

FINAL TECHNICAL REPORT  
November 1, 2000 through October 31, 2001

Project Title: **DEMONSTRATION OF SORBENT INJECTION PROCESS FOR ILLINOIS COAL MERCURY CONTROL**

ICCI Project Number: 00-1/2.2D-1  
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ABSTRACT

The objective of this program was to evaluate sorbent injection for mercury removal in flue gas derived from Illinois bituminous coal. As part of this evaluation, the first full-scale demonstration of carbon injection for mercury control at an Illinois coal-fired power plant was performed. This test was carried out at the University of Illinois Abbott Power Plant located in Champaign, Illinois. Initial fixed-bed mercury tests were performed using a slipstream of the Abbott flue gas to evaluate the relative performance of 19 different mercury sorbents and to determine the most appropriate samples and test conditions to design the subsequent full-scale tests. Sorbents tested in fixed bed studies included commercial activated carbons, corn-, Illinois coal-, tire, lignite-derived activated carbons, and several fly ash and zeolite samples.

Many carbon samples showed good capacities (375°F) in the Abbott flue gas, with most adsorbing over 100 µg Hg/g (normalized to 50 µg/Nm<sup>3</sup>). In general, the carbon-based sorbents had significantly higher capacities than the fly ash or zeolite-based sorbents. However, the cheaper cost of many of these latter sorbents, as compared to carbon sorbents, could possibly outweigh their poorer performance.

Full-scale tests were carried out using Unit 5 (12 Megawatt) of Abbott. The sorbents were injected downstream of the air pre-heater but upstream of the ESP. The duct temperature at this location averaged approximately 390°F during the testing period. Activated carbons tested included a corn-derived activated carbon, Norit America's FGD, and a size-segregated FGD (Fine FGD). They were injected into the flue gas at concentrations between 6 and 24 lb/MMacf. Total mercury removal ranged from 20% to about 73% depending on the carbon injection rate, carbon particle size, and flue gas temperature. In general the performance of the corn-derived carbon was similar to that of the commercial FGD carbon. Fine FGD performed better than the other carbons mainly because it had the smallest mass mean diameter. Mercury capture also improved by lowering the flue gas temperature (spray cooling). The results from this study show that control technologies using injection of powdered activated carbon offer the potential to provide significant mercury removal from the flue gas of utility boilers burning high-sulfur Illinois bituminous coal.

## EXECUTIVE SUMMARY

On December 14<sup>th</sup> 2000, the USEPA announced its intention to regulate mercury emissions from coal-fired boilers under Title III of the Clean Air Act Amendments of 1990. The USEPA plans to issue final regulations by December 15<sup>th</sup> 2004 and is expected to require compliance by December 2007. It is thus important for utilities to determine the options for reducing mercury emissions, their cost effectiveness, and their potential impacts on power plant operation and other air pollutant emissions.

Sorbent injection is one of the many control options for coal-fired utilities being explored by the USDOE, EPRI, and USEPA and their team members. Results from a number of studies indicate that sorbents are capable of removing greater than 90% of the flue-gas mercury generated during combustion. Research also has shown that sorbent effectiveness is dependent on many factors including sorbent properties, coal type, flue gas conditions and composition, fly ash properties, and reaction kinetics. Due to these influences, it is difficult to extrapolate sorbent effectiveness at plants operating at different conditions or burning different fuels.

The objective of this program was to evaluate sorbent injection for mercury removal in flue gas derived from Illinois bituminous coal. As part of this evaluation, the first full-scale demonstration of carbon injection for mercury control at an Illinois coal-fired power plant was performed. This test was carried out at the University of Illinois Abbott Power Plant located in Champaign, Illinois, during summer 2001. Fixed-bed (bench-scale) mercury tests were performed to screen the performance of potential sorbents in both a flue gas simulating that at the Abbott plant and a slipstream of the actual flue gas obtained downstream of air pre-heater and upstream of the ESP of a 12 Megawatt boiler at the Abbott power plant. The duct temperature at this location ranged from 380°-420°F during the testing period. The objective of the bench scale tests was to evaluate the relative performance of different mercury sorbents to determine the most appropriate samples and test conditions to design the subsequent full-scale tests.

The Mercury adsorption capacities of 19 different sorbents were evaluated in bench-scale studies (both simulated flue gas and slipstream of flue gas at Abbott). These tests were performed by URS Corporation. The sorbents tested included two commercial activated carbons-Norit America's (FGD and GAC), activated carbons derived from Illinois bituminous coal (Pilot-5), tire (TDAC), corn byproducts (CAF), lignite (LAC), several fly ash samples including as-received and chemically and physically modified fly ash samples from Abbott and fly ash samples from a commercial eastern bituminous fly ash beneficiation process (EBHL, EBLL), and two zeolite samples (AANP and CBV).

General observations made during the fixed-bed sorbent testing included the following:

- Many carbon samples showed good capacities (375°F) in the Abbott Power ESP inlet flue gas, with most adsorbing over 100 µg Hg/g (normalized to 50 µg/Nm<sup>3</sup>).

- In general, the carbon-based sorbents had significantly higher capacities than the fly ash or zeolite-based sorbents. However, the cheaper cost of many of these latter sorbents, as compared to carbon sorbents, could possibly outweigh their poorer performance.
- Fixed-bed results at Abbott closely resembled results from tests carried out in simulated flue gas.
- “As-received” fly ash from Abbott showed no capacity for mercury at a temperature of 375°F. Size-separation and sulfur-impregnation of the Abbott fly ash resulted in enhanced mercury removal. These results suggest that size-separation and/or sulfur impregnation prior to re-injection of fly ash may improve mercury removal by the indigenous ash.
- Results obtained with two samples produced in a commercial fly ash beneficiation process, operating at a site with eastern bituminous ash, showed that a sample containing high levels of LOI carbon adsorbed more mercury than a sample containing low LOI carbon levels. These results are similar to those observed in bench scale tests.
- A sieved natural zeolite (AANP-Z200) showed better mercury adsorption than a sulfur-impregnated (commercial) zeolite. These results are consistent with laboratory tests that showed that the AANP zeolite displayed higher levels of mercuric chloride adsorption than the CBV sample.

Apogee Scientific Inc., performed the full-scale carbon injection tests at Abbott Power Plant. The plant is a cogeneration facility producing both steam and electricity with a nameplate capacity of 30 MW. There are three boilers at the plant, all spreader-stokers. Abbott Units 5, 6 and 7 have dedicated boilers and ESPs. Effluent from these three units combines before entering single water pre-scrubber and a Chiyoda CT-121 flue gas desulfurization unit. The boilers burn bituminous coal from a mine near Springfield, IL. Full-scale tests were carried out using Unit 5 (12 Megawatt). The sorbents were injected downstream of the air pre-heater (APH) but upstream of the ESP. The duct temperature at this location ranged from 380°-420°F during the testing period and averaged approximately 390°F. The analyzers were located upstream of sorbent injection, at the inlet of the ESP, and at the outlet of the ESP.

Baseline tests revealed that the HCl concentration in the flue gas varied between 111 and 194 ppm. The concentration of elemental mercury in the flue gas ranged from 0.6 to 2  $\mu\text{g}/\text{Nm}^3$ , and the total mercury concentration was between 3 and 4  $\mu\text{g}/\text{Nm}^3$ .

A series of parametric tests were conducted with three activated carbons following the baseline test series. The carbons included a corn-derived activated carbon, Norit America’s FGD, and a size-segregated FGD (Fine FGD). The corn-derived activated carbon was prepared in a pilot-scale rotary kiln. The mass mean diameters of the corn and FGD carbons were about 16 and 18 microns, respectively, and that of the Fine FGD was about 6 microns. The surface areas of the carbons ranged from 400 to 510  $\text{m}^2/\text{g}$ . Carbon injection concentrations varied between 6 and 24 lb/MMacf.

Total mercury removal ranged from 20% to about 73% depending on the carbon injection rate, carbon particle size, and flue gas temperature (Figure 1). No mercury removal was measured between the analyzer downstream of the APH and upstream of ESP (nominally 1 sec residence time between two analyzers). This indicates that the mercury removal mainly occurred across the ESP. Data also suggest that mercury oxidation (elemental to oxidized) occurred across the ESP. In general the performance of the corn-derived carbon was similar to that of the commercial FGD carbon. Fine FGD removed 60% of the total mercury at a carbon injection rate of about 5 lb/MMacf, and the rate increased to 70% when the flue gas was cooled (spray cooling) from 390 to about 340 °F. This level (70%) of mercury removal was observed at 15 lb/Mmacf with the corn-derived carbon with humidification and at 22 lb/MMacf with FGD activated carbon without humidification. These data indicate that carbon injection rate could be reduced substantially by lowering flue gas temperature and reducing the carbon particle size. Carbon injection and flue gas humidification had no effects on ESP operation including, secondary current or voltage.

During the course of this study, a number of attempts were made to obtain about 7,000 pounds of dry fly ash from utilities burning high-sulfur Illinois coal. A fly ash beneficiation company located in Pennsylvania was identified with capabilities to prepare several hundred pounds of concentrated fly ash carbon for a potential full-scale testing. Unfortunately, we were not able to obtain sufficient quantity of fly ash for beneficiation.

The results from this study showed that control technologies using injection of powdered activated carbon offer the potential to provide significant mercury removal from the flue gas of utility boilers burning high-sulfur Illinois bituminous coal. It is likely that most power plants burning high-sulfur coal install wet scrubbers for SO<sub>2</sub> control. Wet scrubbers can effectively remove more than 90% of the oxidized mercury in flue gas. Since high-sulfur Illinois bituminous coals generally have high oxidized mercury concentrations, wet scrubbers alone may be sufficient to remove >80% of the flue gas mercury from these coals. If future regulations require mercury removal of greater than 90%, activated carbon may have to be injected before the existing ESP to capture some of the mercury. Alternatively, carbon injection could be used downstream of the ESP but before a polishing fabric filter. This configuration permits recycling of the carbon to increase its utilization.

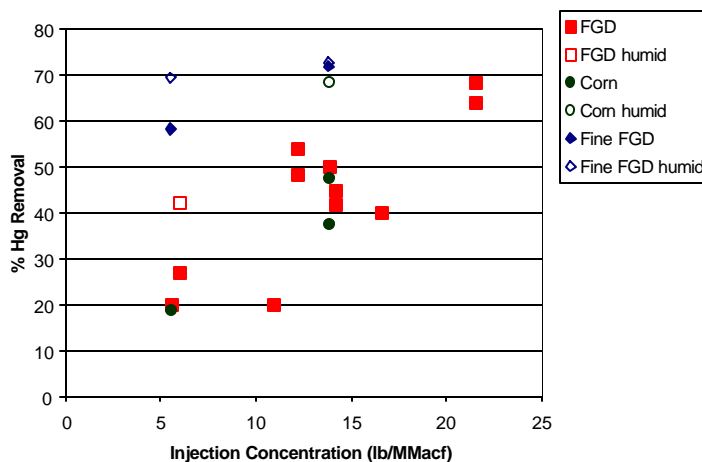


Figure 1. Performance comparison of FGD, Corn and Fine FGD activated carbons.

