Ultra-High Efficiency ESP Development for Fine Particulate and Air Toxics Control – Phase I and II Mercury Removal Investigations

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ABSTRACT

In Phase I of an ABB/DOE research program to develop cost-effective retrofit technologies to improve collection of fine particles and air toxics in electrostatic precipitators (ESPs), test campaigns were conducted in ABB's pilot test facility to evaluate the performance impacts of flue gas cooling, flue gas humidification, pulsed ESP energization and sorbent injection. Each technology was found to provide performance improvements while firing a variety of coals, with cumulative benefits often observed. This paper focuses on the mercury control investigations performed on three coals generating fly ash that is traditionally difficult to collect, presenting results from the Phase I tests and plans for slipstream field testing in Phase II of the program.

INTRODUCTION AND OBJECTIVE

Because approximately ninety percent of U.S. coal-fired utility boilers are already equipped with electrostatic precipitators (ESPs),[1] retrofittable ESP technologies are the only viable means to achieve the Department of Energy's (DOE) goal of a major reduction in fine particulate and mercury emissions (air toxics). EPA's recent issuance of significantly tightened ambient air standards for particles smaller than 2.5 μm ($PM_{2.5}$) creates a new urgency for developing cost-effective means to control fine particulate emissions. This challenge is compounded by the on-going switch in the utility industry to low-sulfur Powder River Basin (PRB) coals, which may generate higher resistivity and difficult-to-collect fly ash. Particulate emissions can increase by a factor of ten when a utility switches to a low-sulfur coal, often resulting in a capacity reduction from the reduced ability of the ESPs to control opacity at high loads.

In Phase I of this program, ABB investigated five technologies to improve the collection of fine particulates and trace metals in ESPs. These technologies included: (i) flue gas cooling, (ii) flue gas humidification, (iii) pulsed energization, (iv) wet ESP and precharger modules, and (v) sorbent injection for mercury control. Extensive tests were conducted with an Eastern bituminous coal and a Powder River Basin sub-bituminous low sulfur coal in an integrated pilot-scale combustor and ESP test facility. The impacts of each retrofit technology on ESP performance, individually and in combination, were evaluated in depth through advanced sampling and measurement techniques. Phase I testing clearly showed that controlling ESP inlet temperature and humidity, in combination with pulsing, was key to effective collection of fine particulates and mercury from low-sulfur coals.

This paper focuses on the mercury control investigations performed in ABB's pilot test facility during the Phase I DOE program and subsequent test campaigns. During the Phase I campaign, it was determined that one of the most effective means of increasing ESP efficiency as well as reducing mercury emissions was to improve fine particulate control. Findings from the Phase I investigations of particulate emissions have been presented in detail elsewhere.[2]

APPROACH AND PROJECT DESCRIPTION

PILOT-SCALE TESTING

The extent of capture of trace metals, especially vapor phase species such as mercury, was determined for the various ESP performance enhancement techniques evaluated in the Phase I test program; namely, flue gas cooling, flue gas humidification and pulsed energization. In addition, ABB examined the possibility of augmenting the positive effects of activated carbon injection, a technique being investigated by several researchers for mercury control. The unique aspect of the ABB approach was to combine activated carbon injection with flue gas cooling. This synergistic approach is expected to decrease the carbon requirements for achieving a prescribed mercury capture efficiency, thus decreasing operating costs for mercury control. One of the Phase I program targets was evaluation of whether flue gas cooling improves the performance of the activated carbon for mercury capture.

Test Facility

Experimental testing was conducted on a pilot scale (3.5 MMBtu/hr - 1 MW_{th}) facility consisting of a combustor, a furnace gas cooling loop and a mobile pilot ESP (Figure 1). The pulverized coal-fired combustor simulated the time-temperature-oxygen concentration profile of a field unit, ensuring that the fly ash-vapor phase species partitioning replicated that of a field unit. The flue gases were cooled by a series of water-cooled heat exchangers and water-cooled ducts. The final temperature control was performed automatically by an air-cooled heat exchanger. Stable and accurate control of the flue gas temperature, to within +/- 2^{o}C, was achieved during the tests.

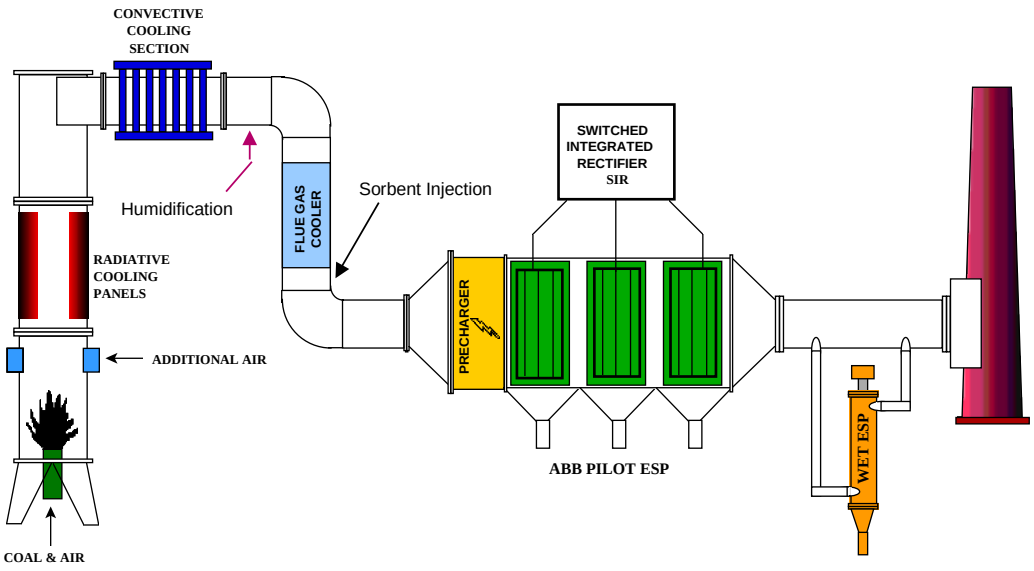


Figure 1 ABB Integrated Combustor - ESP Pilot Test Facility

The ABB pilot ESP was designed to provide extremely high collection efficiencies while effectively modeling full-scale operation. The ESP had three electrical fields, each equipped with an advanced power supply (developed by ABB) called a Switched Integrated Rectifier (SIR). The SIR units allowed more flexible wave forms compared with conventional power supplies, and higher voltage operation without sparkover. The range of specific collection areas

(SCA), the electrode to plate spacing and the three-field configuration of the pilot ESP all contributed to a realistic simulation of full-scale ESP phenomena during the Phase I test program.

