



## Project Summary

# Emission Test Report, Field Test of Carbon Injection for Mercury Control, Camden County Municipal Waste Combustor

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In 1992, the U.S. Environmental Protection Agency (EPA) conducted a parametric testing to evaluate the injection of powdered activated carbon to control volatile pollutants in municipal waste combustor (MWC) flue gas. This testing was conducted at a spray dryer absorber/electrostatic precipitator (SD/ESP)-equipped MWC in Camden County, New Jersey. The primary test objectives were to evaluate the effect of carbon type, feed rate, feed method, and ESP operating temperature on emissions of mercury (Hg) and chlorinated dioxins and furans (CDD/CDF), and to assess the impact of carbon injection on the particulate matter control performance of the ESP. Secondary objectives were to examine the impact of carbon injection on emissions of other metals and volatile organic compounds (VOCs). This testing included operation of three different carbon injection systems and examined 16 different SD/ESP and carbon injection system operating conditions. This test was conducted as a follow-on to an EPA-funded test program at a SD/fabric filter-equipped MWC that focused on the performance of carbon injection for controlling Hg emissions.

The test results indicate that carbon injection upstream of a SD/ESP can achieve high levels (greater than 90%) of Hg and CDD/CDF reduction. Key system operating parameters are carbon feed rate, carbon feed method, and ESP temperature. No detrimental impacts on ESP performance were identified. The study also found that carbon injection does

not have a significant impact on emissions of the other metals sought or of VOCs.

*This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).*

### Introduction

In June 1987, the U.S. EPA's Office of Air Quality Planning and Standards (OAQPS) announced its intention to develop new air pollution rules for MWC facilities. The following fall, EPA's Air and Energy Engineering Research Laboratory (AEERL) and OAQPS began a comprehensive field test and engineering assessment program to evaluate technologies for controlling MWC emissions. The field test program focused on the use of a lime spray dryer absorber and fabric filter baghouse (SD/FF) or a lime SD/ESP system for controlling MWC emissions. Regulations for large MWCs were proposed in late 1989 and finalized in 1991.

In November 1990, the Clean Air Act Amendment (CAAA) required EPA to add Hg emission limits to the MWC standards. Under the direction of EPA, Radian Corporation prepared a technical memorandum summarizing the effectiveness of various technologies in controlling Hg emissions. Based on U.S. field tests and research in Europe and Canada, it was concluded that the control of Hg emissions in MWC SD/particulate matter (PM)



control systems depends on the amount of carbon in the fly ash. Modern mass burn combustors, which typically contain relatively low amounts of carbon in their fly ash, exhibited Hg control efficiencies with acid gas scrubbers ranging from 0 to 40%. Refuse-derived fuel combustors, which contain substantially more carbon in their fly ash, had Hg control efficiencies exceeding 95%. In these applications Hg vapor does not condense but is adsorbed on carbonaceous particles that can be subsequently collected in PM control devices.

Research and field tests in Europe indicated that powdered activated carbon can be used to enhance control of Hg emissions in SD/PM control systems. EPA-sponsored tests in 1991 at the Ogden Martin Systems of Stanislaus, Inc. (OMSS) MWC indicated that powdered activated carbon was effective in controlling Hg emissions in mass burn MWCs with SD/FF systems. It was found that carbon feed rate is the primary factor affecting Hg control. The OMSS testing also indicated that there are no significant differences in Hg control performance as a function of the physical characteristics of the carbon (original material, particle size, pore size, and density), the method of injection (as a dry powder or mixed with the SD's lime slurry), or the location of injection (economizer exit, SD inlet, and into the SD). However, it was not possible to determine how much of the Hg is removed by adsorption onto carbon particulate in the free stream with subsequent PM collection and how much Hg is removed by adsorption as the flue gas flows through the FF cake containing captured carbon.

Because of uncertainties regarding the mechanisms of Hg capture by carbon in SD/FF systems, it is not possible to directly translate the data collected at SD/FF-equipped MWCs to units equipped with SD/ESP systems. Available U.S. data on SD/ESP-equipped MWCs indicated inconsistent and often poor Hg control. Data on the collection of Hg by SD/ESPs is of interest because of the number of such systems already operating commercially, as well as the potential for retrofitting existing ESP-only systems with SDs as needed for control of acid gas and organic emissions.

In addition, very little data are available from either SD/FF- or SD/ESP-equipped MWCs on the effectiveness of carbon injection for reducing emissions of CDD/CDF and various VOCs.

In 1992 EPA sponsored tests at the Camden County, New Jersey, MWC facility to evaluate the use of activated carbon for controlling emissions in SD/ESP sys-

tems. The Camden County and the OMSS tests were directed by AEERL. The report summarizes the objectives and results of the Camden County tests.

## Purpose of Tests

The purpose of the Camden County tests was to evaluate the effectiveness of powdered activated carbon for reducing emissions of Hg, "other" metals, and trace organic emissions from mass burn MWCs equipped with SD/ESP systems. Specific objectives of the tests were to evaluate:

- The relationship of carbon feed rate, the inherent carbon in fly ash, and Hg capture;
- The effects of carbon injection on the control of "other" metals, CDD/CDF, and VOCs;
- The effect of carbon injection rate and method (dry powder or slurried with lime) on Hg and CDD/CDF control;
- The effect of ESP operating temperature on Hg collection, and
- Whether there are long-term impacts of carbon injection on ESP performance in collecting PM and "other" metals.

## Test Design

### Description of Facility

The Camden County MWC is owned and operated by Camden County Energy Recovery Associates, a subsidiary of Foster Wheeler Power Systems, Inc. Located in Camden, New Jersey, it began operating in 1991. The facility contains three identical mass-burn waterwall combustion units, designated as Units A, B, and C. Each unit is capable of burning 317 tonnes (350 tons) per day of municipal solid waste (MSW), and collectively they provide steam for two 17-MW turbine generators. A general schematic of a test unit showing carbon injection and sampling locations is given in Figure 1.

The air pollution control system on each combustor consists of a Deutsche Babcock SD and a Belco five-field ESP. The flue gas leaves the economizer, passes down through a vertical circular duct, through a 90-degree elbow, and through a horizontal circular duct before entering a cyclone. The cyclone separates coarse PM from the flue gas and distributes flue gas to six vertical flow tubes that connect to the base of the SD vessel. A two-fluid nozzle located in the top of each flow tube injects lime slurry up into concurrently flowing flue gas. The lime slurry flow can be controlled by stack sulfur dioxide ( $\text{SO}_2$ ) concentration or it can be set to provide a fixed lime flow rate. Dilution water flow is

controlled by the SD's exit gas temperature. After leaving the SD, flue gas passes through an inverted U-shaped circular duct before entering a five-field ESP. During normal operation, only four of the ESP fields are in operation. Flue gas from each ESP is ducted into a separate flue in the stack. The stack contains four circular flues, one per operating unit, and one for a future unit.