## OBJECTIVES

The objective of this program was to evaluate sorbent injection for removal of mercury from flue gas derived from Illinois bituminous coal. As part of this evaluation, the first full-scale demonstration of carbon injection for mercury control at an Illinois coal-fired power plant was performed. This test was carried out at the University of Illinois Abbott power plant located in Champaign, Illinois, during summer 2001. Bench scale mercury tests were performed to screen the performance of potential sorbents in flue gas simulating that at the Abbott plant. The objective of the bench scale tests was to evaluate the relative performance of different mercury sorbents to determine the most appropriate samples and test conditions to use in small-scale slipstream screening tests conducted at Abbott. The results of these were used to design the subsequent full-scale tests. The project had seven tasks.

Task 1. Preparation and Characterization of Sorbents

Task 2. Retrofitting and Engineering at Power Plant

Task 3. Fixed Bed Testing

Task 4. Full-Scale Sorbent Injection Tests

Task 5. Data Analysis and Process Engineering

Task 6. Project Management and Reporting.

## INTRODUCTION AND BACKGROUND

On December 14<sup>th</sup> 2000, EPA announced its intention to regulate mercury emissions from coal-fired boilers under Title III of the Clean Air Act Amendments of 1990. The USEPA plans to issue final regulations by December 15<sup>th</sup> 2004 and is expected to require compliance by December 2007. It is thus important for utilities to determine the amount of mercury emissions from their power plants, the options for reducing mercury emissions and their cost effectiveness, and their potential impacts on power plant operation and other air pollutant emissions.

Sorbent injection is one of the many control options for coal-fired utilities being explored by the USDOE, EPRI, and USEPA and their team members. Results from a number of studies indicate that sorbents are capable of removing greater than 90% of the flue-gas mercury generated during combustion. Research also has shown that sorbent effectiveness is dependent on many factors including sorbent properties, coal type, flue gas conditions and composition, fly ash properties, and reaction kinetics. Due to these influences, it is difficult to extrapolate sorbent effectiveness at plants operating at different conditions or burning different fuels.

The Illinois Clean Coal Institute and EPRI supported this test program to evaluate sorbent injection for mercury removal from a flue gas derived from Illinois bituminous coal.

Sorbent screening tests were carried out in both the laboratory and in slipstreams of an actual flue gas to evaluate the performance of a number of promising mercury sorbents. The results of these tests were used to determine appropriate sorbents and conditions to use in full-scale sorbent injection tests at the University of Illinois Abbott Power Plant.

Because of the potential regulation of the mercury emissions from utility plants, producers and users of Illinois coal should soon identify effective options for control of mercury emissions. This project provides data that can help utilities burning high-sulfur Illinois coal determine the effectiveness of removing mercury from flue gas using sorbent-based processes. This report presents results from the full-scale field-testing of sorbent-based technology using an actual Illinois coal combustion flue gas.

## EXPERIMENTAL PROCEDURES

### Sorbents Tested

The mercury adsorption capacities of 19 different sorbents (Table 1) were determined in laboratory. FGD and GAC carbons are commercially available activated carbons generated from Texas lignite. These carbon samples were obtained from Norit Americas, Inc. Activated carbons derived from Illinois bituminous coal (Pilot-5), scarp tire (TDAC), corn byproducts (CFA) and North Dakota lignite (LAC) were developed and prepared by the ISGS. CFA-6 was activated for a longer time period than was CFA-5 resulting in a higher surface area for the former. CFA-5 was impregnated with sulfur at 400°C to create CFA-S. Crown-II was derived from Illinois bituminous coal using a single-step process. The corn-derived activated carbons were prepared from corn fibers, which are byproducts from a corn-to-ethanol process. The corn fibers were obtained from Williams Bio-Energy, Pekin, Illinois.

Several fly ash samples were also tested for mercury adsorption in the laboratory. These included samples received from Abbott Power Plant as well as from other plants. Abbott fly ash was modified using both chemical and physical methods prior to testing. This included impregnating the ash with elemental sulfur, or size-separation using wet and dry methods.

Two eastern bituminous coal-derived fly ash samples were also tested. These samples were produced in a commercial fly ash beneficiation process designed to recover unburned carbon from fly ash. The two samples received included a LOI-enriched fraction and a low-LOI carbon fraction of the treated fly ash. Two zeolite samples, one commercial (synthesized) and one natural product, were also tested.

Based on the results from the fixed-bed mercury tests at Abbott, the FGD carbon and the corn-derived carbons were selected for full-scale testing. A pilot-scale rotary kiln located at MicroEnergy Systems, Inc., Oakland, Maryland, was used to prepare about 900 pounds of a corn-derived activated carbon for the full-scale carbon injection tests. A limited full-scale test was also conducted with a size-segregated FGD carbon, designated as FGD Fine, which had a mean particle diameter of about 6 microns compared with about 18 microns for the unprocessed FGD carbon.

Table 1. List of sorbents tested in laboratory.

<b>Sorbent Name</b>	<b>Description</b>
<b>Carbon Samples</b>	
Darco FGD	Activated Carbon from Norit Americas; commercial
Norit GAC	Activated Carbon from Norit Americas; commercial
Pilot-5	AC-1 clone made by ISGS for pilot testing
Crown-II	Activated Illinois bituminous coal; single activation step (ISGS)
TDAC	Tire-derived activated carbon; experimental
CFA-4	Corn-char; experimental
CFA-5	Low surface area corn-char; experimental
CFA-6	High surface area corn-char; experimental
CFA-S	Sulfur impregnated low surface area corn-char; experimental
LAC-0101	Activated carbon derived from lignite; experimental
FGD/Lime	FGD carbon mixed with hydrated lime (1:20 ratio)
<b>Fly Ash Samples</b>	
Abbott Ash	As-received sample of Abbott fly ash; 36% LOI
Abbott-I	Size-separated Abbott ash; wet method (ISGS); 71.7% LOI
Abbott-S	Sulfur-impregnated Abbott ash (ISGS)
Abbott [-325]	Size-separated Abbott ash; 32% LOI
Water Light and Power	As-received sample of Springfield Water Light Power Plant fly ash, 5% LOI (IL coal)
EBHL	Ash with High LOI content derived from eastern bituminous coal*
EBLL	Ash with Low LOI content derived from eastern bituminous coal*
<b>Zeolite Samples</b>	
AANP-Z200	American Adsorbents Natural Product Zeolite sieved to -200 mesh
CBV-400-S	Commercial zeolite impregnated with sulfur at 400°C (ISGS)

\* Samples produced from commercial fly ash beneficiation process

### Laboratory Adsorption Testing

Prior to performing the full-scale mercury adsorption tests at Abbott Power Plant, initial screening tests were carried out in URS Corporation's Austin, Texas, laboratory using simulated flue gas. The purpose of these tests was to evaluate a number of sorbents at conditions similar to those expected at Abbott. These tests also evaluated the effectiveness of various fly ash modifications. Laboratory test results were used to determine which samples should perform the best during field testing.

Figure 1 illustrates the bench scale test apparatus used for the mercury adsorption tests. Table 2 shows the composition of the simulated flue gas used in the bench scale screening tests.

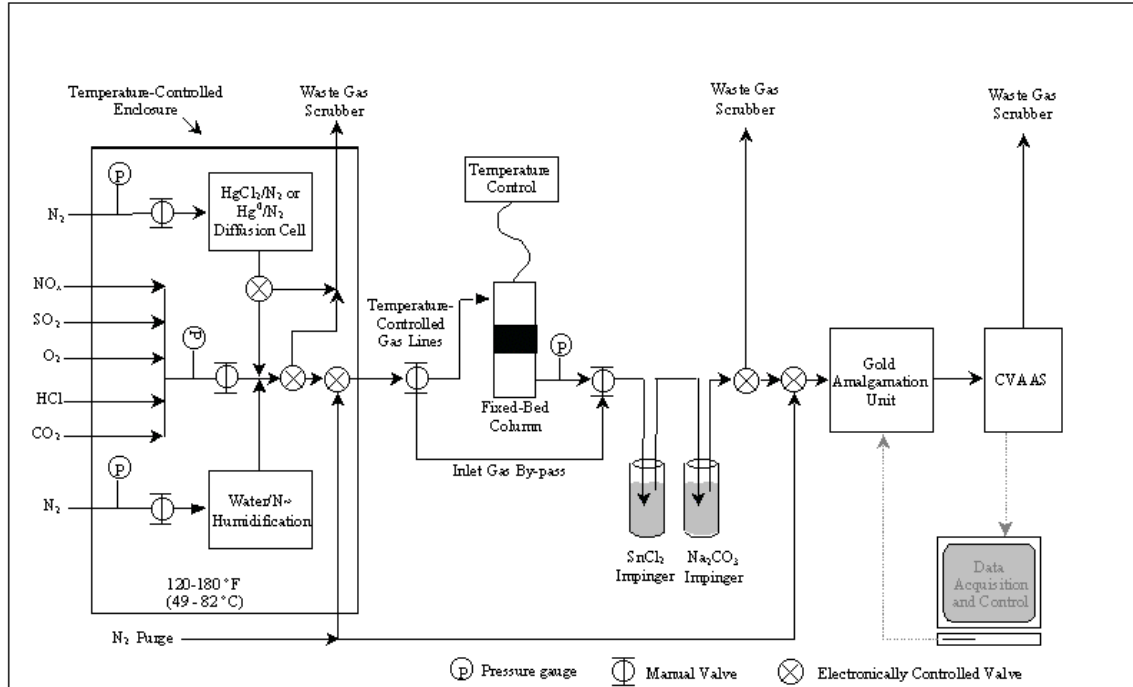


Figure 1. Schematic diagram of the laboratory (bench-scale) mercury test system.

For the laboratory tests, a simulated flue gas was prepared by mixing heated nitrogen gas streams containing  $\text{SO}_2$ ,  $\text{HCl}$ ,  $\text{NO}_x$ ,  $\text{CO}_2$ ,  $\text{O}_2$ , and water. While the simulated gas was clean (contained no particulates), the gas concentration and temperature modeled plant conditions. The gas composition could be varied by appropriately adjusting the various gas rates. Mercury was injected into the gas by contacting nitrogen carrier gas with either re-crystallized mercuric chloride solids or with an elemental mercury permeation tube (VICI Metronics) in a mercury saturation vessel. The temperature of the mercury saturator and the nitrogen flow rate through the saturator controlled the mercury concentration. All gas mixing, water saturation, and mercury injection occurred within a closed, temperature-controlled box designed to prevent water condensation, which can affect the behavior of mercury and the gas concentrations in the flow lines.

Table 2. Simulated flue gas composition used in laboratory tests.

