FIELD STUDIES OF MERCURY CONTROL USING INJECTED SORBENTS

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ABSTRACT

The injection of activated carbon or other sorbents upstream of a particulate control device is one of the most promising methods for controlling mercury emissions from coal-fired utility boilers with electrostatic precipitators (ESP) and fabric filters. Studies carried out at the bench, pilot, and full-scale have shown that a wide variety of factors may influence the mercury removal effectiveness. These factors include the mercury species, flue gas composition, process conditions, existing pollution control equipment design, sorbent characteristics, and the presence of other active surfaces.

Over the past few years, EPRI and Apogee Scientific have developed a program to assess the performance of sorbent injection at various power plant sites using portable ESP and baghouse pilots in conjunction with semi-continuous mercury monitors. These tests have provided a better understanding of how the different factors affecting mercury removal interact and how these can be optimized to achieve better removal effectiveness. This paper will present the results of these sorbent injection tests at ten power plant sites, including the effectiveness of several novel sorbents in addition to commercial activated carbon. A comparison of these test results with an EPRI-developed mathematical model and recent full-scale demonstrations will also be provided.

INTRODUCTION

On December 14th 2000, the U.S. Environmental Protection Agency (EPA) announced its intent to regulate mercury emissions from coal-fired boilers under Title III of the Clean Air Act Amendments of 1990. EPA plans to issue final regulations by December 15th 2004 and is expected to require compliance before 2010. It is thus very 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 the potential impact on power plant operation and other air pollutant emissions.

The injection of activated carbon or other sorbents upstream of a particulate control device is one of the most promising methods for controlling mercury emissions from utility boilers with electrostatic precipitators (ESPs) and fabric filters. A number of studies carried out at the bench-[1-4], pilot-[5-8], and full-scale[9,10] have examined the influence of carbon type, carbon structure, carbon surface chemistry, injection method (dry or wet), amount of carbon injected, and flue gas temperature on mercury removal. Results have indicated that a wide variety of factors may influence the mercury removal obtained with sorbent injection upstream of an ESP or fabric filter baghouse. These factors include the mercury species being removed (oxidized vs. elemental), the flue gas composition, process conditions (e.g., temperature), sorbent characteristics (e.g., size), and the presence of other active surfaces (e.g., fly ash). Results have shown that although general trends between different sorbents and test conditions exist, sorbent performance tends to be site specific depending upon the exact nature of the flue gas at a particular site.

Over the past few years, EPRI has assessed various mercury control technologies including coal cleaning, catalytic oxidation with wet scrubbing, sorbent injection, and novel concepts. Significant progress has been made in the understanding of how these processes work and in developing models and test equipment to evaluate these technologies[11-14]. Based on these developments, EPRI and its test team have developed a program to help utilities evaluate mercury emissions and control options for their power-producing units. The objective of the program is to measure the flue gas mercury concentration, speciation, and removal effectiveness of existing air pollution control equipment at selected power plants, and assess potential options with corresponding feasibility and projected costs to further reduce stack mercury emissions. One option evaluated at all plants is sorbent injection. The performances of selected sorbents are evaluated using a variety of test methods in both simulated and actual flue gas. Test results provide an indication of various sorbent properties and process operating conditions necessary to achieve desired levels of mercury removal. Mathematical modeling is used to estimate effectiveness and costs associated with a full-scale sorbent injection process.

This paper describes the technical approach developed by EPRI to evaluate sorbents for mercury control at coal-fired power plants and the results from many of the evaluations EPRI has contributed funding and technical direction to during the past five years.

TECHNICAL APPROACH

Evaluating sorbent injection for mercury control begins with a series of laboratory and field tests designed to evaluate mercury removal in flue gas specific to the sites tested. Laboratory tests are used to screen a number of potential sorbents at simulated plant conditions. For each specific plant, sorbents are chosen based upon the characteristics of the plant's flue gas and previous results obtained with the sorbent or sorbent type. A control sample, Norit Americas Darco FGD™ carbon, is tested as part of each program. The results of the laboratory screening tests are used to select appropriate samples for testing in actual flue gas at the selected power plant. Small-scale fixed-bed screening tests are then performed in actual flue gas using EPRI's mini sorbent test system. The results of these tests are used to determine which samples to test in an injection system. The test approach and results are described later in this paper.

