Full-Scale Evaluation of Mercury Control by Injecting Activated Carbon Upstream of a Spray Dryer and Fabric Filter

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ABSTRACT

One of the most likely air pollution control configurations to be considered for new units burning subbituminous Powder River Basin (PRB) coal will be a spray dryer absorber (SDA) followed by a fabric filter (FF) because it offers cost advantages to meet stringent multi-pollutant control regulations. However, available data indicate that this configuration demonstrates particularly low, native mercury removal and the effectiveness of non-chemically treated activated carbon is limited.

ADA-ES, Inc., with support from DOE NETL and industry partners, is conducting a mercury control demonstration using sorbent injection into the SDA-FF at Sunflower Electric's 360-MW Holcomb Station. This paper will present results from testing including the effect on mercury emissions of 1) blending PRB coal with bituminous coal, 2) injecting alternative sorbents specifically designed to operate in a halogen-deficient flue gas, and 3) injecting chemical additives onto the coal.

INTRODUCTION

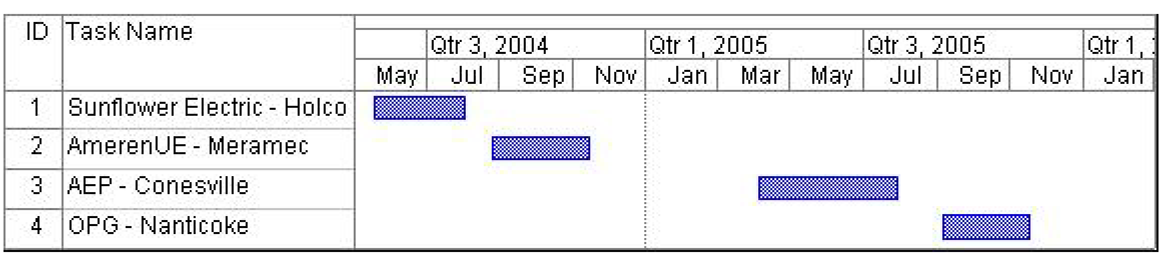
This test program is part of a four-site program funded by the Department of Energy's National Energy Technology Laboratory (NETL) and industry partners to obtain the necessary information to assess the feasibility and costs of controlling mercury from coal-fired utility plants. Host sites that will be tested as part of this program are shown in Table 1. 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. Table 2 shows the schedule for the four test programs.

Table 1. Host Sites Participating in the Sorbent Injection Demonstration Project.

	Coal / Options	APC	Capacity MW / Test Portion	Current Hg Removal (%)*
Sunflower Electric's **Holcomb Station**	PRB & Blend Fuel Additive	SDA – Fabric Filter	360 / 180 and 360 / 360	0−13
Ontario Power Generation's **Nanticoke Station**	PRB & Blend	ESP	500 / 250 and 500 / 500	35
AmerenUE's **Meramec Station**	PRB	ESP	140 / 70	10–20 (estimate)
American Electric Power's (AEP) **Conesville Station**	Bituminous & Blend	ESP + Wet FGD	400 / 400	56

* Based upon recent Ontario Hydro measurements, except Meramec.

Table 2. Test Schedule for Sorbent Injection Demonstration Project.