A controlled portion of the flue gas leaving the dry ESP was routed to the wet ESP test section (Figure 1), supplied by ADA Technologies, Inc., of Englewood, Colorado. The wet ESP test section consisted of a tube with a smooth, weighted wire discharge electrode hung in the center. A sheath of water flowed down the length of the tube when the unit was operated in a wet mode. Tests were performed both with and without the water flow to measure the improvement due to "wet" operation.

Measurement Methods

On-line opacity monitoring was the principal method used for measuring ESP emissions performance. Particulate loading was measured at the dry ESP inlet and outlet and at the wet ESP outlet. A modified version of EPA Method 5/29 was used for gravimetric measurements and trace metal determinations. The Ontario Hydro method (Figure 2) was also utilized for trace metal measurements. A fraction of each recovered Ontario Hydro method train sample was used for mercury analysis.

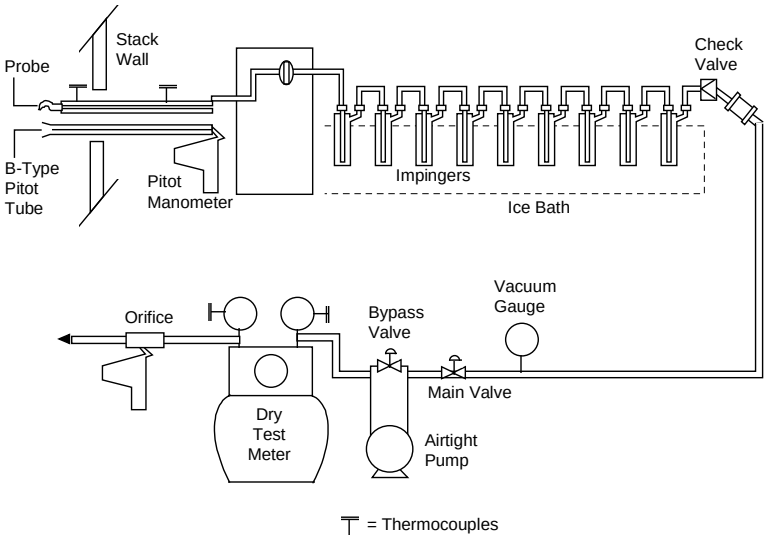


Figure 2 Isokinetic Sampling Train for Gravimetric and Metals Loadings

Gravimetric measurements were made at the ESP inlet and outlet using a total filter and a flue gas flow meter. Mass size distributions of the ash entering and leaving the ESP were obtained with a Berner-type low pressure impactor (BLPI).[3,4] Details of the ESP inlet and outlet particulate measurement techniques were reported earlier.[2]

Vapor phase mercury measurements were made using a modification of the Mercury Speciation Adsorption (MESA) method (Figure 3).[5] The modified MESA system employs two iodated carbon traps assembled in series, with a quartz wool plug installed within a quartz probe upstream of the traps. Particulates in the sampled flue gas were trapped in the quartz wool. The iodated carbon traps were analyzed for the mercury by Cold Vapor Atomic Fluorescence spectroscopy and the data were converted to a vapor phase mercury concentration in the flue gas. MESA measurements were conducted at the dry (main) ESP inlet and outlet, and at the wet ESP outlet.

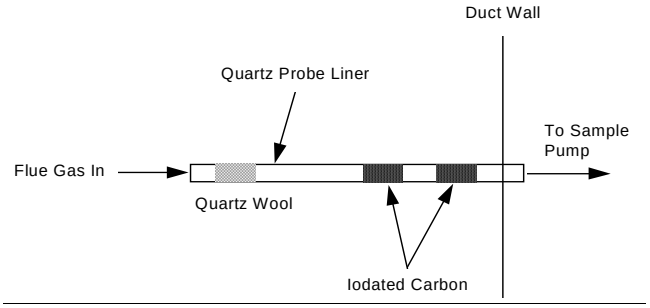


Figure 3 Sketch of Modified Mercury Specification Adsorption (MESA) Sampling Train for Total Mercury Measurements

Test Fuel Description

Results of ASTM analyses on the test coals are shown in Table 1. The test coals for the Phase I program were selected for their representation of coals widely used by U.S. utilities, particularly those coals which are attractive from the standpoint of sulfur emissions reduction. The test coals were also selected for their tendency to form fly ash that is relatively difficult to collect, being relatively low in sulfur, sodium and iron. Technologies that were shown in this program to provide ESP performance improvements with these difficult fuels, should prove advantageous in a broad variety of applications in which performance improvements are desired.

RESULTS

Phase I Test Results

The ABB Phase I program included three test campaigns at the ABB integrated pilot combustor and ESP facility. The first campaign occurred in June 1996, and utilized a low-sulfur, Eastern Kentucky bituminous coal. The second test campaign occurred in November 1996, and evaluated a Powder River Basin sub-bituminous coal. Testing unique to this campaign included in-situ fly ash resistivity measurements, and performance evaluations of a wet ESP module. The fly ash resistivity and mercury measurements for this campaign were performed by ADA Technologies.

A third test campaign (May 1997) was conducted on a medium-sulfur eastern bituminous coal. The objective of these tests was to determine mercury removal with an ESP as a function of flue gas temperature both with and without use of injected sorbent. Mercury concentration measurements were conducted by Advanced Technology Systems, Inc., of Monroeville, PA. The sorbent used was powdered activated carbon from Norit Americas, Inc.

Measurements of mercury emissions from the pilot ESP were made during all three pilot test campaigns. The main objective of the first two measurement campaigns, with the Eastern Kentucky bituminous coal (June 1996) and the Powder River Basin coal (November 1996), was to determine mercury concentrations entering and leaving the ESP as a function of flue gas temperature. Flue gas temperature was expected to impact the condensation of mercury species on to the fly ash. Hence, the removal efficiencies were expected to be different for the different flue gas temperature conditions.

