

FULL-SCALE EVALUATION OF SORBENT INJECTION FOR MERCURY CONTROL ON COAL-FIRED POWER PLANTS

**Presented at Air Quality III
Arlington, VA
September 12, 2002**

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ABSTRACT

This paper provides a summary of the results to date from the U.S. Department of Energy National Energy Technology Laboratory (DOE/NETL) sponsored program to demonstrate sorbent injection technology for the control of Mercury emissions from coal fired power plants. Results from the first two of four demonstrations are described. The program runs through 2003. The tests show that 90% mercury removal is possible when sorbents such as powdered activated carbon (PAC) are injected upstream of a fabric filter while over 60% mercury removal was demonstrated when PAC was injected upstream of an electrostatic precipitator. PAC was shown to be effective in removing both elemental and oxidized species of vapor phase mercury from bituminous and sub bituminous coals. The effects of PAC on fabric filter design and on fly ash utilization are also described.

INTRODUCTION

In December 2000 EPA announced their intent to regulate mercury emissions from the nations coal-fired power plants. Draft legislation indicates that new regulations may require removal efficiencies as low as 50% or as high as 90% from existing sources. Estimates for the cost of meeting mercury regulations range from \$2 to \$5 billion per year for 90% removal (Brown et al., 1999). With mercury regulations imminent, mercury control technologies need to be proven at full scale to document performance and costs.

The most mature retrofit technology available today is the injection of sorbents such as powdered activated carbon (PAC) into the flue gas upstream of the particle control equipment. The gas-phase mercury in the flue gas contacts the sorbent and attaches to its surface. Existing particle control equipment, either an electrostatic precipitator (ESP) or a fabric filter, collects the sorbent with mercury attached along with the fly ash.

The type of particulate control equipment is a key parameter defining both the amount of sorbent that is required and provides the ultimate limitation of the amount of mercury that can be removed. When the sorbent is injected into the flue gas it mixes with the gas and flows downstream. This provides an opportunity for the mercury in the gas to contact the sorbent where it is removed. This is called “in flight” capture. The sorbent is then collected in the particulate control device where there is a second opportunity for sorbent to contact the mercury in the gas.

In an ESP, the carbon is collected on plates that are spaced parallel to the gas flow. Although the residence time in the ESP can be several seconds, there is limited amount of contact between the gas and the collected particles because the gas can be as far as four inches from the plates. On the other hand, the fabric filter provides the ideal opportunity for good interaction between the gas and the sorbent as the gas makes intimate contact with the sorbent collected on the filter. Therefore, sites with fabric filters will achieve higher levels of mercury removal and improved levels of sorbent utilization.

Under a cooperative agreement from the Department of Energy National Energy Technology Laboratory (DOE/NETL), ADA-ES is working in partnership with PG&E National Energy Group (NEG), Wisconsin Energy Corp., Alabama Power Company, a subsidiary of Southern Company, and EPRI on a field test program of sorbent injection technology for mercury control. The test program, which takes place at four different sites during 2001 and 2002, is described in detail elsewhere (Durham et al., 2001). Other organizations participating in this program as industry cost share participants include Ontario Power Generation, First Energy, TVA, Arch Coal, Kennecott Energy, Hamon Research-Cottrell, EnviroCare, and Norit Americas. The objective of this program is to obtain the necessary information to assess the costs of controlling mercury from coal-fired plants using dry injection. The economics will be developed based on various levels of mercury control. These tests represent the first time that PAC has been injected on such a large scale and continuously for periods of several weeks.

Two demonstrations were conducted during 2001 and one in 2002. The first program was completed in the spring of 2001 at the Alabama Power E.C. Gaston Station (Bustard et al. 2002). This unit burns a low-sulfur bituminous coal and uses a COHPAC baghouse to collect the carbon and fly ash. The second program was conducted during the fall of 2001 at the WEC Pleasant Prairie Power Plant (PPPP) (Starns et al., 2002). This unit burns a subbituminous Powder River Basin (PRB) coal and uses an electrostatic precipitator to collect the carbon and fly ash. The third program was completed in the summer of 2002 at PG&E National Energy Group’s Brayton Point Station. This unit burns low sulfur bituminous coals and use electrostatic precipitators for particulate control. The fourth program is scheduled for the fall of 2002 at PG&E National Energy Group’s Salem Harbor Station. Salem Harbor fires bituminous coals with an ESP for particulate control and a SNCR system for NO_x control.

