Field Test Program to Develop Comprehensive Design, Operating and Cost Data for Mercury Control Systems on Non-Scrubbed Coal-Fired Boilers

Quarterly Technical Report
Reporting Period: July 1, 2002 – September 30, 2002

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DISCLAIMER

This technical report was prepared with the support of the U.S. Department of Energy, under Award No. DE-FC26-00NT41005. 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.

ABSTRACT

With the Nation's coal-burning utilities facing the possibility of tighter controls on mercury pollutants, the U.S. Department of Energy is funding projects that could offer power plant operators better ways to reduce these emissions at much lower costs.

Mercury is known to have toxic effects on the nervous system of humans and wildlife. Although it exists only in trace amounts in coal, mercury is released when coal burns and can accumulate on land and in water. In water, bacteria transform the metal into methylmercury, the most hazardous form of the metal. Methylmercury can collect in fish and marine mammals in concentrations hundreds of thousands times higher than the levels in surrounding waters.

One of the goals of DOE is to develop technologies by 2005 that will be capable of cutting mercury emissions 50 to 70 percent at well under one-half of today's costs. ADA Environmental Solutions (ADA-ES) is managing a project to test mercury control technologies at full scale at four different power plants from 2000 – 2003. The ADA-ES project is focused on those power plants that are not equipped with wet flue gas desulfurization systems.

ADA-ES has developed a portable system that will be tested at four different utility power plants. Each of the plants is equipped with either electrostatic precipitators or fabric filters to remove solid particles from the plant's flue gas.

ADA-ES's technology will inject a dry sorbent, such as activated carbon, which removes the mercury and makes it more susceptible to capture by the particulate control devices. A fine water mist may be sprayed into the flue gas to cool its temperature to the range where the dry sorbent is most effective.

PG&E National Energy Group is providing two test sites that fire bituminous coals and both are equipped with electrostatic precipitators and carbon/ash separation systems. Wisconsin Electric Power Company is providing a third test site that burns Powder River Basin (PRB) coal and has an electrostatic precipitator for particulate control. Alabama Power Company will host a fourth test at its Plant Gaston, which is equipped with a hot-side electrostatic precipitator and a downstream fabric filter.

During the eighth reporting quarter, progress was made on the project in the following areas:

PG&E NEG Salem Harbor Station

- Sorbent injection equipment was installed at the site during the quarter.
- Test plans were prepared for the field-testing phase of the project.
- Baseline testing was completed during the quarter.

Technology Transfer

- A number of technical presentations and briefings were made during the quarter. Notable among them was a paper published in the JAWMA. Also, two papers were presented at the Air Quality III Conference and one at the Pittsburgh Coal Conference.

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LIST OF GRAPHICAL MATERIALS

There are no graphical materials included in the main body of this report. There may be graphical materials within attachments included in Appendix B.

EXECUTIVE SUMMARY

ADA-ES began work on a Cooperative Agreement with the Department of Energy in October 2000 to demonstrate full-scale mercury control systems at coal-fired power plants. The project is the next step in the process of obtaining performance and cost data on full-scale utility plants for mercury control systems. Power generating companies that have entered into contracts with ADA-ES are PG&E National Energy Group, Wisconsin Electric Power Company and Alabama Power Company. During the three-year, $6.8 million project, integrated control systems will be installed and tested at four power plants. ADA-ES is responsible for managing the project including engineering, testing, economic analysis, and information dissemination functions.

As of the eighth reporting quarter, progress on the project has been made in the following areas:

- Alabama Power Company Plant Gaston – Field-testing has been completed.
- Wisconsin Electric Pleasant Prairie Power Plant – Field-testing has been completed.
- PG&E NEG Brayton Point Station – Field-testing has been completed.
- PG&E NEG Salem Harbor Station – baseline testing was completed and a test plan for parametric and long-term testing was formulated.

Several technical papers were presented on the project during the eighth reporting quarter at the annual Pittsburgh Coal Conference, and Air Quality III Conference.

INTRODUCTION

Cooperative Agreement No. DE-FC26-00NT41005 was awarded to ADA-ES to demonstrate mercury control technologies on non-scrubbed coal-fired boilers. Under the contract, ADA-ES is working in partnership with PG&E National Energy Group, Wisconsin Electric Power Company, Alabama Power, and EPRI to design and engineer systems to maximize effectiveness and minimize costs to curtail mercury emissions from power plant flue gases. Reports estimate that mercury control could cost the industry from $2 to $5 billion per year. Much of these costs will be associated with power plants that do not have wet scrubbers as part of their air pollution control configurations. The four plants that are being evaluated during the program are typical of this type of application, which is found at 75% of the nearly 1100 units that would be impacted by new regulations.

Detailed topical reports will be prepared for each site that is tested under the program. Quarterly reports will be used to provide project overviews and technology transfer information.

EXPERIMENTAL

Fieldwork was conducted on the project during the eighth reporting quarter at PG&E's Salem Harbor Station in the form of baseline testing. Detailed results of the testing at each power plant will be provided in separate topical reports.

Technology Transfer

Technology transfer activities continued during the seventh reporting quarter of the project. Reference citations of the formal presentations are provided below:

Schlager, R., J. Bustard, M. Durham, C. Lindsey, T. Starns, K. Baldrey, C. Martin, S. Sjostrom, S. Renninger and R. Chang (2002). "Field Evaluations of Sorbent Injection for Mercury Control on Coal-Fired Power Plants," presented at the Nineteenth Annual International Pittsburgh Coal Conference, Pittsburgh, PA, September 23-27.

Schlager, R.J. (2002). "Mercury Control Pilot Testing at Brayton Point Station," presented at the Mercury Standards Technology Feasibility Meeting, Massachusetts Department of Environmental Protection, Boston, MA September 20.

Senior, C., J. Bustard, M. Durham and K. Baldrey (2002). "Characterization of Fly Ash from Full-Scale Demonstration of Sorbent Injection for Mercury Control on Coal-Fired Power Plants," Air Quality III Conference, Arlington, VA, September 9-12.

Bustard, J., M. Durham, T. Starns, C. Martin, R. Schlager, C. Lindsey, K. Baldrey, L. Monroe, T. Coughlin, D. Johnson, S. Renninger and R. Chang (2002). "Full-Scale Evaluation of Sorbent Injection for Mercury Control on Coal-Fired Power Plants," Air Quality III Conference, Arlington, VA, September 9-12.

Bustard, C.J. (2002). "Activated Carbon for Mercury Control on Coal Fired Boilers," Reinhold ESP/FF Conference, Dallas, TX, August 12.

Durham, M.D. (2002). "Update on Full-Scale Activated Carbon Injection for Control of Mercury Emissions," presentation to the Utility MACT Working Group, U.S. Environmental Protection Agency, Washington D.C., August 8.

Durham, M.D. (2002). "Field Evaluation of Mercury Control for Eastern Bituminous and PRB Coals," Coal-Gen, St. Louis, MO, July 31 – August 2.

Bustard, C.J., M. Durham, C. Lindsey, T. Starns, K. Baldrey, C. Martin, R. Schlager, S. Sjostrom, R. Slye, S. Renninger, L. Monroe, R. Miller and R. Chang (2002). "Full-Scale Evaluation of Mercury Control with Sorbent Injection and COHPAC at Alabama Power E.C. Gaston," special edition *JAWMA*, 52, pp. 918-926, August.

Websites Containing ADA-ES Presentations to Regulatory Agencies

Two regulatory agencies have placed information about the project onto their websites. References for these sites are:

Wisconsin DNR website:
http://www.dnr.state.wi.us/org/aw/air/reg/mercury/rule.htm

EPA Electric Utility section 112 Rule Making website:
http://www.epa.gov/ttn/atw/combust/utiltox/utoxpg.html

RESULTS AND DISCUSSION

The major efforts during the eighth reporting quarter focused on completing parametric and long-term testing at Brayton Point, and equipment installation and baseline testing at Salem Harbor. Detailed results of the testing at each power plant will be provided in separate topical reports.

CONCLUSION

Work began on Cooperative Agreement No. DE-FC26-00NT41005 in October 2000. Initial activities include holding a project kickoff meeting, securing the fourth test site (Alabama Power Company Plant Gaston), and performing various planning and administrative functions. Field-testing began during the second reporting period at Plant Gaston, and test planning for the remaining sites began. Test work was completed at the Gaston site during the third reporting period. Site preparations were completed and field-testing began at Wisconsin Electric during the fourth reporting period and all site work was completed during the fifth reporting quarter. Sorbent screening activities were completed at Brayton Point during the sixth reporting quarter. Baseline testing was initiated at Brayton Point in the seventh quarter and parametric testing began. Work at Brayton Point was completed in the eighth quarter. Equipment installation and field-testing began at Salem Harbor during the eighth quarter.

REFERENCES

None this reporting period.

LIST OF ACRONYMS AND ABBREVIATIONS

A&WMA	Air & Waste Management Association
DOE	Department of Energy
JAWMA	Journal of the Air & Waste Management Association

ATTACHMENT A

Accomplishments and Status Assessment
July 1, 2002 – September 30, 2002

- **General**
  The project is progressing on schedule without any major deviations from plan.

- **Alabama Power Company's Plant Gaston**
  This facility was the first to be tested in the program. Prebaseline testing was completed in February, 2001 and the parametric test series was performed in March, 2001. The long-term test series was completed during April, 2001. The test facility was decommissioned during May. Economic analysis and topical report were started in June and are continuing. Ontario Hydro test results have been completed.

- **WEPCO Pleasant Prairie Power Plant**
  Sorbent screening testing was completed at Pleasant Prairie in June, 2001. Equipment installations were completed in August, 2001. WEPCO hosted a public site tour of the mercury control system at the end of August as part of the A&WMA Specialty Conference on Mercury Emissions. Equipment check-out was completed in September and Baseline and Parametric testing began during September 2001. Long-term testing was completed in November, and the mercury control equipment was removed during December and moved to PG&E NEG Brayton Point.

- **PG&E NEG Brayton Point Station**
  Prebaseline testing was performed at Brayton Point during June 2001. Mercury emissions measurements were made at the station during the summer of 2001 as required by the state of Massachusetts. The site was visited in July 2001 to evaluate the ductwork, port locations, equipment locations and platform needs. Some site preparation work was done during September 2001. The mercury control equipment was received by the station in December 2001. Sorbent screening testing was performed at the site in February 2002, baseline testing was completed in June 2002 and parametric and long-term testing was completed during July 2002. Equipment decommissioning was completed by mid August 2002.

- **PG&E NEG Salem Harbor Station**
  Prebaseline measurements were made at Salem Harbor during February 2001. Mercury emissions measurements were made at the station during July 2001 as required by the state of Massachusetts. Injection equipment arrived at the site in late August and installation was completed in early September 2002. Boiler tuning and baseline testing was completed in September 2002. Parametric testing is scheduled for October 2002, and long-term testing is scheduled for November 2002.

- **Technology Transfer**
  A number of technology transfer activities have taken place since the project began in October 2000. More activities are planned for future conferences, symposia and technical publications. Presentations were made during the quarter at Reinhold ESP/FF Conference, Coal-Gen, Annual International Pittsburgh Coal Conference, and Air Quality III Conference. A paper about the project was prepared for JAWMA..

ATTACHMENT B

Technical Papers, Press Releases and Other Published Information

Field Evaluations of Sorbent Injection for Mercury Control on Coal-Fired Power Plants

Presented at Pittsburgh Coal Conference
Pittsburgh, PA
September 25, 2002

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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 lower 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. The first program was completed in the spring 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 flyash. The second program was conducted during the fall 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 flyash.

At each site sorbent injection for mercury control is implemented on full-scale particulate control equipment to obtain performance and operational data. The standard test matrix includes a series of parametric tests conducted to determine the optimum sorbent and operating conditions that would be required for several levels of mercury control. The maximum injection rate is set based on preliminary injection performance data that has been developed through slipstream testing or modeling exercises, the practical limitations of particle control device (PCD) performance, and sorbent cost. Based on results from these tests, a two-week test under optimized conditions is conducted to assess longer-term impacts to the PCD, byproduct management practices and auxiliary equipment operation. During the long-term test, mercury removal efficiencies are measured by the S-CEMs and verified by draft Ontario Hydro method measurements. Combustion byproduct samples are collected concurrently to determine the impact of the sorbents on waste disposal and byproduct reuse practices.

At each site, at least two sorbents are evaluated during the parametric tests. A standard powdered activated carbon (FGD), which is a lignite-derived sorbent supplied by Norit Americas

Inc., is tested in all cases as the benchmark sorbent. The alternative sorbent or sorbents must be commercially available and offer an advantage over the benchmark sorbent.

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.

Figure 1. Carbon injection storage silo and feeder trains installed at PPPP.