Test results from the mercury investigations in each campaign follow, with results presented chronologically.

East Kentucky Coal (Bituminous): Limited mercury measurements were obtained with the East Kentucky bituminous coal. Method 29 was used for all tests. Since there is some debate surrounding the reliability of mercury speciation using this method, only the total mercury concentrations are presented. Measurements were conducted at the ESP inlet and outlet for two flue gas temperatures: 100^{o}C and 150^{o}C. Data are shown in Table 2.

Mercury concentrations at the outlet were below detection limits for both the conditions using the Method 29 sampling technique. Mercury concentrations at the inlet were also low, but detectable. The inlet concentration was 1.36 μg/Nm^3 at 150°C and 0.661 μg/Nm^3 at 100°C.

Lower dust concentrations were also measured at the ESP inlet when flue gas temperature was lowered. This was a result of increased ash dropout in the flue gas ducts due to the lower gas velocity at the lower flue gas temperature. Dust concentrations were measured to be 1.26 g/Nm^3 at 100°C and 2.42 gm/Nm^3 at 150°C. The lower inlet concentration at the lower flue gas temperature, in conjunction with the below-detection-limit measurements at the ESP outlet, suggests that the mercury was mainly condensed on the ash and any associated unburned carbon for these tests. While the levels of unburned carbon in these tests (between 5 and 10 percent) do not typically affect precipitator performance, they are quite high relative to the minimum required for mercury capture. It is therefore likely that the unburned carbon in the ash acted as a mercury sorbent. Since most of the mercury was adsorbed on the collected ash (and unburned carbon), the ESP removed the mercury with high efficiency.

Table 1 Test Coal As-Received Proximate and Ultimate Analyses

	East Kentucky	Powder River Basin (PRB)	Eastern Bit. for Sorbent Injection Tests
Proximate Analysis (Weight %)			
Moisture (Total)	5.0	29.2	2.5
Volatile Matter	29.9	30.8	33.2
Fixed Carbon (By Difference)	58.3	34.4	56.3
Ash	6.8	5.5	8.2
Total	100.0	100.0	100.0
Higher Heating Value (Btu/lb)	13,470	8,312	13,565
Ultimate Analysis (Weight %)			
Moisture (Total)	5.0	29.2	2.5
Hydrogen	4.7	3.5	5.2
Carbon	76.5	48.9	78.0
Sulfur	0.5	0.3	0.9
Nitrogen	1.6	0.9	1.6
Oxygen (By Difference)	4.9	11.7	6.1
Ash	6.8	5.5	8.2
Total	100.0	100.0	100.0
Ash Composition (Wt. % of Ash)			
SiO_2	54.5	35.3	54.3
Al_2O_3	32.4	19.0	32.5
Fe_2O_3	5.5	4.8	5.2
CaO	0.9	20.3	1.1
MgO	0.7	3.8	0.9
Na_2O	0.9	1.4	0.5
K_2O	2.5	0.6	3.1
TiO_2	1.7	1.5	1.4
P_2O_5	0.3	0.9	0.1
SO_3	0.5	11.5	0.8
Total	99.9	100.0	100.3

Table 2 Mercury Measurement Results For East Kentucky Bituminous Coal

Test #	Location	Method	Temperature (^oC)	Total Hg Concentration (μg/Nm3)
16	Main ESP Inlet	Method 29	150	1.36
15	Main ESP Outlet	Method 29	150	< 0.4
14	Main ESP Inlet	Method 29	100	0.66
13	Main ESP Outlet	Method 29	100	< 0.4

Note: Back half, HNO_3, $KMNO_4$ and HCl impingers had Hg levels below method detection limits for all samples. Data are shown only for front half.

Powder River Basin Coal (Sub-Bituminous): Mercury data for various tests with the PRB coal are summarized in Table 3. Both Method 29 and iodated carbon traps (modified Frontier Geosciences Method) were used for determining mercury concentrations in the flue gas. During these tests, both the main ESP and the wet ESP section, downstream of the main ESP, were in operation.

Table 3 Mercury Measurement Results For Powder River Basin Coal

Test #	Location	Method	Temperatures (^oC)	Hg Concentration Total (μg/Nm3)	Hg Concentration Vapor (μg/Nm3)
1	Main ESP Inlet	Iodated Carbon Trap	(155)	13.51	11.62
2	Main ESP Outlet	Method 29	155	14.1	--
3	Wet ESP Out (Water On/Power On)	Iodated Carbon Trap	152/132/75**	9.63	9.35
4	Main ESP Outlet	Iodated Carbon Trap	155	6.41	6.41
5	Wet ESP Out (Water Off/Power On)	Iodated Carbon Trap	152/134 /120**	13.76	13.66
6	Wet ESP Out (Water On/Power Off)	Iodated Carbon Trap	152/132/75**	5.89	5.58
7	Main ESP Inlet	Method 29	135	7.2	---
8	Main ESP Outlet	Method 29	130	8.8	
9	Main ESP Outlet	Iodated Carbon Trap	130	6.04	6.04
10	Main ESP Outlet	Iodated Carbon Trap	130	6.14	6.14
11	Wet ESP (Water On/Power On)	Iodated Carbon Trap	130/117/--**	4.19	4.02

** Temperature at Main ESP Outlet / Wet ESP Inlet / Wet ESP Outlet

The PRB coal had 0.17 ppm (by weight) Hg, translating to about 15 μg/Nm^3 Hg in the flue gas. Carbon levels in the ash were very low (below 3 percent). Mercury concentrations measured in the flue gas were approximately 14 μg/Nm^3, matching the calculated value (Table 3). Vapor concentrations were also quite high (11-12 μg/Nm^3) and close to the total mercury concentration. This is in stark contrast to the testing with the East Kentucky coal, where most of the mercury was adsorbed on the ash.