EQUIPMENT

The transportable sorbent injection system consists of a bulk-storage silo and twin blower/feeder trains each rated at 750 lb/hr. Sorbents are delivered in bulk pneumatic trucks and loaded into the silo, which is equipped with a bin vent bag filter. From the two discharge legs of the silo, the reagent is metered by variable speed screw feeders into eductors that provide the motive force to carry the reagent to the injection point. Regenerative blowers provide the conveying air. A PLC system is used to control system operation and adjust injection rates. Figure 1 is a photograph of the sorbent silo and feed train installed at PPPP. Flexible hoses carried the reagent from the feeders to distribution manifolds located on the ESP inlet duct, feeding the injection probes. Each manifold supplied up to six injectors.

Near real-time vapor phase mercury measurements were made using Semi-Continuous Emissions Monitors (S-CEM) designed and operated by Apogee Scientific. This instrument was developed with EPRI funding to facilitate EPRI research and development efforts. The S-CEMs operate continuously during the test program at each site and provide speciated (Hg^0 and Hg^{2+}), vapor phase mercury concentrations. Details of the operation of these units are described in Sjostrom et al. (2001).



Fig 1. Carbon Injection Storage Silo and Feeder Trains Installed at PPPP.

E.C. GASTON TEST PROGRAM

E.C. Gaston unit 3 is a 270MW boiler firing a variety of low-sulfur washed Eastern bituminous coals. The primary particulate control equipment is a hot-side ESP followed by a COHPAC fabric filter installed into the casing of an abandoned cold-side ESP. The COHPAC system is a hybrid pulse-jet type baghouse, designed to treat flue gas volumes of 1,070,000 acfm at 290°F (gross air-to-cloth ratio of 8.5 ft/min with on-line cleaning). The evaluation was conducted on 1/2 of the gas stream, nominally 135 MW. The A-side was monitored as the control unit.

Results from Gaston Tests

Baseline Tests

After equipment installation and checkout, baseline tests were conducted to document current operating conditions. Measurements made using both the manual Ontario Hydro method and the S-CEMs showed that there was no measurable mercury removal across COHPAC. The average of the inlet and outlet total mercury measurements was about 15 µg/dncm. Coal analyses showed mercury levels in the three coal samples varied between 0.06 and 0.17 µg/g. Since Gaston burns coals from several different coal sources each day, it is difficult to correlate mercury level in the coal to a specific flue gas measurement; however, the higher coal mercury values correlate well with mercury measured in the flue gas. For example, a coal mercury level of 0.17 µg/g is equivalent to a mercury concentration of 15.0 µg/dncm in the flue gas. The Ontario Hydro measurements also showed oxidation across COHPAC. At the inlet the average fraction of oxidized mercury was 61%, and increased to 77% at the outlet.

Parametric Tests

A series of parametric tests was conducted with several activated carbon products to determine the optimum operating conditions for several levels of mercury control up to 90%. In all, 15 different parametric conditions were tested. The primary variables were carbon type and target mercury removal level. Other variables included COHPAC cleaning settings and flow through the baghouse. Although lower flue gas temperatures have been correlated with increased mercury removal, temperature was not a key variable during these tests because normal operating temperatures at this plant were between 250°F and 270°F, which is cool enough for acceptable removal.

Parametric tests measured mercury removal as a function of injection concentration and sorbent type, and the impact of sorbent injection on COHPAC performance. Feedback from the S-CEMs was invaluable in making timely, real-time decisions on test conditions. Examples of the data provided from the S-CEMs are presented in Figure 2. This plot shows the traces from mercury concentrations measured at the inlet and outlet of the baghouse and the sorbent injection rate. As can be seen, almost immediately after starting the injection of the PAC, the outlet mercury begins to drop. Then over the next six hours the outlet mercury continues to decrease while the inlet mercury remains relatively constant. This additional capture of mercury is due to a buildup of the carbon on the bags.

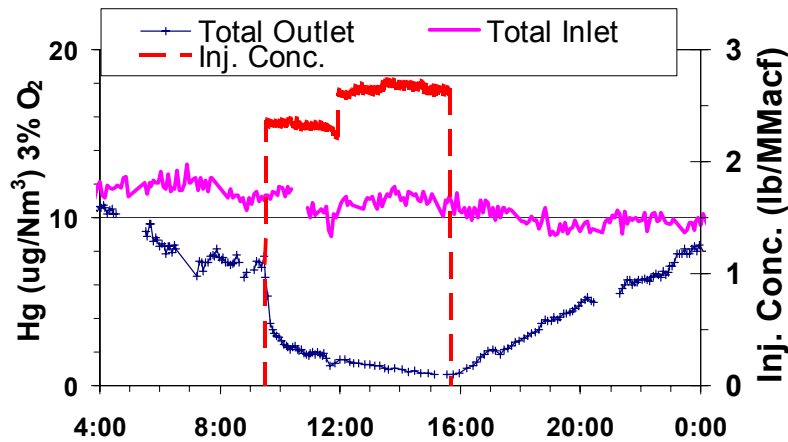


Fig. 2. S-CEM Mercury Measurements During Parametric Tests.