Choosing the Candidate Sorbents

In order to evaluate the potential of a mercury sorbent and model its performance, the equilibrium adsorption capacity and characteristics of the sorbent must be known. Scientists at URS Corporation conduct fixed-bed adsorption (breakthrough) tests to generate sorbent equilibrium data for the programs referenced in this paper.

The capacity of a mercury sorbent is determined by exposing a bed of the sorbent for several hours to gas containing mercury and measuring the effluent from the bed until no mercury is removed by the bed (100% breakthrough). The capacity is typically normalized to 50 $\mu g/Nm^3$ because the capacity of a sorbent is dependent on the concentration of the mercury in the inlet gas stream. For most carbon-based sorbents, the capacity is directly proportional to the inlet mercury. For example, the capacity at 50 $\mu g/Nm^3$ is nominally five times that at 10 $\mu g/Nm^3$.

Sorbents are screened by measuring their capacity in the laboratory using simulated flue gas prior to field-testing in actual flue gas. The purpose of these laboratory tests is to evaluate a number of sorbents at conditions similar to those expected at the selected power plants. These test results are then used to determine the most appropriate samples for the field tests.

Interpreting Fixed-Bed Capacity: What Does it Mean for Injection

The equilibrium capacity of a sorbent is the maximum mercury that a sorbent can adsorb at 50 $\mu g/Nm^3$. When injecting a sorbent into the flue gas, the sorbent is exposed to the gas stream for only a few seconds to several minutes as compared to several minutes to hours in a fixed-bed system. Many carbon-based sorbents have sufficient capacities that the sorbents will be removed from the gas stream long before they approach their equilibrium capacity. For example, assume the mercury concentration of the particulate captured in a baghouse hopper is 50 $\mu g/g$ when mercury removal is at its maximum and excess carbon is not being injected into the baghouse. If the inlet mercury concentration in the gas phase is 10 $\mu g/Nm^3$, the concentration of mercury in the ash normalized to 50 $\mu g/g$ (expressed as an equilibrium capacity, normalized to 50 $\mu g/Nm^3$) is 250 $\mu g/g$. The

equilibrium adsorption capacity of many carbon-based sorbents is > 1000 μg/g. However, the "threshold" capacity, or the capacity required for maximum removal, for the baghouse example is only 250 μg/g. Therefore, for the same size distribution and injection concentration, any sorbent with a capacity in excess of 250 μg/g should result in similar mercury removal when injected into the baghouse in this example. The threshold capacity is expected to be lower in an ESP than a baghouse because the sorbent does not have as long to adsorb mercury before it is removed from the main gas flow. When choosing sorbents, a rule of thumb for interpreting capacity is assuring that the equilibrium capacity is $\geq$ 250 μg/g for baghouse applications and $\geq$ 150 μg/g for ESP applications.

Although many sorbents have different equilibrium adsorption capacities for elemental and oxidized mercury, both are often above the threshold capacity and no species specific difference in mercury removal will be measured when the sorbent is injected in a flue gas stream with a mix of oxidized and elemental mercury. Flue gas components and temperature will often affect the measured capacity of a sorbent and the measured effect may be very different for oxidized and elemental mercury. At higher temperatures, the capacity for one species may drop below the threshold capacity for the particulate collection device. At these times, spray cooling of the flue gas to reduce the temperature to a region where the capacity of the sorbent is above the threshold capacity will improve mercury removal. Otherwise, spray cooling is not expected to affect mercury removal.

SORBENT INJECTION TESTS

Sorbents that demonstrated equilibrium capacities above the identified threshold capacity and offer potential cost savings or other benefits over commercial activated carbons are selected for additional characterization. Tests have been conducted in a slipstream Pollution Control Test (PoCT) system (5 to 50 acfm), Pollution Control Module (PCM) (600 acfm), a pilot wire-tube ESP (150 acfm), two full-scale ESPs (12 and 150 MW), and one full-scale COHPAC baghouse (135 MW). The PoCT system is comprised of several small modules that can be configured as a residence time chamber to simulate removal in the first field of an ESP, a baghouse, or a COHPAC unit. The PCM can be configured as a shake-deflate baghouse, a pulse-jet baghouse, or a wire tube ESP. Much of the data from these systems is available in the literature. (refs)

There are several important parameters to consider when assessing the performance of a sorbent. The obvious parameter characterizing performance is the mercury removal effectiveness. Other parameters that must be considered include:

