Novel Process for Removal and Recovery of Vapor-Phase Mercury

Final Report for Phase II
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Executive Summary

The goal of this project is to investigate the use of a regenerable sorbent for removing and recovering mercury from the flue gas of coal-fired power plants. The process is based on the sorption of mercury by noble metals and the thermal regeneration of the sorbent, recovering the desorbed mercury in a small volume for recycling or disposal. The project was carried out in two phases, covering five years. Phase I ran from September 1995 through September 1997 and involved development and testing of sorbent materials and field tests at a pilot coal-combustor. Phase II began in January 1998 and ended September 2000. Phase II culminated with pilot-scale testing at a coal-fired power plant.

The use of regenerable sorbents holds the promise of capturing mercury in a small volume, suitable for either stable disposal or recycling. Unlike single-use injected sorbents such as activated carbon, there is no impact on the quality of the fly ash.

During Phase II, tests were run with a 20-acfm pilot unit on coal-combustion flue gas at a 100 lb/hr pilot combustor and a utility boiler for four months and six months respectively. These studies, and subsequent laboratory comparisons, indicated that the sorbent capacity and life were detrimentally affected by the flue gas constituents. Sorbent capacity dropped by a factor of 20 to 35 during operations in flue gas versus air. Thus, a sorbent designed to last 24 hours between recycling lasted less than one hour. The effect resulted from an interaction between SO_2 and either NO_2 or HCl. When SO_2 was combined with either of these two gases, total breakthrough was seen within one hour in flue gas. This behavior is similar to that reported by others with carbon adsorbents (Miller et al., 1998).

Additional evidence indicated that the noble-metal crystallites that form the active sorption sites were attacked by the flue gas. Electron micrographs depicted growth of the crystallites, resulting in less surface area for sorption. There was also a 33% loss of metal from the sorbent after four months of test time. These two effects were believed to be caused by acid attack on the noble metal, possibly exacerbated by poor temperature control during the first part of the testing. Ash accumulation on the sorbent was also noted, although it is not known if this affected sorbent performance.

Process economics were calculated using a basis of 10^6 acfm and 10 µg/m^3 of mercury, and further assuming a 60% plant availability. These assumptions yield a total of 62 kg (135 lb) of mercury captured annually. Using only the cost for the sorbent and its anticipated three-year life, the cost for mercury recovery is estimated at \$29,600/lb Hg – comparable to that for other more developed technologies, such as carbon injection. Given the level of uncertainty in this estimate the economics of the regenerable sorbent are questionable for use in flue gas containing acid gases.

The sorbent's higher capacity when treating scrubbed flue gas holds more promise for its use downstream of acid-gas scrubbers and in industrial applications that do not involve NOx- or HCl-bearing acid-gas streams. Within the utility sector, such an application is the capture of mercury downstream from a flue-gas desulfurization (FGD) system. Approximately 20% of coal-fired power plants use some form of FGD. Recent mercury monitoring data indicates that wet FGD systems capture 85% to 95% of oxidized mercury but virtually none of the elemental mercury (DeVito & Rosenhoover, 1999). Depending on the mercury speciation, this "slip" can

allow several μg/m^3 of mercury in the stack gas – possibly more than would be allowed should regulations be promulgated. A polishing step with a regenerable sorbent is attractive because no particulate capture is required, as is needed with injected sorbents.

During the course of this project ADA refined a continuous mercury analyzer for use in flue gas applications. The development built on prior DOE-funded research and culminated with assembly of a field-deployable instrument. The analyzer was used successfully during the final laboratory and field testing conducted within this project.

Introduction

The purpose of this project was to investigate the application of a regenerable sorbent-based process for removing and recovering mercury in the flue gas of coal-fired power plants. The process is based on the sorption of mercury by noble metals and the thermal regeneration of the sorbent, recovering the desorbed mercury for recycling or disposal. ADA Technologies holds a patent on this process (US 5,409,522) and had previously tested it under conditions typical of municipal waste incinerators. In this process, the noble metal sorbent is thermally regenerated, and the mercury is recovered for commercial recycle or disposal. ADA has adopted the name "Mercu-RE" to describe its process.

When compared with single-use sorbents such as activated carbon, The Mercu-RE process has the following potential:

- high mercury removal efficiencies regardless of the chemical form of the mercury

- no impact on fly ash quality,

- minimization of mercury-contaminated solid or liquid wastes, and

- removal of mercury from the biosystem.

Figure 1 contrasts the fate of mercury in the Mercu-RE process with the fate of mercury in an uncontrolled coal-fired combustor and in a system using state-of-the-art carbon injection for mercury control.
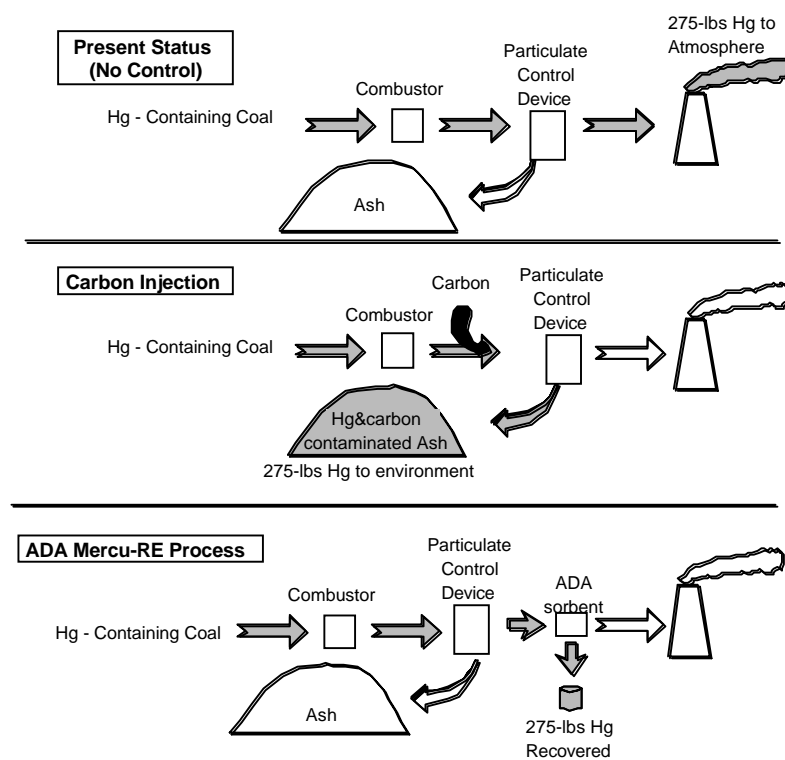
Figure 1. Fate of Mercury in Various Control Schemes (assumes $2x10^6$ ACFM at 10 µg Hg/Nm^3 and 60% capacity over one year)

The quantities of ash and mercury in Figure 1 are typical of those generated annually by a 500 MW coal-fired utility. It should be noted that while waste incinerators are regulated for a maximum mercury discharge concentration of 50 µg/m³, most coal-fired power plants have mercury emissions at or below 10 µg/m³. Thus, mercury control in power plants involves achieving much lower mercury levels than currently reached in other combustion processes.

Regulatory and Technical Drivers

Mercury and its compounds are a group of chemicals identified in Title III of the 1990 Clean Air Act (CAA) Amendments as air toxic pollutants. Mercury forms several volatile compounds that are emitted from stationary sources. Municipal and hazardous waste incinerators together comprise an estimated 30% of the emissions of mercury in the U.S. and are now regulated by the Environmental Protection Agency (EPA). The EPA estimates that 33% or about 50 tons of the U.S. anthropogenic mercury emissions are from coal-fired power plants (US EPA 1997). Electric power utilities remain the only major industrial source of mercury that is unregulated and starting in 1999 the EPA undertook a comprehensive data gathering program to better quantify the emissions from this sector. The EPA is under a court order to reach a decision regarding the regulation of mercury emissions from power plants by December 2000.

A coal-fired utility boiler emits several different mercury compounds, primarily elemental mercury, mercuric chloride ($HgCl_2$), and mercuric oxide (HgO), each in different proportions depending on the characteristics of the fuel being burned and on the method of combustion. The concentration of mercury in the flue gas is typically below 1 ppb by volume, i.e., below about 10 µg/m³. At these low concentrations, the efficacy of carbon-based sorbents is severely compromised. Not only is the thermodynamic capacity of carbon sorbents reduced at these low mercury concentrations, but the rate at which the mercury gets to the carbon can be limited by gas phase mass transfer kinetics (e.g. Carey et al, 1997). As a consequence, to achieve mercury removal efficiencies exceeding 50%, approximately 10,000 pounds of injected carbon is required per pound of mercury removed.

Currently, there is no single control method that will reliably collect different mercury species simultaneously. Further, existing control systems vary in efficiency as the flue gas temperature varies, and generate secondary hazardous wastes because they capture mercury using sorbents or reagents that are used only once. Wet scrubbing, for example, is efficient only for water-soluble mercury species such as $HgCl_2$ (Hargrove et al., 1997, DeVito & Rosenhoover, 1999). Elemental mercury is not captured by wet scrubbers. Further, less than 20% of all coal-fired utilities employ wet scrubbers (for SO_2 control), and it is not economically feasible to install a wet scrubber solely for mercury control. Wet scrubbing is therefore not an option as a retrofit for mercury control.

Tests of carbon injection, both activated and chemically-impregnated, have been reported by several research teams: Miller et al., 1994, Sjostrom et al., 1997, Bustard & Chang 1994, and Butz & Chang, 1999. Results are widely variable and are explained by the dependence of the sorption process on temperature and mercury speciation and also on fly ash chemistry. Chang & Offen (1995) state that with operating and annualized capital costs, carbon injection will cost between $14,000 and $38,000 per pound of mercury removed, which equates to over $4 million

per year for a 250-MW power plant.

Brown provides an excellent overview of the issues related to mercury emissions from coal-fired power plants (Brown 1999). None of the commonly considered approaches to mercury control nor, to our knowledge, any other method of mercury control for flue gases, remove all forms of mercury and involve a regenerable sorbent and recovery of recyclable mercury, as does ADA's Mercu-RE process.