It is interesting to note that after the PAC injection has been halted, the outlet mercury remains low indicating continued mercury removal by the PAC still on the bags. It takes approximately six to eight hours for the outlet mercury to return to baseline levels. During this time, the bags were being cleaned several times. Therefore, some carbon remained on the bags through multiple cleans.

Figure 3 presents mercury removal efficiencies as activated carbon injection concentrations were varied during the parametric tests for several activated carbons. This figure shows that mercury removal increased nearly linearly with injection rate up to 2 lbs/MMacf and then leveled off at about 90% removal with higher injection providing little additional benefit. This figure also shows that there was no measurable performance difference between the different high-capacity sorbents.

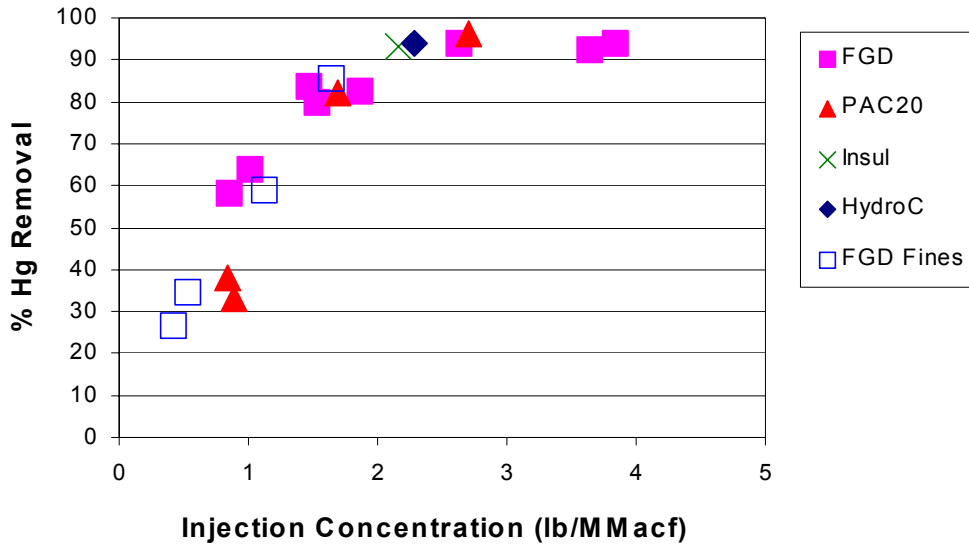


Fig. 3. Mercury Removal Trends Across COHPAC as a Function of PAC Injection Concentrations. Measurements Made During Parametric Tests, March 2001.

Carbon injection significantly increased the cleaning required frequency of the COHPAC baghouse. Figure 4 presents actual cleaning frequencies at different carbon injection concentrations. At an injection concentration of 2 lbs/MMacf, the cleaning frequency increased from 0.5 to 2 pulses/bag/hour, or a factor of 4. Acceptable cleaning frequencies at this site to maintain acceptable pressure drop and long-term bag life are considered to be less than 1.5 pulses/bag/hour.

Long-Term Tests

Long-term testing was conducted at “optimum” plant operating conditions as determined from the parametric tests. During these tests, carbon was injected continuously 24 hours per day, for 9 days. Based on results from the parametric tests, Darco FGD activated carbon was chosen as the sorbent for these tests. Injection rate was determined taking into consideration both mercury removal and the projected increase in COHPAC cleaning frequency. An injection concentration of 1.5 lbs/MMacf was chosen to maintain COHPAC cleaning frequency below 1.5 pulses/bag/hour.

Similar to the baseline test series, mercury was measured by both the S-CEMs and manual methods (Ontario Hydro). COHPAC performance, coal and ash samples, plant CEM data were collected. During these tests an EPA audit of the manual measurements was performed.

