

Demonstration of Dry Carbon-Based Sorbent Injection for Mercury Control in Utility ESPs and Baghouses

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Introduction

Coal has been the predominant fossil fuel used to generate electricity in the United States. It is important that coal continues to be a major source of fuel, as long as it can be burned in an economical and environmentally appropriate manner. The 1990 Clean Air Act Amendment (CAAA) has required that the Environmental Protection Agency (EPA) assess the health risks associated with air toxic emissions from fossil-fuel-fired utility boilers. A considerable level of attention has specifically been given to mercury in terms of its environmental release and impacts.

Domestic coal-fired power plants emit approximately 40 to 80 metric tons of mercury to the atmosphere annually, approximately 30% of all mercury emissions from human activities. However, the mercury concentration in utility flue gas is in the extremely dilute range of 0.1 to 1 part per billion. The EPA is assessing whether such low concentrations of mercury emissions from coal-fired utilities pose any significant health risk and whether mercury regulations would be necessary or appropriate. In anticipation of possible mercury control regulations, DOE has funded Public Service Company of Colorado (PSCo) to evaluate carbon-based sorbents for mercury control at utility coal-fired power plants.

Many trace metals in flue gas are normally present in the solid state, in the flyash particles, and can be removed effectively by an efficient particulate collector. However, mercury forms a number of volatile compounds and the extent of their removal across existing emission control devices is poorly understood. This is partly due to difficulty in measuring these trace amounts of mercury accurately and partly because of the different forms in which it exists. Typically, the total concentration of mercury in a utility flue gas stream is less than $20\mu\text{g}/\text{Nm}^3$ (1). The fraction of the total mercury found in the condensed form on the particulate varies with site, fuel, and flue gas conditions.

Pending EPA decisions may eventually result in a mandate that requires utilities to install additional pollution control equipment to control vapor phase mercury. Specially designed emissions-control systems will be needed to capture the volatile compounds effectively. Current commercial technologies used at municipal solid waste (MSW) incinerators include injecting sorbents into the gas stream, passing

the gas through a packed bed of sorbent (used in Europe and Japan), or using a wet system to capture mercury compounds. Injected sorbents are most commonly activated carbons or carbons treated chemically to produce sulfide or iodide compounds with mercury. Packed-bed adsorbers typically use carbon-based materials for collecting mercury. Wet systems include equipment such as scrubber towers, spray dryers, and wet electrostatic precipitators.

One method used for mercury removal in MSW plants is currently being evaluated for utility plants through DOE and EPRI funding: the use of activated carbon injected into the flue gas (2,3). Fairly high mercury removal efficiencies are obtained by this method in MSW plants. However, mercury concentrations in these process gases are generally several orders of magnitude above the amounts found in flue gas from utility boilers. The gas conditions and mercury species found at the two types of facilities are also significantly different. Preliminary studies on utility flue gas indicate that sorbent injection can be used to remove mercury (4,5). Sorbent injection also represents a technology that is more easily retrofitted into an existing pollution control system and may be installed at a lower cost than other technologies.

For any newly-developed control technology to be of use, however, it must undergo extensive evaluation under actual operating conditions. The impact of sorbent injection technology on existing pollution control systems must be known before a decision to install such a system is made. The overall objective of the program discussed in this paper is to evaluate the effectiveness of dry sorbents for mercury removal at coal-fired utilities with a variety of particulate control systems.

Initial investigations of the use of dry carbon-based sorbent injection for mercury control on utility applications have shown that carbon-based sorbents are capable of removing gaseous phase mercury. Because of the difficulty in capturing and measuring mercury, however, it is important to evaluate these technologies extensively on actual utility flue gas. Testing has been performed since July 1996 on a slipstream of flue gas from PSCo's Comanche Station in Pueblo, Colorado. The test fixture is a 600 acfm particulate control module that can be configured as an electrostatic precipitator, a pulse-jet baghouse, or a reverse-gas baghouse. Sorbent is injected into the flue gas slipstream prior to the particulate control module, and is removed by the module. Flue gas temperature and sorbent residence time can be changed to evaluate a range of plant operating conditions. In addition, the effect of flyash on mercury capture can be evaluated because the flue gas slipstream can be taken from either upstream or downstream of Comanche Station's full-scale reverse-gas baghouse. This paper describes the results of initial pilot testing with the pilot configured as an electrostatic precipitator, a pulse-jet baghouse, and a reverse-gas baghouse.

For this program, a concerted effort was made to minimize the parameters that interfere with analyzing the data. A laboratory-scale field test device that can be configured as an electrostatic precipitator, a pulse-jet baghouse, or a reverse-gas baghouse was designed and fabricated. The temperature of the test fixture can be controlled and sorbent residence time can be changed, allowing simulation of many plant operating conditions. The test facility allows for a variety of configurations because it is designed to extract flue gas either upstream or downstream of the existing baghouse, which results in a standard filtering configuration for the test fixture or provides nearly particulate-free flue gas. The device has been integrated with an existing pilot-scale facility at PSCo's Comanche Station.

This paper describes the test facility, sorbents identified for testing and the factors which may affect their performance, the test matrix, initial results and a discussion of general trends observed.

Approach

Description of Test Facility

The lab-scale test facility was designed and fabricated to permit significant control over the operating conditions during evaluations. In addition to changing the particulate control configurations, operating parameters such as duct temperature, flue gas moisture content, in-duct sorbent residence time, and flue gas mercury concentration can be controlled and varied. Sorbent effectiveness is being evaluated for temperatures from 200°F (expected cold weather baseline at Comanche) to 325°F. Duct cooling can be achieved by spray cooling with water (increased moisture content) or dry cooling with a heat exchanger. The sorbent injection ports are located for in-duct sorbent residence times of 0.75 to 1.5 seconds to evaluate the effect of residence time on sorbent effectiveness. An overall schematic of the test fixture is shown in Figure 1.

The 30 foot high main collection vessel is incorporated into the 8-foot by 10-foot framework shown in the photo in Figure 2. The injection section and collection section are built within the framework and are accessible from platforms at 10-feet, 20-feet and 30-feet. A mast is installed on the tower to allow configuration changes in the control module without the assistance of a crane. The boom on the mast extends 25 feet above the tower. At most, two people are required for major configuration changes, such as from the electrostatic precipitator to the pulse-jet baghouse. This change includes removing the four 10-inch diameter gas passages, each 20-feet long.

The injection section is a 12-inch diameter pipe with 4-inch ports at five locations along its 16-foot length. Flue gas entering the injection section is heated with an electrical resistance heater upstream of the injection section. Water cooled coils are installed at this location to cool the gas when cooling is necessary without adding moisture to the gas.