Gas Component	Concentration
$\text{SO}_2$	1600 ppm
$\text{HCl}$	50 ppm
$\text{NO}_x$	400 ppm
$\text{H}_2\text{O}$	7%
$\text{CO}_2$	12%
$\text{O}_2$	6%
$\text{Hg}^0$	20-40 $\mu\text{g}/\text{Nm}^3$
$\text{N}_2$	Balance

The reaction gas flowed at about 1 standard L/min through heated Teflon lines (120°C) to a temperature-controlled column (1.27-cm ID) containing the sorbent to be studied. The sorbent was mixed in a sand diluent prior to being packed in the reaction column. In the column, the gas was heated to the reaction temperature before contacting the sorbent by passing it across a bed of pyrex spheres designed to enhance heat exchange. The column temperature is controlled using an internally mounted thermocouple shielded from the gas with a glass sheath. The reaction gas flowed downward through the column to minimize the chance of selective flow or channeling through the bed. The bed material was supported by a fritted glass disk and packed with quartz wool. The linear gas velocity through the empty column was approximately 11 m/min at 135°C.

Prior to each adsorption test, the sorbent/sand mixture was equilibrated at the desired adsorption temperature for at least one hour before contacting flue gas. During this time, the inlet gas bypassed the sorbent column and passed to the analytical system (described below) to determine the inlet mercury concentration and speciation. After the inlet mercury concentration was established, the adsorption test was initiated by diverting the flue gas through the sorbent column. The amount of mercury exiting the column was measured on a semi-continuous basis until 100% mercury breakthrough is detected.

During normal test operation, the effluent gas from the fixed-bed column flowed through heated lines to an impinger containing  $\text{SnCl}_2$  solution that reduced any oxidized mercury compounds to elemental mercury. After passing through the  $\text{SnCl}_2$  impinger, the gas flowed through a buffer solution ( $\text{Na}_2\text{CO}_3$ ) and an alkaline solution ( $\text{NaOH}$ ) to remove acid components ( $\text{SO}_2$  and  $\text{HCl}$ ) from the gas, thus protecting the downstream, analytical gold surface. Gas exiting the impingers flowed through a gold amalgamation column where the mercury in the gas was adsorbed (<60°C). After adsorbing mercury onto the gold for a fixed period of time (typically 3 minutes), the mercury concentrated on the gold was thermally desorbed (>500°C) in nitrogen or argon and sent as a concentrated mercury stream to a cold-vapor atomic absorption (CVAA) spectrophotometer for analysis. Therefore, the total effluent mercury concentration was measured semi-continuously with a 3-minute sample time followed by a 4-minute analytical period.

A semi-continuous mercury analyzer was utilized to determine mercury adsorption. The analyzer provided near real-time feedback during testing. The analyzer consisted of a commercially available cold vapor atomic absorption spectrometer (CVAAS) coupled with a gold amalgamation system (Au-CVAAS). The system was calibrated using vapor-phase elemental mercury.

Using the analytical methods described above, mercury adsorption breakthrough curves were generated. The percent breakthrough was determined as a function of time by normalizing the measured mercury concentration at the outlet of the sorbent bed to the inlet mercury concentration. The adsorption capacity of the sorbent ( $\mu\text{g Hg adsorbed/g sorbent}$ ) at any given time “t” was determined by summing the total mass of mercury adsorbed through time “t” (area above the breakthrough curve) and dividing by the carbon mass. The equilibrium adsorption capacity was defined by the time when the outlet mercury concentration was first equal to the inlet concentration.

### Fixed-bed mercury tests at Abbott power plant

In order to evaluate the potential of a given mercury sorbent and model its performance, the equilibrium adsorption capacity and characteristics of the sorbent must be known. If a particular sorbent has a small equilibrium capacity for mercury, the mercury removal rate will be adversely affected since equilibrium will be rapidly approached. Sorbent equilibrium data can be generated by conducting fixed-bed, adsorption (breakthrough) tests.

Mercury adsorption breakthrough tests were conducted at the Abbott Power Plant located on the University of Illinois Urbana-Champaign campus. The plant is a cogeneration facility producing both steam and electricity. With a nameplate capacity of 30 MW, the plant generates approximately one-third of the electricity demand of the university. There are three boilers at the plant, all spreader-stokers, Figure 2. Abbott Units 5, 6 and 7 have dedicated boilers and ESPs. Effluent from these three units combines before entering a single water pre-scrubber and a Chiyoda CT-121 flue gas desulfurization unit. The boilers burn a bituminous coal from a mine near Springfield, IL.

Fixed-bed adsorption tests were carried out using a flue gas slipstream obtained just downstream of the Unit 6 (a 12 Megawatt stoker-boiler) air pre-heater, upstream of the ESP. The duct temperature at this location ranged from 380°-420°F during the testing period and averaged approximately 390°F.

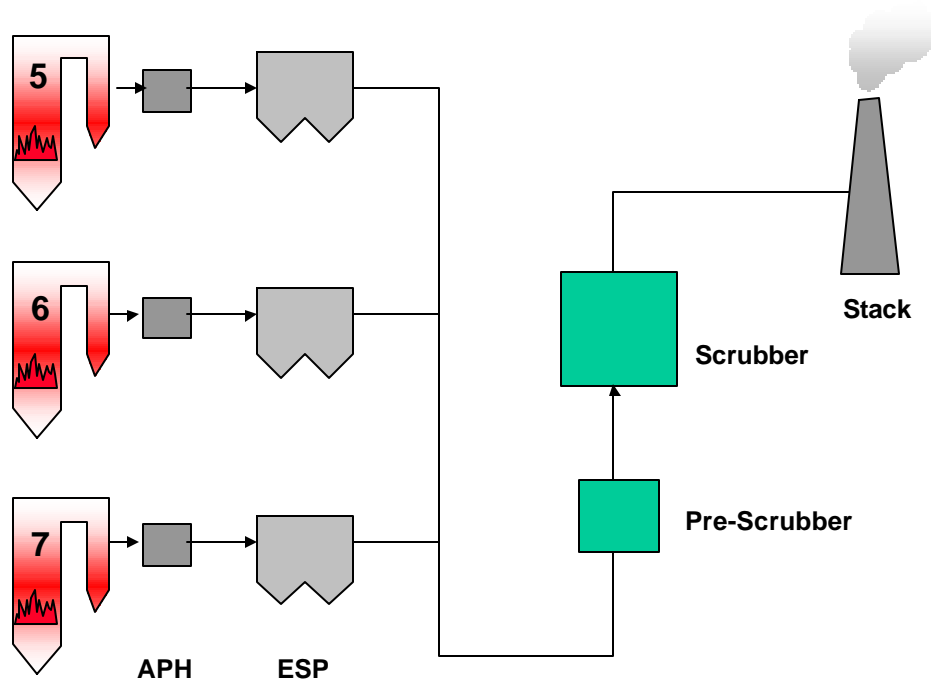


Figure 2. Layout of Units 5, 6 and 7 at Abbott Power Plant.

Figure 3 illustrates the mercury sorbent test apparatus used at Abbott Power Plant. A slipstream (30-40 acfm) was drawn obtained from the flue gas duct and flowed through an annular sintered metal tube. A dust-free gas sample was obtained by pumping gas, at a desired flow rate, through the sintered metal. For the mercury adsorption tests, approximately 1-2 standard L/min of filtered flue gas was flowed through heated Teflon™ lines (120°C) to a temperature-controlled hotbox containing a Teflon™ sorbent column (3.7-cm ID). The sorbent is mixed in a sand diluent prior to being packed in the reaction column. The flue gas flows downward through the column to minimize the chance of selective flow or channeling through the bed. The bed material was supported by a perforated Teflon™ disk and packed quartz wool. The bed material was supported by a perforated Teflon™ disk and packed quartz wool.

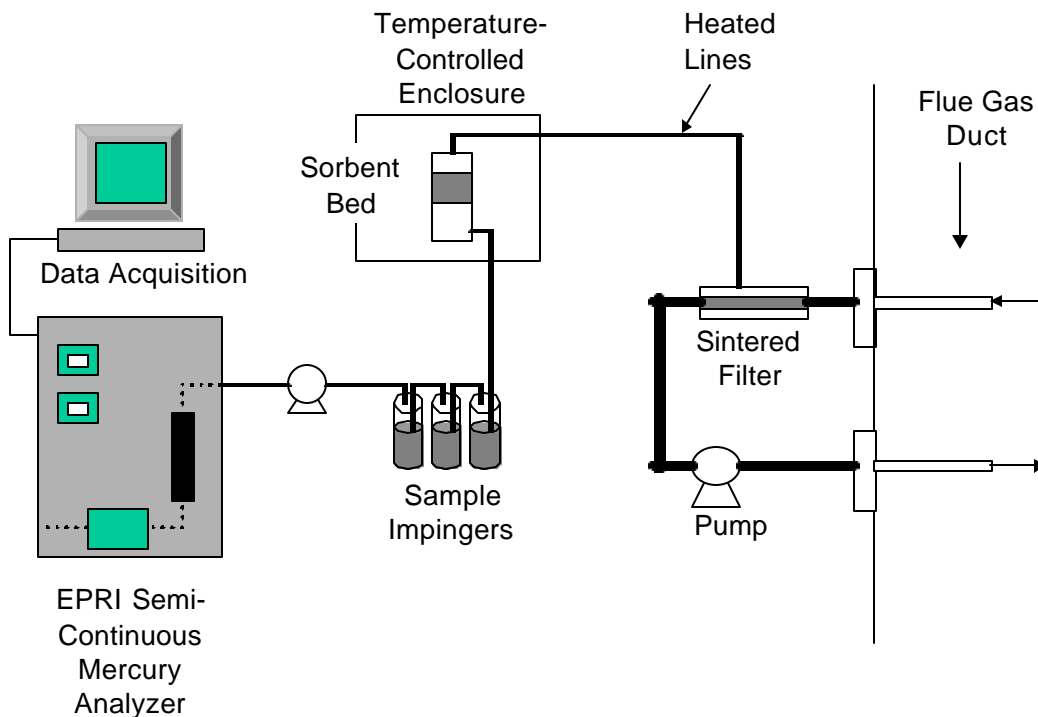


Figure 3. Field Mercury Test Unit

Prior to each adsorption test, the sorbent/sand mixture was equilibrated at the desired adsorption temperature for at least one hour before contacting flue gas. During this time, the inlet gas bypassed the sorbent column and passed to the analytical system (described below) to determine the inlet mercury concentration and speciation. After the inlet mercury concentration was established, the adsorption test was initiated by diverting the flue gas through the sorbent column. The amount of mercury exiting the column was measured on a semi-continuous basis until 100% mercury breakthrough was detected.

During normal test operation, the effluent gas from the fixed-bed column flowed through heated lines to an impinger containing  $\text{SnCl}_2$  solution that reduced any oxidized mercury

compounds to elemental mercury. After passing through the  $\text{SnCl}_2$  impinger, the gas flowed through a buffer solution ( $\text{Na}_2\text{CO}_3$ ) and an alkaline solution ( $\text{NaOH}$ ) to remove acid components ( $\text{SO}_2$  and  $\text{HCl}$ ) from the gas, thus protecting the downstream, analytical gold surface. Gas exiting the impingers flowed through a gold amalgamation column where the mercury in the gas was adsorbed ( $<60^\circ\text{C}$ ). After adsorbing mercury onto the gold for a fixed period of time (typically 3 minutes), the mercury concentrated on the gold was thermally desorbed ( $>500^\circ\text{C}$ ) in nitrogen or argon and sent as a concentrated mercury stream to a cold-vapor atomic absorption (CVAA) spectrophotometer for analysis. Therefore, the total effluent mercury concentration was measured semi-continuously due to the time associated with sampling and analysis.