Summary of Phase I

The Phase I program consisted of five tasks (Roberts et al., 1998):

Task 1 – Screen Sorbent Configurations in the Laboratory

Task 2 – Design and Fabricate Bench-Scale Equipment

Task 3 – Test Bench-Scale Equipment on Pilot Combustor

Task 4 – Evaluate Economics Based on Bench-Scale Results

Task 5 – Reporting

In Task 1, we demonstrated that the sorbents are thermally durable and are regenerable through at least 55 cycles of mercury uptake and desorption. We also demonstrated two low-pressure-drop configurations of the sorbent, namely, a particulate form and a monolithic form. We showed that the particulate form of the sorbent would remove 100% of the mercury if the bed residence time exceeded 0.1 seconds. In principle, the particulate form of the sorbent could be imbedded in the back side of a high-temperature bag filter in a full-scale application. With typical bag face velocities of four feet per minute, the thickness of the particulate layer would need to be about 2 mm to accomplish the mercury removal.

A monolithic form of the sorbent would likely be more practical in a full-scale power plant application. For example, catalyst monoliths are currently used in selective catalytic reduction (SCR) applications. With that in mind, ADA purchased commercially-available metallic monoliths. The active sorbent was impregnated onto an alumina wash-coat layer within the flow channels of the monoliths. At face velocities approaching 1.5 ft/sec, these monoliths had less than 0.05 inches of water pressure drop. The monolithic form of the sorbent went through 21 cycles of mercury sorption and desorption in the laboratory and demonstrated simultaneous uptake of both mercury and mercuric chloride.

Under Task 3, ADA tested a 20-cfm skid-mounted system at CONSOL's pilot coal-combustor. The unit ran for over 700 hours while testing flue gas from the combustion of four different coals (January through June, 1997). Sorption of mercury was tracked with ADA's continuous mercury analyzer. Sorption and desorption were seen, but were difficult to quantify. In a final series of tests we verified quantitative desorption of one of the sorbent beds. Near the end of the test program one monolith from each of the sorbent modules was removed and retested in the laboratory by passing elemental mercury in a nitrogen/oxygen mixture through the monolith. These tests found that the monoliths had retained their capacity for mercury even though they had been through hundreds of hours of testing in the field and were covered with a thin ash layer. This laboratory test was run using elemental mercury in a nitrogen/oxygen gas

mixture. As we will see, this test proved to be an insufficient measure of sorbent performance in flue gas.

Under Task 4, ADA assessed the economics of a 250 MW installation of the mercury sorption technology. The technology appeared to have economic advantages versus injection of activated carbon, with an estimated annualized cost one-fifth that for carbon injection. This economic assessment was approximate given the early stage of the technology but was encouraging for the eventual commercial implementation of the technology.

The Phase I program demonstrated all key attributes of a new technology for removing mercury from flue gases, namely,

- removal of greater than 95% of both elemental and oxidized forms of mercury in the laboratory,

- removal of total mercury from flue gas in limited field trials,

- ability to regenerate the sorbent,

- ability to scale up, and

- favorable economics.

Objectives for Phase II

For Phase II, ADA proposed a two-year program to advance this mercury control technology to small-scale proof-of-concept. The overall goal was to demonstrate reliable regeneration of the sorbent with recovery of mercury and to achieve mercury removal for several months of test time on power plant flue gas. The specific structure of Phase II involved six tasks as outlined in Table 1 below.

Table 1. Description of Phase II Tasks (Tasks 1-5 were accomplished in Phase I).

Task	Title	Goals
6	Implement Improved Heat Transfer Method	To accomplish better heat transfer in the desorption step so that high flow rates of regeneration gas are not needed. Modify the equipment skid based on knowledge gained from Phase I.
7	Establish Routine Operation at Pilot Coal Combustor	To establish, on real flue gas, the routine operation of the 20-ACFM unit.
8	Install and Shakedown Pilot System at Utility Site	To move the pilot unit to the utility site and to prepare it for long-term testing.
9	Test for Long-Term Performance at Utility Site	To determine if the pilot unit can efficiently remove mercury from flue gas and whether the sorbent module can be effectively regenerated repeatedly under field conditions.
10	Prepare Economic Assessment for Full-Scale System	To estimate cost for implementing the process at a 500 MW power plant (about two million ACFM of flue gas).
11	Phase II Reporting	To meet DOE requirements for documentation and to disseminate information to the research and industrial community.

Description of Equipment and Modifications from Phase I

In Phase I of this project ADA designed and built a skid-mounted test unit to treat 20 acfm of flue gas. The unit consisted of a particulate filter, two sorbent vessels, a flue gas blower, an air heater and blower to regenerate each bed, and the associated controllers, valves, and electrical equipment to operate the test unit. The skid footprint measured 4' by 8'. The unit had two onboard, programmable logic controllers (PLCs) and could be operated remotely via telephone line.

Process control and data acquisition for the skid was handled by the two PLCs. PLC-1 was responsible for controlling the flue gas flow rate through the skid, monitoring pressures and temperature throughout the process, and coordinating valve sequencing and air heater temperatures for the sorption and desorption cycles. Data from PLC-1 were automatically downloaded to a computer at one to five minute intervals. These data included gas and sorbent temperatures, flue gas flow rate, gas pressure and sorption cycle status. PLC-2 was dedicated to the control of twelve heat trace circuits used to maintain the temperature of the vessels and flue gas piping at 300°F.

In Phase I, ADA used a shell-and-tube configuration for the sorbent bed, with sorbent-coated monoliths installed on the tube-side. Hot gas was applied to the shell-side in order to heat the sorbent to the required regeneration temperature. Following the completion of Phase I, ADA considered three options for enhancing the rate of heating the sorbent during regeneration: continuing with shell-side hot gas, using electric heaters on the shell-side, or direct tube-side hot gas heating. The third option was selected for implementation in Phase II because it was well suited for use in full-scale applications.

By applying the hot gas directly to the sorbent on the tube-side we were able to achieve rapid heating and close packing of the sorbent. However, a high gas flow rate is required to supply enough energy to heat the sorbent to the regeneration temperature. To achieve this flow rate and maintain thermal efficiency, a regeneration blower recirculates hot gas through the sorbent bed until the required regeneration temperature in reached. After the bed has stabilized at the regeneration temperature, a slow purge gas drives the mercury-laden gas to the mercury recovery device (Figure 2). A benefit of this technique is the lack of any shell-side contact. Thus the sorbent is packed closer together, further aiding the heating process. Packing density becomes very important on larger systems where high flow rates will necessitate large sorbent beds.
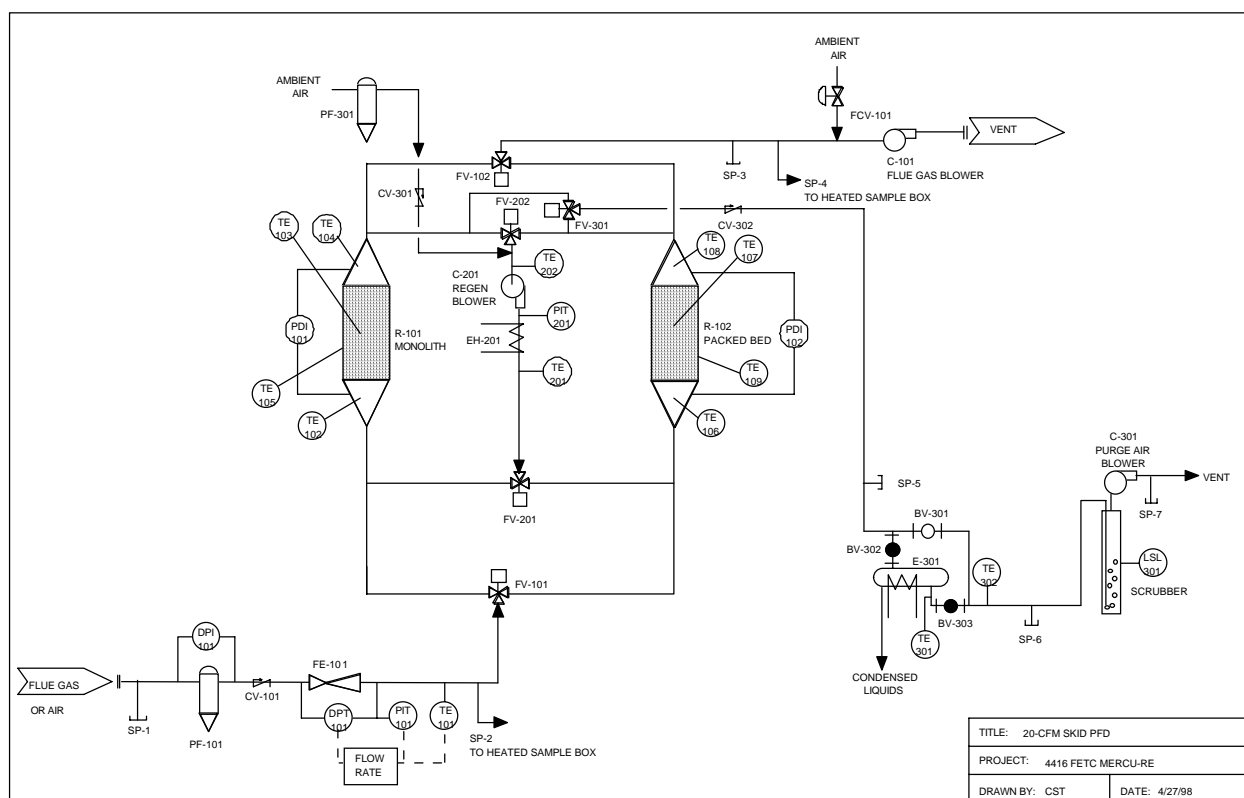
Figure 2. Schematic of 20-cfm equipment skid.

