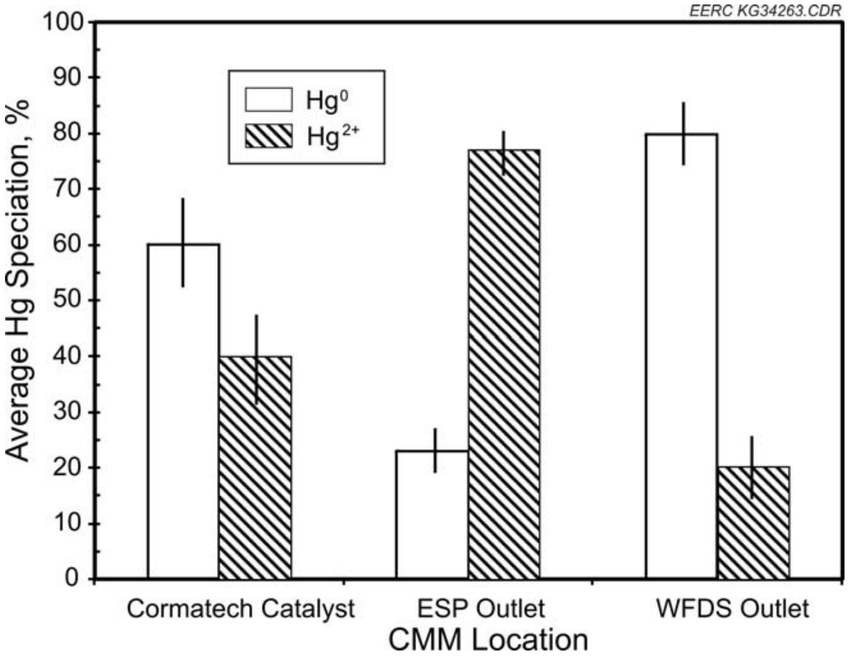

Figure 21. Average Hg speciation results obtained from the Cormetech catalyst and ESP and WFDS outlets during baseline Knight Hawk coal combustion. Error bars represent 95% confidence intervals.

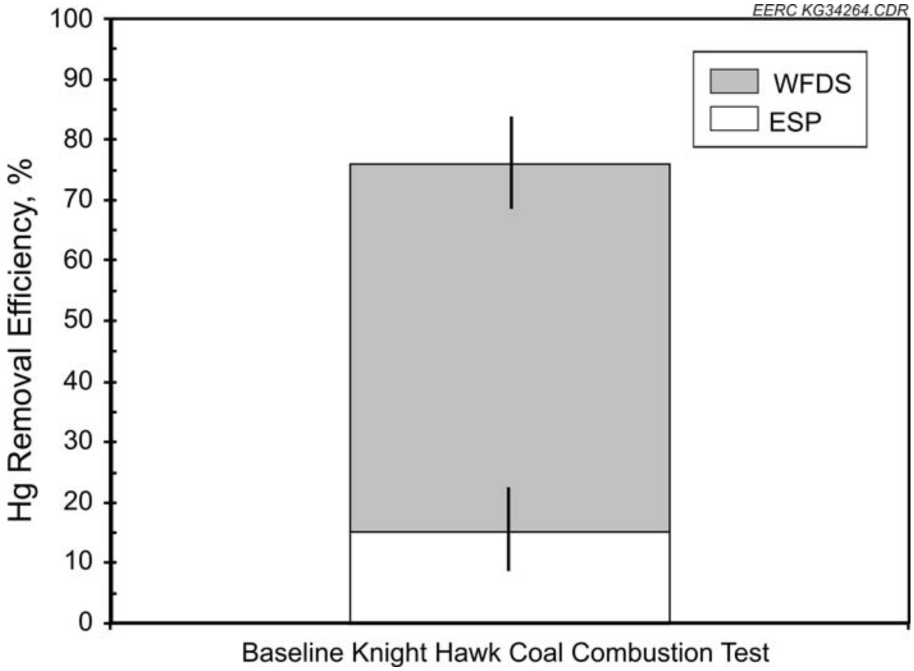

Figure 22. Comparison of average ESP and WFDS Hg capture efficiencies obtained during Knight Hawk coal combustion in the CTF equipped with a Cormetech catalyst. Error bars represent 95% confidence intervals.

DARCO Hg was injected into the Knight Hawk coal combustion flue gas downstream from the Cormetech catalyst and upstream of the ESP, as described in Table 7. Presented in Figures 23–26 are the average CMM and Hg removal results obtained during baseline and DARCO Hg injection tests. As indicated in Figures 23–25, DARCO Hg injections did not significantly affect the Hg speciation of Knight Hawk coal combustion flue gas. DARCO Hg injections, however, systematically improved ESP Hg capture with each increase in injection rate, as shown in Figure 26.

A SEA designated as SEA2 was coinjected with DARCO Hg to improve Hg removal performance. As indicated in Figure 27, the SEA2 significantly improved ESP Hg removal performance relative to DARCO Hg injection alone (Figure 26). The overall Hg removal performance of the ESP and WFDS, however, only improved slightly relative to DARCO Hg injection alone. In an attempt to improve the Hg capture efficiency of DARCO Hg and SEA2 injection, trona was also injected. Trona injection, as indicated in Figure 28, increased the ESP Hg removal performance of DARCO Hg and SEA2 injections at 1.2 lb/Macf and 0.6 ppmv, respectively, by about 10% and improved the overall Hg removal performance of the ESP and WFDS to approximately 90%.

Trona and limestone were coinjected with DARCO Hg. The ESP and WFDS Hg removal efficiencies during DARCO Hg and trona or limestone coinjection, however, did not significantly improve relative to DARCO Hg injection alone, as indicated in Figures 26, 29, and 30.

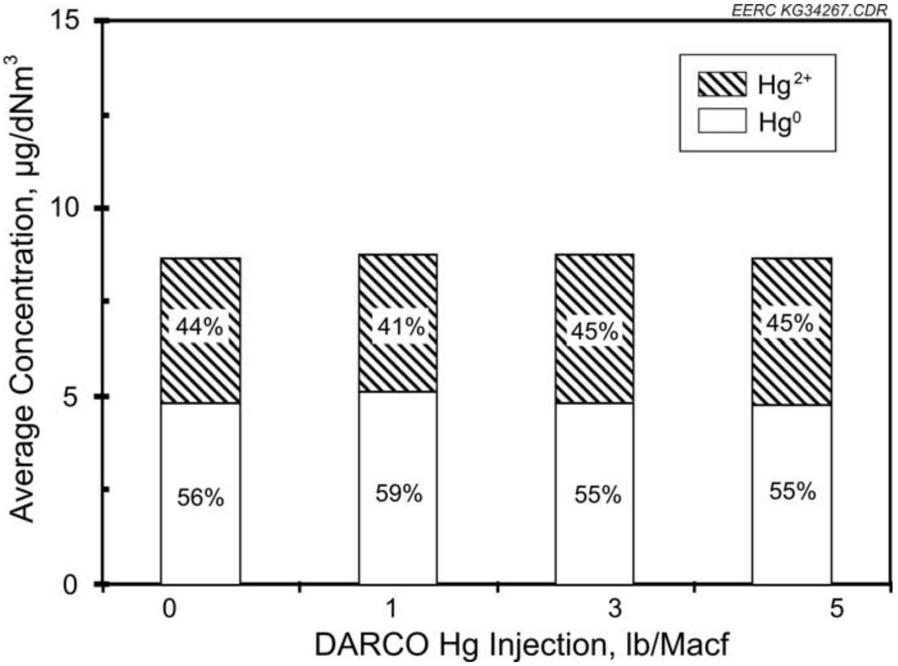

Figure 23. Average CMM results obtained from the inlet to the Cormetech catalyst during baseline Knight Hawk coal combustion and DARCO Hg injection conditions. The relative proportions (%) of Hg^0 and Hg^{2+} are indicated within each of the bars.

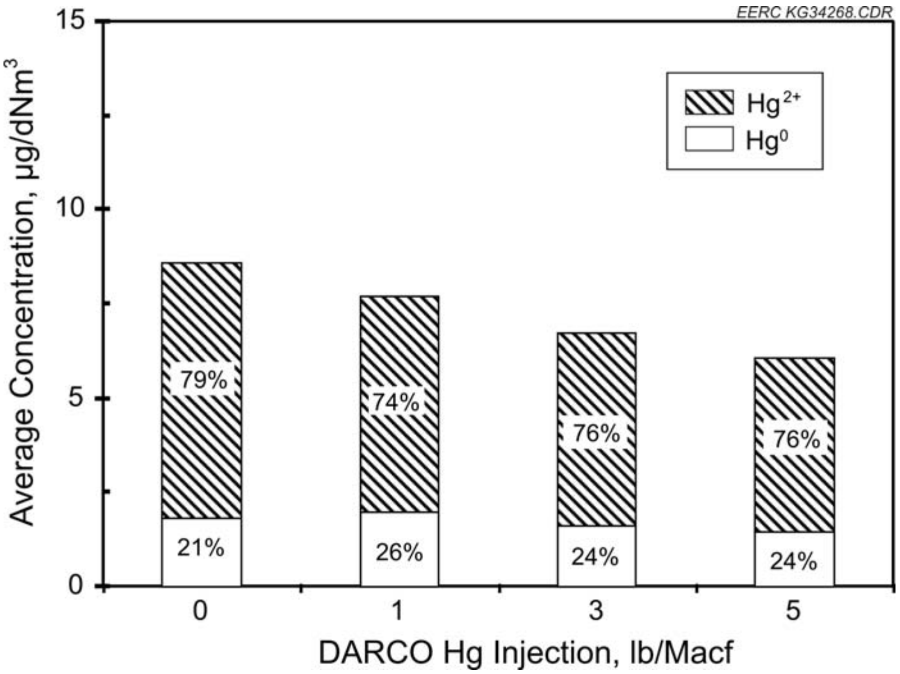

Figure 24. Average CMM results obtained from the ESP outlet during baseline Knight Hawk coal combustion and DARCO Hg injection conditions. The relative proportions (%) of Hg^0 and Hg^{2+} are indicated within each of the bars.

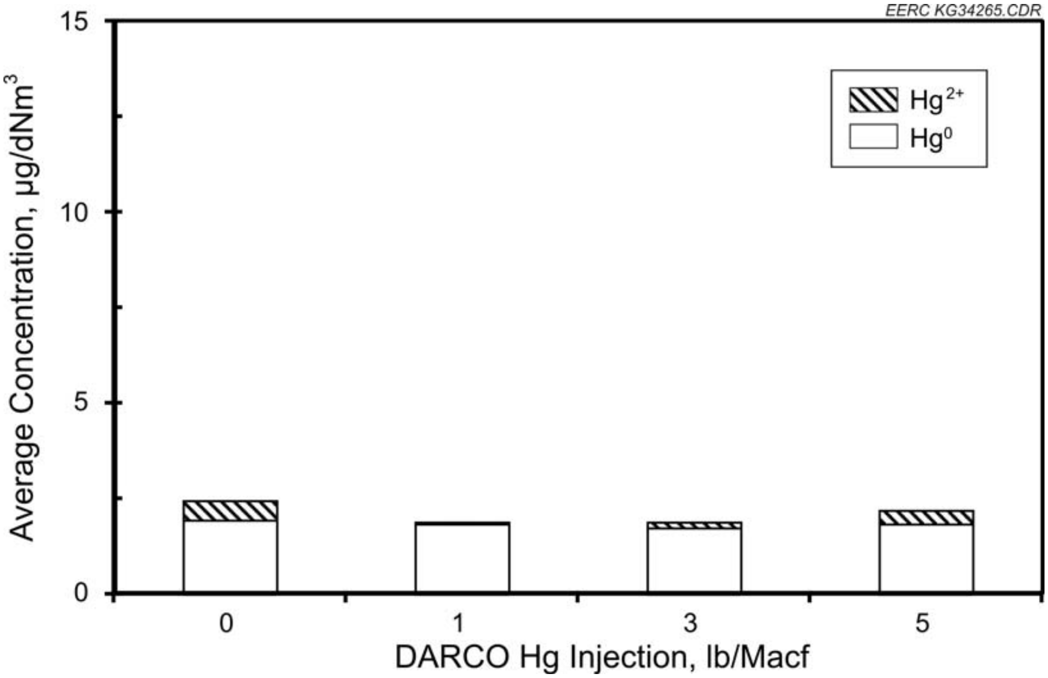

Figure 25. Average CMM results obtained from the WFDS outlet during baseline Knight Hawk coal combustion and DARCO Hg injection conditions.