During mercury adsorption tests, the effluent mercury can be fully or partially oxidized due to reactions between the inlet mercury, mercury sorbent, and flue gas components. The percentage of inlet elemental mercury oxidized across the sorbent was determined by replacing the  $\text{SnCl}_2$  impinger with an impinger containing tris (hydroxymethyl)-aminomethane (Tris) solution. The Tris solution has been shown in other EPRI studies to capture oxidized mercury while allowing elemental mercury to pass through without being altered. The Tris impinger captures any effluent oxidized mercury, and only elemental mercury is detected by the downstream analytical system. The difference between the total measured effluent mercury ( $\text{SnCl}_2$  impinger) and the effluent elemental mercury represents the amount of elemental mercury oxidized in the gas.

Using the analytical methods described above, mercury adsorption breakthrough curves were generated. The percent breakthrough was determined as a function of time by normalizing the measured mercury concentration at the outlet of the sorbent bed to the inlet mercury concentration. The adsorption capacity of the sorbent ( $\mu\text{g Hg}$  adsorbed/g sorbent) at any given time “t” was determined by summing the total mass of mercury adsorbed through time “t” (area above the breakthrough curve) and dividing by the carbon mass. The equilibrium adsorption capacity was defined by the time when the outlet mercury concentration was first equal to the inlet concentration.

#### Full-Scale Sorbent Injection Tests

Full-scale carbon injection tests were conducted using Abbott Unit 5. A sketch of the layout of Unit 5 is shown on Figure 4.

Mercury Measurements. Three semi-continuous mercury analyzers were used during this program to provide near real-time feedback during baseline, screening, and long-term testing. Continuous measurement of mercury at the inlet and outlet of the particulate collector is considered a critical component of a field mercury control program where mercury levels fluctuate with boiler operation (temperature, load, etc.) and decisions must be made concerning parameters such as sorbent feed rate and cooling. The analyzer consists of a commercially available cold vapor atomic absorption spectrometer (CVAAS) coupled with a gold amalgamation system (Au-CVAAS). The system is calibrated using vapor-phase elemental mercury.

A sketch of the system is shown in Figure 5. The analyzers was located upstream of sorbent injection, at the inlet of the ESP, and at the outlet of the ESP.

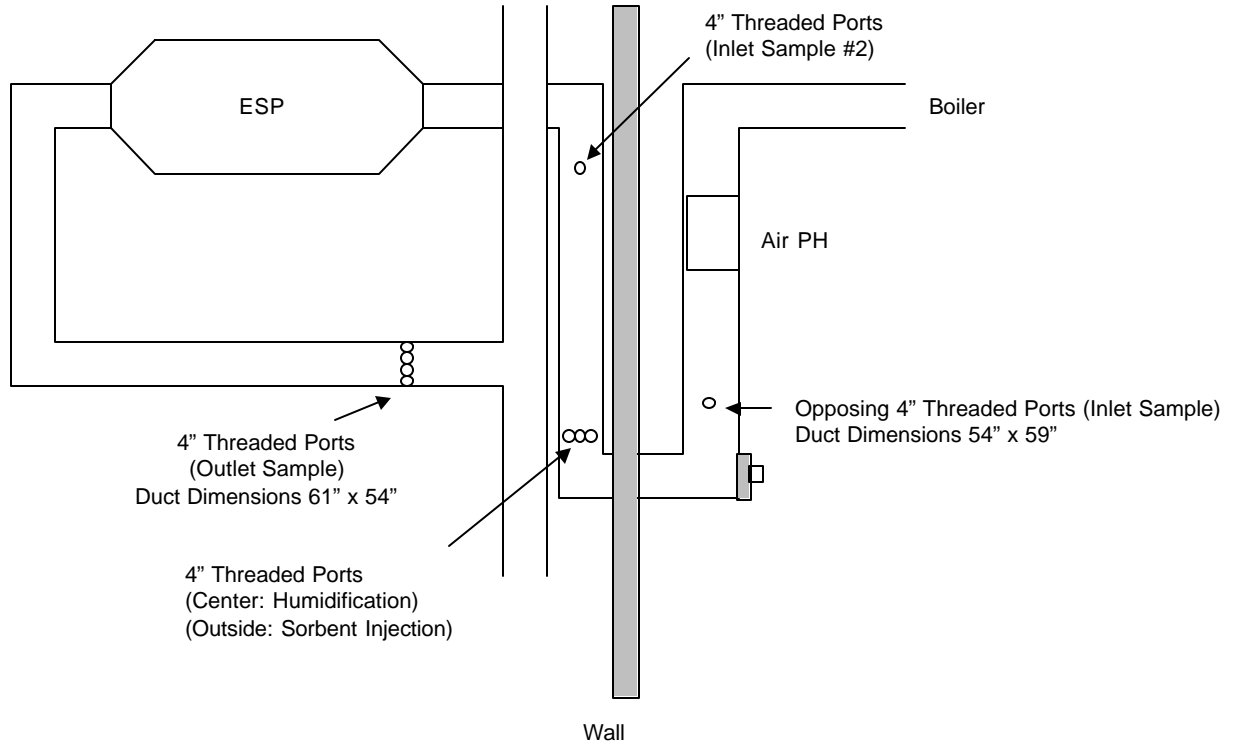


Figure 4. Layout of Abbott Unit 5.

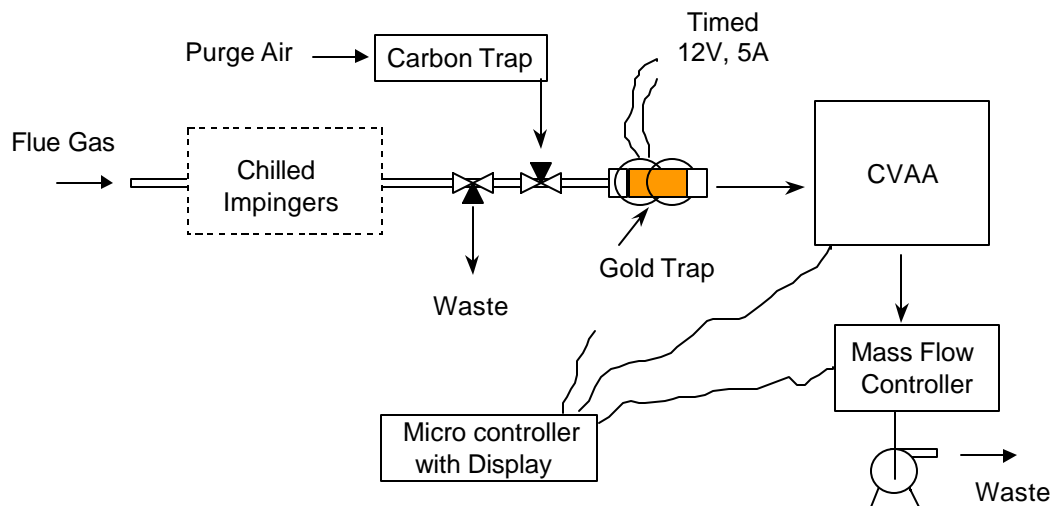


Figure 5. Sketch of the mercury measurement system.

Although it is very difficult to transport non-elemental mercury in sampling lines, elemental mercury can be transported without significant problems. Since the Au-CVAAS measures mercury by using the distinct lines of the UV absorption characteristic of  $\text{Hg}^0$ , the non-elemental fraction must either be converted to elemental mercury (for total mercury measurement) or removed (for measurement of the elemental fraction) near the sample extraction point. This minimizes any losses due to the sampling system.

For total vapor-phase mercury measurements, all non-elemental vapor-phase mercury in the flue gas must be converted to elemental mercury. A reduction solution of stannous chloride in hydrochloric acid was used to convert  $\text{Hg}^{2+}$  to  $\text{Hg}^0$ . The solution was mixed as prescribed in the draft Ontario Hydro Method for Manual Mercury Measurements. To measure speciated mercury, an impinger of potassium chloride (KCl) solution mixed as prescribed by the draft Ontario Hydro Method was placed upstream of the stannous chloride solution to capture oxidized mercury. Unique to this instrument is the ability to continuously refresh the impinger solutions to assure continuous exposure of the gas to active chemicals. The analyzers were configured to automatically switch from measuring total vapor-phase mercury to measuring elemental mercury during the Abbott tests.

Sorbent Feeder. Norit Americas, Inc provided the sorbent feeder used at Abbott. The feeder, which can deliver from 15 to 60 lb/hr activated carbon, was calibrated twice a day, before and after each test run.

Humidification. The duct temperature at Abbott Unit 5 upstream of the ESP was nominally 360 to 410 °F. Although activated carbon may be effective at these temperatures, a humidification system was installed at Abbott to reduce the duct temperature during some tests. The humidification system consisted of three humidification lances with three dual fluid nozzles per lance. The plant has approved cooling to 375 °F without additional authorization. This temperature was achievable with less than 3 gallons of water per minute. The humidification lances were located downstream of the carbon injection.

## RESULTS AND DISCUSSION

### Task 1. Preparation and Characterization of Sorbents

The list of sorbents tested in simulated flue gas at URS Corporation and in the fixed-bed at Abbott Power Plant is given in Table 1 (see Experimental Procedures). Based on the results from the fixed-bed mercury tests at Abbott, three sorbents were identified for full-scale injection tests. These included commercially available FGD carbon, size-segregated FGD, and a corn-derived activated carbon. About 900 pounds of the corn-derived activated carbon was prepared using corn fibers, a byproduct from a corn-to-ethanol process, in a pilot-scale rotary kiln located in Oakland, Maryland. The mass mean diameter of the FGD is nominally 18 microns while the MMD of the size-segregated sample is nominally 6 microns. Based on model predictions, the finer FGD carbon should be more effective at removing mercury because it provides a larger surface area

Table 3. Properties of activated carbons used in full-scale mercury tests at Abbott.

Sorbent	Description	Surface Area	Sorbent Size MMD	Size distribution 90% <
Darco FGD	Activated Carbon from Norit Americas; commercial	509 m <sup>2</sup> /g	17.98 μm	38.79 μm
Fine FGD	Size Segregated FGD	487 m <sup>2</sup> /g	5.95 μm	13.18 μm
Corn Char	Pilot Kiln corn-char; experimental	410 m <sup>2</sup> /g	15.82 μm	35.02 μm

for mass transfer per pound of sorbent injected. Select properties of the activated carbons used for full-scale carbon injection tests are presented in Table 3.

### Task 2. Retrofitting and Engineering at Power Plant

Activities of this task were discussed in the Experimental Procedure section.

### Task 3. Fixed-Bed Testing

Sorbent screening tests were conducted both in the laboratory, using a simulated flue gas, and with actual flue gas at Abbott Power Plant. Both sets of tests were designed to determine the most effective sorbents to use for full-scale injection testing. This was achieved by performing mercury breakthrough tests designed to determine the equilibrium adsorption capacity of each sorbent. In addition, the effect of temperature and linear velocity on mercury adsorption by several sorbents was also evaluated.