- sorbent availability
- sorbent cost
- shipping costs
- special handling requirements

- impact on particulate control equipment
- impact on waste disposal or ash sales

Injection Terminology: Injection Ratio versus Injection Concentration

During many of the evaluations funded by EPRI, the injection rate is recorded as injection concentration in lb/MMacf. The ratio of carbon to mercury, or injection ratio is a misleading term because, like the equilibrium adsorption capacity, the ratio required is affected by the inlet mercury concentration. However, the injection concentration required should be essentially independent of the inlet concentration for most coal-fired flue gas applications. Since the injection concentration required is independent of the inlet concentration and the mercury concentration at coal-fired utilities ranges from <1 to 30 $\mu g/Nm^3$ (ref), projecting the cost for mercury removal as dollars per pound removed can also lead to confusion.

TEST LOCATIONS

EPRI and Apogee personnel have been involved in sorbent evaluations, using the approach described above, for several utilities at several sites over the past several years. The sites are chosen because they are important indicators for the utility either because they represent several similar units or they are one of the host utility's larger units. This paper summarizes results for injection into ESPs and COHPAC baghouses for tests conducted on the PoCT, PCM, EPRI pilot ESP, and for three full-scale units. A summary of the units tested is presented in Table 1.

Table 1. Host site, locations for sorbent evaluations.

Site ID	Fuel Composition		Temperature (^{o}F)	Test Scale	Configuration
	S (%)	Cl (ppm)			
S1	0.5	700	280-350	PCM	ESP
S2	0.4	10	260-350 280-300	PoCT Full	COHPAC, ESP ESP
S3*	0.7	10	300	PoCT	ESP
S4*	0.8	65	275-300	PoCT	ESP
S5	Pending		300-310	PoCT	ESP, COHPAC
B1	0.9	1200	280 240-280	PoCT Pilot ESP	COHPAC ESP
B2*	3.8	2500	360	Full	ESP
B3	1.4	200	270	Full	COHPAC
L1*	1.1	100	310-350	PoCT	ESP
M1	Pending		310	PoCT	COHPAC

* Scrubber located downstream of test unit
B = bituminous, S = subbituminous, L = lignite, M = mix