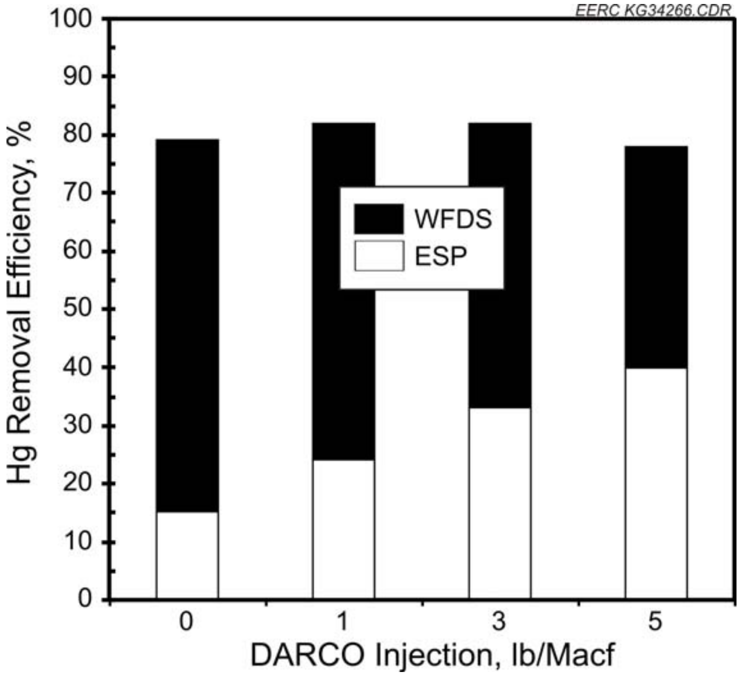

Figure 26. Comparison of average ESP and WFDS Hg capture efficiencies obtained during baseline Knight Hawk coal combustion and DARCO Hg injection conditions.

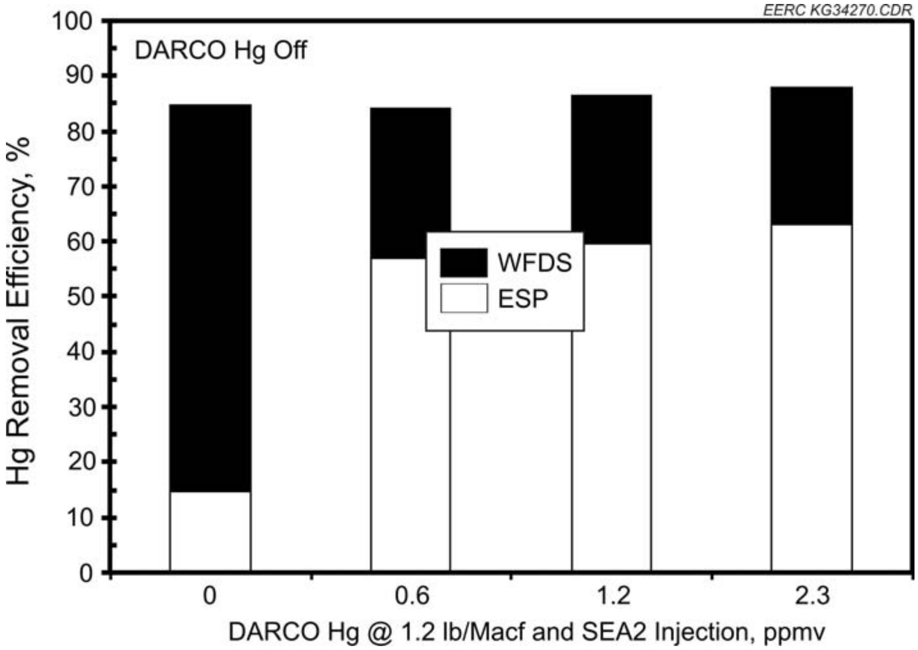

Figure 27. Comparison of average ESP and WFDS Hg capture efficiencies obtained during baseline Knight Hawk coal combustion and DARCO Hg and SEA2 coinjections.

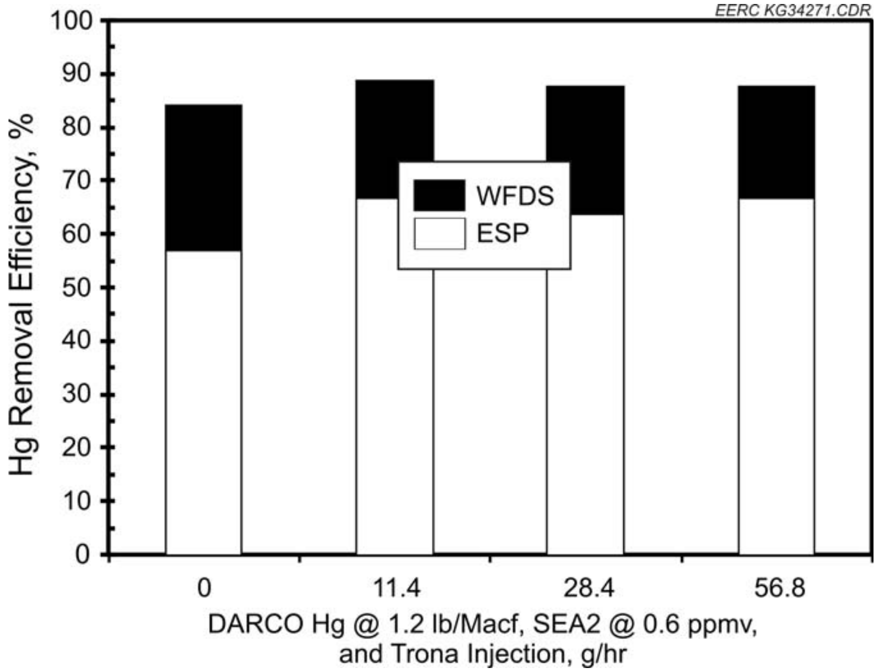

Figure 28. Average ESP and WFDS Hg capture efficiencies during DARCO Hg and SEA2 injections at 1.2 lb/Macf and 0.6 ppmv, respectively, as a function of trona injection rates.

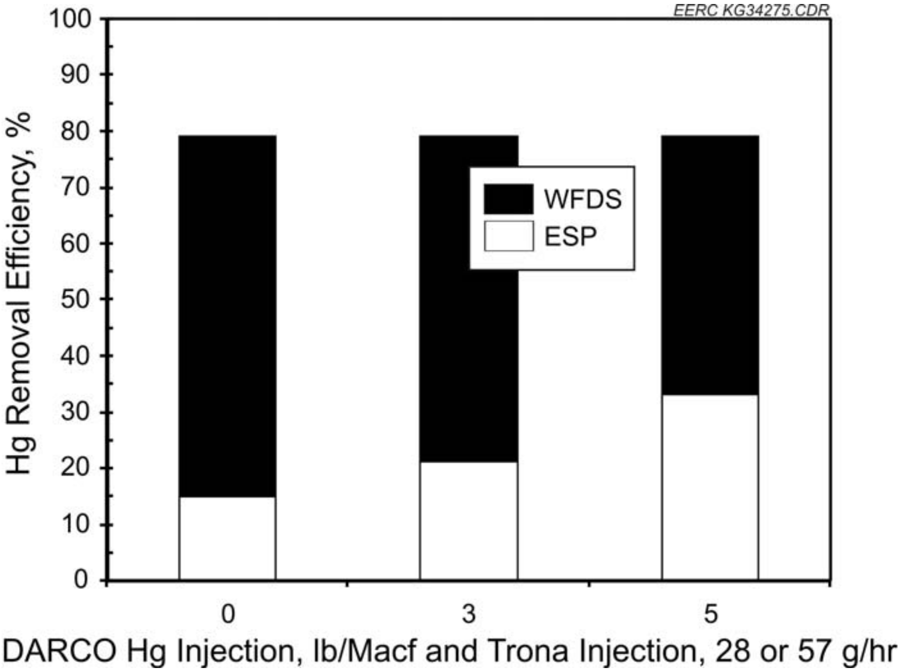

Figure 29. ESP and WFDS Hg removal efficiencies obtained during baseline Knight Hawk coal combustion and DARCO Hg and trona injection conditions.

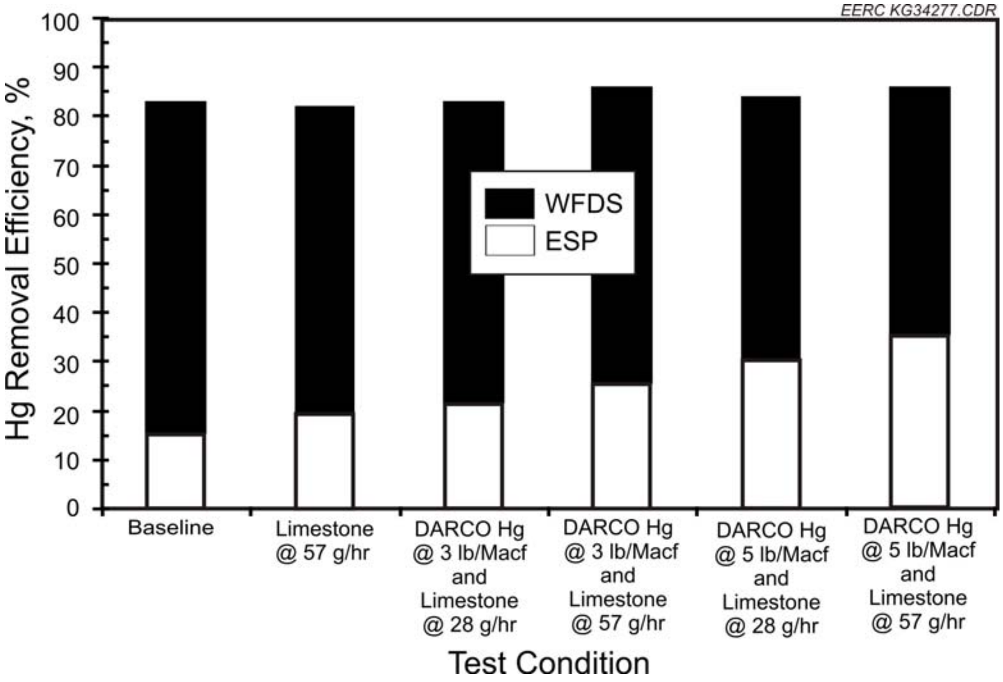

Figure 30. ESP and WFDS Hg removal efficiencies obtained during baseline Knight Hawk coal combustion and DARCO Hg and limestone injection conditions.

Presented in Figure 31 are ESP and WFDS Hg removal efficiencies obtained during baseline Knight Hawk coal combustion and DARCO Hg-LH and trona injection conditions. The combination of DARCO Hg-LH and trona injection did not improve ESP or WFDS Hg removal performance relative to DARCO Hg injection alone (Figure 26) or DARCO Hg and trona coinjection (Figure 29).

Envergex Sorbents E11 and E21 were evaluated for ESP and WFDS Hg removal performance, as indicated in Figures 32 and 33. A comparison of the Hg removal efficiencies in Figures 32 and 33 to those in Figure 26 indicates that the Envergex sorbents provided Hg capture similar to DARCO Hg. The coinjection of limestone with Envergex E21 improved ESP Hg capture efficiency by about 5% relative to Envergex E21 injection alone, as indicated in Figure 34.

Presented in Figure 35 are the ESP and WFDS Hg removal efficiencies obtained during the injections of Envergex Hg E23 into Knight Hawk coal combustion flue gas. Envergex Hg E23 provided Hg capture performance similar to DARCO Hg for relatively low injection rates of ≤6 lb/Macf. At much higher injection rates of 12 and 18 lb/Macf, however, Envergex Hg E23 improved ESP Hg removal efficiencies to about 40% and 50%, respectively, and overall, ESP–WFDS Hg removal performance approached 90%.

Compared in Figures 36 and 37 are ESP and WFDS Hg removals obtained during baseline Knight Hawk coal combustion and the injection of Envergex E25 and Envergex Hg E25, respectively. At extremely high injection rates of 35 and 48 lb/Macf, Envergex E25 injection provided ESP Hg removals of about 80% and overall ESP–WFDS Hg removals of about 95%. The Envergex Hg E25 provided Hg capture performance similar to the Envergex E25 sorbent.

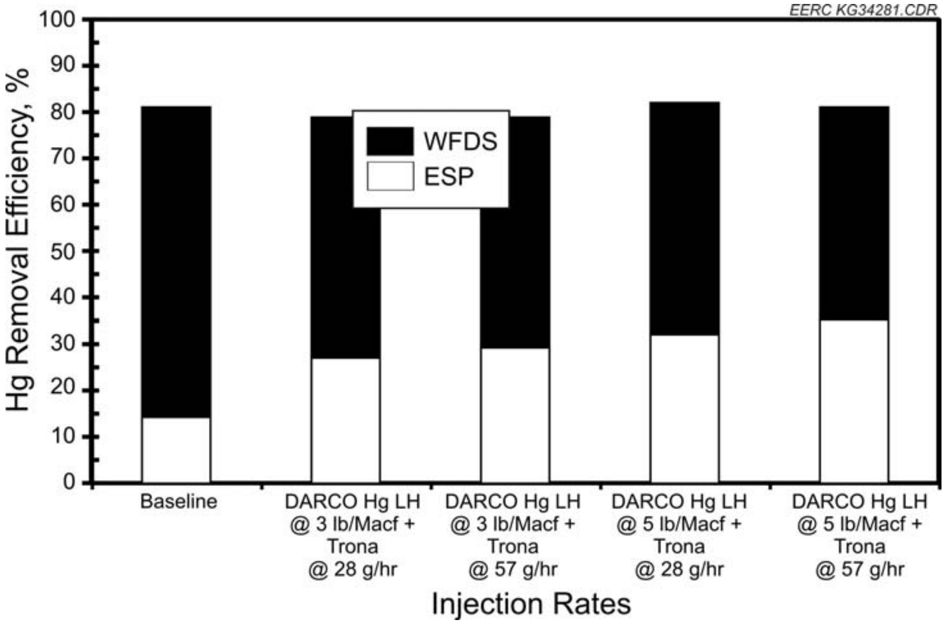

Figure 31. ESP and WFDS Hg removal efficiencies obtained during baseline Knight Hawk coal combustion and DARCO Hg-LH and trona injection conditions.