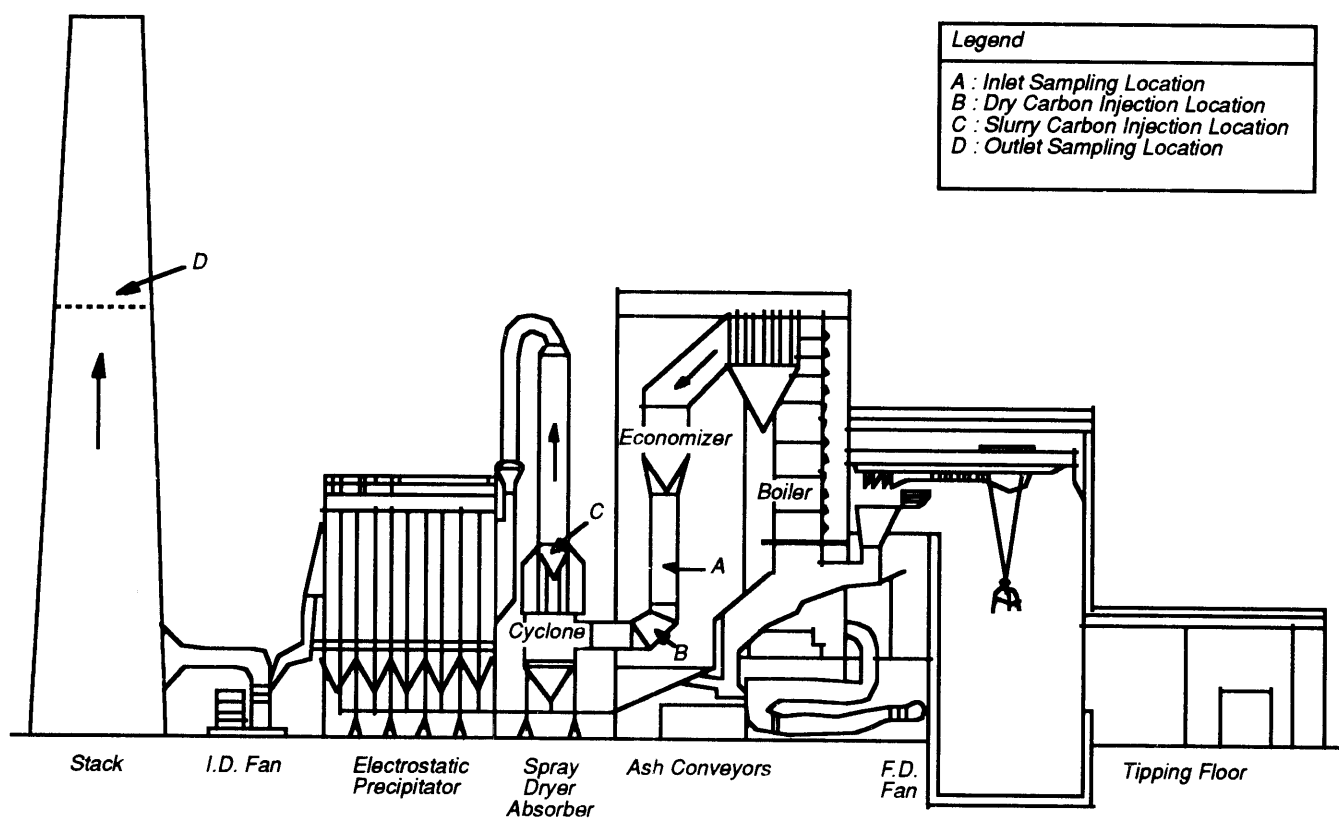
The process control systems include a Bailey Net 90 for the boiler, a separate control and data display system for the SD/ESP, and two separate continuous emission monitoring (CEM) data acquisition systems. The CEM systems include extractive monitors for  $\text{SO}_2$  and oxygen ( $\text{O}_2$ ) at the economizer exit and monitors for  $\text{O}_2$ , carbon dioxide ( $\text{CO}_2$ ), water ( $\text{H}_2\text{O}$ ), carbon monoxide (CO), total hydrocarbons (THCs), methane ( $\text{CH}_4$ ),  $\text{SO}_2$ , hydrogen chloride (HCl), nitrogen oxides ( $\text{NO}_x$ ), and opacity in the stack.

### Test Matrix

The Camden County MWC test project encompassed three distinct testing efforts and was conducted in two phases (see Table 1). Phase I concerned only Unit B. These tests, defined as Phase I-B tests, were used to select the carbon type and carbon feed rates to be used for the Phase II performance tests. The Phase II tests included two distinct efforts. The primary effort, conducted on Unit B (II-B tests), investigated the effects of key carbon injection system operating variables on Hg control efficiency. The other Phase II tests, conducted on Unit A (II-A tests), investigated the potential long-term impacts of extended carbon injection on ESP performance.

Triplicate sampling runs were conducted for each test condition and one test condition was completed during each test day. Plant process instruments and CEM equipment were used to monitor combustor and SD/ESP operating conditions during each run.

**Phase I-B Tests.** During Phase I-B tests, carbon was injected as a dry powder into the flue gas duct just upstream of the SD (see Figure 1). The tests evaluated Hg control levels for two carbon types and two carbon feed rates. Both of the tested carbons, Darco PC-100 and Darco FGD from the American Norit Company, were used during the OMSS tests. The first carbon (PC-100) was a thermally activated, bituminous-coal-based carbon with medium surface area and high tamped density. The second carbon (FGD) was thermally activated from lignite and had a lower surface area, smaller average particle size, and lower tamped density than