Very little Hg removal occurred across the main ESP (Test 1) or across the "wet" ESP section when operated in a dry mode (Test 5) at the high temperature. The data in Table 3 show the large impact of flue gas temperature on mercury removal from the flue gas. The inlet concentration of about 14 μg/Nm^3 at 155^{o}C corresponds to the value of 0.17 ppm Hg measured in the coal. When the flue gas temperature was lowered (Test 7), the inlet mercury loading decreased by a factor of two to 7.2 mg/Nm^3 at 135^{o}C. The concentrations at the main ESP outlet at this operating condition (Tests 8-10) were in the range of 6-8.8 mg/Nm^3 at 130^{o}C, again indicating minimal removal across the ESP during the Powder River Basin coal tests. It is concluded that mercury adsorption at the lower flue gas temperature must have occurred on the ash deposited in the flue gas ducts leading up to the ESP.

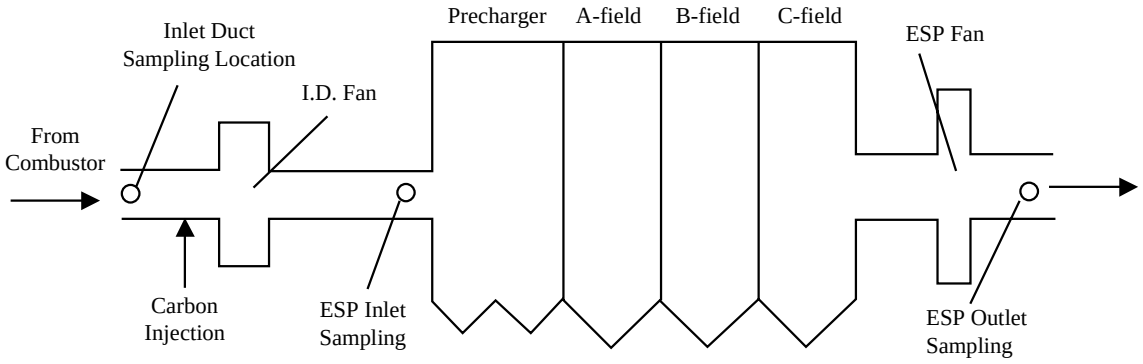
When the wet ESP was operated in a "wet" mode, the flue gas was cooled significantly because of water evaporation. This was evident in the temperature differential between the inlet and the outlet of the wet ESP (Table 3). A portion of the flue gas mercury was removed in the wet ESP due to this large temperature drop (Tests 6, 11).

The preferential removal of mercury with flue gas cooling highlights the importance of maintaining low flue gas temperatures in particulate removal devices. A lower flue gas temperature can also be synergistic with sorbent injection schemes and will result in lower sorbent consumption and increased mercury capture.

Eastern Bituminous Low Sulfur Coal #2: Additional mercury capture investigations were performed to follow up these interesting results. The main objective was to measure sorbent performance as a function of flue gas temperature in conjunction with ongoing combustion tests at ABB's pilot facility.

Vapor phase mercury measurements were made using a modification of the Mercury Speciation Adsorption (MESA) method, described earlier. The sorbent used in these tests was a lignite-based activated carbon manufactured specifically for the removal of heavy metals and other contaminants found in incinerator flue gases (DARCO FGD, from Norit Americas, Inc.). It has been quite effective for the removal of gaseous mercury in incinerator flue gas, suggesting that it is quite active for capture of oxidized mercury species. The sorbent was injected upstream of the ESP at a location such that the residence time from the point of injection to the ESP inlet was about one second. A schematic of the sampling locations during these tests is shown in Figure 4.

Figure 4 Sampling and Carbon Injection Locations During Mercury Capture Testing (May 1997)



Vapor phase mercury measurements with the modified MESA method were performed at an inlet duct location upstream of carbon injection, at the ESP inlet and at the ESP outlet. Ontario Hydro method for mercury speciation, a method modified from EPA Method 29, was used at the ESP inlet and ESP outlet locations. Detailed data on mercury concentrations at the different locations obtained with these methods are provided in Tables 4, 5 and 6 for the different operating conditions. The test matrix included 4 different operating conditions: with and without

carbon injection at low flue gas temperature (100°C), and with and without carbon injection at high flue gas temperature (140°C).

Table 4 Mercury Measurement Results For Eastern Bituminous Coal At 100°C (May '97)

Test #	Carbon Injection C:Hg	Location	Method	Temp. (°C)	Total Hg Concentration (μg/Nm3)	Vapor Hg Concentration (μg/Nm3)	Vapor Hg Conc. (Oxidized) (μg/Nm3)	Vapor Hg Conc. (Elemental) (μg/Nm3)
1	0	Inlet Duct	Iod. Carbon Trap	100		1.26		
2	0	Main ESP In	Iod. Carbon Trap	100		0.86		
3	0	Main ESP Out	Iod. Carbon Trap	100		0.56		
4	180,000	Inlet Duct	Iod. Carbon Trap	100		1.57		
5	180,000	Main ESP In	Iod. Carbon Trap	100		0.23		
6	180,000	Main ESP Out	Iod. Carbon Trap	100		< 0.02		
7	0	Main ESP In	Ontario Hydro	100	1.69	0.41	0.27	0.14
8	0	Main ESP Out	Ontario Hydro	100	0.67	0.66	0.47	0.18
9	180,000	Main ESP In	Ontario Hydro	100	---	--	--	--
10	180,000	Main ESP Out	Ontario Hydro	100	0.07	< 0.005	< 0.005	< 0.005

Table 5 Mercury Measurement Results For Eastern Bituminous Coal At 100°C – Test Round 2 (May '97)