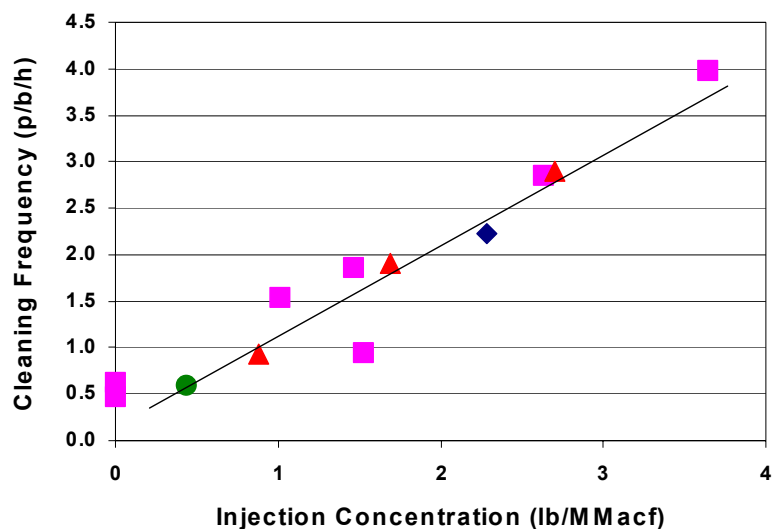


Fig. 4. COHPAC Cleaning Frequency in Pulses/Bag/Hour as a Function of PAC Injection Concentration.

Table 1 presents average, speciated mercury removal across COHPAC. The overall average reduction in total mercury is 90%. At the outlet the predominant species of mercury is the oxidized form; however, it is still 85% less than what was present upstream of PAC injection.

Table 1. Average Mercury Removal Efficiencies Across COHPAC as Measured with Ontario Hydro Method.

Sampling Location	Particulate ($\mu\text{g/dncm}^1$)	Oxidized ($\mu\text{g/dncm}^1$)	Elemental ($\mu\text{g/dncm}^1$)	Total ($\mu\text{g/dncm}^1$)
COHPAC Inlet	0.2	6.4	4.6	11.2
COHPAC Outlet	0.1	0.9	0.0	1.1
Removal Efficiency (%)	50	86	99	90

Normal: T = 32°F

Figure 5 presents inlet and outlet mercury concentrations as measured by the S-CEMs, boiler load, and PAC injection concentration during the last five days of the long-term test. Periods when Ontario Hydro measurements were made are also identified. The S-CEMs indicate that mercury removal was nominally 87, 90, and 88% during the Ontario Hydro tests. This correlates well with the manual measurements.

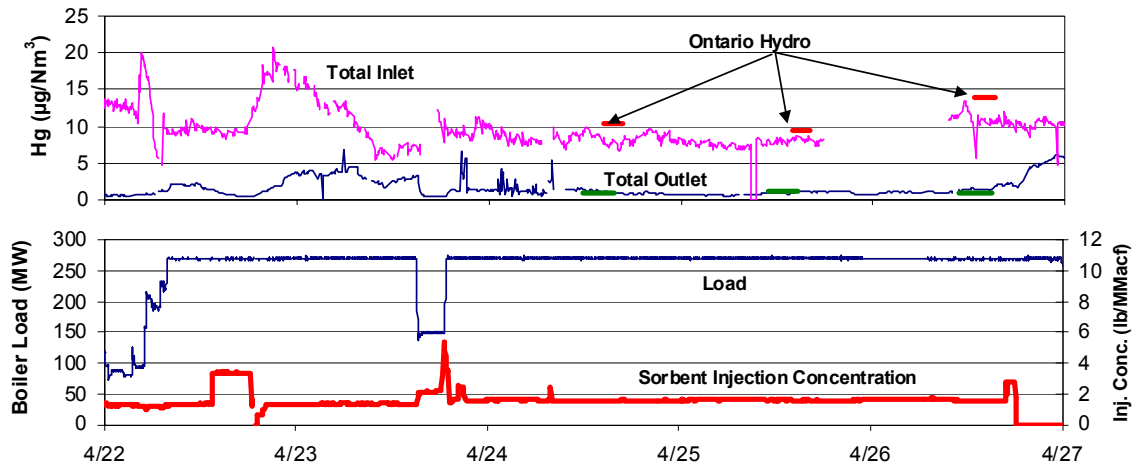


Fig. 5. Inlet and Outlet COHPAC Mercury Concentrations, Boiler Load and PAC Injection Concentration During Long-Term Tests, April 2001.

PLEASANT PRAIRIE TEST PROGRAM

Wisconsin Energy Corporation owns and operates Pleasant Prairie Power Plant located near Kenosha, Wisconsin. Tests were conducted on $\frac{1}{4}$ of the 600MW Unit 2 that fires a variety of Powder River Basin, low-sulfur sub bituminous coals.