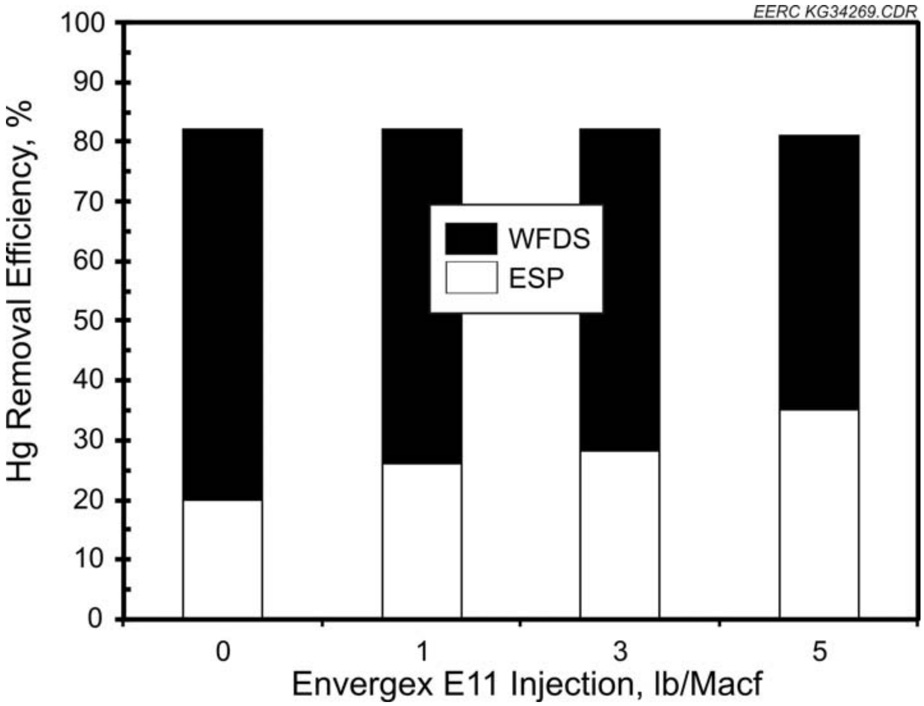

Figure 32. ESP and WFDS Hg capture efficiencies obtained during baseline Knight Hawk coal combustion and the injection of Envergex E11.

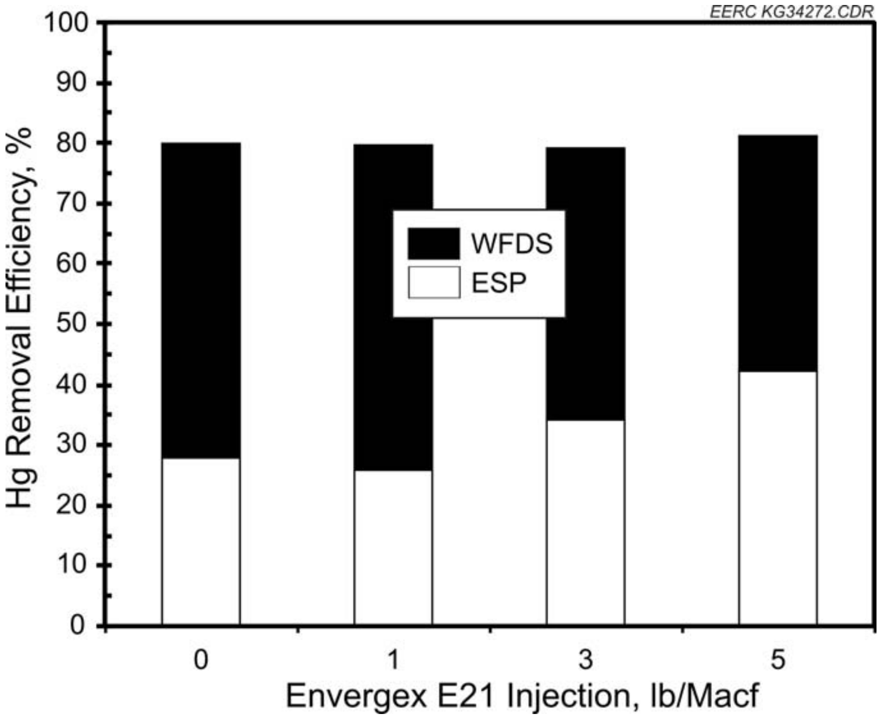

Figure 33. ESP and WFDS Hg capture efficiencies obtained during baseline Knight Hawk coal combustion and the injection of Envergex E21.

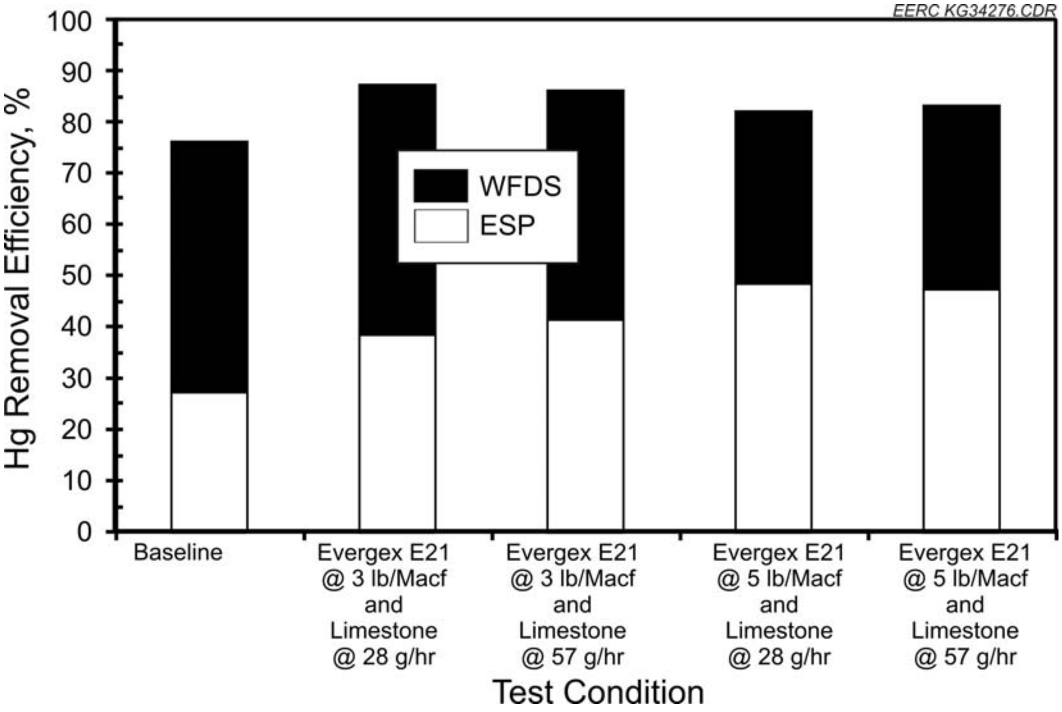

Figure 34. ESP and WFDS Hg capture efficiencies obtained during baseline Knight Hawk coal combustion and the coinjection of Envergex E21 and limestone.

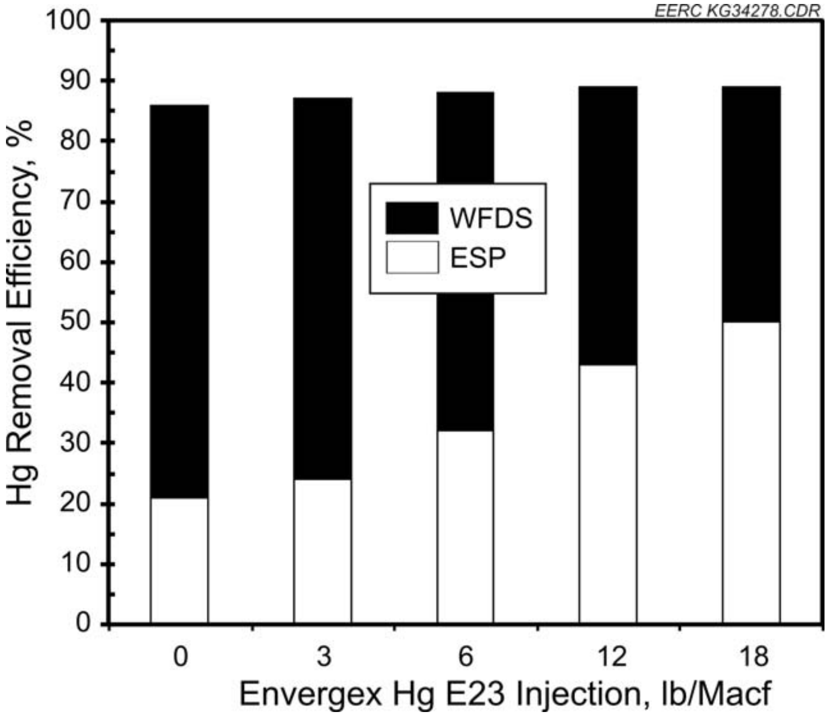

Figure 35. ESP and WFDS Hg capture efficiencies obtained during baseline Knight Hawk coal combustion and the injection of Envergex Hg E23.

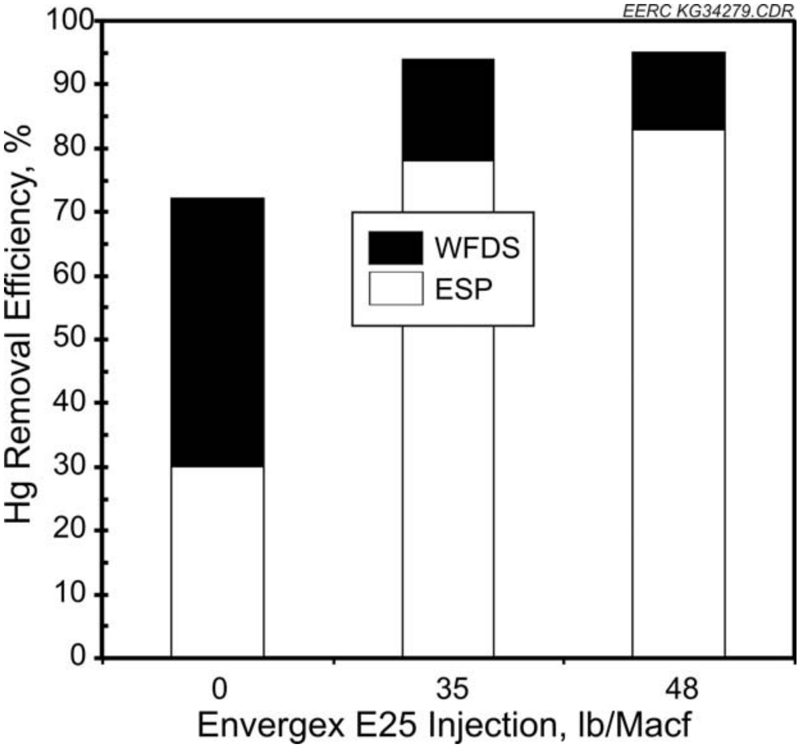

Figure 36. ESP and WFDS Hg capture efficiencies obtained during baseline Knight Hawk coal combustion and the injection of Envergex E25.

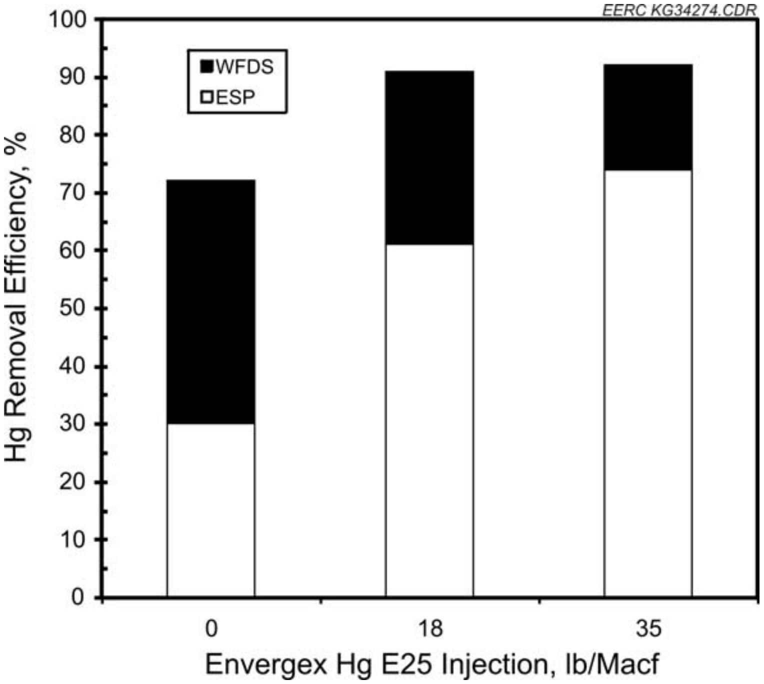

Figure 37. ESP and WFDS Hg capture efficiencies obtained during baseline Knight Hawk coal combustion and the injection of Envergex Hg E25.