Near real-time vapor phase mercury measurements were made using a Semi-Continuous Emissions Monitor (S-CEM) designed and operated by Apogee Scientific. This instrument was developed with EPRI funding to facilitate EPRI research and development efforts. Two analyzers are dedicated to the program and are set up at the inlet and outlet of the PCD. The S-CEMs operate continuously over the seven-week 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).

E.C. GASTON TEST PROGRAM

The E.C. Gaston Electric Generating Plant, located in Wilsonville, Alabama, has four 270 MW balanced draft and one 880 MW forced draft coal fired boilers. All units fire a variety of low-sulfur, washed, Eastern bituminous coals. The primary particulate control equipment on all units are hot-side ESPs. In 1996 Alabama Power contracted with Hamon Research-Cottrell to install COHPAC downstream of the hot-side ESP on Unit 3 (Miller et al., 1999).

COHPAC is an EPRI patented concept that places a high air-to-cloth ratio baghouse downstream of an existing ESP to improve overall particulate collection efficiency. 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 COHPAC baghouse consists of four (4) isolatable compartments, two compartments per air-preheater identified as either A- or B-Side. The evaluation was conducted on the B side 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% mercury removal. 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.

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.

Figure 2. S-CEM mercury measurements during parametric tests.

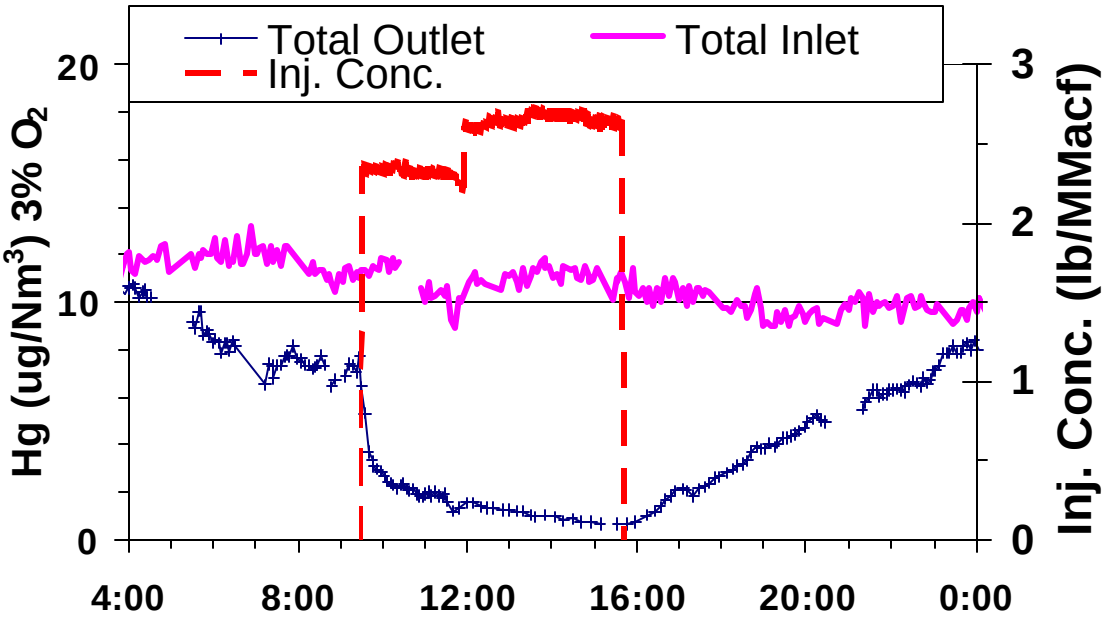
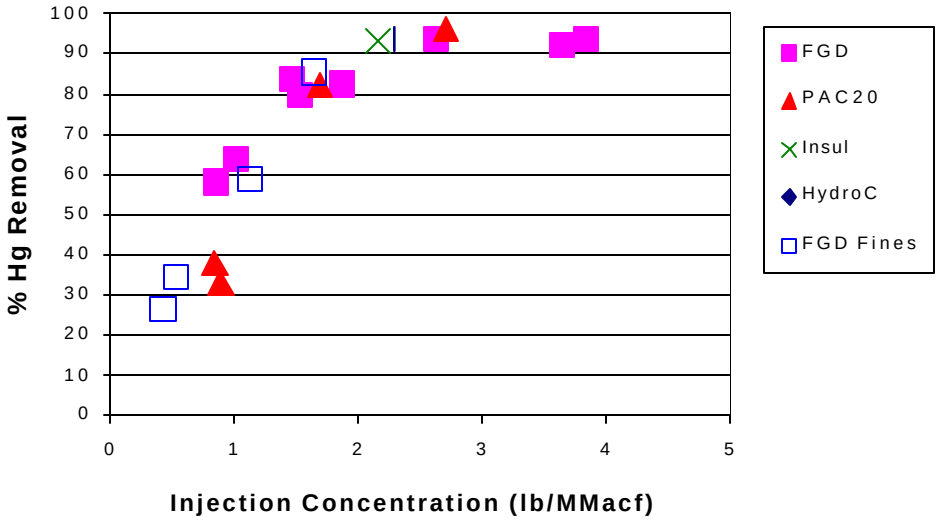


Figure 3. Mercury removal trends across COHPAC as a function of PAC injection concentrations. Measurements made during parametric tests, March 2001.



Carbon injection significantly increased the cleaning 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 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.

Figure 4. COHPAC cleaning frequency in pulses/bag/hour as a function of PAC injection concentration.

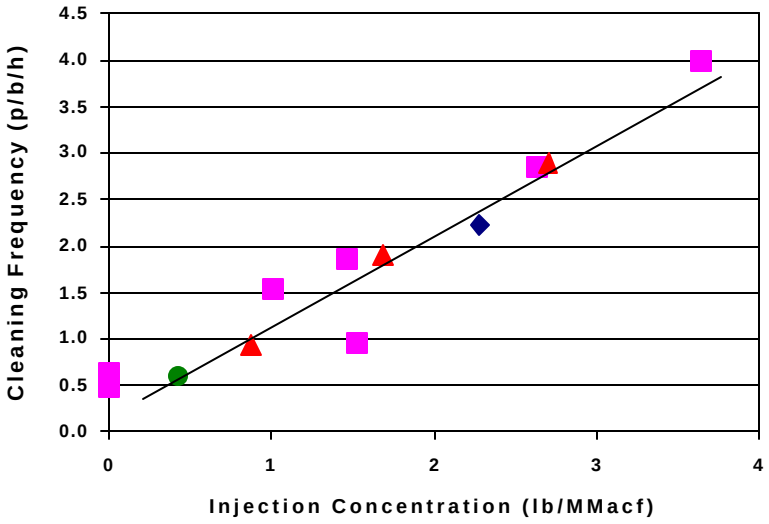


Table 1 presents average, speciated mercury removal across COHPAC. The overall average reduction in total mercury is 90%. At the outlet the predominant species of mercury is the oxidized form; however, it is still 85% less than what was present upstream of PAC injection.

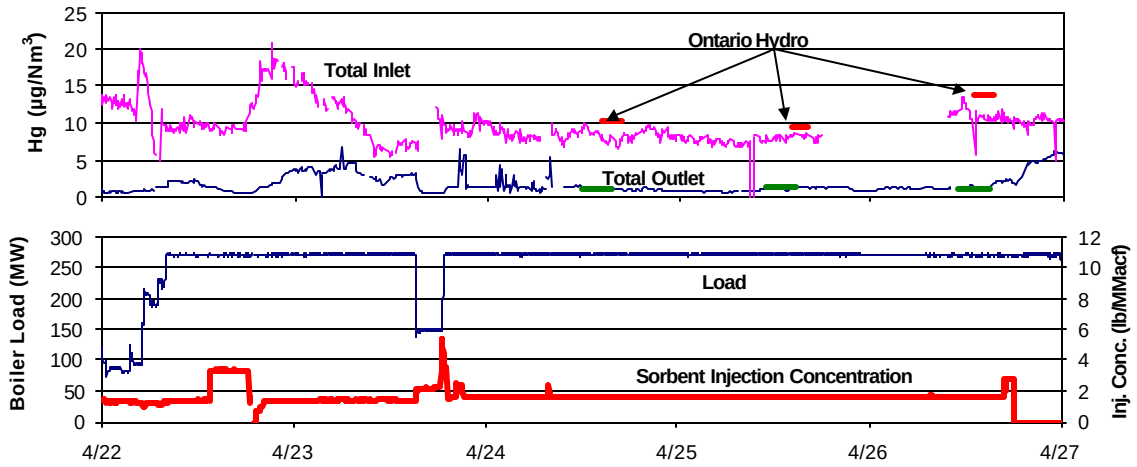
Table 1: Average Mercury Removal Efficiencies Across COHPAC as Measured With Ontario Hydro Method.

Sampling Location	Particulate ($\mu g/dncm^1$)	Oxidized ($\mu g/dncm^1$)	Elemental ($\mu g/dncm^1$)	Total ($\mu g/dncm^1$)
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^{o}F

Figure 5 presents inlet and outlet mercury concentrations as measured by the S-CEMs, boiler load, and PAC injection concentration during the last 5 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.

Figure 5. Inlet and outlet COHPAC mercury concentrations, boiler load and PAC injection concentration during Long-Term Tests, April 2001.



Conclusions from the Gaston Test Program

A full-scale evaluation of mercury control using activated carbon injection upstream of a COHPAC baghouse was conducted at Alabama Power Company's Plant Gaston Unit 3. Results and trends from these relatively short-term tests were encouraging. Effective mercury removal, up to 90% efficiency, was obtained for short-operating periods (8 hrs) by injecting powdered activated carbon upstream of COHPAC.

Actual mercury removals were in reasonably close agreement with theoretical model predictions for 80 to 90% removal (1.5 to 2 vs. 3 lbs/MMacf) considering that the model is based on a uniform PAC particle size of 15 microns when in fact the actual FGD carbon used has a wide size distribution with significant numbers of particles below 15 microns[4].

A significant increase in the cleaning frequency of the COHPAC baghouse occurred with the injection of activated carbons. At this site, 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) need to occur to determine the impact of carbon injection on bag life (pressure drop and bag strength) and outlet particulate emissions.

PLEASANT PRAIRIE POWER PLANT SITE DESCRIPTION

Wisconsin Energy Corporation owns and operates Pleasant Prairie Power Plant located near Kenosha, Wisconsin. The plant has two (2) 600 MW balanced-draft coal-fired boilers. Unit 2

was chosen to be the test unit. The units fire a variety of Powder River Basin (PRB) low sulfur, sub-bituminous coals.

The primary particulate control equipment consists of cold-side ESPs, of weighted wire design and liquid sulfur trioxide (SO_3) flue gas conditioning. The precipitators were designed and built by Research-Cottrell and Wahlco supplied the flue gas conditioning system. The installation is comprised of four (4) electrostatic precipitators that are arranged piggyback style and designated 2-1, 2-2, 2-3, and 2-4. Each of the four precipitators is two (2) chambers wide and four (4) mechanical fields deep with eight (8) electrical fields in the direction of gas flow. The specific collection area (SCA) is 468 ft^2/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. One precipitator's ash can be isolated from the balance of the unit. The 2-4 ESP is the top box of the piggyback-configuration and therefore had a long duct run which could accommodate both sorbent injection and spray cooling, and still have adequate residence time for both. 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.

TEST RESULTS

Baseline Tests

After equipment installation and checkout, a set of baseline tests was conducted. During this test, 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 µg/g. At PPPP a coal mercury level of 0.099 µg/g is equivalent to a mercury concentration of about 13.7 µg/dncm @ 3% O_2 in the flue gas.

Both the S-CEMs and the modified Ontario Hydro Method were used to measure mercury across the 2-4 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.

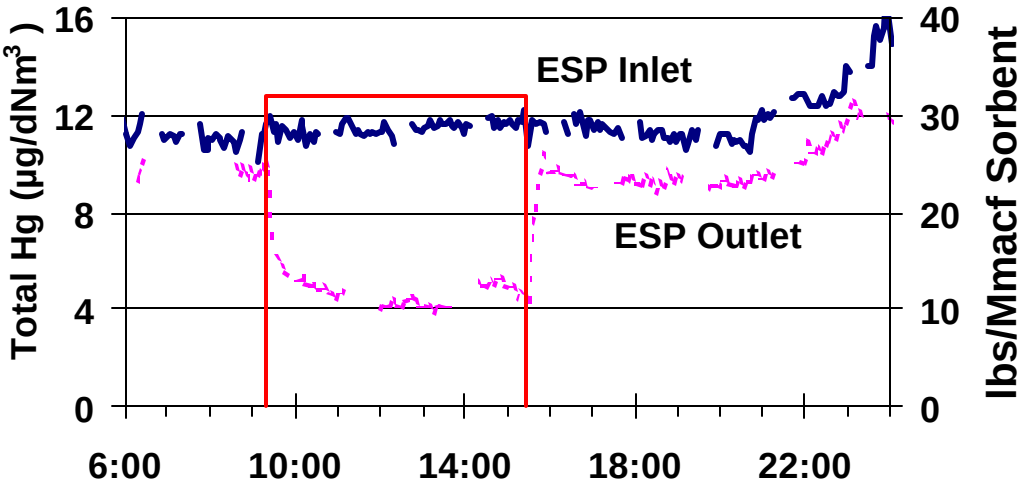
Parametric Tests

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, SO_3 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, SO_3 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.