The primary particulate control equipment consists of Research-Cottrell weighted wire cold-side ESPs with sulfur trioxide (SO_3) flue gas conditioning. The specific collection area (SCA) is $468 \text{ ft}^2/\text{kacfm}$.

Hopper ash is combined from all four precipitators in the dry ash-pull system. The ash is sold as a cement powder substitute in concrete and is considered a valuable byproduct. Sorbent for mercury control was injected into the ductwork downstream of the SO_3 injection grid. The sorbent had approximately 0.75 seconds of residence time in the duct before entering the ESP. A spray cooling system provided by EnviroCare International was installed upstream of sorbent injection to adjust flue gas temperature.

Test Results

Baseline Tests

During baseline and parametric tests, boiler load was held steady at “full-load” conditions during testing hours, nominally 7:00 am to 7:00 pm. Coal samples collected during baseline tests and analyzed for mercury levels showed an average concentration of $0.099 \text{ } \mu\text{g/g}$. At PPPP a coal mercury level of $0.099 \text{ } \mu\text{g/g}$ is equivalent to a mercury concentration of about $13.7 \text{ } \mu\text{g}/\text{dnm}$ @ $3\% \text{ O}_2$ in the flue gas.

Both the S-CEMs and the modified Ontario Hydro Method were used to measure mercury across the ESP. The average flue gas temperature during this period was 290°F. The data show minimal baseline mercury removal across the ESP. The predominant species of mercury, whether at the inlet or outlet of the ESP, was elemental. Similar to measurements conducted at Gaston, there was oxidation of mercury in the direction of flow, in this case, across the ESP.

Parametric Tests

A series of parametric tests was conducted to determine the optimum operating conditions for several levels of mercury control. Primary variables were injection concentration, carbon type, SO₃ flue gas conditioning on/off and spray cooling to 250°F. In all, 16 different parametric conditions were tested. Standard conditions were with the boiler at full load operation, SO₃ conditioning on, and no spray cooling.

Mercury removal was monitored as a function of the sorbent injection concentration. In addition, the impact of sorbent injection on the performance of the ESP was monitored. An example of the data from the S-CEMs during the first week of parametric testing is presented in Figure 6. This graph is very similar to performance observed during the baghouse tests in which the outlet mercury concentration began to drop almost immediately after the start of injection. There was some relatively minor additional drop in concentration over the next several hours. However in contrast to the baghouse test in which mercury continued to be captured after injection was halted, mercury capture in the ESP disappeared almost immediately after PAC injection was stopped. This indicates that most of the mercury is captured “in flight” with little additional capture by the carbon collecting on the plates.

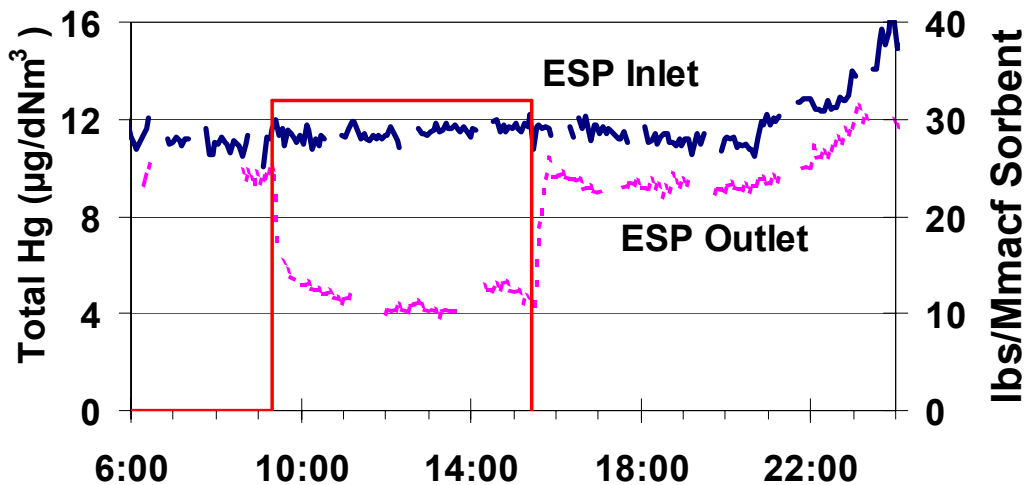


Fig. 6. S-CEM Mercury Measurements During the First Week of Parametric Tests with Norit Darco FGD PAC.