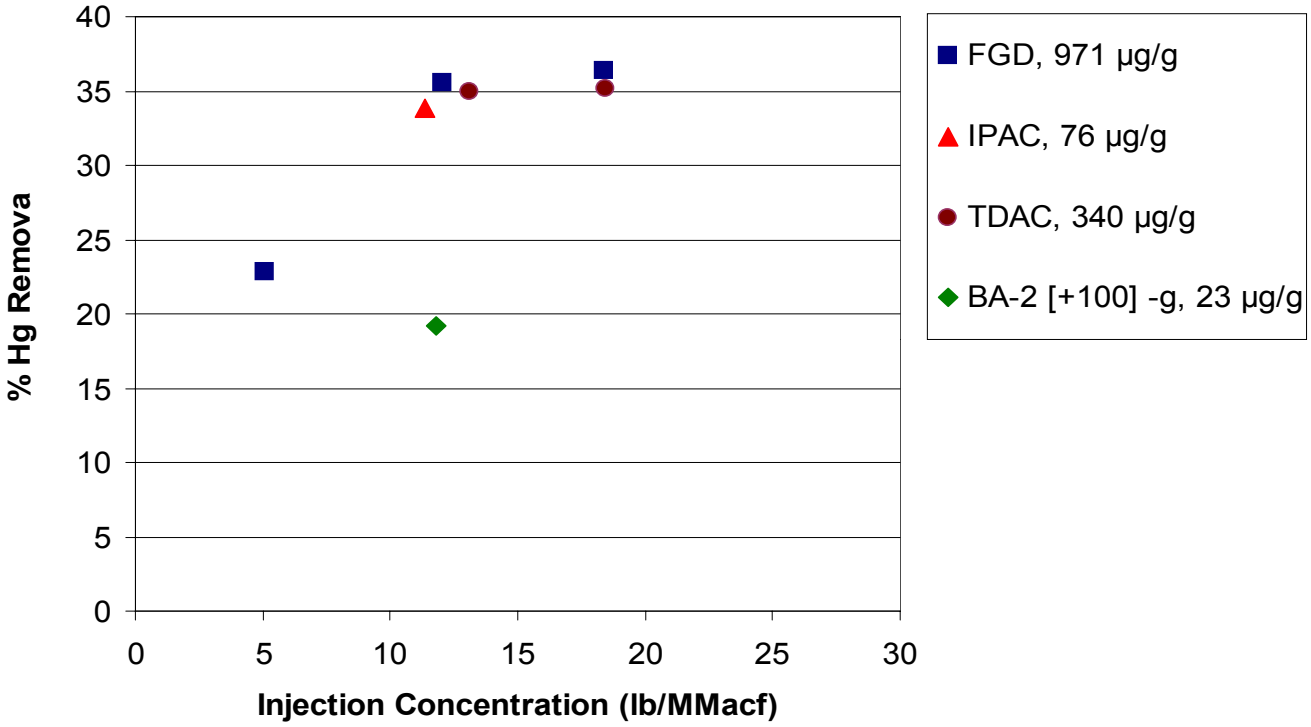
INJECTION TEST RESULTS AND DISCUSSION

Results from injection testing conducted over the past six years with ESPs and COHPAC units are summarized in the following section. The effect on mercury removal of specific parameters including sorbent capacity, flue gas temperature, and injection concentration are included.

Effect of Sorbent Capacity on Mercury Removal

Results from tests conducted with four different sorbents on the PoCT residence time chamber, which simulates removal in the first field of the ESP, are presented in Figure 1. Three of the sorbents are carbon-based materials with equilibrium adsorption capacities ranging from 76 to 971 µg/g. The carbon-based materials are produced from lignite coal (FGD) pistachio nut shells (IPAC) and waste tires (TDAC). Although the equilibrium capacity between these sorbents differs by more than an order of magnitude, the mercury removal measured when any of these sorbents were injected into the residence time chamber was similar. This indicates that the threshold mercury capacity is lower than 76 µg/g for this configuration and in this flue gas. However, when the ash-based sorbent with an equilibrium adsorption capacity 23 µg/g was injected into the system, the mercury removal was significantly lower, indicating that the equilibrium adsorption capacity of this sorbent was lower than the threshold capacity.

Figure 1. Effect of sorbent capacity on mercury removal in an ESP (PoCT Residence Chamber). Site S3.



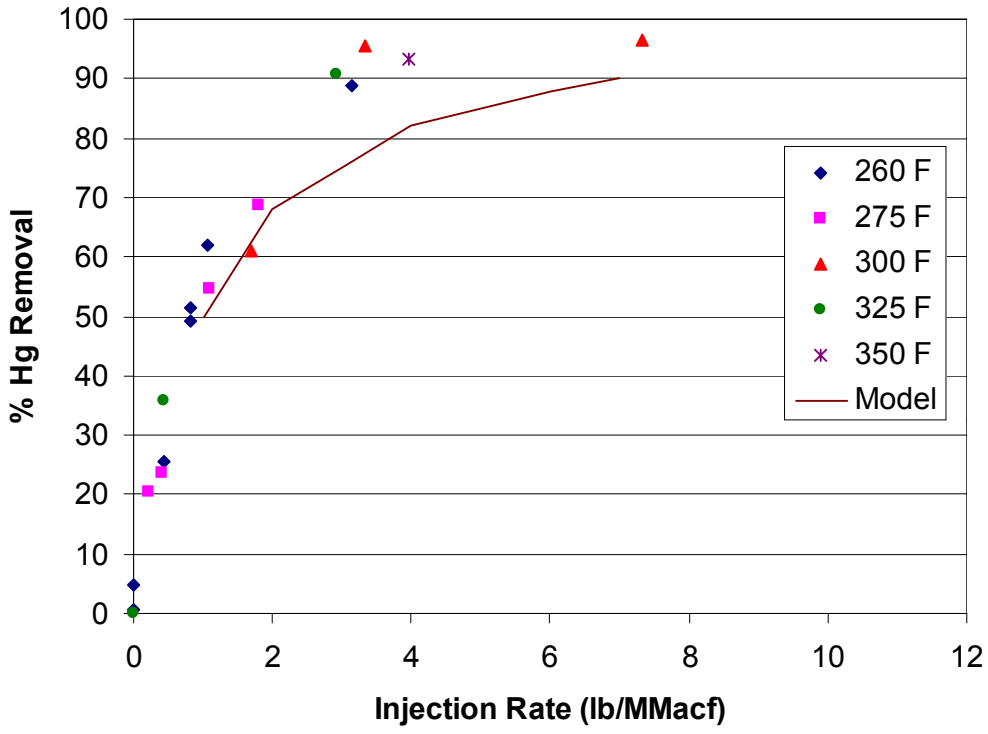
Effect of Temperature on Mercury Removal

Temperature affects sorbents differently depending on the flue gas. Results presented here include evaluations conducted at a site burning PRB coal and a site burning a high sulfur bituminous coal.

