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Investigation and Demonstration of Dry Carbon-Based Sorbent Injection for Mercury Control

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Abstract

The U.S. Department of Energy (DOE) issued Public Service Company of Colorado (PSCo) a cost sharing contract to evaluate carbon-based sorbents for mercury control on a 600 acfm laboratory-scale particulate control module (PCM). The PCM can be configured as simulate an electrostatic precipitator, a pulse-jet fabric filter, or a reverse-gas fabric filter and is installed on an operating coal-fired power plant. Three different dry carbon-based sorbents were tested this quarter to determine their mercury removal capability in the different configurations.

The project is currently in the seventh quarter of an eight-quarter Phase I project. Testing in all configurations is nearly complete. Original plans included the use of an on-line mercury analyzer to collect test data. However, due to very low baseline mercury concentration, on-line measurement did not provide accurate data. The project used a modified MESA method grab sample technique to determine inlet and outlet mercury concentrations. A major concern during sorbent evaluations was the natural ability of the flyash at the test site to remove mercury. This often made determination of sorbent only mercury removal difficult.

The PCM was configured as a reverse-gas baghouse and brought online with "clean" flue gas on March 10th at an A/C of 2.0 ft/min. The dustcake forms the filtering media in a reverse gas baghouse. In the absence of flyash, the bags were precoated with a commercially available alumina silicate material to form an inert dustcake. Some baseline tests were completed with clean gas for comparison to clean gas pulse jet tests. The PCM was reconfigured as a TOXECON unit in April 1997 with testing completed in May 1997. TOXECON, an EPRI patented technology, is a pulse-jet baghouse operating at a high A/C ratio downstream of a primary particulate collector with sorbent injection upstream of the baghouse for air toxics removal. Mercury removals of 0 to 97% were obtained depending on test conditions.

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Executive Summary

The overall objective of this two-phase program is to investigate the use of dry carbon-based sorbents for mercury control at coal-fired utilities. This information is important to the utility industry in anticipation of pending regulations. During Phase I, a 600 cfm laboratory-scale particulate control module (PCM) that could be configured as an electrostatic precipitator (ESP), a pulse-jet baghouse, or a reverse-gas baghouse was designed, built and integrated with an existing pilot-scale facility at PSCo's Comanche Station. Flue gas entering the PCM was taken from either upstream of Comanche's full scale fabric filter to allow testing with the PCM operating as a primary particulate collector, or downstream of Comanche's fabric filter to allow testing with little flyash in the flue gas. Three candidate sorbents were injected into the flue gas upstream of the test device and mercury concentration measurements were made to determine the mercury removal efficiency for each sorbent. If the project continues into Phase II, testing will be continued at this scale to verify results and measurements will be made across full-scale utility particulate collectors to scale-up baseline results from this phase of the project.

In previous quarters evaluations have been conducted with the PCM configured as an electrostatic precipitator and as a pulse-jet baghouse. In the current quarter work has continued with injection of various carbon sorbents in the reverse-gas baghouse and TOXECON configurations. Testing with the modified MESA method has been used to measure total mercury concentrations. The current modified MESA method consists of an isokinetic sampling system to remove particulate followed by an iodated carbon trap to sample the particulate free gas at the inlet. Where little ash is present, such as at the outlet of the PCM, an iodated carbon trap drawing gas directly from the gas stream is used..

The PCM was configured as a reverse gas baghouse on March 4,1997 and brought on-line with "clean" flue gas. The bags were precoated with a commercially available bag treatment material. Several tests were conducted with "clean" gas before "dirty" gas was introduced into the PCM. A CEM capable of measuring NO_x, NO, NO_2 , SO_2 , CO, and O_2 was installed on site to allow testing with sodium sesquicarbonate injection for SO_2 removal. Carbon injection for mercury removal in both configurations was completed with most results in the 50 to 90% mercury removal range. SO_2 removal obtained during sodium sesquicarbonate injection was lower than expected but in the range of 30 to 40%. Testing continued with "dirty" gas through April 25, 1997.

The PCM was reconfigured as a TOXECON unit in April 1997 with testing completed in May 1997. TOXECON, an EPRI patented technology, is a pulse-jet baghouse operating at a high A/C ratio downstream of a primary particulate collector with sorbent injection upstream of the baghouse for air toxics removal. Mercury removals of 0 to 97% were obtained depending on test conditions.

Finally, the PCM was reconfigured as an ESP in late May and testing continued until early July. This testing consisted of injecting several different ashes obtained from other coal-fired utility boiler to evaluate mercury removal capabilities in the ESP configuration. Most mercury removals were lower than expected in the range of 0 to 20% removal with ash injection at rates similar to normal full scale ESP.

Introduction

This report describes ongoing work in a two-phase program to investigate the use of dry carbon-based sorbents for mercury control on coal-fired utilities. A laboratory-scale field particulate control module (PCM) that can be configured as an electrostatic precipitator, a pulse-jet baghouse, or a reverse-gas baghouse was designed, built and integrated with an existing pilot-scale facility at Public Service Company of Colorado (PSCo)'s Comanche Station in Pueblo, Colorado. Carbon-based sorbents were injected upstream of the PCM and mercury concentration measurements were made to determine the mercury removal efficiency for each sorbent. This report includes work performed this quarter and is not intended to be a summary of work performed to-date. Earlier project work referred to in this report is described in previous quarterly reports.

Equipment Description

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

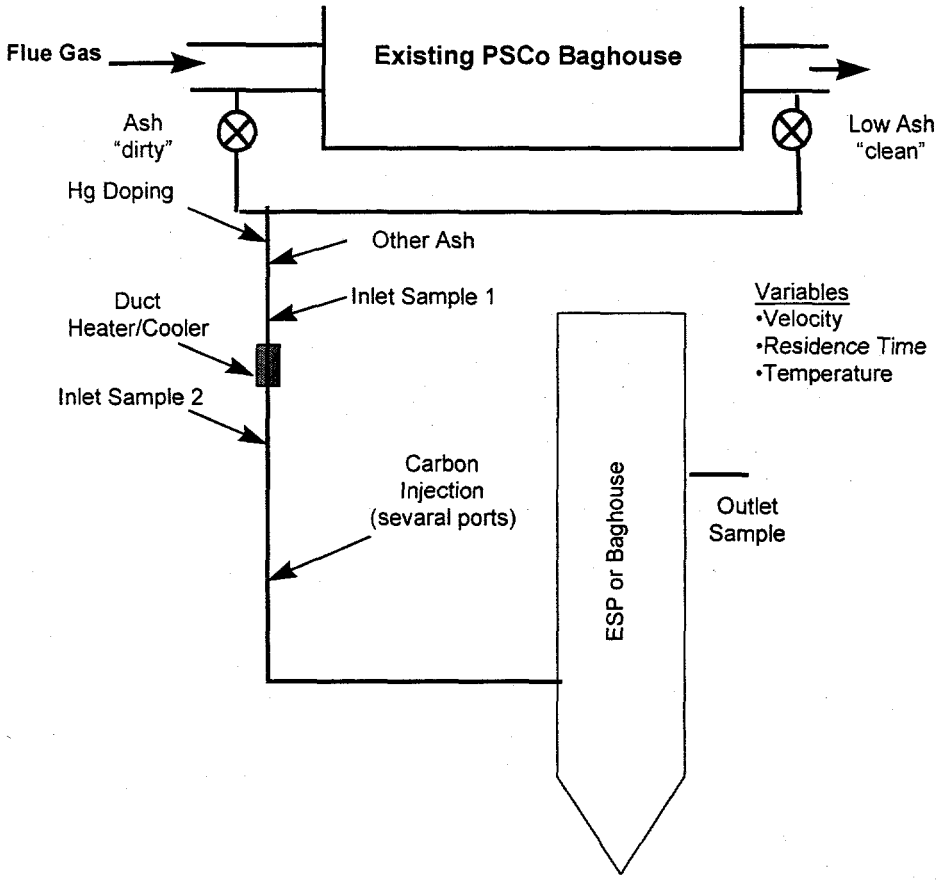

Figure 1. Schematic of laboratory-scale test fixture.

The PCM was designed with interchangeable collection members allowing configurations such as an ESP, pulse-jet baghouse, reverse-gas baghouse or TOXECON. A general description of the PCM and descriptions of the ESP and pulse-jet configurations are included in previous quarterly reports.

Reverse Gas Baghouse

The PCM was configured as a reverse gas baghouse by 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 35 lbs. 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.

The bags were cleaned by reversing gas flow across the bags from outlet to inlet causing the bags to gently collapse, thus breaking off the dust cake collected on the inside of the bags. The ash fell into the ash hopper at the bottom of the compartment. The PCM system used Comanche's hot, clean, dry preheat air for reverse-gas. During a clean, automatic valves were actuated to close the outlet duct of the PCM and open the reverse gas line. This allowed reverse gas to enter the compartment through the outlet plenum. Cleans were initiated when pressure drop across the bags exceeded a threshold level.

Initially, the PCM in the reverse-gas baghouse configuration was brought on-line with "clean" flue gas from downstream of Comanche's full-scale baghouse. Neutralite, an alumina silicate precoat material, was applied to the bags to create an inert dustcake during no-ash sorbent tests. The Neutralite was not cleaned off the bags during "clean" gas testing. Tests were conducted under baseline conditions (no sorbent injection) and Norit carbon injection at 1 and 2 lb/MMacf.

Testing continued with mercury sorbent evaluations in "dirty", flyash-laden flue gas. Tests were conducted under baseline conditions and Norit or AC-1 injection up to 5 lb/MMacf. Testing with sodium sesquicarbonate injection for SO_2 removal concurrently with carbon injection for mercury removal was implemented during some of the reverse gas testing to determine if any synergistic effects of mercury removal and SO_2 removal could be observed. The actual test matrix as completed is shown in Table 1.