Figure 6. S-CEM mercury measurements during the first week of parametric tests with Norit Darco FGD PAC.

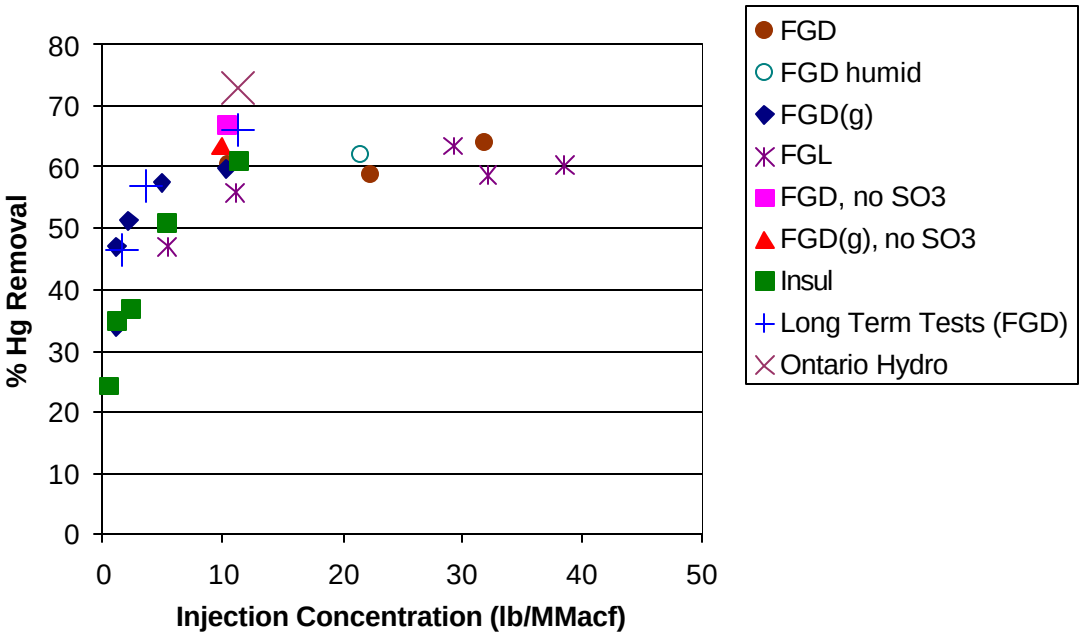


A summary of results from all the parametric tests is presented in Figure 7. This figure plots mercury removal efficiency as a function of sorbent injection concentration. The different symbols represent different test conditions including carbon type, SO_3 off and spray cooling. This graph shows that 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 SO_3 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.

Figure 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 ft^2/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 ft^2/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 original test plan called for injecting sorbents at one condition, 24 hours/day, for up to two weeks to obtain the highest mercury removal rates possible within equipment limitations. However, results from the parametric tests showed significant mercury removal at low injection rates. This raised interest in the long-term performance under these conditions. 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 2-4 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 2. 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 flyash in concrete. First of all, flyash samples with even low concentrations of carbon were discolored. Even though the carbon content was below ASTM standards, the darker color would make the material less marketable when there are other sources of ash without PAC.

More importantly, the flyash 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 meant that the ash could not be sold for use in concrete. The impact of PAC was so severe that the ash failed foam index tests for five weeks following the end of the

carbon injection tests. 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.

Conclusions from Pleasant Prairie Tests

A full-scale evaluation of mercury control using activated carbon injection upstream of an ESP was conducted at Wisconsin Electric's Pleasant Prairie Power Plant Unit 2. Results and trends from these relatively short-term tests were encouraging. Mercury removal increased with PAC injection rate producing 73% removal at a feed rate of 10 lb/MMacf. However, there was no additional mercury removal obtained by injection at rates above 10 lb/MMacf. Tests confirmed that PAC is effective for capturing both elemental and oxidized mercury concentrations. The PAC injection produced no negative impacts on the performance of the relatively large ESP. The tests also determined that PAC had a significant impact on the marketability of the fly ash. Fly ash could not be used for concrete with any trace of PAC present.

PAC COST ANALYSIS

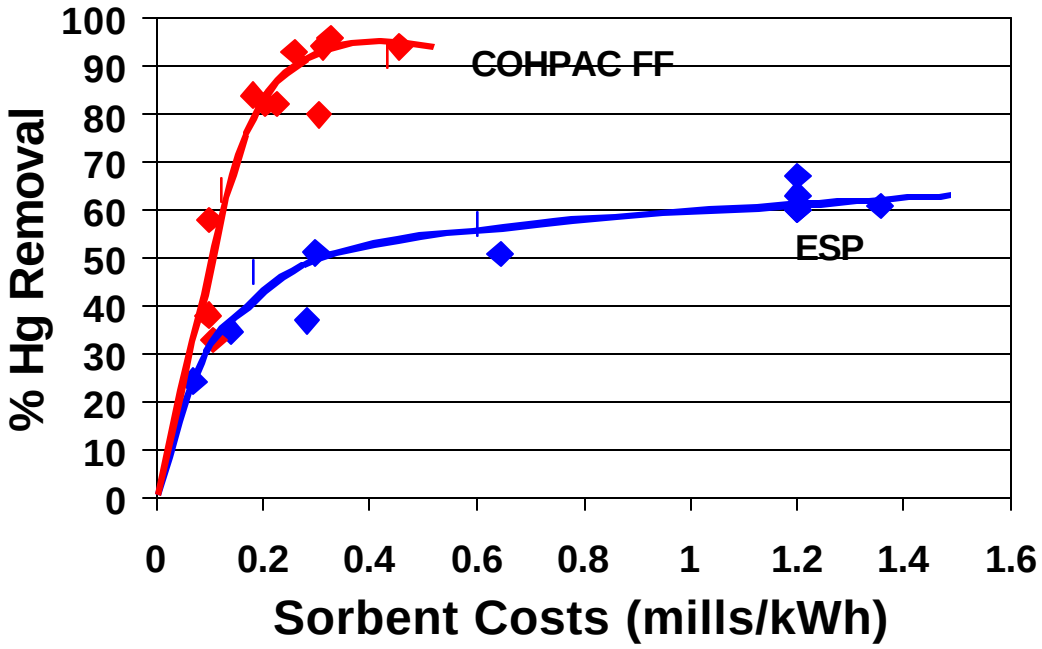
The requirements and costs for full-scale, permanent, commercial implementation of the necessary equipment for mercury control using PAC injection technology are being finalized for PPPP Unit 2. Preliminary capital and sorbent costs for mercury removal using sorbent injection into the ESP have been developed.

The estimated uninstalled cost for a sorbent injection system and storage silo for the 612 MW Unit 2 is $720,000 ± 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.

Figure 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.

5. Outage time can be significantly reduced with COHPAC systems in comparison to major ESP rebuilds/upgrades.

CONCLUSIONS ON THE STATUS OF PAC-BASED MERCURY 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 contract 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.

Additional short-term field tests and long-term demonstrations are planned to further develop this promising technology so that it will be commercially available to meet state and Federal mandates for reduction of mercury emissions. These programs will be directed at determining the costs and capabilities of PAC injection for different boiler types, coal characteristics, equipment configurations, and plant operating conditions.

REFERENCES

1. Brown, T.D., D.N. Smith, R.A. Hargis and W.J. O'Dowd. "Mercury Measurement and Its Control: What We Know, Have Learned, and Need to Further Investigate," *J. Air & Waste Management Association*, pp. 1-97, June 1999.

2. Bustard, C.J., M. Durham, C. Lindsey, T. Starns, K. Baldrey, C. Martin, R. Schlager, S. Sjostrom, R. Slye, S. Renninger, L. Monroe, R. Miller and R. Chang (2002). "Full-Scale Evaluation of Mercury Control with Sorbent Injection and COHPAC at Alabama Power E.C. Gaston," special edition *JAWMA*, June.

3. Bustard, C.J., S.M. Sjostrom, and R. Chang (1997). "Predicting COHPAC Performance"; presented at EPRI-DOE-EPA Combined Utility Air Pollutant Control Symposium, Washington D.C., August 25-29.

4. Durham, M.D, C.J. Bustard, R. Schlager, C. Martin, S. Johnson, S. Renninger. "Field Test Program to Develop Comprehensive Design, Operating and Cost Data for Mercury Control Systems on N-on Scrubbed Coal-Fired Boilers". Presented at the Air & Waste Management Association 2001 Annual Conference and Exhibition, June 24-28, 2001, Orlando, FL.

5. Durham, MD, C.J. Bustard, R. Schlager, C. Martin, S. Johnson, S. Renninger. "Controlling Mercury Emissions from Coal-Fired Utility Boilers: A Field Test" *EM, Air & Waste Management Association's Magazine for Environmental Managers, pp 27 – 33, July 2001.*

6. Meserole, F.B., R. Chang, T.R. Carey, J. Machac, and C.F. Richardson, "Modeling Mercury Removal by Sorbent Injection," J. Air & Waste Mange. Assoc., 49, 694-704, 1999.

7. Miller, Richard, W. Harrison, B. Corina, K. Cushing, R. Chang. "COHPAC (Compact Hybrid Particulate Collector) The Next Generation in Particulate Control Technology Alabama Power Company's E. C. Gaston Units #2 and #3 "A Success Story". Presented at the EPRI-DOE-EPA Combined Utility Air Pollution Control Symposium: The MEGA Symposium, Atlanta Georgia, August 16 – 20, 1999.

8. Sjostrom, S, T. Ebner, P. Harrington, R. Slye, R. Chang, "Field Studies of Mercury Control using Injected Sorbents", Presented at the A&WMA Annual Meeting, Baltimore, MD, June, 2002.

9. Sjostrom, S, T. Ebner, T. Ley, R. Slye, C. Richardson, T. Machalek, R. Richardson, R. Chang, F. Meserole. "Assessing Sorbents for Mercury Control in Coal-Combustion Flue Gas". Presented at the "A&WMA Specialty Conference on Mercury Emissions: Fate, Effects and Control," Chicago, IL, August 21 –23, 2001.

10. Sjostrom, S.M., J. Bustard, M. Durham Ph.D, R. Chang Ph.D. *"Mercury Removal Trends in Full-Scale ESPs and Fabric Filters"*. Presented at the "A&WMA Specialty Conference on Mercury Emissions: Fate, Effects and Control," Chicago, IL, August 21 –23, 2001.

11. Starns, T., C.J. Bustard, M.D. Durham, C. Lindsey, C. Martin, R. Schlager, B. Donnelly, S. Sjostrom, P. Harrington, S. Haythornthwaite, R. Johnson, E. Morris, R. Chang and S. Renninger (2002). "Full-Scale Test of Mercury Control with Sorbent Injection and an ESP at Wisconsin Electric's Pleasant Prairie Power Plant," to be presented at the 95th A&WMA Annual Meeting, Session AE-1, Baltimore, MD, June 23-27.

CHARACTERIZATION OF FLY ASH FROM FULL-SCALE DEMONSTRATION OF SORBENT INJECTION FOR MERCURY CONTROL ON COAL-FIRED POWER PLANTS

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ABSTRACT

With impending regulation of mercury from coal-fired power plants, it is important to concentrate efforts on the most mature retrofit control technologies. Injection of powdered activated carbon (PAC) has been deemed the most mature technology, but has until recently only been demonstrated in bench- and pilot-scale experiments. Under a DOE/NETL cooperative agreement, ADA-ES is working in partnership with a number of power generating companies on a field evaluation program of sorbent injection upstream of existing particulate control devices. This program represents the first time that PAC has been injected on such a large scale and continuously for periods of several weeks. An important component of the field demonstration program is to characterize the fly ash that results from injection of PAC upstream of a baghouse or ESP. Leaching analyses were performed using several widely accepted methods in order to assess the stability of the ash byproduct in landfill situations. Other tests were performed to characterize the ash byproduct for industrial use. The reports of all analyses are presented in this paper.

INTRODUCTION

In December 2000, EPA announced their intent to regulate mercury emissions from nation's coal-fired power plants. Legislation is currently being drafted, with indications that the final 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 at the level of 90% removal efficiency range from $2 to $5 billion per year. With mercury regulations imminent, mercury control technologies need to be proven at full scale to document performance and costs.

The Department of Energy's National Energy Technology Laboratory (NETL) is the primary funding agency on an industry cost-shared test program to obtain the necessary information to assess the costs of controlling mercury from coal-fired utility plants that do not have scrubbers for SO_2 control.