Control System

The control system is designed to allow manual or automatic operation of the pilot. The primary control elements for the pilot are a Programmable Logic Controller (PLC) and an intelligent data-logger. Pneumatic actuators on several valves, including the inlet, outlet, bypass, flow control, purge, and hopper discharge valves permit automatic flow control, off-line cleaning, and isolation of the pilot for shut-down. The control system is programmed to bring the pilot off-line, clean the bags or rap the plates, and purge the system for alarm trip conditions. Trip conditions include low boiler load and low duct temperature for all configurations and high duct temperature and high tubesheet pressure drop during the fabric filter tests. The bag cleaning or plate rapping sequence can be controlled automatically or manually at the control panel. Parameters which are monitored and recorded include: gas temperatures, flowrate, pressures, boiler load, secondary voltage and current (ESP), cleaning/rapping frequency, and pulse pressure or reverse gas flow (fabric filter). Data are stored in time-stamped arrays for analysis and graphical presentation.

ESP Configuration

The pilot-scale electrostatic precipitator is a wire-tube type unit. It is more practical to use a tube-type precipitator design for ESP pilots treating flow below approximately 1000 acfm primarily because gas “sneakage” around the active section and changes in the electric field at the edges of the plates become dominating factors in flat plate designs for low flow rates. Sneakage in a wire/plate ESP becomes a major concern in pilots treating flue gas in this flowrate range because the spacing required between the high voltage components and ground is the same in the pilot-scale as in a full-scale. Although the distance required between high voltage and ground is a small fraction of the overall ESP box height in a

full scale ESP where plates are 20 to 40 feet tall, it becomes a significant percentage of the box height for a pilot ESP, which may be only a few feet. In a wire-tube ESP, all the gas flows through the active section, a constant electric field formed between the corona wire and grounded tube.

It is important to maintain the same wire-to-collector spacing in a pilot ESP as in the full-scale design being modeled, as this spacing defines the electrical field strength. A typical wire-to-plate spacing in an older full-scale ESP is 4.5 inches. The collector tube diameter in the pilot ESP is 10 inches to provide a wire-to-tube wall spacing of 5 inches.

The ESP pilot fabricated for these tests is designed to treat 620 acfm in a wire-tube configuration. The pilot is operated with a velocity through the 20 foot long collection section of 5 ft/sec. The specific collection area (SCA), a standard measure of collection area to total gas flow, at these operating conditions is 327 ft²/Kacfm. This SCA is representative of many older ESPs installed at utilities in the United States. A 0.1-inch diameter smooth electrode wire is installed in each tube of the pilot ESP.

Four 10-inch diameter pipes are hung from a tubesheet at the top of the 28-inch diameter collection vessel housing. The 10-inch diameter pipes serve as the gas passages for the ESP. Four electrodes, one on the centerline of each gas passage, are attached to a rigid frame and powered from a single T/R set. The lower frame is weighted to keep the wires straight and a pneumatic vibrator is attached for cleaning ash from the electrodes. The top frame is attached to the high voltage bus at the feedthrough insulators. The T/R set is located at ground level and power is brought to the electrodes through a shielded bus. The T/R set is controlled by an automatic voltage controller (AVC) and is set to simulate conditions in a full-scale wire-plate ESP. For these tests, the T/R set is operated in the 40 KV, 15A range.

Pulse-Jet Configuration

The pilot pulse-jet was designed to filter 628 acfm flue gas at an air-to-cloth ratio of 4 ft/min. Six full-scale bags are installed in the pilot. Full-scale bags are used to better simulate the filtering and cleaning characteristics experienced in a full-scale unit.

When the control module is configured as a pulse-jet baghouse, the four 10-inch diameter ESP tubes and the corresponding tubesheet are removed and replaced with a tubesheet with six 5-inch diameter holes. Six 20-foot long bags are hung from the pulse-jet tubesheet. A rigid steel cage is inserted into each bag. Flue gas enters the bag compartment at the bottom and passes through the bags from outside to inside, depositing the particulate matter on the outside of the bags. The flue gas then flows out of the compartment through the outlet plenum on the clean side of the tubesheet. Flue gas in the outlet duct passes an annutube flow sensor, the flow control damper, and through a section of duct located beneath the ash hopper. Ash from the hopper is fed into this duct section by a rotary valve. The particulate laden gas then returns to the host duct. The bags are cleaned with a pulse of compressed air from a pulse pipe located above each row of three bags.

Reverse-gas Configuration

The PCM was configured as a reverse gas baghouse by removing the pulse jet baghouse tubesheet near the top of the PCM and installing a cell plate with seven 8-inch diameter holes near the bottom of the PCM. Each bag was attached to the cell plate by a metal snap band and a fiberglass double-beaded gasket sewn into the bottom of the bag. The 21-foot long, 8" diameter full-scale fiberglass bags were sealed at the top by a metal bag cap. The caps were attached to tensioning springs at the top of the PCM and the bags were pre-tensioned to a load of approximately 35s. Flue gas entered the bag compartment from the bottom and passed through the cell plate into the interior of the bags. The gas

then flowed from inside to outside of the bags, deposited the ash on the inside of the bags, and exited the compartment via the outlet plenum.

Sorbent Injection

A feed hopper is used to store and supply sorbent to the feeder. Sorbent is injected into the duct via a screw feeder with an electronic control for feed rate to allow the operator to change the injection rate independent of gas flow.

Sorbents are injected into an injection section upstream of the main particulate collection section. The injection section is a 12-inch diameter pipe with 4-inch ports at five locations along its 16-foot length. These port locations are spaced to allow in-duct sorbent residence times from 0.75 to 1.5 seconds at typical operating conditions. Flue gas flows into the test fixture through a heater assembly at the top of the unit, into the injection section and then into the lower portion of the main collection section.

Mercury Measurement

Mercury measurements are made with the Mercury Speciation Adsorption (MESA) method. The MESA system employs four solid sorbent traps in series, and a quartz probe with a glass wool plug installed upstream of the traps. The series of traps is contained in a heated probe. During sampling, flue gas passes through the glass wool in the quartz probe where particulate is removed. Particulate-free flue gas then passes through the first sorbent trap, a potassium chloride (KCl) impregnated soda lime sorbent. This trap adsorbs the oxidized mercury species in the flue gas. The second trap is identical to the first and serves as a backup oxidized trap. The final two traps are iodated carbon, a sorbent which adsorbs all forms of mercury. Since the iodated carbon traps are downstream of the KCl impregnated soda lime sorbent traps which have captured the oxidized species, mercury collected in the iodated carbon is reported as elemental mercury. The sum of the mercury in the four traps is considered total vapor phase mercury. Following sampling, the traps are analyzed for mercury content using cold vapor atomic fluorescence spectroscopy (CVAFS) (6).