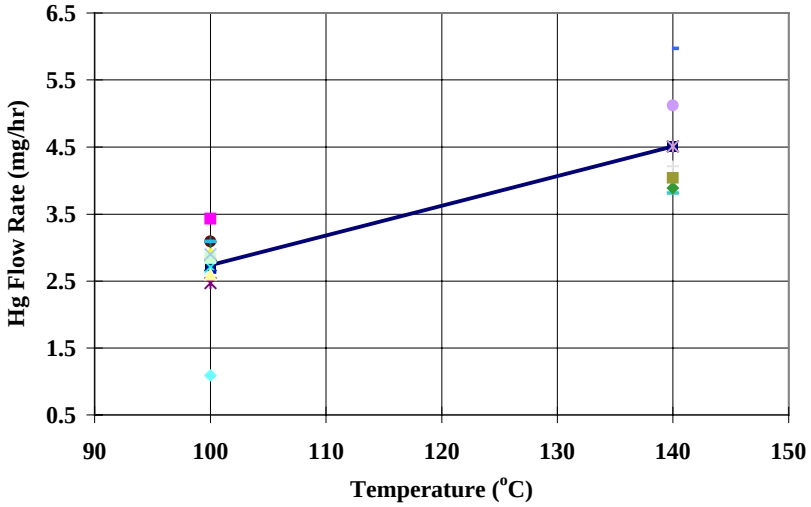
Test #	Carbon Injection C:Hg	Location	Method	Temp. (°C)	Total Hg Concentration (µg/Nm3)	Vapor Hg Concentration (µg/Nm3)	Vapor Hg Conc. (Oxidized) (µg/Nm3)	Vapor Hg Conc. (Elemental) (µg/Nm3)
1	0	Inlet Duct	Iodated Carbon Trap	100		1.97		
2	0	Main ESP Inlet	Iodated Carbon Trap	100		1.95		
3	0	Main ESP Outlet	Iodated Carbon Trap	100		1.51		
4	40,000	Inlet Duct	Iodated Carbon Trap	100		1.98		
5	40,000	Main ESP Inlet	Iodated Carbon Trap	100		0.15		
6	40,000	Main ESP Outlet	Iodated Carbon Trap	100		0.18		
7	0	Main ESP Inlet	Ontario Hydro	100	2.66	1.29	0.96	0.33
8	0	Main ESP Outlet	Ontario Hydro	100	1.50	1.49	1.34	0.15
9	40,000	Main ESP Inlet	Ontario Hydro	100	---	----	----	---
10	40,000	Main ESP Outlet	Ontario Hydro	100	0.29	0.18	0.15	< 0.005

Table 6 Mercury Measurement Results For Eastern Bituminous Coal At 140°C (May '97)

Test #	Carbon Injection C:Hg	Location	Method	Temp. (°C)	Total Hg Concentration (µg/Nm3)	Vapor Hg Concentration (µg/Nm3)	Vapor Hg Conc. (Oxidized) (µg/Nm3)	Vapor Hg Conc. (Elemental) (µg/Nm3)
1	0	Inlet Duct	Iodated Carbon Trap	140		3.58		
2	0	Main ESP Inlet	Iodated Carbon Trap	140		3.28		
3	0	Main ESP Outlet	Iodated Carbon Trap	140		2.56		
4	40,000	Inlet Duct	Iodated Carbon Trap	140		2.88		
5	40,000	Main ESP Inlet	Iodated Carbon Trap	140		0.44		
6	40,000	Main ESP Outlet	Iodated Carbon Trap	140		0.48		
7	0	Main ESP Inlet	Ontario Hydro	140	2.43	1.58	1.19	0.39
8	0	Main ESP Outlet	Ontario Hydro	140	3.81	3.75	1.59	2.16
9	40,000	Main ESP Inlet	Ontario Hydro	140	----	----	----	----
10	40,000	Main ESP Outlet	Ontario Hydro	140	0.46	0.45	0.4	< 0.10

Sorbent loadings were such that the carbon to mercury ratio was 40,000:1. A higher carbon to mercury ratio of 180,000:1 was also tested. Several first-of-a kind observations resulted from this test campaign. The inlet concentrations of vapor phase mercury as a function of flue gas temperature are shown in Figure 5. These data are very similar to those obtained with the PRB coal. More than forty percent of the vapor phase mercury was removed with the ash when the flue gas temperature was lowered from 140°C to 100°C. Note that the carbon levels in the ash were below two percent during these tests. This indicates that the native ash has an adsorption capacity for mercury, which is enhanced by operating at low flue gas temperatures.

Figure 5 Effect Of Flue Gas Temperature On ESP Inlet Mercury Loading



Sorbent performance also improved significantly as the flue gas temperature was decreased. At 140°C, vapor phase mercury removal was about 80 percent (Figure 6). Greater than 90 percent of the vapor phase mercury was removed from the flue gases at 100°C, on the basis of the inlet measurements before carbon injection at this temperature. Carbon flow rates during these tests were 3 g/min, corresponding to a C/Hg ratio of 40,000:1.

Vapor phase mercury measurements at the ESP inlet (Figure 7) indicate values similar to those obtained at the ESP outlet, but with more scatter in the data. The scatter occurs mainly due to the sampling of both particulates and vapor phase mercury at the ESP inlet location, and the potential removal of vapor phase mercury in the quartz wool filter located upstream of the carbon traps in the modified MESA method. At the ESP outlet location, the concentration of ash in the flue gas is very low and the vapor phase mercury data are more accurate, as evidenced by the repeatability in the measurements (Figure 6). The fact that vapor phase mercury concentrations at the ESP inlet location were similar to those at the ESP outlet (Figures 6 and 7) suggests that most of the mercury capture by the sorbent occurred in the duct leading up to the ESP. Given that most of the mercury capture occurred in the flue gas duct, it becomes critical to evaluate the effects of residence time available for sorbent contact and the temperature profile in the duct. These factors will be further evaluated as part of the Phase II project.