Background: Mercury Removal across Dry Scrubbers on Subbituminous Coals

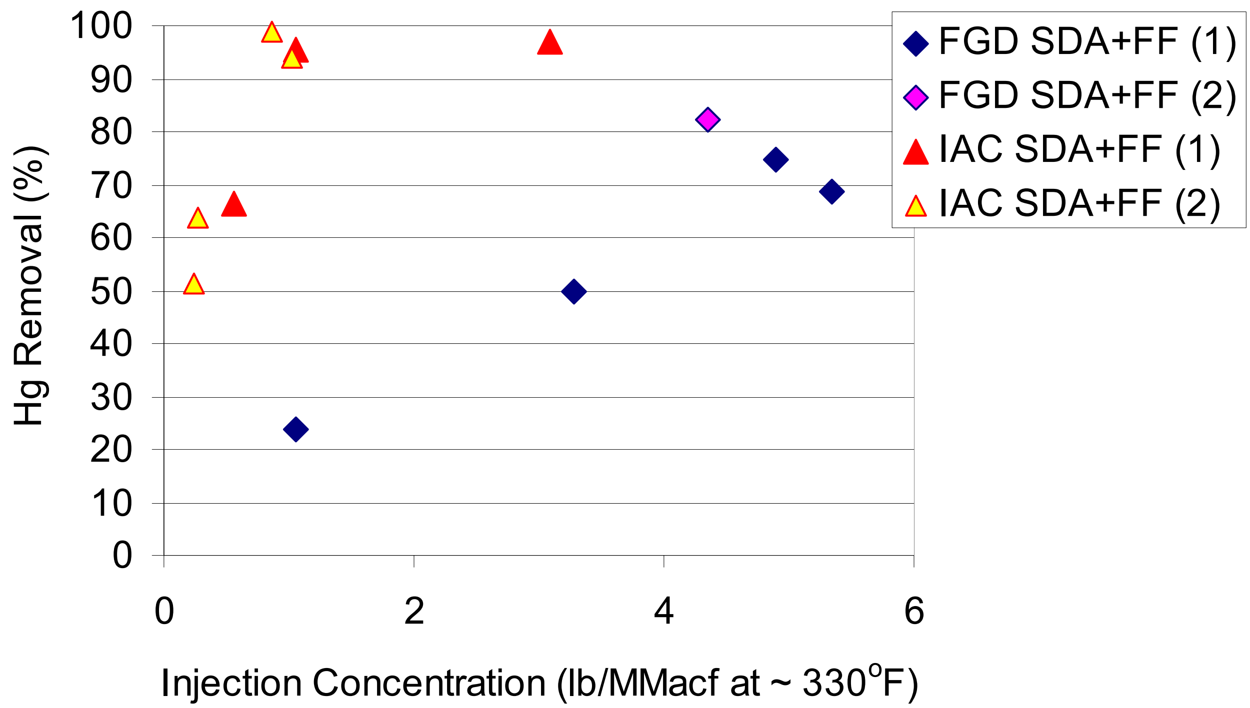
One of the most difficult applications for mercury control is a plant that burns a western subbituminous coal and uses a spray dryer absorber (SDA) to capture sulfur dioxide. This was first seen in the ICR data where fabric filters (FF) without an SDA averaged 72% capture of mercury for units firing subbituminous coals. However, when a spray dryer was added to the configuration, the average mercury capture dropped to 25%. Sjostrom et al. (2002a) reviewed data from 20 units using fabric filters as either the primary or polishing particulate control device to evaluate the native removal across a fabric filter. The clearest trend indicated that for subbituminous coal, the mercury removal on plants with spray dryers was lower than for the three plants without spray dryers (~5–39% vs. ~55–82%). This occurred in spite of the lower temperature of the fabric filter associated with the spray dryer units. For fabric filters without spray dryers, mercury collection is known to increase substantially when temperatures go below 260^{o}F (Lindau, 1983).

Because the overall SDA-FF removal is low, it appears that the spray dryer removes components from the flue gas that are critical to mercury removal by subbituminous fly ash collected in a fabric filter. It is believed that these components are halogens, which are also critical components for untreated activated carbon to be effective in removing elemental mercury based on fixed bed simulations and pilot-scale experiments.

Additional tests were conducted by EPRI at the Great River Energy Stanton Station to evaluate mercury removal at sites burning low-rank fuels that have a spray dryer (Sjostrom et al., 2002b and 2003). Figure 1 shows the impact of a spray dryer on mercury removal resulting from injecting standard activated carbon with a fabric filter. Tests confirmed that injecting a halogen-treated carbon, in this case iodine, could produce excellent mercury control with the SDA-FF configuration (IAC in Figure 1). Mercury removal levels exceeding 90% were obtained at injection rates of 1 lb/MMacf and above. These tests confirm that it is possible to modify the activated carbons to perform in a halogen-deficient flue gas. Unfortunately, the iodated carbons cost ten times more than the standard activated carbons and are therefore cost prohibitive.

The SDA-FF configuration is one of the most likely air pollution control configurations to be considered for new units burning PRB coal. Thus, the focus of the project at Holcomb Station was to identify and evaluate cost-effective mercury control options for plants with this pollution control configuration.

Figure 1. Mercury Removal with Activated Carbon Injected Upstream of a Spray Dryer.



1) EPRI/GRE Full-Scale Testing at Stanton Station Unit 10, 2002 short-term parametric tests (~3 hrs) (Sjostrom et al., 2002b).
2) EPRI/GRE Full-Scale Testing at Stanton Station Unit 10, 2003 short-term parametric tests (~8 hrs) (Sjostrom et al., 2003).

DESCRIPTION OF HOST SITE

Holcomb Station is located near Garden City, Kansas. The unit is a load-following sub-critical 360-MW pulverized coal opposed-fired Babcock & Wilcox Carolina-type radiant boiler designed to burn PRB coal. The existing unit is equipped with three spray dry absorber modules followed by two very low air/cloth ratio reverse air fabric filters. A sketch of the Unit 1 gas path with mercury measurement locations identified is shown in Figure 2. Holcomb typically burns 100% PRB coal. Holcomb will burn up to about five different coals during the test program, but Jacobs Ranch (located near Gillette, Wyoming) and Black Thunder (Black Thunder mine near Wright, Wyoming) were fired during the coal blending, baseline, and parametric tests. Key operating parameters for Holcomb Unit 1 are shown in Table 3.

Figure 2. Sketch of Holcomb Unit 1 Spray Dryer Absorber and Fabric Filter Modules.