A modified DARCO sorbent, designated as DARCO E26, was injected into the Knight Hawk coal combustion flue gas, as indicated in Figure 38. The modifications, however, did not significantly improve the Hg capture performance of DARCO Hg, as evidenced by comparing Figures 38 with 26.

The effectiveness of injecting Envergex E27 into Knight Hawk coal combustion flue gas for capturing Hg in an ESP and WFDS is indicated in Figure 39. Envergex E27 was less effective than Envergex E25 (Figure 36) or Envergex Hg E25 (Figure 37) at similar injection rates.

Presented in Table 15 are representative NO_x and SO_2 concentrations and APCD removal performances obtained during Knight Hawk coal combustion. As indicated in Table 15, NH_3 injection with the Cormetech catalyst and WFDS were very effective in removing NO_x and SO_2, respectively, from the Knight Hawk coal combustion flue gas.

Low-Sulfur Knight Hawk Bituminous Coal Combustion Testing of a Hitachi Catalyst, an ESP, and a WFDS

Presented in Figure 40 are average CMM results obtained during the baseline testing of low-sulfur Knight Hawk coal combustion flue gas. The average CMM total Hg concentration measured at the Hitachi catalyst inlet is biased 28% low relative to the coal calculated flue gas total Hg value plotted in Figure 40. The total Hg concentration measured at the catalyst inlet is very similar to the total Hg concentration measured at the ESP outlet, indicating that the coal

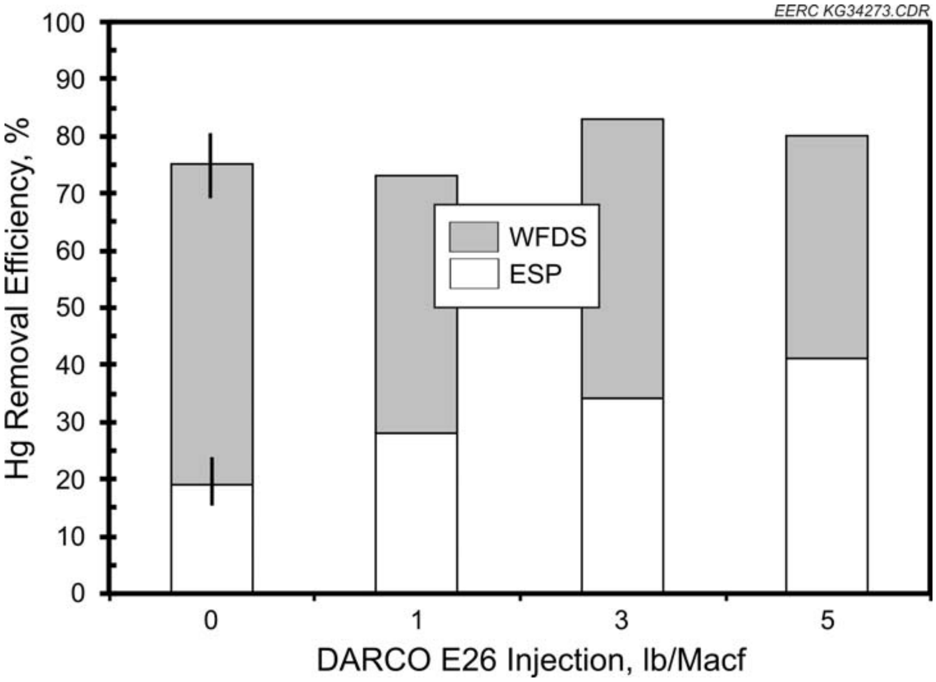

Figure 38. ESP and WFDS Hg capture efficiencies obtained during baseline Knight Hawk coal combustion and the injection of DARCO E26.

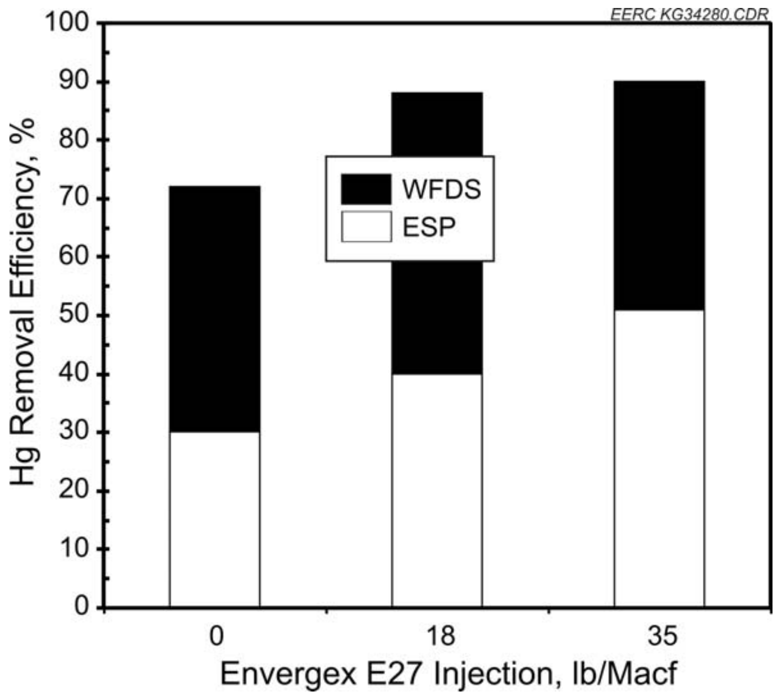

Figure 39. ESP and WFDS Hg capture efficiencies obtained during baseline Knight Hawk coal combustion and the injection of Envergex E27.

calculated flue gas total Hg concentration is probably too high. The CMM results from the Hitachi catalyst location were relied on for calculating ESP and WFDS Hg removal because of the apparent positive bias in the coal calculated flue gas Hg concentration. Similar to the previous CMM results obtained during Conesville and Knight Hawk coal combustion, the results from the low-sulfur Knight Hawk coal combustion flue gas indicate that Hg^0 oxidation occurs downstream from the Hitachi catalyst and that most of the Hg^{2+} is captured by the WFDS.

Presented in Figures 41 and 42 are average ESP and WFDS Hg removal efficiencies determined during baseline low-sulfur Knight Hawk coal combustion and DARCO Hg and DARCO Hg-LH injection conditions, described in Table 8. In contrast to the ESP removal effectiveness of

Table 15. Representative Continuous Emission-Monitoring and APCD Performance Results Obtained During Knight Hawk Coal Combustion Testing of a Cormetech Catalyst and WFDS

NO_x/NH_3	Furnace NO_x, ppmv	SCR Outlet NO_x, ppmv	SCR NO_x Removal, %	Furnace SO_2, ppmv	WFDS Outlet, SO_2, ppmv	WFDS SO_2 Removal, %
Off	452	412	9	3513	30	99
1:1	353	30	91	3400	218	94
1:2	352	49	86	3319	274	92

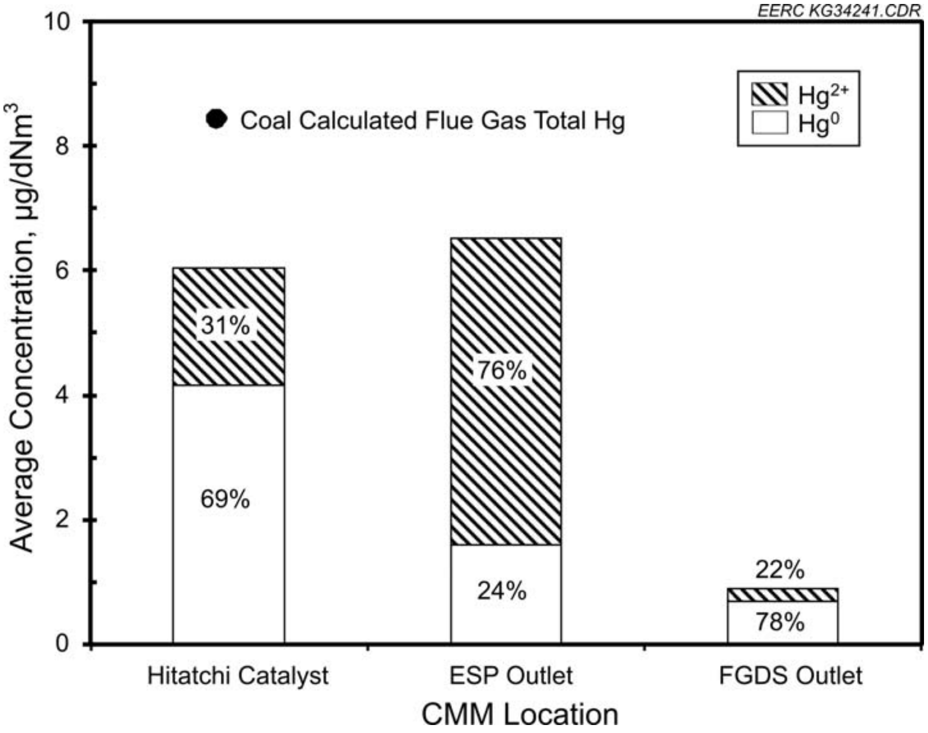

Figure 40. Average CMM results obtained during baseline low-sulfur Knight Hawk coal combustion.

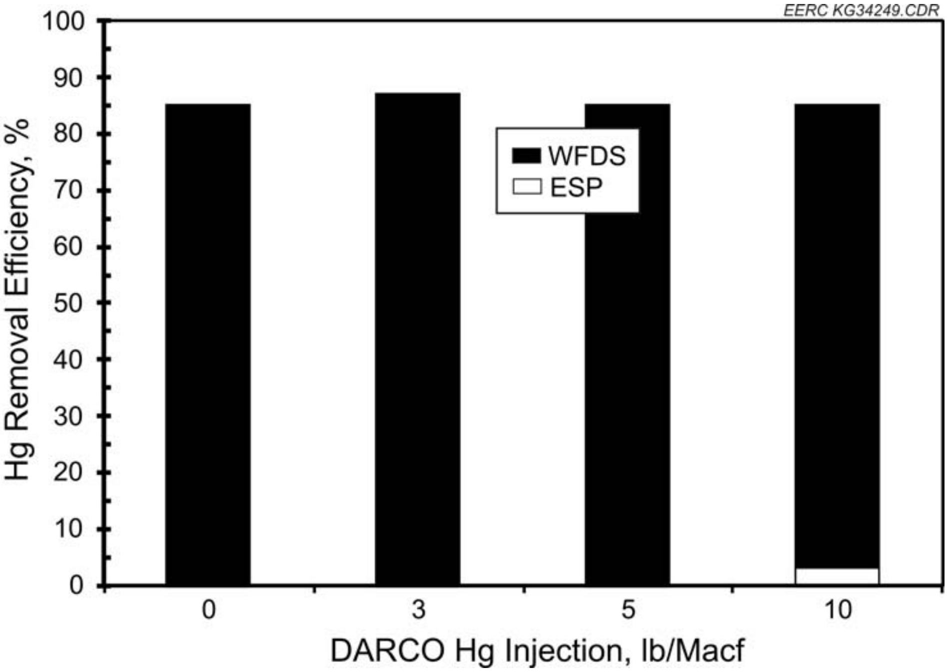

Figure 41. Average ESP and WFDS Hg removals obtained during baseline low-sulfur Knight Hawk coal combustion and DARCO Hg injection conditions.

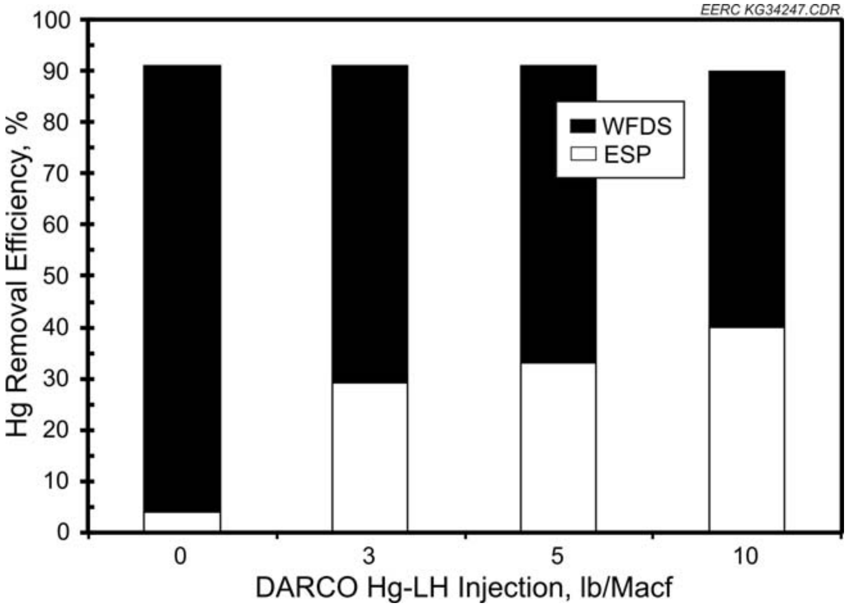

Figure 42. Average ESP and WFDS Hg removals obtained during baseline low-sulfur Knight Hawk coal combustion and DARCO Hg-LH injection conditions.