The most mature retrofit technology available today is the injection of sorbents such as powdered activated carbon (PAC) into flue gas upstream of particulate control devices (PCDs). The gas-phase mercury in the flue gas is adsorbed (either chemically or physically) on the sorbent. This can take place in-flight or once the sorbent has deposited on the bags of a fabric filter. Preliminary evidence suggests that sorbent deposited in ESPs can also remove gaseous mercury to some degree. Existing particulate control equipment collects the mercury containing sorbent along with the fly ash.

Issues related to the implementation of PAC-injection for mercury control on coal-fired power plants include:

- Cost of sorbents and associated capital equipment.
- Impact on operation of existing particulate control device.
- Impacts on the fly ash, which includes loss of byproduct sales due to contamination and potential for leaching of mercury from the ash in either utilization or disposal of ash.

In this paper, report on measurements of the leachability of sorbent-containing fly ash from two full-scale tests of PAC-injection at coal-fired utility boilers.

Ash Utilization From Coal-Fired Power Plants

PAC-injection applied to coal-fired boilers will result in the fly ash being mixed with a certain amount of mercury-containing sorbent. This material will be sent to land disposal or used in specific applications (assuming that the presence of the sorbent is compatible with the application). Since the mercury on the spent sorbent may be present in a different form than on fly ash, it is necessary to consider what might be the most likely routes for release of mercury in sorbent-fly ash mixtures and how sorbent-containing coal utilization byproducts (CUBs) should be tested.

In the US, approximately 67% of all fly ash produced from utility coal combustion is disposed of in landfills or surface impoundments. The remaining 33% is used for a variety of commercial applications as shown in Table 1 (taken from Reference 1).

There are approximately 600 waste disposal sites for CUBs in the US, half are landfills and half are surface impoundments. Note that here CUBs include other streams such as bottom ash and scrubber sludge. A 1999 EPA study estimated that about half of the CUB landfills and a little less than a third of the surface impoundments have some type of liner, the most common type being compacted clay. Volatilization of mercury from landfills was estimated by EPA to be small. To date, there has been no evidence based on laboratory leaching studies for leaching of large amounts of mercury from fly ash under landfill conditions.

Leaching appears to be the most likely pathway for liberation of mercury from fly ash. Volatilization may be important for certain applications of fly ash as filler in concrete applications. Volatilization is, of course, the primary pathway for mercury if fly ash is used as a raw material in cement kilns. However, volatilization will be complete in this case.

When considering leaching of mercury from CUBs, whether it takes place in landfills or in concrete, it is difficult to specify one single condition (in terms of pH and temperature) that will apply in every case. There are many different leaching solutions that have been tested with fly ash. Since conditions may vary from one landfill to another, and since the inorganic portion of the fly ash may be acidic or basic, it is hard to specify a single test that can be applied to all future end-uses or disposal options for CUBs. In this work, we used a variety of different leaching procedures to characterize the stability of sorbent-containing fly ash in the environment.

Table 1. Fate of Fly Ash from Coal Combustion in the United States in 1999.[1]

Fate	Millions of tons	%	Potential release mechanisms
Land disposal	42.210	67.0%	Leaching, windblown dust
Concrete/grout	10.000	15.9%	Leaching, volatilization (application-specific)
Structural fills	3.200	5.1%	Unlikely
Waste stabilization	1.900	3.0%	Unlikely
Mining applications	1.500	2.4%	Leaching
Raw feed for cement kiln	1.300	2.1%	Volatilization in the kiln, with recovery in fines
Road base/subbase	1.200	1.9%	Not expected to be significant
Flowable fill	0.850	1.3%	Unlikely
Other	0.840	1.3%	
Total	63.000		

Description Of Field Demonstration Program

Under a DOE/NETL cooperative agreement, ADA Environmental Solutions is working in partnership with PG&E National Energy Group (NEG), Wisconsin Electric, a subsidiary of Wisconsin Energy Corp., Alabama Power, a subsidiary of Southern Company, and EPRI on a field test program of sorbent injection upstream of existing particulate control devices for mercury control. Other organizations participating in the program include Ontario Power Generation, First Energy, TVA, Arch Coal, Kennecott Energy, Hamon Research-Cottrell, EnviroCare and Norit Americas.

The four sites, shown below in Table 2, burn coal and have particulate control devices only (no scrubbers) that are representative of three-quarters of the coal-fired electric utility boilers in the US. At each site, sorbent injection for mercury control is implemented on full-scale particulate control devices to obtain performance and operational data. Combustion byproduct samples are collected concurrently to determine the impact of sorbents on waste disposal and byproduct reuse practices. The tests are conducted in three distinct phases:

- Baseline testing;
- Parametric testing; and
- Long-term testing.

Baseline measurements are conducted before the sorbent injection equipment is installed. During this phase, mercury concentrations in the flue gas are measured with a Semi-continuous Emissions Monitor (S-CEM) and by the Draft Ontario Hydro method. During this period, operating data and coal and ash data are also collected.

Table 2. Test sites for dry sorbent injection.

Test Site	Coal	Particulate Control Device
PG&E NEG Salem Harbor	Low sulfur bituminous	Cold-Side ESP
PG&E NEG Brayton Point	Low sulfur bituminous	Cold-Side ESP
Wisconsin Electric Pleasant Prairie	Powder River Basin (PRB) sub-bituminous	Cold-Side ESP
Alabama Power E.C. Gaston	Low sulfur bituminous	Hot-Side ESP, plus COHPAC Fabric Filter

A series of parametric tests are then conducted to determine the optimum sorbent and operating conditions that would be required for several levels of mercury control. The maximum injection rate is set based on the preliminary injection performance data that have been developed from consideration of slip-stream testing, modeling exercises, the practical limitations of the particulate control device (PCD), and sorbent costs.

Based on results from these tests, a two-week test under optimized conditions (i.e., the long-term test) is conducted to assess the long-term impacts to the PCD, byproduct management practices and auxiliary equipment operation. During the long-term test, mercury removal efficiencies are measured by the S-CEMs and verified by Draft Ontario Hydro method measurements.

At each site, at least two sorbents are evaluated during the parametric tests. A standard powdered activated carbon is tested in all cases as a benchmark sorbent; this is FGD carbon, a lignite-derived sorbent supplied by Norit Americas.

Testing at two of the four sites was completed in 2001. The first test was conducted at Alabama Power's Gaston Unit 3 in the spring of 2001; the results have been documented elsewhere.[2] This site was chosen because of the particulate control configuration that exists at the plant. Specifically the PCD consists of a hot-side electrostatic precipitator (HESP) following by a Compact Hybrid Particulate Collector (COHPAC), a high air-to-cloth ratio baghouse used for polishing purposes. Gaston fires a variety of low-sulfur, washed bituminous coals.

COHPAC units, while not common, have several advantages that make them promising for future mercury control. These include:

- Sorbents are mixed with a small amount of ash, typically 1% of the total fly ash coming out of the boiler, which reduces sorbent impacts on ash residue and waste disposal.
- Pilot-plant studies and theory indicate that in general baghouses require one-tenth the sorbent to achieve mercury removal efficiencies that are comparable to ESPs.

- COHPAC requires much less physical space than either a large ESP or a full-size baghouse system, thus potentially representing a less costly retrofit technology.
- Outage time for COHPAC installation can be significantly reduced in comparison to major ESP upgrades or rebuilds.

Results from Gaston showed that during a ten-day period of continuous injection at a rate of 1.5 lb/MMacf, an average mercury removal efficiency of 78% was observed with short-term removal efficiencies approaching 90%. PAC-injection significantly increased the cleaning frequency of the COHPAC baghouse. New COHPAC units designed for PAC-injection will need to take this into account and consider lower air-to-cloth ratios.

The second test was conducted at Wisconsin Electric's Pleasant Prairie Power Plant, Unit 2 during fall of 2001.[3] This site was of key interest because it was the only plant included in the DOE/NETL program that burned western sub-bituminous coal. The PCD was an ESP, which represents the PCD of choice at over 90% of the nation's coal-fired utility boilers. Other features of this test site include:

- The ability to isolate one ESP treating one-quarter of the unit or about 150 MW.
- The challenge of implementing mercury control at a site where baseline mercury measurements in 1999 showed no significant mercury removal across the PCD and the mercury in the gas-phase is dominated by elemental mercury.
- A duct configuration with long, unobstructed runs that allows adequate space for the installation of water injection lances upstream of the sorbent injection lances so that the effects of spray cooling (to achieve lower flue gas temperatures) on mercury control could be evaluated.
- A high quality, Class C fly ash product that is sold for use in concrete.

The long-term tests at Pleasant Prairie were divided into three five-day periods of continuous injection at rates of 1 lb/MMacf, 3 lb/MMacf, and 10 lb/MMacf. The average mercury removal efficiencies for the three injection rates were 40-50%, 50-60%, and 60-70%, respectively. Increasing injection concentration above 10 lb/MMacf did not increase mercury removal. PAC-injection effectively removed both elemental and oxidized mercury from the gas phase. PAC did not have any significant impact on ESP performance. Some measures of fly ash quality were affected by the sorbent injection.

EXPERIMENTAL

Sample Description

During the sorbent injection testing at both Gaston and Pleasant Prairie, coal feeder samples were taken. Table 3 gives selected properties of the coals burned at Gaston and Pleasant Prairie.

Table 3. Fuel characteristics.

	Gaston	Pleasant Prairie
Rank	Bituminous	PRB
Sulfur, wt%	1.24	0.32
Ash, wt%	14.78	5.10
Moisture, wt%	6.85	30.69
HHV, Btu/lb	11,902	8,385
Hg, ìg/g	0.136	0.109
Cl, ìg/g	169.0	8.1

Ash samples were taken from the hoppers of the ESP at Pleasant Prairie; at Gaston, samples were taken from both the HESP hoppers and the COHPAC baghouse hoppers. The ash was analyzed for loss-on-ignition (LOI) and mercury content. Selected ash samples were subjected to leaching protocols, as described below.

At Gaston Station, a commercial sorbent (Norit Americas FGD Carbon) was used for the long-term test. This sorbent had a surface area of 600 m^2/g and a mass-mean diameter of 18 microns. The sorbent was injected into the duct upstream of a COHPAC baghouse that was treating one half of the gas flow representing 135 MW. The injection rate was 1.5 lb/MMacf. Figure 1 shows the speciation of mercury during the long-term sorbent injection tests, based on Ontario Hydro measurements taken during the long-term testing. Measurements were made at the inlet to the HESP and at the inlet and outlet to the COHPAC baghouse. At the inlet to the COHPAC baghouse, the mercury was a mixture of gaseous elemental and oxidized forms. The difference between the inlet and the outlet of the COHPAC baghouse illustrates the amount of mercury that was removed as a result of sorbent injection.

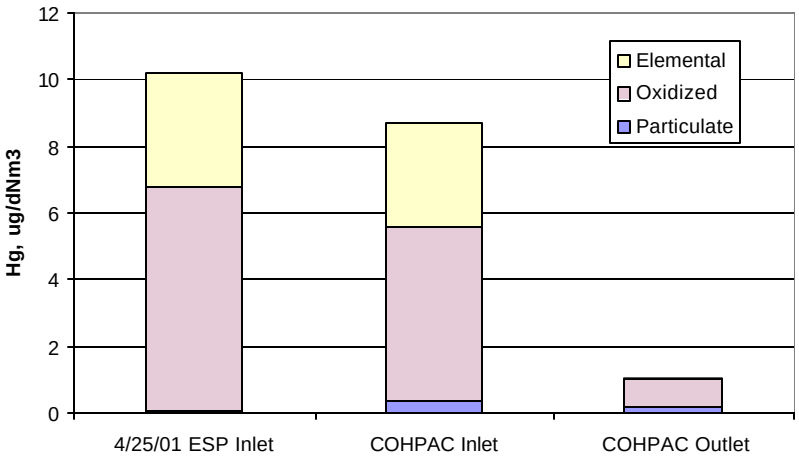

Figure 1. Mercury in flue gas at Gaston Station during long-term PAC testing at 1.5 lb/MMacf injection rate as measured by Ontario Hydro method.

Figure 2 shows the mercury and LOI contents of the ash samples from Gaston, both with and without sorbent injection. The A-side of the COHPAC baghouse had no sorbent injection and thus represents the baseline ash composition. This ash had 10-15% LOI and a mercury content similar to that of the HESP ash (0.2 to 2 ìg/g). The B-side, in contrast, had 20-35% LOI and 10-50 ìg/g Hg, or at least ten times more mercury than the baseline. Because most of the ash was removed in the HESP, over half the COHPAC ash from the long-term testing was spent sorbent. The mercury content of this ash was therefore higher than one would expect from injection of PAC upstream of a single baghouse or ESP. The high mercury levels in the COHPAC (B-side) ash make it interesting to assess for leaching potential.

At Pleasant Prairie, LOI of the ash was approximately 0.5%. A commercial sorbent (Norit Americas FGD Carbon) was used for the long-term test. This sorbent had a surface area of 600 m^2/g and a mass-mean diameter of 18 microns.