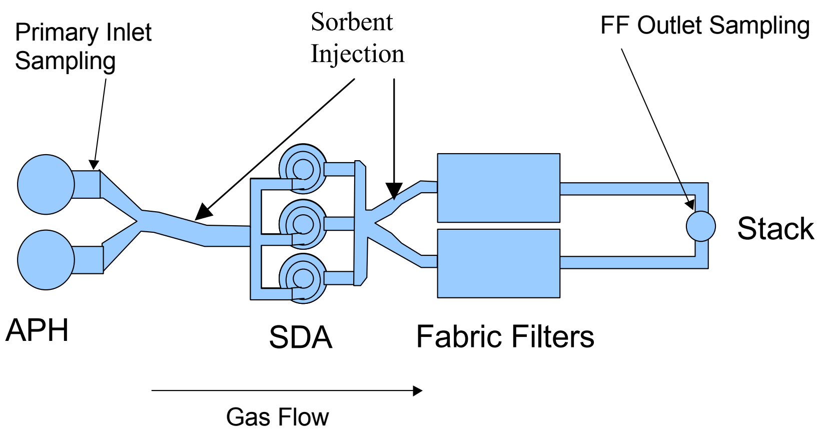


Table 3. Holcomb Key Operating Parameters.

Unit	1
Size (MW)	360
Coal	PRB
Heating Value (as received)	8,700
Sulfur (as received, % by weight)	0.3–0.5
Chlorine (µg/g, dry)	8
Mercury (µg/g, as received)	0.04–0.12
Particulate Control	Fabric Filter (Joy Western)
Sulfur Control	SDA (Niro Joy Western)
Ash Reuse	Disposal

A sorbent injection system was designed, fabricated, and installed at the Holcomb site. The system, pictured in Figure 3, has a 2,500 ft^3 storage capacity, which is capable of holding approximately 40,000 lbs of sorbent material. The system is also equipped with dual feeder/blower assemblies capable of accurately delivering 0–1,000 lbs/hr to the desired injection location. Other new features include variable speed blowers, silo load cells, increased efficiency vent filter, and Ethernet connectivity for remote monitoring.

Figure 3. Photograph of Activated Carbon Injection System at Holcomb.

TEST PROGRAM

The field test plan at Holcomb has five primary tasks:

1. Baseline tests;
2. Coal blending tests;
3. Sorbent screening;
4. Parametric tests; and
5. Long-term tests.

Baseline Testing on 100% PRB Coal

The baseline testing was conducted between May 17 and May 20, 2004. Boiler load was held constant at full load and the air pollution equipment was operated under standard full-load conditions (standard soot blowing, fabric filter cleaning logic, SDA recycle, etc.). ASTM Method 6784-02 (speciated mercury using the Ontario Hydro method) and M26A (HCl and HF) measurements were conducted in conjunction with continuous mercury measurements using mercury analyzers. Results from Ontario Hydro testing were within 12% of the measurements made using the analyzers. Daily averages of the mercury concentrations measured using the analyzers are presented in Table 4. As shown, the mercury at the inlet to the SDA and at the stack was primarily elemental and the removal was less than 25%.

Table 4. Daily Average Vapor-Phase Mercury during Baseline Tests.

Date	Inlet Hg ($\mu g/Nm^3$)	Inlet Hg^0 ($\mu g/Nm^3$)	Outlet Hg ($\mu g/Nm^3$)	Outlet Hg^0 ($\mu g/Nm^3$)	Hg Removal (%)
5/18/04	10.4	10.3	8.3	7.7	19
5/19/04	11.9	12.8	9.2	8.7	23
5/20/04	12.7	12.8	12.9	12.0	-3

Note: All mercury values corrected to 3% O_2.