Results collected at Site S2 (PRB coal) using the PoCT COHPAC system are shown in Figure 2. During these tests, the temperature was increased from 260 to 350°F. Although the temperature change was 90°F, no effect on mercury removal was noted at this test site.

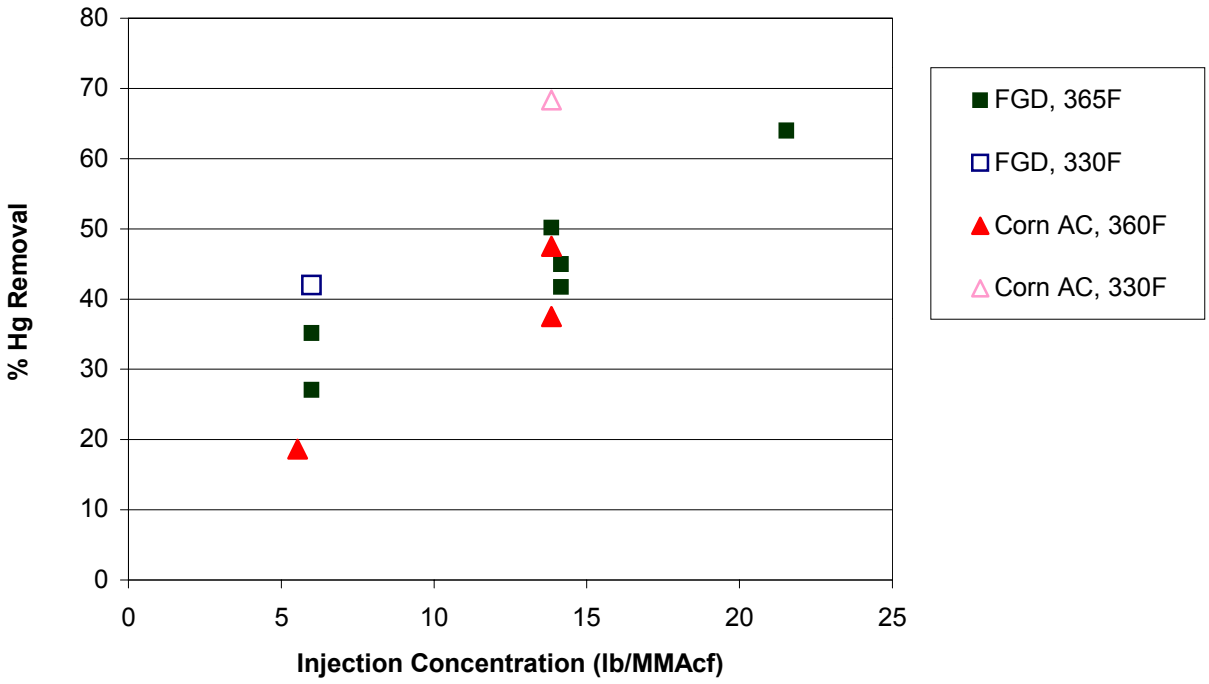
Based upon fixed-bed test results conducted at this site, the equilibrium adsorption capacity is affected by temperature. At 250°F, the capacity was 8800 µg/g. At 300°F, the equilibrium capacity was 880 µg/g (ref). Although no capacity data are available at 350°F, the injection data indicates that the equilibrium capacity is still above the threshold capacity at this temperature. This data suggests that spray cooling to 260°F would not improve mercury removal across a COHPAC baghouse at this site. During full-scale testing at Site S2, Wisconsin Electric's Pleasant Prairie Power Plant, the effect of spray cooling was evaluated. Lowering the gas temperature by spray cooling from 300 to 250°F did not improve the mercury removal across the ESP. (ref. Tucson).

