Full-Scale Evaluation of Carbon Injection for Mercury Control at a Unit Firing High Sulfur Coal

Paper #14

Sharon M. Sjostrom
ADA-ES, Inc.
8100 SouthPark Way, Unit B, Littleton, CO 80120
sharons@adaes.com

Cody Wilson, Jean Bustard
ADA-ES, Inc.
Littleton, CO

Gary Spitznogle, Aimee Toole
American Electric Power Corporation
Columbus, OH

Andrew O'Palko
U.S. Department of Energy National Energy Technology Laboratory
Morgantown, WV

Ramsay Chang, Ph.D.
EPRI
Palo Alto, CA

ABSTRACT

Limited field tests to date show that the effectiveness of activated carbon injection for mercury control decreases as the coal sulfur concentration increases. Sorbent vendors are developing activated carbons and other sorbents that are more effective in a high sulfur gas environment. Little data exists for units firing high sulfur bituminous coal. ADA-ES and AEP, with support from DOE NETL, EPRI, and industry partners, are conducting a mercury control demonstration using sorbent injection into the ESP at AEP's 400-MW Conesville Station Unit 6 in Conesville, Ohio. This paper will present results from testing a variety of activated carbons and other alternative sorbents on mercury emissions, the influence of flue gas temperature on mercury removal efficiency, and a discussion on the effectiveness of a mercury CEM in this challenging environment.

INTRODUCTION

The test described in this paper is part of a five-site program funded by the Department of Energy's National Energy Technology Laboratory (NETL) and industry partners to obtain the necessary information to assess the feasibility and costs of controlling mercury from coal-fired utility plants. These host sites reflect a combination of coals and existing air pollution control configurations representing 78% of existing coal-fired generating plants and, potentially, a significant portion of new plants. Many of the host sites included in this program were considered challenges or unknowns in 2003 when the proposal was submitted because of their flue gas characteristics or air pollution control configurations. In general, the native mercury removal at all test sites is limited. Testing at four of the sites was completed in 2004 and 2005. Testing at the final site, AEP's Conesville Station, is currently underway.

Host Site Description: Conesville Unit 6

AEP's Conesville Power Plant is located near Coshocton, Ohio. The Unit 6 boiler is a 400-MW Combustion Engineering (ALSTOM) designed tangential fired PC unit that normally fires high sulfur eastern bituminous coal. The unit is equipped with cold-side Research Cottrell ESPs. Flue gas is drawn through the ESPs via ID fans. The ID fans discharge flue gas into two Universal Oil Products wet lime absorber modules. The modules have partial bypass capability and have been retrofitted with a B&W tray design. The system is typically operated with the bypassed closed. The bypass valves have a design leak rate of 5% of the flow. A sketch of the unit layout is presented in Figure 1. A sketch of the ESP showing port and hopper locations is presented in Figure 2. This figure will be referenced throughout this paper. Most of the testing was conducted on the entire 400-MW unit. Operating parameters are included in Table 1.

Figure 1. Layout Sketch of Conesville Units 5 and 6.

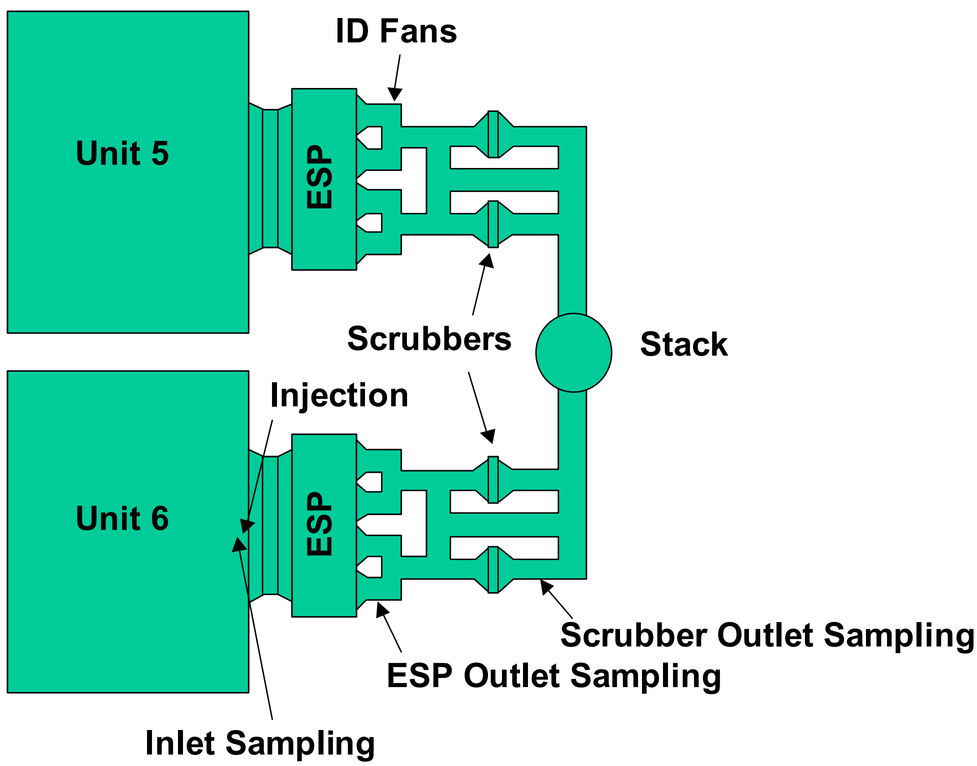
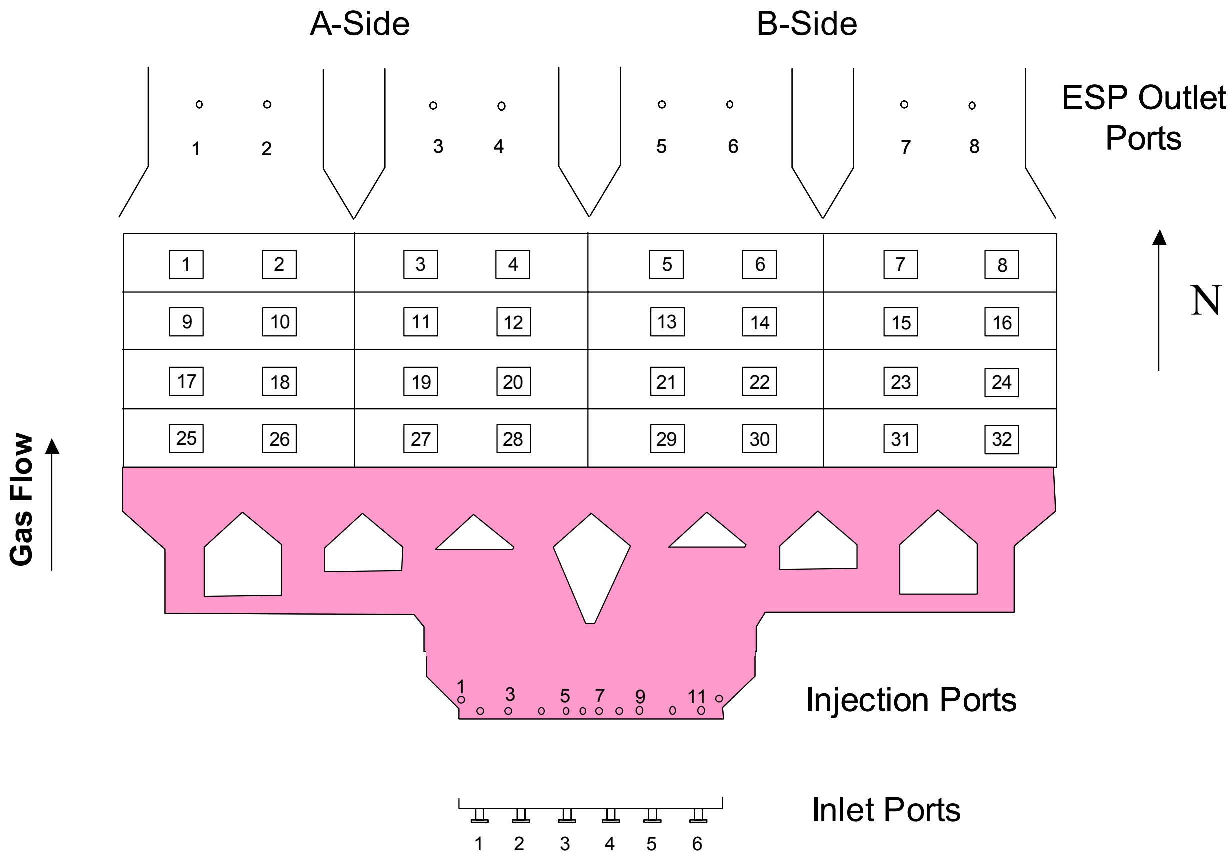