The dual-vessel design of the 20-acfm skid allowed ADA to examine two different bed configurations at the start of Phase II. The first vessel (R-101) contained three 8-inch diameter x

6-inch long sorbent-coated metal monoliths. This design supplied the same surface area and mass of noble metal as in the Phase I system, but with fewer, larger monoliths. Each monolith contained 21-mg of gold as the active noble metal impregnated onto an alumina wash-coat. In the second vessel (R-102) ADA used a 8-inch diameter x 6-inch deep bed of ¼" alumina Raschig rings. The rings were impregnated with 0.05% gold, giving a total gold content of 1.0 g in the packed bed – significantly more noble metal than in the monoliths. ADA has used packed beds in other mercury removal applications. Compared to monoliths, the rings allow for a higher loading of noble metal sorbent per mass of support material, thereby reducing bed size and simplifying regeneration. The drawback of a packed bed is the slightly higher pressure drop and potential fouling from entrained ash. The different support materials are shown in Figure 3.
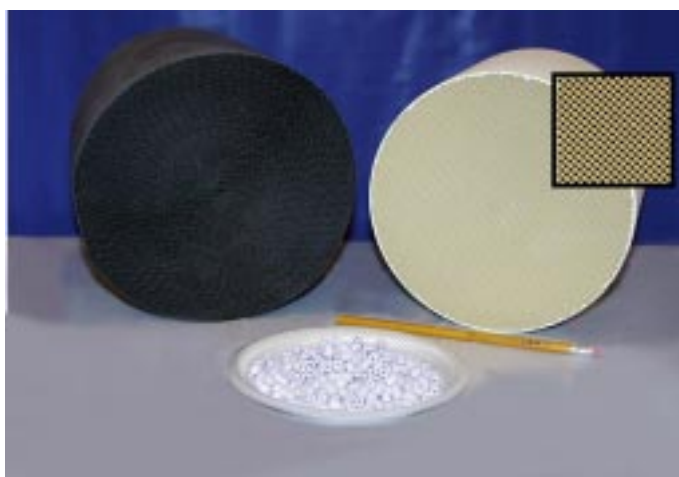
Figure 3. Sorbent support materials. Metal monolith (background left) and ¼" Raschig rings (foreground) used at CONSOL and ceramic monolith (background right) used at Hudson Station.

Wet Scrubber for Mercury Capture

Initially a refrigerated condenser was used to capture mercury from the regeneration gas. Condensation is straightforward, but is not the most efficient means of capturing the mercury. Even at 0°C, mercury's vapor pressure results in a 240 ppbv (2000 µg/m3) vapor-phase mercury concentration, indicating that a substantial amount of mercury would escape a condenser operating at that temperature. Offgas from the condenser can be routed back into the sorbent beds, but this will hasten the breakthrough time of the bed during its sorbing cycle.

The recovery method developed and tested by ADA is wet scrubbing of the regeneration purge gas using a chemical scrubbing solution. The efficacy of this technique was tested with a small-scale scrubbing column. The column had a 3" (76 mm) internal diameter and a 24" (610 mm) packing height of 90% void packing. A spiral nozzle was used for uniform liquid distribution. The nozzle had a conical spray pattern enabling uniform wetting of packing material; the liquid flow rate was 1 gpm (4 L/min). The scrubber schematic is shown in Figure 4.
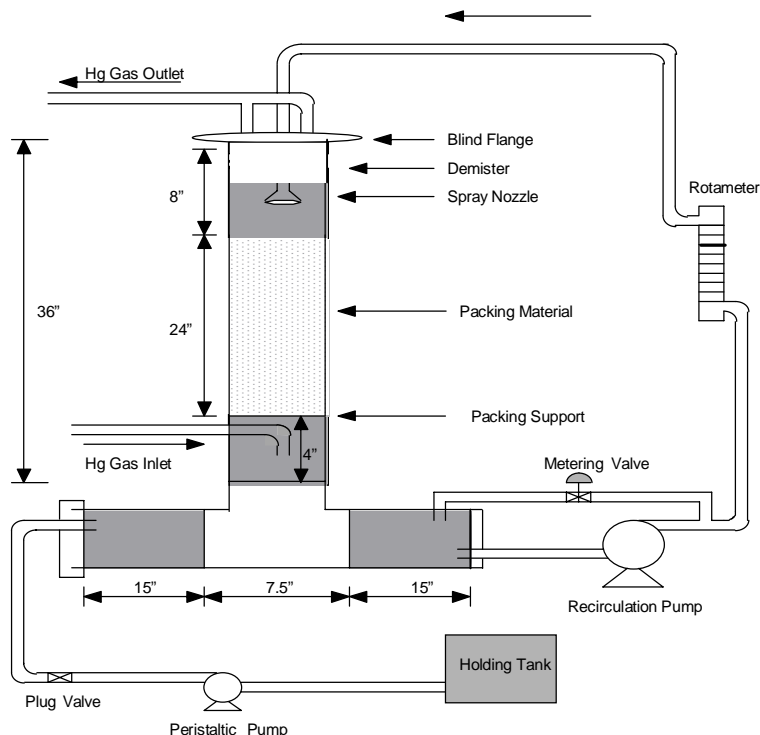
Figure 4. Diagram of wet scrubber used in laboratory tests for mercury capture.

The scrubber utilizes an oxidizing additive to oxidize elemental mercury in the gas stream. Oxidized forms of mercury are readily captured in wet scrubbers, thus the column trapped both oxidized and elemental forms of mercury. A key issue addressed during these tests was the capture efficiency for elemental mercury (Hg^0) as a function of additive concentration.   The column's removal efficiency was determined by use of ADA's bench-top mercury analyzer.   The analyzer was calibrated with a known mercury concentration via a 208-ng/min permeation tube.

A diffusion vial with a mass loss of 5 mg/min was used to spike a 47-standard-L/min nitrogen gas stream feed stream. The gas could be routed to a bypass loop or delivered to the absorption column. The bypass loop enabled measurement of the mercury concentration at the inlet to the column.

The greatest removal efficiency for both elemental and speciated mercury was achieved with a 0.5% solution (Table 2). Another aspect of these tests was the formation of a precipitate in the scrubbing solution. Initially, the precipitate was thought to consist of corrosion products from metallic surfaces (brass and stainless steel) within the absorption column system. Subsequent testing indicated that the precipitate was a reaction product of the mercury/additive chemistry.   These tests were carried out in a 1-liter plastic cylinder filled with stainless steel packing material and 0.5% solution. A mercury containing gas was bubbled through the packed column for 7 days. A precipitate was deposited on the cylinder wall and packing material.   This test was followed by a second test where Hg^0 was bubbled in a 0.5% solution with no packing material in cylinder. The precipitate was still evident in the solution. The precipitate appeared as a reddish-brown solid, prompting speculation that the material contained mercuric oxide.

Table 2. Scrubber efficiency for capture of mercury.

Test Date	Additive Conc.	Mercury Species	Inlet Hg Conc. (μg/m^3)	Outlet Hg Conc. (μg/m^3)	Removal Efficiency
11/05/98	0.05%	elemental	316	239	24%
11/06/98	0.5%	elemental	184	37	80%
11/09/98	0.5%	elemental	141	4	97%
11/16/98	0.09%	elemental	20	10	48%
11/17/98	0.09%	elemental	119	57	52%
11/18/98	0.18%	elemental	137	19	86%
12/02/98	0.5%	HgCl$_2$	162	5	97%
12/03/98	0.5%	elemental	113	12	89%

In a separate series of tests, the purge gas from the regeneration of one of ADA's mercury-sorbents was sent to the scrubber column. The data trace from one test is shown in Figure 5. As long as the additive concentration was maintained in the column liquor, overall capture efficiency was over 98%. In an actual application, the offgas from the scrubber could be piped back to the sorbing bed, thereby eliminating any air emission from the regeneration process.
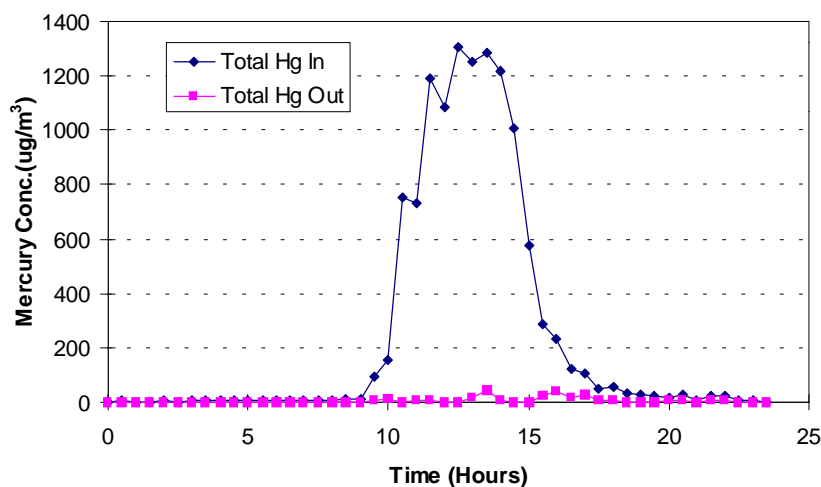
Figure 5. Mercury capture across scrubber during regeneration of one of ADA's sorbents.

The scrubber solution and solids were next contacted with calcium polysulfide solution to stabilize the trapped mercury as mercuric sulfide. Following the stabilization, the supernatant solution was filtered through a 0.45-micron filter and analyzed for total mercury. Analysis showed mercury levels of 0.019 to 0.00056 mg/L. The stabilized solids gave a leachate reading of 0.025 mg/L when subjected to the EPA Toxicity Characteristic Leaching Protocol (TCLP) – equivalent to the required passing level. ADA is confident that optimization of the stabilization procedure would allow the waste solids to consistently pass TCLP.

ADA carried out additional scrubber tests using calcium polysulfide solutions directly within the wet scrubber. However, the polysulfide solutions were prone to fouling and must be constantly monitored to maintain a high pH so as not to form toxic hydrogen sulfide gas. The oxidizing scrubber followed by polysulfide stabilization was determined to be a more suitable approach.

Testing at CONSOL Pilot Coal-Combustor

In late July 1998, ADA shipped the refurbished pilot skid to CONSOL (Library, PA) for installation on the flue gas stream from the R&D facility's 100-lb/hr coal combustor. As in Phase I, the equipment was set up to draw a 20-cfm slipstream from downstream of CONSOL's ESP. Although this location provides a largely ash-free flue gas, the unit incorporated an additional prefilter to eliminate any fly ash effect on the sorbent. About halfway through the test period at the pilot combustor, problems with the existing cartridge filter on the inlet to the skid led ADA to replace that unit with a small fabric filter containing two 5" diameter by 17"-long Ryton filter bags. The skid's control software was modified to accommodate the new baghouse and to provide automated back-pulsing of the filters. With the new baghouse in place, the skid logged 375 hours on flue gas. Cumulative time on flue gas came to 637 hours while at CONSOL.