Table 1. 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	0
		300 - 325 °F	0
	Norit	duct heater off	0.3 - 0.5, 1-2, 5
		300 - 325 °F	0.3 - 0.5, 1-2, 5
	AC-1	duct heater off	0.3 - 0.5, 1-2
		300 - 325 °F	0.3 - 0.5, 1-2
Sodium Injection			
	Sodium Sesquicarbonate	duct heater off	0
		300-325 °F	0
	Sodium + Norit	duct heater off	1
		300-325 °F	1

TOXECON

TOXECON is a pulse-jet baghouse with sorbent injection for air toxics removal operating at a high A/C ratio downstream of a primary particulate collector. EPRI has patented the TOXECON technology. This configuration for the PCM was designed to filter 633 acfm of flue gas at an air-to-cloth ratio of 16 ft/min. The target operating air-to-cloth ratio for these tests was 12 ft/min, which meant that the flow was somewhat below the design value. To achieve this ratio, two 15-foot long bags were hung from the TOXECON tubesheet. An annulus was installed to increase the can velocity (upward gas velocity in the vessel on the dirty-side of the tubesheet) to approximately 900 ft/min at an A/C ratio of 12 ft/min to better simulate the flows in a full scale unit. Because TOXECON is intended for use downstream of a primary particulate collector, the ducting for the PCM version was configured to draw flue gas downstream of the

existing Comanche baghouse. The operation of TOXECON is similar to a conventional pulse-jet baghouse except that cleaning is initiated by a timer and the bags are cleaned off-line.

The PCM was reconfigured for TOXECON testing on April 27. Sorbent injection testing in the TOXECON configuration began on May 2, 1997. As with the reverse gas configuration, testing in the TOXECON configuration also included some combined tests of sodium sesquicarbonate injection for SO_2 removal and carbon injection for mercury removal.

Limited testing was scheduled for the TOXECON configuration. Tests included Norit evaluation in three temperature ranges as shown in Table 2. Flue gas mercury samples were collected during baseline (no injection) and at two Norit injection rates for each temperature range. SO_2 and mercury measurements were made during sodium sesquicarbonate injection to characterize any possible synergistic effects that this combined control scheme may produce.

Table 2. TOXECON Configuration Test Matrix

Sorbent	Temp °F	Carbon Inj. Rate (lb/MMacf)
None	< 250	0
	duct heater off	0
	300 - 325	0
Norit	< 250	0.5, 2
	duct heater off	0.5, 2
	300 - 325	0.5, 2
Sodium Sesquicarbonate	duct heater off	0
	300-325 °F	0
Sodium + Norit	duct heater off	1
	300-325 °F	1

Results and Discussion

Test results are presented for each configuration in which the PCM was tested. Data tables are provided which include summaries of test conditions, mercury concentrations, and the mercury removal efficiency as measured in extracted gas samples. The mercury removal as a function of sorbent injection ratio (lbs/MMacf) is plotted for each configuration. Another important independent variable noted on many of the graphs is the flue gas temperature. The mercury measurement method used during theses tests was the modified MESA train described earlier in this report.

ESP Configuration- Flyash Re-Injection Evaluation

Several flyashes were evaluated for their ability to remove mercury when re-injected upstream of the ESP as mercury sorbents. The flyashes chosen for testing included Comanche's flyash, a high and low LOI flyash from a Powder River Basin coal from the Rochelle mine burned on two different units at Arapahoe Station, flyash from Cherokee Station burning a Midwestern coal from the 20 Mile mine, and flyash from a plant burning Eastern bituminous Blacksville coal. The LOI and mercury content of the test ashes before injection are shown in Table 3. The table also lists the type of particulate collection originally used to collect the fly ash. In general, the units with baghouses show much higher mercury concentration in the ash than one of the two ESP units, suggesting that these ashes originally adsorbed mercury. Variations between ashes may also relate to the cleaning frequency, flue gas temperature, and other operational parameters in addition to differences in ash composition.

Table 3. Mercury and LOI of Test Flyashes

Flyash	LOI %	Base Particulate Control	Mercury in Ash µg/Nm^3
Comanche	0.58	Baghouse	871
Arapahoe (low LOI)	0.43	ESP	37
Arapahoe (high LOI)	5.28	Baghouse	753
Cherokee(Midwestern)	4.68	Baghouse	202
Blacksville(Eastern)	1.47	ESP	623

The initial mercury removal results are shown in Figure 2, a graph of mercury removal verses flyash injection rate for all ashes tested in Phase I. The data suggests that some flyashes may remove mercury at lower temperatures. For example, the high LOI ash from Arapahoe showed up to 42% mercury removal and the low LOI Arapahoe ash showed up to 18% mercury removal at injection rates of 1 gr/acf. An injection rate of 1 gr/acf, a typical ash concentration in flue gas, equals a concentration of 143 lb/MMacf, the unit used to define the injection rates of the carbon sorbents.

The data shown on Table 4 includes two higher temperature tests with Blacksville flyash showing an increase in mercury of 26 of 128 %. In Table 4 the host temperature is the flue gas temperature of the full-scale ductwork. The PCM temperature is the average of the inlet and outlet of the PCM. Since the flyash injected into the system contained mercury, it is possible that mercury desorbed from the ash. As all testing was done with "clean" flue gas, all testing was complete with mercury doping. However, note that the inlet mercury concentrations measured during these tests were quite low, 1.12 and 0.64 $\mu g/Nm^3$, a range which sampling limitations prevent accurate mercury removal calculations.

Further investigation is required to better understand the reasons for different mercury removal on the different flyashes. While the data obtain suggest some possible reasons for mercury variations, insufficient testing was completed to determine test repeatability and determine the effect of different operating conditions. Further analysis is required in Phase II of this program. In addition, it is suggested that the pilot data be matched to the full scale originally collecting the ash to verify that the pilot accurately simulates a full scale unit.

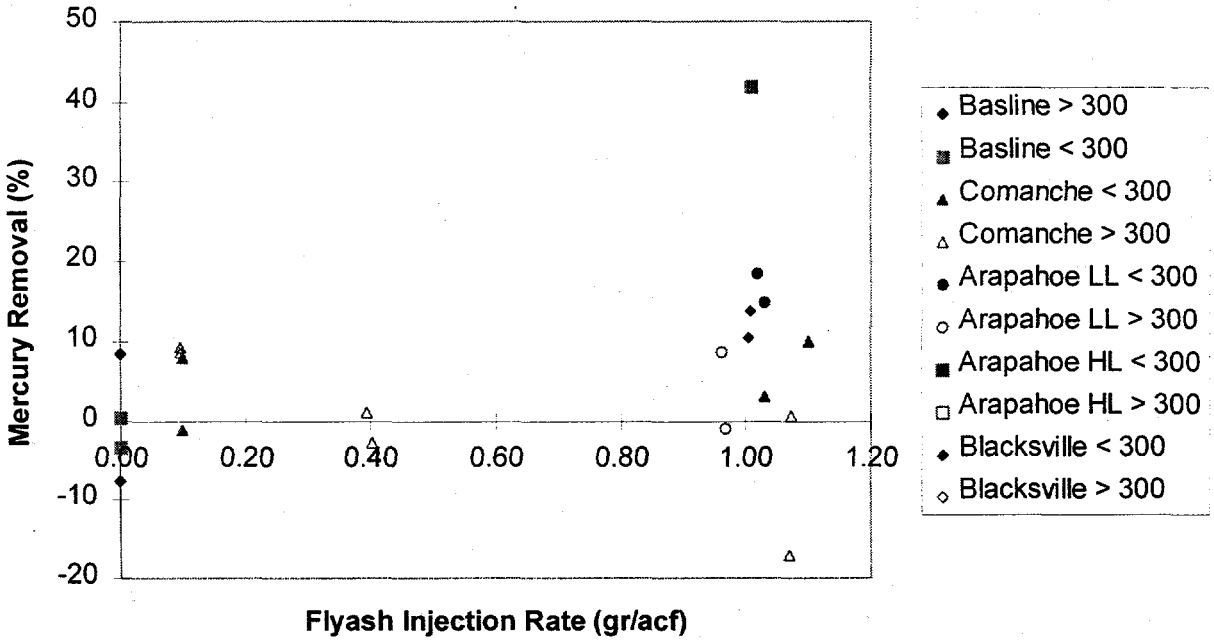

Figure 2. Mercury removal with flyash re-injection

Table 4. ESP Evaluation with Flyash Re-injection

Ash	Host Temp (F)	PCM Temp (F)	injection rate (gr/acf)	gas flow (acfm)	Load (MW)	Total Hg Inlet (ug/Nm^3)	Total Hg outlet (ug/Nm^3)	Total Hg removal (%)
None	312	313	0.00	590	343	6.92	6.34	8
None	313	313	0.00	584	342	6.12	6.58	-8
None	273	278	0.00	593	313	5.03	5.21	-4
None	274	277	0.00	589	310	5.11	5.09	0
Coman	311	309	0.39	592	358	6.16	6.09	1
Coman	310	307	0.40	582	360	4.73	4.86	-3
Coman	308	309	0.10	595	362	7.85	7.12	9
Coman	309	309	0.10	597	362	6.99	6.38	9
Coman	309	309	1.07	595	361	6.53	6.50	1
Coman	309	308	1.07	598	360	5.37	6.28	-17
Coman	310	273	0.10	601	290	3.55	3.60	-1
Coman	314	273	0.10	603	305	3.58	3.30	8
Coman	313	272	1.03	598	333	4.10	3.98	3
Coman	316	272	1.10	560	332	4.53	4.08	10
A low	311	308	0.96	604	363	5.98	5.46	9
A low	308	310	0.97	600	364	6.18	6.24	-1
A low	273	272	1.02	598	333	5.43	4.43	18
A low	275	272	1.03	592	333	4.98	4.24	15
Blacks	272	309	0.99	598	361	1.12	1.41	-26
Blacks	272	309	0.99	599	359	0.64	1.45	-128
Blacks	273	273	1.01	599	329	6.26	5.40	14
Blacks	275	272	1.00	601	332	5.05	4.52	11
A high	269	310	0.97	594	361	1.20	0.83	31
A high	270	310	0.97	597	361	0.90	0.84	7
A high	276	271	1.01	610	340	4.75	2.76	42

*Coman=Comanche, A low = Low LOI Arapahoe, Blacks = Blacksville, A high = High LOI Arapahoe

Reverse-Gas Configuration

The PCM was configured as a reverse-gas baghouse on March 4, 1997. Following a week of "clean" gas tests, the damper upstream of Comanche's full-scale baghouse was opened and the baghouse began filtering "dirty" flue gas. Mercury removal evaluations were conducted on "clean" gas at PCM temperatures from 271 - 278 °F with Norit activated carbon injection rates of 0 - 1.7 lb/MMacf. Testing was conducted on "dirty" gas at PCM temperatures from 269-317°F and with Norit and AC-1 injection rates of 0 - 4.8 lb/MMacf. Limited testing also took place with concurrent sodium sesquicarbonate injection for SO_2 control.