While laboratory tests do not always provide an accurate assessment of adsorption capacities, they do provide a method of comparing sorbents to each other. By ranking sorbents by which had the highest capacity in the lab, the best performers in the field could be predicted. Adsorption tests carried out in actual flue gas provided a more realistic comparison of different sorbents enabling prediction of full-scale (sorbent injection) performance. Parametric tests carried out in actual flue gas provided insight as to the expected effect of various process modifications on mercury removal.

#### Simulated Flue Gas Testing (laboratory results)

Bench-scale tests designed to measure sorbent adsorption capacities for both oxidized and elemental forms of mercury were carried out at URS Corporation's Austin, TX, laboratory. These tests measured the effectiveness of sorbents at adsorbing mercury from a simulated flue gas. While the simulated gas was clean (contained no particulates), flue gas concentrations and temperatures modeled plant conditions.

The specific sorbents tested were determined based on results of past laboratory and/or field tests conducted for EPRI. Laboratory tests were conducted at conditions simulating those expected at Abbott and at 325°F. This temperature was chosen for the laboratory tests based upon historical data provided for Unit 6 duct temperature indicating temperatures in the 320°–340°F range.

Figure 6 displays the laboratory results obtained for carbon-based sorbents. In general, the trends observed with both types of mercury were similar for the various sorbents. The Norit Americas GAC activated carbon showed the highest capacity for both  $\text{HgCl}_2$  and elemental mercury (2257  $\mu\text{g Hg/g}$  sorbent capacity for  $\text{HgCl}_2$  oxidized; 2880  $\mu\text{g Hg/g}$  sorbent capacity for  $\text{Hg}^0$ ). Samples prepared by ISGS from various precursors, including tire char, corn fiber, lignite, and Illinois bituminous coal (Pilot-5), showed similar results to Norit's Darco FGD which serves as the "baseline" mercury sorbent. Only Crown-II, which is derived from Illinois bituminous coal and is activated using a simple single processing step, showed no capacity for either form of mercury.

Figure 7 displays laboratory results for fly ash and zeolite-based mercury sorbents. Most of these samples showed better results for mercuric chloride adsorption than for elemental mercury. For  $\text{HgCl}_2$  adsorption, AANP-Z200 and Abbott-I ash had the highest capacities, adsorbing 1831 and 221  $\mu\text{g Hg/g}$  sorbent, respectively. For elemental mercury, CBV-400-S performed the best, adsorbing 138  $\mu\text{g Hg/g}$  sorbent. The "as-received" Abbott fly ash showed good adsorption of both mercury types (approximately 50  $\mu\text{g/g}$ ) at 325°F suggesting its potential removal of mercury in the Abbott flue gas duct. It is interesting that the Abbott fly ash showed much better mercury removal than the Water City ash, which is also derived from Illinois bituminous coal. It is believed that this difference is related to the higher LOI carbon content of the Abbott ash. This possibility is supported by results obtained with two ash samples obtained from a commercial fly ash beneficiation process. Here, a high-LOI sample (EBHL) showed much better removal than a low-LOI fraction obtained from the same process.

Zeolite samples were capable of achieving high levels of mercury adsorption, although the extent depended upon the type of mercury present in the gas. The AANP zeolite was

able to remove large amounts of mercuric chloride whereas the CBV-400-S was effective at removing elemental mercury. These results are similar to those obtained in previous tests with these samples.

Comparing the results in Figures 6 and 7, it should be noted that in general, the carbon-based sorbents had significantly higher capacities than the fly ash or zeolite-based sorbents. However, the cheaper cost of many of these latter sorbents, as compared to carbon sorbents, could possibly outweigh their poorer performance.

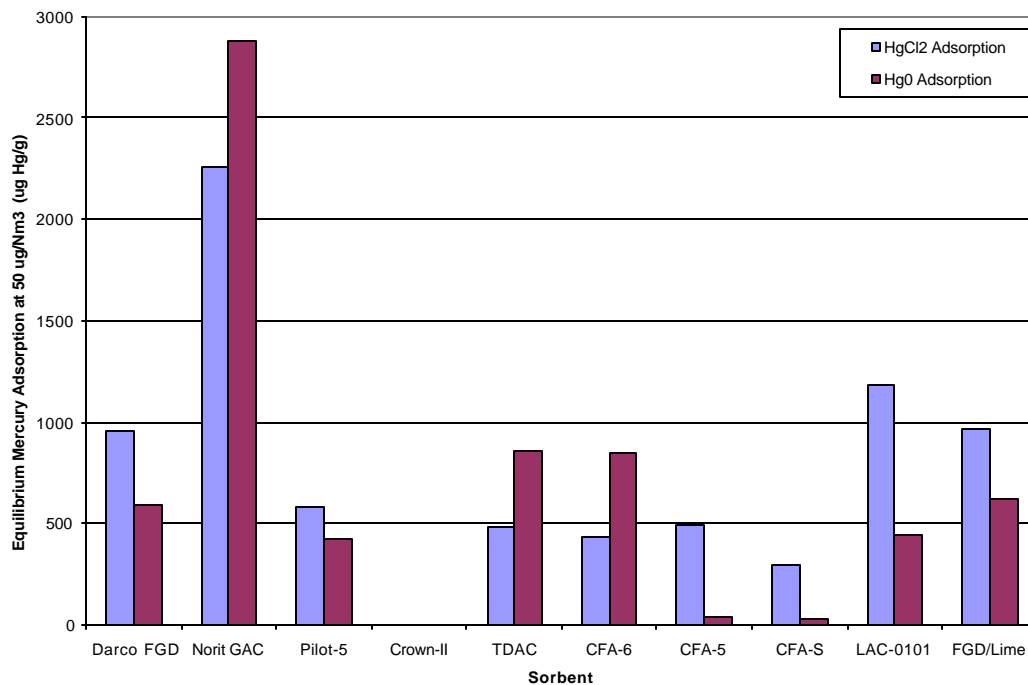


Figure 6. Laboratory Results for Carbon-based Sorbents

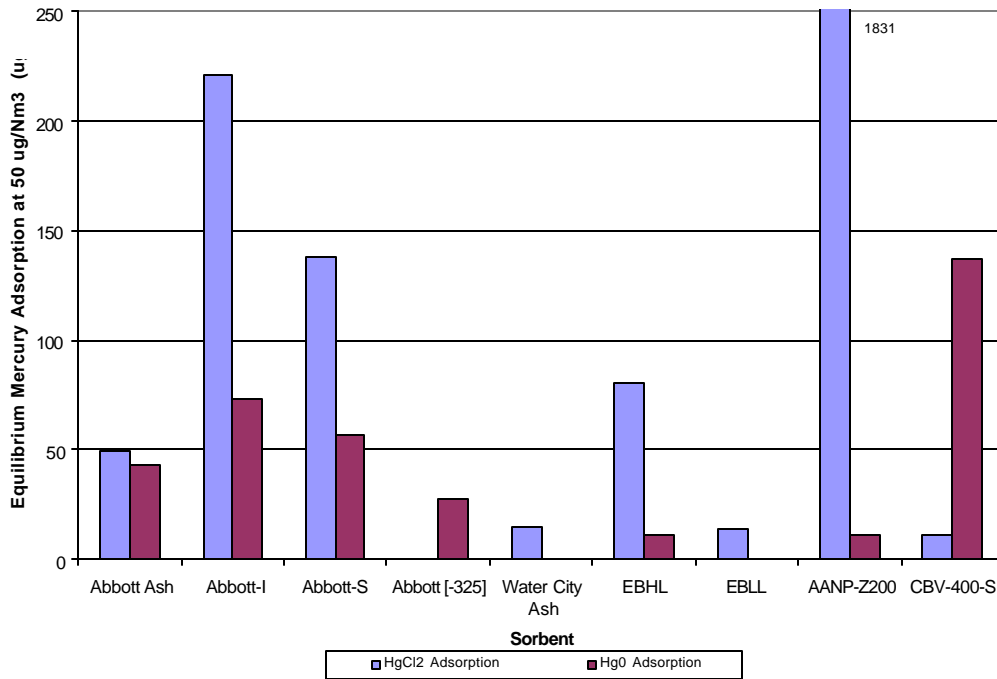


Figure 7 . Laboratory Results for Fly Ash or Zeolite-based Sorbents

Field Testing of Fixed-Bed Sorbent at Abbott

Small-scale fixed-bed mercury adsorption tests were carried out at Abbott Power Plant using a flue gas slipstream obtained from the outlet of the Unit 6 air pre-heater (ESP inlet). Table 4 lists the test matrix developed for the field adsorption testing.

Table 4. Test Matrix for Field Adsorption Testing

Sorbent	Sorbent	Completed		
		325F	375F	Linear
<b>Carbon</b>				
Darco	Darco	x	x	x
Norit GAC	Norit		x	
Pilot 5 (ISGC Illinois coal-	Pilot-		x	x
Illinois coal-derived AC	Crown-		x	
TDAC (ISGS tire-derived	TDA		x	
Corn Char (high surface area)	CFA-		x	
Corn Char (low surface area)	CFA-		x	
Sulfur-treated Corn	CFA-		x	
LAC-0101 (ISGS Lignite-derived	LAC-	x	x	
EGD/l ime	EGD/l im		x	
<b>Fly Ash</b>				
Abbott	Abbott	x		
Abbott-1	Abbott-	x	x	
Abbott-S	Abbott-	x	x	
Abbott [-325]	Abbott [-	x	x	
Water City Ash (Illinois coal-	Water City		x	
E. Bituminous High LOI	EBH		x	
E. Bituminous Low LOI	EBL		x	
<b>Zeolite</b>				
AANP	AANP-	x	x	
CBV-400-	CBV-400-		x	

Tests were carried out at a temperature of 375°F. The objective was to compare a number of promising mercury sorbents to determine which would be the best candidates for full-scale sorbent injection testing. Figure 8 shows the equilibrium mercury adsorption capacities for several carbon samples tested at Abbott Power Plant at 375°F. Figure 9 shows similar results for fly ash and zeolite samples.

General observations made during the fixed bed sorbent testing include the following:

- Many carbon samples showed good capacities (375°F) in the Abbott Power ESP inlet flue gas, with most adsorbing over 100  $\mu\text{g Hg/g}$  (normalized to 50  $\mu\text{g/Nm}^3$ ). A high surface area corn char (CFA-6) and lignite activated carbon (LAC-0101) performed the best with capacities of 550 and 350  $\mu\text{g/Nm}^3$ , respectively.
- Fixed-bed test results at Abbott Power were essentially the same as the tests carried out with simulated flue gas. Since the field tests were run at higher temperatures than the laboratory tests (375°F vs. 325°F), actual capacities cannot be compared. However, those sorbents that performed better in the laboratory, performed better in actual flue gas.