During the testing at CONSOL, the cycling and operation of the skid was routine and none of the control problems witnessed during the Phase I testing were seen. The only serious problem encountered was due to ash plugging the inlet filter. Figure 6 depicts the temperatures of the two sorbent vessels throughout four days of sorbing and regeneration. The 8-hour regeneration cycle is clearly seen. The skid has been able to consistently reach and maintain regeneration temperatures.
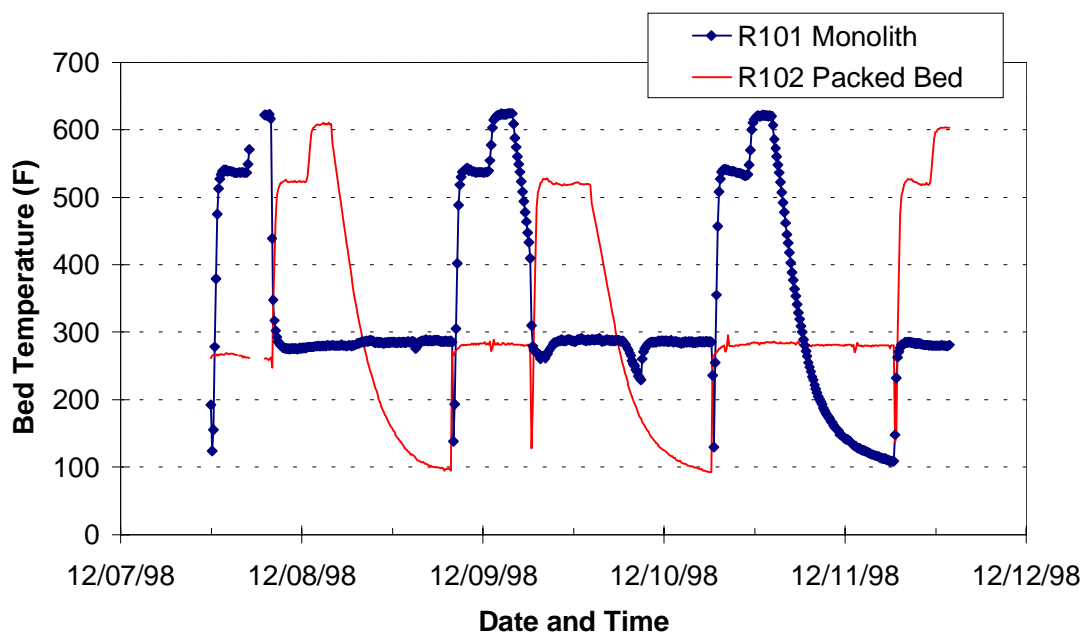
Figure 6. Sorbent bed temperatures as a function of cycle time.

Iodated-carbon traps (IC traps) were used as the primary sampling method for determining mercury removal efficiency. These traps collect all forms of mercury, and are subsequently quantified by digestion and analysis of the trap at Frontier Geosciences (Seattle, WA). Initially we sampled only the outlet flue-gas (downstream of the sorbent bed) with the hope that ADA's continuous mercury analyzer would be able to quantify inlet mercury levels. However, the mercury analyzer was unable to reliably measure the low-level inlet stream concentration and we subsequently switched to pulling both inlet and outlet samples using the IC traps. Because the skid switches between the two sorbent vessels every 24 hours, sampling was carried out on two consecutive days during the week. In this fashion we obtained inlet and outlet data for each sorbent vessel during the week. The data indicated removal efficiencies in excess of 90 percent for each configuration at the outset of the testing. However, these levels dropped to 60% to 70% as the testing continued (Figure 7).

During the four-month test period that the skid operated it logged approximately 637 hours on flue gas. (The pilot combustor runs 24 hours per day during the work-week but is often down for maintenance or modifications.) Several different fuel blends were burned during the period (Table 3). When the combustor was down the skid drew room air through the sorbent beds and continued its 24-hour cycling. Total run time exceeded our target value of 200 hours per sorbent bed.
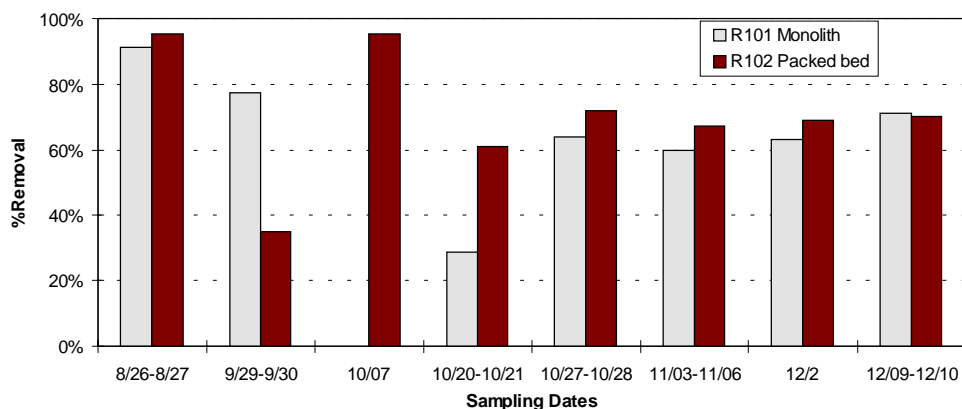
Figure 7. Observed mercury removal efficiency from 20-acfm Skid while at the CONSOL pilot combustor. Data obtained using IC traps.

Table 3. Coals burned during testing at CONSOL.

Dates	Coal Source(s)	Comments
Aug. 10-21	Low-sulfur plant coal	
Aug. 24-28	Blacksville 2	
Aug. 31 – Sept. 4	Rend Lake	
Sept. 8-11	McElroy products (2)	
Sept 14-18	none	maintenance period
Sept. 21-25	McElroy, full wash	
Sept. 28 – Oct. 2	McElroy	
Oct. 5-9	Low-sulfur plant coal	
Oct. 12-16	none	coal preparation period
Oct. 19-30	McElroy, full wash	
Nov. 2-6	McElroy	
Nov. 9-25	none	coal prep. and maintenance
Nov. 30 – Dec. 23	Rend Lake	

The data in Figure 7 suggested that the sorbent beds stabilized at removal levels around 65%. The baghouse became operational in early October. Prior to installation of the baghouse, the inlet filters would rapidly plug, requiring maintenance personnel to open the filter housing and manually clean the cartridges. On one occasion a filter blewout and allowed a full ash loading to reach the beds. It is unknown how the ash impacted sorbent performance, but sorbent fouling is one possible explanation for the drop in removal efficiency.

The inlet mercury concentrations reported from the IC trap data were significantly higher than anticipated, based on historical data for CONSOL's coal (Figure 8). This generated concern during the testing and ADA and CONSOL reviewed the sampling protocols and data calculations. However, no errors or sampling discrepancies were found. The analytical laboratory was also consulted, but they found no errors in their procedures. A plot of inlet mercury concentration

versus time indicated that the inlet values remained high throughout the testing, but did display a downward trend.

During the trial period the combustor burned several different feed stocks, including petroleum cokes. An initial hypothesis was that some contamination within the pilot combustor or 20-acfm skid was responsible for the high readings. Triplicate samples were pulled on the ESP ducting upstream of the mercury treatment skid on December 10th. These samples returned a value of 43 $\mu g/m^3$, suggesting that nothing on the mercury treatment skid itself (e.g., a contaminated sample port) was creating the high mercury readings. Also, the inlet sample port was replaced when the baghouse was added in September 1998 and the inlet readings remained quite high – further evidence that the inlet sample port was not a source of contamination.

The second possibility is that the IC traps are providing artificially high readings for mercury due to some interference, analysis error, or miscalculation. Given that the beds were showing significant removal of the mercury (with no sign of breakthrough) and that the ADA analyzer detected little or no mercury, we initially favored this explanation. Although the ADA analyzer was having difficulty detecting low levels of mercury in flue gas, calibration with 50 ug/m^3 to 200 ug/m^3 sources gave large, well-resolved peaks. This response should be sufficient to detect similar levels in the flue gas. At the time it was felt that the inlet/outlet IC traps were providing data that was in error in absolute terms but representative in relative terms.
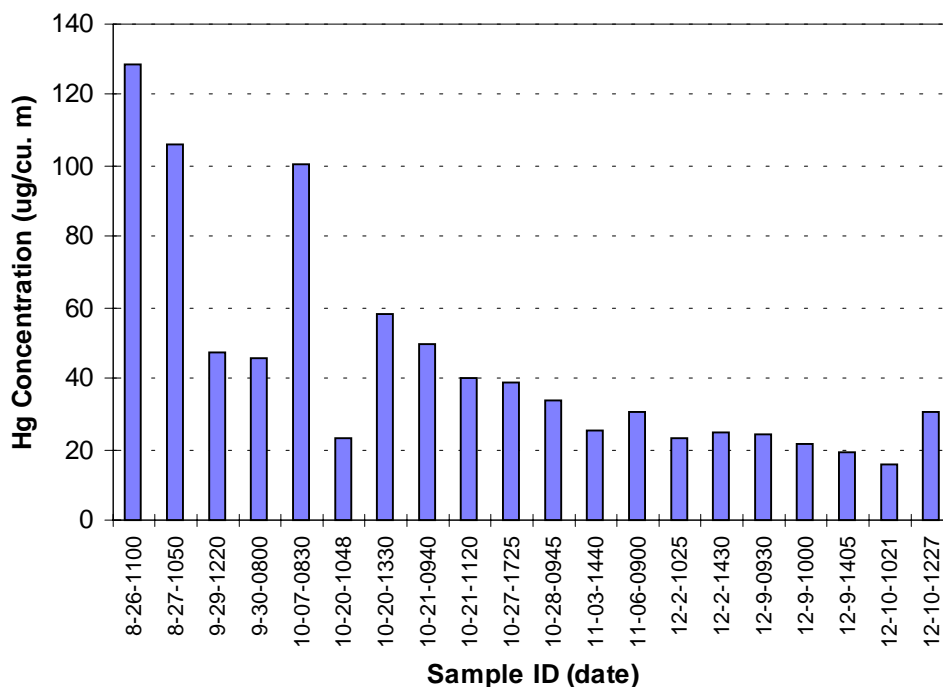
Figure 8. Mercury concentration at the inlet to the sorbent beds. Data obtained using IC traps.