A summary of results from all the parametric tests is presented in Figure 7. This figure plots mercury removal efficiency as a function of sorbent injection concentration. The different symbols represent different test conditions including carbon type, SO₃ off and spray cooling. This graph shows that there was a rapid increase in mercury removal with PAC injection up to an injection concentration of about 5 lbs/MMacf. Increasing the sorbent injection rate from 5 to 10 lbs/Mmacf showed an incremental 10% increase in mercury removal. No significant additional removal was observed when the rate of sorbent injection was raised above 10 lbs/MMacf.

As stated above, this apparent ceiling of 70% removal was surprising. Poor sorbent distribution in the gas stream could contribute to this problem. To prove that distribution was not a problem, several tests were conducted with the injection lances in different configurations that would alter distribution patterns. No measurable change in mercury removal was noted.

Similar to the results at Gaston, there was no significant difference in performance among the four high-capacity carbons, even with the finer grain carbons. There was also no impact of either SO₃ injection or spray cooling on mercury removal. Earlier tests had indicated that both of these factors could effect the capacity of the sorbents to hold mercury. However, all of the sorbents tested had a significant amount of excess capacity so minor increases or decreases in capacity would not result in a change in overall mercury removal.

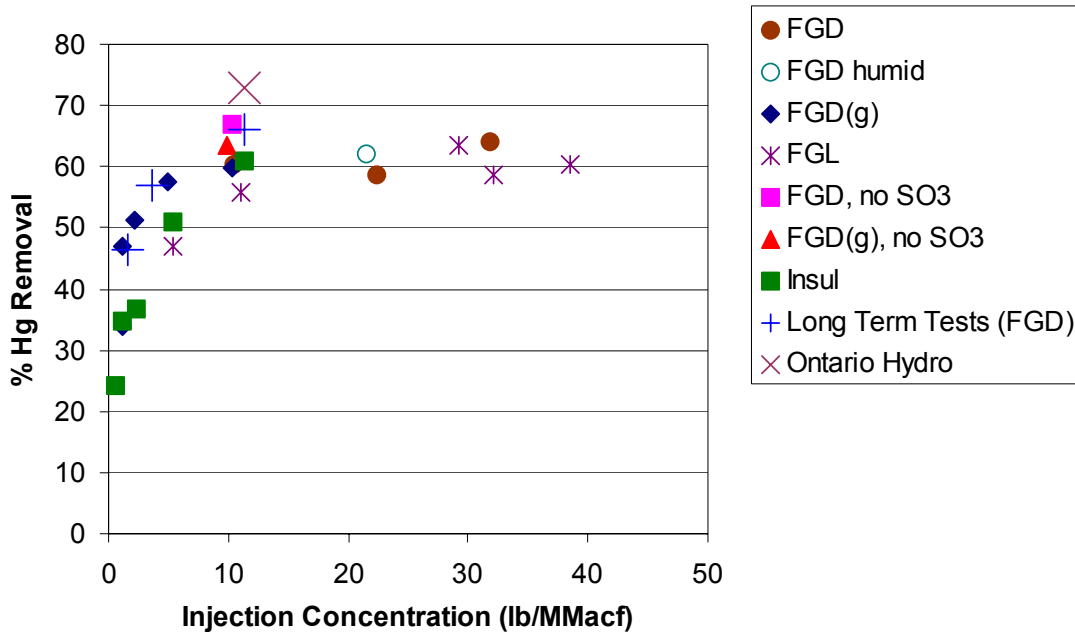


Fig. 7. Mercury Removal Trends for Parametric and Long-Term Tests at PPPP.

One of the significant observations made during the testing was that carbon injection had no impact on the performance of the ESP. Some improvement in power levels was seen during the spray cooling tests. This is a relatively large ESP with an SCA in excess of 400 ft²/kacfm

and was capable of handling even very large carbon injection rates (up to 40 lb/MMacf) without producing any measurable increase in particulate emissions. Additional tests need to be conducted on a smaller ESP (SCA less than 200 ft²/kacfm), which is representative of many of the older units. The amount of PAC that can be injected without increasing emissions from the ESP may be limited when applied to these smaller collectors.

Long-Term Tests

The long-term test was divided into three injection periods at feed rates of approximately 1, 3, and 10 lb/Macf, each lasting five days.

Figure 7 presents mercury removal with respect to PAC injection concentration for both the parametric and long-term tests. Mercury removal rates as measured with the S-CEMs for each of three long-term test conditions can be seen as the large crosses at 1.6, 3.7, and 11.3 lbs/MMacf. These data points represent the average over the entire 5-day period. The average mercury removal was 46% at 1.6, 57% at 3.7, and 66% at 11.3 lbs/MMacf. These results fall within the trends developed during the parametric tests, showing that no significant additional increase in mercury removal was achieved with longer run times.