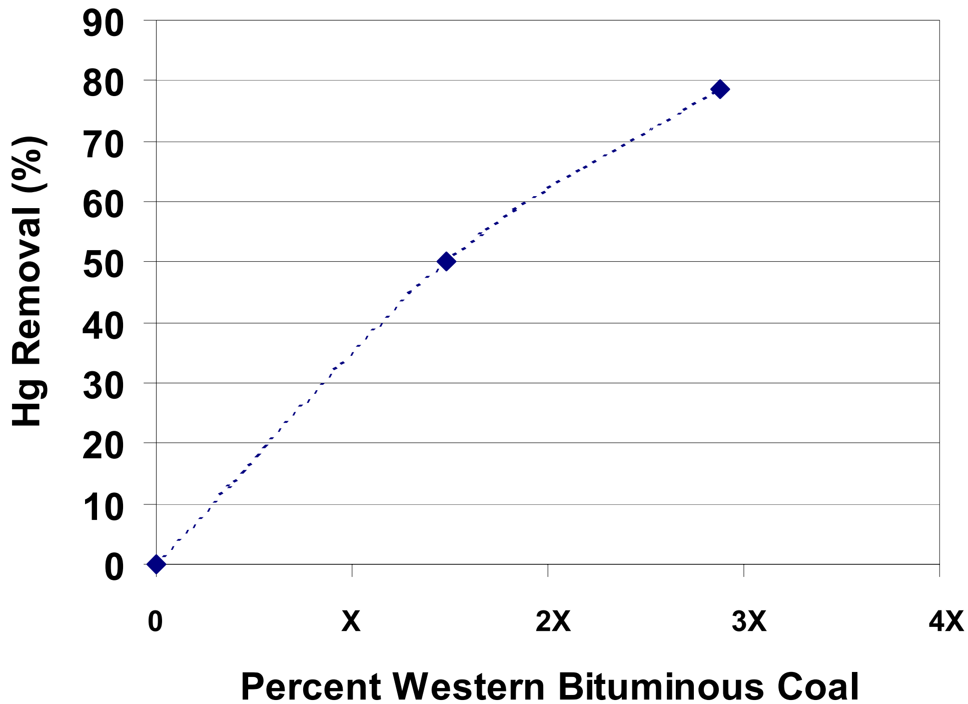
Coal Blending Tests

One option for improved mercury removal across an SDA-FF is firing a blend of subbituminous PRB and western bituminous coal. One week of coal blending tests was conducted at Holcomb. The baseline PRB coal was from the Jacobs Ranch mine. During blending tests, PRB coal from the Black Thunder mine was co-fired with western bituminous coal from the West Elk mine. Holcomb does not have equipment designed specifically for coal blending. After discussing several options for getting two different blends of coal into the boiler, the most practical option was to bring in a partially loaded train of PRB coal and top it off with a bituminous coal that was delivered separately.

Vapor-phase mercury concentrations were monitored at the outlet of the air pre-heater on the A-side of the unit and at the stack. Three sets of EPA Draft M324 samples were also collected for a secondary mercury measurement. There were no Ontario Hydro tests run during the period of the blend testing.

Two different blend ratios of Black Thunder and West Elk were evaluated. The vapor-phase mercury removal during the first blend test was an average of 50% compared to no removal with 100% Jacobs Ranch PRB during this test period. The removal across the SDA-FF during the second blend test increased to 76% (81% based upon M324 samples). These results are summarized in Figure 4.

Figure 4. Summary of Coal Blending Tests.



Ash and coal analyses are underway to help identify the factors that may have resulted in high mercury removal during the blending tests at Holcomb. Initial results from analyses of the coals fired during the baseline and coal blending tests are presented in Table 5 and indicate that the chlorine and fluorine concentrations for the two PRB coals were similar. The Black Thunder coal has lower sulfur content than the Jacobs Ranch coal. Therefore, during periods of coal blending of Black Thunder and West Elk, less lime was required to maintain the outlet SO_2 concentration at the desired level. Although the West Elk coal contains over ten times the chlorine as the Black Thunder, it is still fairly low in chlorine at 106 µg/g.

Table 5. Results from Coal Analyses (dry basis).

Coal	Hg (µg/g)	Cl (µg/g)	F (µg/g)	S (%)
Jacobs Ranch (PRB)	0.105	7.9	76	0.56
Black Thunder (PRB)	0.077	8.0	80	0.32
West Elk (W. Bit)	0.103	106	84	0.93

Analysis of the ash collected in-flight, upstream of the SDA during coal blending tests indicated that the carbon content of the ash increased slightly (nominally 0.2%) during the blending period. Recent evaluations on the effect of unburned bituminous carbon on mercury removal on pilot-scale combustors firing PRB coal suggest that low levels of unburned carbon may result in significant improvements in mercury removal (Lissianski et al., 2003; Gale, 2004). It is uncertain whether an increase in carbon in the ash could be solely responsible for the high mercury removal at Holcomb.

Sorbent Screening

Prior to parametric testing at Holcomb Station, screening tests were conducted to evaluate the mercury removal performance of various sorbents under conditions simulating a full-scale fabric filter. Overall, 23 tests were conducted with 20 different sorbents from 10 vendors.

The test apparatus is described in greater detail in another paper (Amrhein et al., 2004). Flue gas was extracted from between the SDA and FF at Holcomb. Ash was separated from the flue gas at the point of extraction with an inertial filter. The gas was then transported through a heated line to a temperature-controlled enclosure housing three particulate filters. The use of three filters permitted a direct side-by-side comparison of three samples at a time. Premixed samples of ash and sorbent were distributed onto the filters by suction prior to installation into the enclosure. The filters are followed by chemical impingers to convert all mercury to elemental mercury, and a chiller to remove moisture. Total elemental mercury concentration was measured at the inlet and filter outlets using two mercury analyzers. A typical test lasted between 10 and 12 hours.

Table 6 presents selected results from sorbent screening tests at Holcomb Station. CB 200xF is an iodated carbon from Calgon (previously Barnebey Sutcliffe) that has demonstrated promising performance during previous EPRI-funded programs (see “IAC” in Figure 1) and was identified as the high benchmark sorbent for these tests. DARCO FGD was identified as the low benchmark sorbent for the tests.