The sorbent was injected upstream of the ESP. The injection rates ranged from 1 to 10 lb/MMacf. However, leaching tests were performed only on the ash collected from the highest injection rate, 10 lb/MMacf.

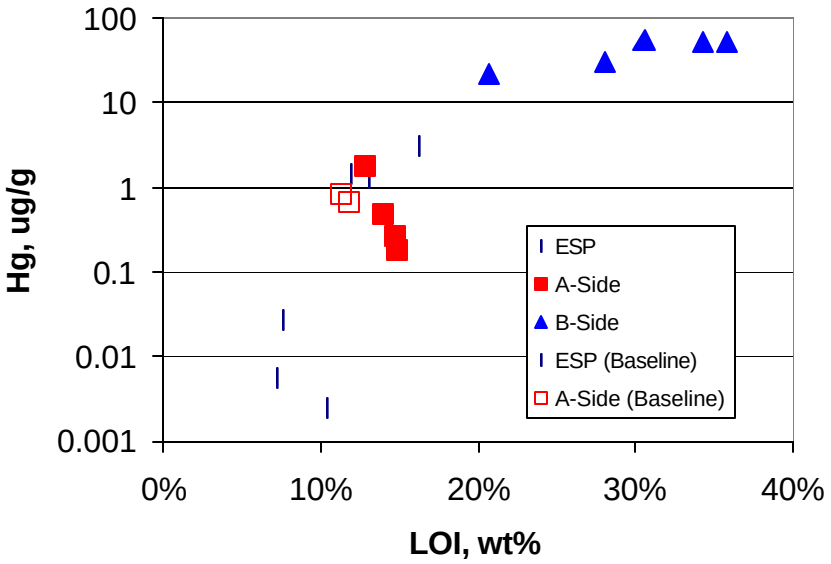

Figure 2. Mercury and LOI contents of ash from Gaston long-term PAC testing at 1.5 lb/MMacf injection rate.

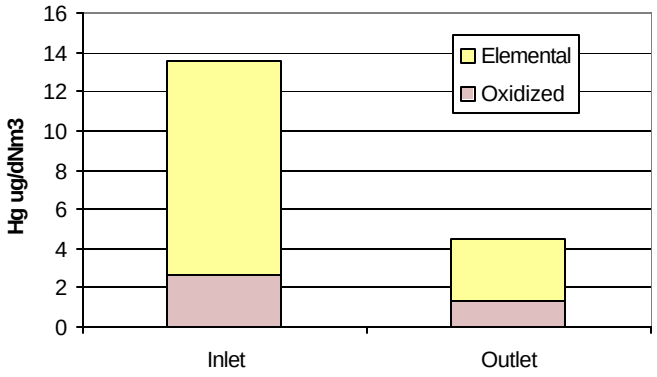

Figure 3. Mercury in flue gas (gas-phase only) at Pleasant Prairie during long-term PAC testing at 10 lb/MMacf injection rate as measured by S-CEM.

Figure 3 shows the gas-phase mercury measured at Pleasant Prairie using the S-CEM. This technique does not measure particulate-bound mercury, but baseline Ontario Hydro measurements showed that only 10-15% of the mercury was particulate-bound at the ESP inlet.

Figure 4 shows the mercury and LOI contents of the ash samples from Pleasant Prairie, both with and without sorbent injection. The baseline (no sorbent) ash had an LOI of 0.5% and <0.5 ìg/g of mercury. Addition of sorbent increased the LOI to a maximum of 2.5–3.5%. There was a linear increase in mercury content with LOI and little difference between ash from the front and back hoppers. Notice that the maximum mercury content for Pleasant Prairie ash (at 10 lb/MMacf injection rate) was ten times lower than the maximum mercury content for Gaston ash (at 1.5 lb/MMacf). This illustrates a fundamental difference between PAC-injection upstream of a baghouse as compared to an ESP. The mercury content of sorbent-ash mixtures from baghouses will be significantly higher than that from ESPs. Although, it should be noted that Gaston represents an extreme in ash mercury content because of the COHPAC baghouse.

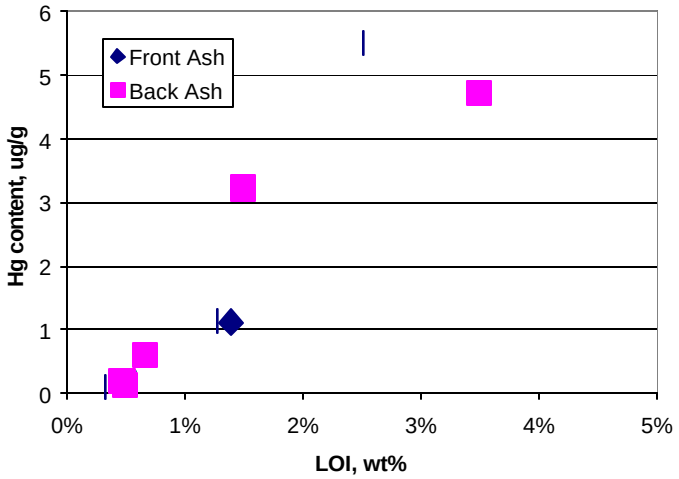

Figure 4. Mercury and LOI contents of ash from Pleasant Prairie long-term PAC testing at 0-10 lb/MMacf injection rate.

Leaching Protocol

Many standard leaching procedures exist. The procedure used most often is the toxicity characteristic leaching procedure (TCLP). The method was designed to simulate leaching in an unlined, sanitary landfill, based on a co-disposal scenario of 95% municipal waste and 5% industrial waste. The method is an agitated extraction test using leaching fluid that is a function of the alkalinity of the phase of the waste. Typically an acetic acid solution having a pH of 2.88 is used. Details of the procedure can be found in Reference 4.

The synthetic ground water leaching procedure (SGLP) was developed at the University of North Dakota Energy and Environmental Research Center (EERC) and was designed to simulate the leaching of CUBs under important environmental conditions. It was initially used to characterize highly alkaline CUBs, primarily fly ash produced from the combustion of low rank coals. The procedure was modeled after the TCLP, but allowing for disposal conditions other than those of a sanitary landfill. Deionized water is used as the leaching solution instead of the acidic solutions used in the TCLP. The SGLP was designed primarily for use with materials such as low-rank coal ash that undergo hydration reactions upon contact with water. Test conditions are end-over-end agitation, a 20:1 liquid to solid ratio and a thirteen-hour equilibration time. Details of the procedure can be found in Reference 5.

Long-term leaching is a subset of SGLP has been used previously to identify mineralogical changes that might occur in the wastes as a result of long-term contact with water. The samples were prepared as in the SGLP, but analysis of the leachate was made at 30 and 60 days.

RESULTS AND DISCUSSION

Leaching Results

Samples from both Gaston and Pleasant Prairie were leached at EERC using the standard TCLP procedure and also the synthetic groundwater leaching procedure (SGLP). Separate samples of Pleasant Prairie ash collected during the long-term PAC-injection were analyzed using the ASTM water leaching protocol. The Gaston samples were also subjected to sulfuric acid leaching (SAL) at a pH of 2, following procedures similar to TCLP and SGLP. This is an extreme condition that might simulate acid mine drainage. The Pleasant Prairie samples were leached for longer times (30 and 60 days) using SGLP. The concern here is the slow reactions that can take place in some high calcium ashes that are exposed to water. One duplicate measurement was made for the TCLP procedure and one for the SGLP procedure. Table 5 gives the leaching results from EERC. With one exception, all of the results (in terms of Hg in leachate) were below the detection limit of 0.01 mg/L.

Ash samples from Pleasant Prairie collected separately by Wisconsin Electric were analyzed by the utility using the ASTM water leaching procedure (ASTM D-3987). Mercury concentrations in the leachate are shown in Table 6. Measurements were made of other trace metals, but these are not shown. The baseline sample was taken after the conclusion of the long-term testing. Three samples were taken during the long term sorbent injection tests at the three different sorbent injection rates. These samples were composites of three different pails; the LOI and

mercury content were not measured on the composites, so these have been estimated from a simple average.

Table 5. Leaching results (EERC).

Plant	Sample Type	Location	Inj.Rate lb/MMacf	Hg in Leachate (mg/L or ppbw) TCLP	SGLP	SGLP-30	SGLP-60	SAL
Gaston	COHPAC Ash	B-Side	1.5	0.01	<0.01			<0.01
Gaston	COHPAC Ash	B-Side	1.5		<0.01			
Gaston	COHPAC Ash	B-Side	1.5	<0.01	<0.01			<0.01
Prairie	Front Ash	Composite	10	<0.01	<0.01	<0.01	0.01	
Prairie	Back Ash	Composite	10	<0.01	<0.01	<0.01	0.01	
Prairie	Back Ash	Composite	10	<0.01				

Table 6. Leaching results, Pleasant Prairie ash only (Wisconsin Electric).

Sample Type	Location	Hg, ì g/g (AR) (est.)	LOI, wt% (est.)	Inj.Rate lb/MMacf	Hg in Leachate (ppbw)
Front Ash				0	<0.028
Front Ash	Composite	0.7	1.1	1	<0.028
Front Ash	Composite	0.7	1.1	1	0.033
Front Ash	Composite	0.9	1.6	3	<0.028
Front Ash	Composite	0.9	3.6	10	<0.028

With one exception, all of the results (in terms of Hg in leachate) were below the detection limit of 0.028 ppbw. The results for water leaching are consistent with the SGLP leaching carried out by EERC on the Pleasant Prairie samples. All tests show the amount of mercury leached from the sorbent/ash mixtures is low and generally below the detection limit of the method.

Other Ash Impacts

Leaching is not the only measure of the impact of PAC on fly ash. When fly ash is sold as a product, it is important to determine whether the fly ash is still saleable after the addition of PAC. In the case of Pleasant Prairie, the ash is sold as a "Class C" fly ash, which is added to cement during manufacture of concrete. To this end, Wisconsin Electric conducted several tests that fall under the protocol for the ASTM C-618. Table 7 shows the results of those tests, along with the limits of what can be considered Class C fly ash.

Fly ash from the long-term tests conformed to the ASTM C-618 tests. However, ash samples with carbon of any concentration failed another important test called the Foam Index Test. This is a rapid field test used to determine the amount of surfactant (air entrainment agent) needed to meet the freeze/thaw requirements for using concrete at temperatures below freezing in the winter. Results from the Foam Index Test (Table 8) were the most important because failing this test prohibited the plant from selling this ash. In fact, the ash failed the Foam Index test for five weeks after the PAC-injection was halted.

Table 7. Results of ASTM C-618 tests performed on Pleasant Prairie Fly Ash.

Sample Type	Inj.Rate lb/MMacf	LOI, wt%	7-day strength activity index	Water required %of control	Autoclave, % exp.
Front Ash	0	0.58%	91.3	94.2	-0.06
Front Ash	1	1.04%	84.3	95	0.01
Front Ash	3	1.58%	86.8	94.6	0.01
Front Ash	10	3.57%	84.1	96.2	-0.02
Class C limit		*<6%*	*>75*	*<105*	*<0.8*

Table 8. Results of Foam Index Test on Pleasant Prairie ESP ash.

Salable Contract Limit is 25 Drops

Injection Concentration (lbs/Mmacf)	Unburned Carbon in Ash (%)	Foam Index (Drops)	Comment
0	**0.55**	**15**	**Normal**
1	**1.1**	**>72**	**Maxed out**
3	**1.6**	**>72**	**Maxed out**
10	**3.6**	**>72**	**Maxed out**

CONCLUSIONS

Samples from the two plants were very different from one another. The Gaston sample (the product of a bituminous coal) had a high LOI and mercury content, in spite of the low sorbent injection rate, because most of the ash was removed upstream of the COHPAC baghouse by a hot-side ESP. Thus the sample had a relatively high proportion of sorbent. The Pleasant Prairie sample (the product of a sub-bituminous coal) had a low LOI and mercury content. Sorbent was injected upstream of an ESP and was combined with the full ash stream. The LOI and mercury content were much lower than the Gaston sample.

Little or no detectable Hg leached by ASTM water leach, TCLP, SGLP (including 30- and 60-day leaching), sulfuric acid leach (bituminous ash). The Pleasant Prairie (PRB) ash conformed

to the ASTM C-618 standard for Class C fly ash, but did not pass the Foam Index test that is also required for sale of this ash for use in concrete formulation.

ACKNOWLEDGMENTS

David Hassett at EERC carried out the SGLP, TCLP and sulfuric acid leaching analyses. Thanks to Bruce Ramme at Wisconsin Electric for providing the foam index, water leaching and ASTM C-618 analysis results.

REFERENCES

1. Kilgroe, J.D., Sedman, C.B., Srivastava, R.K., Ryan, J.V., Lee, C.W., Thorneloe, S.A., 2001, "Control of Mercury Emissions from Coal-Fired Electric Utility Boilers: Interim Report", U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Laboratory, Air Pollution Prevention and Control Division, EPA-600.R-01-109, December 2001.