Recently, some researchers have found that some elemental mercury may be adsorbed in the first two traps and reported as oxidized mercury, particularly in flue gas with high NO the presence of high SO_2 (7). However, it has also been reported that there is good correlation between the total mercury as reported by the MESA method and other mercury sampling methods (6,7). Because Comanche Station burns a low sulfur coal and has low NO levels, the MESA oxidized mercury results should not be biased high. However there is still some controversy regarding this technique. Therefore, the majority of the MESA trains identified for testing contained only the iodated carbon traps and the results were reported as total vapor mercury. A few full MESA trains were used to indicate the variation in mercury speciation in the flue gas and the effect of each of the two sorbents on elemental and oxidized mercury.

A set of tests were conducted with the standard MESA train with the two sets of sorbent traps reversed. Based upon laboratory data, there was some concern that some mercury would exit the iodated carbon traps as Hg^{++} . When placed downstream of the iodated carbon traps, a KCl impregnated soda lime trap should capture any remaining oxidized mercury species. The results indicated that no mercury was captured in the downstream traps.

Sampling System - Developments

Results from ESP testing with the modified Mercury Speciation Adsorption (MESA) method showed high mercury levels on the quartz wool particulate filter. Although the MESA is sampled non-isokinetically, a large fraction of mercury on the particulate under some conditions indicates significant

mercury adsorption onto the flyash. The flyash entering the MESA train and collecting on the glass wool particulate filter may not be representative of the flue gas flyash concentration as it is not sampled isokinetically and is dependent on parameters such as flyash size distribution and gas velocities.

In addition to the mercury measurement concerns using the MESA related to isokinetic sampling, other changes within in the system (such as changes in bulk flue gas temperature) further complicated data analysis. During testing at Comanche, the flue gas is often cooled or heated to a target temperature for a particular test condition. If the temperature of the flyash is modified, it is likely that the ash is adsorbing or desorbing mercury; thus the vapor mercury downstream of heating/cooling will be different than what was upstream of heating/cooling. The inlet sampling location is downstream of heating/cooling and it is possible that ash is not in equilibrium with the flue gas with respect to mercury in the gas or adsorbed on the flyash when it reaches this sampling location. Carbon sorbents are injected just downstream of the inlet sampling port. If mercury continues to adsorb onto the flyash beyond the inlet sampling location, vapor mercury removal is occurring that should not be attributed to the sorbent. Since the temperature of the flue gas in Comanche's duct changes with Comanche operation, different amounts of heating or cooling are required to maintain the PCM at a given temperature. It is likely the fraction of mercury vapor adsorbed/desorbed will be affected by the variations in heating/cooling. Thus, although baseline flyash mercury removal measurements were made, significant uncertainty remains when assessing contribution of the flyash to overall mercury removal during sorbent injection for this dynamic system. If a representative total mercury measurement can be obtained, erroneous conclusions concerning the affinity of a sorbent for mercury drawn from non-isokinetic flue gas sampling could be minimized.

Comanche flyash adsorbs mercury and it is likely that forcing the flue gas through a fixed bed of flyash (i.e. EPA method 29 or similar sampling filter) would increase the amount of mercury collected on the ash and bias the vapor measurements low. Sorbents, such as activated carbon, are evaluated for their ability to remove mercury from the vapor phase and unrepresentative low inlet vapor measurements could introduce difficulties in assessing the effectiveness of the sorbent. Rigorous sample system development and testing is outside the scope of this project; therefore, the selected device must be similar to existing devices that have proven effective for mercury measurement. For initial tests, the front-end of a Method 29 sampling train will be used with the addition of glass cyclones upstream of the particulate filter. The cyclones should remove a large fraction of the flyash, thus minimizing the contact of the flue gas and flyash. A sketch of the arrangement is shown in Figure 3, Figure 4 is a photograph of the sampling system.

Mercury Doping System

The mercury doping system was designed to introduce a known concentration of elemental mercury vapor into the duct feeding flue gas to the particulate collector. The fundamental design of this doping system is based on previous systems designed on other DOE programs. Nitrogen is passed at a constant rate over liquid mercury in a temperature controlled container. The mercury concentration in the gas exiting the vessel is determined by the temperature of the vessel and the nitrogen flowrate. This system was used on some pulse-jet tests when the inlet mercury concentration was below $1\mu\text{g}/\text{m}^3$.

Project Description/Technology

The two sorbents tested are Darco FGD activated carbon from American Norit (referred to in this paper as Norit carbon) and an experimental carbon identified as AC-1. Norit is an activated carbon derived from lignite and is used to remove mercury in municipal solid waste (MSW) combustors in Europe and the United States. It has also been used in several utility mercury removal tests including previous tests at Comanche Station. The second sorbent proposed is identified as AC-1, an activated carbon prepared

from a bituminous coal. Initial laboratory evaluations of AC-1 have shown promising results as compared with other carbon-based sorbents, including Norit activated carbon. AC-1 was chosen for testing because of the promising technical results and it is projected that producing this sorbent on a commercial scale will be less costly than producing Norit activated carbon.

Performance Evaluation Parameters

The effectiveness of a mercury sorbent is determined by the amount of sorbent needed to achieve a specific removal efficiency. Due to the low mercury concentrations typical in flue gas, the mass ratio of sorbent to mercury needed for high removal efficiencies (> 90%), expressed as a ratio of mass sorbent: mass mercury, is expected to be high (> 10,000:1) under most conditions. This assumes that the candidate material is an effective sorbent and mercury removal is therefore mass transfer limited (i.e. the removal is dependent on how much mercury reaches the sorbent surface. Once the mercury reaches the sorbent surface, it will be adsorbed). In practice, the capacity (expressed as $\mu\text{g Hg adsorbed/g carbon}$) is limited by the gas conditions, including composition, velocity, and temperature, and the sorbent surface area, including pore size. A mass transfer limit represents a best case scenario. To improve mercury mass transfer and therefore removal effectiveness, long residence times, small sorbent particle sizes, and good sorbent-gas mixing are needed. Residence times > 1 second and sorbent size < $10\ \mu\text{m}$ are desirable. In general, baghouses are expected to be more effective for mercury capture than ESPs due to the increased contact time between sorbent and mercury afforded by the dust cake build up on the filter bag surface. When residence time is limited (such as in the ductwork connecting an ESP to the air heater outlet), much larger amounts of sorbent or very small sorbent sizes are needed to compensate for the short contact time.

Variations in concentrations of flue gas components such as SO_2 , H_2O , HCl and NO_x can affect sorbent effectiveness (8). Testing on a bench-scale Norit carbon fixed bed shows that the presence of HCl improves while SO_2 inhibits adsorption. Such effects point to the difficulty of predicting mercury removal effectiveness under specific flue gas conditions. In addition, some types of flyash appear to adsorb mercury under certain conditions which are currently undefined. Due to the large quantity of flyash present in the flue gas (relative to mercury), there could be significant mercury removal in some cases even without sorbent injection.

Test Matrix

This paper discusses preliminary results from initial tests in the ESP, pulse-jet, and reverse-gas configurations. As shown in the ESP test summary in Table 1, three sets of tests were conducted with the ESP: baseline, Norit activated carbon and AC-1 activated carbon. Tests were conducted in three temperature ranges at three injection rates.