DARCO Hg injection into the Conesville and Knight Hawk coal combustion flue gases, as evidenced in Figures 13 and 26, respectively, similar injections into the low-sulfur Knight Hawk coal combustion flue gas did not significantly improve ESP Hg capture. DARCO Hg-LH, however, was significantly more effective in promoting ESP Hg capture from the low-sulfur Knight Hawk coal combustion flue gas, as indicated in Figure 42.

Average ESP and WFDS Hg removal efficiencies determined during the baseline low-sulfur Knight Hawk coal combustion and Envergex 28 injection conditions, described in Table 8, are presented in Figure 43. Envergex 28 injections were more effective in promoting ESP Hg capture than DARCO Hg injections (Figure 41) and provided ESP Hg removal performance similar to DARCO Hg-LH (Figure 42).

Presented in Figure 44 are average ESP and WFDS Hg removals determined during baseline low-sulfur Knight Hawk coal combustion and Envergex 30 and 24 injection alone and in combination. Envergex 30 and 24 injection at 3 and 30 lb/Macf, respectively, improved ESP Hg capture relative to baseline capture by about 10% and 30%, respectively. Dual injections of Envergex 30 and 24 at 3 and 15 lb/Macf did not significantly improve ESP Hg capture relative to Envergex 30 injection alone. Doubling of the Envergex 24 injection rate to 30 lb/Macf while maintaining Envergex 30 at 3 lb/Macf significantly improved ESP Hg removal to about 53%.

The effects of injecting Envergex 31 alone and in combination with Envergex 24 on ESP and WFDS Hg removal performance are shown in Figures 45 and 46. Injection of Envergex 31 was relatively ineffective for promoting ESP Hg capture. Dual injection of Envergex 31 and 24 at 5 and 15 lb/Macf provided Hg removal performance similar to Envergex 30 injection at

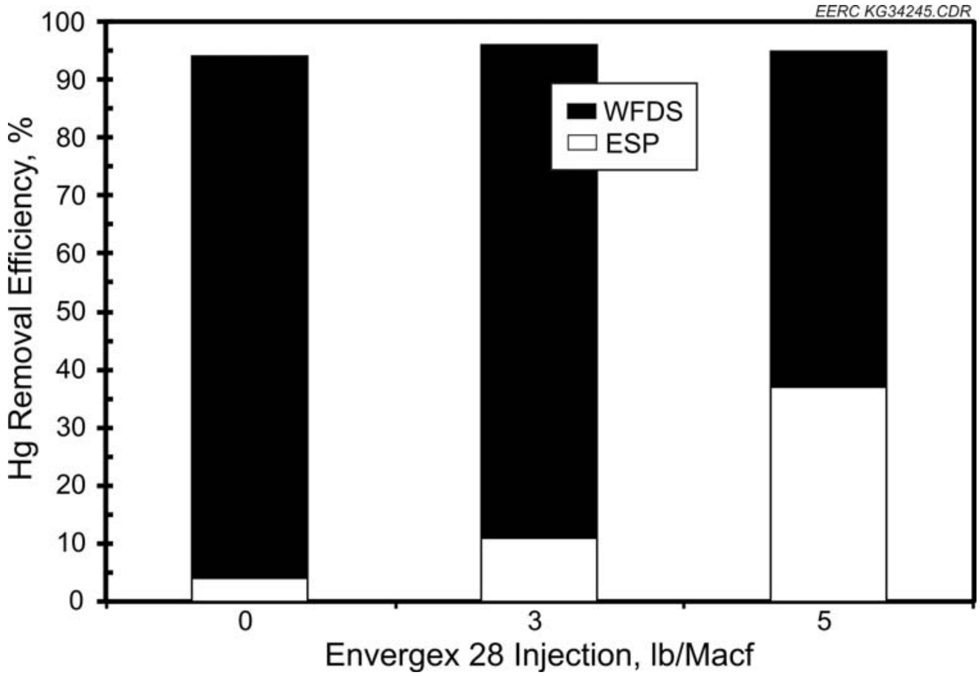

Figure 43. Average ESP and WFDS Hg removals obtained during baseline low-sulfur Knight Hawk coal combustion and Envergex 28 injection conditions.

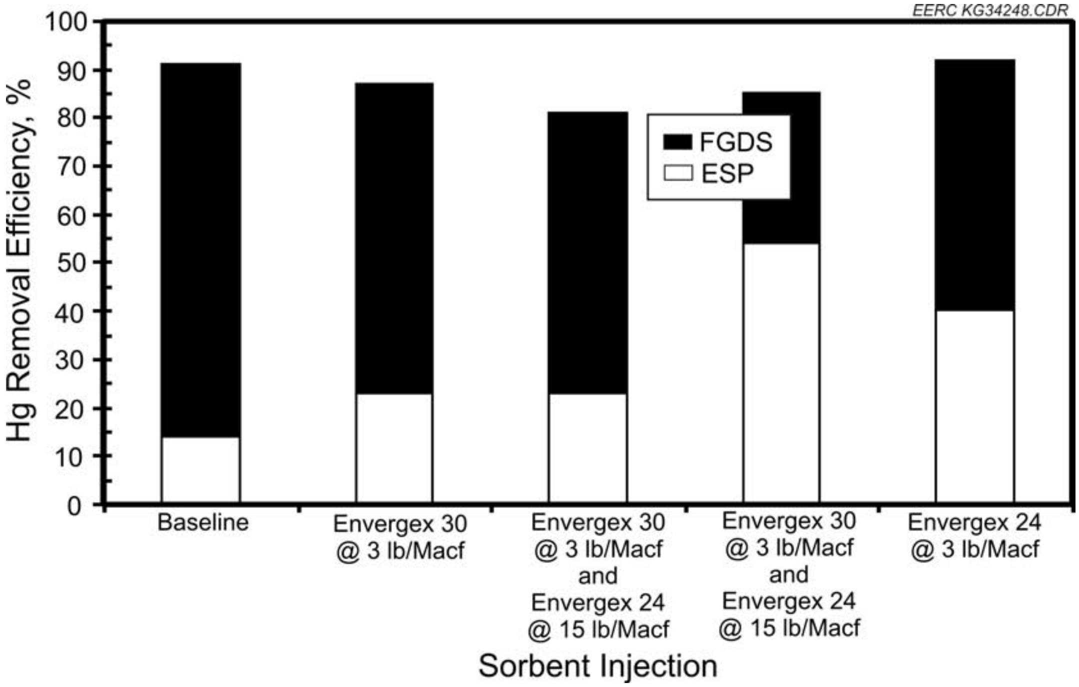

Figure 44. Average ESP and WFDS Hg removals obtained during baseline low-sulfur Knight Hawk coal combustion and Envergex 30 and 24 injection alone and in combination.

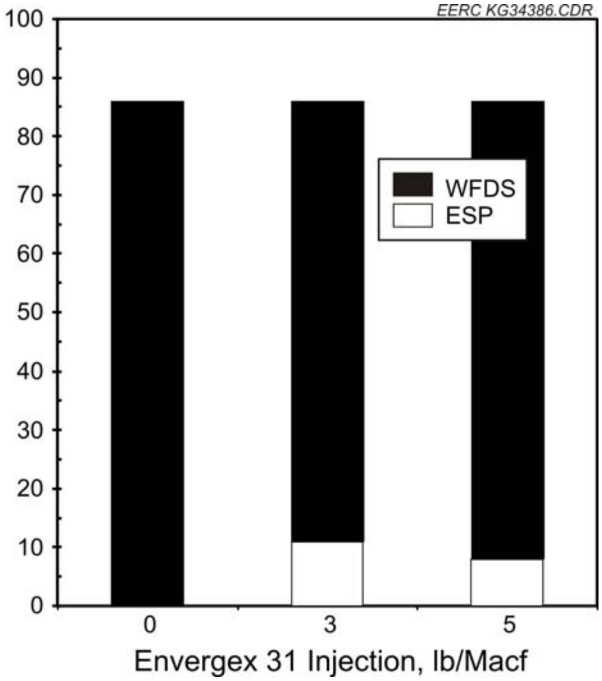

Figure 45. Average ESP and WFGD Hg removal obtained during baseline low-sulfur Knight Hawk coal combustion and Envergex 31 injection.

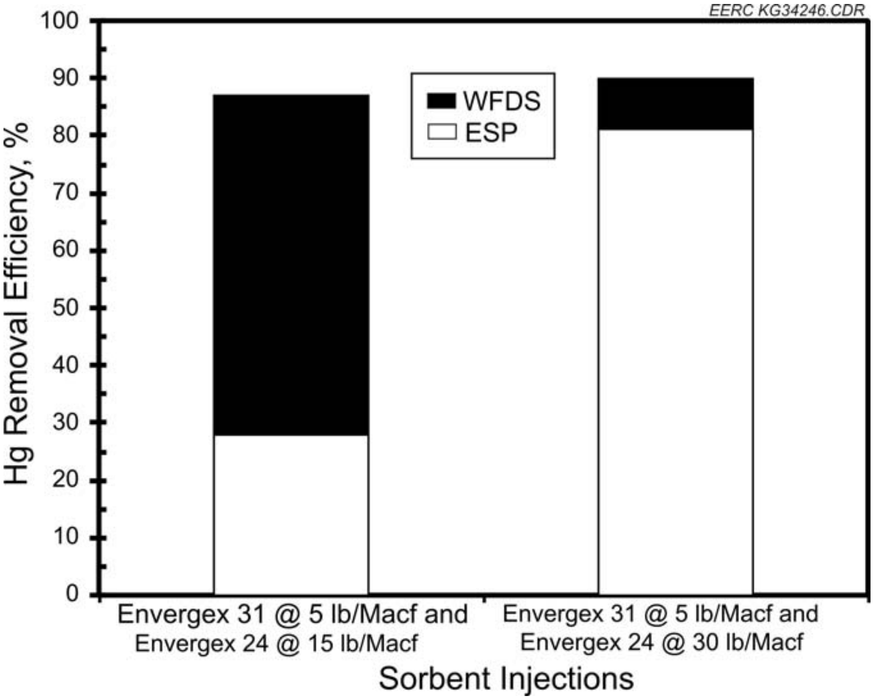

Figure 46. Average ESP and WFDS Hg removal obtained during coinjection of Envergex 31 and 24 into the low-sulfur Knight Hawk coal combustion flue gas.

3 lb/Macf, as shown in Figure 44. Doubling of the Envergex 24 injection rate greatly improved ESP Hg capture efficiency to about 80%. Although not shown in Figure 46, the injection of Envergex 24 alone at 30 lb/Macf provided similar ESP and WFGS Hg removal performance for the dual injection of Envergex 31 and Envergex 24 at 30 lb/Macf. As indicated in Figure 47, Envergex 33 injection was effective in promoting ESP Hg capture but at very high injection rates of 16.5 and 33.0 lb/Macf.

The testing occurring on March 4 and 5, 2009, described in Table 8, was focused on the effects of varying NH_3 and limestone injection conditions on Hg speciation and APCD performance. Average CMM results that were obtained during baseline (i.e., with NH_3 and limestone injections turned off) low-sulfur Knight Hawk coal combustion over a combined time period of 8 hours on March 4 and 5, 2009, are presented in Figure 48. Similar to previous CMM results, the average total Hg concentration measured at the inlet to the Hitachi catalyst is biased low relative to the coal calculated flue gas value but compares very favorably to the catalyst and ESP inlet total Hg concentrations. The results in Figure 47 indicate that Hg^0 oxidation occurs across the Hitachi catalyst before entering the ESP. The ESP captured a small amount of Hg^{2+}, whereas the WFDS captured essentially all of the Hg^{2+}.

Presented in Figures 49–51 are average CMM results obtained at the ESP outlet and WFDS outlet locations during NH_3 injection (NO_x–NH_3 ratio of 1:0.8) and varying limestone injection rates into the low-sulfur Knight Hawk coal combustion flue gas. In comparison to the results in Figure 48, the results in Figures 49–51 indicate that NH_3 and limestone injection did not significantly affect Hg^0 oxidation, ESP Hg capture, or Hg capture in the WFDS. In addition, the average CMM results in Figures 52 and 53 indicate that increasing NH_3 injection to a NO_x–NH_3 ratio of 1:1 (equivalent to ≈330 ppmv) or turning NH_3 off in the presence of limestone injection at 56.8 g/hr (2.5 g/kg coal) did not significantly affect Hg^0 oxidation and ESP or WFDS Hg capture efficiencies.