2. Bustard, C.J., Durham, M., Lindsey, C., Starns, T., Bladrey, K., Martin, C., Sjostrom, S., Slye, R., Renninger, S., Monroe, L., 2001, "Full-Scale Evaluation of Mercury Control with Sorbent Injection and COHPAC at Alabama Power E.C. Gaston," presented at the EPRI-EPA-DOE-AWMA Mega Symposium and Mercury Conference, Chicago, IL, August 21-23, 2001.

3. Starns, T., Bustard, J., Durham, M., Lindsey, C., Martin, C., Schlager, R., Donnelly, B., Sjostrom, S., Harrington, P., Haythornthwaite, S., Johnson, R., Morris, E., Change, R., Renninger, S., 2002, "Full-Scale Test of Mercury Control with Sorbent Injection and an ESP at Wisconsin Electric's Pleasant Prairie Power Plant," presented at the Air & Waste Management Association 95th Annual Conference and Exhibition, Baltimore, MD, June 23-27, 2002.

4. U.S. EPA, 1990, "Toxicity Characteristic Leaching Procedure," Federal Register, Vol.55, No., 61, March 1990, pp. 11798-11877.

5. Hassett, D.J., 1987, "A Generic Test of Leachability: The Synthetic Groundwater Leaching Method," North Dakota Mining and Mineral Resources Research Institute, Grand Forks, North Dakota.

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Full-Scale Evaluation of Mercury Control with Sorbent Injection and COHPAC at Alabama Power E.C. Gaston

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ABSTRACT

The overall objective of this project was to determine the cost and impacts of Hg control using sorbent injection into a Compact Hybrid Particulate Collector (COHPAC) at Alabama Power's Gaston Unit 3. This test is part of a program funded by the U.S. Department of Energy's National Energy Technology Laboratory (NETL) to obtain the necessary information to assess the costs of controlling Hg from coal-fired utility plants that do not have scrubbers for SO_2 control. The economics will be developed based on various levels of Hg control.

Gaston Unit 3 was chosen for testing because COHPAC represents a cost-effective retrofit option for utilities with existing electrostatic precipitators (ESPs). COHPAC is an EPRI-patented concept that places a high air-to-cloth ratio baghouse downstream of an existing ESP to improve overall particulate collection efficiency. Activated carbons were injected upstream of COHPAC and downstream of the ESP to obtain performance and operational data.

Results were very encouraging, with up to 90% removal of Hg for short operating periods using powdered activated carbon (PAC). During the long-term tests, an average Hg removal efficiency of 78% was measured. The PAC injection rate for the long-term tests was chosen to maintain COHPAC cleaning frequency at less than 1.5 pulses/bag/hr.

IMPLICATIONS

Sorbent injection technology represents one of the simplest and most mature approaches to control Hg emissions from coal-fired boilers. However, no application experience was available from actual full-scale installations in the U.S. power industry. A field test program representing the initial step toward defining technology to be used by power-generating companies in meeting new Hg regulations is being conducted for the NETL. The first full-scale test was completed in the spring of 2002 on a unit that burns a low-sulfur bituminous coal and uses a COHPAC baghouse to collect the carbon and fly ash.

INTRODUCTION

In December 2000, the U.S. Environmental Protection Agency (EPA) announced their intent to regulate Hg emissions from the nation's coal-fired power plants. Draft legislation indicates that new regulations may require removal efficiencies as high as 90% from existing sources. In anticipation of these regulations, a great deal of research has been conducted during the past decade to characterize the emission and control of Hg compounds from the combustion of coal. The U.S. Department of Energy,

EPA, and EPRI funded much of this research. The results are summarized in the comprehensive 1999 Air & Waste Management Association Critical Review article.[1] As a result of these efforts, the following was determined: (1) trace concentrations of Hg in flue gas can be measured relatively accurately, (2) Hg is emitted in a variety of forms, (3) Hg species vary with fuel source and combustion conditions, and (4) control of Hg from utility boilers will be both difficult and expensive.

This latter point is one of the most important and dramatic findings from the research conducted to date. Because of the large volumes of gas to be treated, the low concentrations of Hg, and the presence of difficult-to-capture species such as elemental Hg, some estimates show that 90% Hg reduction for utilities could cost the industry as much as $5 billion per year.[1] Most of these costs will be borne by power plants that burn low-sulfur coal and do not have wet scrubbers as part of their air pollution equipment.

With regulations rapidly approaching, it is important to concentrate efforts on the most mature retrofit control technologies. Injection of dry sorbents such as powdered activated carbon (PAC) into the flue gas and further collection of the sorbent by electrostatic precipitators (ESPs) and fabric filters commonly is used in municipal waste incinerators for Hg control and represents the most mature and potentially most cost-effective control technology for power plants.

Under a U.S. Department of Energy National Energy Technology Laboratory (NETL) cooperative agreement, ADA-ES is working in partnership with PG&E National Energy Group (NEG); Wisconsin Electric, a subsidiary of Wisconsin Energy Corp.; Alabama Power Co., a subsidiary of Southern Company; and EPRI on a field evaluation program of sorbent injection upstream of existing particulate control devices for Hg control.[2] The test program, which will take place at four different sites during 2001 and 2002, is described in detail in the July 2001 *EM*.[3] Other organizations participating in this program as industry cost-share participants include Ontario Power Generation, First Energy, TVA, Kennecott Energy, Hamon Research-Cottrell, EnviroCare, and Norit Americas.

Gaston Unit 3 was chosen as the first test site, because Compact Hybrid Particulate Collector (COHPAC) represents a cost-effective retrofit option for utilities with ESPs. The COHPAC is an EPRI-patented concept that places a high air-to-cloth ratio baghouse downstream of an existing ESP to improve overall particulate collection efficiency. The advantages of this configuration are

(1) sorbents are mixed with a small fraction of the ash (nominally 1%), which reduces the impact on ash reuse and waste disposal;
(2) pilot plant studies and theory[4] indicate that compared with ESPs, baghouses require one-tenth the sorbent to achieve similar removal efficiencies;
(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 reduced significantly with COHPAC systems in comparison with major ESP rebuilds/upgrades.

E.C. GASTON SITE DESCRIPTION

The E.C. Gaston Electric Generating Plant, located in Wilsonville, AL, has four 270-MW balanced-draft and one 880-MW forced-draft coal-fired boilers. All units fire a variety of low-sulfur, washed, eastern bituminous coals. The primary particulate control equipment on all units is a hot-side ESP. Units 1 and 2 and Units 3 and 4 share common stacks. In 1996, Alabama Power contracted with Hamon Research-Cottrell to install COHPAC downstream of the hot-side ESP on Unit 3. This COHPAC system was designed to maintain the stack opacity levels of Units 3 and 4 at less than 5% on a 6-min average.[5]

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 COHPAC baghouse consists of four isolatable compartments—two compartments per air-preheater identified as either A- or B-side. Each compartment consists of two bag bundles, each having a total of 544 23-ft-long polyphenylene sulfide (PPS) felt filter bags, 18-oz/yd^2 nominal weight. This results in a total of 1088 bags per compartment, or 2176 bags per casing.[5] The evaluation was conducted on half of the gas stream, nominally 135 MW. The side chosen for testing was B-side. A-side was monitored as the control unit.

The hot-side ESP is a Research-Cottrell weighted wire design. The specific collection area (SCA) is 274 ft^2/1000 acfm. Depending on the operating condition of the hot-side ESP, nominally 97–99+% of the fly ash is collected in the ESP. The remaining fly ash is collected in the COHPAC system. The average inlet particulate mass concentration into COHPAC between January 1997 and April 1999 was 0.0413 gr/acf.[5] Hopper ash from both the ESP and the baghouse are sent to a wet ash pond for disposal. A hydrovactor system delivers the fly ash to the pond.

Figure 1 shows a diagram of the location of the various components of the air pollution control train. Design parameters obtained from Alabama Power for Gaston Unit 3 are presented in Table 1. For the Hg control program, carbon-based dry sorbents were injected upstream of COHPAC and downstream of the ESP over an 8-week period.

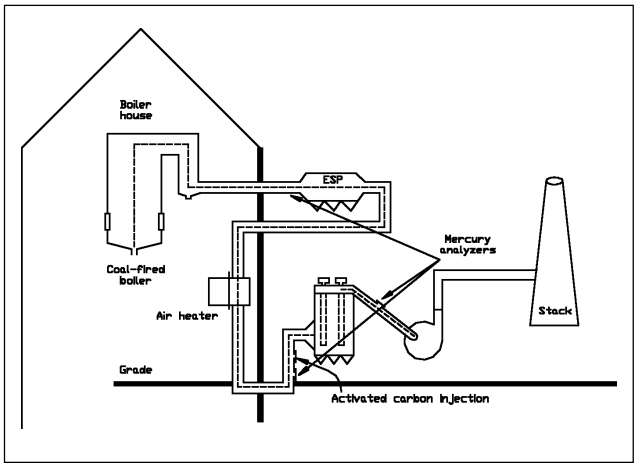

Figure 1. Flow schematic of Gaston Unit 3, showing injection and measurement locations.

TEST EQUIPMENT

The critical elements of the program were the actual field tests and measurements, which relied on accurate, rapid measurements of Hg concentration and an injection system that realistically represented commercially available technology. Near-real-time vapor-phase Hg measurements were made using a semi-continuous emissions monitor (S-CEM) designed and operated by Apogee Scientific. This instrument was developed with EPRI funding to facilitate EPRI research and development efforts.[6] The locations of the analyzers are shown in Figure 1. The S-CEMs operated continuously for more than 7 weeks providing speciated, vapor-phase Hg concentrations at the inlet and outlet of COHPAC. Norit Americas supplied a portable dilute-phase pneumatic injection system that is typical of those used at municipal solid waste facilities for Hg control with activated carbon. ADA-ES designed the distribution and injection components of the system.

Sorbent requirements for various levels of Hg control were predicted based on empirical models developed through EPRI funding.[4] The values used were based on a uniform sorbent size of 15 μm (size of commercially available PAC) and a bag cleaning frequency of 2 pulses/bag/hr (it was also assumed all bags were cleaned at the same time when, in practice, the bags are cleaned in sections or rows). Rates used to design equipment for the Gaston test are presented in Table 2. The system was sized for a maximum injection rate of 100 lb/hr.

Figure 2 shows the portable injection skid supplied by Norit Americas and installed for use at Plant Gaston Unit 3B. Activated carbon delivered to the plant in 900-lb supersacks was loaded onto the skid by a hoist. The sorbent was metered by a variable speed screw feeder into the conveying line. A blower/eductor provided the motive air to carry the sorbent ~100 ft to the injection point.

Sorbent was pneumatically transported via flexible hose from the feeder to a distribution manifold at the injection level and injected into the flue gas through six injection probes (three/duct). Figure 3 shows the distribution manifold. The injection system operated without plugging while injecting carbon-based products with D50 particle size of 18 μm. The distribution system plugged once while feeding a finer material with a D50 of 6–7 μm.

Table 1. Site description summary, Gaston Unit 3.

Parameter Identification	Description
Boiler manufacturer	B&W wall-fired
Burner-type	B&W XCL
Low NO_x burners	Yes
NO_x control (post-combustion)	None
Temperature (APH outlet)	290 °F
Coal (Typical—This Unit Fires a Variety of Coals)	
Type	Eastern bituminous
Heating value (Btu/lb)	13,744
Moisture (%)	6.9
Sulfur (%)	0.9
Ash (%)	13.1
Hg (μg/g)	0.06
Cl (%)	0.03
Control Device	
Type	Hot-side ESP with COHPAC
ESP manufacturer	Hamon Research-Cottrell
Design	Weighted wire
Specific collection area (ft^2/1000 afcm)	274
Flue gas conditioning	None
Baghouse manufacturer	Hamon Research-Cottrell
Design	Pulse-jet, low-pressure–high-volume
Air-to-cloth ratio (acfm/ft^2)	8.5:1 (gross), on-line cleaning

TEST RESULTS

Pre-Baseline Tests

The first field measurements were made prior to installing the injection equipment. The objectives for the pre-baseline

Table 2. Predicted injection rates for FGD carbon on B-side of COHPAC.[3]

Target Hg Removal Efficiency (%)	Predicted Injection Concentration (lb/Mmacf)	Predicted Injection Rate[a] (lb/hr)
50	0.5	<30
75	1.5	45
90	3.0	90

[a]Injection rate based on nominal flow at full load of 500,000 acfm.