Figure 2. Sketch of Conesville Unit 6 ESP with Port and Hopper Locations Identified.



The temperature across the ESP is stratified due to the air pre-heater design. Temperatures measured in the injection ports during testing indicate a 75°F temperature gradient (nominally 290°F in port 2 on the A-side to 365°F in port 10 B-side). The flue gas SO_3 concentration is nominally 30 ppm, based upon previous measurements by AEP.

Table 1. Conesville Key Operating Parameters.

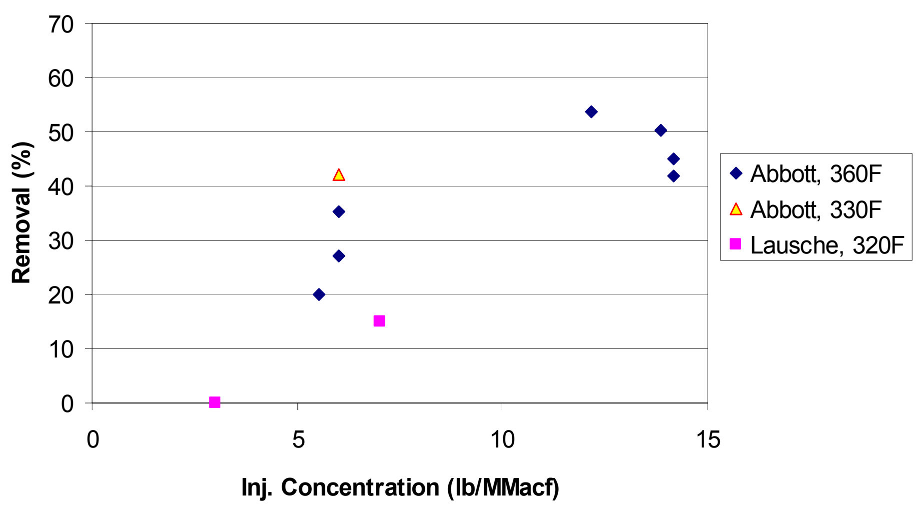
Unit	6
Size (MW)	400
Test Portion (MWe)	400
Coal	High sulfur Ohio Basin Bituminous
Heating Value (as received)	11,020
Sulfur (% by weight)	3.31
Chlorine (ppm dry)	273
Mercury (ppm dry)	0.381
Particulate Control	Cold Side ESP SCA = 301 ft^2/kacfm
Sulfur Control	Wet FGD
Ash Reuse	FGD Sludge Stabilization

Background: Impact of High Sulfur Flue Gas on Activated Carbon

Some of the more difficult applications for mercury control with sorbent injection are sites firing high-sulfur bituminous coals. Laboratory studies conducted over the past 15 years by URS Group, UNDEERC and others, indicate that SO_x in the flue gas can significantly affect the mercury adsorption capacity of fly ash and activated carbon (CEA, 2005; Carey et al., 1998). In general, results from laboratory studies suggest that SO_2 and SO_3 reduce the equilibrium mercury capacity of activated carbon and fly ash because these sulfur compounds occupy surface sites on the carbon that adsorb and oxidize mercury. The equilibrium capacity of a sorbent is the maximum mercury that a sorbent can adsorb at 50 µg/Nm^3. The threshold capacity is the minimum at which performance is not limited by adsorption capacity. When injecting a sorbent into the flue gas, the sorbent is exposed to the gas stream for only a few seconds to several minutes as compared to several minutes to hours in a fixed-bed system. Since the concentration of SO_2 is much higher than mercury in flue gas, especially in high-sulfur eastern bituminous coals, the overall adsorption capacity is likely dependant on the SO_2 and SO_3 concentration in the gas as it forms H_2SO_4 on the surface of the carbon.