**Figure 1.** Schematic of the Camden County Municipal Waste Combustor.

**Table 1.** Test Matrix-Camden County MWC, Spring 1992

Phase-Condition	ESP Inlet Temperature °C (°F)	Number of Operating ESP Fields	Carbon Type	Carbon Feed Method	Nominal Carbon Feed Rate kg/hr (lb/hr)	Sample Analytes*
I-B1	132 (270)	4	None	None	None	Hg, PM, %C
I- B2	132 (270)	4	FGD	Dry	4.5 (10)	Metals, PM, %C
I- B3	132 (270)	4	PC-100	Dry	4.5(10)	Hg, PM, %C
I- B4	132 (270)	4	PC-100	Dry	27 (60)	Hg, PM, %C
I- B5	132 (270)	4	FGD	Dry	27 (60)	Hg, PM, %C
II-B6	177 (350)	4	None	None	None	Hg, PM, %C
II-B7	177 (350)	4	FGD	Dry	23 (50)	Metals, PM, %C
II-B8	132 (270)	4	FGD	Dry	11 (25)	Hg, PM, %C
II-B9	132 (270)	4	FGD	Dry	2.3 (5)	Hg, PM, %C
II-B10	132 (270)	4	None	None	None	Metals, PM, %C, CDD/CDF, VOC
II-B11	132 (270)	4	FGD	Dry	23 (50)	Metals, PM, %C, CDD/CDF, VOC
II-B12	132 (270)	4	FGD	Slurry	23 (50)	Metals, PM, %C, CDD/CDF
II-B13	132 (270)	4	FGD	Slurry	11 (25)	Metals, PM, %C
II-A1	132 (270)	4	None	None	None	Hg, Cd, Pb, PM, %C, PSD <sup>b</sup>
II-A2	132 (270)	4	FGD	Slurry	23 (50)	Hg, Cd, Pb, PM, %C, PSD
II-A3	132 (270)	4	FGD	Slurry	23 (50)	Hg, Cd, Pb, PM, %C, PSD
II-A4	132 (270)	4	FGD	Slurry	23 (50)	Hg, Cd, Pb, PM, %C, PSD
II-A5	132 (270)	3	FGD	Slurry	23 (50)	Hg, Cd, Pb, PM, %C, PSD

\* Metals: Ag, As, Ba, Be, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Sb, Se, Ti, V

<sup>b</sup> PSD: Particle size distribution

the coal-based carbon. The lower target carbon feed rate was 4.5 kg/hr (10 lb/hr), which equates to a flue gas concentration of approximately 60 mg of carbon per dscm of flue gas<sup>1</sup> and is approximately equal to the high carbon feed rate for tests conducted at OMSS. The higher target carbon feed rate of 27 kg/hr (60 lb/hr) is about 360 mg/dscm and was expected to achieve Hg removals in excess of 90%.

During each run, simultaneous sampling was conducted at the economizer exit and in the stack for total PM and Hg using the multiple metals sampling train. The ports at the economizer outlet are located approximately 2 equivalent duct diameters from the nearest upstream flow disturbance and 1.6 diameters from the nearest downstream disturbance. The stack ports are located near the 62-m (205-ft) elevation in the 112-m (366-ft) stack. Each sampling run was 1 hour long.<sup>2</sup> In addition, an EPA Method 5 type sampling train was operated at the economizer exit to collect a daily composite sample of PM. The composite sample was then used to determine the percent carbon in the fly ash caused by incomplete combustion.

Both carbon types indicated similar levels of Hg control during the I-B tests. Thus, the cheaper Darco FGD was selected as the carbon for use in the Phase II tests.

**Phase II-B Tests.** The Phase II-B parametric tests included eight test conditions for evaluating the impact of carbon feed rate, carbon feed method, and flue gas temperature on Hg control (see Table 1). During each run, simultaneous sampling was conducted at the economizer exit and in the stack for total PM and Hg using the multiple metals sampling train. During six of the test conditions (five from II-B and one from I-B), the sampling fractions collected by the multiple metals train were analyzed for 16 other metals. These metals were antimony (Sb), arsenic (As), barium (Ba), beryllium (Be), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), manganese (Mn), molybdenum (Mo), nickel (Ni), selenium (Se), silver (Ag), thallium (Tl), and vanadium (V). In addition, a Method 5 type sampling train was operated at the economizer exit to collect a daily composite sample of PM for determination of percent carbon in the fly ash.

Except for the three test conditions discussed below, each sampling run was 1 hour long.

The testing also included sampling for CDD/CDF emissions during Conditions B10, B11, and B12, and for VOCs during Conditions B10 and B11. Each sampling run during these three test conditions was 2 hours in duration.

**Phase II-A Tests.** Phase II-A tests were conducted to evaluate potential detrimental impacts on ESP performance due to carbon injection over an extended time period, and to assess the relationship between PM collection efficiency and Hg control. To satisfy these objectives, 5 days of sampling were conducted over a 12-day period on Unit A. Following an initial day of testing without carbon injection to establish baseline performance, Darco FGD carbon was added to the lime slurry feed tank and continuously pumped into the SD.

As shown in Table 1, the first 4 days of sampling were conducted with four ESP fields in service. These tests were run on the day prior to the start of carbon injection and on the first, third, and eighth days after the start of carbon injection. After completion of testing on the eighth day, the fourth ESP field was turned off (the fifth field was off for all tests), thus resulting in operation with only three fields. The fifth day of sampling was conducted after the unit had been operating with three fields for 4 days. This sampling schedule was designed to allow the ESP to reach equilibrium operation with three fields. These tests were conducted to evaluate the effects of carbon injection on smaller three-field ESPs.

During each run, simultaneous sampling was conducted at the economizer exit and in the stack for total PM, Hg, Cd, and Pb using the multiple metals sampling train. Also, during each run, two eight-stage Andersen impactors were used to measure the particle size distribution (PSD) of PM in the stack gas. The two PSD trains were run throughout each test day to collect sufficient PM for quantitative measurement of the weight gain by each impactor stage. In addition, a Method 5 type sampling train was operated at the economizer exit to collect a daily composite sample of PM for determination of percent carbon in the fly ash. The PM and PSD data provided a direct method of evaluating degradations in ESP performance that might be associated with carbon injection.

## Carbon Feed Systems

Carbon was fed to Units A and B by two different methods using three different injection systems. The testing on Unit B included injection of dry carbon and addition of carbon into a slurry mix tank installed just prior to the SD. Carbon was injected into Unit A by addition of carbon to lime slurry in the feed tank.

The dry injection system consisted of a screw feeder and a pneumatic transport system. The carbon injection probe consisted of a 0.025-m (1-in.) pipe inserted in the flue gas duct upstream of the SD (see Figure 1). The end of the probe was cut at a 45° angle, which faced downstream. Experiments conducted prior to the Phase I tests suggested that the cyclone removed little, if any, of the dry injected powdered carbon.

Prior to the start of the test project, the carbon feed system was calibrated. The carbon feed rate was confirmed for each test by recording the amount of each carbon addition and the time between each pair of refillings.

At the end of each testing day, the carbon feed rate was adjusted to the target level for the next day of testing. The feeder was then operated overnight at this feed rate to condition the SD/ESP prior to the start of the next day of testing.

The second carbon feed system for Unit B involved addition of carbon to the lime slurry in a feed tank installed near the SD inlet. Estimated carbon retention time in the slurry with this system was about 10 minutes. Lime slurry was supplied to this small feed tank from the plant's existing slurry system. Carbon feed rates were determined in the same manner as the dry injection system, and the carbon was carried in the lime slurry to the SD.

During the Phase II-A tests, carbon was added to the plant's lime feed tank during each slaking cycle. The average carbon injection rates were calculated from the amount of carbon added during each timed slaking cycle. The lime/carbon slurry mixture was injected into the reactor with the existing slurry feed through the atomization system. The carbon retention time in the slurry during these tests is estimated at 3 to 8 hours, with an average of approximately 5 hours.