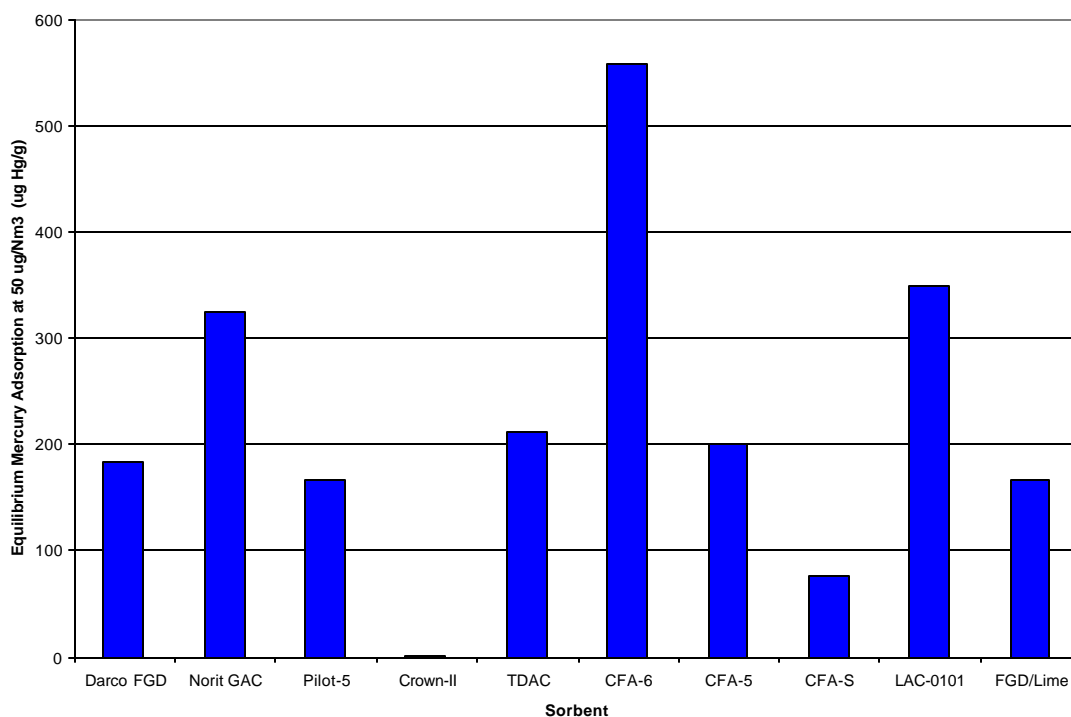


Figure 8. Mercury Adsorption by Carbons at 375°F: Fixed-Bed Tests Abbott Unit 6.

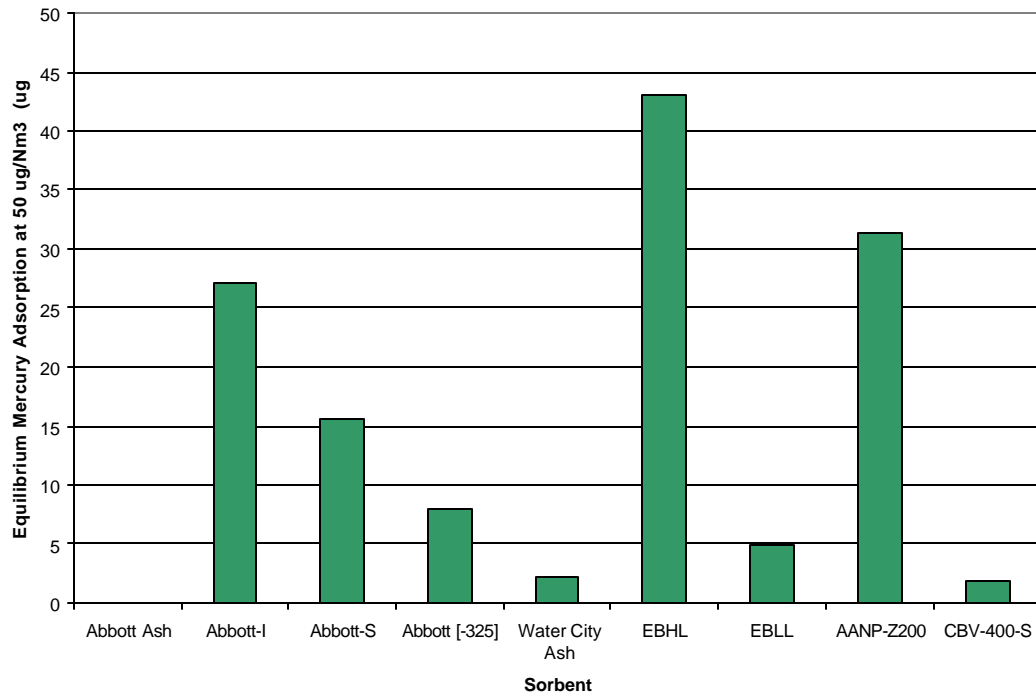


Figure 9. Mercury Adsorption by Fly Ashes and Zeolites at 375°F: Fixed-Bed Tests Abbott Unit 6.

- “As-received” fly ash from Abbott showed no capacity for mercury at a temperature of 375°F. Size-separation and sulfur-impregnation of the Abbott fly ash resulted in enhanced mercury removal. These results suggest that size-separation and/or sulfur impregnation prior to re-injection of fly ash may improve mercury removal by the indigenous ash. Additional tests are needed to determine optimal ash processing conditions.
- Results obtained with two samples produced in a commercial fly ash beneficiation process, operating at a site with eastern bituminous ash, showed that a sample containing high levels of LOI carbon adsorbed more mercury than a sample containing low levels of LOI carbon. These results are similar to those observed in bench scale tests.
- A sieved natural zeolite (AANP-Z200) showed better mercury adsorption than a sulfur-impregnated (commercial) zeolite. These results are consistent with laboratory tests that showed that the AANP zeolite displayed higher levels of mercuric chloride adsorption than the CBV sample.

Since the mercury sorbents are being analyzed for their effectiveness in an injection process, additional properties, other than just adsorption capacity, should be considered. The residence time that the sorbent spends in the ductwork/particulate control device may influence the extent of mercury removal that can be achieved. Two signs of sorbent effectiveness at short residence times are the initial percent breakthrough (inverse of the extent of adsorption) and the slope of the breakthrough curve. Figure 10 displays both the initial percent breakthrough and breakthrough slopes for the sorbents tested at Abbott.

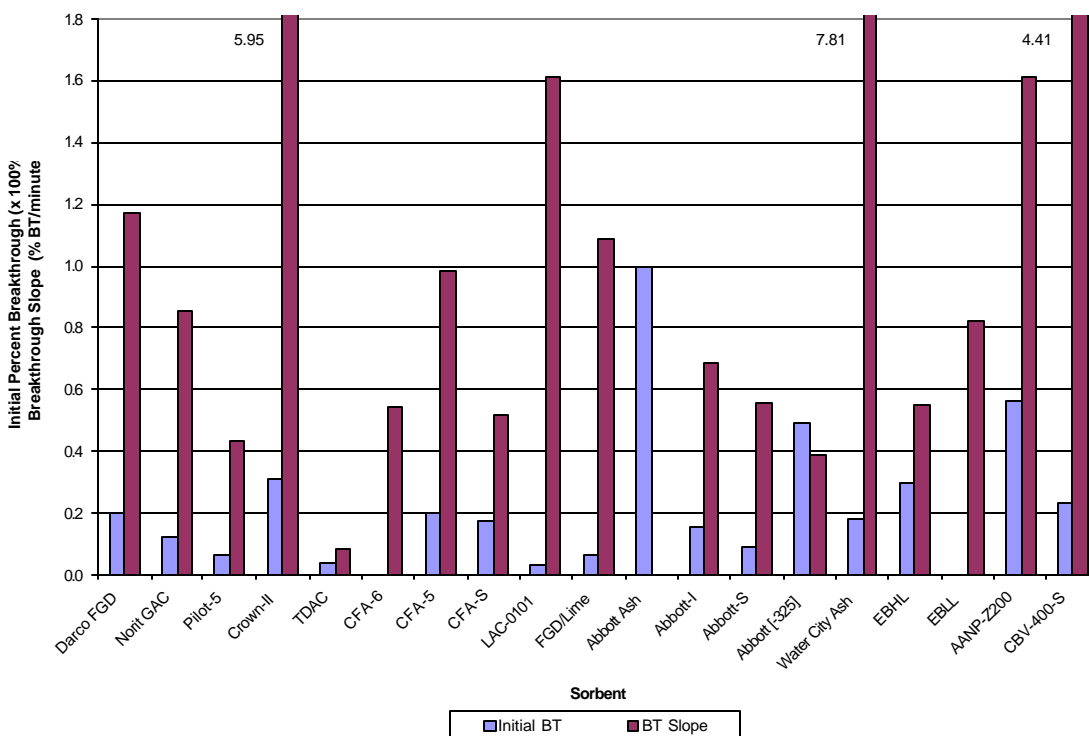


Figure 10. Initial Percent Breakthrough and Breakthrough Slopes: Fixed-Bed Tests Abbott Unit 6.

A desirable sorbent for an injection process would have a low initial percent breakthrough with a high equilibrium capacity. A low initial percent breakthrough is desirable because it represents the ability to immediately adsorb a high percentage of mercury, without the need for any further conditioning. A low breakthrough slope would also be desirable although most effective sorbents display a sharp (e.g., high) slope after a period of low initial breakthrough.

As evident in Figure 10, the majority of sorbents had initial breakthroughs of less than 20% of the inlet mercury level. The sorbents CFA-6 and LAC-0101 not only had the highest capacities of the sorbents tested, but also had extremely low initial percent breakthroughs. Hence, both would be good candidates for sorbent injection. Table 5 ranks each sorbent based on the categories of greatest capacity, lowest initial percent breakthrough and lowest breakthrough curve. Sorbents showing no capacity for mercury adsorption were excluded from all categories.

Table 5. Categorical Ranking of Field Sorbents Abbott Unit 6, 375°F

Ranking	Greatest Ads. Capacity (ug/g sorbent)	Lowest Initial % BT	Lowest BT Slope
1	CFA-6	CFA-6	TDAC
2	LAC-0101	EBLL	Abbott [-325]
3	Norit GAC	LAC-0101	Pilot-5
4	TDAC	TDAC	CFA-S
5	CFA-5	Pilot-5	CFA-6

### Effect of Flue Gas Temperature

Increased flue gas temperature can adversely affect the mercury adsorption capacity of some sorbent materials. Tests were conducted at Abbott Power Plant with seven sorbents to determine the effect of temperature on mercury adsorption. The sorbents tested included two carbon sorbents, one zeolite and four variations of the indigenous fly ash at Abbott. Figure 11 displays the results of the temperature tests.

Results obtained with FGD carbon indicated an appreciable increase in capacity as the flue gas temperature was decreased from 375° to 325°F. These results are similar to those obtained in previous laboratory tests with mercuric chloride and suggest a potential benefit to cooling the Abbott flue gas. Results obtained with a lignite-derived activated carbon, however, showed no appreciable effect of temperature.

Results obtained with Abbott ash indicated that cooling the flue gas would result in increased mercury removal; only the -325 MESH separated sample did not show this effect. Similar improvement was also observed with the AANP zeolite.