Operation

Initially, the bags were tensioned at 50 lbs and the reverse-air flow was set for an air-to-cloth (A/C) ratio of 3 ft/min. Within 10 hours of operation at an A/C ratio of 2 ft/min and a clean initiate pressure drop of 5 inches H_2O, the single compartment baghouse was in a continuous clean. The pressure drop was increasing more rapidly than expected based on average mass loading measurements of less than 1 gr/acf, and the cleaning was not effective. The flow was lowered to an A/C of 1 ft/min and remained in operation there until flows were checked and calibration of the pressure transducers was verified.

The PCM reverse-gas baghouse was shut down to modify the configuration to more closely resemble the operating conditions for the Comanche full-scale baghouse. The bags were weighed and manually lowered into the hopper to remove the flyash. The bag weights with flyash loading were 15-18 lbs, while the post-dustcake release weights were 6-8 lbs. The bags were re-tensioned at 30 lbs and the cleaning logic was modified to better represent a clean on the full-scale Comanche baghouse. The null before the clean was set to 15 seconds and the reverse-air time was set to 30 seconds, both matching the full-scale settings at Comanche. The settling time for the PCM was set to 30 seconds (the full-scale setting was 60 seconds). Reverse-gas flow was also lowered to an A/C of 1 ft/min.

The baghouse was brought back on-line at an A/C of 2 ft/min for approximately 24 hours before shut down due to poor cleaning. The bags were again manually lowered to remove the dustcake and re-attached. The PCM was brought back on-line at an A/C ratio of 1.5 ft/min and a reverse-air face velocity of 3 ft/min. With a clean-initiate setpoint of 5 in. H_2O tubesheet differential, the PCM was cleaning every 2 hours. Figure 3 shows a trace of the A/C ratio and the tubesheet pressure drop on March 26 and 27.

It is believed that the poor cleaning was related to ash settling in the injection section during a clean and then becoming re-entrained when forward flow restarted after the clean. Figure 4 shows the flow diagram for the PCM. During filtering, the reverse-gas valve is closed, the bypass valve is closed, and the inlet and outlet valves are open. The hopper is sealed from the outlet duct by a rotary airlock, as shown in the figure. Flow is monitored in the outlet duct during cleaning to assure that flue gas is not passing through the airlock.

Initially, the cleaning logic was programmed to close the outlet damper and open the reverse-gas damper for a clean. With this logic, all of the reverse-gas flow exited via the inlet line. This was not effective and the logic was modified to also open the bypass damper during a clean. This was an attempt to reduce pressure loss in the duct during cleaning and, thus, increase the reverse-gas flow to an A/C of 3 ft/min (900 acfm). It is possible that some ash was settling in the sorbent injection section as flue gas exited the pilot through the inlet valve during cleaning. This ash may have been carried back onto the bags following a clean. The reverse-gas velocity in the 12-inch diameter sorbent injection section is 19 ft/sec, which is slow enough to promote ash settling. Although most of the ash should fall into the hopper during a clean, the increased reverse-gas velocity through the bags during cleaning may also have carried ash into the injection section. The cleaning logic was again modified to close the inlet damper during cleaning and force all of the reverse-gas flow through the bypass. This modification effectively increased the time between cleans 2 to 3 times and reduced the post clean pressure drop by nearly 1 inch H_2O. It was therefore adopted for use in the remainder of the tests.

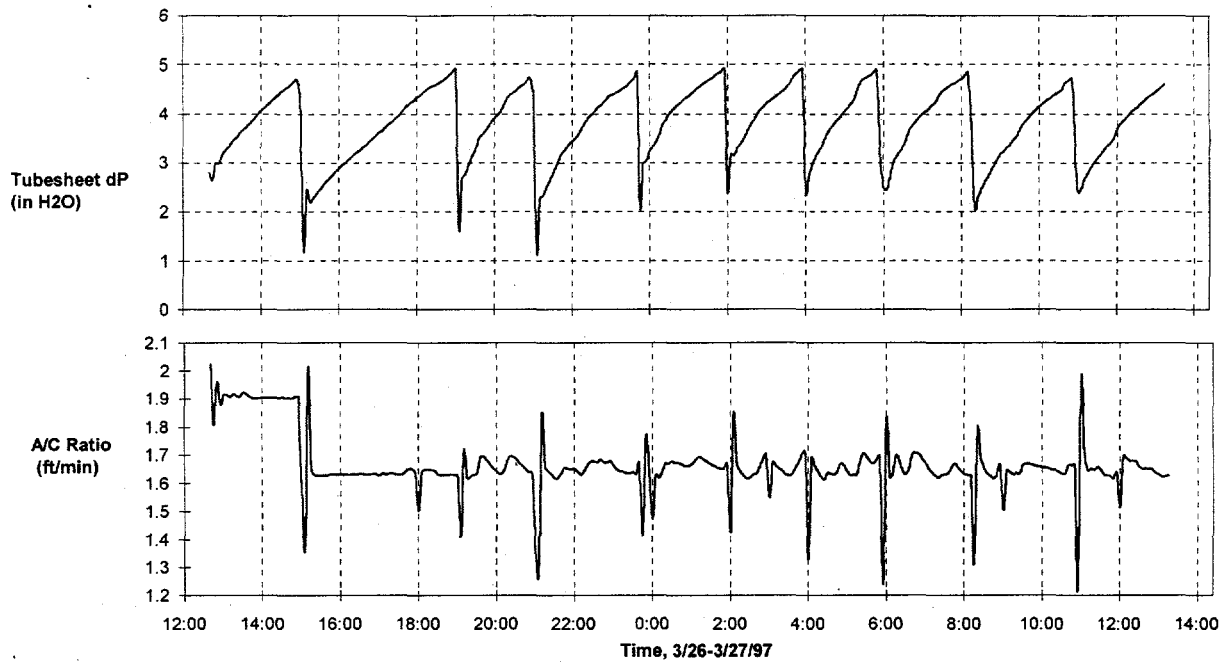

Figure 3. Trace of 5 minute averages of A/C ratio and tubesheet pressure drop.

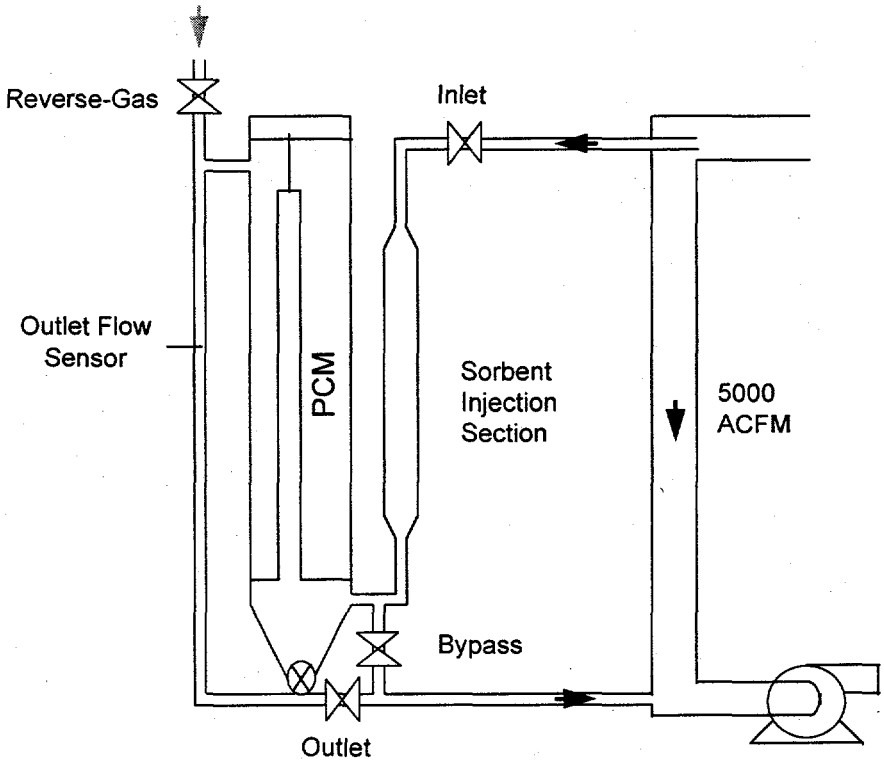

Figure 4. PCM flow diagram.

The addition of activated carbon did not measurably affect the rate of increase of differential pressure across the bags. This was expected because the carbon injection comprises a small fraction of the total particulate entering the baghouse.