In December CONSOL technicians pulled Ontario-Hydro (O-H) samples on the inlet and outlet gases in an attempt to resolve the puzzling IC trap data. During this sampling we simultaneously pulled IC traps. The O-H and IC trap data are reported in Figure 9. Whereas the IC trap results showed 70% removal, consistent with earlier tests, the O-H numbers indicated no mercury removal. In fact, the O-H numbers reported higher mercury on the outlet than in the inlet.
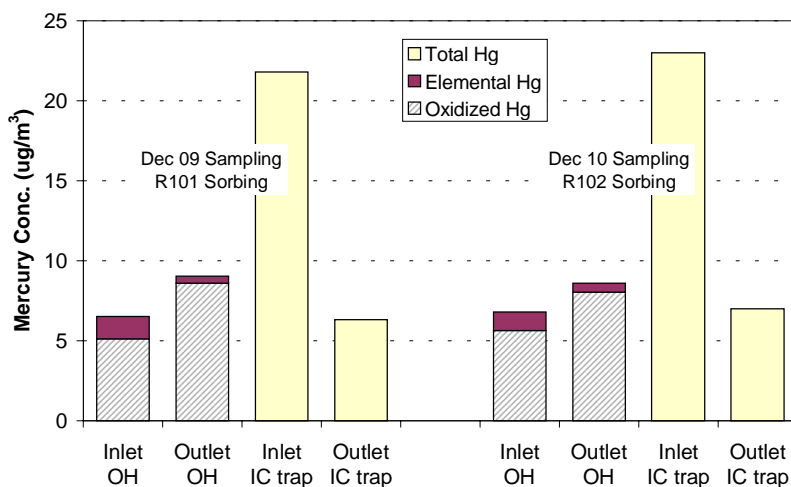
Figure 9. Comparison of simultaneous Ontario-Hydro (O-H) and IC Trap samples. In most cases, the average of triplicate samples are reported.

The O-H data indicate that the inlet IC traps are being selectively biased to high values. This negates the previously held belief that the IC traps were all biased high by some error in analysis or conversions. Frontier Geosciences is aware of no known interferents that would generate erroneously high results on IC traps. Moreover the interfering species would have to be removed by the sorbent beds to create the error in the inlet samples only. At the conclusion of the test period on the pilot combustor the overall performance of the sorbent was clouded in uncertainty due to the conflicting O-H and IC trap data. Diagnostic tests seemed to discount any obvious errors in either method. To ultimately resolve this issue it was decided to remove the sorbent from the skid and evaluate it using standard laboratory performance tests.

Analysis of Used Sorbents

The first indication of a change in the sorbent was the disappearance of the characteristic pale purple color. Whereas the fresh material is uniformly purplish, the used sorbent was white. The used materials had a coating of brown ash on the surface, but washing this layer off revealed a white sorbent underneath. Crushing the sorbent rings revealed them to be white throughout. Samples of fresh sorbent and the used rings (from R-102) were sent to local laboratories for analysis. We examined the sorbent for the accumulation of chlorine, nitrogen and sulfur species that might indicate sorbent poisoning or fouling. We also assayed for the amount of active noble metal on the sorbent. These findings are provided in Table 4.

Table 4. Results from analysis of fresh (F) and used (U) sorbent following testing at CONSOL.

Sample ID	Total Chloride (mg/kg)	Total Nitrate (mg/kg)	Total Sulfate (mg/kg)	Total Noble Metal (mg/kg)
F101/4	720	ND	98	480
F102/5	590	0.73	98	720
F103/6	590	8.30	200	740
Average	633±75	5±5	131±59	647±145
U101/4	24	ND	93,000	510
U102/5	18	ND	93,000	360
U103/6	29	ND	84,000	440
Average	24±6	ND	90,000±5200	437±75

Two items are apparent from the Table 4 findings – a large amount of sulfate was recovered from the used samples and there was a loss of approximately 1/3 of the noble metal. The large chloride reading on the fresh material is an artifact of the impregnation process. Assuming the sulfate originated as SO_2, the amount recovered equals a roughly 20% coverage of the sorbent surface area. It is unknown if the SO_2 covered the sorbent uniformly or was localized to the noble metal sites. Certainly this amount of SO_2 could completely cover the noble metal sites; however, it is more likely that the SO_2 would favor adsorption onto the alumina support.

The loss of noble metal was a more serious finding. While loss of metal would by itself lead to a drop in sorbent capacity, it also indicates that the metal achieved some mobility during the operation of the skid. Thus, it is possible that metal crystallite size was altered. This is consistent with the loss of purple color. The color loss suggests the crystallites are no longer of "colloidal" size. We first attempted to ascertain crystallite size of the fresh and used sorbent with X-ray Diffraction Spectroscopy (XRD). Because of the low percent-loading, the metal line in the XRD samples was difficult to distinguish from the background noise in both the fresh and used samples so these tests were inconclusive.

SEM Analysis

ADA carried out three sets of scanning electron microscopy (SEM) tests on the sorbent rings that were used during the CONSOL tests. Initial results from a contract SEM laboratory proved inconclusive – presumable due to the small size of the crystallites and relatively low initial loading of metal. These SEM photos showed little difference between the fresh and spent sorbent, although there was some indication of spalling. Spalling would be consistent with condensation within the sorbent pores, as it can result from the explosive evaporation of moisture from within the material. The main finding from the first SEM analysis was the relatively large amount of fly ash on the surface of the sorbent.

The samples were next sent to a more sensitive SEM instrument at the University of Denver. These tests were carried out with a low-vacuum SEM system, which allowed for greater resolution. The gold particles were easy to identify on the fracture surface of the exposed samples using a backscattered electron image. A backscattered electron image is obtained from the higher energy electrons that are scattered off atomic nuclei in the direction of the electron

beam. For larger nuclei (atoms of larger atomic number) the backscattered image is more intense. As a result, gold atoms show up as light objects on the darker alumina background. The disadvantage of using backscattered electron imaging is that the beam penetrates deeper into the sample and worsens the ultimate resolution of the image.

As in prior analyses, the fresh gold-impregnated alumina rings were compared to exposed rings. The fresh sorbent has a purple to pink color on the outside and on the inner surface of fractured and sanded rings. The exposed rings had a red speckled color on the exterior with a white interior on both the fractured or sanded surface. A fractured and sanded surface was examined in the SEM for gold particles on both ring types.

Figure 10 shows backscattered electron images of the exposed and fresh rings. The gold particles were relatively easy to find in the exposed rings. The light spheres in the lefthand image are fly ash particles. The bright "dots" in this image were examined at higher magnification and with energy dispersive spectrometry (EDS) to determine their elemental composition. The size of those particles determined to be gold was recorded. EDS was also used to examine the fracture surfaces of fresh and exposed ring materials. The main elements on a fresh ring are aluminum and oxygen with a smaller amount of carbon – typical of an alumina surface. For the exposed rings, additional elements of sulfur, silicon, magnesium, sodium and iron were detected. Quantitative analysis of the elements in these spectrums is not possible due to the irregularity of the fracture surfaces.

Particles of gold could not be found on the fractured surface of the fresh rings. However, after light sanding with 600-grit sandpaper, gold particles could be identified (Figure 10, right image). The larger, light particles in this image are iron particle contaminates from sandpaper. Some of the tiny light dots in this image were examined at high magnification and with EDS and were found to be gold particles.

As shown in Table 5, the SEM found crystallite growth from approximately 33 to 160 nm in diameter. The smallest particle examined was about 10 nm and this appears to be close to the smallest particle that can be resolved on the SEM. This average neglects undetectable particles with a size less than 10 nm, thus the true average size of the fresh crystallites is probably even smaller. Prior sorbents made by ADA have had average crystallite diameters of 20 nm. Assuming no loss of mass, the available surface area shrinks proportionally with the crystallite diameter. Thus a five-fold growth in diameter of noble-metal sites results in a corresponding five-fold decrease in surface area for mercury capture. Combining this decrease with a one-third loss of metal, suggests that the sorbent capacity could have dropped by roughly 93%.

Table 5. Data from the analysis of the sorbent used during testing at CONSOL. Metal crystallites grew during exposure to flue gas.

Sample	Number of readings	Crystallite Size (nm)
Fresh Sorbent	5	33 ±15
Used Sorbent	40	160 ±140

The conclusion from the more sensitive SEM study confirmed the speculation from earlier work, namely, (1) gold particles grew in size during exposure and (2) the rings adsorbed contamination, notably fly ash and SO_2, during exposure. Growth of the gold crystallites is suspected to be the cause of the fall-off in sorbent performance with exposure time.
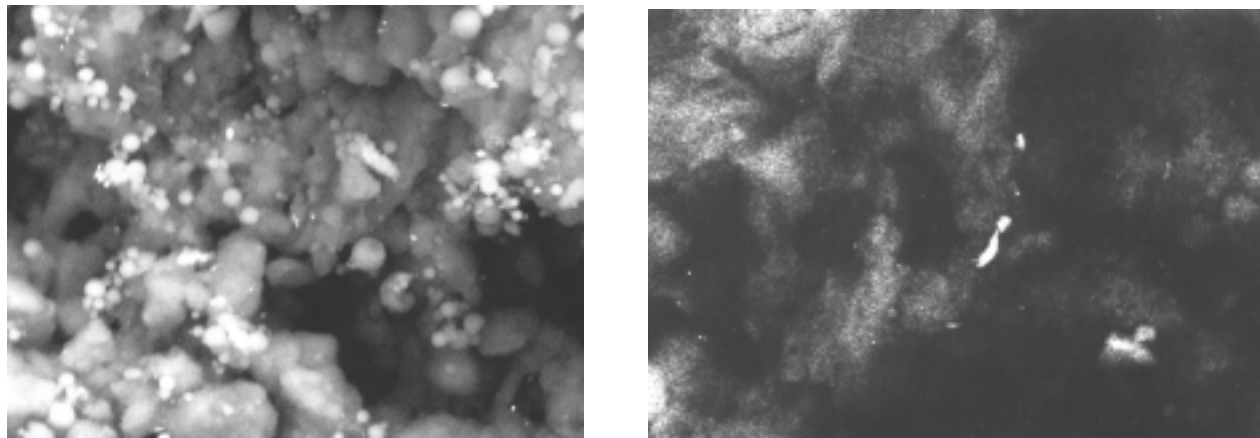
Figure 10. A backscattered electron image from the fracture surface of an exposed ring (left) and from the sanded surface of a fresh ring (right). The width of the left picture is approximately 57 μm, the right picture is approximately 26μm wide.