Figure 2. Carbon injection skid installed at Plant Gaston.

tests were to (1) document Hg emissions across COHPAC, and (2) perform screening tests for Hg adsorption characteristics of several activated carbons that were candidate sorbents for the full-scale tests. Table 3 presents vapor-phase

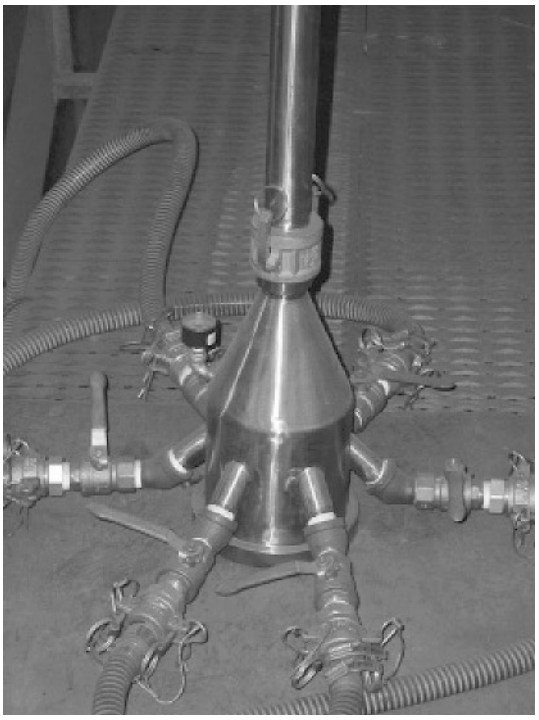

Figure 3. Distribution manifold for injection lances at Plant Gaston.

Table 3. Pre-baseline Hg measurement results (S-CEM).

Location	Total Hg μg/dncm @ 3% O_2 [a]	Oxidized Hg %
ESP inlet	7–10	5–33
ESP outlet/COHPAC inlet	7–10	29–51
COHPAC outlet	7–10	52–76
Mercury removal across ESP	0%	
Mercury removal across COHPAC	0%	

[a]Normal: T = 32 °F

Hg measurements during the pre-baseline tests in January on Unit 3. Two analyzers were used for these tests. The analyzers were set up to measure simultaneously across either the hot-side ESP or COHPAC. Because the hot-side ESP outlet and the COHPAC inlet are the same sampling ports, this analyzer was not moved. Flue gas temperatures were nominally 650 °F at the inlet to the hot-side ESP and between 240 and 270 °F at the COHPAC inlet and outlet.

The results show that vapor-phase Hg varied between 7 and 10 μg/dncm at all three locations. These variations appeared to be caused by changes in coal, because there was no measurable removal of vapor-phase Hg across either the hot-side ESP or COHPAC. These results are comparable to those made during the EPA information collection request (ICR) measurements in 1999 on Unit 1 for total Hg concentrations and removal efficiencies. The ICR measurements showed total Hg concentrations between 6.0 and 7.5 μg/dncm and no Hg removal across the hot-side ESP.[7]

No Hg removal was measured across COHPAC without the addition of sorbents. A review of data collected through the ICR at other plants shows that there was significant natural Hg capture on units with conventional-type baghouses when firing bituminous coals.[7] This natural collection is assumed to occur because of exposure of the flue gas to ash on the bag dustcake. Ash samples from both the hot-side ESP and COHPAC were tested for loss-on-ignition carbon and Hg adsorption capacity by URS Corp. Analysis of the ash showed high carbon content throughout the total size distribution and an adsorption capacity that indicates the ash should be capable of collecting Hg. However, because COHPAC is downstream of the hot-side ESP and the ESP was in excellent condition at the time of the tests, the inlet loading to COHPAC was very low (0.04 g/acf on average and less than 0.01 g/acf during the tests), so there was a relatively small amount of ash present on the bags to react with the Hg.

The portion of vapor-phase Hg in the oxidized state increased in the direction of flow. There was a greater percentage of elemental Hg at the hot-side inlet (economizer outlet) than there was at either the COHPAC inlet

or outlet. The most significant oxidation occurred across the COHPAC baghouse. Similar phenomena have been documented across baghouses with fiberglass and PPS fabric bags.[8]

Baseline Tests

After equipment installation and checkout, a set of baseline tests was conducted immediately prior to the first parametric test series to document current operating conditions. During this test, boiler load was held steady at "full-load" conditions during testing hours, nominally 7:00 a.m.–7:00 p.m. The Hg across the B-side of the COHPAC was measured using two separate methods: S-CEMs and modified Ontario Hydro method.

In addition to monitoring Hg removal, it was also important to document the performance of COHPAC during sorbent injection. The primary COHPAC performance indicator at this site was cleaning frequency. Pressure drop/drag is controlled by the cleaning frequency. It was expected that cleaning frequency would increase with the increased particulate loading from sorbent injection. Cleaning frequency was monitored before, during, and after sorbent injection.

Results from the Ontario Hydro tests conducted by Southern Research Institute are presented in Table 4. Similar to pre-baseline measurements, there was no measurable Hg removal across COHPAC. The average of the inlet and outlet total Hg measurements was ~15 μg/dncm. Coal analyses showed Hg levels in the three coal samples varied between 0.06 and 0.17 μg/g. Because Gaston burns coals from several different coal sources each day, it is difficult to correlate Hg level in the coal to a specific flue gas measurement; however, the higher coal Hg values correlate well with Hg measured in the flue gas. For example, a coal Hg level of 0.17 μg/g is equivalent to an Hg 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 Hg was 61%, and it increased to 77% at the outlet. Flue gas temperatures during these tests were nominally 255 °F.

Table 4. Baseline Ontario Hydro measurements at COHPAC inlet and outlet.

Date/Location	Particulate (μg/dncm[a])	Oxidized (μg/dncm[a])	Elemental (μg/dncm[a])	Total (μg/dncm[a])	Percent Oxidized
3/6/2001 inlet	0.0	11.6	6.6	18.2	63
3/6/2001 inlet	0.0	8.0	7.0	15.0	53
3/7/2001 inlet	0.2	9.0	4.3	13.5	67
Average inlet	0.1	9.5	5.9	15.6	61
3/6/2001 outlet	0.0	10.2	4.6	14.8	69
3/6/2001 outlet	0.0	12.5	3.0	15.5	81
3/7/2001 outlet	0.0	10.9	2.4	13.3	82
Average outlet	0.0	11.2	3.3	14.5	77

[a]Normal: T = 32 °F

Parametric Tests

A series of parametric tests was conducted to determine the optimum operating conditions for several levels of Hg control up to 90% Hg removal, for several activated carbon products. The NETL scope of work required that only commercially available sorbents should be considered in these technology demonstration tests. Norit Americas lignite-based PAC, Darco FGD, was chosen as the benchmark sorbent. Sorbent type and injection concentration for the long-term tests were chosen based on results from these tests.

In all, 15 different parametric conditions were tested. The primary variables were carbon type and target Hg removal level. Other variables included COHPAC cleaning settings and flow through the baghouse. Although lower flue gas temperatures have been correlated with increased Hg removal, temperature was not a key variable during these tests, because normal operating temperatures at this plant were between 250 and 270 °F, which is cool enough for acceptable removal. Results from laboratory and pilot plant tests suggest Hg capture is more difficult at temperatures greater than 300 °F. A summary of the parametric tests is presented in Table 5. Unless noted, all tests were conducted with the boiler at full load conditions and COHPAC cleaning at a drag initiate set point of 0.6 in. w.c./ft/min. A description of the different carbons used in these tests is presented in Table 6.

Parametric tests measured Hg 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 4. These data are from the first week of parametric tests 1–4, with Darco FGD. Reduction and recovery of outlet Hg concentration can be seen to correlate with relative injection rates.

Figure 5 presents Hg removal efficiencies as activated carbon injection concentrations were varied during the parametric tests for several activated carbons (see Tables 5 and 6 for description of test conditions). This figure shows that Hg removal increased nearly linearly with injection rate up to 2 lb/Mmacf, and then leveled off at ~90% removal with higher injection providing no additional benefit. This figure also shows that there was no measurable performance difference between the different PACs.

Table 5. Summary of parametric test conditions.

Test Series	Carbon Name Efficiency (%)	Target Hg Removal	Non-Standard Conditions
1–5	Darco FGD	50, 75, and 90	Standard
6–9	Norit PAC2B	50, 75, and 90	Standard
10	None	Baseline	Standard
11	Darco Insul	90	Standard
12	HydroDarco-C	90	Standard
13 a–c	Darco FGD	75	Change to pressure drop initiate clean
14	Darco FGD	50	Lower A/C to 4 ft/min
15	Darco FGD	50	Compare to test 14 with A/C = 7 ft/min

Carbon injection significantly increased the cleaning frequency of the COHPAC baghouse. Figure 6 presents actual cleaning frequencies at different carbon injection concentrations. At an injection concentration of 2.0 lb/Mmacf, the cleaning frequency increased from 0.5 to 2 pulses/bag/hr, or a factor of 4. Acceptable cleaning frequencies at this site to maintain long-term bag life are considered to be less than 1.5 pulses/bag/hr.

Long-Term Tests

Long-term testing at "optimum" plant-operating conditions as determined from the parametric tests was planned to gather data on Hg removal efficiency over time, the effects on COHPAC and balance of plant equipment of sorbent injection, and operation of the injection equipment to determine the viability and economics of the process. During these tests, carbon was injected continuously 24 hr/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 Hg removal and the projected increase in COHPAC cleaning frequency. An injection concentration of 1.5 lb/Mmacf was chosen to maintain COHPAC cleaning frequency at less than 1.5 pulses/bag/hr.

Table 6. Description of Norit carbons used in parametric tests.

Name	Description	Particle Size Distribution[a]		
		D95	D50	D5
Darco FGD	Lignite AC	52	15–20	<3
Norit PAC2B	Subbit/Bit blend AC	52	15–20	<3
Darco Insul	Fine chemically washed specialty product	25	6–7	<2
HydroDarco-C	Coarser FGD	100	30	3

[a]Percent of particles less than size in μm.

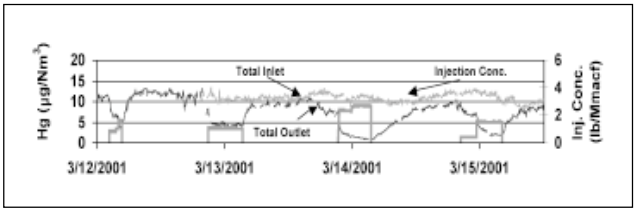

Figure 4. S-CEM Hg measurements during the first week of parametric tests with Norit Darco FGD PAC.

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

The long-term tests started on April 18, and carbon was injected continuously until April 26. Full-load boiler conditions were held between the times of 7:00 a.m. and 8:00 p.m., with load under dispatch control at other times for the first 5 days. During the three days when the Ontario Hydro tests were conducted, full load was maintained 24 hr/day. At the beginning of this test series, time was needed to work out a COHPAC cleaning logic issue, and there was a short period when load was lowered to fix a mill problem. The final 7 days of the test were conducted at the optimized PAC feed rate and COHPAC cleaning logic.

Three sets of Ontario Hydro measurements were made at three locations: (1) inlet of the hot-side ESP, (2) COHPAC inlet, and (3) COHPAC outlet. Arcadis G&M Inc. conducted the hot-side measurements using an experimental in-duct, quartz thimble to minimize sampling artifacts often seen with this method. Artifacts have been known to occur when the particulate collected on the filter captures vapor-phase Hg, resulting in higher particulate-phase Hg than is actually present. Sampling artifacts from particulate on the filter were not as much of a concern at the other two locations, because either the hot-side ESP or COHPAC already had removed most of the particulate.

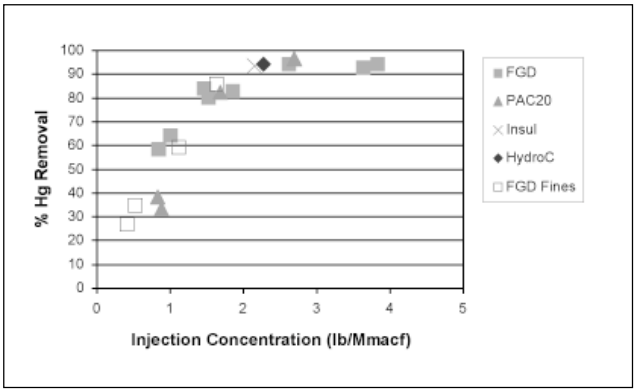

Figure 5. The Hg removal trends across COHPAC as a function of PAC injection concentrations. Measurements made during parametric tests, March 2001.

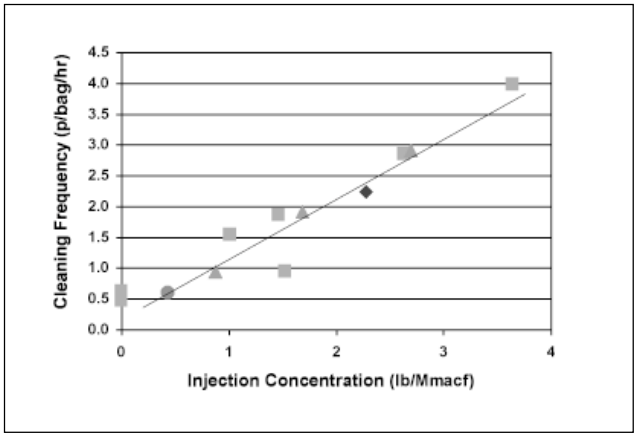

Figure 6. COHPAC cleaning frequency in pulses/bag/hr as a function of PAC injection concentration. Measurements made during parametric tests, March 2001.