## Interpretation of Results

### Mercury

A summary of key operating data and Hg test results is presented in Table 2.

<sup>1</sup>Based on a flue gas flow rate of 75,000 dscm/hr. Unless otherwise noted, all flue gas flow rates used in this paper are corrected to standard conditions [20°C (68°F), 101.3 kPa (14.7 psia)] and all concentrations to 7% O<sub>2</sub> in dry gas.

<sup>2</sup>All run durations in this paper are actual sampling times and exclude times for port changes and resolving equipment problems.

**Table 2. Summary of Test Conditions and Mercury Test Results**

Phase-Condition	Run	Carbon Type	Injection Method	ESP Inlet Temperature °C(°F)	Carbon Injection Concentration mg/dscm	Total Carbon at Cyclone Inlet mg/dscm	Mercury Concentration at Inlet µg/dscm	Mercury Concentration at Outlet µg/dscm	Mercury Removal Efficiency %
I-B1	1	None	None	132 (269)	0	79	356	175	50.8
	2			131 (267)	0	79	1363	210	84.6
	3			128 (262)	0	79	711	54	92.4
	AVG			130 (266)	0	79	810	146	75.9
I-B2	4	FGD	Dry	134 (274)	73	154	972	296	69.5
	5			130 (266)	79	160	593	63	89.4
	6			135 (275)	78	159	835	149	82.2
	AVG			133 (272)	77	158	800	169	80.4
I-B3	7	PC-100	Dry	129 (264)	89	154	593	134	77.4
	8			133 (272)	73	138	639	29	95.5
	9			134 (273)	88	153	586	102	82.6
	AVG			132 (270)	83	148	606	88	85.2
I-B4	10	PC-100	Dry	129 (265)	477	579	491	21	95.7
	11			143 (290)	456	558	440	14	96.8
	12			144 (291)	418	520	512	17	96.6
	AVG			139 (282)	450	552	481	17	96.4
I-B5	13	FGD	Dry	135 (275)	430	534	680	9	98.6
	14			136 (277)	444	548	820	13	98.4
	15			128 (262)	450	554	644	12	98.2
	AVG			133 (271)	441	546	715	12	98.4
II-B6	10	None	None	176 (348)	0	74	365	301	17.5
	11			177 (350)	0	101	249	177	28.9
	12			176 (349)	0	55	349	261	25.2
	AVG			176 (349)	0	77	321	246	23.9
II-B7	13	FGD	Dry	178 (352)	313	387	964	107	88.9
	14			178 (352)	329	429	506	22	95.6
	15R			173 (344)	324	418	778	59	92.4
	AVG			176 (349)	322	411	749	63	92.3
II-B8	16	FGD	Dry	131 (267)	173	305	545	40	92.7
	17			128 (263)	149	276	455	23	95.0
	18			128 (262)	190	306	525	24	95.4
	AVG			129 (264)	171	295	508	29	94.4
II-B9	19	FGD	Dry	130 (266)	30	111	485	103	78.8
	20			130 (266)	46	141	957	170	82.2
	21			129 (265)	43	129	463	124	73.2
	AVG			130 (266)	40	127	635	132	78.1
II-B10	25	None	None	132 (269)	0	83	663	388	41.5
	26			130 (266)	0	98	433	279	35.6
	27			126 (258)	0	91	384	207	46.1
	AVG			129 (264)	0	91	493	291	41.0
I-B11	28	FGD	Dry	133 (271)	357	506	626	20	96.8
	29			134 (273)	342	504	635	16	97.4
	30			132 (269)	387	505	664	16	97.7
	AVG			133 (271)	362	505	642	17	97.3
II-B12	34	FGD	Slurry	132 (269)	324	385	299	50	83.2
	35			132 (269)	325	368	521	77	85.3
	36			135 (275)	336	403	300	69	77.0
	AVG			133 (271)	328	385	373	65	81.8
II-B13	37	FGD	Slurry	130 (266)	183	233	382	78	79.7
	38			128 (263)	194	265	377	81	78.5
	39			129 (264)	200	248	974	158	83.8
	AVG			129 (264)	192	249	578	106	80.7
II-A1	1	None	None	136 (277)	0	100	268	121	54.9
	2			132 (270)	0	86	430	290	32.6
	3			134 (273)	0	198	610	322	47.2
	AVG			134 (273)	0	128	436	244	44.9

(continued)

**Table 2.** (Continued)

Phase-Condition	Run	Carbon Type	Injection Method	ESP Inlet Temperature °C (°F)	Carbon Injection Concentration mg/dscm	Total Carbon at Cyclone Inlet mg/dscm	Mercury Concentration at Inlet ug/dscm	Mercury Concentration at Outlet ug/dscm	Mercury Removal Efficiency %
II-A2	4	FGD	Slurry	129 (265)	344	427	302	55	81.9
	5			129 (265)	346	468	403	78	80.7
	6			130 (266)	343	450	1412	261	81.5
	AVG			129 (265)	344	448	706	131	81.4
II-A3	7	FGD	Slurry	137 (278)	402	579	530	43	91.9
	8			132 (269)	356	412	458	108	76.4
	9			142 (288)	386	629	690	156	77.4
	AVG			137 (278)	381	540	559	102	81.9
II-A4	22	FGD	Slurry	141 (285)	442	640	643	49	92.3
	23			139 (283)	391	567	816	90	89.0
	AVG			140 (284)	417	604	730	70	90.7
II-A5	31	FGD	Slurry	139 (283)	269	381	335	40	88.0
	32			139 (283)	280	404	295	51	82.6
	33			140 (284)	249	356	364	52	85.6
	AVG			139 (283)	266	380	331	48	85.4

Note: Particulate matter was not measured at the Inlet during Phase I; therefore, carbon concentrations were estimated using the average PM inlet concentration for all Phase II-B tests. All concentrations are referenced to 7% O<sub>2</sub> in dry gas at 20°C (68°F) and 101.3 kPa (14.7 psia). Test II-B7-15R was conducted due to possible problems caused by interruption of carbon feed toward the end of Test II-B7-15.

The table includes data on carbon type, injection rate and method, ESP inlet temperature, total carbon concentration at the cyclone inlet, inlet and stack Hg concentrations, and Hg removal efficiency.

**Impact of Carbon Type.** The influence of carbon type was examined during Phase I-B tests with dry injection of lignite-based carbon (Conditions B2 and B5) and coal-based carbon (Conditions B3 and B4). Conditions B2 and B3 were conducted at a low carbon feed rate corresponding to approximately 80 mg/dscm of flue gas. Conditions B4 and B5 were conducted at a high carbon feed concentration of approximately 450 mg/dscm.