Standard Sorption Tests on Used Sorbent

Sorbent samples pulled from the test skid were also subjected to standard laboratory performance tests using known gas mixtures. Standard tests in ADA's sorbent test apparatus indicated that the used sorbent from the CONSOL testing had lost roughly 70% to 80% of the its capacity for mercury. Recall that data regarding the coalescence of crystallites and loss of metal suggested up to a 93% decrease in capacity. These laboratory sorption tests were run with elemental mercury in air at temperatures of 280°F. Data traces are shown in Figures 11 and 12. Superficial velocities during these lab tests were higher than that in the 20-acfm skid in order to accelerate the testing times.

The noble metal is known to be stable in flue gas at 300°F and in inert atmospheres at much higher temperatures. It is possible to remove the metal under aqueous acidic conditions. This led to the theory that acid attack on the metal may have generated volatile metal salts that were subsequently lost from the alumina surface. The chloride salt, in particular, has a measurable vapor pressure at temperatures over 180°C (355°F), well within our regeneration temperature. The key in this scenario is generating the acids necessary to dissolve the metal. To ascertain if this was possible, we re-examined the time/temperature profile of the skid. As operated, one bed was on line for 24 hours, then cycles off-line for an 8-hour regeneration, then waits to return online (see Figure 6). After the regeneration cycle, the bed cools to roughly 90°F. When this cool bed cycles back online it is rapidly warmed by the hot, moist flue gas. The bed takes about

30 to 60 minutes to reach flue gas temperature. The flue gas composition is ~5% water vapor, giving a dew point temperature of slightly over 100°F. Therefore it is possible that moisture condenses within the pores of the sorbent as the flue gas initially contacts the cool sorbent. Acid gases within the flue gas (HCl, NOx, and SO_2) could react with this water to form an acid mixture capable of attacking the noble metal. Although this attack would be brief (the moisture will quickly evaporate as the sorbent heats up), over the course of several months it may be sufficient to degrade the metal crystallites. This phenomenon could also cause the spalling seen in the SEM images.
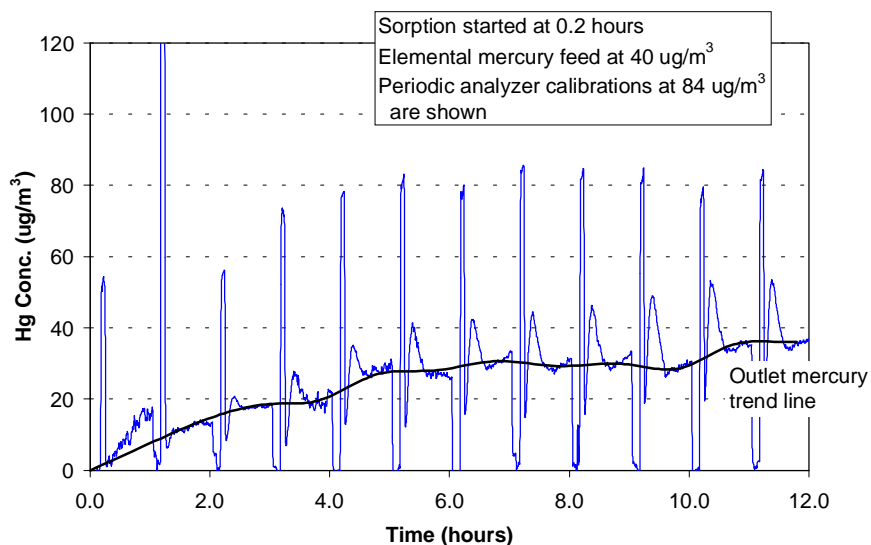
Figure 11. Sorbent capacity test of fresh sorbent. Complete breakthrough occurs at about 12 hours. Test number 021099.
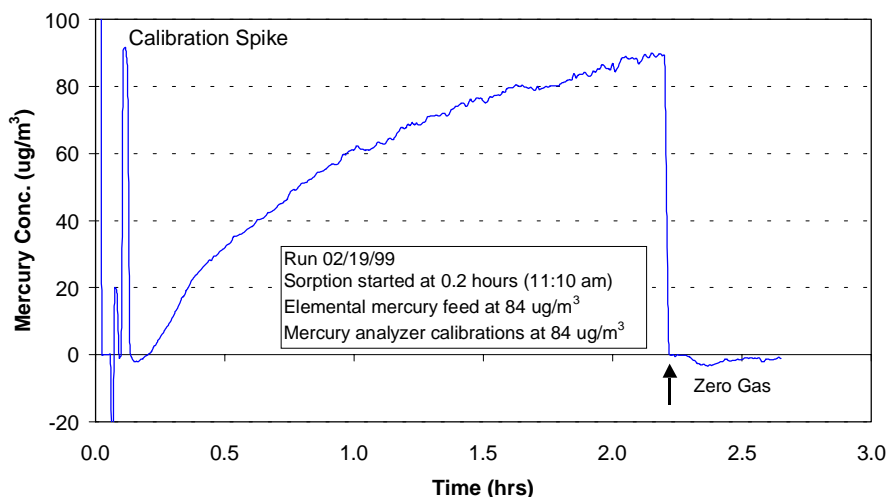
Figure 12. Sorbent capacity test of used sorbent. Complete breakthrough occurs at about 2 hours. Used sorbent air test #2, 021999.

Test Results of the Acid Gas Dew-Point Tests

A series of lab trials were developed to test the theory that the loss of gold was the result of dissolving the noble metal in a solution of nitric and hydrochloric acids derived from the flue gas. These acids form *aqua regia* – a mixture named for its ability to dissolve gold. For this to happen, the flue gas must pass through a dew-point temperature, although pore condensation may occur at higher temperature than bulk condensation. A condensed phase on the sorbent surface would provide a media for the dissolution of gold. Once the sorbent is heated to sorption temperatures, the dissolved gold could redeposit as a gold salt such as gold chloride. This salt could subsequently be vaporized during the high temperature sorbent regeneration step.

The purpose of these laboratory tests was to perform repeated sorption and desorption cycles on a sorbent sample in a manner similar to that seen by the sorbent at CONSOL. The sorbent was cooled to near room temperatures at the end of the desorption cycle. It was expected that when the flue gas contacts the cool sorbent, the gas would pass through a dew-point temperature. When this happened, acid gas components such as the nitrogen dioxide, hydrogen chloride and sulfur dioxide could dissolve in the condensed water phase and react with the gold on the sorbent. The simulated flue gas used for the tests is shown in Table 6.

During the tests, the sorbent was first cooled to 80°F and simulated flue gas flowed over the sorbent for two hours. After that time, the sorbent was heated to 280°F over a one hour period. The sorbent was then heated to desorption temperature of 700°F and held at that temperature for 3.5 hours. At that time the sorbent was cooled to room temperature and the cycle was repeated. Two tests were conducted each day until eight cycles were completed.

At the end of the eight cycles, the sorbent was removed from the test fixture and ground to a powder. Samples of fresh and exposed sorbents were sent to an outside laboratory (ECS, Englewood, CO) to determine the amount of gold in the samples. Results showed that the gold content of the fresh and exposed samples were 430 and 400 ppm, respectively. While this appears to be a slight decrease, the numbers were not statistically different within the level of error of the method. Although the ICP analysis for the sorbent samples was statistically the same, visually, the sorbent samples were different. The exposed sorbent had a fainter color than did the fresh sorbent. This color change agrees with the loss of color from the field-tested sorbent, suggesting that coalescence of the gold is underway.

Table 6. Gas composition used in laboratory cycling tests.

Component	Concentration by Volume
Sulfur Dioxide	1600 ppm
Hydrogen Chloride	50 ppm
Nitrogen Dioxide	20 ppm
Oxygen	3%
Carbon Dioxide	12%
Water	8%
Nitrogen	Balance (~77%)

Testing at Hudson Station Power Plant

Operational Changes

In March 1999, the pilot equipment was removed from the CONSOL R&D facility, mounted inside a portable office trailer, and relocated to Hudson Generating Station in Jersey City, NJ. Hudson Station's Unit 2 is a 650 MW, load-following unit that burns bituminous eastern coal. This unit is equipped with a four-field electrostatic precipitator manufactured by Research Cottrell. The coal burned at the Hudson Station is pulverized eastern bituminous coal, typically containing less than 1% sulfur and about 0.1% chlorine. Hudson Station hosts a transportable pulse-jet baghouse (TPJ) involved in prior flue-gas treatment research. The TPJ draws approximately 5000 cfm from the downstream side of the plant's ESP. ADA's pilot mercury treatment skid tapped into this duct to draw a 20-cfm slipstream into the equipment trailer for testing (Figure 13).

Figure 13. ADA equipment trailer at Hudson Station. TPJ is directly behind the trailer.

A key change in the test equipment was the installation of fresh sorbent monoliths and modification of the regeneration cycle times to prevent the sorbent bed from cooling below flue gas temperature. The fresh sorbent still followed ADA's BVI formulation, but was now deployed onto ceramic monoliths. This contrasts with the metal monoliths and ceramic rings used during the testing at CONSOL. The ceramic monoliths were 7.5-inch diameter by 7-inch long, 200-cell-per-square-inch cordierite, manufactured by Corning. Two of these monoliths were installed in series within vessel R-101. Each monolith contained 30-mg of gold as the active noble metal. Operation of the skid was modified to use only one vessel, R-101, for the sorption testing at Hudson. The sorbing cycle was maintained at 24 hours, and the regeneration cycle time was increased to 12 hours. This schedule prevented the regenerating bed from cooling to below 300°F – compare Figure 6 to Figure 14. Because regeneration time was less than sorption time, the use of one vessel allowed an individual sorbent sample to achieve more time on flue gas. Ceramic monoliths were selected for their greater resistance to corrosion and better ability to accept the impregnation liquor, compared to metal monoliths.
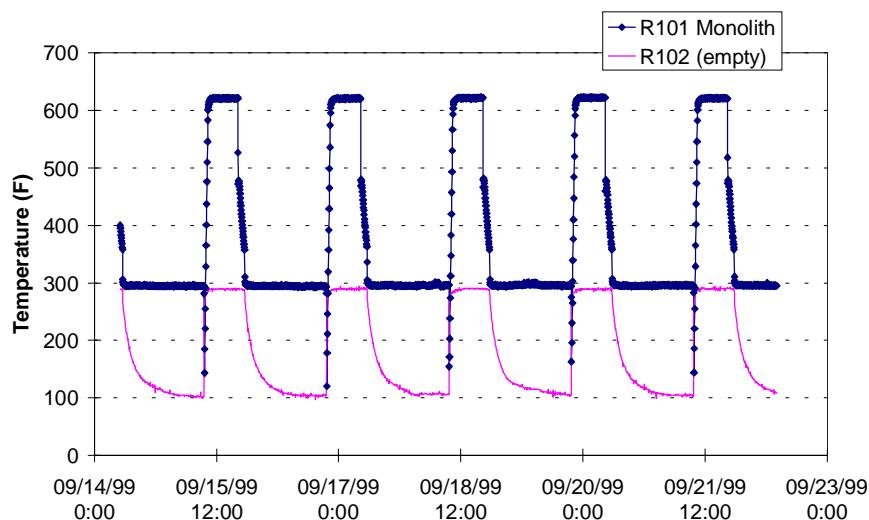
Figure 14. Temperature profile of sorbent monolith during sorbing and regeneration cycles.