The best performance was obtained with the CB 200xF, indicating 94% removal at an equivalent injection concentration of 2 to 3 lb/MMacf. FGD-E3 was chosen for parametric testing at Holcomb because of its promising performance and relatively low cost. The second sorbent chosen for parametric testing at Holcomb was 208CP. This material, available through Calgon, demonstrated much better performance than the DARCO FGD and was one of two non-treated sorbents that demonstrated promising performance.

Table 6. Selected Results from Sorbent Screening Tests at Holcomb Station.

Sorbent	Cumulative Average Mercury Removal (%)			Cost (FOB) $ / lb
	1–2 lb/MMacf	2–3 lb/MMacf	3–4 lb/MMacf	
CB 200xF		94	99	$7.71
FGD-E3	63	82	96	$0.65
208CP	55	53	54	$0.85
DARCO FGD	28	30	39	$0.42

Parametric Tests

A series of parametric tests was conducted to determine the optimum operating conditions for several levels of mercury control, especially those options to achieve mercury control levels above that which is possible with standard activated carbon. Parametric tests were conducted between May 22 and June 11, 2004. Primary variables of interest included:

- Sorbent type
  - DARCO FGD (benchmark sorbent, no chemical treatment)
  - Calgon 208CP (highly activated, no chemical treatment)
  - FGD-E3 (halogen-treated)
- Sorbent injection concentration
- Sorbent injection location
  - Upstream and downstream of SDA
- Enhancement additive with/without sorbent injection
  - Coal Additive
  - Flue Gas Additive

Two of the sorbents were tested at two different injection locations. The first injection location was upstream of the SDA. This injection location allowed the entire unit (i.e., 360 MW) to be treated. The second sorbent injection location was downstream of the SDA and upstream of the fabric filter. At this injection location, sorbent was injected into only one of the two inlet ducts going into the fabric filter, or one-half of the flue gas entering the fabric filter. Figure 2 shows the sorbent injection locations for Holcomb.

All sorbent injection concentrations were calculated based upon the stack flow from the plant CEM and calculated at the SDA inlet temperature (nominally 290^{o}F) for comparison purposes, regardless of injection location (inlet or outlet of SDA).

Sorbent Type and Injection Concentration

Three sorbents were evaluated during the parametric test period. The benchmark sorbent was DARCO FGD, a Texas lignite coal-based activated carbon product supplied by NORIT Americas. The other two sorbents were chosen based upon results from sorbet screening tests conducted at Holcomb in April. A brief description of the test sorbents is listed below:

- **DARCO FGD—**Activated carbon made from Texas lignite coal. General physical properties for DARCO FGD are:
    - Surface area = 600 m^2/g
    - Bulk density, tamped = 32 lb/ft^3
    - Particle size, mean = 17–20 μm
- **208CP—**Highly activated carbon made from coconut shells and provided by Calgon (previously Barnebey Sutcliffe). This material was chosen for testing because of the promising results from the screening tests and because it is not chemically treated with any chemicals that may off-gas in the flue gas or leach from the collected solids. Mass mean diameter = 46 μm.
- **FGD-E3—**Texas lignite coal-based activated carbon treated with a halogen for improved performance in halogen-deficient gas streams. This sorbent is available on an experimental basis through NORIT Americas. Similar physical characteristics as DARCO FGD.

The performance of all test sorbents was compared at the SDA inlet injection location. These results are presented in Figure 5. The mercury removal achieved with the 208CP was similar to the benchmark DARCO FGD. The test duration for these tests was between 4 and 7 hours, which was enough time for the outlet mercury to reach a stable concentration. The FGD-E3 demonstrated the best performance of the three sorbents, resulting in 77% mercury removal at an injection concentration of 0.7 lb/MMacf as compared to 50 to 54% for the 208CP and DARCO FGD at an injection concentration of 1.0 lb/MMacf. Two of the injection concentrations shown for FGD-E3 (1.5 and 4.3 lb/MMacf) represent fairly short tests (< 130 minutes) and the mercury removal had not yet reached steady state. It is expected that, with continuous injection of FGD-E3, the mercury removal at 1.5 lb/MMacf would be higher than the 77% measured during the short test.

Sorbent Injection Location

The improved performance of the FGD-E3 when injected upstream of the SDA suggests that additional halogens are required for optimal sorbent performance at Holcomb. Another indicator of the importance of halogens could be seen when comparing the performance of DARCO FGD and FGD-E3 injected upstream and downstream of the SDA. Ninety percent mercury removal was achieved at a DARCO FGD injection concentration of 5.7 lb/MMacf upstream of the SDA at Holcomb. The mercury removal was limited to less than 35% when DARCO FGD was injected downstream of the SDA at injection concentrations up to 5.7 lb/MMacf. The injection concentrations indicated above are calculated at the SDA inlet temperature for comparison purposes. The actual injection concentration is approximately 17% higher at the SDA outlet location due to the reduced gas volume at the lower temperatures (175°F downstream of the SDA as compared to 290°F upstream of the SDA).