At the low carbon feed rate, the calculated removal efficiency was 70 to 89% with the lignite-based carbon and 78 to 96% with the coal-based carbon. At the high carbon feed rate, the removal efficiency was 98 to 99% with the lignite-based carbon and 95 to 97% with the coal-based carbon. While the coal-based carbon appeared to be marginally better at the low feed rate, both carbons resulted in similar performances at the high injection rate. Because there was no clear distinction in the removal efficiency of these two carbons, the remaining tests were conducted using the more economical lignite-based carbon. The similarity in performance of these two carbons when injected as a dry powder is consistent with the results of the OMSS testing.

**Impact of Carbon Injection Rate.** Figures 2 and 3, respectively, present Hg removal efficiency and stack gas Hg concentration as a function of carbon injection rate for all Unit B tests with lignite- and coal-based carbons. These figures also include all tests for Unit A and Unit B without carbon injection. The rectangular data points show the removal efficiencies and stack gas concentrations measured during individual runs conducted at an ESP temperature of approximately 132°C (270°F) and while injecting either dry lignite-based carbon or no carbon. The specific test conditions are A1, B1, B2, B5, B8, B9, B10, and B11. Carbon injection concentrations for these tests ranged from 40 to 450 mg/dscm.

These figures show that increased carbon injection concentrations increase Hg removal and decrease stack gas Hg concentration. Increased injection concentrations also decrease the variability in Hg reduction and stack gas Hg concentration between individual runs of the same test condition. These tendencies were also observed during the OMSS test program. However, the carbon feed rates at Camden County were significantly higher than at OMSS, where the highest feed rate of dry carbon corresponded to an injection concentration of about 70 mg/dscm.<sup>10-12</sup> (Note that the pulse-jet-cleaned FF for the OMSS test unit had a cleaning cycle of about 12 minutes; thus the carbon in the filter cake had a much longer average contact time

with "free stream" Hg than carbon collected in an ESP.)

For a 132°C (270°F) ESP inlet temperature and dry carbon injection concentrations above 150 mg/dscm, Hg removals were 93% or greater and stack gas Hg concentrations were less than 50 µg/dscm. At higher injection rates, there were relatively small incremental increases in Hg reduction and decreases in stack gas Hg concentration. At these feed rates, the variability in Hg reduction between runs of a given test condition was 3% or less. At carbon feed rates of less than 150 mg/dscm, the Hg removal efficiencies were noticeably lower and the run-to-run variability between individual runs was as much as 20% during a single test condition.

The greatest variation in Hg reduction and stack gas Hg concentration was observed during tests without carbon injection, Conditions A1, B1, and B10. In particular, during Runs 2 and 3 of Condition B1, removal efficiencies were 85 and 93%, nearly 40% higher than other runs with no carbon injection. Stack gas Hg concentrations during Runs 2 and 3 were 210 and 54 µg/dscm, respectively. It was initially believed that these high Hg removal efficiencies reflected poor combustion conditions caused by high waste moisture content (it rained heavily for several days preceding the B1 tests) and in the case of Run 2, high inlet Hg concentrations. However, similar "wet waste" conditions during the B10 tests did not result

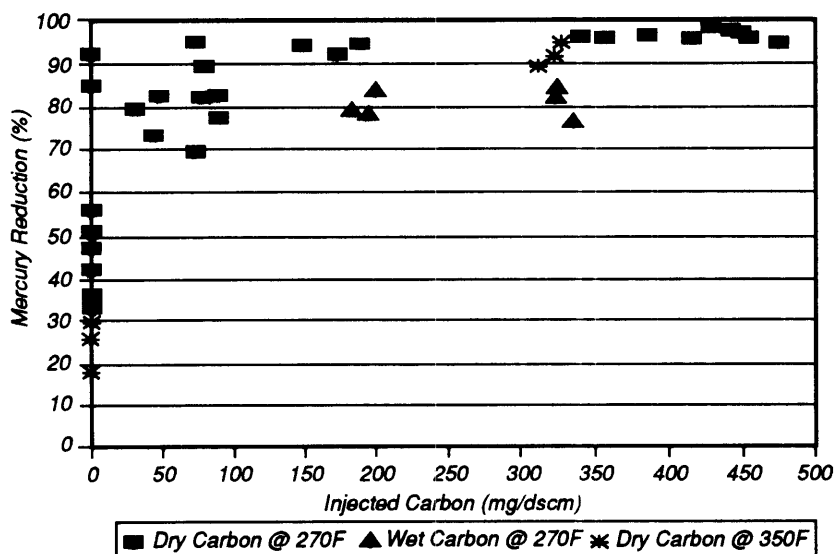


Figure 2. Dependence of mercury reduction on carbon injection rate and method at 132°C (270°F) and 177°C (350°F).

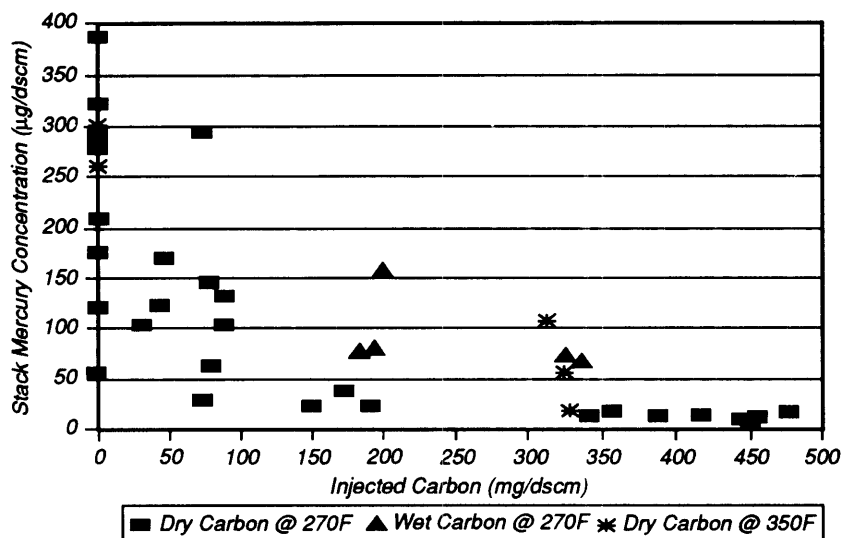


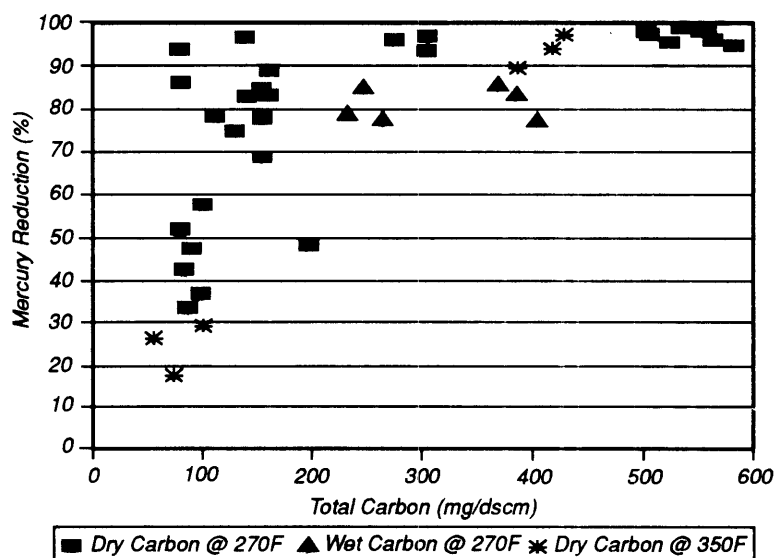
Figure 3. Dependence of mercury concentration on carbon injection rate and method at 132°C (270°F) and 177°C (350°F)