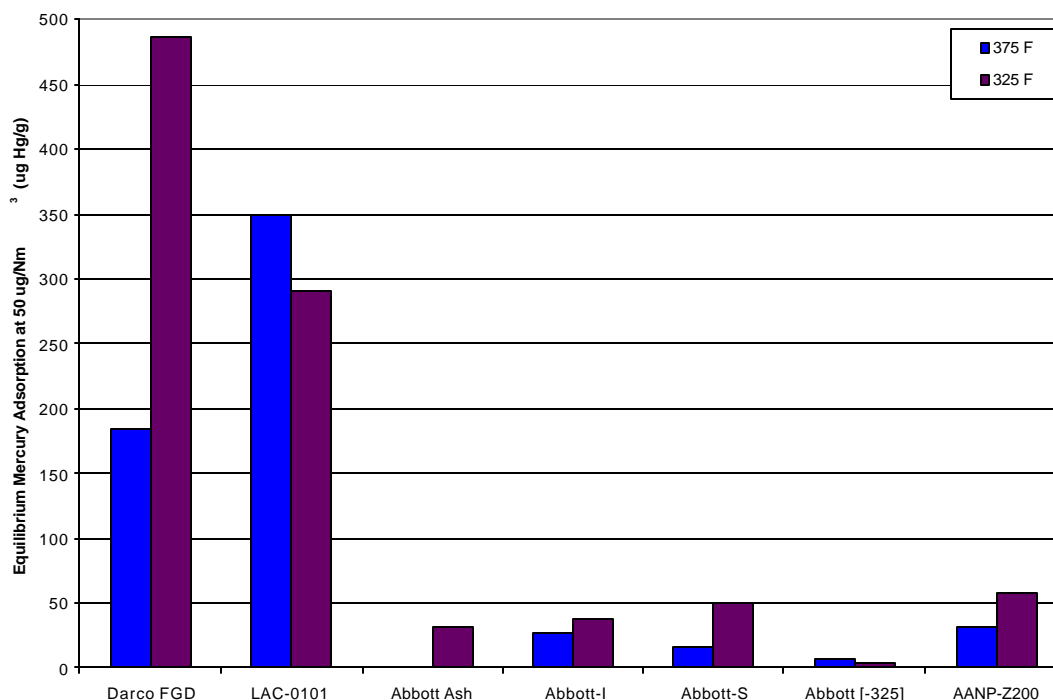


Figure 11. Effect of Temperature on Mercury Adsorption: Fixed-Bed Tests Abbott Power ESP Inlet.

#### Task 4. Full-Scale Carbon Injection Testing at Abbott

Full-scale carbon injection tests were conducted using Abbott Unit 5. Operating parameters for Unit 5 are shown in Table 6. An analysis of the coal currently burned at Abbott is shown in Table 7. The coal analysis from samples collected in 1998 by CONSOL (ICCI Project Number 97-1/5.1A-8(2)) is also shown. The earlier coal sample represents the coal burned during mercury measurements at Abbott in 1998. The results indicated that less than 30% of the mercury is in the elemental form and the oxidized mercury is effectively removed in the scrubber. The results also indicated that there is significant unburned carbon in the fly ash entering the ESP and that 85% of the ash from the coal is bottom ash (only 15% enters the ESP).

Evaluation of baseline mercury removal and the mercury removal effectiveness of three sorbents, commercially available FGD, size segregated FGD, and a corn-derived activated carbon, were conducted during twenty days of testing in July and August 2001 at Abbott Power Plant. The properties of the activated carbons are presented in Table 3. Testing included evaluating the effect of sorbent feed rate and temperature on mercury removal.

Table 6. Abbott Unit 5 Operation

<b>Parameter</b>	<b>Description</b>
<b>Boiler</b>	
Type	Stoker
Equivalent Mwe	11
<b>Coal*</b>	
Coal Type	Bituminous Turris Coal Company Springfield, IL
Heating Value (Btu/lb)	12700
Moisture (%)	16.7
Sulfur (%)	3.84
Ash (%)	10.8
Hg ( $\mu\text{g/g}$ )	0.07
Cl (%)	0.25
Coal Burn Rate (Tons/Day)	135-144
<b>ESP</b>	
Type	Cold-Side
ESP Manufacturer	Precipitator Pollution Control
Design	Sonic Horn Cleaning
Specific Collection Area ( $\text{ft}^2/1000\text{acfm}$ )	551
<b>Process</b>	
Temperature at APH outlet ( $^{\circ}\text{F}$ )	360 - 410
Gas Flow at Inlet (acfm)	65000
Gas Velocity at Inlet (ft/sec)	50
Distance from Inj. Ports to ESP (ft)	50

\*Coal analysis from 7/01 not available

### Baseline Testing

During the first four days of testing, baseline mercury and HCl measurements were made. The baseline mercury measurements were made with analyzers located at the inlet and outlet of the ESP. The HCl concentration in the duct was also measured at the inlet of the ESP by bubbling the flue gas through an impinger and analyzing the sample. The HCl Concentrations varied between 111 and 194 ppm. The concentration of the elemental mercury in the flue gas ranged from 0.6 to 2  $\mu\text{g}/\text{Nm}^3$ , and the total mercury concentration was between 3 and 4  $\mu\text{g}/\text{Nm}^3$  (Tables 8 and 9).

Table 7. Analysis of Coal Burned at Abbott

Ultimate Analysis	<b>6/98*</b> <sup>1</sup>	<b>3/00</b>
Total Moisture	15.64	16.68
Volatile Matter	42.48	40.84
Ash	10.13	10.81
Carbon	70.44	70.18
Hydrogen	5	4.78
Nitrogen	1.28	1.26
Oxygen	8.72	8.88
Sulfur	4.21	3.84
Chlorine	0.23	0.25
Fluorine, ppm	114	
Hg, ppm	0.09	0.07
Heating Value Btu/lb	12731	12719
<b>Mineral Analysis</b>		
SiO <sub>2</sub>	50.88	52.42
Al <sub>2</sub> O <sub>3</sub>	18.68	13.78
TiO <sub>2</sub>	0.93	0.74
Fe <sub>2</sub> O <sub>3</sub>	19.61	21.40
CaO	3.85	3.62
MgO	0.9	0.55
Na <sub>2</sub> O	1.66	1.50
K <sub>2</sub> O	2.21	1.34
P <sub>2</sub> O <sub>5</sub>	0.16	0.06
SO <sub>3</sub>	1.92	3.76
Undetermined	-.79	0.71

\* Average of 3 samples, all values dry basis

Table 8. HCl measured at Abbott Power Plant, Air Preheater Outlet.

Test ID	Date	HCl (ppm)
7014-Cl-2	7/14/2001	194
7014-Cl-1	7/14/2001	111
7014-Cl-1A	8/16/2001	141
7014-Cl-2A	8/17/2001	182
7014-Cl-3A	8/17/2001	120
7014-Cl-4A	8/17/2001	166
7014-Cl-5A	8/17/2001	143

Table 9. Flue Gas Mercury Speciation measured with S-CEM at Abbott Unit 5, 7/29/01

Species	APH Outlet	ESP Inlet	ESP Outlet
Elemental ( $\mu\text{g}/\text{Nm}^3$ )	0.8 to 1.2	0.6 to 2	0.1 to 0.4
Total ( $\mu\text{g}/\text{Nm}^3$ )	3 to 4	3 to 4	1 to 3.2

#### Parametric Testing: Mercury Removal Effectiveness

A series of parametric tests were conducted following the baseline test series. The FGD parametric tests included three days of constant injection (8 hours per day) at a concentration of 15 lb/MMacf (baseline data), two days of injection at four different injection concentrations and one day of sorbent injection with spray cooling at two different sorbent injection concentrations. Following spray cooling tests with the FGD, a day of spray cooling tests with the fine FGD was conducted. The same injection concentrations were repeated with the fine FGD for comparison. Four injection concentrations were tested without spray cooling over the two days. These injection concentrations were 6 to 24 lb/MMacf and were the same as the concentrations tested with the FGD. Two days of testing were scheduled with the corn-derived activated carbon. Three injection concentrations, (6 to 24 lb/MMacf) without spray cooling and 15 lb/MMacf with spray cooling, were evaluated. The test matrix is presented in Table 10. The amounts of carbon used during the full scale injections tests were: FGD, 2600 lb; FGD-Fine, 900 lb, corn-derived carbon, 700 lb. Data collected during the carbon injection tests are summarized in Table 11.

The results from the full-scale carbon injection tests are shown in Figure 12. Total mercury removal ranged from 20% to about 73% depending on the carbon injection rate. No mercury removal was measured between the analyzer downstream of the APH and upstream of the ESP (nominally 1 sec residence time between two analyzers). This indicates that the mercury removal occurred when the flue gas contacted the carbon particles in the ESP. Data also suggest that mercury oxidation (elemental to oxidized) occurred across the ESP.

In general the performance of the corn-derived carbon was similar to that of the commercial FGD carbon. The size-segregated FGD (FGD-Fine with MMD of about 6 microns) removed 60% of the total mercury at carbon injection rate of about 5 lb/MMacf, and increased to 70% when the flue gas was cooled to about 340 °F. These observations support the results from several mathematical models that show external mass transfer

Table 10. Full-Scale Carbon Injection Test Matrix at Abbott Power Plant.

<b>ID</b>	<b>Sorbent</b>	<b>Other Tests</b>	<b>Injection Conc. (lb/MMacf)</b>	<b>Schedule</b>
B1	Baseline	HCl	0	Day 1-4
S1-a	FGD	Cyclone	15	Day 5-7 (8 hrs/day)
S1-b	FGD		6	Day 8 (1-3 hours)
S1-c	FGD		12	Day 8 (1-3 hours)
S1-d	FGD		18	Day 9 (1-3 hours)
S1-e	FGD		24	Day 9 (1-3 hours)
S1-f	FGD	Spray cool	12	Day 10 (1-3 hours)
S1-g	FGD	Spray cool	18	Day 10 (1-3 hours)
S2-a	FGD - Fine	Spray cool	12	Day 11 (1-3 hours)
S2-b	FGD - Fine	Spray cool	18	Day 11 (1-3 hours)
S2-c	FGD - Fine		6	Day 11 (1-3 hours)
S2-d	FGD - Fine		12	Day 11 (1-3 hours)
S2-e	FGD - Fine		18	Day 12 (1-3 hours)
S2-f	FGD - Fine		24	Day 12 (1-3 hours)
B2	Baseline		0	Day 13
S3-a	CFA		6	Day 14 (1-3 hours)
S3-b	CFA		15	Day 14 (1-3 hours)
S3-c	CFA		24	Day 15 (1-3 hours)
S3-d	CFA	Spray cool	15	Day 15 (1-3 hours)

limits mercury capture during carbon injection process. With humidification, the removal with FGD Fine at 5lb/MMacf carbon injection rate was comparable to the removal with FGD at 22 lb/MMacf. These data indicate that the carbon injection rate could be reduced substantially by lowering flue gas temperature and reducing the carbon particle size. Humidification (cooling from 390 to 340 °F) also improved the performance of the FGD and corn-derived carbons.