Results from EPA M26A tests conducted during the baseline test period indicate that HCl and HF were fairly low at the inlet to the SDA (0.5 and 1.5 ppm respectively) and 41% of the HCl and 75% of the HF was removed in the SDA. Adsorption of HCl or HF by DARCO FGD may contribute to the improved performance when the sorbent is injected upstream of the SDA. The concentration of these halogens may be too low at the SDA outlet to enhance sorbent performance. There was no change in the FGD-E3 performance when injected whether upstream or downstream of the SDA, indicating that flue gas constituents such as HCl or HF are not required for the effective performance of FGD-E3. These results are presented in Figure 6.

Figure 5. Results of Alternative Sorbent Tests, Holcomb Station.

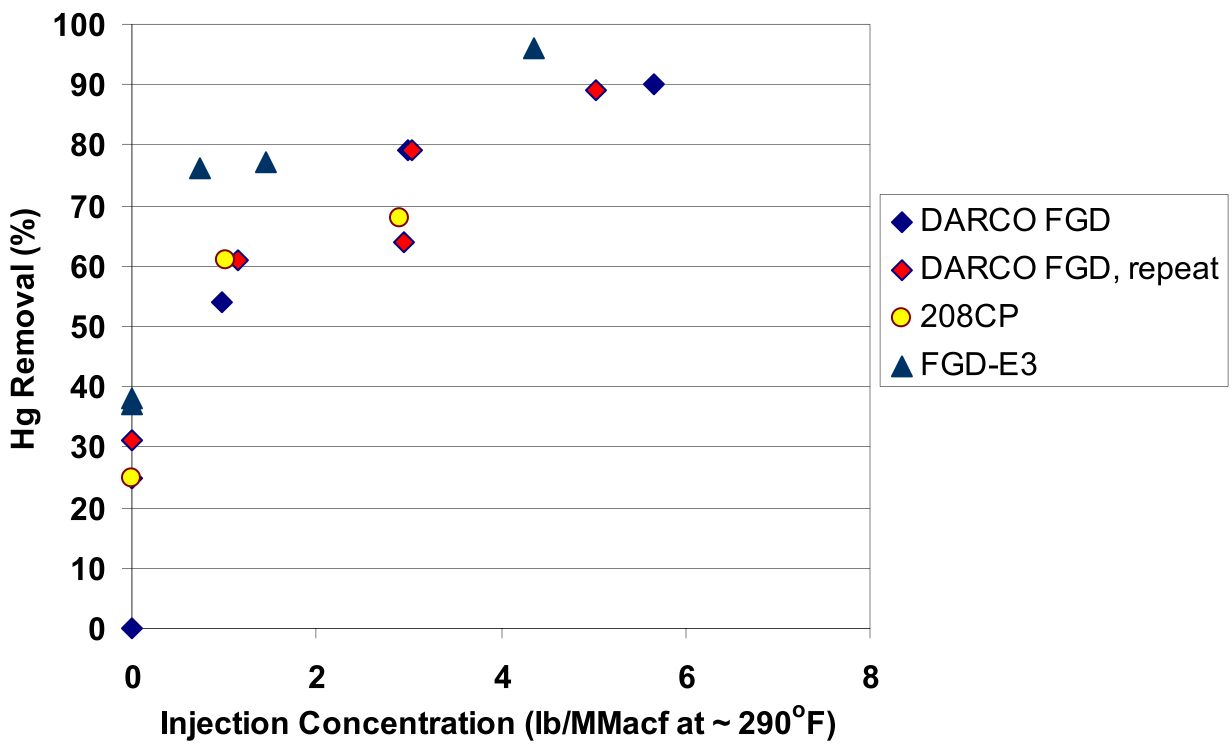
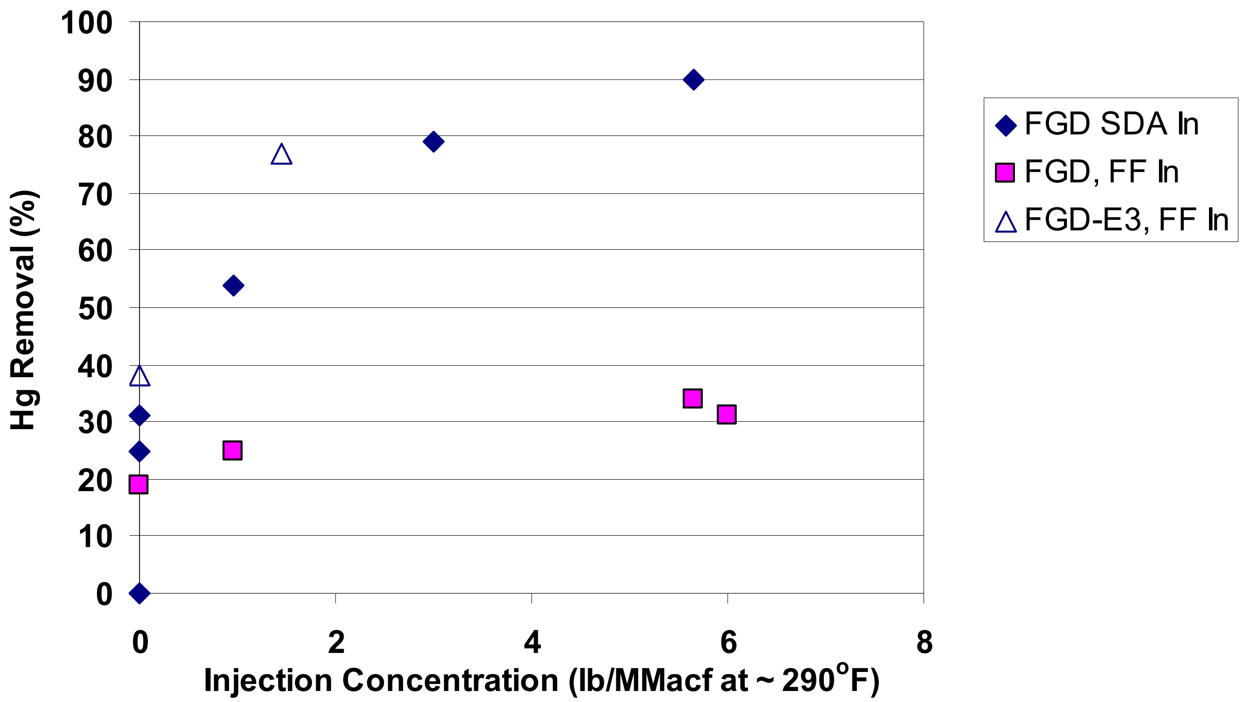