Three sets of Ontario Hydro measurements were made at the inlet and outlet of the ESP and the average removal efficiency is shown in Figure 7 as the large X at 11 lbs/MMacf. Results from the Ontario Hydro measurements are presented in Table 2. The average inlet mercury concentration was 17.4 µg/dncm, with over 80% being measured as elemental mercury. Coal samples taken during this period had an average mercury level of 0.133 µg/g, or an equivalent flue gas concentration of 21.7 µg/g. The outlet mercury concentrations show the effect of carbon injection with lower mercury emissions for all species and 70.4% and 74.5% reduction of the elemental and oxidized species respectively. The overall average reduction in total mercury was 72.9%. At the outlet the predominant species of mercury is the elemental form; however, it is still 70% less than what was present upstream of PAC injection.

Table 7. Speciated Mercury Measured by Ontario Hydro Method, Long-Term Tests at PAC Injection Concentration = 11 lbs/MMacf.

	Particulate (µg/dncm^a)	Elemental (µg/dncm^a)	Oxidized (µg/dncm^a)	Total (µg/dncm^a)
ESP Inlet	1.0	14.7	1.7	17.4
ESP Outlet	0	4.3	0.4	4.7
Removal Efficiency (%)	100	70.7	74.5	72.9
% of Total at Inlet	5.7	84.5	9.8	
% of Total at Outlet	0	91.5	8.5	

Note a. Normal: T = 32°F

The S-CEM and Ontario Hydro removal efficiency results show good correlation, within 10%. The was the case even though the S-CEM measures only vapor phase mercury and the Ontario Hydro measurements showed nearly 6% particulate mercury at the inlet.

Ash Characterization

The fly ash from PPPP is sold for use in concrete and is a cream colored, highly desirable product. The effects of carbon injection on the salability of this ash were of prime concern. It was learned that PAC injection had two negative impacts on the potential use of the fly ash in concrete. First of all, fly ash samples with even low concentrations of carbon were discolored. Even though the carbon content was below ASTM C-618 standards, the darker color would make the material less marketable when there are other sources of ash without PAC.

More importantly, the fly ash with PAC at any concentration failed foam index tests. These are field tests used to determine the amount of Air Entrainment Additives needed to meet freeze thaw requirements. This means that with PAC injection, the plant would not only loose revenues from ash sales, it would incur additional expenses to land fill the material.

PAC COST ANALYSIS

The requirements and costs for full-scale, permanent, commercial implementation of the necessary equipment for mercury control using PAC injection technology are being finalized for PPPP Unit 2. Preliminary capital and sorbent costs for mercury removal using sorbent injection into the ESP have been developed.

The estimated uninstalled cost for a sorbent injection system and storage silo for the 612 MW Unit 2 is \$720,000 \pm 30%. Sorbent costs for 60 to 70% mercury control were estimated based on a long-term PAC injection concentration of 10 lbs/MMacf. For PPPP Unit 2, this would require an injection rate of nominally 1,400 lbs/h. Assuming a unit capacity factor of 80% and a delivered cost for PAC of \$0.50/lb, the annual sorbent cost for injecting PAC into the existing ESP would be about \$5,000,000. PAC costs for 50% control at an injection concentration of 1 lb/Mmacf would be about \$600,000. Additional cost information is being developed for balance of plant impacts.

For any plant that is currently selling its ash for use in concrete, there would be an addition cost associated with lost ash revenues and landfill fees. These costs will vary from site to site, but for example at PPPP, it is estimated that these costs would be \$5MM/yr for a single 600 MW plant.

An alternate approach to mercury control would be to add a COHPAC baghouse downstream of the existing ESP. Data collected from the field test at Gaston indicate mercury removal levels of up to 90% were obtained with COHPAC (a baghouse). Figure 8 presents a summary of the mercury removal trends measured at both Gaston and PPPP and the projected annual sorbent costs of PAC in \$/MWh.