Mercury Removal

Sorbent evaluations in the reverse-gas configuration were conducted in three distinct test sets: mercury removal in "clean" flue gas, mercury removal in "dirty" flue gas, and mercury removal with sodium-based sorbent injection for SO_2 removal.

"Clean" Flue Gas Testing

Testing in the reverse-gas configuration with little flyash present is somewhat unusual because the particulate itself forms the primary filter. To minimize the amount of sorbent passing through the fabric, a commercially available precoat material made from alumina silicate and expected to be inert was used to form a dustcake for these tests.

The mercury removal results as a function of injection rate are shown in Figure 5. These few data points suggest that up to 90% mercury can be achieved with 1 lb/MMacf Norit activated carbon. However, lower removal was recorded at higher carbon injection rates. The PCM operating conditions were quite similar during these seven tests, as is shown in the trend histories of system temperatures, tubesheet pressure drop, boiler load and flow through the PCM in Figures 6 and 7 and on Table 5. The Norit injection rates and the inlet (black line) and outlet (gray line) mercury concentrations are also shown on the figures. During test 7, shown in Table 5 and on Figure 7, a carbon feeder problem occurred, making test 7 data is invalid. Test procedures were examined for test 6, but no abnormalities could be found to explain the lower-than-expected mercury removal. Further testing at different operating conditions and repeat testing at the current operating conditions would be required to explain this questionable data.

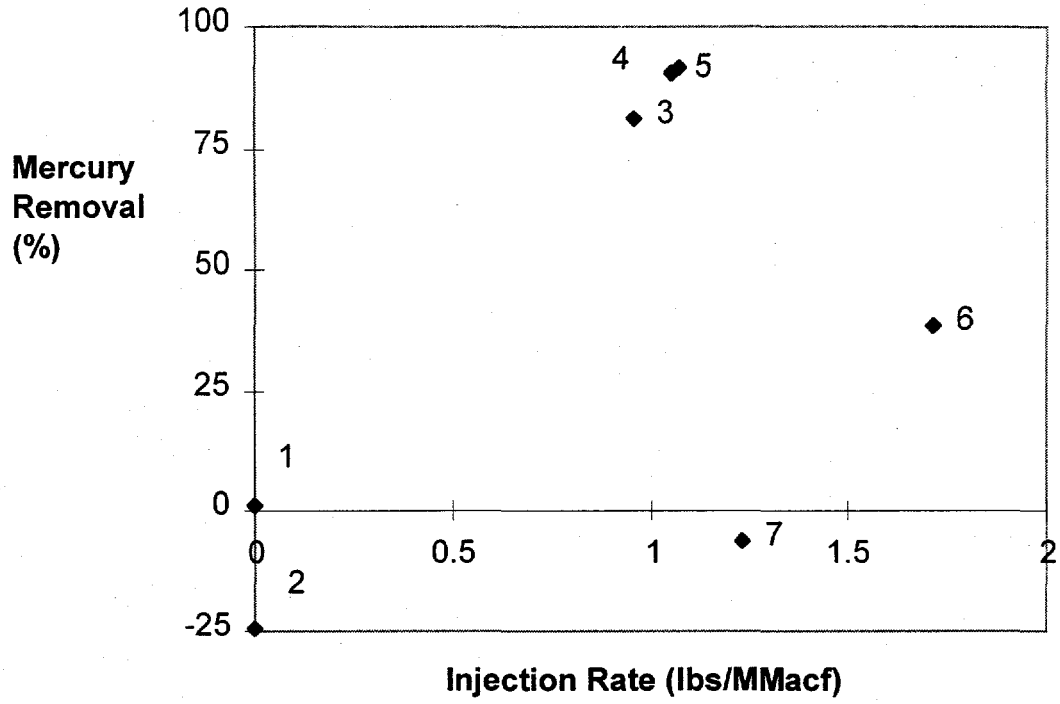

Figure 5. Mercury removal with Norit activated carbon in "clean" flue gas on a reverse-gas baghouse.

Table 5. PCM Operation and Mercury Removal During "Clean" gas Reverse-Gas Testing

Test ID	Sorbent	ΔP (in H_2O)	PCM Temp (°F)	Inlet Temp (°F)	Host Load (MW)	Inj. Rate (lb/MMacf)	Total Hg Inlet (ug/Nm^3)	Total Hg Outlet (ug/Nm3)	Hg Rem. (%)
1	None	1.0	275	278	347	0.0	8.62	8.49	2
2	None	0.9	276	280	346	0.0	7.17	8.92	-24
3	Norit	0.9	277	283	343	1.0	6.97	1.31	81
4	Norit	0.9	278	283	342	1.1	8.61	0.81	91
5	Norit	0.8	278	283	335	1.1	11.1	0.92	92
6	Norit	1.0	271	275	344	1.7	12.5	7.67	39
7	Norit	1.0	273	277	343	1.2	11.4	12.10	-6

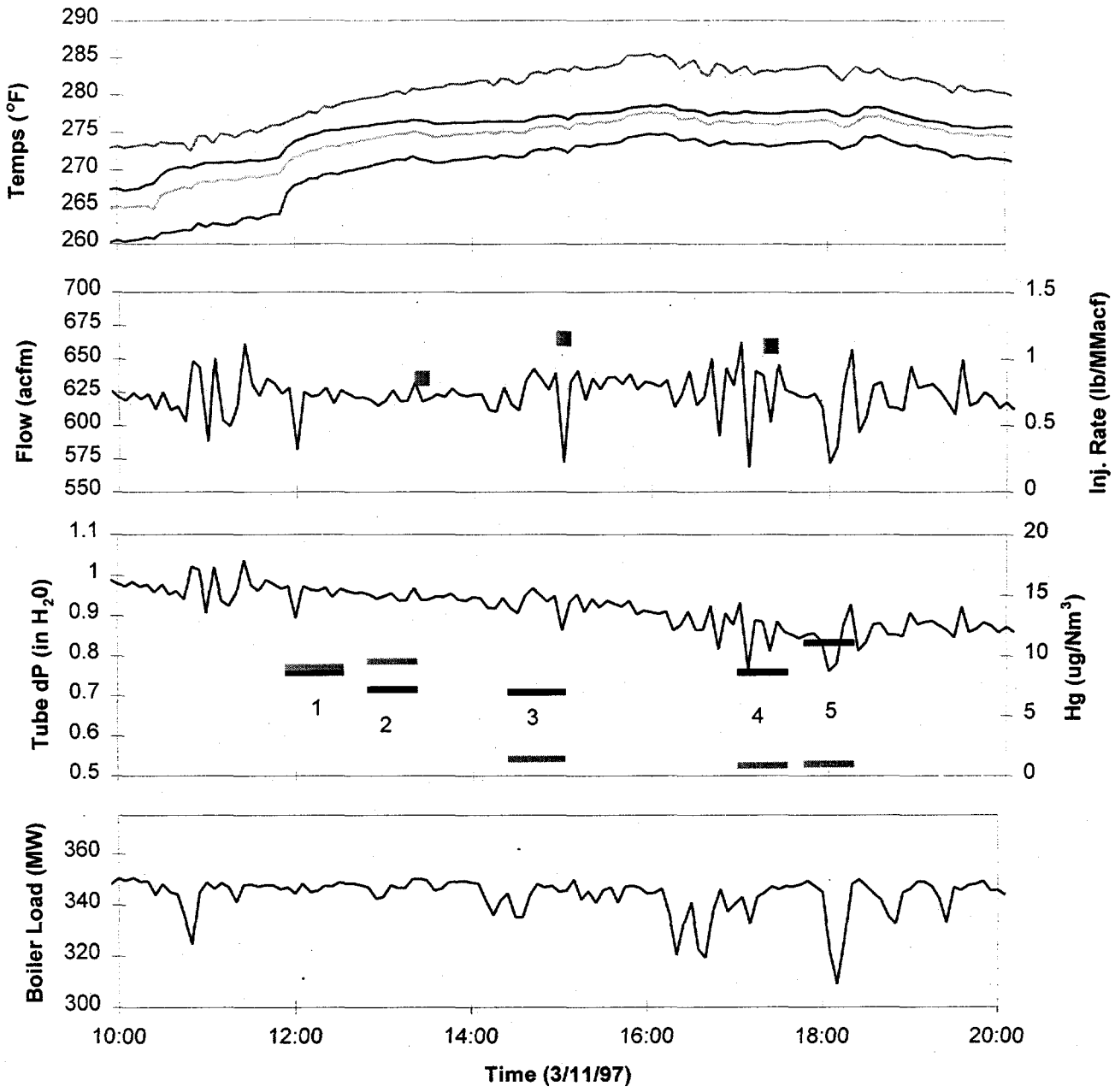

Figure 6. Trend operating history during "clean" gas testing on March 11, 1997.