Full-scale field tests also indicate that standard activated carbon is less efficient in high-sulfur environments. Activated carbon injection tests were conducted at the University of Illinois' Abbott Power Plant in Champaign, Illinois, in 2001 (Sjostrom, 2002). This site fires high sulfur (3.8%) bituminous coal with 2500-ppm chlorine. Equilibrium adsorption capacity measurements were conducted for DARCO Hg at this site at temperatures of 375 and 325°F. At 375°F, the equilibrium adsorption capacity was 184 µg/g. At 325°F, the equilibrium adsorption capacity was 486 µg/g. Injection tests were conducted at Abbott at two flue gas temperatures: 360°F and 330°F, and the results suggests a slight increase in the mercury removal performance of DARCO Hg at the lower temperature. Injection tests were also conducted at the Lausche plant of Ohio University (1000 ppm SO_2 and 20 ppm SO_3 in flue gas). Test results from both Abbott and Lausche, shown in Figure 3, indicate limited mercury removal performance of DARCO Hg.

Figure 3. Injection Test Results from Abbott and Lausche Power Plants.



Equilibrium adsorption capacity measurements were also made at We Energies Pleasant Prairie Power Plant (P4) upstream and downstream of SO_3 injection for ESP flue gas conditioning (Bustard, 2003). These data indicate a significant impact on the mercury capacity of DARCO Hg due to both SO_3 and temperature. During full-scale tests at P4, decreasing the temperature using spray cooling from 300°F to 250°F did not improve the mercury removal measured across the ESP when injecting DARCO Hg for mercury control. This suggests that the threshold capacity, or the capacity at which a change in performance is expected during injection testing, was less than 425 µg/g at P4, the equilibrium adsorption capacity measured at 300°F in the presence of SO_3. The equilibrium data also suggests that the capacity can be significantly improved at higher temperatures (300°F) in the presence of SO_3 if the sorbent is mixed with an alkali material such as lime. No improvement was noted at the lower temperature (250°F). The P4 and Abbott results are presented in Table 2.

Table 2. Equilibrium Adsorption Capacities Measured at Two Sites with SO_3 Present in Flue Gas.

Site	SO_3	Temperature (°F)	Equilibrium Adsorption Capacity (µg/g) Normalized to 50 µg/Nm^3
P4	None	250	8823
P4	SO_3 FGC	250	3355
P4 (D. Hg + Lime*)	SO_3 FGC	250	2091
P4	None	300	880
P4	SO_3 FGC	300	425
P4 (D. Hg + Lime*)	SO_3 FGC	300	>1504
Abbott	Coal	375	148
Abbott	Coal	325	486

**Lime to sorbent ratio was 60:1.*

Full-scale injection testing conducted at Southern Company's Plant Daniel indicated that, unlike Pleasant Prairie, SO_3 used for flue gas conditioning had a negative impact on sorbent performance (Berry, 2005). Daniel was firing a low sulfur western bituminous coal during the tests and is configured with an ESP for particulate control.

CONESVILLE RESULTS

The test program at Conesville was designed to evaluate and demonstrate the effectiveness of sorbents for mercury control in high sulfur flue gas. In addition to identifying and testing sorbents, the test team also assured good sorbent distribution through modeling by Reaction Engineering International (REI) and stratification measurements at the outlet of the ESP and in the hopper ash. Two mercury CEMS, Thermo Electro Freedom System™, were placed at the inlet and outlet of the ESP to characterize typical mercury concentrations, speciation, and native mercury behavior. The performance of these systems was verified using Ontario Hydro (OH) measurements and sorbent trap measurements (STM, modified 40 CFR Part 75, appendix K). These systems have been operating continuously since installation and have provided fairly reliable service throughout the program. They are operated remotely from the ADA-ES offices in Colorado.

Baseline Results

One week of baseline testing (no sorbent injection) was completed during the week of March 13, 2006. During the baseline tests, Unit 6 was held at standard full-load operating conditions from nominally 07:00–19:00 hours and the air pollution equipment was operated under standard full-load conditions. STM and Ontario Hydro tests were also conducted to measure total (STM and OH) and speciated (OH) mercury concentrations.

The coals fired during baseline testing were typical of Conesville, averaging in preliminary analyses at 3.5% sulfur and 12,920 Btu/lb (dry basis). The mercury concentration in the coals varied from 144 to 268 ng/g. A summary of select coal parameters measured during baseline testing is presented in Table 3.

Table 3. Summary of Baseline Coal Analyses.

	Mine			Weighted Average
	CAM-Ohio	**Oxford**	**Conesville PP**	
% Ash	8.7	13.6	10.1	11.9
% Sulfur	2.4	4.1	2.5	3.5
Hg (ng/g)*	268	256	144	
Br (µg/g)*	11.8	23	6.1	
Cl (µg/g)*	1140	687	808	
HHV (Btu/lb)	13710	12586	13082	12920
% Total Fired**	22	61	17	

** Hg, Br, Cl values from single coal samples, others are average of received loads, dry analysis.*
***Percent of total coal fired during baseline testing.*

The Ontario Hydro and Hg CEM data both indicate very little to no mercury removal across the ESP. The Ontario Hydro results show very little particulate-bound mercury, around 30% elemental mercury at the inlet and outlet of the ESP, and around 90% elemental mercury at the WFGD outlet. The Hg CEM data at the ESP inlet during the Ontario Hydro runs indicate an oxidized fraction of about 60%, which is somewhat higher than predicted by the Ontario Hydro measurements. The mercury removal across the system, including the WFGD, was 50 to 60%.