Figure 2: Effect of temperature on mercury removal with FGD Carbon with PoCT COHPAC, Site S2 (PRB flue gas) (Capacity for Model = 500 µg/g)



Evaluations conducted at a site burning high sulfur bituminous coal (University of Illinois' Abbott Power Plant in Champaign, IL) indicate that there may be an effect of temperature on mercury removal across the full-scale ESP at this site. The data presented in Figure 3 shows mercury removal results for two carbon-based sorbents, FGD and an experimental corn-based material. As shown, the effectiveness of both sorbents improves when the gas temperature is lowered by water spay cooling from 360 to 330°F. Equilibrium adsorption capacity measurements were conducted for FGD at this site at temperatures of 375 and 325°F. At 375°F, the equilibrium adsorption capacity was 184 µg/g. At 325°F, the equilibrium adsorption capacity was 486 µg/g. The injection data suggests that for this ESP and this flue gas, the threshold capacity is below the equilibrium capacity at higher temperatures. Therefore, spray cooling to increase the equilibrium adsorption capacity above the threshold capacity should increase the mercury removal across the ESP.

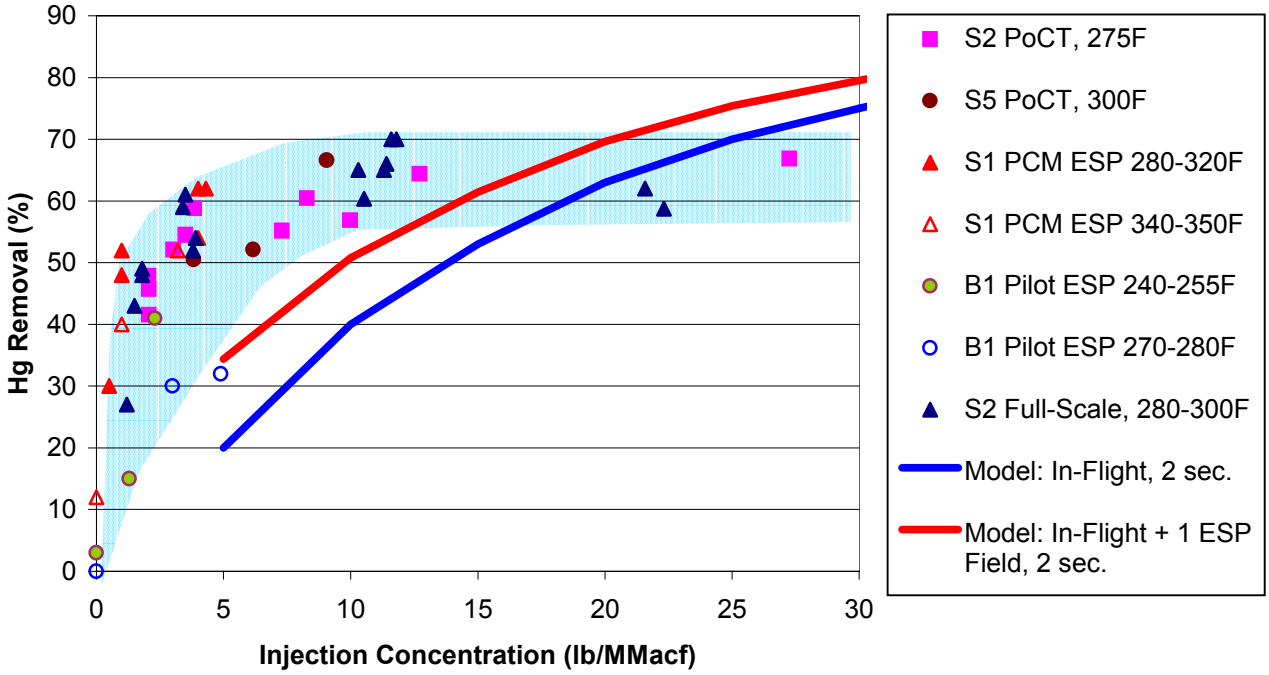
Figure 3. Effect of temperature on mercury removal with FGD and corn-based carbon with full-scale ESP, Site B2 (high sulfur bituminous flue gas)