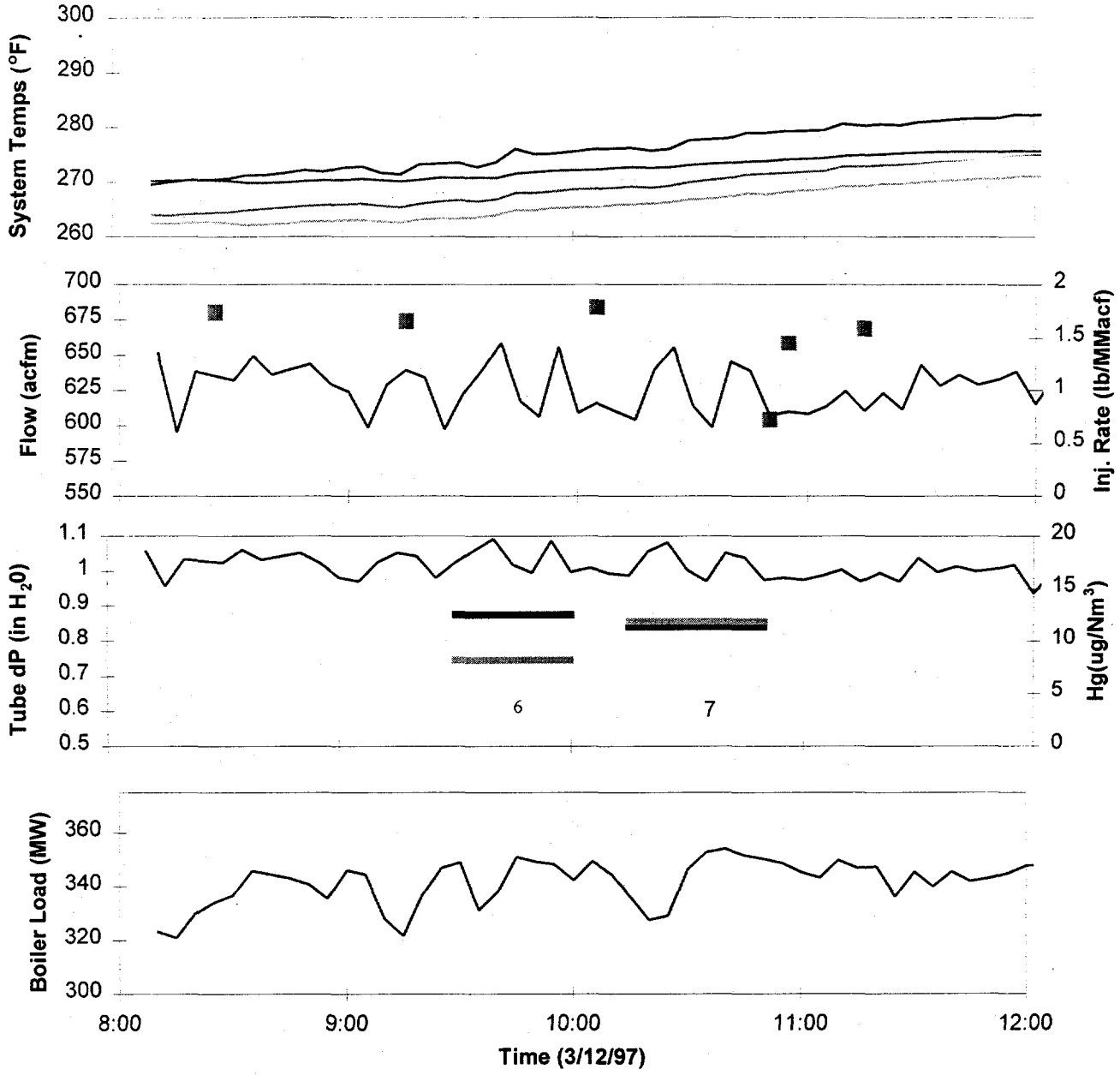

Figure 7. Trend operating history during "clean" gas testing on March 12, 1997.

"Dirty" Flue Gas Testing

Following "clean" flue gas tests, the inlet dampers were adjusted to provide the PCM with flue gas from upstream of Comanche's full-scale baghouse. Recall that mercury measurements at the PCM inlet 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 non-isokinetically at the PCM outlet using only an iodated carbon trap to capture mercury.

The PCM operating parameters, carbon injection rates and mercury concentrations measured are shown in Table 6. Several samples collected 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. Recall that 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 high particulate-bound mercury and low inlet temperature data are highlighted in the table and 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. The highlighted temperatures are all at or below 286 °F and the highlighted particulate-bound mercury concentrations are all above 4.3 $\mu g/Nm^3$. The largest particulate-bound mercury concentration measured at temperatures above 286 °F was 1.96 $\mu g/Nm^3$.

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 noted on the graph 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 statistically significant effect on mercury removal.

Table 6. PCM Operation and Mercury Removal During "Dirty" Reverse-Gas Testing

Sorbent	ΔP (in H2O)	PCM Temp (°F)	Inlet Temp (°F)	Host Load (MW)	Inj. Rate (lb/MMacf)	Inlet Hg IC Trap (ug/Nm³)	Inlet Ash Hg (ug/Nm³)	Total Hg Inlet (ug/Nm³)	Total Hg Outlet (ug/Nm³)	Total Hg Rem (%)
None	3.6	269	278	345	0.00	8.58	1.21	9.79	9.55	2
None	4.2	269	284	344	0.00	9.52	1.21	10.73	8.66	19
None	4.5	305	297	338	0.00	6.92	1.25	8.18	8.72	-7
None	5.6	307	310	343	0.00	7.85	1.25	9.10	6.03	34
Norit	5.6	281	285	343	0.58	6.78	0.34	7.12	2.55	64
Norit	5.7	284	293	341	0.59	5.67	0.34	6.01	2.35	61
Norit	4.7	295	311	344	1.48	6.28	0.97	7.25	3.62	50
Norit	5.2	296	310	345	1.49	5.36	0.97	6.33	3.36	47
Norit	5.0	290	293	336	4.80	7.13	0.94	8.08	0.81	90
Norit	5.6	290	297	331	4.79	5.88	0.94	6.83	0.80	88
Norit	4.5	303	251	324	0.50	2.86	5.68	8.54	3.50	59
Norit	4.8	305	256	325	0.50	2.11	5.68	7.79	3.30	58
Norit	5.3	317	271	321	1.37	2.80	4.69	7.50	1.85	75
Norit	5.8	317	272	336	1.35	1.26	4.69	5.95	1.29	78
Norit	5.7	311	270	309	5.03	1.04	6.26	7.30	1.98	73
Norit	6.0	312	270	310	5.07	1.30	6.26	7.56	1.85	76
AC-1	4.1	314	286	342	0.48	4.33	4.30	8.63	2.39	72
AC-1	4.4	315	286	345	0.47	3.92	4.30	8.23	2.19	73
AC-1	4.0	315	288	344	1.37	5.40	1.96	7.35	2.47	66
AC-1	4.3	316	289	352	1.38	4.68	1.96	6.64	2.08	69
AC-1	3.6	290	302	363	0.48	1.93	1.68	3.61	1.29	64
AC-1	4.5	287	302	362	0.49	5.08	1.68	6.76	1.47	78
AC-1	4.5	297	302	361	1.45	6.81	1.04	7.85	1.23	84
AC-1	5.0	297	303	360	1.43	6.12	1.04	7.16	1.23	83

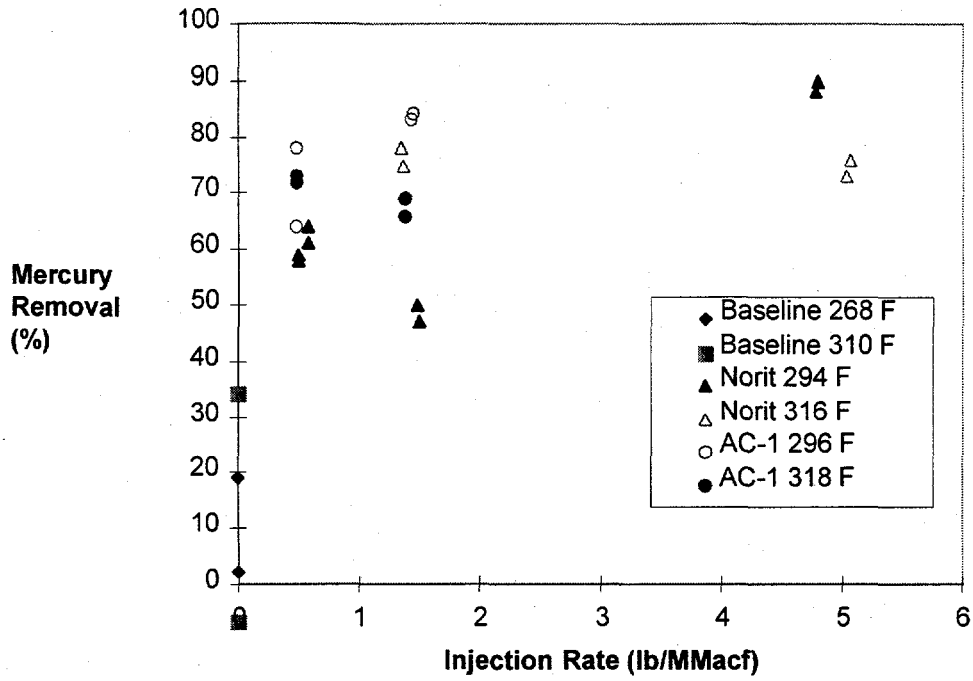

Figure 8. Mercury removal during "dirty" gas reverse-gas tests.

"Dirty" flue gas with sodium sesquicarbonate injection

The final set of reverse-gas tests was conducted with sodium sesquicarbonate injection for SO_2 removal. Tests were conducted at PCM temperatures from 244 - 307 °F using "dirty" fluegas. Sodium was injected at a normalized stoichiometric ratio of 1 during testing at PCM temperatures below 250 °F and 1.2 during testing at PCM temperatures above 305 °F. Following mercury measurements with sodium injection alone, Norit was injected at ratios of 1 - 1.2 lb/MMacf with sodium sesquicarbonate. Triplicate mercury measurements were made for each test point in this set of tests. The average mercury removal with sodium sesquicarbonate injection and no carbon injection at 245 °F was 55 %. With Norit injection rate of 1.2 lb/MMacf, mercury removal increase to 62%. The only comparison data without sodium injection was obtained at higher PCM temperatures and thus is not directly comparable. However, data collected with carbon injection indicate a higher mercury removal increase over the baseline removal at this injection level. It is possible that sodium injection could interfere with the mercury removal process. Further data should be collected and analyzed to determine if the presence of sodium sesquicarbonate in this flue gas at lower temperatures impedes mercury removal or the data was within the normal variation of the data.