Figure 6. Results of Injection Location Tests, Holcomb Station.



Enhancement Additive With/Without Sorbent Injection

Results from the DARCO FGD and FGD-E3 tests confirm that a halogen-treated carbon can outperform a non-treated carbon on a configuration such as Holcomb. Another option for introducing halogens is to treat the gas stream rather than using treated carbons. Two tests were conducted at Holcomb to evaluate this option.

One of the parametric testing conditions was to add a chemical to the coal to increase the halogen concentration in the flue gas in an attempt to enhance mercury capture. The additive was KNX, a proprietary ALSTOM Power mercury control technology.

KNX was applied to the coal at the crusher house prior to entering the transfer house and coalbunkers. At this chemical injection location, it was estimated that it would take 4–5 hours before the "treated" coal would be fired in the boiler. The chemical additive was applied to the coal continuously for a period of 48 hours. This would ensure that the entire system was "conditioned" with the additive. During this testing condition, mercury speciation at the outlet of the air preheater changed substantially from baseline levels.

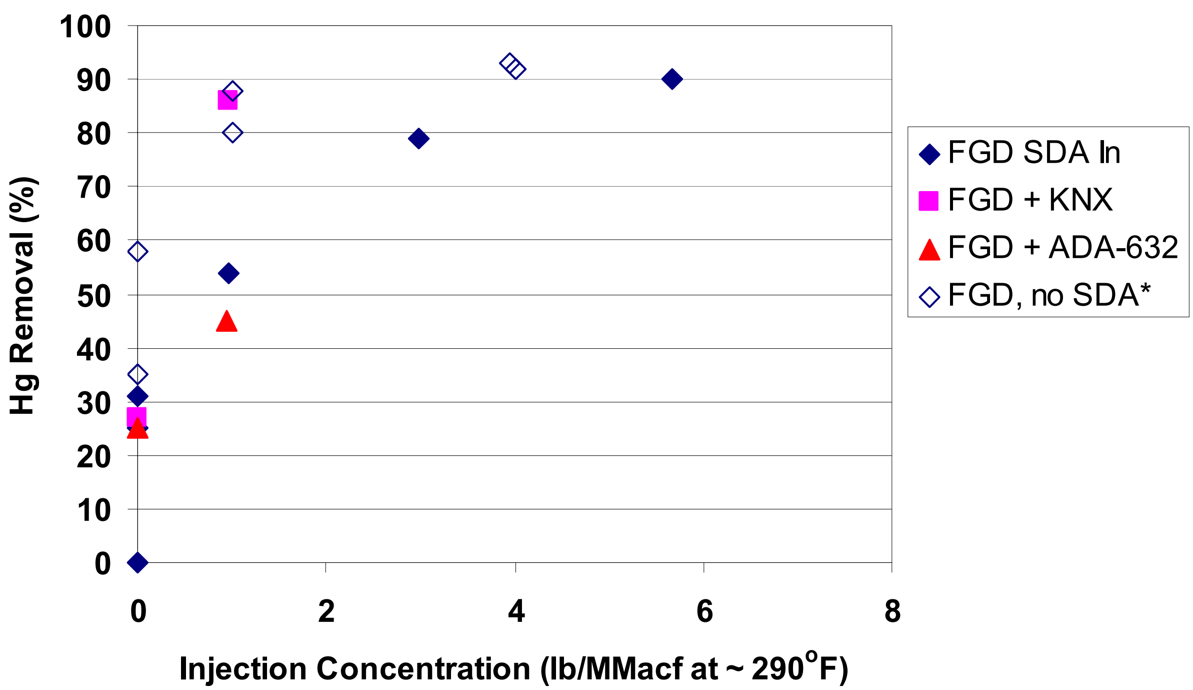
During this period of testing, the unit was burning coal from the Jacobs Ranch mine. At normal operating conditions this coal yielded a total vapor-phase mercury concentration of 18 to 22 $\mu g/Nm^3$ at the outlet of the air preheater with 70 to 90% in the elemental form. During the chemical additive tests, the fraction of elemental mercury at the air preheater outlet decreased to 20 to 30%.