Sorbent Performance

Routine operation of the test equipment at Hudson Station began in mid-May. During the first week of operation, ADA contracted with CONSOL to pull Ontario-Hydro samples of the inlet and outlet gas at the skid. ADA staff, with the assistance of Maplewood Testing, pulled IC traps at that time. Triplicate inlet/outlet samples were taken on May 19th. In addition to being downstream of Hudson's ESP, the ADA skid also contained the small baghouse described previously. This baghouse was designed to minimize the effects of ash for the initial test period at the power plant. Thus, there was virtually no ash present in the samples. The sample results are depicted in Figure 15. Whereas the Ontario-Hydro (OH) samples provide speciation information regarding whether the captured mercury is elemental or oxidized, the IC traps record only total mercury. The results mimic those seen during the December 1999 runs at CONSOL – the OH samples indicate no removal, while the IC traps show 83±5% removal across the sorbent. It is worth noting that the sorption cycle began at 3:36 am on May 19th, meaning that the sorbent was approximately 9.5 hours into its 24-hour sorption cycle at the time of the first sampling.

The OH samples indicated that 84% of the vapor-phase mercury in the Hudson flue gas was oxidized. This is typical of an eastern bituminous coal and consistent with previous data from the plant. Similar speciation was found during the December sampling at CONSOL, where another eastern coal was being used (Figure 9). Previous mercury levels recorded at Hudson were around 4 $\mu g/m^3$, consistent with the OH results listed above. Mercury levels of 15 to 20 $\mu g/m^3$, like those indicated by the IC trap data, are unlikely, suggesting that the inlet IC trap data were biased high.
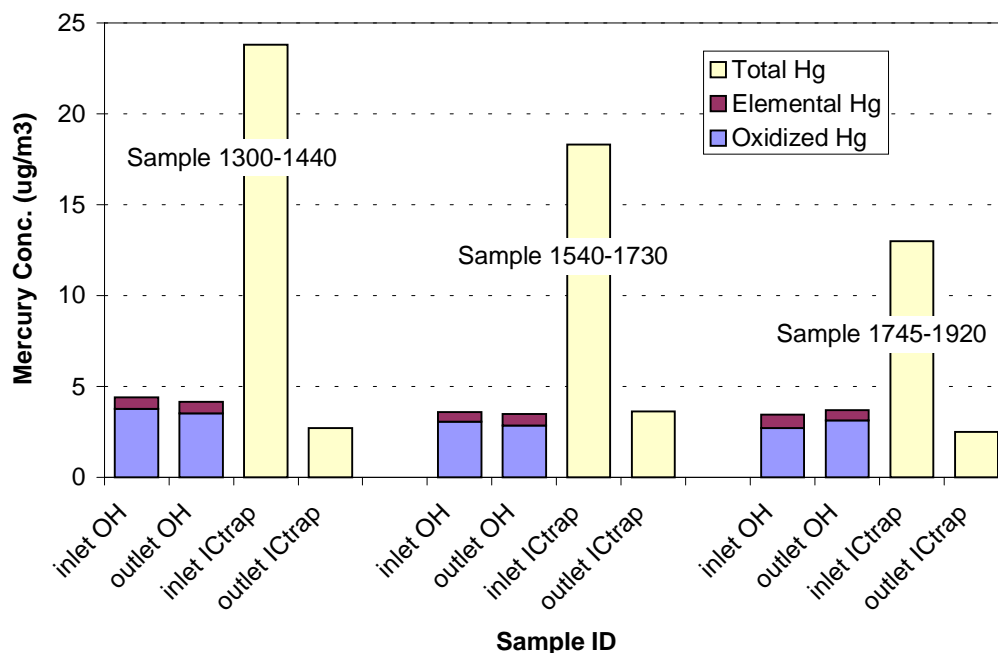
Figure 15. Comparison of Ontario-Hydro (OH) and Iodated-carbon (IC) trap data from 05/19/99 testing at Hudson Station.

On the basis of the OH results, the sorbent monoliths are removing none of the incoming mercury. These monoliths were installed fresh for the Hudson tests and thus had very little (less than 20 hours) time on flue gas at the time of these tests. Small versions of the monoliths were tested in ADA's laboratory prior to installation in the 20-cfm skid and those tests (with elemental mercury) indicated high removal efficiencies.

Subsequent to the May testing, it was suspected that the inlet sample port used for the IC Traps (SP-1A) was contaminated. It was also noted that there was a downward trend in the triplicate samples taken from that port, that is, the first sample of a triplicate series was always higher that the second and third. Perhaps the gas flow generated by pulling a sample desorbed a local accumulation of some mercury species, giving an artificially high concentration reading for the first sample.

On July 30th, ADA pulled IC traps from two different inlet ports to check if there was some contamination at the primary port. These tests showed that there was little difference between ports SP-1A and SP-2 and that port SP-1A actually had slightly better sample precision. However, the physical orientation of SP-1A prevents the IC trap from protruding into the flue-gas pipe. We elected to pull all subsequent inlet samples from port SP-2, where the IC trap can be inserted into the flowing gas stream. This is the same port used by the Ontario-Hydro sampling team. As shown in Figure 16, the IC Trap data reported virtually no mercury capture following the switch to port SP-2 on July 30th. Those later results are consistent with the O-H sampling numbers.
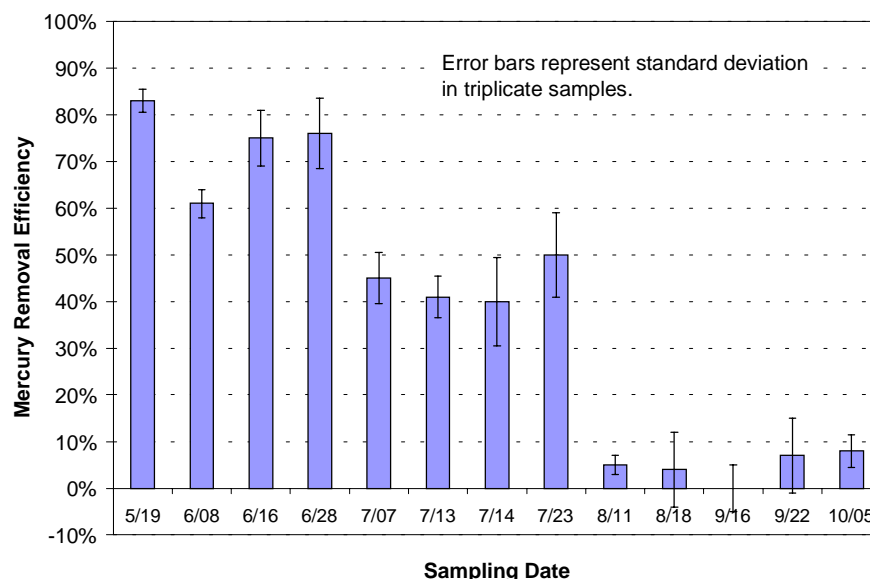
Figure 16. Summary of IC Trap data from pilot unit at Hudson Station. Inlet sample port was switched from SP-1A to SP-2 after 7/23 sampling.

The primary conclusion of the sampling at Hudson was that the sorbent was achieving very little mercury removal, even when freshly installed. This led to a series of laboratory tests to clarify the cause of the low removal efficiency.

Operation of the test equipment at Hudson Station was stopped on November 8, 1999 when the plant was taken off-line for maintenance. The sorbent operated for roughly 1900 hours of sorbing time between May 18 and November 8, 1999. Testing at Hudson did not resume until May 2000, following a series of laboratory tests to investigate the cause of the poor sorbent performance witnessed at CONSOL and Hudson.

Tests at Hudson Station using an Acid-Gas Scrubber

Throughout the winter of 2000, ADA undertook a number of laboratory tests to ascertain the cause of the poor performance of the sorbent. The detailed results of these tests are described in the section on *Results from Laboratory Work*. Ultimately, the cause of the lower than expected sorption capacity results from an interaction between the sorbent and certain acid gases in the flue gas.

To verify this interaction, ADA completed a final set of tests at Hudson Station during May and June 2000. For these tests the small baghouse at the entrance to the pilot skid was converted into an acid-gas scrubber. The bags were removed from the baghouse and a stainless steel support plate was installed inside the 11"-diameter vessel. Approximately 22 lbs of acid-gas sorbent in the form of sodium carbonate-coated alumina beads (1/8" diameter, 20% by weight sodium carbonate) were added to the vessel. The flue gas inlet was replumbed from the side of

the vessel to the conical bottom. The configuration of the equipment for these tests is shown in Figure 17. Enough acid-gas sorbent was made for six days of testing.