At temperatures above 305 °F, the average baseline mercury removal was 10 %. At an injection rate of 1 lb/MMacf, the mercury removal was 41 to 76 %. These results are depicted on Figure 9. The higher temperature data collected during earlier tests in the absence of sodium sesquicarbonate indicated similar mercury removal rates.

PCM operating parameters and mercury measurements made during the sodium sesquicarbonate injection tests are shown in Table 7. During isokinetic ash sampling, a single ash sample is collected while multiple (duplicate or triplicate) vapor mercury samples are collected. It is interesting to note that during three of the four triplicate tests reported on the table, the vapor mercury concentration decreased with time. The decreasing mercury concentration downstream of the sampling filter suggests that ash collected on the sampling filter is removing additional mercury as the ash layer thickness increases.

Table 7. Mercury Measurements during Sodium Sesquicarbonate Injection

Sorbent	PCM Temp (°F)	Inlet Temp (°F)	ΔP (in H_2O)	inj rate (lb/MMacf)	Inlet Hg IC* (ug/Nm^3)	Inlet flyash Hg (ug/Nm^3)	Inlet total Hg (ug/Nm^3)	Outlet Hg* (ug/Nm^3)	Hg removal (%)
None	244	257	3.37	0.0	0.77	7.78	8.55	4.28	50
None	245	259	3.71	0.0	1.48	7.78	9.26	3.89	58
None	246	261	3.96	0.0	1.55	7.78	9.33	4.09	56
Norit	249	270	4.88	1.2	3.12	7.42	10.54	4.01	62
Norit	248	267	5.25	1.2	2.89	7.42	10.31	3.86	63
Norit	247	265	5.62	1.2	2.58	7.42	10.00	3.95	60
None	317	281	3.38	0.0	1.71	8.21	9.91	8.91	10
None	319	284	3.70	0.0	0.82	8.21	9.03	10.18	-13
None	320	279	3.95	0.0	0.69	8.21	8.90	8.01	10
Norit	307	252	3.69	1.0	1.24	10.58	11.82	6.95	41
Norit	307	252	3.93	1.0	0.75	10.58	11.33	3.04	73
Norit	307	257	4.27	1.0	0.29	10.58	10.87	2.60	76

* Captured in an iodated carbon trap

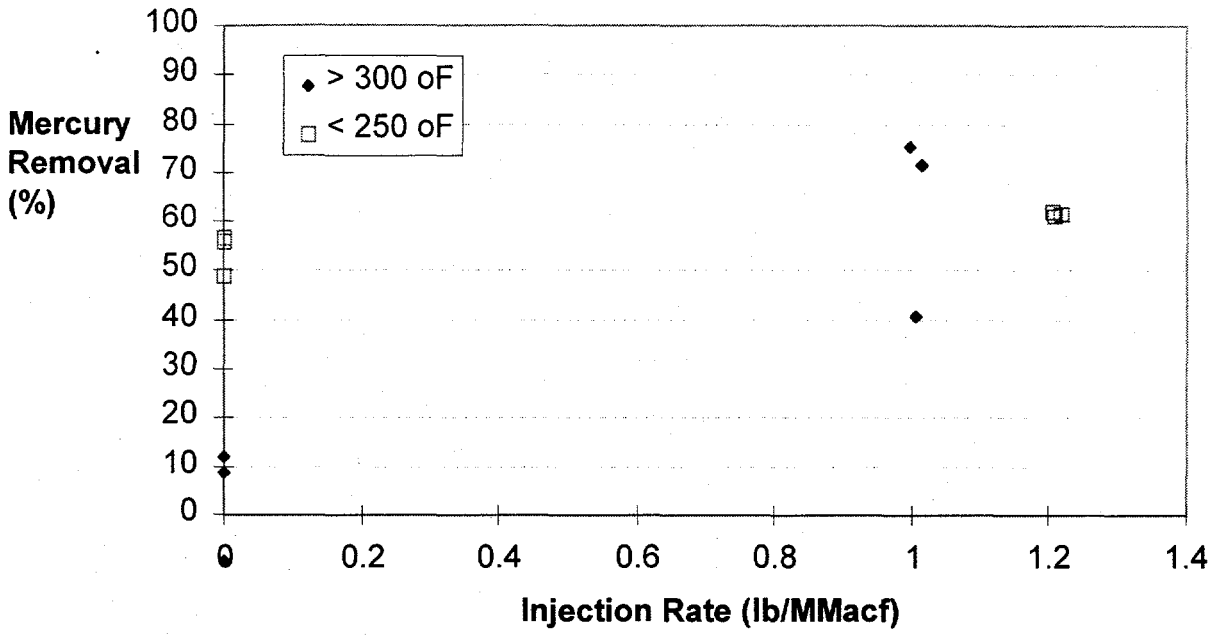

Figure 9. Mercury removal during sodium sesquicarbonate injection.

Data presented in Table 8 are the SO_2 and NO_x concentrations measured during sodium injection. Test results show 26 - 37% SO_2 removal and a slight reduction in NO and NOx in most cases.

Full-scale sodium sesquicarbonate tests have been conducted at other sites including the City of Colorado Springs' Nixon Plant in Fountain Colorado and Public Service Company of Colorado's Arapahoe Generating Station in Denver, Colorado (1,2). Results from these earlier tests indicate approximately 50% SO_2 removal is possible at similar operating temperatures and sorbent injection rates on full scale units. The maximum removal achieved at Comanche was 37%.

The size of the sorbent used at Comanche, 27 micron MMD, was slightly larger than an optimal 10 - 20 micron MMD size. Although the sorbent utilization and SO_2 removal has been shown to decrease with increasing sorbent size, the low SO_2 removal rates achieved at Comanche were much lower than expected due to a size effect alone. Another possible contributor to the low removal explored during the recent tests was potential sorbent fall-out in the duct. The pilot was designed to permit an on-line collection of all material in the hopper. It is expected that most of the sorbent was reaching the bags (and not falling directly into the hopper) because

insignificant material was collected in the hopper during filtering and most of the flyash/sorbent mixture expected to have entered the filter vessel was knocked into the hopper when the bags were cleaned. The cause of the lower-than-expected SO_2 removal has not been resolved and further testing would be required to determine the reason for these results.

Table 8. NOx/SOx (corrected to 3% O_2) Collected During Sodium Injection Tests.

NSR	NO ppmd @3%O2		NO_2 ppmd @3%O2		NOx ppmd @3%O2		SO_2 ppmd @3%O2		% SO_2 rem	PCM Temp (°F)	Avg ΔP (in H_2O)	Load (MW)
	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet				
1.0	199	184	6	25	210	210	300	207	31	244	3.37	314
1.0	199	178	6	27	210	205	300	218	27	245	3.71	309
1.0	199	175	5	26	207	200	305	225	26	246	3.96	318
1.0	234	206	7	22	252	232	314	227	28	249	4.88	352
1.0	234	205	7	23	252	232	314	215	32	248	5.25	315
1.0	234	229	7	25	252	268	314	216	31	247	5.62	319
1.2	221	177	-3	21	226	198	305	198	35	317	3.38	338
1.2	221	171	-3	24	226	193	305	192	37	319	3.70	337
1.2	221	159	-3	23	226	181	305	196	36	320	3.95	309
1.2	171	234	3	23	173	275	288	188	35	307	3.69	312
1.2	171	189	3	19	173	215	288	198	31	307	3.93	322
1.2	171	161	3	16	173	176	288	186	35	307	4.27	337

TOXECON Configuration

Testing with the PCM in the TOXECON configuration began May 2, 1997. Mercury removal evaluations were conducted at temperatures from 241 to 313 °F with injection rates from 0 to 2.5 lb/MMacf Norit activated carbon and an iodine impregnated activated carbon. A short series of tests was also conducted during sodium sesquicarbonate injection for SO_2 removal.

Operation

There is very little flyash present in the flue gas downstream of Comanche's full-scale baghouse. When the PCM was configured as a TOXECON unit operating on this "clean" flue gas, the dustcake on the bags developed slowly. The cleaning logic was set to clean the bags once per day which maintained the pressure drop across the fabric below 2 inches H_2O.

When a sorbent such as carbon or sodium was injected into the baghouse, a distinct change in the rate of pressure drop increase across the fabric was noted. Figure 10 shows a trace of $\Delta P/\Delta t$, the rate of pressure drop increase across the fabric, for no carbon injection, 0.5 lb/MMacf Norit injection, and 2.0 lb/MMacf Norit injection on May 6, 1997. As shown, the baseline $\Delta P/\Delta t$ was nearly 0 inches H_2O/min. At the low Norit injection rate, the $\Delta P/\Delta t$ was an average of 0.002 inches H_2O/min. This is roughly an additional 0.1 inches H_2O per hour. At the high Norit injection rate, the pressure drop increased 0.007 inches H_2O/min, or an additional 0.4 inches H_2O per hour. At these carbon injection rates on a "clean" flue gas stream, minimal cleaning would be required to maintain the pressure drop across the fabric below a reasonable 5 inches H_2O.

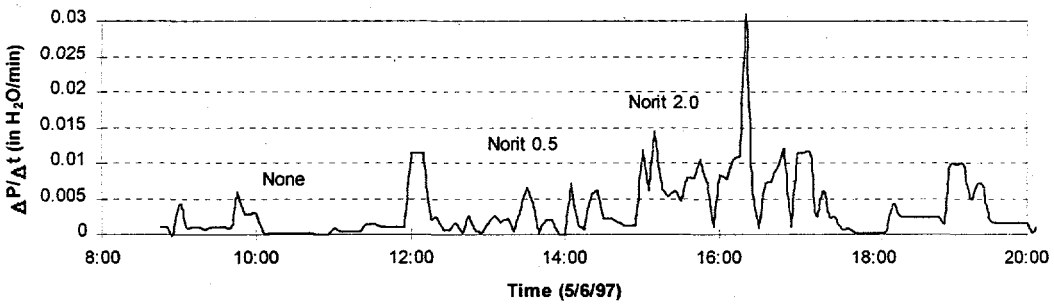

Figure 10. Rate of pressure increase across fabric with varying carbon injection rates.