Effect of Injection Concentration on Mercury Removal: ESPs

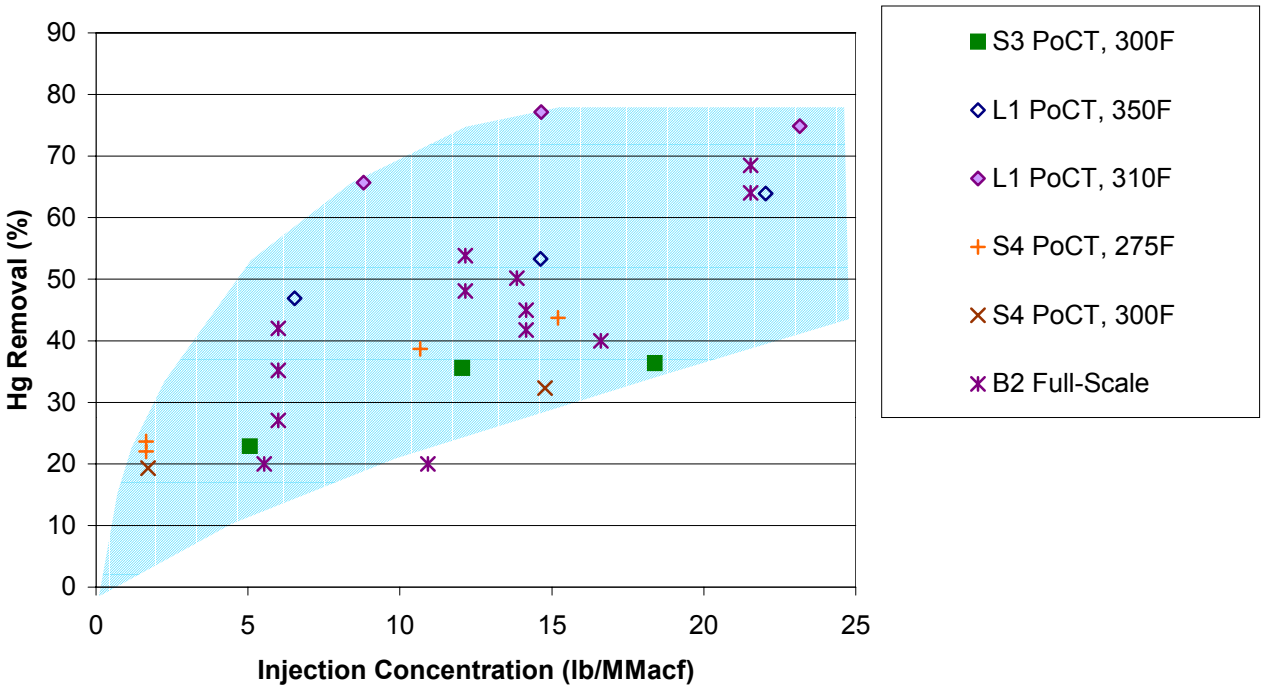
Mercury removal results from ESP evaluations on 10 units burning bituminous, subbituminous, and lignite coals are presented in Figures 4 and 5. The data collected in Figure 4 are for plants that do not have a scrubber installed downstream of the test ESP. The data collected at the PoCT, PCM, pilot, and full-scale indicate that the mercury removal for all tests is fairly consistent. The data also suggests that, although the model predicts mercury removal above 70% is possible, data from the field tests sites indicates that there may be a limit to the mercury removal achievable in an ESP. The results show that for the non-scrubbed units, the mercury removal rapidly increases to near the maximum achievable at injection rates between 5 and 10 lb/MMacf. In general, little improvement is noted at injection rates above 10 lb/MMacf.

Figure 4. Summary of ESP injection test results on non-scrubbed units.



Data presented in Figure 5 shows mercury removal in over a broader range than in Figure 4. For some of these units, the mercury removal continues to improve up to injection concentrations of 20 lb/MMacf. All units in Figure 5 have a scrubber installed downstream of the test ESP to removal SO_2 and/or particulate. The characteristic that separates the data in Figure 4 from Figure 5 is the presence of a scrubber, not the level of sulfur in the coal or flue gas (some units shown in Figure 4 have higher sulfur levels than some units in Figure 5). Therefore, although sulfur may play a role in the effectiveness of activated carbon for mercury removal, insufficient data are available to characterize the effect.