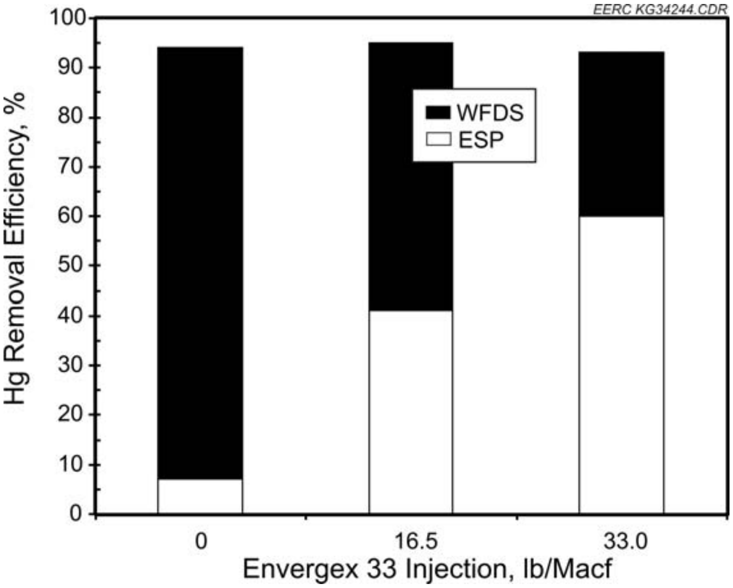

Figure 47. Average ESP and WFDS Hg removals obtained during baseline low-sulfur Knight Hawk coal combustion and Envergex 33 injection conditions.

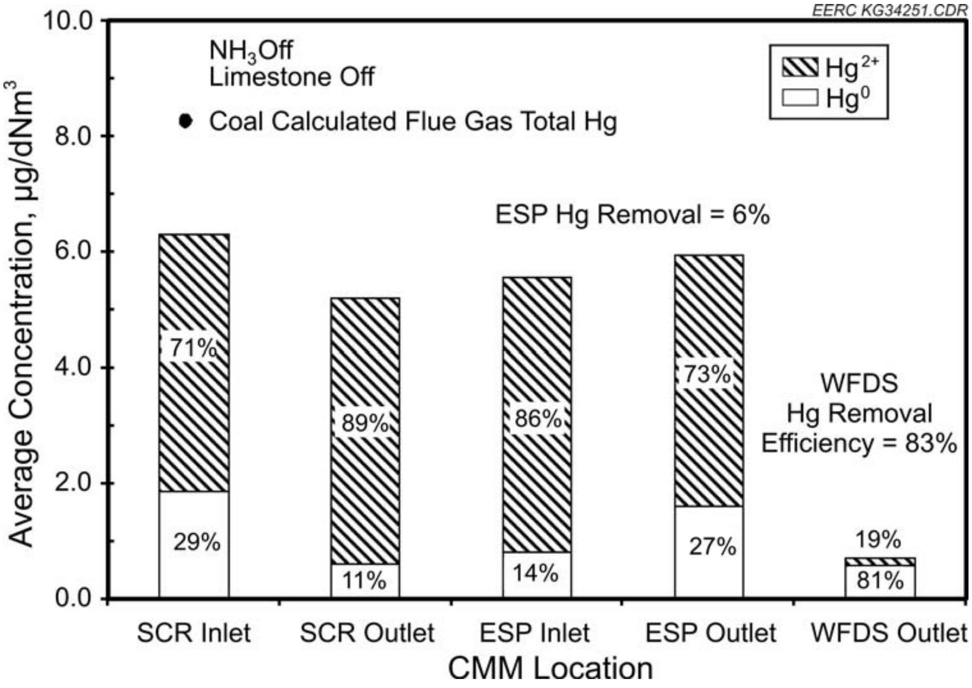

Figure 48. Average CMM results and APCD performance obtained during 8 hours of baseline low-sulfur Knight Hawk coal combustion.

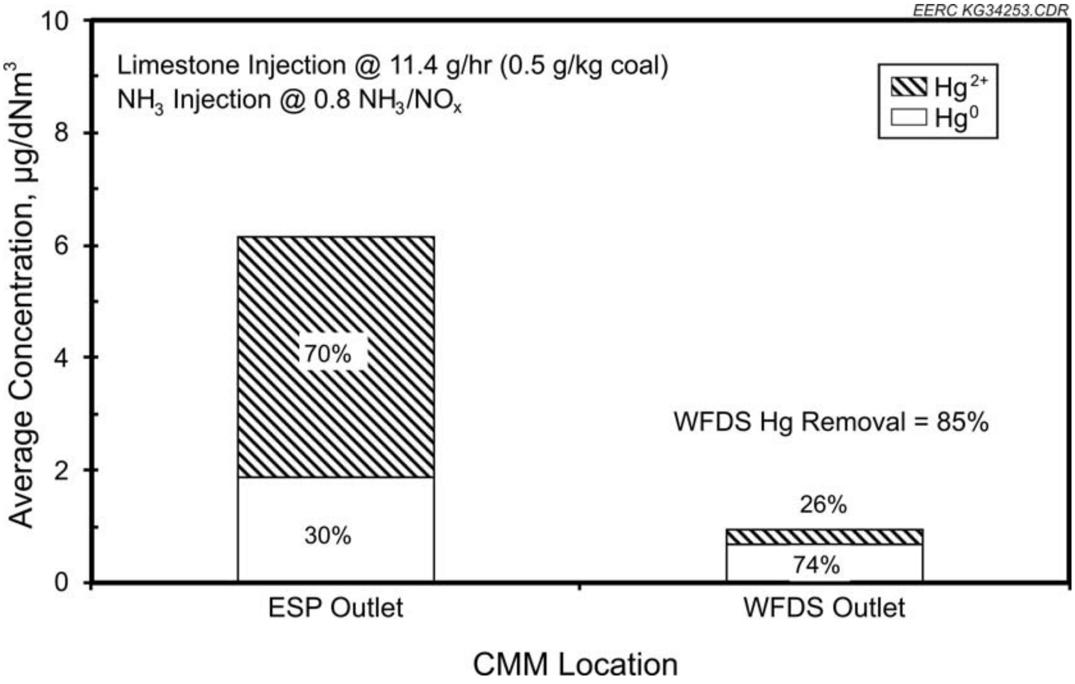

Figure 49. Average CMM results obtained at the ESP outlet and WFDS outlet locations during NH_3 and limestone injection at a NO_x–NH_3 ratio of 1:0.8 and 11.4 g/hr (0.5 g/kg coal), respectively, into the low-sulfur Knight Hawk coal combustion flue gas.

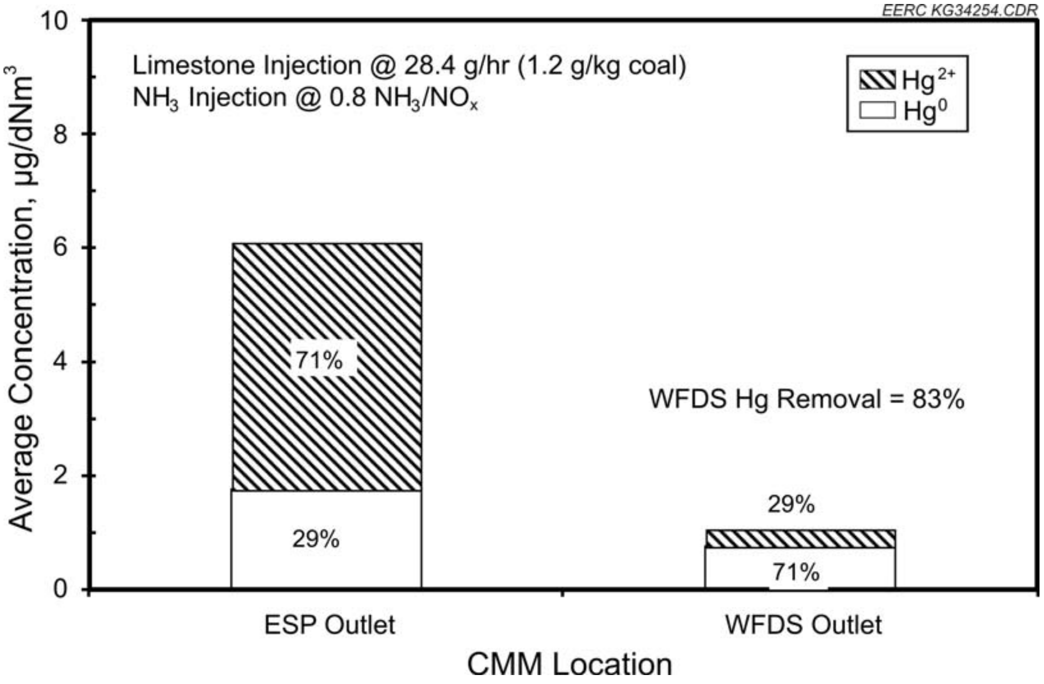

Figure 50. Average CMM results obtained at the ESP outlet and WFDS outlet locations during NH_3 and limestone injection at a NO_x–NH_3 ratio of 1:0.8 and 56.8 g/hr (2.5 g/kg coal), respectively, into the low-sulfur Knight Hawk coal combustion flue gas.

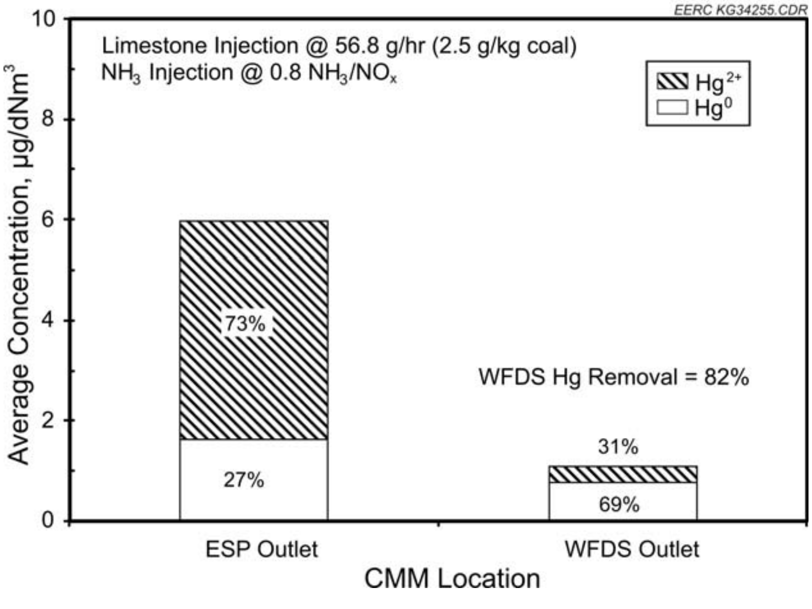

Figure 51. Average CMM results obtained at the ESP outlet and WFDS outlet locations during NH_3 and limestone injection at a NO_x–NH_3 ratio of 1:0.8 and 28.4 g/hr (1.2 g/kg coal), respectively, into the low-sulfur Knight Hawk coal combustion flue gas.

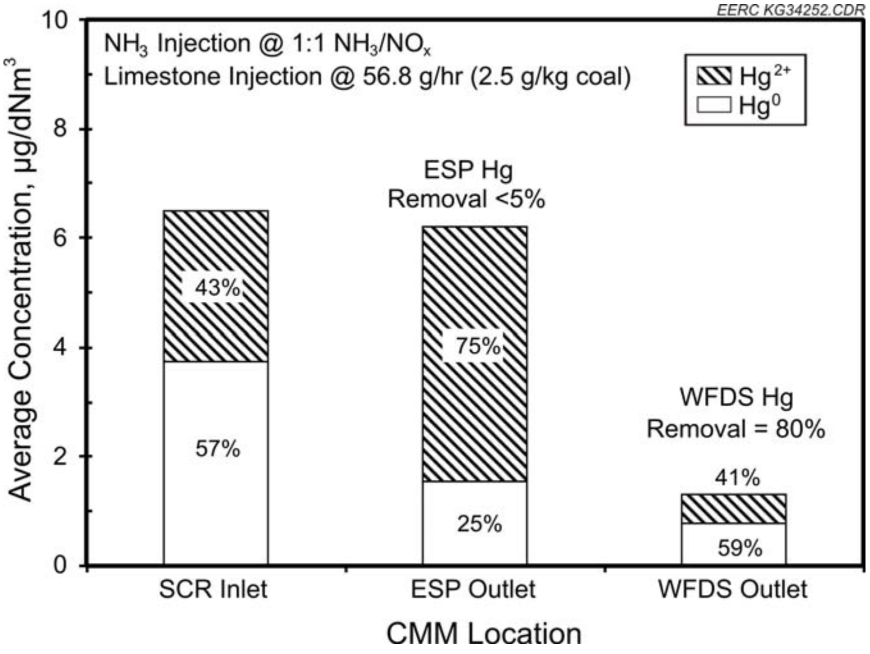

Figure 52. Average CMM results obtained at the SCR inlet, ESP outlet, and WFDS outlet locations and APCD Hg removal efficiencies obtained during NH$_3$ and limestone injection at a NO$_x$–NH$_3$ ratio of 1:1 and 56.8 g/hr (2.5 g/kg coal), respectively, into the low-sulfur Knight Hawk coal combustion flue gas.