Ash analyses confirmed the result that very little mercury is removed across the ESP. Ash mercury was always below 1 lb/TBtu, and typically well below this level. For comparison, the flue gas mercury levels were typically in the range of 13 to 35 lb/TBtu. The mercury concentration in the inlet field hopper ash was nearly four times higher on the cool-side of the ESP, indicating that the 75°F temperature variation across the duct affects the mercury removal effectiveness of the native fly ash. Ash LOI in the first field was under 1% in all cases, and more concentrated (up to 3%) in the back fields. Correlation between mercury content and LOI (with higher LOI corresponding to greater mercury concentrations) was seen in the front two fields but not in the back two fields.

Sorbent Screening Tests

One of the keys to a successful program at Conesville is identifying sorbents that will be effective in high-sulfur flue gas. Forty-six (46) materials were tested at Conesville from 14 different suppliers. The suppliers are included in Table 4.

Table 4. Companies Providing Sorbents for Sorbent Screening Tests.

Supplier	**General Description**
Advanced Fuel Research	Activated Carbon
Calgon	Activated Carbon
California Earth Minerals	Non-Carbon Based
Donau	Activated Carbon
EERC	Activated Carbon
Engelhard	Non-Carbon Based
Frontier Geosciences	Activated Carbon
NEST	Non-Carbon Based
NORIT	Activated Carbon
Sorbent Technologies	Activated Carbon
TDA Research	Non-Carbon Based
Zinkan	Non-Carbon Based
AEP	Alkali Materials
ADA-ES	Blends of sorbents

Fixed-bed screening results indicated that several sorbents performed better in Conesville flue gas than the benchmark DARCO Hg. Most of these sorbents were blends of alkali materials, such as trona, and activated carbon. The range of equilibrium adsorption capacity for DARCO Hg was less than 600 µg/g, compared with over 800 µg/g for many of the blends. Based upon the results from P4, it was expected that some of these materials would demonstrate 40 to 50% mercury removal at Conesville with moderate injection concentrations.

Because of uncertainty regarding the initial screening results and similar performance of several materials, the test team modified the original test plan to include several sorbents in the full-scale evaluation instead of two. The parametric test plan was also modified to "screen" the candidate sorbents at a single injection concentration for nominally 2 hours to choose the best performer prior to characterizing the sorbents performance over a range of injection concentrations.

Parametric Testing Results

Based on the results of all sorbent screening tests, fifteen sorbents were selected for full-scale testing included DARCO Hg, a sorbent derived from a Texas-lignite coal and manufactured by NORIT Americas. This sorbent has been tested in various lab, pilot, and full-scale mercury control demonstrations and is considered the benchmark for performance comparisons. DARCO Hg has a bulk density of 25-30 lbs/ft^3. Other sorbents tested at full-scale are listed in Table 5.

Table 5. Sorbents Selected for Conesville Full-Scale Tests Based on Screening Tests and Availability.

Sorbent
Calgon RUV-N and RUV+
Sorbent Technologies EXP-2
Donau Desorex DX700C
NORIT DARCO Hg
NORIT DARCO Hg-LH
NORIT DARCO E-xx
EERC C5SL

Mercury Removal

Four weeks of parametric testing were conducted: March 21–24, March 27–31, May 8–12, and May 15–19, 2006. The sorbents tested were as shown in Table 5, including six E-series sorbents (12, 13, 14, 18, 19, 20) and a finer version of DARCO Hg, Insul. The DARCO E-series products included mixes of alkali with carbon, other substrates (e.g., non-coal based), and other mixes of sorbents and materials that may protect the sorbents from SO_3. NORIT produced several of these materials at the request of the test team.

The parametric tests consisted of "screening" the sorbents by injecting at the maximum achievable continuous feed rate of the injection system for 2 to 3 hours. Due to difficulties controlling the feed rate, the actual injection concentrations ranged from 9 to 18 lb/MMacf from sorbent to sorbent during the first two weeks of testing. The problems with the feeder were resolved during the second week of testing and all subsequent tests were conducted at an injection concentration of 8 lb/MMacf. During the final two weeks of parametric testing, two different lance designs were tested to evaluate the impact on mercury removal.

The effectiveness of the sorbents tested was limited, with mercury removal ranging from 5 to 31% at injection concentrations up to 18 lb/MMacf. The maximum incremental removal by a sorbent was 31% (DARCO E-12 at 12 lb/MMacf). The next-highest removal was 25% (Sorbent Technologies EXP-2 at 10 lb/MMacf). Although the injection concentrations varied, the results indicate that none of the sorbents were able to achieve the minimum project mercury removal goal of 50% at an injection concentration below 10 lb/MMacf. A summary of the results is presented in Figure 4. During several later tests, an alternative lance configuration was used that only treated the B-side of the duct. An example of the mercury trend graphs during the second week of parametric testing is shown in Figure 5.

Figure 4. Summary of Short Screening Test Results.