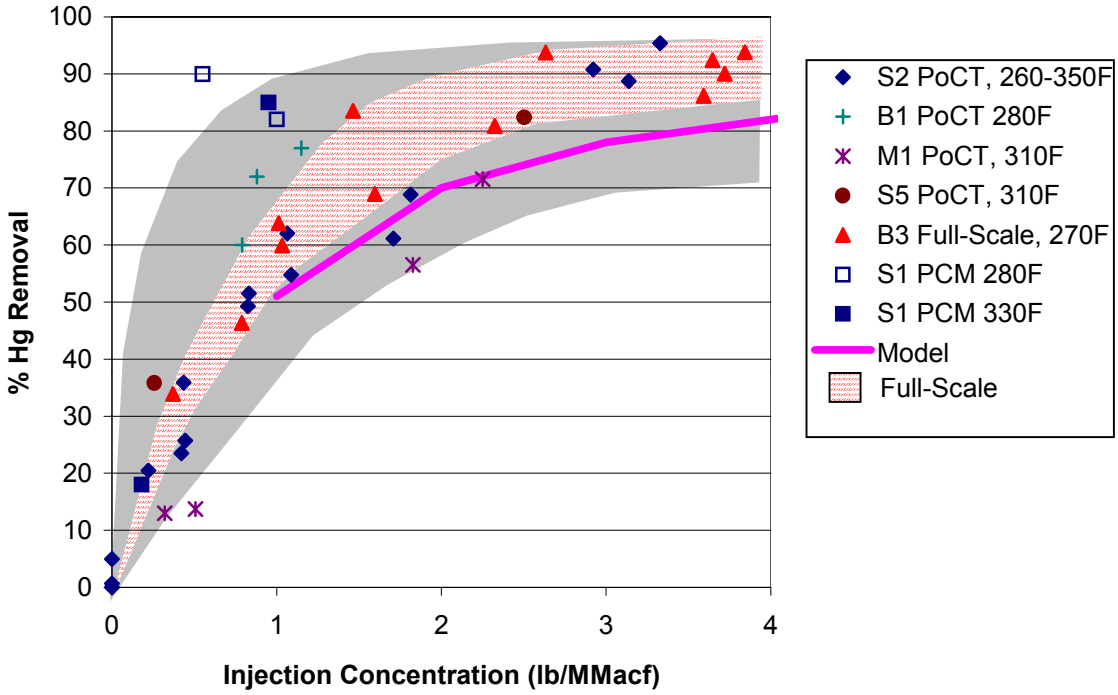
Figure 5. Summary of ESP injection test results upstream of scrubber on scrubbed units.



Effect of Injection Concentration on Mercury Removal: COHPAC

The mercury removal evaluated across seven COHPAC units is presented in Figure 6. As shown, the mercury removal for the COHPAC units typically increases rapidly to near the maximum removal at injection concentrations between 2 and 3 lb/MMacf, as compared to the ESP on non-scrubbed units that required between 5 and 10 lb/MMacf to achieve mercury removal near the maximum achievable. There are operational and performance differences between the units. Unfortunately, sufficient data are not available to determine the reasons that the mercury removal is lower in some flue gas streams than others.

Figure 6. Summary of mercury removal by FGD activated carbon injection upstream of COHPAC.



CONCLUSIONS

- All sorbents with the same size distribution are expected to demonstrate similar mercury removal effectiveness when injected upstream of an ESP or COHPAC fabric filter when their equilibrium adsorption capacity is above the threshold capacity.

- In general, very little temperature effect has been measured at sites where the predominant flue gas species is elemental mercury and the temperature range is between 250 and 350^{o}F.

- At sites where the equilibrium adsorption capacity of a sorbent is below the threshold capacity at higher operating temperatures, spray cooling should improve the mercury removal across the particulate collector.

- The mercury removal for ESPs on units that do not have a scrubber installed downstream of the ESP typically increases rapidly to near the maximum removal achievable at injection concentrations between 5 and 10 lb/MMacf. In general, little improvement is noted at injection rates above 10 lb/MMacf.

- The highest mercury removal measured during ESP tests on units that do not have a scrubber installed downstream of the ESP was 70%.

- There was more variability in the mercury removal results on the ESPs tested on units with a scrubber installed downstream of the ESP. Although sulfur may play a role in the effectiveness of activated carbon for mercury removal, insufficient data are available to characterize the effect.

- The mercury removal for the COHPAC units typically increases rapidly to near the maximum removal at injection concentrations between 2 and 3 lb/MMacf.

- PoCT, PCM, and pilot ESP results are similar to results collected on full-scale units.

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