Following the ESP tests, it became apparent that altering the temperature within the test fixture may be making the data difficult to interpret. It is believed that changes in the temperature of the entrained flyash caused mercury to adsorb onto or desorb from the particulate. Therefore, during the pulse-jet tests, the temperature of the flue gas was not altered during sorbent injection testing when flyash was present in the flue gas. Baseline tests were conducted in three temperature ranges to evaluate the effect of temperature on mercury removal by the particulate alone. During these tests, particulate was sampled isokinetically during mercury measurements. Subsequent tests were conducted with minimal flyash in the flue gas (inlet penetration located downstream of Comanche's full-scale baghouse) and the flue gas mercury concentration was increased by doping with elemental mercury. A summary of pulse-jet tests is shown on Table 2.

Preliminary Results

ESP Configuration

Twenty three valid test points using two different sorbents at various operating conditions were collected during the ESP tests. Preliminary mercury removal results using the Norit and AC-1 sorbents are summarized on Figure 5, which presents mercury removal as a function of sorbent feed rate. The data indicate that an overall mercury removal of 15 to 70% was possible based on mercury captured in solid iodated carbon (IC) traps upstream and downstream of the ESP. Baseline (no sorbent injection) removals of 11 to 36% (average approximately 30%) are shown. The mercury fractions captured on the flyash collected by the glass wool plug in front of the IC sampling traps show 2 to 37% of the total mercury collected in the sample. This ash is collected non-isokinetically and may not be representative of the particulate matter present in the flue gas. Although the mercury in the particulate sample may be biased due to the sampling method, the data strongly suggest that mercury is adsorbing onto the flyash. Thus, while the overall mercury removals shown provide indicators of a sorbent's effectiveness for mercury control, significant scatter in the mercury removal data can be expected due to mercury adsorbed onto the flyash and may not relate to an accurate measurement of the sorbent's ability to remove mercury.

Although an exact determination of the sorbent-related mercury removal has not been possible, it is believed that a maximum of roughly 60% vapor phase mercury removal has been achieved. In order to obtain a rough estimate of the sorbent's mercury removal capability, the average vapor phase mercury removal during baseline testing (no sorbent injection) of 30% was used to estimate the ability of the sorbent to remove mercury. For example, during the 1.2 lb/MMa Norit test point, 58% vapor mercury removal was measured. Correcting the data to an assumed 30% flyash mercury removal reduces the total vapor mercury removal due to sorbent injection to 40%.

Since total (vapor + mercury adsorbed on the flyash) isokinetic measurements were not made during the ESP tests, information regarding mercury desorption or adsorption onto the flyash is inconclusive. It is believed that mercury adsorbing onto the flyash has contributed to the scatter in the mercury removal results and has made identifying trends of changes in removal effectiveness with temperature very difficult. Because high flyash mercury adsorption was not expected, the flue gas temperature was purposefully altered for many of the tests, complicating data interpretation. In initial tests, the inlet sample was collected with the flue gas in equilibrium with the host duct, upstream of flue gas cooling or heating. In the subsequent tests, inlet samples were collected just downstream of the heating/cooling section. It is believed that mercury measurements made at the two inlet sampling locations may be different due to flyash adsorption/desorption. Mercury removal calculations based on IC trap mercury measurements taken at these two locations may not be directly comparable. The data are still being analyzed.

All data shown except three inlet measurements were conducted with the modified MESA method (glass wool plug for particulate followed by two iodated carbon traps). The full MESA train contains a KCl/soda lime trap designed to capture speciated mercury ($Hg(++)$) upstream of the iodated carbon trap. The results from these tests suggest that $Hg(++)$ is 11 to 34% of the vapor fraction. The data also indicate that the mercury collected on the glass wool plug during these tests is 8 to 19% of the total mercury collected in the train. Studies show that the total mercury measurements reported by the MESA train are comparable to other methods. However, some researchers contend that the KCl/lime trap can overestimate the fraction of speciated mercury (thus underestimate the elemental fraction) under some conditions including NO_x in the presence of ≥ 1500 ppm SO_2 in the flue gas (7). Comanche's flue gas has low SO_2 (250 ppm), however, recent mercury samples have not been collected at Comanche with other

methods to verify the ability of the MESA to adequately speciate at this site. However, the data indicate that the majority of the mercury captured at Comanche is elemental mercury. The actual elemental fraction in the gas stream may be higher than reported if the MESA train is reporting high biased speciated mercury concentrations.

In addition to measuring the mercury in the flue gas, two coal samples and two PCM hopper ash samples were collected and analyzed. The two coal samples were collected on the same day and show a slight variation in mercury concentration (57.4 and 62.06 ng/g). However, a recent study of the variability in the analysis of mercury in coal (9) suggests that, of the eleven laboratories studied, the intralaboratory repeatability for a coal sample mercury analysis averaged 20 ng/g. Thus, the variation in the reported coal mercury levels is not considered significant. The two ash samples collected showed much higher mercury concentrations (3073.74 ng/g and 1818.49 ng/g). These were collected in the ESP hopper at temperatures below 210°F. Based on recent mass tests, the inlet particulate loading to the pilot ESP was 3.3 lb/MMBtu. If the mercury in the coal is 60 ng/g and all the mercury were collected with the flyash, the mercury concentration in the ash would be roughly 2000 ng/g. Thus, the mercury collected with the flyash is a significant fraction of the mercury in the flue gas at these lower temperatures.

Pulse-Jet Configuration

Figure 6 is a summary of the mercury removal data as a function of sorbent injection rate during the pulse-jet tests. The plot includes results from the pulse-jet extracting the gas slipstream from either: 1) “clean”, low ash in the flue gas from downstream of the full-scale fabric filter at Comanche, or 2) conventional “dirty” flue gas prior to the fabric filter. During “dirty” tests at temperatures below 250°F, 66% of the mercury was removed across the pulse-jet by the flyash (no sorbent injection) and 12% mercury removal was achieved across the pulse-jet at a flue gas temperature of 275°F. At lower injection rate tested, 0.6 lb/MMacf, 20 to 35% of the mercury removal can be attributed to sorbent injection alone. At the higher injection rate, 2.1 lb/MMacf, the sorbent appeared to remove 60 - 70% of the mercury. There was little difference noted in the performance of the AC-1 carbon compared to the Norit carbon during these tests.

During “dirty” pulse-jet testing, samples were collected isokinetically at the inlet to the pulse-jet. A cyclone was used to remove a large portion of the flyash, followed by an EPA Method 29 particulate filter to collect the fines. An iodated carbon trap was placed at the outlet of the M29 filter to collect the vapor-phase mercury. Data collected at the inlet of the pulse-jet indicated that 25 to 58% of the mercury captured in the sampling train was collected in the cyclone and the on the filter. The cyclone/filter assembly was maintained at 250°F for these tests.