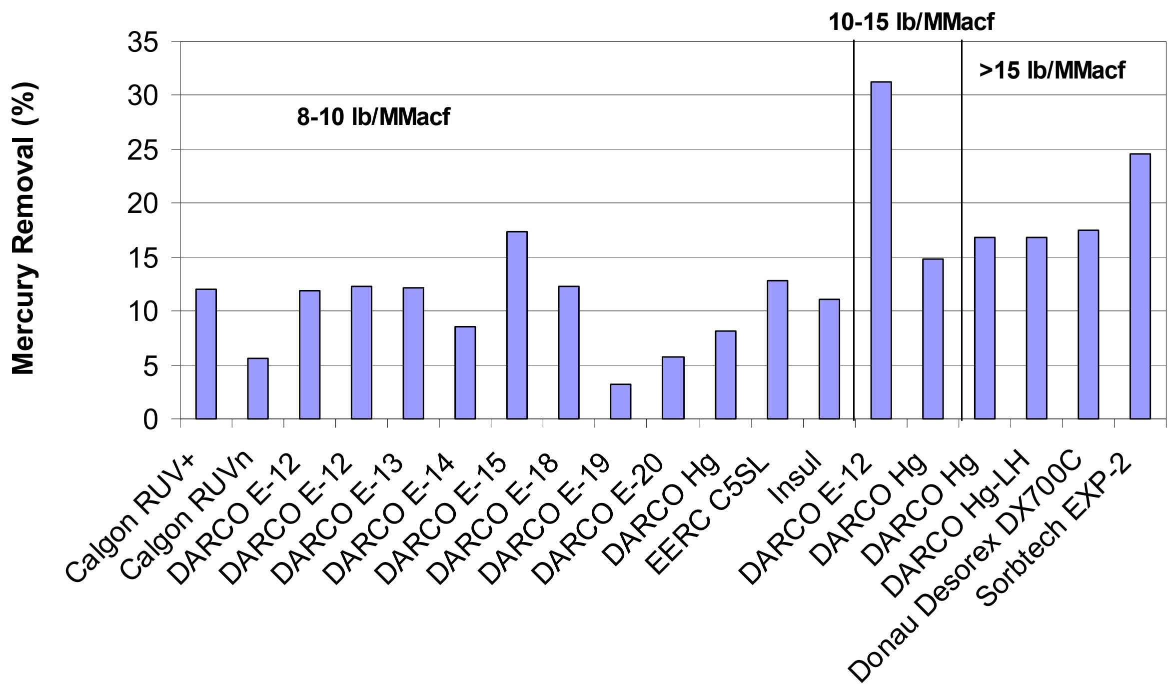
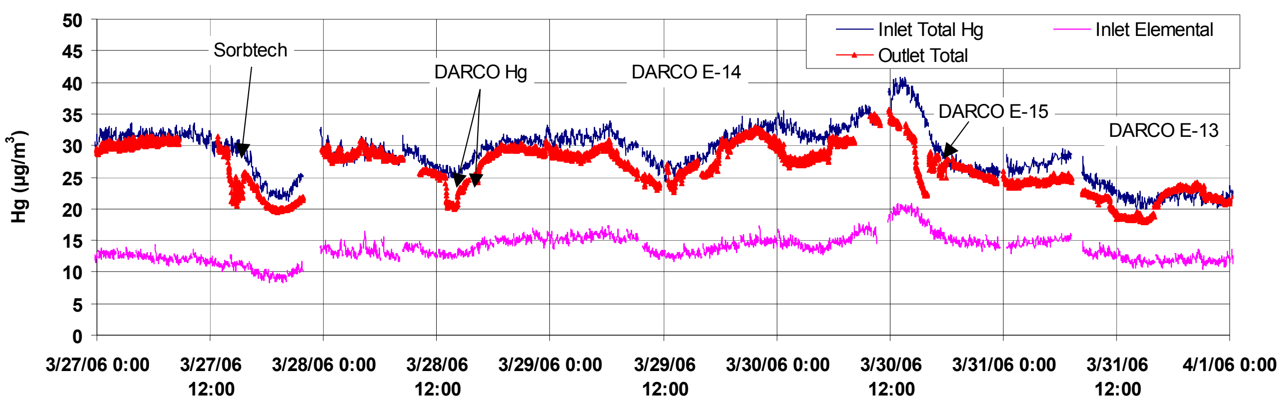


Figure 5. Mercury Trend Graph during Parametric Test Week 2.

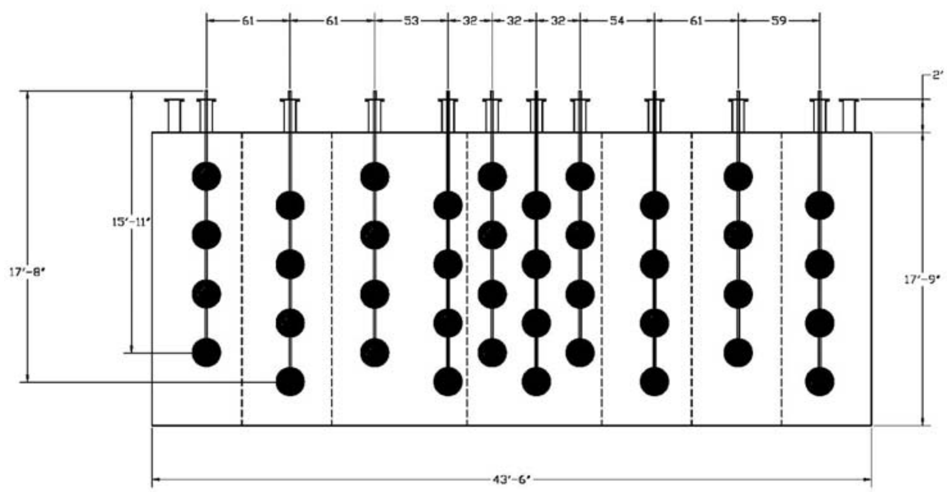


Sorbent Distribution

Sorbent distribution modeling was included in the plans for Conesville because of the number of turning vanes in the inlet ductwork. Additional modeling and stratification measurements were conducted to assure the test team that the poor mercury removal measured was a function of the sorbent properties and not the distribution grid.