Figure 11 shows a trend of the pressure increase across the fabric with sodium injection. As shown, an injection rate of 12 grams/minute into TOXECON (66 lb/MMacf) results in a rate of pressure increase of 0.01 inch H_2O/min, or 0.6 inch H_2O per hour.

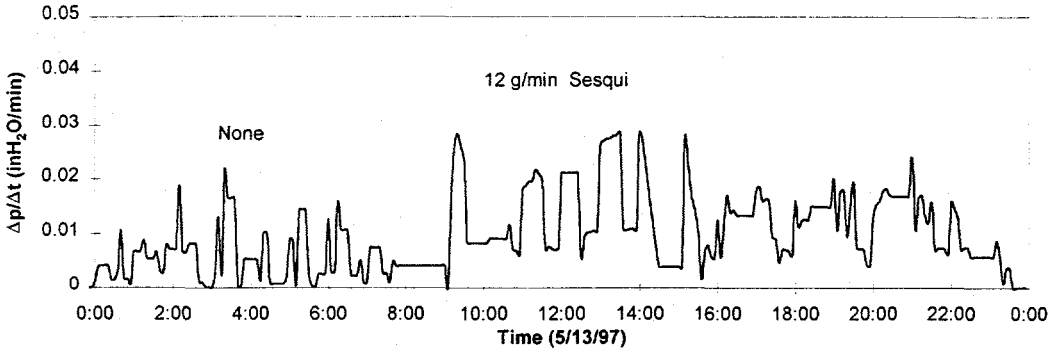

Figure 11. Rate of pressure increase across fabric with sodium sesquicarbonate injection.

Mercury Removal

The PCM operating conditions and mercury sample analyses for tests conducted without sodium injection are shown in Table 9. The data on the table are presented in three PCM temperature blocks (separated by a blank line) of 240-250 °F, 270 - 290 °F, and 310 - 313 °F. The mercury removal data are also presented graphically in Figure 12. During the lower temperature tests, the mercury removal reached an average of 94% at an injection rate of 0.47 lb/MMacf. Little additional removal was achieved by increasing the injection rate.

During the 270-290 °F tests, the data suggests that significant removal can also be achieved at a low Norit injection rate of 0.49 lb/MMbtu. However, a closer examination of the data suggests that the high removal may be a residual effect of an earlier test. The 0.49 lb/MMacf test was conducted 3 hours after completing the 2 lb/hr Norit injection test and the bags were inadvertently cleaned *only* once. It is likely that some carbon was still on the bags from the high injection rate tests. Due to these concerns, the data point is not include in Figure 12. In addition, the mercury removal achieved during these low injection rate tests was nearly identical to that achieved during the previous test. The results from this data suggest potential for intermittent carbon injection with TOXECON where little cleaning is required because of the low inlet flyash load. Further investigation into batch feeding to determine the potential mercury saturation of the carbon should be completed.

Iodine impregnated activated carbon was tested in the 270-290 °F temperature range and the data indicates that mercury removal with this sorbent is similar to the removal achieved with Norit activated carbon.

During the baseline middle and high temperature tests, the mercury concentration at the outlet was actually *higher* than measured at the inlet. A trend graph of pilot operation during these tests is shown in Figure 13. The graph shows a step increase in the PCM temperature that the duct heater was turned on approximately four hours before the middle temperature tests and another step increase approximately two hours before the high temperature tests. The black and gray lines indicate the baseline testing completed during this period. The temperature increase is caused by changing the temperature of the duct heater coils in the gas stream. It is likely that residual ash was present on the heater coils and changing the temperature of the coils likely caused mercury to desorb from the surface of the coils and the ash on the coils. It is possible that 3 to 4 hours of operation at a new temperature is not adequate to desorb the volatile mercury from the coils/ash. It is unknown how long of period of time is required for the mercury to devolatize. Future testing should consider moving the flue gas heater further upstream and monitoring the inlet mercury after the sufficient time has occurred to devolatize the mercury from the fly ash. Laboratory testing may be required to determine the needed residence time.

The results from Norit injection at the higher temperatures indicate little mercury removal is possible at an injection rate of 0.6 lb/MMacf. A maximum average mercury removal of 56 % was achieved at an maximum injection rate of 2.47 lb/MMacf at the higher temperatures.

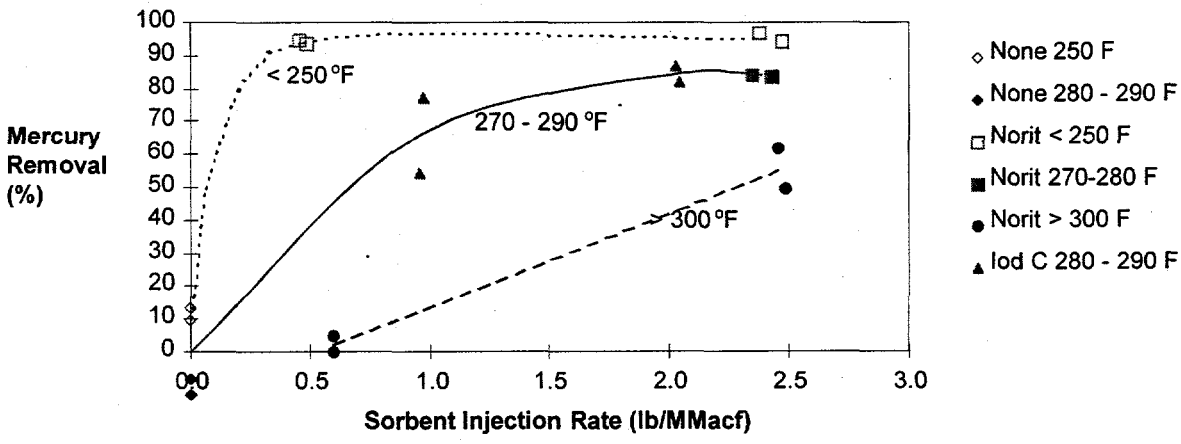

Figure 12. Mercury removal in TOXECON.

Table 9. TOXECON Operation and Mercury Removal

Sorbent	PCM Temp (°F)	Inlet Temp (oF)	ΔP (in H2O)	Host Load (MW)	inj rate (lb/MMacf	Total Hg inlet (μg/Nm³)	Total Hg Outlet (μg/Nm³)	Hg Removal (%)
None	249	267	1.28	355	0.00	2.30	2.00	13
None	252	274	1.29	358	0.00	2.65	2.40	10
Norit	248	256	1.65	304	0.48	1.82	0.12	93
Norit	246	260	1.83	312	0.46	2.09	0.11	95
Norit	243	261	2.30	312	2.37	2.23	0.07	97
Norit	241	261	2.63	305	2.47	3.20	0.18	94
None	277	283	1.35	354	0.00	3.91	4.44	-13
None	278	285	1.36	353	0.00	3.83	4.15	-8
Norit	273	276	2.78	353	0.49	4.32	0.15	97
Norit	273	280	2.82	352	0.49	4.64	0.14	97
Norit	275	288	3.28	364	2.34	11.69	1.84	84
Norit	277	293	3.64	362	2.43	180.69	29.39	84
IoC	283	297	1.34	358	0.97	5.06	1.16	77
IoC	285	300	1.47	359	0.96	4.99	2.28	54
IoC	287	300	1.87	358	2.04	4.48	0.80	82
IoC	288	302	2.17	358	2.03	4.22	0.56	87
None	313	299	1.48	353	0.00	4.00	7.26	-81
None	313	299	1.54	353	0.00	3.66	6.44	-76
Norit	313	311	1.41	359	0.59	4.45	4.44	0
Norit	313	313	1.49	359	0.60	3.78	3.60	5
Norit	310	312	1.99	360	2.48	3.13	1.58	50
Norit	311	312	2.45	359	2.45	3.73	1.43	62