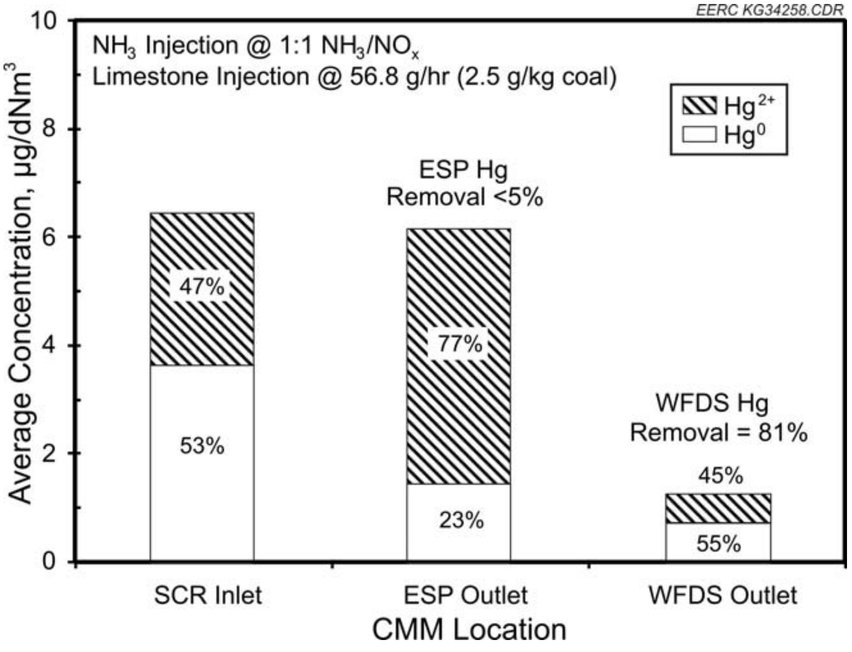

Figure 53. Average CMM results obtained at the SCR inlet, ESP outlet, and WFDS outlet locations and APCD Hg removal efficiencies obtained during limestone injection alone at 56.8 g/hr (2.5 g/kg coal) into the low-sulfur Knight Hawk coal combustion flue gas.

On the last day of testing, average CMM results were obtained at the SCR and ESP inlet and outlet locations and the WFDS outlet during separate NH_3 and limestone injections at a NO_x–NH_3 ratio of 1:0.8 (≈270 ppmv) and 56.8 g/hr (2.5 g/kg coal), respectively, into the low-sulfur Knight Hawk coal combustion flue gas. The average CMM results in Figure 54 indicate that NH_3 injection at a NO_x–NH_3 ratio of 1:0.8 (equivalent to ≈270 ppmv) did not significantly affect Hg^0 oxidation relative to baseline testing conditions (Figure 48). A comparison of average total Hg concentrations measured at the SCR inlet and ESP outlet locations indicates an ESP Hg removal of 22%. However, a comparison of ESP inlet and outlet total Hg concentrations indicates an ESP Hg removal of <5%, which is similar to that indicated by the baseline test results in Figure 48. NH_3 injection did not significantly improve on the relatively high WFDS Hg removal performance obtained during baseline conditions. The average CMM results in Figure 55 obtained during limestone injection at 56.8 g/hr (2.5 g/kg coal) are identical, within analytical uncertainty, to those in Figure 54, indicating that, similar to NH_3 injection, limestone injection did not significantly affect Hg^0 oxidation or ESP and WFDS Hg removal efficiencies.

Summarized in Tables 16 and 17 are the NO_x, SO_2, and SO_3 concentrations and Hitachi SCR catalyst NO_x and WFDS SO_2 removal efficiencies obtained during the baseline low-sulfur Knight Hawk combustion tests and NH_3 and/or limestone injection tests. As expected, NO_x removals increased significantly during NH_3 injections. Limestone injections did not significantly improve on WFDS SO_2 removal performance during NH_3 injections. In the absence of NH_3 injection, however, limestone injection did slightly improve the SO_2 removal performance of the WFDS relative to baseline testing conditions.

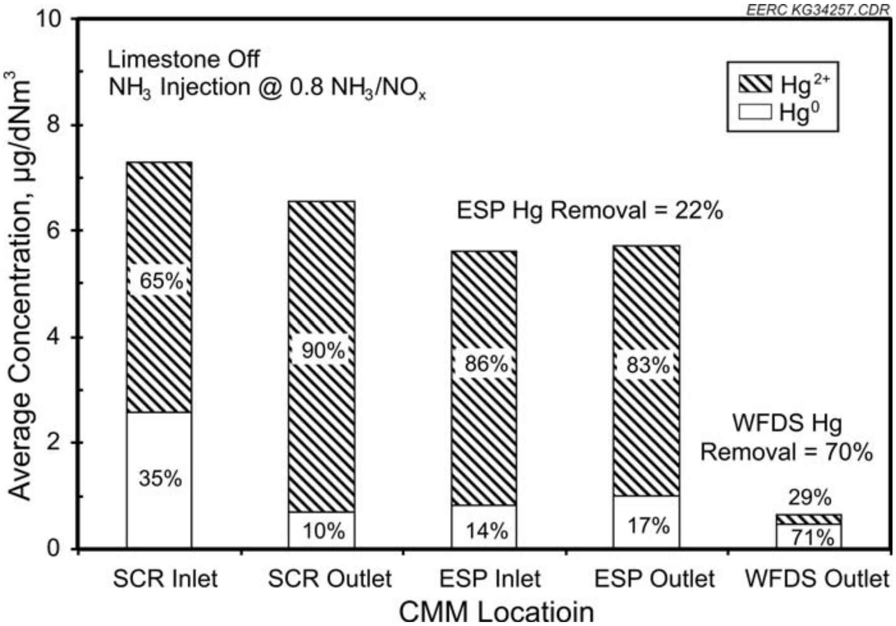

Figure 54. Average CMM results obtained at the SCR inlet, SCR outlet, ESP inlet, ESP outlet, and WFDS outlet and APCD Hg removal efficiencies obtained during NH_3 injection at a NO_x–NH_3 ratio of 1:0.8 (≈270 ppmv) into low-sulfur Knight Hawk coal combustion flue gas.

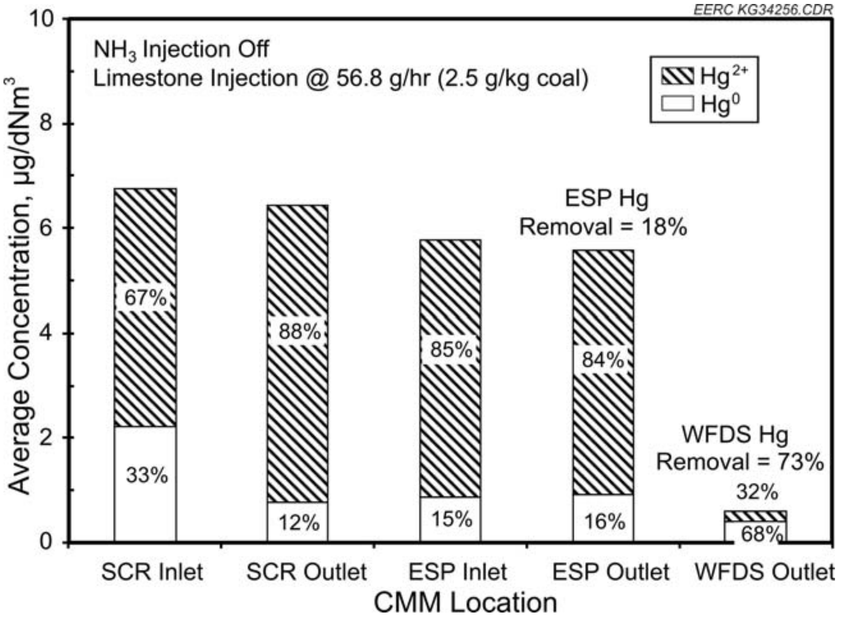

Figure 55. Average CMM results obtained at the SCR inlet, SCR outlet, ESP inlet, ESP outlet, and WFDS outlet and APCD Hg removal efficiencies obtained during limestone injection alone at 56.8 g/hr (2.5 g/kg coal) into low-sulfur Knight Hawk coal combustion flue gas.

Table 16. Average Continuous Emission-Monitoring and APCD Performance Results Obtained During Low-Sulfur Knight Hawk Coal Combustion Testing of a Hitachi Catalyst and WFDS

NO_x/ NH_3	Furnace NO_x, ppmv	SCR Outlet NO_x, ppmv	SCR NO_x Removal, %	Furnace SO_2, ppmv	SCR Inlet SO_3, ppmv	SCR Outlet SO_3, ppmv	WFDS Outlet, SO_2, ppmv	WFDS SO_2 Removal, %
Off	335	310	7	1999	NA[a]	NA	44	98
1:1	451	72	84	2118	<1	14.1	401	81

[a] Not analyzed.

Table 17. Average Continuous Emission-Monitoring Results Obtained During Baseline Low-Sulfur Knight Hawk Coal Combustion and NH_3 and Limestone Injection Conditions

NO_x/NH_3	Limestone Injection, g/kg coal	Furnace NO_x, ppmv	SCR Outlet NO_x, ppmv	SCR NO_x Removal, %	Furnace SO_2, ppmv	WFDS Outlet, SO_2, ppmv	WFDS SO_2 Removal, %
Off	Off	331	285	14	1980	688	65
1:0.8	Off	336	66	80	1976	487	75
1:0.8	0.5	368	116	68	1981	571	71
1:0.8	1.2	367	97	74	1981	600	70
1:0.8	2.5	346	96	72	1984	565	72
1:1	2.5	331	42	87	1978	622	69
Off	2.5	319	286	10	2008	587	71
Off	2.5	367	293	20	1979	516	74

Task 4 – Blending Tests

The Antelope coal and Antelope–Knight Hawk coal blends described in Table 12 were burned in the CTF to evaluate the effects of coal blending on Hg emission control using a Hitachi Zosen catalyst and ESP. Unfortunately, problems with the CMM instruments resulted in erratic Hg concentrations that were unacceptable for evaluating Hg emission control during the coal blend combustion tests. OH method results were obtained, however, at the ESP outlet location during the combustion of the Antelope–Knight Hawk blends at ratios of 90:10 and 80:20. OH method results are presented in Figure 56. The results in Figure 56 indicate that most of the Hg was present as Hg^{2+}. Based on the calculated flue gas Hg concentrations in Table 12, ESP Hg removal efficiencies were determined, as indicated in Figure 56. An increase of 10% in the blend proportion did not significantly affect Hg speciation or capture in the ESP.

The deposits produced in the CTF during the Antelope and Antelope–Knight Hawk coal combustion tests were analyzed using a point count technique on an automated scanning electron microscope (ASEM) to evaluate the effects of coal blending on ash deposition (i.e., slagging and fouling) severity. 250 points were randomly analyzed on each of the deposits. The average compositions from those 250 analyses on each deposit are presented in Table 18. As expected based on the Antelope and Knight Hawk coal ash compositions in Table 11, increased blend ratios of Knight Hawk contribute to increased Fe_2O_3 in the coal ash deposits. The ASEM analyses indicated that the deposits are composed mostly of a calcium aluminosilicate glass.

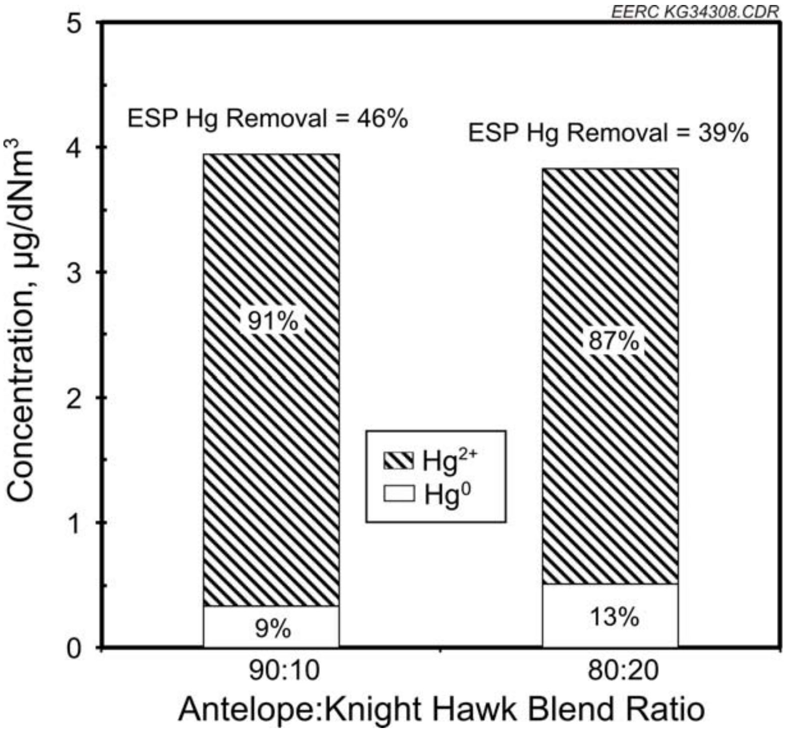

Figure 56. OH method Hg measurement results obtained from the ESP outlet during Antelope–Knight Hawk coal blend combustion.