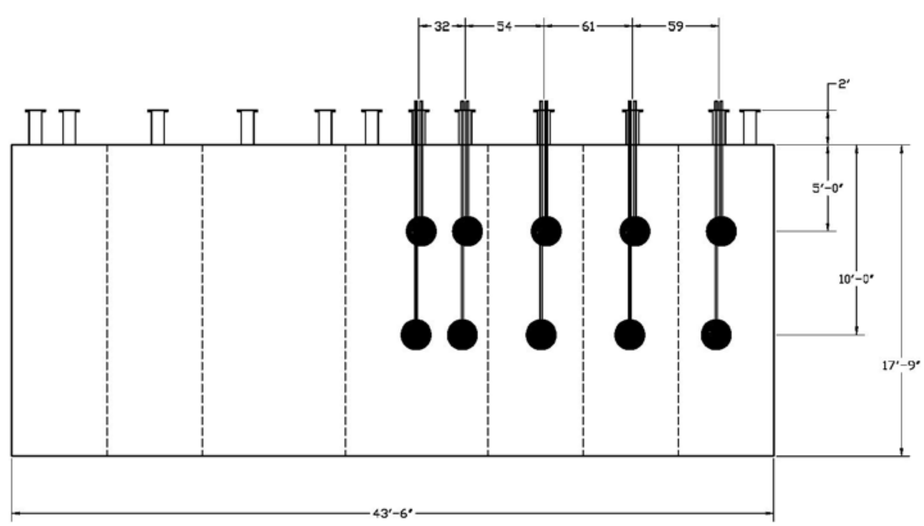
The CFD modeling indicated that the sorbent was fairly well distributed across the ESP inlet duct at Conesville if 10 of the 12 injection ports were used. During all injection tests with multi-nozzle lances, the recommended 10 ports were utilized. A sketch of the multi-nozzle lance arrangement is shown in Figure 6.

Figure 6. Multi-Nozzle Lance Arrangement.



Several tests were conducted with single nozzle lances. This arrangement, which treated the B-side of the ESP only, is shown in Figure 7. STM measurements were made across the outlet duct to determine if stratification in mercury removal was occurring.

Figure 7. Single Nozzle Lance Arrangement.



STM traps were conducted simultaneously across the duct at two depths with two traps per duct. Results from STM analysis indicate that, other than one outlier, there was no indication of sorbent stratification at the outlet of the ESP using either the multi- or single-nozzle lance arrangement. These results are presented in Figures 8 and 9.

Figure 8. STM Measurements with Multi-Nozzle Lance Arrangement.

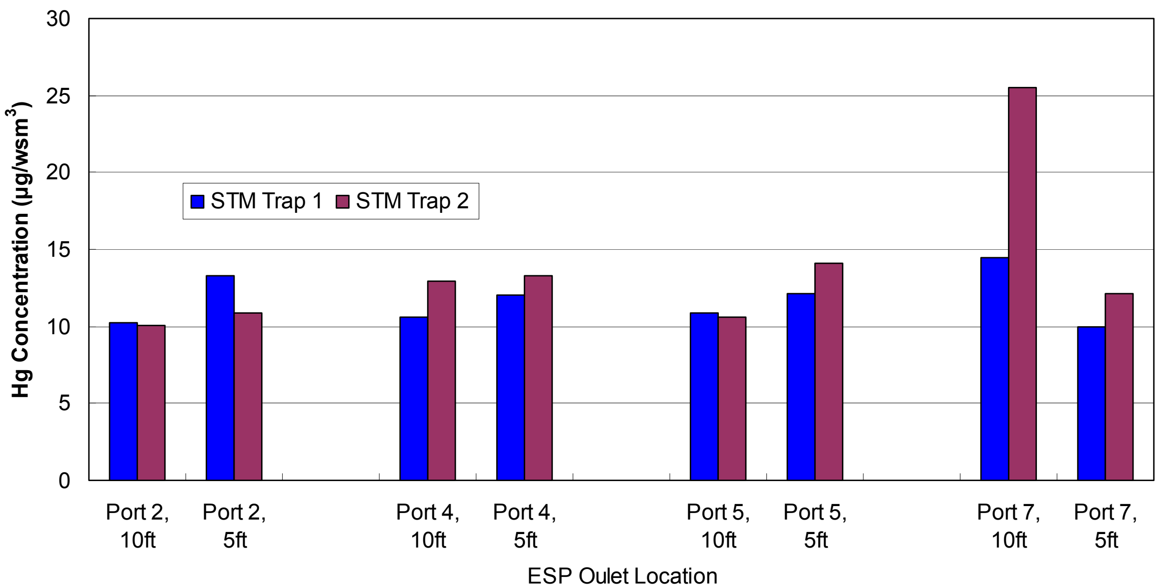
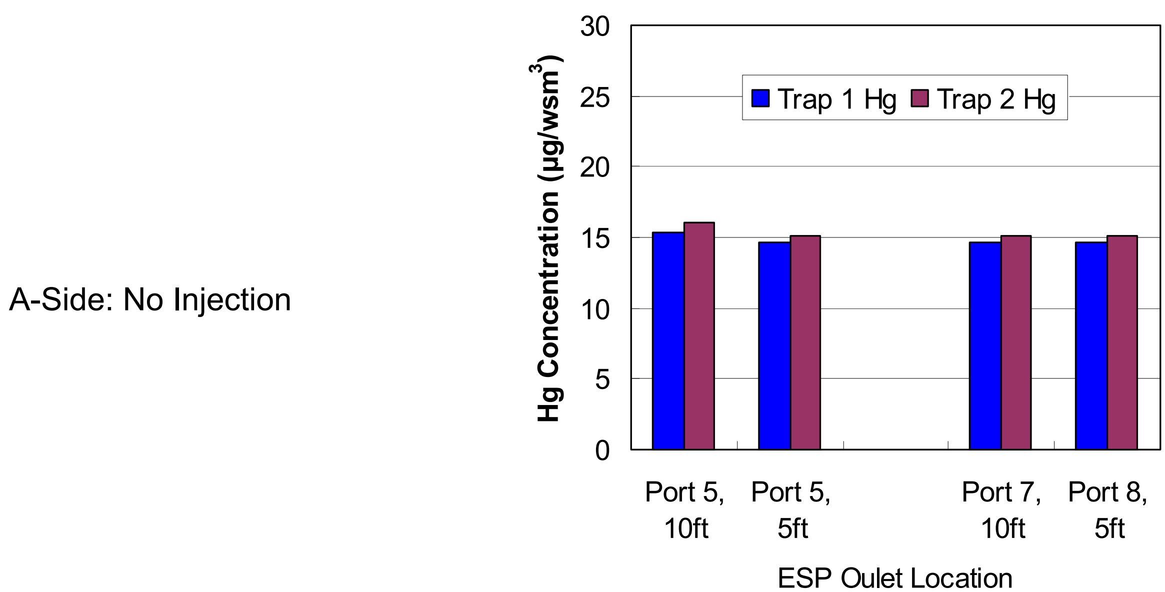


Figure 9. STM Measurements with Single-Nozzle Lance Arrangement.