Figure 6 Mercury Flow Rates At ESP Outlet With Carbon Injection

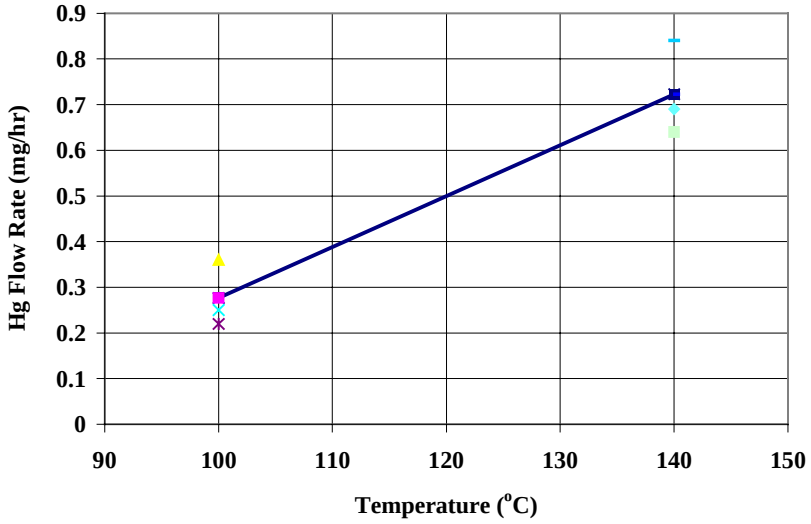
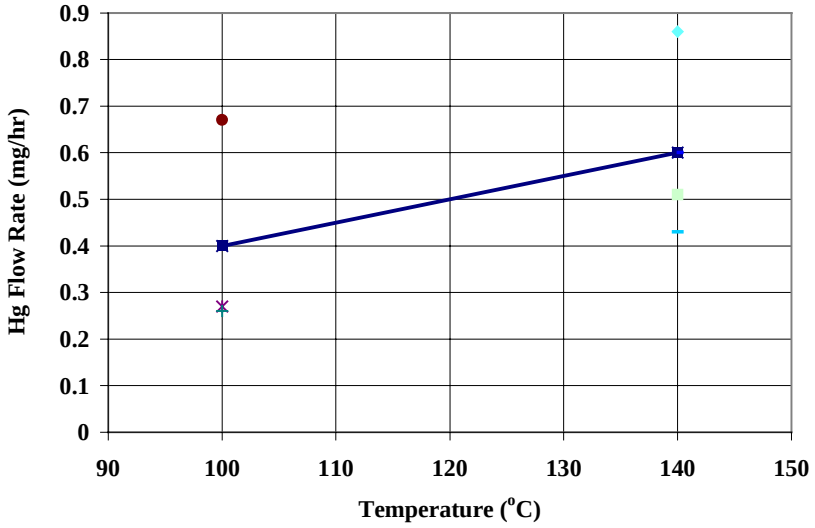
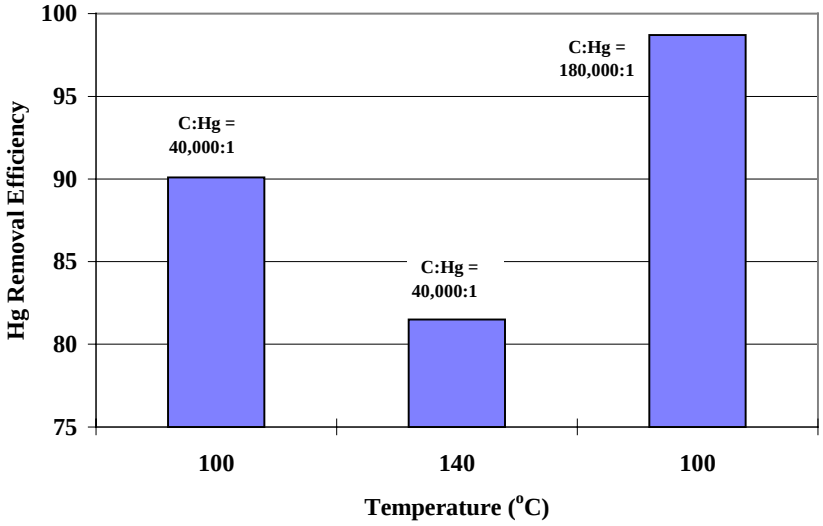


Figure 7 Hg Flow Rates At ESP Inlet With Carbon Injection



Vapor phase mercury removal efficiencies are plotted in Figure 8 for the various flue gas temperatures and sorbent flow rates. Close to 97 percent removal was obtained at carbon to Hg ratios of 180,000:1. Although these sorbent injection rates are very high and not likely economical, these data demonstrate that high capture efficiencies are possible with activated carbon injection.

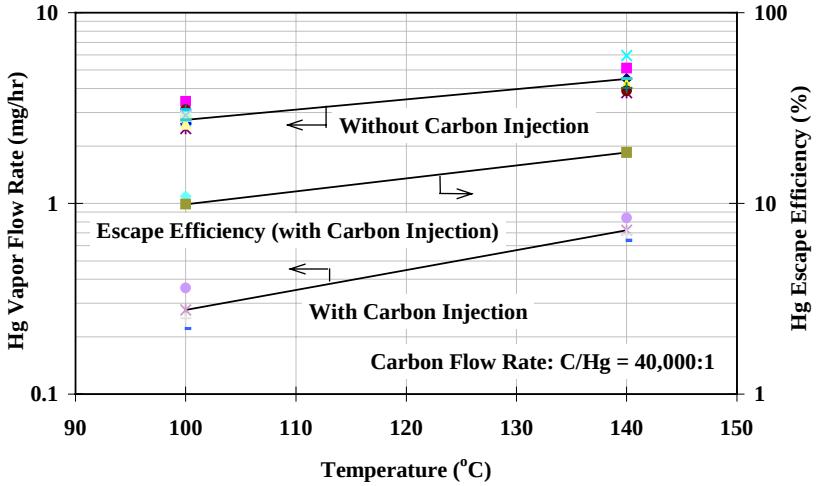
Figure 8 Vapor Phase Hg Removal Efficiencies With Carbon Injection Using ESP



The effect of carbon injection on the ESP operation was also determined in these tests. Opacity data showed that there was little change in the outlet emissions, with carbon injection. Operating voltages also did not change, indicating little impact on ESP operation. ESP collection efficiencies were consistently above 99 percent for all cases. Due to the short-term nature of the tests conducted here, it is not possible to extrapolate what will happen to ESP performance with continuous long-term carbon injection. Long-term operation and carbon re-entrainment remain issues that will be addressed in Phase II.

A summary plot of the vapor phase mercury capture tests is provided in Figure 9. The testing performed in Phase I unambiguously demonstrated the synergism between operation at low flue gas temperature and activated sorbent injection for mercury control during coal combustion.

Figure 9 Vapor Phase Hg Capture Testing In Pilot ESP: Effect Of Carbon Injection and Flue Gas Temperature



FUTURE ACTIVITIES

PHASE II FIELD TEST PLANS

Background

In Phase II of the ABB/DOE research project, ABB will conduct a field test program at Commonwealth Edison's Waukegan Station Unit 8, located in Waukegan, Illinois. The testing will occur on the same pilot-scale ESP unit utilized in Phase I, configured in Phase II for slipstream operation. Up to 20,000 pounds per hour of flue gas will be extracted from the inlet of the Unit 8 precipitator by means of a 24-point sampling grid with nozzles sized for isokinetic flow. The flue gas will then be conditioned by means of heaters, coolers and a humidification system to achieve controlled flue gas flow, temperature and moisture content at the pilot ESP inlet.