Due to the concerns and difficulties measuring sorbent-only mercury removal, several tests were conducted using “clean” fluegas obtained from Comanche’s fabric filter outlet. Baseline mercury levels after Comanche’s fabric filter were very low, probably due to the ability of the flyash to remove mercury at the lower flue gas temperatures experienced during these winter tests and the high ash collection efficiency of Comanche’s fabric filter. In order to minimize the impact of sampling errors, a mercury doping system was used to increase the baseline mercury concentration from less than 2 ug/Nm³ to 20 ug/Nm³.

During the “clean” flue gas tests, 0 to 25% mercury removal was measured with no sorbent injection. At temperatures below 260°F, 28 - 78% mercury removal was achieved at carbon injection rates below 1 lb/MMacf and a maximum mercury removal of 95% was measured at 5.7 lb/MMacf. The high sorbent injection rate corresponds to a carbon:mercury weight ratio of 16,000:1. The removal was slightly lower at temperatures above 275°F, as shown in Figure 6.

The fractional removal of mercury as a function of sorbent injection rate appeared to be independent of both whether particulate matter was present in the flue gas and the starting gas-phase mercury concentration. This observation implies that the mercury uptake is gas phase mass transfer controlled. During low-ash tests, the elemental mercury concentration in the flue gas was increased by doping. The resulting mercury concentrations collected on the iodated carbon sampling traps (representing the gas-phase mercury concentration) were as much as a factor of ten times higher than the tests conducted in the presence of flyash. Based on data presented in Figure 6, it appears that the baseline mercury removal in the presence of flyash, a concentration of approximately 50 to 70 lb/MMacf, is comparable to the low ash mercury removal at a Norit or AC-1 injection rate of approximately 0.3 lb/MMacf.

Figure 7 shows the mercury removal measured during the pulse-jet configuration with particulate laden flue gas. One set of data shown (diamonds) represents removal calculated from the inlet mercury concentrations (the sum of the flyash contribution and the mercury collected in the iodated carbon mercury trap) as compared to the mercury collected in the outlet iodated carbon trap. The second set of data points (squares) represents mercury removal calculated with the same data set using only the mercury concentrations in the iodated carbon traps (the mercury in the flyash is ignored). This exercise was conducted to compare pulse-jet data collected when isokinetic ash samples were available with ESP samples collected when an isokinetic ash sample was not available for mercury analysis. The baseline (no sorbent injection) data were collected at 250°F and 275°F. The sorbent injection data were collected at 230 °F with AC-1 and Norit carbons. This data comparison indicates that, with isokinetic ash sampling, the data are tightly grouped for tests conducted at similar temperatures. Data scatter is introduced when the flyash contribution is ignored. This scatter is similar to the scatter observed during ESP testing when only IC traps were used for mercury measurements.

Reverse-Gas Configuration

Mercury measurements at the PCM inlet during reverse-gas testing were made by collecting an ash sample isokinetically at duct temperature and then sampling a portion of the ash-free flue gas with an iodated carbon trap to capture the vapor mercury. The flyash and iodated carbon trap were then analyzed for mercury content. Flue gas was sampled isokinetically at the PCM outlet using an iodated carbon trap to capture mercury since interference from ash was not an issue at this sampling location.

Tests were conducted in two temperature ranges: 280 - 290°F and 300-320°F. Mercury removal during the lower temperature tests ranged from 2-19% with no carbon injection to 90% removal at a Norit injection rate of 4.8 lb/MMacf. At the higher temperatures, the mercury removal was slightly lower. At 0.5 lb/MMacf Norit, the mercury removal was 58%. With 5 lb/MMacf, the mercury removal was 74%. AC-1 was also tested in the reverse-gas configuration and the mercury removal was similar to that experienced with Norit injection. The test matrix is shown in Table 3.

Several samples indicated a significant fraction of the total mercury was captured with the flyash. The higher particulate-bound mercury fraction was more apparent at lower inlet temperatures, as would be expected. The inlet sampling location is *upstream* of the main duct heater and the duct temperature here may be cooler than in the rest of the PCM. The data indicate that there is a change in the ability of the flyash to sorb or retain mercury at a gas temperature of approximately 280°F.

A stepwise linear regression analysis was performed on this data set to determine the factors influencing mercury removal. The analysis showed that injection rate and PCM temperature are the predominant effects, as expected from previous tests. Higher temperatures result in lower mercury removal and higher carbon injection rates result in higher mercury removals. These effects are reflected in the graphed data in Figure 8. Another parameter that was evaluated was the pressure drop across the bags, which is

influenced by the amount of ash and carbon on the bags. This pressure drop also produced a slight, but statistically significant effect on mercury removal.

Waste Characterization

The EPA classification of the collected sorbent and flyash mixture is of great concern in the use of sorbent technologies for the removal of mercury from flue gas streams. If the combined sorbent-flyash product collected in the particulate collector hopper remains in a nonhazardous category, it can be handled and disposed of using methods currently employed to dispose of flyash. Samples collected and analyzed during ESP, pulse-jet, reverse-gas and TOXECON testing at Comanche indicate that the sorbent-flyash material is nonhazardous.

The TCLP (toxicity characteristic leaching procedure) from five samples collected during carbon injection at Comanche Station are shown in Table 4. These results show that all 8 RCRA elements of concern are well below regulatory limits. ESP sample A was collected while injecting 0.47 g/m³ Norit carbon and ESP sample B was collected while injecting 0.05 g/m³ Norit carbon. Samples were collected for TCLP analysis during testing with each particulate control device.

Discussion

Assessing the effectiveness of a sorbent under typical operating conditions in actual flue gas requires flue gas sampling upstream and downstream of a primary particulate collector. The adsorption of mercury onto flyash at Comanche Station complicated evaluations during this program. During ESP testing, samples were collected non-isokinetically and mercury removal was calculated based upon mercury captured in MESA solid sorbent sampling traps. Isokinetic sampling was utilized for inlet measurements during pulse-jet testing with particulate laden flue gas. The data gathering process is still underway for this program and a number of data analysis and sampling concerns still exist, thus final conclusions have not been formulated. The significant observations included in this paper are summarized below.