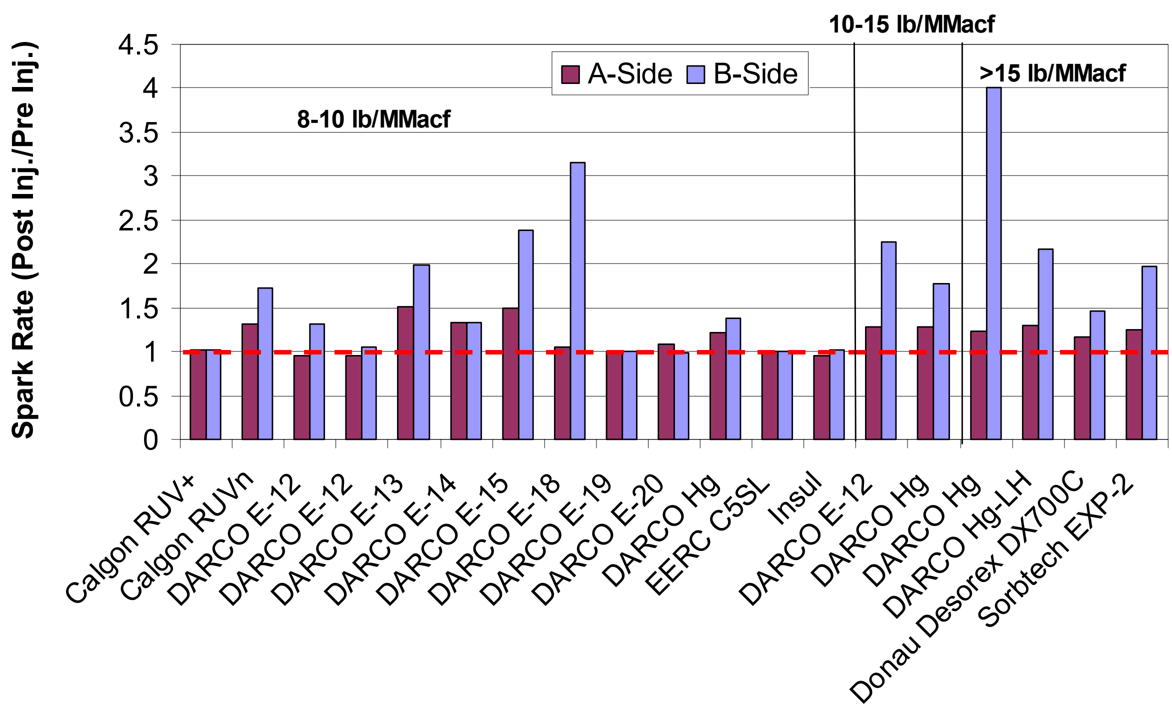


REI carried the CFD model to the next level by incorporating equilibrium adsorption characteristics in with the predicted sorbent loading. Equilibrium characteristics of DARCO Hg that were measured at Conesville with the fixed-bed screening apparatus were incorporated into REI's model. The results of the model predicted 9 to 22% mercury removal if DARCO Hg were injected at 10 lb/MMacf, depending upon the reactivity of the sorbent. Injection tests at 9.5 lb/MMacf of DARCO Hg resulted in 8% mercury removal. The model predicted nominally 6 to 13% less removal at the hottest portion of the duct compared to the coolest, depending on the reactivity of the sorbent. The STM stratification measurements presented in Figures 8 and 9 indicate the mercury removal on the warmer B-side was equivalent to the cooler A-side. Mercury stratification was measured in the inlet-field hopper samples, but the concentrations were within the range measured during baseline testing.