As in the Phase I campaigns, the focus of the Phase II tests will be determination of the independent and cumulative impacts of flue gas cooling and humidification, and precipitator energization scheme on the collection of particulates generated while firing low-sulfur coal. Additionally, the impacts of sorbent injection on mercury capture will be investigated in more detail than was possible in Phase I. The test coal in Phase II will be a Powder River Basin coal similar to that used in Phase I. By moving to the field in Phase II, with the ABB pilot precipitator configured in a slipstream configuration using full-scale flue gas and particulates, the following Phase II goals may be met:

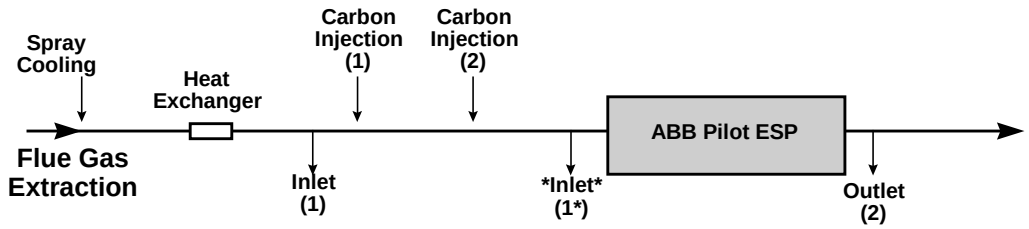
- Performance of long-term testing to determine whether the positive effects of cooling, humidification and pulsing on fine particulate emissions and mercury capture documented in Phase I testing continue over time, and whether fouling and corrosion occur at the relatively low flue gas temperatures and high moisture levels evaluated
- Acquisition of detailed performance data for use in commercial design efforts
- Evaluation of mercury control with a combination of flue gas cooling and sorbent injection, including an investigation of the longer-term efficacy of these methods
- Evaluation of a range of flue gas velocities and specific collection areas typical of full-scale ESPs in the U.S.
- Characterization of the impacts of cooling, humidification, and pulsing on the emitted particle size distribution

This presentation of the Phase II test plan will focus on the mercury control investigations.

The goal of the carbon injection testing planned for ABB's Pilot ESP at Commonwealth Edison's Waukegan Station is to obtain mercury removal data under operating conditions that are representative of full-scale wire plate ESP operation. A carbon injection system will be installed and carbon injection testing will be conducted on the pilot ESP to determine mercury removal efficiency. This will be established by measuring the concentration of both the speciated forms of mercury vapor and the particulate-bound mercury in the flue gas both upstream and downstream of the pilot ESP.

System Description

The testing parameters that can be varied at ABB's pilot facility include heating and cooling of the flue gas by non-contact heat exchangers and by spray cooling, in-duct residence time of the injected carbon, carbon injection rate, and sampling location. Sampling at the pilot ESP inlet will allow determination of the extent of mercury capture that occurs in the ductwork between the carbon injection point and the ESP (see Figure 10).



Variables:
- **Temperature**
- **Moisture**
- **Residence Time (by injection location)**
- **Carbon Injection Rate**
- **Sample Location**

Figure 10. Schematic of ABB Pilot ESP and Test Variables

Measurements and calculations performed during carbon injection testing will include the following:

- Pilot inlet and outlet speciated vapor phase mercury and particulate bound mercury
- Pilot inlet and outlet total mercury concentrations
- Pilot and duct temperatures
- Pilot inlet and outlet opacity
- Pilot ESP electrical parameters including secondary voltages and currents
- Carbon feed rate
- Gas flow rate through the pilot ESP
- Residence time of the carbon through the pilot ESP
- Pilot hopper ash samples for mercury analysis and loss on ignition (LOI) analysis

A carbon injection system has been designed and installed for the mercury removal testing planned at Waukegan Station. The carbon injection system consists of a horizontal discharge screw feeder, a dry material eductor, and two sorbent injection lances. During testing, carbon will be loaded into the carbon feeder and the feeder will be calibrated for the required feed rate. Calibration of the feeder will be determined by weighing timed catches from the feeder. The feed rate will be checked before and after each mercury test by catching a small quantity from the feeder and weighing to verify the feed rate of the carbon. To transport the carbon to the duct, the discharge of the carbon feed screw will be located directly over the suction port of the eductor, and the carbon will fall into the eductor. Compressed motive air will then deliver the carbon through a static-resistant line to one of two injection lances installed in the ductwork. The lances will be located approximately 55 feet and 27 feet upstream of the pilot ESP inlet. This placement will provide residence times of approximately 1.0 second and 0.5 second, respectively, at a nominal flue gas flow rate of 10,000 lb/hr.

Measurement Methods and Test Plan

Measurement methods to be employed in the Phase II mercury capture evaluations include the Ontario Hydro method and modified MESA method described earlier.

The scope of testing planned for Waukegan Station will consist of a preliminary test campaign and two, more

thorough test series. Depending on the results that are obtained as testing proceeds, the test matrix will be modified to maximize the value of intermediate results.

“Series One” testing will include two trips to Commonwealth Edison's Waukegan Station. Preliminary testing will be conducted during the first trip, and the results of this testing will be used to establish the testing procedures for the balance of tests during Series One. The first trip (preliminary) will consist of testing for mercury concentrations by the Ontario Hydro method to determine the particle/vapor split of mercury and the vapor speciation of mercury. If the particulate split of mercury is found to be less than fifteen percent (<15%) of the total mercury in the flue gas, it will be assumed that the fly ash produced from this coal at this station *does not significantly* adsorb/desorb mercury. If the particulate split of mercury is found to be greater than fifteen percent (>15%) of the total mercury in the flue gas, it will be assumed that the fly ash produced from this coal at this station *significantly* adsorbs/desorbs mercury. Ontario Hydro testing will include duplicate or triplicate inlet and outlet sample train runs at two temperatures. One blank train will also be analyzed. Additionally, iodated carbon traps (THIC and in-situ isokinetic THIC) for total and particulate mercury will be run simultaneously with the Ontario Hydro sample trains in order to validate their future use at this site. Because it is unknown if the ash will adsorb/desorb mercury, both the THIC for total mercury and an in-situ isokinetic THIC for particulate plus vapor mercury will be run simultaneous to the Ontario Hydro at the *inlet sample location only*. Simultaneous Ontario Hydro and the simple THIC will be sampled at the outlet sample port. It is deemed unnecessary to perform isokinetic sampling at the outlet sample port location because it is assumed that there is very little particulate at that location. Table 7 shows the test matrix planned for preliminary testing.