in abnormally high Hg captures. Review of the three previous quarterly Hg emission tests from Unit B shows reductions during three-run tests of 41 to 43%, 41 to 55%, and 30 to 73% (all based on EPA Method 101A). These data suggest that Hg removals without carbon injection at Camden are typically between 30 and 55%, but removals can be either higher or lower.

**Impact of Inherent Carbon.** Hg capture in SD/PM control systems is believed to depend on the amount of inherent carbon contained in combustor fly ash. To quantify the amount of unburned carbon present in the flue gas, a composite PM sample was collected at the economizer exit during each test condition and analyzed for carbon content. The carbon levels measured during each day were between 1.1 and 2.2% of the dried sample weight. The percent carbon found in each daily sample was then multiplied by the measured PM loading at the economizer exit for each run on that day. The resulting estimate of inherent carbon was then added to the concentration at which activated carbon was injected to estimate the total carbon level in the flue gas (see Figure 4). Note that this approach provides only a rough estimate of the total entrained carbon. Specifically, this approach provides a single estimate of the PM's carbon content for each day, and any run-to-run variations in combustion conditions that could result in increased carbon levels during an individual run are not measured. Also the amount of carbon available for Hg absorption at locations downstream of the SD's inlet cyclone is overestimated. Visual inspection of cyclone catches showed a substantial number of large inherent carbon particles in the collected fly ash.

As shown in Figure 4, the 30-55% reduction in emitted Hg at 132°C (270°F) in the absence of carbon injection could be explained by the presence of approximately 100 mg/dscm of unburned carbon associated with the combustor fly ash. The high levels of Hg capture obtained during test conditions B11 and B5 can be partially explained by the high levels of inherent carbon during these two conditions (2.2% during B11 and 1.9% during B5). At OMSS, the carbon content of the fly ash from the combustor (0.5-1.0%) was approximately half the level at Camden County, and the Hg reduction without carbon injection was also approximately half the average Camden level (25%).

**Impact of Carbon Injection Method.** The relationship between the carbon injection method and Hg removal and stack



**Figure 4.** Mercury reduction as a function of total carbon concentration in flue gas and carbon injection method at 132°C (270°F) and 177°C (350°F).

gas Hg concentrations is shown in Figures 2 and 3, respectively. At the medium carbon injection concentration (149 to 200 mg/dscm), Hg removal efficiencies were 92 to 95% with dry carbon injection (Condition B8) and 79 to 84% when the carbon was injected with the lime slurry (Condition B13). For medium carbon injection rates, dry injection resulted in stack gas Hg concentrations ranging from 23 to 40 µg/dscm, while slurry injection resulted in stack Hg concentrations ranging from 78 to 158 µg/dscm. At the carbon injection concentrations >324 mg/dscm, Hg removal efficiencies were 97 to 98% with dry injection (Condition B11) and 77 to 85% with slurried carbon (Condition B12). For these tests, the dry carbon injection test stack gas Hg concentrations ranged from 16 to 20 µg/dscm, while the slurry carbon injection test stack gas Hg concentrations ranged from 50 to 77 µg/dscm.

This observation is in contrast to the OMSS results, which found that feed method did not have a significant impact on Hg emissions and Hg removal. The cause of this difference is uncertain, but may be due to the different carbon type used or the type of PM control device. The carbon used at OMSS during slurry testing was coal-based, rather than lignite-based as used during slurry testing at Camden County. Also, the carbon collected in the filter cake during the OMSS test was retained on the bags for about 12 minutes and thus was probably dry

during most of its contact time with flue gas, thus effectively functioning like dry carbon relative to Hg capture.

In contrast, a very short period (on the order of 10 seconds) was available for the carbon to dry out in the ESP. Carbon retention time in the slurry on Unit A was estimated to be 3 to 8 hours, but only 8 to 10 minutes for Unit B. The carbon feed concentration during each of these conditions was approximately 360 mg/dscm. The Hg removal efficiency for Units A and B was very similar, with both units averaging 82%. It can be concluded that the decreased Hg adsorbency of carbon when mixed with slurry occurred in less than 8 to 10 minutes.

**Impact of ESP Temperature.** Figure 5 shows the effects of ESP inlet temperature and total carbon concentration on Hg removal efficiency and stack gas Hg concentration. When operating without carbon injection and an ESP inlet temperature near 132°C (270°F) [Conditions B1 and B10], Hg removals ranged from 36 to 92% and stack gas Hg concentrations ranged from 54 to 388 µg/dscm. At the higher ESP temperature of 177°C (350°F) [Condition B6], the Hg removals were 18 to 29% and the stack gas concentrations were 180 to 300 µg/dscm. At high total carbon concentrations (360 mg/dscm) and 132°C (270°F) ESP temperature (Condition B11), Hg removals were 97 to 98%. At similar carbon feed rates, but an ESP inlet temperature of 177°C (350°F) [Con-

dition B7], Hg removals were 89 to 96% and stack gas Hg concentrations were 22 to 107 µg/dscm. These data suggest that the ability of carbon to absorb Hg is directly related to flue gas temperature, but that, even at a relatively high ESP inlet temperature of 177°C (350°F), activated carbon injection results in high Hg reductions.

**Impact of PM Control Efficiency.** The PM control efficiency of the ESP averaged 99.8% or more for all test conditions. The PM concentrations in the stack ranged from 1.1 to 8.9 mg/dscm (0.0005 to 0.004 gr/dscf). These levels of PM control and emission did not exhibit any apparent relationship between PM control and Hg removal efficiency for the tests conducted at the Camden facility.