- 1) Comanche's flyash appears to adsorb vapor-phase mercury at all tested temperatures. An average removal of approximately 30% has been observed during ESP testing with no sorbent injection, although significant variations between tests have been noted. An average of 66% mercury removal was observed during pulse-jet testing at temperatures below 250°F. Up to 15% mercury removal was observed at 275°F in the pulse-jet configuration. Up to 19% removal was observed in the reverse-gas configuration at a temperature of 269°F.
- 2) Due to the low temperatures available on the host unit, non-isokinetic ash sampling, and the belief that heating and cooling affect the mercury removal, insufficient data are available to determine if sorbent effectiveness changes significantly at different operating temperatures in the ESP configuration. Data available from the pulse-jet testing at temperatures from 260 to 275°F and the reverse-gas configuration at temperatures from 269 - 311°F suggest that mercury removal increases with lower flue gas temperatures.
- 3) Measuring mercury at the low concentrations present in coal-fired flue gas is quite challenging. An isokinetic sampling system which uses iodine-impregnated carbon traps was developed in this program which reduced the data scatter considerably. Possible adsorption of mercury by the flyash increases the importance of accurate particulate measurements to determine the total mercury concentration and sorbent mercury removal efficiency.
- 4) Overall vapor phase mercury removals of 15% to 70% have been observed with the ESP configuration of the PCM. These removals include the Hg removal obtained from the flyash which is believed to be significant and in the range of 30% at Comanche at the tested temperatures.

- 5) A maximum of 95% mercury removal was observed in the pulse-jet configuration. This result was obtained in a “clean”, low-ash flue gas condition with elemental mercury doping and temperatures of 260 to 275 F. During “dirty” testing with flyash, up to 90% of the mercury was removed. It is expected that approximately 66% of this removal can be attributed to the flyash.
- 6) A maximum of 90% mercury removal was observed in the reverse-gas configuration. These data were collected at a PCM temperature of 290F and a Norit injection rate of 4.8 lb/MMacf. Up to 20% of this removal can be attributed to flyash.
- 7) Mercury removal increases with increasing carbon injection up to the maximum injection ratio of 2 lb/MMacf tested in the ESP, 5.7 lb/MMacf in the pulse-jet baghouse, and 5 lb/MMacf in the reverse-gas baghouse.
- 8) Any improvements in mercury removal in the ESP due to an increase in sorbent residence time is uncertain.
- 9) In general, mercury removal was higher in the pulse-jet and reverse-gas baghouse than in the ESP for all temperatures tested.

Applications and Future Activities

This testing has confirmed that activated carbon injection does have potential for control of mercury emissions from coal-fired power plants if mercury control is desired. Both sorbents which were tested successfully lowered mercury emissions in conjunction with all three particulate control configurations examined in these preliminary tests, even at the ultra-low mercury levels present in coal-fired flue gas. Items for further study include the long-term impacts of carbon injection, such as ESP performance, bag life, and ash carbon content. The quantity of carbon required for injection can be reduced if temperature is controlled, and this is one aspect which should be quantified in further detail. In addition, the direct applicability of pilot results to full-scale coal combustors should be confirmed through larger scale testing of carbon injection and comparison data at the Comanche unit. These data will allow more reliable cost projections for a full-scale system.

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Table 1. ESP Test Summary

Sorbent	Collection Temp (oF)	Inj. Rate (lb/MMacf)
Baseline	200-210	N/A
	230-260	N/A
Norit	200-220	1
	230-260	0.2-0.4, 1-1.2, 1.7-1.9
	275-290	1-1.2, 1.7-1.9
AC-1	230-260	1-1.2, 1.7-1.9
	275-290	1-1.2, 1.7-1.9

Table 2. Pulse-Jet Test Summary

Particulate in Flue Gas	Sorbent	Collection Temp (°F)	Inj Rate (lb/MMacf)
Conventional (High Ash)	None	200, 245, 275	N/A
	Norit	230*	0.7, 2.1
	AC-1	210*	0.7, 2.1
Low Ash	None	265*, 280	
	Norit	260*	0.29, 1.9
		275	0.57, 1.9, 5.7
	AC-1	270*	0.53, 1.71
		280	0.75, 1.3, 5.3

*No heating or cooling

Table 3. Reverse-Gas Configuration Test Matrix

	Sorbent	Temp °F	Carbon Inj. Rate (lb/MMacf)
No Ash	None	duct heater off	0
	Norit	duct heater off	1, 2
Full Ash Loading	None	duct heater off 300 - 325 °F	0 0
	Norit	duct heater off 300 - 325 °F	0.3 - 0.5, 1-2, 5 0.3 - 0.5, 1-2, 5
	AC-1	duct heater off 300 - 325 °F	0.3 - 0.5, 1-2 0.3 - 0.5, 1-2

Table 4. TCLP Summary

Element	ESP A	ESP B	Pulse-Jet Ash + C	Regulatory Limits
As Analyzed Value (mg/L)				(mg/L)
Arsenic	<0.28	<0.28	<0.28	5.0
Barium	1.1	1.3	28.5	100.0
Cadmium	<0.014	<0.014	<0.014	1.0
Chromium	<0.061	<0.061	<0.061	5.0
Lead	<0.26	<0.26	<0.26	5.0
Selenium	<0.42	<0.42	<0.42	1.0
Silver	<0.51	<0.51	<0.51	5.0
Mercury	<0.0002	<0.0002	<0.0002	0.2

Figure 1. Schematic of laboratory-scale test fixture.