Table 18. Chemical Compositions of Antelope and Antelope–Knight Hawk Coal Ash Deposits, elemental oxide, SO_3-free, wt%

Antelope–Knight Hawk Coal Blends Date:	100% 6/25/08	90:10 6/27/08	80:20 6/27/08	70:30 6/28/08
SiO_2	56.8	58.0	51.5	52.8
Al_2O_3	12.6	11.3	15.1	13.4
Fe_2O_3	10.1	11.9	12.8	16.6
TiO_2	1.20	1.40	1.30	0.90
P_2O_5	2.40	1.80	2.40	1.60
CaO	13.7	12.0	13.0	11.3
MgO	1.60	1.40	1.90	1.30
Na_2O	0.40	0.60	0.50	0.50
K_2O	1.20	1.60	1.50	1.60

Quartz is a nonreactive mineral in both coals that survived the combustion conditions and remains in the deposits. Anorthite ($CaAl_2Si_2O_8$) is ubiquitous in the deposits mainly because of the relatively high CaO content of the Antelope coal ash and SiO_2 and Al_2O_3 contents of both coal ashes as indicated in Table 10. Anorthite crystallized during cooling of the calcium aluminosilicate melts produced in the CTF. An iron oxide component, most likely hematite (Fe_2O_3), in the deposits gradually increased from 4.0 wt% in the Antelope coal ash deposit to 4.5, 6.0, and 9.6 wt% as the Knight Hawk blend proportions increased by 10%, 20%, and 30%, respectively. Hematite is primarily an oxidation product of the relatively large amounts of pyrite (FeS_2) common to U.S. bituminous coals.

The deposit chemical compositions in Table 18 were used to calculate slag viscosity as a function of temperature for the Antelope and Antelope–Knight Hawk coal blends. Presented in Figure 57 are the predicted viscosities plotted as a function of temperature for the Antelope and Antelope–Knight Hawk coal blends. For reference, a viscosity of 250 poise (log viscosity = 2.398 poise) is the maximum viscosity at which slag can be tapped from a furnace. The predicted slag viscosities for a typical furnace exit gas temperature of 2200° to 2400°F are very high, suggesting that the parent Antelope coal and the Antelope–Knight Hawk coal blends should not pose a slagging problem. The predicted slag viscosities for a given temperature are very similar regardless of blend proportion, suggesting that blending with Knight Hawk coal at $\leq$30% should not significantly affect slagging propensity.

Task 5 – Reporting and Management

The project manager, Mr. Jason Laumb, coordinated all of the testing performed within the various project tasks and subtasks. During the course of the project, meetings were held with the principal investigators (PIs), Mr. John Kay and Mr. Brandon Pavlish, and co-PI, Mr. Nick Lentz, to ensure communication and joint planning of tests. Reporting consisted of monthly reports to ICCI, quarterly management reports to DOE, and this draft final report for all of the project sponsors. This draft report will be revised based on comments and recommendations received from the project sponsors.

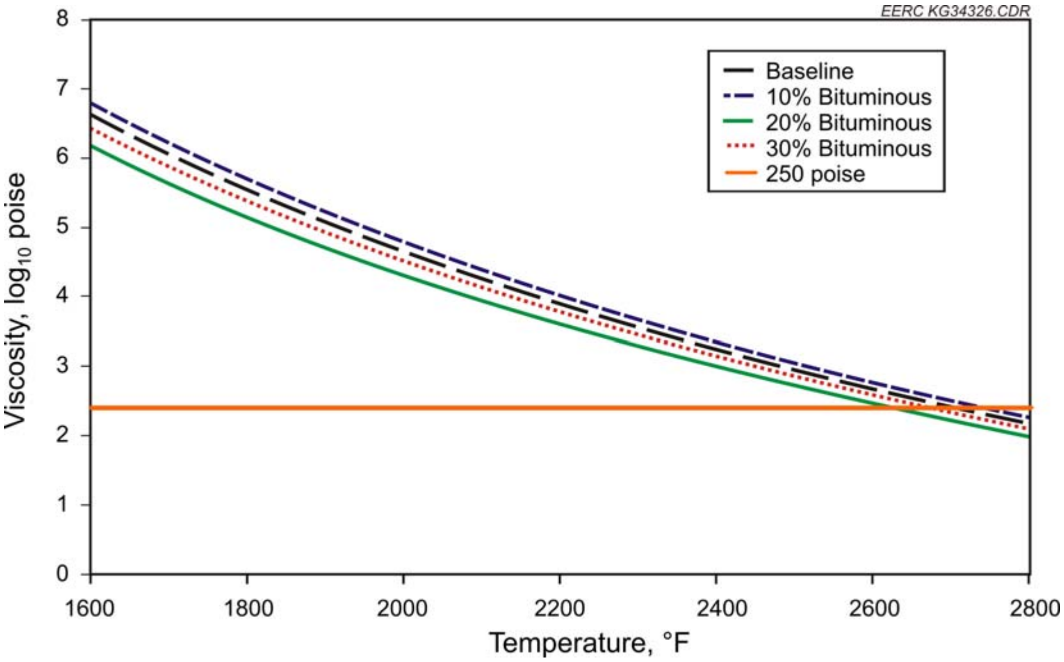

Figure 57. Predicted slag viscosity versus temperature relationships for the Antelope and Antelope–Knight Hawk coal blends.

CONCLUSIONS AND RECOMMENDATIONS

The EERC developed an applied research consortium project to test cost-effective Hg control technologies for utilities burning bituminous coals. Hg control technology evaluations were performed using the EERC's CTF. The CTF was fired on pulverized bituminous coals at 550,000 Btu/hr (580 MJ/hr). The CTF was configured with the following APCDs: SCR unit, ESP, and WFDS. The Hg control technologies investigated as part of this project included ACI (Norit Americas, Inc. and Envergex sorbents), Hg^0 oxidation catalysts (i.e., the noble metals in Hitachi Zosen, Cormetech, and Hitachi SCR catalysts), SEAs (a proprietary EERC additive, trona, and limestone), and blending with a PRB subbituminous coal. These Hg control technologies were evaluated separately, and many were also tested in combination.

Bituminous coals from the Conesville Coal Preparation Company and Knight Hawk Coal Mine were used in evaluating Hg control. In addition, the Knight Hawk coal was blended with a PRB subbituminous coal from the Antelope Mine at Antelope–Knight Hawk blend proportions of 90:10, 80:20, and 70:30 on a heating value basis. Mercury contents of the Conesville, Knight Hawk, low-sulfur Knight Hawk, and Antelope coals averaged 0.168, 0.0902, 0.0804, and 0.0595 ppm on a dry basis, respectively. Mercury contents of the Antelope–Knight Hawk coal blends ranged from 0.0525 to 0.0673 ppm on a dry basis. Chlorine concentrations of the Conesville, Knight Hawk, low-sulfur Knight Hawk, and Antelope coals were 382, 137, 1006, and 6 ppm on a dry coal basis, respectively. The Conesville, Knight Hawk, and low-sulfur Knight Hawk coals possessed the general characteristics of bituminous coals; that is, relatively high chlorine and sulfur but low alkaline-earth metal contents that resulted in a flue gas containing significant proportions of Hg^0 and Hg^{2+}. Conversely, the subbituminous Antelope coal had lower chlorine and sulfur but higher alkaline-earth metal contents that resulted in a combustion flue gas containing Hg^0 as the dominant Hg species.

CMM results were used to evaluate the proportions of Hg^0 and Hg^{2+} forms in the flue gases and ESP and WFDS Hg removal performances obtained during baseline combustion conditions for the Conesville, Knight Hawk, and low-sulfur Knight Hawk coals. The CMM results obtained during baseline Antelope coal combustion were unreliable and were, therefore, not useful for evaluating Hg^0 and Hg^{2+} or APCD Hg removal performance. Baseline combustion conditions involved tests when no sorbents or SEAs were being injected. NH_3 injection, however, occurred during most of the baseline combustion tests. NH_3 did not significantly affect Hg^0 oxidation or capture in the ESP or WFDS units. All three bituminous coal combustion flue gases contained significant proportions of Hg^0 and Hg^{2+}, especially at the SCR inlet or between the catalyst layers. CMM at the ESP outlet indicated that Hg^0 oxidation occurred downstream from the SCR catalysts. The ESP was ineffective in capturing Hg, but the WFDS was very effective in capturing Hg^{2+} but not Hg^0. Based on the baseline coal combustion results, the primary goal and benefit of injecting sorbents and/or SEAs was to significantly improve ESP Hg capture so that the potential for Hg reemission from the WFDS could be reduced.

The industry standard practice of injecting DARCO Hg and/or DARCO Hg LH was performed during combustion of the bituminous coals for comparability purposes with the alternative technologies that were evaluated. Conesville coal combustion tests indicated that DARCO Hg injections at reasonable rates improved ESP Hg capture from <10% to about 50%. The WFDS effectively removed Hg from the Conesville coal combustion flue gas at efficiencies of ≥80% because most of the Hg downstream from the Hitachi Zosen and Cormetech catalysts and ESP occurred as Hg^{2+}. The WFDS was not as effective in removing Hg from the Knight Hawk coal combustion flue gas because less Hg^{2+} was present. Injections of DARCO Hg into the Knight Hawk coal combustion flue gas improved ESP Hg removal performance from 15% to 25% to a maximum of 40%. The combination of DARCO Hg and SEA2 injections at 1.2 lb/Macf and 0.6–2.3 ppm, respectively, further improved ESP Hg removal to about 60%. Combining trona injections with low DARCO Hg and SEA2 injections at 1.2 lb/Macf and 0.6 ppm, respectively, significantly improved ESP Hg capture to approximately 70%. Trona injections combined with DARCO Hg injections, however, were not as effective in enhancing ESP Hg capture as injecting DARCO Hg alone. Coinjections of limestone with DARCO Hg did not significantly improve ESP Hg removal performance. The combination of DARCO Hg LH and trona injections provided similar ESP Hg removal performance as coinjections of DARCO Hg and trona or limestone. The Envergex E11, E21, and Hg E23 sorbents and DARCO E26 provided similar ESP Hg capture performance as DARCO Hg at an equivalent injection rate. The combination of Envergex E21 at 5 lb/Macf and limestone injections improved ESP Hg removal to about 50%. At very high injection rates of 12 to 48 lb/Macf, Envergex E23, E25, and E27 provided ESP Hg removals ranging from 40% to 80%.

The WFDS was most effective in removing Hg from the low-sulfur Knight Hawk coal combustion flue gas downstream of a Hitachi catalyst. In contrast to the Conesville and Knight Hawk coals, DARCO Hg injections were ineffective in promoting ESP Hg capture from the low-sulfur Knight Hawk coal combustion flue gas. Injections of DARCO Hg LH into the low-sulfur

Knight Hawk coal combustion flue gas, however, enhanced ESP Hg removal to 30%–40%. Injections of Envergex 28 and 30 provided similar ESP Hg removal efficiencies as DARCO Hg LH at an equivalent injection rate. Coinjection of Envergex 30 at 3 lb/Macf with Envergex 24 significantly improved ESP Hg removal to about 50% but only at a very high Envergex 24 injection rate of 30 lb/Macf. The injection of Envergex 24 alone at 30 lb/Macf provided an ESP Hg removal of 40%. Injection of Envergex 31 at 3 and 5 lb/Macf did not significantly improve ESP Hg removal performance. Coinjections of Envergex 31 at 5 lb/Macf with Envergex 24 at 15 and 30 lb/Macf improved ESP Hg capture to about 30% and 80%, respectively. Relatively high injections of Envergex 33 at 16.5 and 33 lb/Macf provided ESP Hg removal efficiencies of 40% and 60%, respectively. Limestone injections in the presence or absence of NH_3 injection did not significantly affect ESP or WFDS Hg removal performance.

Although the CMM results obtained during Antelope–Knight Hawk coal combustion were unreliable, OH method Hg measurement results were obtained at the ESP outlet during combustion of the Antelope–Knight Hawk blends at ratios of 90:10 and 80:20. The results indicated that most, about 90%, of the Hg occurred as Hg^{2+}. ESP Hg removal efficiencies were similar for both blends, with an average of 42%. An increase of 10% in the blend proportion did not significantly affect Hg speciation or capture in the ESP.

Continuous emission monitoring and limited SO_3 analysis results were obtained during Conesville, Knight Hawk, low-sulfur Knight Hawk, and Antelope coal combustion testing of Hitachi Zosen, Cormetech, and Hitachi catalysts upstream of a WFDS. Limited SO_3 analyses indicated that SO_3 concentrations at the outlets of the SCR catalysts were <1% of the SO_2 exiting the furnace. NH_3 injections combined with the SCR catalysts effectively reduced NO_x emissions by >80%. The WFDS was also effective in reducing SO_2 emissions by >80%.

The deposits produced in the CTF during the Antelope and Antelope–Knight Hawk coal combustion tests were analyzed using a point count technique on an ASEM to evaluate the affects of coal blending on ash deposition, slagging, and fouling severity. As expected, based on the Antelope and Knight Hawk coal ash compositions, increased blend ratios of Knight Hawk contributed to increased Fe_2O_3 in the coal ash deposits. ASEM analyses indicated that the deposits were composed mostly of a calcium aluminosilicate glass. An iron oxide component, most likely hematite (Fe_2O_3), in the deposits gradually increased from 4.0 wt% in the Antelope coal ash deposit to 4.5, 6.0, and 9.6 wt% as the Knight Hawk blend proportions increased by 10%, 20%, and 30%, respectively. Predicted slag viscosities for a typical furnace exit gas temperature of 2200° to 2400°F were very high, suggesting that the parent Antelope coal and the Antelope–Knight Hawk coal blends should not pose a slagging problem. The predicted slag viscosities for a given temperature were very similar regardless of blend proportion, suggesting that blending with Knight Hawk coal at $\leq$30% should not significantly affect slagging propensity.

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