#### Plant Operation

The following observations were made during the full-scale carbon injection testing at Abbott Power Plant.

- Flue gas temperature at carbon injection port: inlet temperature ranged from 340 to 390°F during evaluations.

Table 11. Data Collected During Injection Tests.

<b>Parameter</b>	<b>Sample/Signal/Test</b>	<b>Frequency (Test IDs)</b>
HCl at ESP inlet	Manual (specific ion electrode (SIE))	B1
Duct Velocity	Full Traverse – inlet and outlet of ESP	B1
Carbon in outlet, ash loading and size distribution	LOI test on particulate Cyclones	S1-a
Mercury ESP inlet 1 and outlet of ESP	S-CEM	All
Mercury at inlet 2	S-CEM	S1-x, S2-x, S3-x
Coal	Batch sample: Hg, Chlorine, sulfur	All, Sample Daily
ESP Ash	Batch sample: Hg, LOI, carbon migration	B1, S1-a
Coal	Plant Signals: burn rate (lb/hr), quality (lb/MMBTU, %ash)	All
Unit Operation	Plant Signals: Steam flow, stack flow NO <sub>x</sub> , SO <sub>2</sub> , O <sub>2</sub> , Opacity	All
Temperature	Analyzer probe: ESP Inlet and Outlet	All
ESP Operation	ESP power, spark rate, etc. as available	All
Sorbent Injection	Batch calibration of feeder	S1-x, S2-x, S3-x
Humidification rate	Flow meter on lances	S1-f, S1-g, S2-a, S2-b, S3-d

- ESP performance: no effect on ESP secondary current or voltage due to sorbent injection or humidification was noted.
- Effect of soot blowing on Hg concentrations: soot blowing caused a spike in temperature and mercury concentrations as measured at all three analyzers. The system often took two to three hours to return to pre-soot blowing mercury levels.

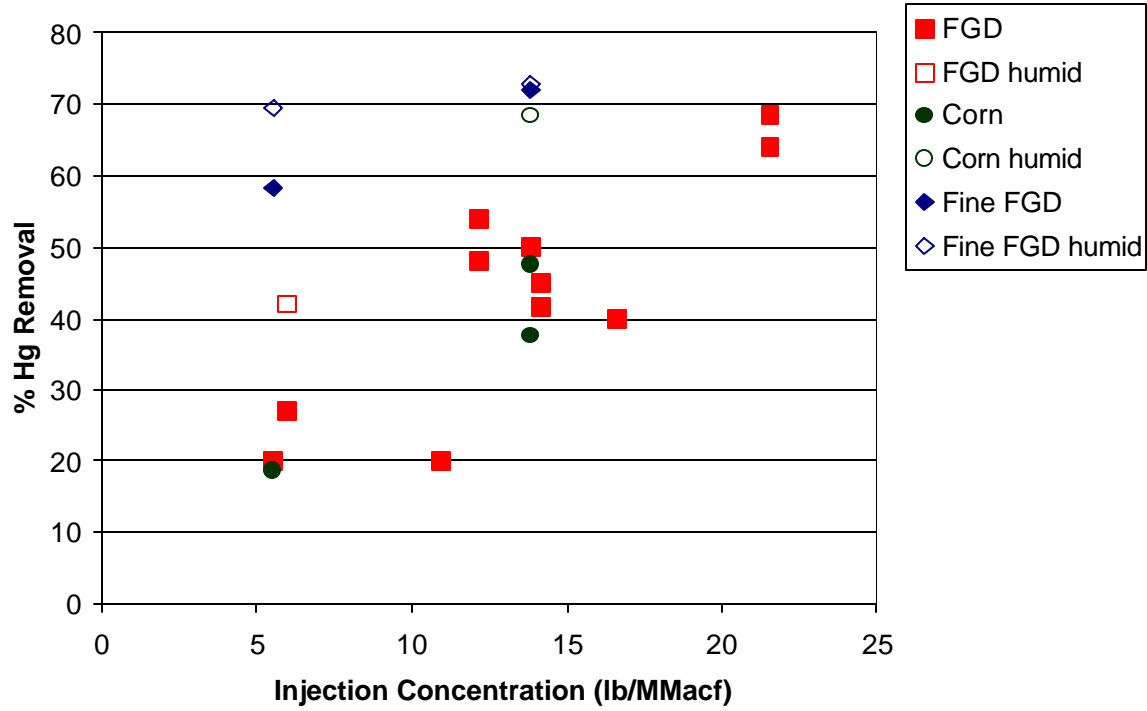


Figure 12. Performance comparison of FGD, Corn and Fine FGD activated carbons.

### Task 5. Data Analysis and Process Engineering

The activities of this task were presented under Tasks 3 and 4.

### Task 6. Project Management and Reporting.

Monthly Progress Reports and a Final Technical and Management Report were prepared and submitted to the ICCI.

## CONCLUSIONS AND RECOMMENDATIONS

The objective of this program was to evaluate sorbent injection for mercury removal in flue gas derived from Illinois bituminous coal. As part of this evaluation, the first full-scale demonstration of carbon injection for mercury control at an Illinois coal-fired power plant was performed. This test was carried out at the University of Illinois Abbott power plant located in Champaign, Illinois, during summer 2001. Fixed-bed (bench-scale) mercury tests were performed to screen the performance of potential sorbents in a flue gas simulating that at the Abbott plant and using a flue gas slipstream obtained just downstream of the air pre-heater and upstream of the ESP of the Unit 6 (a 12 Megawatt stoker-boiler). The duct temperature at this location ranged from 380°-420°F during the testing period. The objective of the bench scale tests was to evaluate the relative performance of different mercury sorbents to determine the most appropriate samples and test conditions to design the subsequent full-scale tests.

The mercury adsorption capacity of 19 different sorbents was evaluated in bench-scale studies (both simulated flue gas and slipstream of flue gas at Abbott). These tests were performed by URS Corporation. The sorbents tested included two commercial activated carbons Norit America's (FGD and GAC), activated carbons derived from Illinois bituminous coal (Pilot-5), tire (TDAC), corn byproducts (CAF), lignite (LAC), several fly ash samples including as-received and chemically and physically modified fly ash samples from Abbott and fly ash samples from a commercial eastern bituminous fly ash beneficiation process (EBHL, EBL), and two zeolite samples (AANP and CBV).

General observations made during the fixed-bed sorbent testing included the following:

- Many carbon samples showed good capacities (375°F) in the Abbott Power ESP inlet flue gas, with most adsorbing over 100 µg Hg/g (normalized to 50 µg/Nm<sup>3</sup>).
- In general, the carbon-based sorbents had significantly higher capacities than the fly ash or zeolite-based sorbents. However, the cheaper cost of many of these latter sorbents, as compared to carbon sorbents, could possibly outweigh their poorer performance.
- Fixed-bed tests at Abbott gave essentially the same results as tests carried out with simulated flue gas.
- "As-received" fly ash from Abbott showed no capacity for mercury at a temperature of 375°F. Size-separation and sulfur-impregnation of the Abbott fly ash resulted in enhanced mercury removal. These results suggest that size-separation and/or sulfur impregnation prior to re-injection of fly ash may improve mercury removal by the indigenous ash.
- Results obtained with two samples produced in a commercial fly ash beneficiation process, operating at a site with eastern bituminous fly ash, showed that a sample containing high levels of LOI carbon adsorbed more mercury than a sample containing low LOI carbon levels. These results are similar to those observed in bench scale tests.
- A sieved natural zeolite (AANP-Z200) showed better mercury adsorption than a sulfur-impregnated (commercial) zeolite (CBV). These results are consistent with

laboratory tests that showed that the AANP zeolite displayed higher levels of mercuric chloride adsorption than the CBV sample.

Apogee Scientific Inc., performed full-scale carbon injection tests at Abbott Power Plant. The plant is a cogeneration facility producing both steam and electricity and has a nameplate capacity of 30 MW. There are three boilers at the plant, all spreader-stokers. Abbott Units 5, 6 and 7 have dedicated boilers and ESPs. Effluent from these three units combines before entering single water pre-scrubber and a Chiyoda CT-121 flue gas desulfurization unit. The boilers burn a bituminous coal from a mine near Springfield, IL. Full-scale tests were carried out using Unit 5 (12 Megawatt). The sorbents were injected downstream of the air pre-heater, upstream of the ESP. The duct temperature at this location ranged from 380°-420°F during the testing period and averaged approximately 390°F. The analyzers were located upstream of sorbent injection, at the inlet of the ESP, and at the outlet of the ESP.

Base line tests revealed that the HCl concentration in the flue gas varied between 111 and 194 ppm. The concentration of elemental mercury in the flue gas ranged from 0.6 to 2  $\mu\text{g}/\text{Nm}^3$ , and the total mercury concentration was between 3 and 4  $\mu\text{g}/\text{Nm}^3$ .

A series of parametric tests were conducted with three activated carbons following the baseline test series. The carbons included a corn-derived activated carbon, Norit America's FGD, and a size-segregated FGD (Fine FGD). The corn-derived activated carbon was prepared in a pilot-scale rotary kiln. The mass mean diameters of the corn and FGD carbons were about 16 and 18 microns, respectively, and that of the Fine FGD was about 6 microns. The surface areas of the carbons were 400 to 510  $\text{m}^2/\text{g}$ . Carbon injection concentrations were 6 to 24 lb/MMacf.

Total mercury removal ranged from 20% to about 73% depending on the carbon injection rate. No mercury removal was measured between the analyzers downstream of the APH and upstream of the ESP (nominally 1 sec residence time between two analyzers). This indicates that the mercury removal occurred mainly across the ESP. Data also suggest that mercury oxidation (elemental to oxidized) occurred across the ESP. In general the performance of the corn-derived carbon was similar to that of the commercial FGD carbon. Fine FGD removed 60% of the total mercury at a carbon injection rate of about 5 lb/MMacf, and increased to 70% when the flue gas was cooled (spray cooling) to about 340 °F. With humidification, the removal with FGD Fine at 5lb/MMacf carbon injection rate was comparable with the removal observed with FGD at 22 lb/MMacf. These data indicate that the carbon injection rate could be reduced substantially by lowering the flue gas temperature and reducing the carbon particle size. Humidification (cooling from 390 to 340 °F) also improved the performance of the FGD and corn-derived carbons. Carbon injection and flue gas humidification had no effect on ESP operation, including secondary current or voltage.

The results from this study show that control technologies using injection of powdered activated carbon offer the potential to provide significant mercury removal from the flue gas of utility boilers burning high-sulfur Illinois bituminous coal. It is likely that most

power plants burning high-sulfur coal has installed wet scrubbers for SO<sub>2</sub> control. Wet scrubbers can effectively remove more than 90% of the oxidized mercury in flue gas. Since high-sulfur Illinois bituminous coals generally have high oxidized mercury concentrations, wet scrubbers alone may be sufficient to remove >80% of the flue gas mercury from these coals. If future regulations require mercury removal of greater than 90%, activated carbon may need to be injected before the existing ESP to capture some of the mercury. Alternatively, carbon injection could be used downstream of the ESP but before a polishing fabric filter. This configuration permits recycling of the carbon to increase its utilization.

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