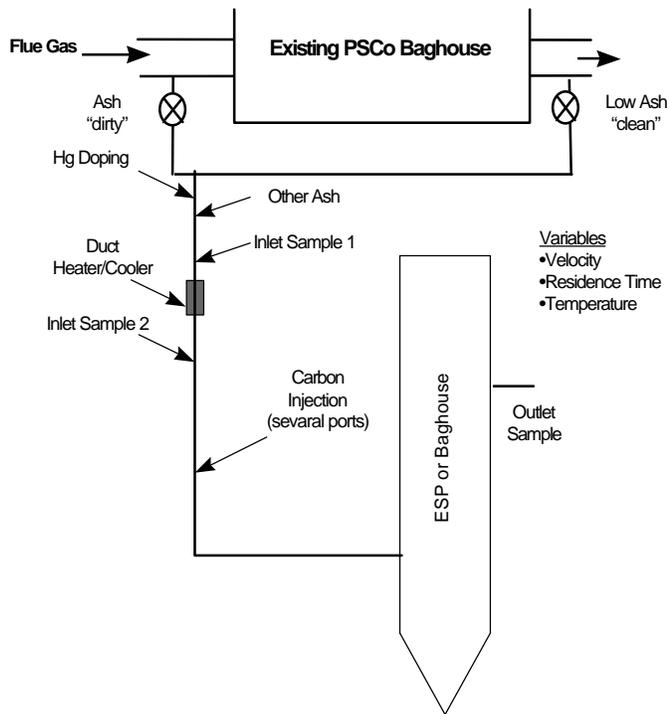


Figure 2 Photograph of control module installed at Comanche Station

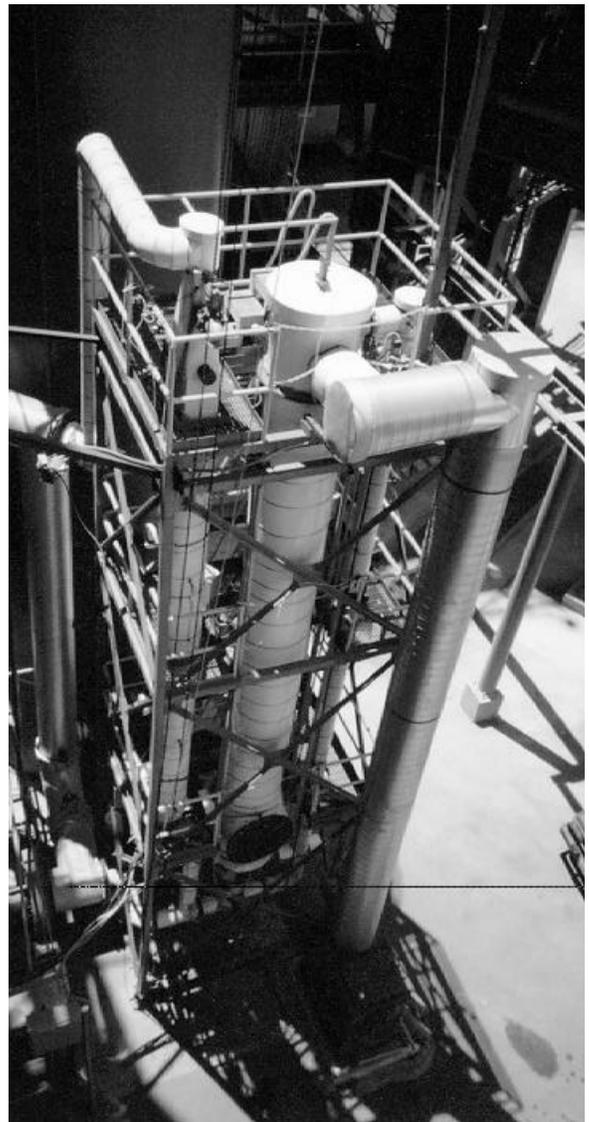


Figure 3. Isokinetic particulate sampling system used with MESA train.

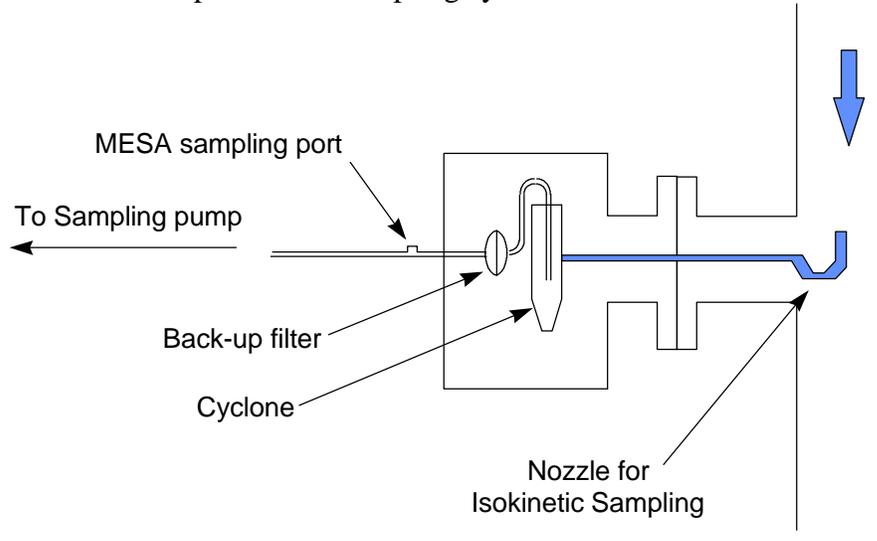


Figure 4. Photograph of isokinetic ash sampling system.

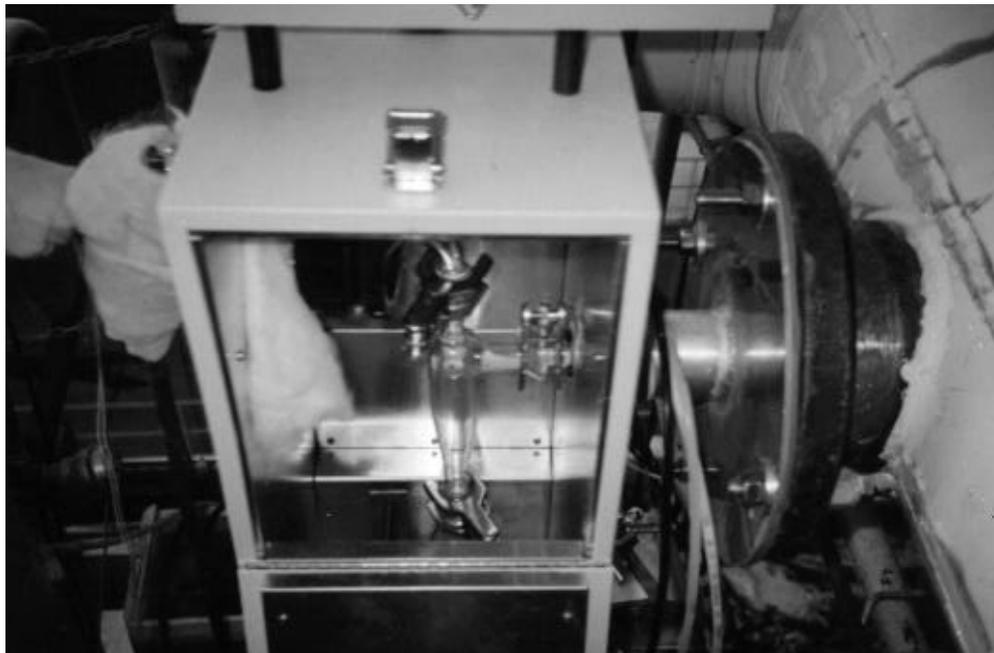
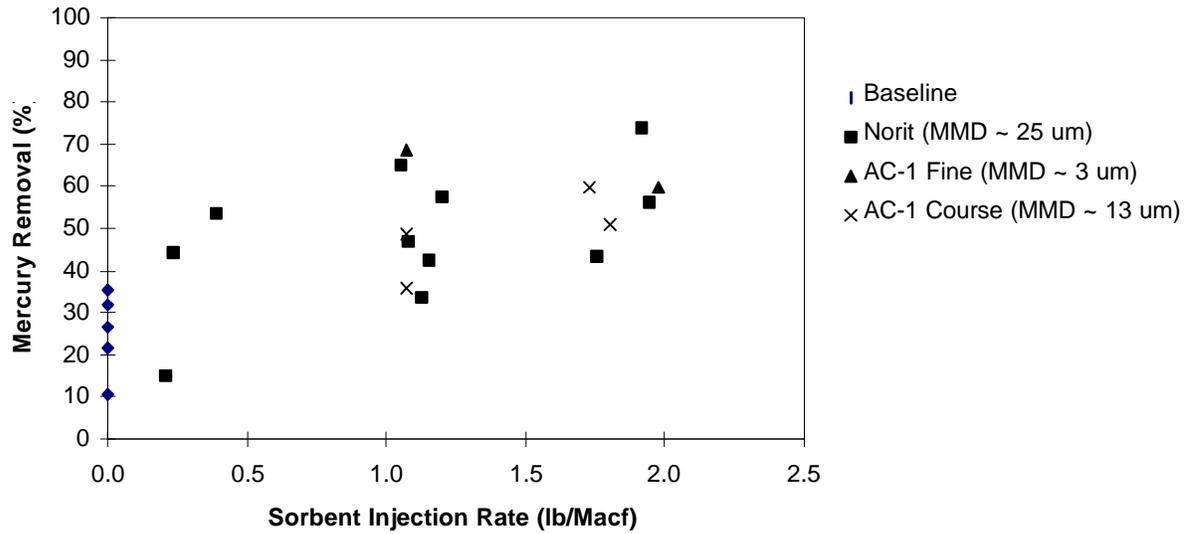