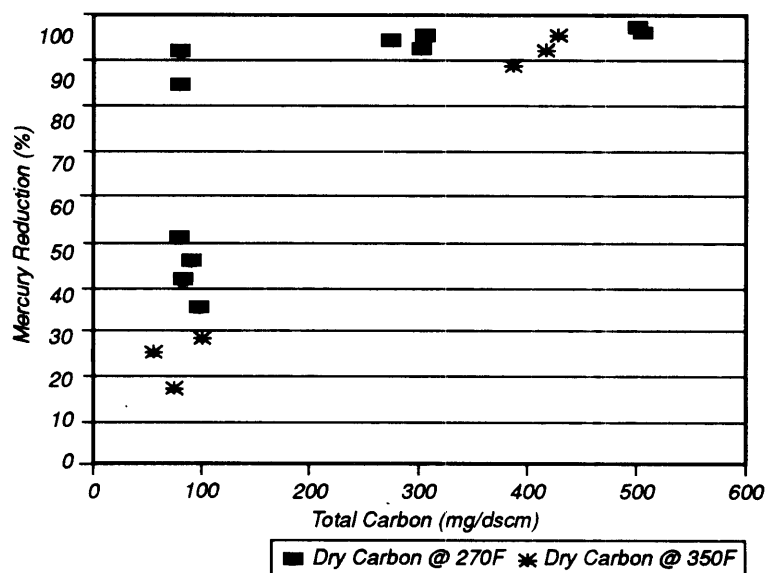
## Multivariate Regression Analysis of Hg Control

A stepwise multivariate regression analysis was used to assess the statistical significance of individual process variables and to develop predictive equations for Hg removal efficiency and stack gas Hg concentration. These analyses identified three statistically significant process variables influencing Hg control efficiency: carbon feed rate, ESP inlet temperature, and carbon injection method. The analyses also identified four statistically significant process variables affecting stack gas Hg concentration: carbon feed rate, carbon injection method, ESP inlet temperature and inlet Hg concentration.

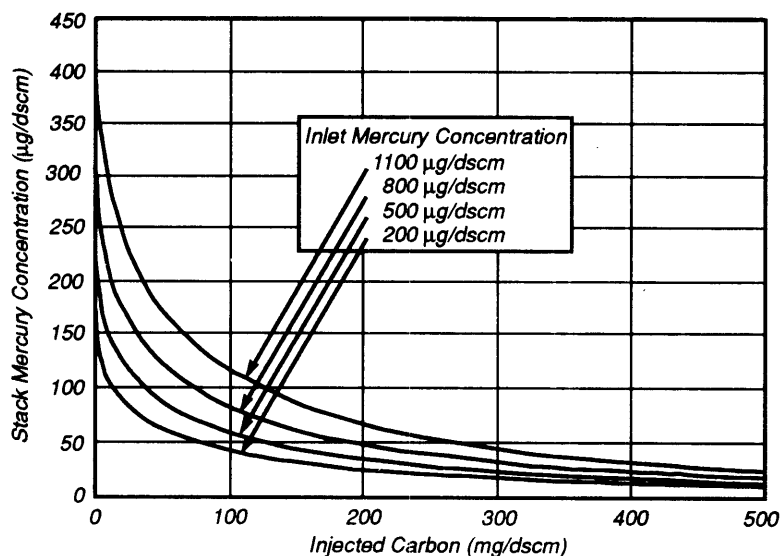
Figure 6 shows the predicted stack gas Hg concentrations for the injected carbon concentrations for the best regression model based on an ESP operating temperature of 132°C (270°F) and inlet Hg concentrations of 200, 500, 800, and 1,100 µg/dscm. Note that most of the reduction in stack Hg concentration occurs at injected carbon concentrations below about 100 mg/dscm. At injected carbon concentrations above this level, the stack Hg concentration decreases, but the reduction is much more gradual. Considering the degree of control by inherent fly ash carbon, the variations in the inlet flue gas Hg concentration, and the variation in reduction efficiency of the carbon injection process, complying with an Hg emission limit of 100 µg/dscm at the Camden facility would probably require injected carbon concentrations in the range of 150 to 200 mg/dscm.

The absence of inlet Hg concentration as a statistically significant variable for predicting Hg removal efficiency is in contrast to the OMSS data and is believed to reflect the difference in control capability





**Figure 5.** Mercury reduction as a function of total carbon concentration at 132°C (270°F) and 177°C (350°F).



**Figure 6.** Regression lines for stack mercury concentration as a function of inlet mercury concentration and dry carbon injection rate at 132°C (270°F).

of systems equipped with a FF versus an ESP. With a FF, carbon will adsorb Hg both while entrained in the flue gas and after it is collected in the filter cake. When inlet Hg levels vary (e.g., due to a short-duration spike in Hg concentration), the unsaturated carbon on the filter cake is able to adsorb additional Hg and to moderate the spike at the FF outlet. In this situation, the efficiency of the control system (i.e., entrained carbon and filter cake) can increase for short periods. During these periods the outlet concentration is not strongly dependent on inlet concentration until there is "breakthrough" of the filter cake carbon. The ability of the filter cake to buffer outlet Hg spikes in inlet Hg levels is similar to the ability of the excess sorbent in the filter cake to moderate fluctuations in inlet acid gas levels. With an ESP, most of the Hg reduction occurs while the carbon is entrained in the flue gas and is controlled by the likelihood of contact between carbon particles and Hg prior to the collection of carbon with the fly ash on the ESP plates. Once a carbon particle is collected on an ESP plate, the potential for contact with Hg is greatly reduced, because of both the removal of carbon from flue gas and the limited opportunity for Hg in flue gas to contact carbon collected on plates of the ESP. In this case the Hg capture is limited by the total concentration of suspended "free stream" carbon, and the outlet Hg concentrations for a given carbon loading are highly dependent on inlet concentrations.

### Other Metals

Flue gas concentrations of the 16 other metals in addition to Hg were determined during six test conditions (see Table 1). Five of these test conditions were conducted at 132°C (270°F): no carbon injection (B10), dry carbon injection at a low and a high feed rate (B2 and B11, respectively), and slurry injection of carbon at a medium and a high feed rate (B13 and B12, respectively). The sixth test condition was conducted at 177°C (350°F) with dry carbon injection (B7).

For Cd, Pb, As, Ba, and Cu, metals removal efficiencies exceeded 99% during all test conditions. For Cr and Mn removal efficiencies exceeded 99% except during the high temperature run (B7) and for Mn during the medium feed rate carbon-in-slurry test condition (B13). For Mo and Ni, removal efficiencies showed significant variability, ranging from a low of 72% for Mo during the high temperature test condition up to 98%. Removal efficiencies for Sb, Be, Co, and V could not be precisely determined because their concentrations in the stack were below

their analytical detection limits. Removal efficiencies for Ag and Tl could not be estimated because concentrations of these metals were below their analytical detection limits at both the inlet and outlet sampling locations. Considering the poor recovery of matrix spikes used for analytical quality assurance, the data for Se were unacceptable and are not reported here.