Table 7. Preliminary Testing Test Matrix

ABB Pilot ESP

Testing matrix

Series One, Preliminary Testing, Ontario Hydro Method

Mercury measurement by Iodated Carbon Trap (THIC method)

Simultaneous O.H. and THIC

Temperature (F)	Test #	Carbon Injection Rate (lbs/MMacf)	# of O.H. samples	# of Modified MESA samples	# of in duct iso-K MESA samples
"non-Controlled" (~270 F)	p-1		5	4	6	3
	p-blank1				2	1
"Controlled" + Moisture (~200 F)	p-2		5	4	6	3
	p-blank2				2	1

The test matrix used during the second trip to Waukegan Station for Series One testing will be dependent on the results of the first trip. The largest number of data points can be obtained with the simplest test method, therefore, the simplest test method that will provide accurate data will be used. If the ash is determined *not* to adsorb/desorb mercury, testing will proceed according to matrix "A1", which will consist of simple iodated carbon trap (THIC method) sampling at the inlet and outlet sample locations. If the ash is determined to adsorb/desorb mercury, testing will proceed according to matrix "A2", which includes isokinetic sampling at the inlet sample port. The isokinetic sampling method may be either an in-situ sample or an extractive sample. This matrix will produce approximately 2/3 the data that matrix "A1" will produce due to the increased scope of work required for isokinetic sampling. Figure 11 is Matrix "A1" which would be performed if the ash at Waukegan Station is shown not to adsorb/desorb mercury.

Matrix "A1"

ABB Pilot ESP

Mercury measurement by Iodated Carbon Trap (modified MESA method)
Simple iodated carbon trap sampling

Temperature (F)	Test #	Carbon Inj. Rate (lb/MMacf)	Residence Time (sec)	# of samples	
	f-blank			2	
"Non-Controlled"	f-1	0	1	6	
(~270)	f-2	2	1	6	
	f-3	2	1	6	*
	f-4	5	1	6	
"Controlled"- No Moisture	f-5	0	1	6	
(~230 F)	f-6	2	1	6	
	f-7	2	1	6	*
"Controlled" + Moisture	f-8	0	1	6	
(~230 F)	f-9	2	1	6	
	f-10	2	1	6	*
	f-11	0	0.5	6	
	f-12	2	0.5	6	
"Controlled" + Moisture	f-13	0	0.5	6	
(~200 F)	f-14	2	0.5	6	
	f-15	5	0.5	6	
	f-16	0	1	6	
	f-17	0	1	6	*
	f-18	2	1	6	
	f-19	2	1	6	*
	f-20	5	1	6	
	f-21	5	1	6	*

* outlet just upstream of ESP, duct effect on removal only

Figure 11. Test Matrix if ash does not adsorb mercury (non isokinetic)

A second, “Series Two” test campaign will be developed based on whether the same coal is burned at Waukegan Station and on the results of the Ontario Hydro testing that occurred during Series One testing under ABB's PRDA subcontract. If the same coal as Series One testing is burned at Waukegan Station, then the results of initial Ontario Hydro sampling will be used to determine future testing. If a new coal is burned, then Ontario Hydro sampling will again be deemed necessary to determine the particle/vapor split of the mercury in the flue gas.

In either case, Series Two tests will be designed to complement Series One findings, and to evaluate the effects of long-term carbon injection on the pilot ESP performance. Continuous carbon injection for several days is planned, during which mercury and particulate tests will be run periodically to evaluate whether mercury or particulate removal efficiency is affected by carbon injection. Electrical parameters and opacity will be monitored closely to determine any degradation in ESP performance.

CONCLUSIONS

Mercury emissions were measured as a function of flue gas temperature for three coals. Mercury emissions decreased as the flue gas temperature was lowered for all the coals examined in Phase I of the DOE program, indicating the increased ability of the native ash to capture mercury at a lower flue gas temperature. Also, in tests with activated carbon injection for vapor phase mercury capture, higher capture efficiencies were obtained at the lower flue gas temperature. Greater than 90 percent of vapor phase Hg was captured at 100^{o}C with C:Hg ratios of

40,000:1. An important conclusion from Phase I testing was that the vapor phase mercury was captured in the inlet duct to the ESP rather than in the ESP. To be able to design and cost a commercial control system, additional data on the effects of sorbent/Hg ratios, duct residence times and flue gas temperature on sorbent effectiveness are required. Longer term testing to evaluate if the carbon collected in the ESP is re-entrained (adversely affecting ESP performance) is also needed. These evaluations will be conducted in Phase II of the ABB/DOE program.

Flue gas humidification, cooling, pulsed energization and sorbent injection have been selected for more thorough evaluation in Phase II. In Phase II, ABB will install a pilot ESP in slipstream operation at Commonwealth Edison's Waukegan Station 16, Unit 8, in Waukegan, Illinois. Relocation of the pilot facility to the field will allow:

- Long-term testing to verify that positive effects of cooling, humidification and pulsing on particulate emissions and trace metal capture do not deteriorate, and that fouling and corrosion do not occur
- Evaluation of mercury control with a combination of cooling and sorbent injection, investigating sorbent type and injection rate, residence time and flue gas temperature
- Acquisition of performance data for commercial design with full-scale flue gas and ash
- Evaluation of a range of flue gas velocities and specific collection areas typical of full-scale ESPs
- Testing with additional low-sulfur coals, on-line comparison of pilot and full-scale ESP performance, and more detailed characterization of the impacts of ESP operation on the emitted size distribution ($PM_{2.5}$)

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