Although the fraction of oxidized mercury at the inlet of the SDA increased substantially, no increase in mercury removal across the system was noted. The speciation at the outlet of the fabric filter was only slightly different than before KNX addition (nominally 80% elemental compared to typically > 90% elemental mercury). This suggests that either the KNX addition resulted in a sampling artifact that biased the elemental mercury measurement at the air preheater outlet, or the SDA-FF was reducing oxidized mercury back to the elemental form.

The final day of chemical additive testing included the injection of the DARCO FGD sorbent at the SDA inlet location in conjunction with addition of the KNX additive to the coal. The sorbent injection concentration at the inlet to the SDA was 1.1 lb/MMacf while the chemical additive flowrate was held steady at 20 gph. This parametric testing condition showed the total mercury capture across the system was 86% compared to 54% with DARCO FGD alone (no KNX). These data, plotted in Figure 7, clearly indicate the improved performance of DARCO FGD when halogens are added to the flue gas.

An additional data set is included on the graph in Figure 7 comparing the performance of DARCO FGD + KNX with performance of DARCO FGD on a unit burning PRB coal with a fabric filter and no SDA (Sjostrom et al., 1997). The data indicate that the addition of KNX allows the DARCO FGD to perform as well as it would in the absence of an SDA.

Figure 7. Impact of the Addition of Proprietary Additive (KNX) on Mercury Removal.



* Data collected with DOE pilot plant at Xcel Energy's Comanche Station in 1998.

An additional enhancement additive test was conducted to determine if a halogenated compound could be added directly to the flue gas to improve the performance of untreated activated carbon.

The chemical was ADA-623, a proprietary chemical provided by ADA-ES. This material was chosen based upon promising screening tests. ADA-623 was injected at the outlet of the SDA with and without DARCO FGD. No change in speciation or removal was noted above that expected without the additive. It is possible that the solid ADA-623 material tested was not adequately ground to the appropriate size for in-duct injection. Therefore, the results are inconclusive.

CONCLUSIONS

Power plants that burn PRB coal and have spray dryer absorbers and fabric filters for air pollution control systems represent a challenging application for controlling mercury emissions. ICR measurements and subsequent full-scale field tests have confirmed that the spray dryer removes a key gas-phase constituent that is critical for the adsorption of vapor-phase mercury onto solid surfaces. This results in very low levels of native mercury removal, typically < 20%, at plants with this configuration. In addition, the effectiveness of injecting standard activated carbon is greatly diminished by this same effect.

This test program was designed to provide a full-scale evaluation of different technologies that can overcome the limited mercury removal achievable at these sites. Each technology was based on supplementing certain halogens that are not available in sufficient quantities in these coals.

The program was very successful in that three different technologies were found that have the potential to produce high levels (>80%) of mercury removal in this difficult application. These technologies are:

1. Coal Blending: By blending western bituminous coal with PRB coal, the mercury removal across the system increased to almost 80% even without injecting another sorbent. It is highly likely that firing a blend of Black Thunder and West Elk coals with ACI could result in greater than 90%. Results with other coal blends must be evaluated.

2. Chemical Addition to the Coal: KNX, a proprietary chemical developed by ALSTOM Power, was found to enhance the performance of a standard activated carbon. Mercury removal of 86% was measured at a carbon feed rate of just 1.0 lb/MMacf.

3. Chemically Enhanced Sorbent: A proprietary product of NORIT Americas, FGD-E3, produced mercury removal in excess of 90%. Long-term results with this product will confirm the viability of this approach.

It should be noted that the first two approaches were tested for very short periods of time. However, the effects were verified and demonstrated the potential of these technologies. Additional longer-term tests need to be conducted to fully realize their capabilities.

ACKNOWLEDGMENTS

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