These data indicate that the 13 detected metals, with the possible exception of Mo, are emitted from the combustor primarily as PM and that emissions of these metals are controlled predominantly by the PM control device. There also appears to be an effect of ESP temperature on the control of Cr, Mn, and Ni but, given the small size of the data set, this relationship may be due to random chance. Injection of activated carbon did not have a quantifiable impact on emissions of any of the 13 detected metals, which were generally removed at high levels.

### Organic Compounds

Economizer outlet and stack gas concentrations of CDD/CDF were measured during Conditions B10 (no carbon injection), B11 (dry carbon at 132°C [270°F]), and B12 (slurry carbon at 132°C [270°F]). During Condition B10 without carbon injection, the total CDD/CDF removal efficiency across the SD/ESP was 78 to 80%. During Condition B11 with a high injection concentration of dry carbon (360 mg/dscm), the removal efficiency was 95 to 98%. During Condition B12 with a high injection concentration of carbon in slurried lime (330 mg/dscm), the removal efficiency was 96 to 97%. These data suggest that, unlike Hg, the CDD/CDF removal efficiency of dry and slurried carbon injection was similar.

As shown in Figure 7, stack gas concentration of CDD/CDF was reduced from 40 to 60 ng/dscm without carbon injection to less than 7 ng/dscm for dry carbon injection and less than 13 ng/dscm for slurry injection. The higher stack CDD/CDF levels during slurry injection of carbon reflect the higher concentration of CDD/CDF measured at the economizer outlet during two of the Condition B12 runs of approximately 375 ng/dscm, compared to 130 to 220 ng/dscm for the other seven runs. The carbon injection concentration into slurry also averaged nearly 10% below that for dry carbon injection. The reduction of CDD/CDF emissions by carbon injection is consistent with European field test results.

Sampling for VOCs was conducted during Conditions B10 (no carbon injection) and B11 (dry carbon injection). There ap-

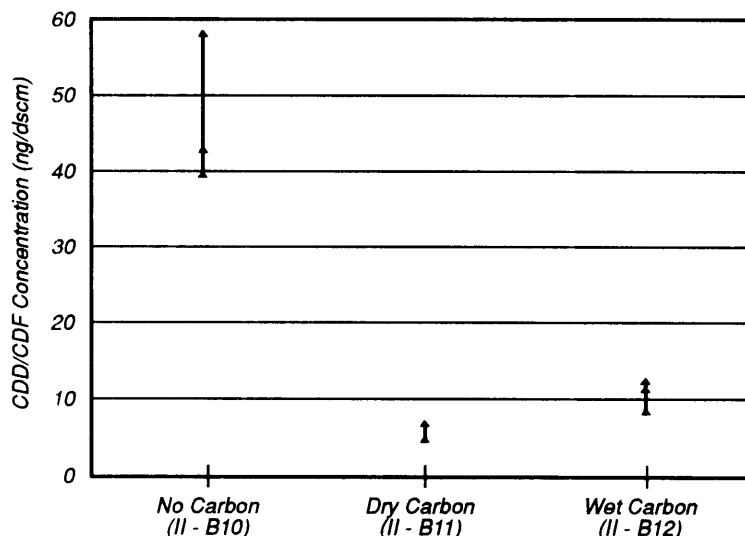


Figure 7. Stack CDD/CDF concentration with and without carbon injection into flue gas at 132°C (270°F).

peared to be a reduction in the level of some compounds (carbon disulfide, benzene, chlorobenzene) across the SD/ESP and an increase in others (trichloro-fluoromethane, methylene chloride, toluene). Of significance to this study, there was no apparent impact of carbon injection on reduction of any of these compounds in the SD/ESP system.

### Acid Gases

As noted in Description of Facility, above, various gaseous components in the flue gas were monitored during each test condition. Emissions of SO<sub>2</sub>, HCl, and NO<sub>x</sub> were monitored using the plant CEM system.

The SO<sub>2</sub> data displayed a general increase in SO<sub>2</sub> removal with increasing carbon injection rate. However, the size of the data set and the scatter in the data are such that this apparent relationship may be due to random chance. No relationship between carbon feed rate and HCl or NO<sub>x</sub> emissions was apparent.

### Impact of Carbon Injection on ESP Performance

ESP performance test results from Unit A were evaluated using average PM, Cd, and Pb removal efficiencies and the percent of total PM less than 2 µm during each test condition. There was no consistent change in any of these parameters during the first four test conditions, indicating that carbon injection did not alter ESP performance. During Condition A5, with the fourth ESP field out of service, there was no apparent change in PM re-

moval efficiency. However, the removal efficiency for Cd and Pb decreased, and the percent of emitted PM less than 2 µm increased. These changes are consistent with the expected enrichment of volatile metals onto fine particulate and the reduced ability of the ESP to collect fine particulate when the fourth ESP field was out of service. Stack opacity, ESP voltage, and ESP current remained within normal operating ranges during the entire Unit A test period.

### Conclusions

The collected data and results calculated for the Camden County tests led to several conclusions:

- Hg reductions in excess of 90% were achieved by injection of dry carbon at both of the ESP operating temperatures examined (132°C [270°F] and 177°C [350°F]).
- The most important process variables affecting Hg emissions were carbon feed rate, carbon injection method, and ESP operating temperature.
- The amount of unburned carbon present in fly ash played a significant beneficial role in controlling Hg emissions.
- The two carbons tested (Darco FGD and Darco PC-100) were similarly effective in controlling Hg emissions when injected as a dry powder. (No slurry tests were conducted with the coal-based PC-100.)
- Injecting carbon (the lignite-based Darco FGD) with lime slurry was

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less effective in reducing Hg emissions than dry injection. This contrasts with the results of the OMSS tests and may be due to the performance characteristics of an ESP versus a FF or to differences in carbon properties (Darco PC-100 was used in the OMSS tests).

- Multivariate regression analyses identified three statistically significant process variables influencing Hg control efficiency: carbon feed

concentration, ESP inlet temperature, and carbon injection method. The four significant process variables which influence stack gas Hg concentrations are: carbon feed concentration, ESP inlet temperature, carbon feed method, and inlet flue gas Hg concentration.

- Injecting carbon reduced stack emissions of CDD/CDF by over 75% so that CDD/CDF removals increased to 95% or more. However, there was no apparent effect

of carbon injection on emissions of VOCs.

- Emissions of metals other than Hg were primarily associated with PM, and their control was determined mainly by the efficiency of PM removal. A possible exception to this relationship was Mo. Carbon injection had no apparent benefit on the emission control of these metals.
- Carbon injection had no discernible impact on the ESP efficiency in controlling PM.

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*The complete report, entitled "Emission Test Report, Field Test of Carbon Injection  
for Mercury Control, Camden County Municipal Waste Combustor," (Order No.  
PB94-101540; Cost: \$27.00; subject to change) will be available only from:*

*National Technical Information Service*

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