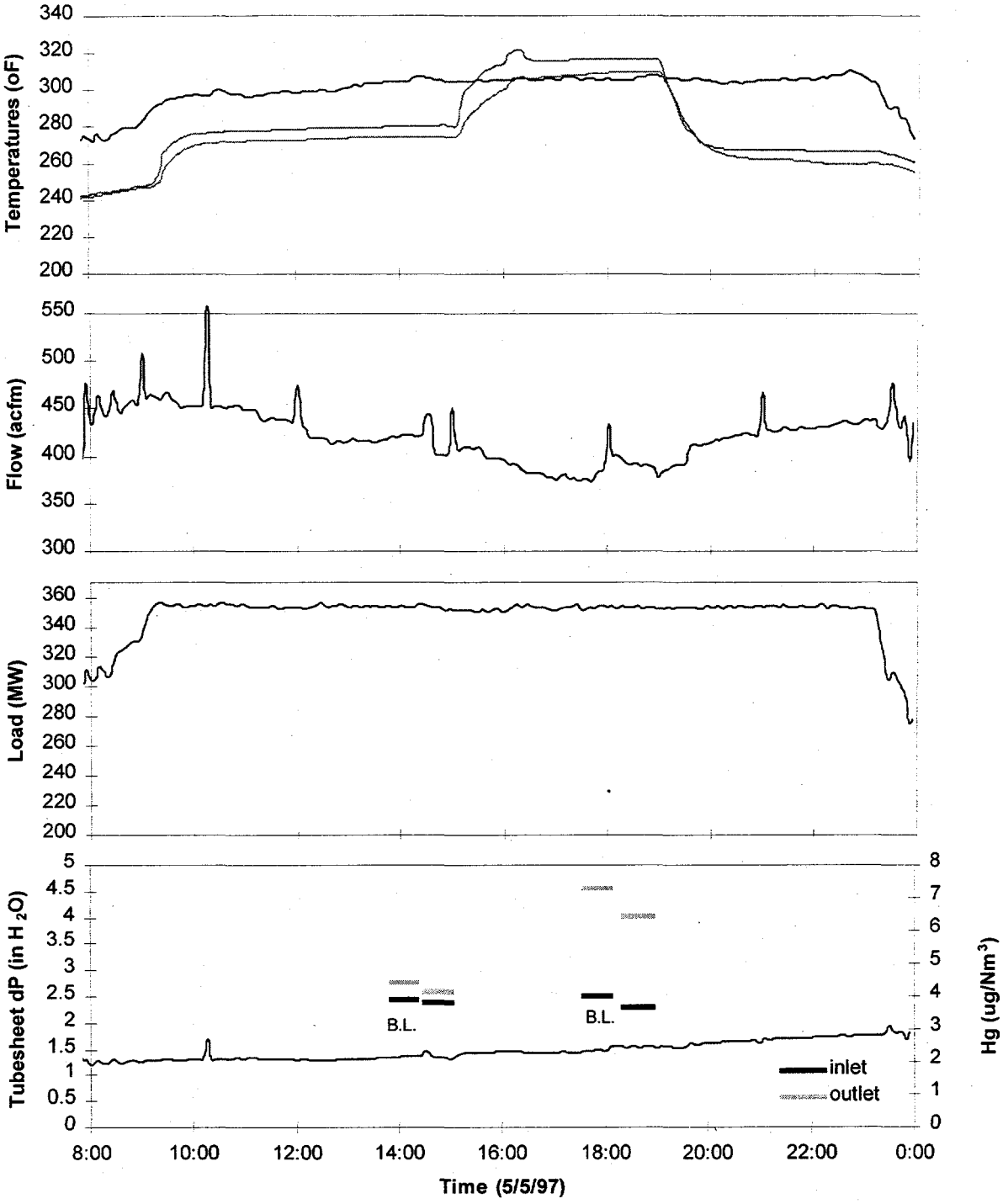

Figure 13. Trend graph of TOXECON operation during baseline mercury measurements

Sodium Sesquicarbonate for SO_2 Removal

A series of tests was conducted to determine mercury removal with sodium injection for SO_2 removal with the TOXECON configuration. Sodium sesquicarbonate was injected at a normalized stoichiometric ratio of 1 with PCM temperatures from 271 to 307 °F. Norit was injected at 0.91 to 1.07 lb/MMacf during some tests. The results from these tests, shown in Table 10, indicate inconsistent results. For example, with no sorbent injection 5 - 12 % mercury removal was measured at a PCM temperature of 283 °F and 34 - 45% removal was measured at 302 °F. With 0.91 to 1.07 lb/MMbtu carbon injection, the mercury removal was 20 - 30% at the lower temperature and -20 to -13% at the higher temperature. The PCM operating data is being analyzed to determine if another parameter, such as the time since the temperature was modified, may be confounding the mercury removal results.

Table 10. TOXECON with Sodium Sesquicarbonate Injection

Sorbent	PCM Temp (°F)	Inlet Temp (°F)	ΔP (in H_2O)	Host Load (MW)	inj rate (lb/MMacf)	Total Hg Inlet (ug/Nm³)	Total Hg Outlet (ug/Nm³)	Hg Removal (%)
None	283	292	3.92	362	0.00	3.67	3.23	12
None	283	294	4.68	360	0.00	3.61	3.43	5
Norit	272	282	2.86	343	0.91	2.38	1.91	20
Norit	271	282	4.00	344	0.92	2.73	1.92	30
None	302	304	2.23	363	0.00	4.14	2.28	45
None	303	307	2.98	363	0.00	4.53	3.00	34
Norit	306	312	2.58	363	1.07	3.68	4.16	-13
Norit	307	313	3.84	362	1.07	3.51	4.22	-20

Table 11 shows the SO_2 and NO_x concentrations measured during sodium sesquicarbonate injection. Test results show 11 - 15% SO_2 removal and a slight reduction in NO and NOx.

Previous sodium sesquicarbonate tests have been conducted at Comanche Station under similar operating conditions on a 3700 acfm pilot baghouse. The baghouse was operating on fluegas from downstream of Comanche's full-scale baghouse. The average SO_2 removal during

these previous tests was 35%. The maximum removal achieved at Comanche during the current tests was 15%. Testing was conducted to determine if sorbent drop out was causing the lower than expected removal but dropout was not occurring. Further testing is required to better understand this lower than expected SO_2 removal.

Table 11. NOx/SOx Collected During Sodium Injection Tests.

NSR	NO (ppmd @ 3%O2)		NO_2 (ppmd @ 3%O2)		NOx (ppmd @ 3%O2)		SO_2 (ppmd @ 3%O2)		% SO_2 rem	PCM Temp	ΔP	Load
	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet		(°F)	(in H_2O)	(MW)
1.2	156	148	1	6	156	154	301	263	13	260	3	330
1.3	202	196	3	10	208	206	290	260	12	284	3.5	360
1.3	152	147	2	5	152	150	259	225	15	301	2.5	345
1.7	179	169	10	16	189	183	241	216	11	308	3	360

Mercury in Coal and Ash

A grab sample was collected from the full-scale reverse-gas baghouse and analyzed for mercury. Results from the analysis showed 1035 ng/g mercury in the ash sample. This suggests significant mercury removal is occurring within the full-scale baghouse.

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 samples collected during carbon injection upstream of the PCM at Comanche Station are shown in Table 12. These results show that all 8 RCRA elements of concern are well below regulatory limits. In fact, the levels of most metals were below detection limits.

Table 12 TCLP Summary Report from Testing This Quarter

El.	Tox. Ash	Tox. Ash+C	Rev-Gas Ash	Rev-Gas Ash+C	Regulatory Limits
		As Analyzed Value (mg/L)			(mg/L)
As	0.35	0.75	<DL	<DL	5.0
Ba	<DL	<DL	15.5	23.3	100.0
Cd	0.035	0.015	<DL	<DL	1.0
Cr	<DL	<DL	<DL	<DL	5.0
Pb	<DL	<DL	<DL	<DL	5.0
Se	0.68	<DL	<DL	<DL	1.0
Ag	<DL	<DL	<DL	<DL	5.0
Hg	<DL	<DL	<DL	<DL	0.2

*<DL (detection limit). Arsenic < 0.28, Barium < 0.51, Cadmium < 0.014, Chromium < 0.061, Lead < 0.26, Selenium < 0.42, Silver < 0.51, Mercury < 0.0002 mg/L

Activities Scheduled for Next Quarter (July 1 - September 30, 1997)

The primary activities scheduled for next quarter are completing the field testing in Phase I of the project, analyzing these results, and planning for Phase II. The tests remaining to be completed or analyzed are the flyash re-injection tests and several repeat test conditions in the ESP configuration. The repeat test conditions were identified because initial ESP testing was conducted without isokinetic ash sampling during mercury analysis, and the temperature control across the ESP was not tightly controlled.

Preliminary Conclusions

A significant amount of quality data was collecting during the Phase I test program. Most tests were completed with double and some with triplicate analysis to improve accuracy. However, there are significant difficulties measuring the very low mercury concentrations that were encountered at Comanche. Many questions remain on temperature variation of the flue gas when particulate is present. Despite these problems the following conclusions summarize the major data collected during the test program. It is recommended that further data collection and repeat testing be conducted to confirm the accuracy of the data and widen the band of operating conditions with data available.

- In all tested configurations with fly ash present, it was found that Comanche's fly ash obtained mercury removal without sorbent injection. Mercury removal increased substantially as flue gas temperature decreased below 280 °F. The maximum baseline mercury removal of over 60% was obtained with the pulse-jet configuration operating at 250°F.
- Sorption of mercury by the flyash significantly increases the importance of collecting a representative particulate sample and analyzing the particulate and vapor-phase mercury to determine mercury removal efficiency. The use of an isokinetic sample train with a cyclone to limit flue gas contact with particulate sample on the high-ash inlet tests reduced data scatter in the results and was believed to provide the most accurate data.
- Significant pulse jet and TOXECON testing was also conducted using "clean" flue gas with little fly ash in order to obtain a more accurate representation of the sorbent's effectiveness across the flue gas temperature range. At flue gas temperatures below 270 °F, 90% and higher mercury removals were shown at carbon injection rates of 0.5 to 2.0 lbs/MMacf. At temperatures, in the range of 300 °F, carbon injection was increased to 2.5 to 3.0 lbs/MMacf to obtain approximately 60% removal.
- No significant differences were noted in the mercury removal performance of AC-1 and Norit activated carbons. One test with iodine impregnated carbon in the TOXECON configuration also resulted in mercury removal rates similar to Norit and AC-1. This infers that the reaction is gas-phase mass transfer controlled.
- During these short-term PCM evaluations, activated carbon injection did not impact power levels in the ESP or tubesheet pressure drop in the pulse-jet or reverse-gas configurations.
- Over the range of inlet mercury concentrations tested (roughtly 2 to 13 $\mu g/Nm^3$), initial mercury concentration did not significantly effect the required carbon injection rate to obtain a desired mercury removal.
- No improvements in SO_2 collection with carbon injection or mercury collection with sodium sesquicarbonate injection were noted in either configuration tested (reverse-gas and TOXECON).

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2. Fuchs M.R., J.R. Glass, C.S. Galloway and G.M. Blythe. "Full-Scale Demonstration of Desulfurization by Dry Sodium Injection" EPRI Report Number GS-6860, July 1990.