Figure 5. Vapor Mercury Removal, ESP Configuration



*Removal based on mercury collected in iodated carbon traps (nisokinetic sampling).

Figure 6. Total Mercury Removal, Pulse-Jet Configuration

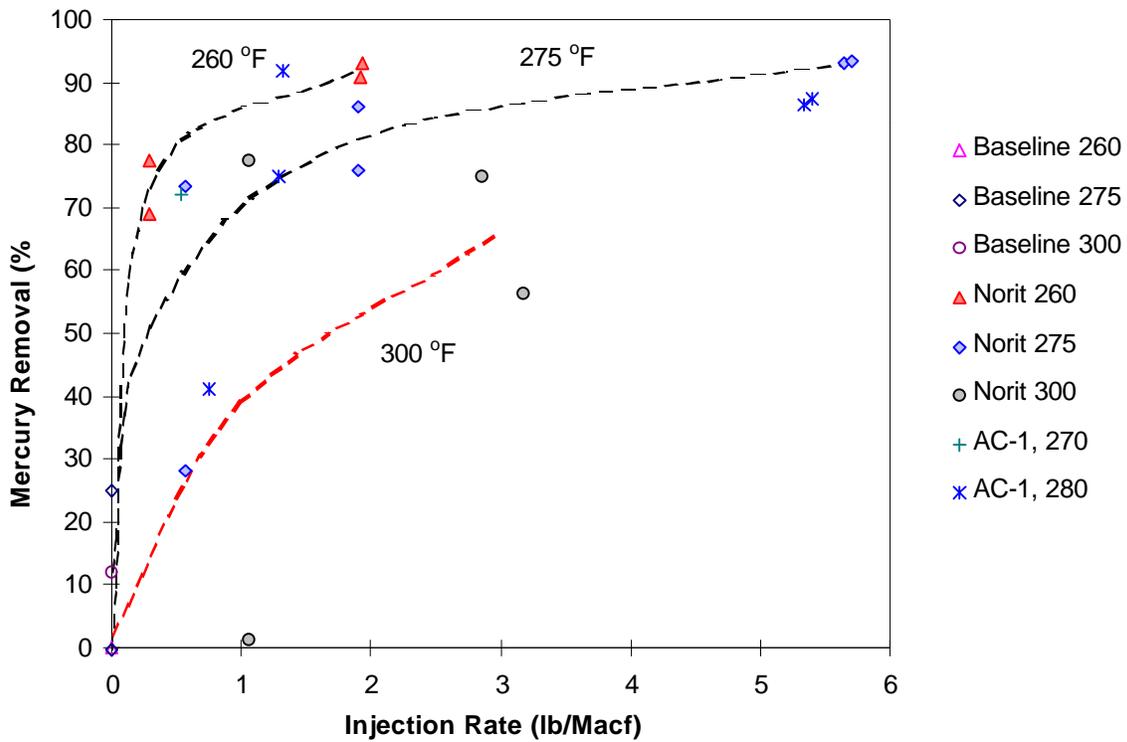


Figure 7. Data Scatter Introduced when Mercury Fraction on Flyash is Disregarded. Pulse-Jet Configuration.

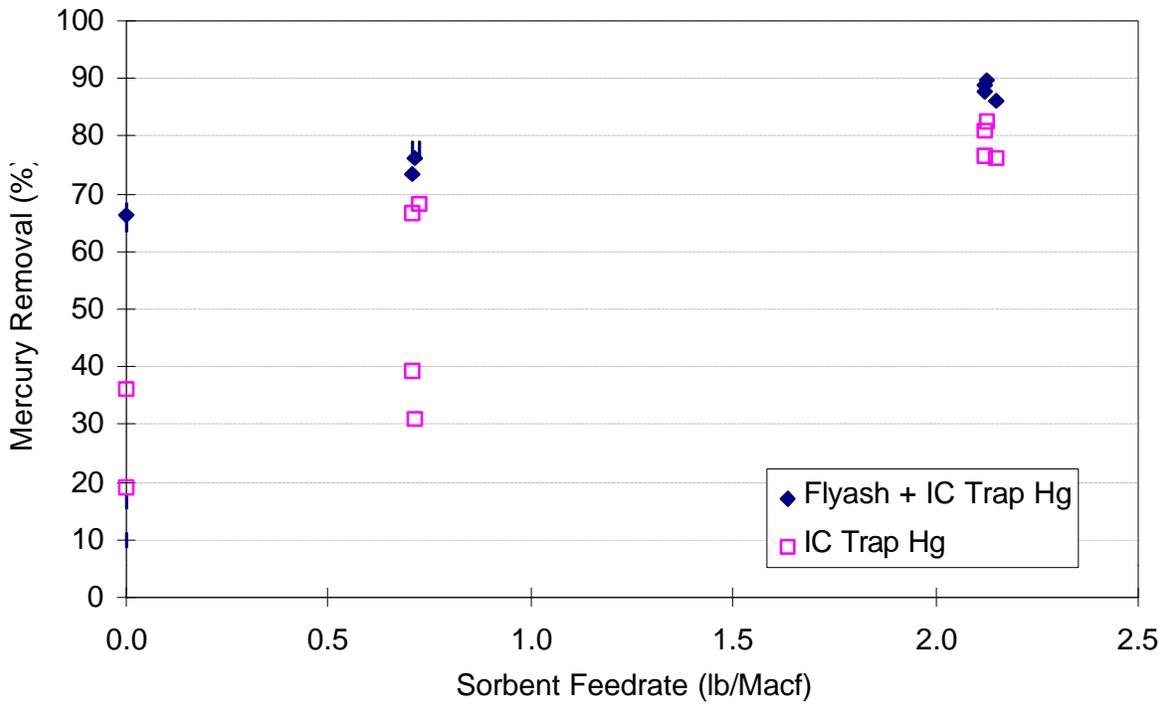


Figure 8. Total Mercury Removal, Reverse-Gas Configuration