Impact on ESP

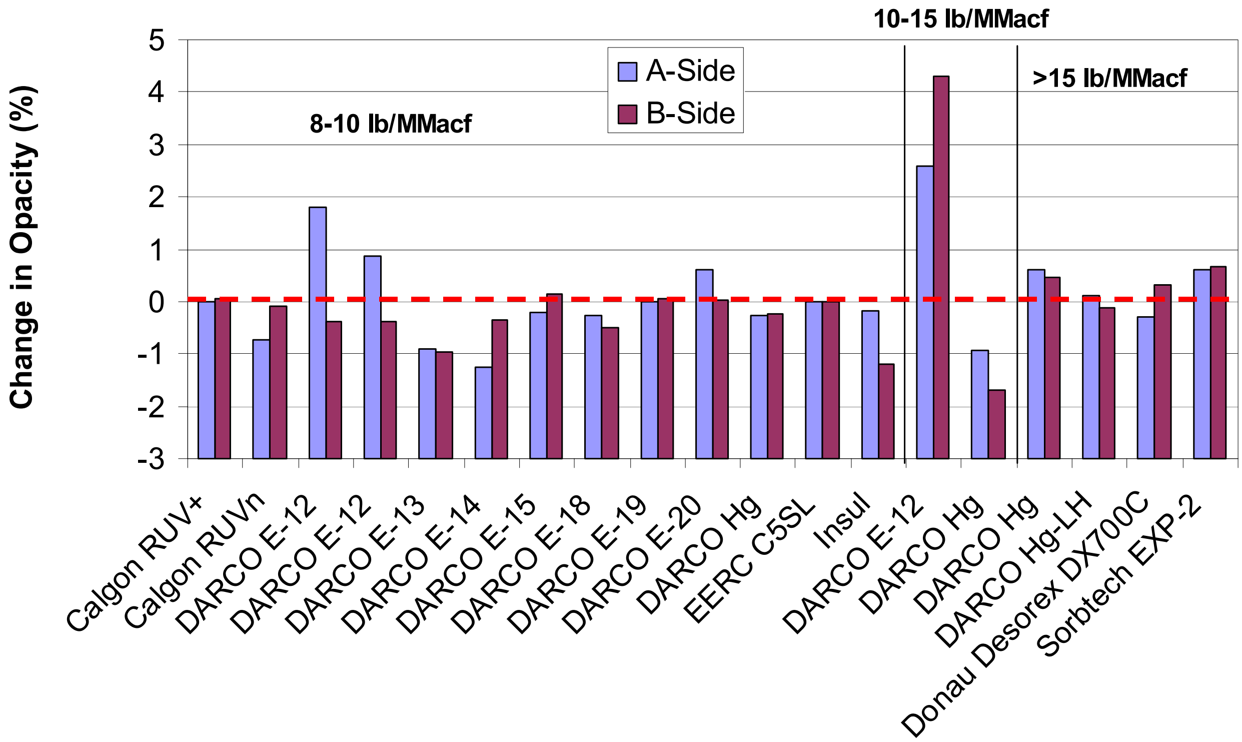
ESP performance was affected by some sorbents, in terms of spark rates and power. Opacity spikes were also noted during some tests, which may have been attributable to sorbents or to normal unit operational variations. The spark rate increase was significant for some sorbents at injection concentrations below 10 lb/MMacf, such as DARCO E-15 and E-18. Injecting DARCO E-12 at 12 lb/MMacf resulted in an increased spark rate on the B-side of the ESP four times above baseline levels. In most cases, the impact of the sorbent was greater on the B-side (warmer side) of the ESP. These results are presented in Figure 10.

Figure 10. Impact of Sorbent Injection on Spark Rate.



Average opacity did not change when injecting any sorbent, except DARCO E-12. This sorbent increased the B-side opacity by over 4% while injecting 12 lb/MMacf into the ESP. These results are presented in Figure 11. Although the average opacity was not changed, the maximum opacity spikes increased significantly for several materials, especially when injecting these materials at concentrations greater than 10 lb/MMacf.

Figure 11. Change in ESP Outlet Opacity due to Sorbent Injection.



CONCLUSIONS

The flue gas at Conesville has proven to be challenging for all sorbents tested to date at the site. Based upon these results, none of these materials warrant further testing at Conesville.
In general, the results indicate that:

- ESP native mercury capture is very low at Conesville, from 0 to 20%. The mercury is 60–70% oxidized at the ESP outlet, upstream of the WFGD, and 90% elemental at the WFGD outlet.
- Most of the oxidized mercury is removed in the WFGD.
- Mercury ranges from 13 to 33 lb/TBtu at the ESP (baseline results).
- Most but not all sorbents increased T/R set spark rates or impacted opacity spikes.
- The maximum incremental removal by a sorbent was 31% (DARCO E-12 at 12 lb/MMacf). The next-highest removal was 25% (Sorbent Technologies EXP-2 at 10 lb/MMacf).
- All other sorbents tested yielded <20% incremental mercury capture.
- The mercury CEM installed at Conesville has demonstrated extended, unattended operation with fairly reliable performance.

The challenges identified and characterized at Conesville may represent a much larger hurdle to mercury control for the industry than high sulfur units alone. The presence of SO_3 in flue gas appears to decrease mercury capture by activated carbon, sometimes dramatically. SO_3 may be present in sufficiently high concentrations in several common configurations including low sulfur units using SO_3 for flue gas conditioning and units with SCRs where the SCR is converting sufficient SO_2 to SO_3. Although sorbents tested at Conesville did not show significant mercury removal, they have demonstrated tolerance to SO_3 and many may be applicable to other configurations with lower flue gas SO_2 or SO_3 concentrations.

ACKNOWLEDGMENTS

This paper was prepared with the support of the U.S. Department of Energy, under Award No. DE-FC26-03NT41986. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of the DOE.

This testing program is possible through the leadership of DOE and many industry partners. Primary funding for this program is though the DOE Cooperative Agreement with significant cost share for testing at Conesville from industry partners including EPRI, American Electric Power Company, AmerenUE, ADA-ES, DTE Energy, Dynegy Generation, MidAmerican, Ontario Power Generation, Southern Company, TVA, EPCOR, Babcock & Wilcox, and NORIT Americas. The hard work, dedication, and support of Conesville plant personnel, especially Georgeanne Hammond and Paul Medaugh, and the ADA-ES on-site test team are also acknowledged, as well as support from Connie Senior at Reaction Engineering for her technical insights and oversight of the modeling efforts.

REFERENCES

1. Bustard, C.J. “Field Test Program to Develop Comprehensive Design, Operating, and Cost Data for Mercury Control Systems,” U.S. DOE Cooperative Agreement No. DE-FC26-00NT41005 Topical Report No. 41005R12, May 2003.
2. Canadian Electricity Association (CEA), Mercury Information Clearinghouse, Quarter 5 –Mercury Fundamentals, January 2005.
3. Carey, T.C., O.W. Hargrove, C.F.Richardson, R.Chang, and F.B.Meserole (1998), “Factors Affecting Mercury Control in Utility Flue Gas Using Activated Carbon,” J. Air & Waste Manage. Assoc., 48, 1166–1174.
4. Sjostrom, S., T. Ebner, T. Ley, R. Slye, R. Chang, “Evaluation And Comparison of Novel, Low-Cost Sorbents for Mercury Control,” presented at the Nineteenth Annual International Pittsburgh Coal Conference, September 23-27, 2002.
5. Berry, Mark, et al. (2005). “Full-Scale Evaluation of Activated Carbon Injection,” presentation at the Air Quality V Conference, Arlington, VA, September 19-21.

KEYWORDS

Mercury Control
High Sulfur Coal
Activated Carbon
Sorbent Injection