Table 7 presents the results from each of the Ontario Hydro measurements. These data show that the inlet to the hot-side ESP and the inlet to COHPAC have similar average Hg concentrations and speciation. The outlet Hg concentrations show the effect of carbon injection with overall low Hg emissions for all species. Table 8 presents average speciated Hg removal across COHPAC. The overall average reduction in total Hg is 90%. At the outlet, the predominant species of Hg is the oxidized form; however, it is still 85% less than what was present upstream of PAC injection.

Figure 7 presents inlet and outlet Hg concentrations as measured by the S-CEMs, boiler load, and PAC injection concentration during the last 5 days of the long-term test. Periods when Ontario Hydro measurements were made are also identified. The S-CEMs indicate that Hg removal was nominally 87, 90, and 88% during the Ontario Hydro tests. This correlates well with the manual measurements. However, it is important to note that the S-CEMs showed that the average Hg removal efficiency over the multi-day time period was 78%, with variations from 36 to more than 90%. This difference is probably caused by varying coal and operating conditions over time. Figure 7 also shows that, during this 5-day period, inlet Hg concentration varied by nearly a factor of 5. Outlet concentrations can be seen to follow the inlet, and there are times during these transitional periods when removal efficiencies are fairly low. During the period when the Ontario Hydro tests were run, inlet Hg levels were low and fairly steady. These tests were conducted under ideal conditions and may show the best-case condition for Hg control at this injection rate.

During the test program, sorbent was injected at a constant rate, with no attempt to increase sorbent when the inlet Hg concentration increased. However, the data in Figure 7 highlight the importance of having CEMs to use as process control for a permanent Hg control system. The most challenging time for COHPAC performance was during the period with continuous full-load operation and PAC injection. The cumulative cleaning frequency increased to a high of 1.3 pulses/bag/hr, but was mostly maintained at levels less than 1.0 pulse/bag/hr.

Table 7. Long-term Ontario Hydro measurements at hot-side ESP inlet, COHPAC inlet, and COHPAC outlet.

Date/Location	Particulate (μg/dncm[a])	Oxidized (μg/dncm[a])	Elemental (μg/dncm[a])	Total (μg/dncm[a])	Percent Oxidized
4/24/2001 ESP inlet[b]	0.5	2.9	5.6	9.0	32
4/25/2001 ESP inlet[b]	0.0	7.3	3.7	11.0	66
4/26/2001 ESP inlet[b]	0.1	6.2	3.0	9.3	66
Average ESP Inlet	**0.2**	**5.5**	**4.1**	**9.8**	**55**
4/24/2001 COHPAC inlet	0.1	4.9	5.2	10.3	48
4/25/2001 COHPAC inlet	0.4	5.6	3.4	9.4	60
4/26/2001 COHPAC inlet	0.2	8.5	5.2	13.9	62
Average COHPAC Inlet	**0.2**	**6.3**	**4.6**	**11.2**	**56**
4/24/2001 COHPAC outlet	0.1	0.9	0.1	1.0	91
4/25/2001 COHPAC outlet	0.2	0.9	0.1	1.1	78
4/26/2001 COHPAC outlet	0.1	0.9	–0.0	1.0	93
Average COHPAC Outlet	**0.1**	**0.9**	**0.1**	**1.0**	**87**

[a]Normal: T = 32 °F; [b]Tests conducted by Arcadis using an in-stack (heated) quartz thimble.

Coal and Ash Characterization

Coal and ash samples were collected daily during the baseline, parametric, and long-term tests. Gaston fires a variety of washed, low-sulfur eastern bituminous coals. Because several different coals can be fired in a day, the daily coal samples provide relative Hg concentrations but may not be representative of specific test periods. Standard ultimate and proximate analyses were conducted, as were measurements for Hg, Cl, and S.

Ash samples were collected from the hot-side ESP, control-side (A-side) COHPAC, and test-side (B-side) COHPAC hoppers. Ash generated from the E.C. Gaston Plant is impounded using a wet ash handling system. The ash is not currently beneficially reused; therefore, ash characterization testing concentrated on measuring Hg and carbon content. Archived ash samples will be submitted for leaching tests at a later date.

The Hg content of coal samples taken during the long-term tests varied between 0.09 and 0.21 mg/g. This is consistent with flue gas Hg measurements that showed considerable variability in Hg concentration. This variability has implications on how Hg

Table 8. Average Hg removal efficiencies across COHPAC as measured with Ontario Hydro method.

Sampling Location	Particulate (μg/dncm[a])	Oxidized (μg/dncm[a])	Elemental (μg/dncm[a])	Total (μg/dncm[a])
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

[a]Normal: T = 32 °F

control technologies will be implemented. The B-side ash, mixed with sorbent, showed ~30% carbon content as compared with 12% in the A-side ash. The sorbent-ash mixtures from the B-side had ~30 times the Hg of the A-side hopper ash, indicating removal of Hg by the sorbent across COHPAC.

PAC ANNUAL COSTS

The requirements and costs for full-scale, permanent, commercial implementation of the necessary equipment for Hg control using PAC injection technology are being finalized for Gaston Unit 3. Preliminary capital and sorbent costs for 80% Hg removal have been developed. The estimated uninstalled cost for a sorbent injection system and storage silo for the 270-MW Unit 3 is $575,000 ± 30%. Sorbent costs were estimated for nominally 80% Hg control based on the long-term PAC injection concentration of 1.5 lb/Mmacf. For Gaston Unit 3, this would require an injection rate of nominally 80 lb/hr. Assuming a unit capacity factor of 80% and a delivered cost of $0.50/lb for PAC, the annual sorbent cost for injecting PAC into the existing COHPAC baghouse would be about $300,000. Additional cost information is being developed for balance of plant impacts.

CONCLUSIONS

A full-scale evaluation of Hg control using activated carbon injection upstream of a COHPAC baghouse was conducted at Alabama Power Co.'s Plant Gaston Unit 3. Results and trends from these relatively short-term tests were encouraging.

- Effective Hg removal, up to 90% efficiency, was obtained for short operating periods (8 hr) by injecting PAC upstream of COHPAC.
- A significant increase in the cleaning frequency of the COHPAC baghouse occurred with the injection of activated carbons. At this site, the maximum acceptable cleaning frequency and pressure drop limited the amount of sorbent that could be injected and, therefore, the maximum Hg 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.
- On average, ~78% Hg removal was obtained when PAC was injected into COHPAC 24 hr/day during long-term tests. The Hg removal varied throughout the period and ranged from 36 to 90%.
- To verify S-CEM measurements during the long-term tests, Hg removal across COHPAC was measured following the draft Ontario Hydro method. Results show an average 90% removal for the three test periods. These results confirm the high Hg removal measured with the S-CEMs.
- Actual Hg removals were in reasonably close agreement with theoretical model predictions for

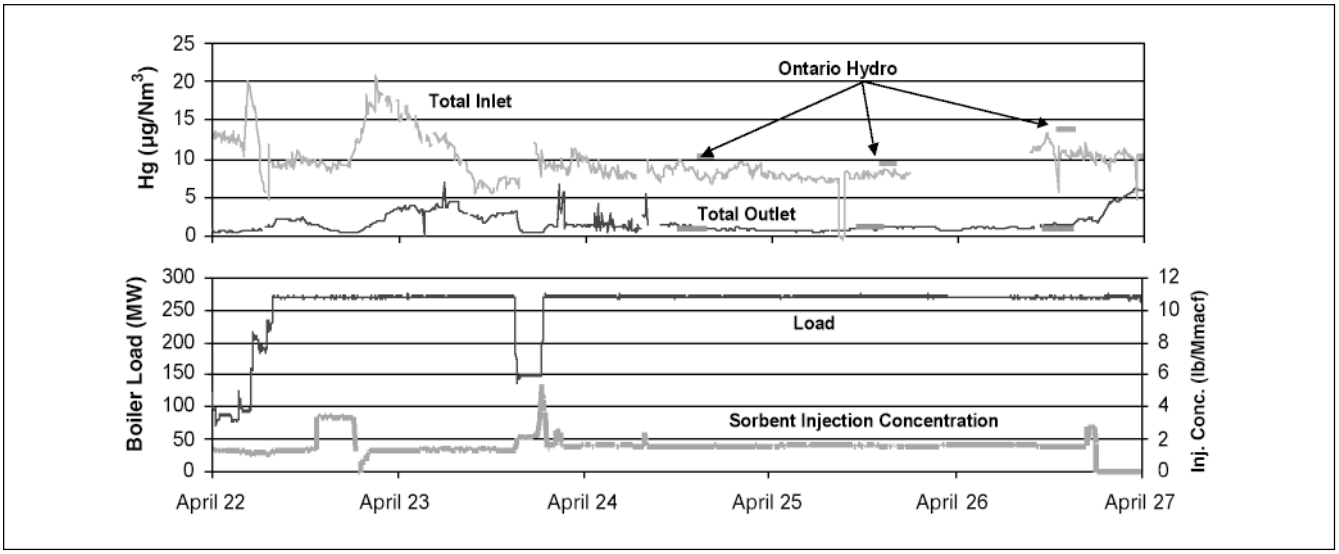

Figure 7. Inlet and outlet COHPAC Hg concentrations, boiler load, and PAC injection concentration during long-term tests, April 2001.

80–90% removal (1.5–2 vs. 3 lb/MMacf), considering that the model is based on a uniform PAC particle size of 15 µm when, in fact, the actual FGD carbon used has a wide size distribution with significant numbers of particles less than 15 µm.[4] The model also assumed a cleaning frequency of 2 pulses/bag/hr (all bags cleaned at the same time), whereas the bags were actually cleaned at ~1–2 pulses/bag/hr [bags cleaned 15 (one row) at a time] during the tests.

- Additional testing over longer periods (up to a year) must occur to determine the impact of carbon injection on bag life (pressure drop and bag strength) and outlet particulate emissions.

REFERENCES

1. Brown, T.D.; Smith, D.N.; Hargis, R.A.; O'Dowd, W.J. Mercury Measurement and Its Control: What We Know, Have Learned, and Need to Further Investigate; *J. Air & Waste Manage. Assoc.* **1999**, *49*, 1-97.
2. Durham, M.D.; Bustard, C.J.; Schlager, R.; Martin, C.; Johnson, S.; Renninger, S. Field Test Program to Develop Comprehensive Design, Operating, and Cost Data for Hg Control Systems on Non-Scrubbed Coal-Fired Boilers. Presented at the Annual Conference and Exhibition of A&WMA, Orlando, FL, June 24–28, 2001.
3. Durham, M.D.; Bustard, C.J.; Schlager, R.; Martin, C.; Johnson, S.; Renninger, S. Controlling Hg Emissions from Coal-Fired Utility Boilers: A Field Test; *EM* **2001**, *July*, 27-33.
4. Meserole, F.B.; Chang, R.; Carey, T.R.; Machac, J.; Richardson, C.F. Modeling Hg Removal by Sorbent Injection; *J. Air & Waste Manage. Assoc.* **1999**, *49*, 694-704.
5. Miller, R.; Harrison, W.; Corina, B.; Cushing, K.; Chang, R. COHPAC: The Next Generation in Particulate Control Technology at Alabama Power Co.'s E.C. Gaston Units 2 and 3, A Success Story. Presented at the EPRI-DOE-EPA Combined Utility Air Pollution Control Symposium: The MEGA Symposium, Atlanta, GA, August 16–20, 1999.
6. Sjostrom, S.; Ebner, T.; Ley, T.; Slye, R.; Richardson, C.; Machalek, T.; Richardson, R.; Chang, R.; Meserole, F. Assessing Sorbents for Hg Control in Coal-Combustion Flue Gas. Presented at A&WMA's Specialty Conference on Hg Emissions: Fate, Effects, and Control, Chicago, IL, August 21–23, 2001.
7. The U.S. Environmental Protection Agency Web site: http://www.epa.gov/ttn/atw/combust/utiltox/utoxpg.html; accessed 2001.
8. Sjostrom, S.M.; Bustard, J.; Durham, M.; Chang, R. Hg Removal Trends in Full-Scale ESPs and Fabric Filters. Presented at A&WMA's Specialty Conference on Hg Emissions: Fate, Effects, and Control, Chicago, IL, August 21–23, 2001.
9. Hassett, D.J.; Pflughoeft-Hassett, D.F.; Laudal, D.L.; Pavlish, J.H. Hg Release from Coal-Combustion Byproducts to the Environment. Presented at the Mercury in the Environment Specialty Conference, Minneapolis, MN, September 15–17, 1999.

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