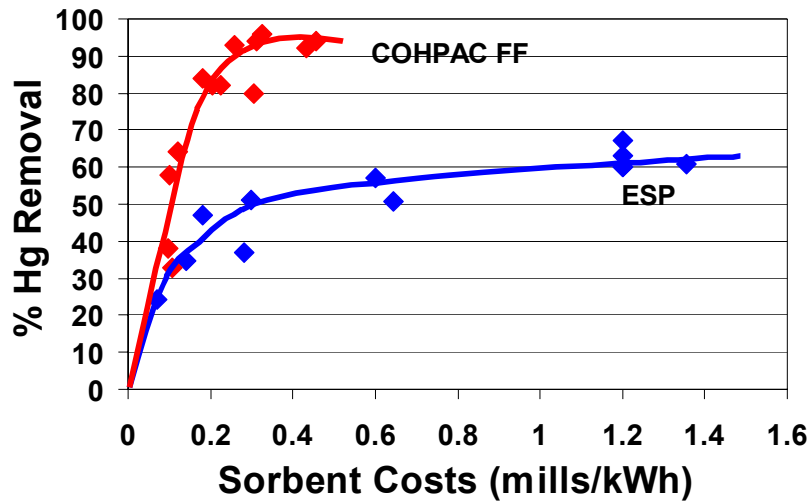


Fig. 8. Comparison of Projected, Annual Sorbent Costs for an ESP and COHPAC Fabric Filter Based on Results from NETL Full-Scale Tests, 2001.

In addition, to providing higher levels of mercury removal at reduced sorbent costs, there are many additional benefits to the COHPAC approach, such as:

1. The ash collected in the ESP remains suitable for sale and reuse in concrete;
2. The volume of solid material that contains mercury is significantly reduced and remains separate from the majority of the by-products;
3. Capital costs for COHPAC are less than other options such as replacing the ESP with a full-sized baghouse or larger ESP;
4. COHPAC requires much less physical space than either a larger ESP or full-size baghouse system; AND
5. Outage time can be significantly reduced with COHPAC systems in comparison to major ESP rebuilds/upgrades.

BRAYTON POINT TEST PROGRAM

The most recent demonstration was conducted at PG&E National Energy Group's Brayton Point Station. These tests were conducted from June through July, 2002. Results from these tests are currently being evaluated and will be released in the Fall of 2002.

CONCLUSIONS ON THE STATUS OF PAC BASED HG CONTROL

Sorbent injection for mercury control represents the most mature approach for controlling mercury emissions from coal-fired boilers. The equipment has been successfully scaled up and operated at a scale capable of treating power plant flue gas. From two field test programs, it has been demonstrated that activated carbon is effective on both elemental and oxidized species of mercury. This is a tremendous advantage over wet scrubbers, which are only capable of capturing oxidized mercury and are thus only effective on certain bituminous coals. In contrast, PAC has been shown to be capable of treating flue gas from bituminous and subbituminous coals.

The most important parameter impacting the performance of PAC injection is the type of particulate control equipment. With a fabric filter mercury removal levels in excess of 90% are achievable at sorbent feed rates in the 2-4 lb/MMacf range. However, in an ESP with less contact between the gas and collected sorbent, it will require a feed rate of at least 10 lb/MMacf to achieve removal in the 70% range.

Initial testing with a PRB ash determined that the presence of even trace amounts of activated carbon in the ash rendered the material unacceptable for use in concrete. Based upon these results, programs have begun to beneficiate the ash so that it can remain marketable. One approach that is currently commercially available is the COHPAC baghouse. With this configuration, the ash is collected upstream of the carbon injection and remains acceptable for sale. The downstream baghouse provides the primary control device for the PAC resulting in high levels of mercury control at relatively low sorbent injection rates. Other approaches to treating the carbon in the ash include separating the carbon from the ash, combusting the carbon, and chemical deactivation of the carbon.

A significant increase in the cleaning frequency of the COHPAC baghouse occurred with the injection of activated carbons. At Gaston, the maximum acceptable cleaning frequency and pressure drop limited the amount of sorbent that could be injected and therefore the maximum mercury removal actually achievable. Based on these results, it will be necessary to take into consideration the sorbent injection rate in the design of future COHPAC baghouses and perhaps design the baghouses more conservatively. Based on an empirical model of COHPAC performance developed by Bustard et al., (1997), COHPAC performance should be acceptable at a gross air-to-cloth ratio of 6 ft/min and a PAC injection concentration of 3 lbs/MMacf. Additional testing over longer periods (up to a year) are planned to determine the impact of carbon injection on bag life (pressure drop and bag strength) and outlet particulate emissions.

ACKNOWLEDGEMENTS

We would like to acknowledge the assistance of key personnel from the power generating companies and other supporting members of our Mercury Control Team including:

Dr. Larry Monroe, Principal Research Engineer – Southern Company
Mr. Terry Coughlin, Project Manager – Wisconsin Electric
Mr. Richard Johnson, Chief Engineer and Resource Manager – Wisconsin Electric
Mr. Brian Wright, Mechanical Engineer – PG&E National Energy Group
Mr. Scott Renninger, Program Manager – DOE NETL
Dr. Ramsay Chang, Project Manager - EPRI

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