Prior laboratory tests had shown that the sodium carbonate would remove SO_2 and roughly 65% of mercuric chloride from a gas stream. Because the majority of the mercury in the Hudson flue gas is oxidized, we decided to add elemental mercury to the flue gas to obtain sufficient mercury in the gas stream to test the sorbent monoliths. A mercury permeation tube was installed to dose mercury into the gas piping upstream of the acid-gas scrubber (see Figure 17). The permeation tube was held within a temperature controlled chamber. A fixed flow of air carried the mercury vapors from the chamber into the 2" flue gas line. This dosing resulted in the total mercury concentration of approximately 15 to 25 $\mu g/m^3$ exiting the acid-gas scrubber.
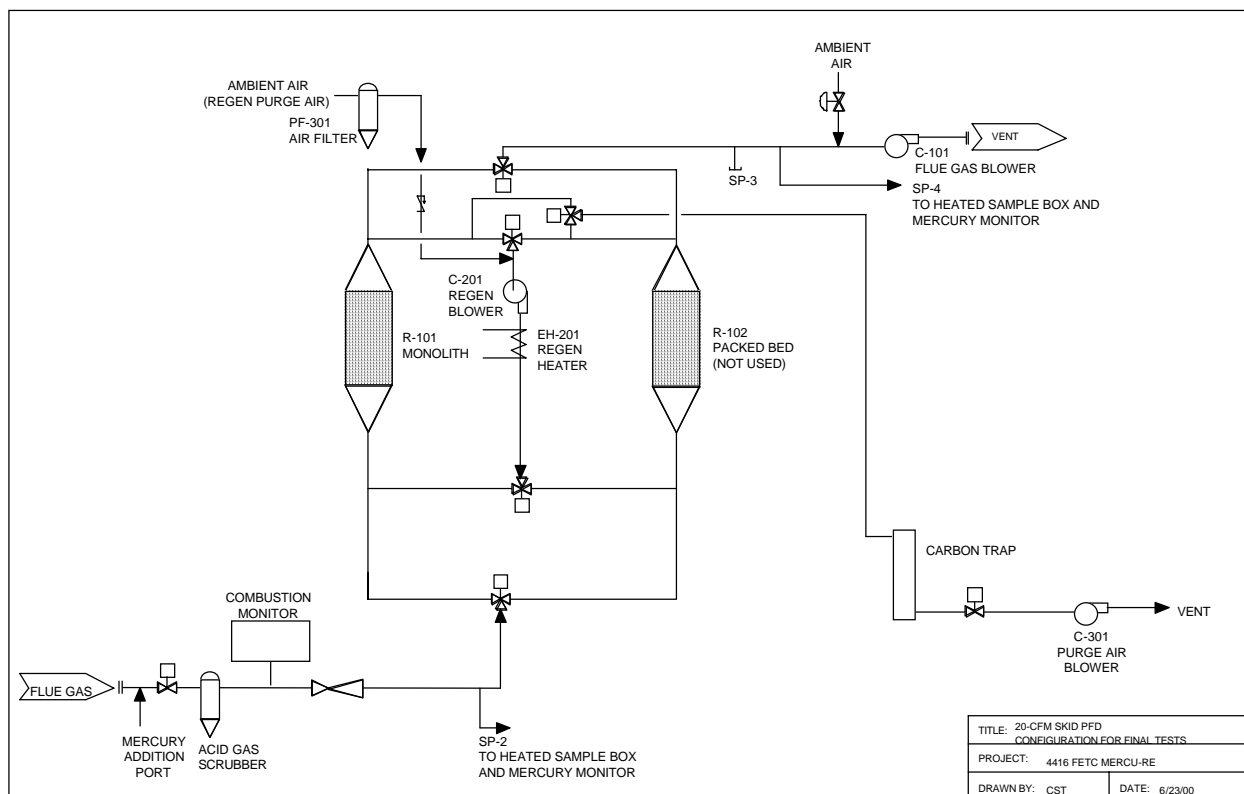
Figure 17. Process flow schematic for the pilot skid as used during the June, 2000 tests.

In May 2000, ADA carried out modification and repairs to the pilot skid to allow the restarting of testing. Repairs the equipment skid and trailer itself were necessary because an ash-hauling truck from the power plant accidentally hit the ADA equipment trailer in March, resulting in significant damage to the trailer and equipment. The final run began the last week in June. Figure 18 depicts the mercury concentration during the relevant days. This chart shows the total mercury readings from ADA's mercury monitor for the two-day span, covering two sorbing cycles. The unit completed regeneration cycles at 9 am on 06/28 and at 7 pm on 06/29. Some data were acquired during the regeneration cycle by connecting the analyzer to the purge gas stream. Large mercury spikes overwhelmed the detector.

The solid horizontal bars on Figure 18 denote time periods when the analyzer was sampling the inlet gas to the monoliths (Port SP-2 on Figure 17). At other times the analyzer was either monitoring the outlet gas from the monoliths (from port SP-4) or a mercury-free zero gas. The sawtooth trace in the figure denotes the zero gas valve position. When "up," zero gas is being supplied to the analyzer. There appears to be about 2-$\mu g/m^3$ difference between the zero and outlet samples during the first three hours of the run started on 06/28. That difference increased to 3-5 $\mu g/m^3$ toward the end of the 24-hour sorbing cycle. The hump in the signal during the night of 6/28 is due to thermal drift in the analyzer electronics. Assuming an average feed concentration of 20 $\mu g/m^3$, overall capture efficiency for the 24-hour cycle was 81%. Data from 6/29 through 6/30 also show little difference between zero gas and outlet concentration. The erratic data on 6/30 is probably due to the rising SO_2 concentration – either causing the onset of breakthrough or creating a deviation in the analyzer signal. The analyzer was calibrated for the low SO_2 level and was not recalibrated during the run. The rising SO_2 level is indicative of the scrubbing bed reaching saturation.
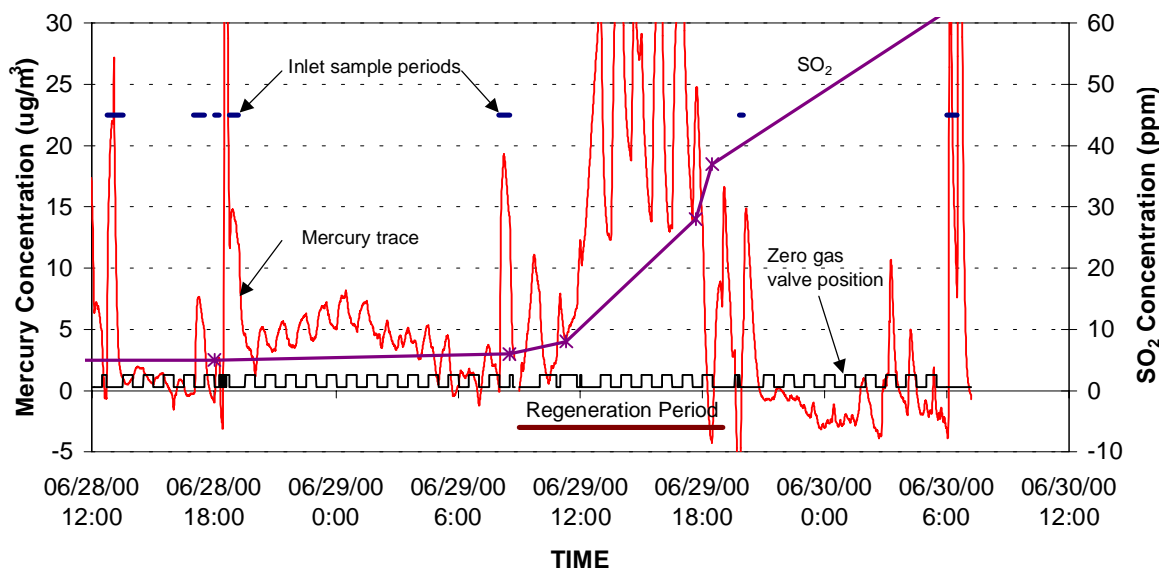
Figure 18. Mercury trace from final testing at Hudson Station.

The data from these runs confirm that the regenerable sorbent can remove mercury from flue gas when acid-gas scrubbing is provided. The mercury analyzer exhibits some scatter, however, the real time readings are invaluable for field testing of emerging mercury control technologies.

Corrosion Coupons

During the latter part of the test time at Hudson Station, a series of gold coupons was placed in the flue gas stream to investigate possible attack on the gold by the gas. The coupon rack was placed in the Hudson ductwork, downstream of the ESP. Temperature at the point of installation was 270°F.

Samples exposed for two weeks and four weeks were subsequently analyzed by SEM. Optical analysis of the samples revealed a large number of small spheres from the fly ash on the surface. The samples were further examined using backscattered electron imaging (BEI) and secondary electron imaging (SEI). The merits of backscattered electrons was described previously under section *SEM Analysis*. SEI uses low energy electrons that are ejected from near the surface of the sample by the electron beam. For each electron in the beam, many secondary electrons can be ejected. As a result, secondary electron images have better signal to noise ratios and they can resolve smaller surface detail.

Particles on the gold foil were easy to detect by BEI. Figure 19 shows BEI of the coupons exposed for 2 weeks and 4 weeks. The lighter regions on both images are areas where the gold is not covered by the particles on the surface. The sample exposed for four weeks has particles blocking most of its surface area.

Figure 20 shows a clearer, SEI image of the two-week sample. The actual surface of the gold foil was obscured by particles on the surface. Initially, a blast of air was used to try to remove the particles. The air blast was not sufficient to remove particles. Next, the samples were soaked in distilled water and placed into an ultrasonic cleaner. This removed almost all of the particles. Low magnification images of the cleaned surfaces are shown in Figure 21 for the two-week and four-week samples. The residue shown on the surface of the images in Figure 21 contains high concentration of Fe, Cr, Ni and O. Most likely the residue was a result of the oxidation of the stainless steel holder and subsequent deposition on the gold foil.

The electron beam was first concentrated on a large area and a spectrum was obtained from the energy dispersive spectrometer (EDS) to determine the major elemental components. Overall energy spectrums are shown in Figure 21. The spectrum from the sample exposed for four weeks has a higher concentration of S, Si, Al, O and several other trace metals and smaller amounts of exposed Au – indicative of a blanket of ash covering the surface.

The top portion of the stainless steel holder was examined in the SEM for comparison with the gold foil. Before examination the stainless steel holder was cleaned with distilled water and placed into an ultrasonic cleaner. Optically, the surface appeared darker compared to unexposed stainless steel with small dark surface pits. In the SEM, no residues were observed, and the X-ray spectrum showed Fe, Cr, and Ni, with smaller amounts of O and S.

Overall conclusions for the corrosion coupons were:

- Even at short exposure times, the gold surface was extensively covered by fly ash cenospheres and other substances. Longer exposure time led to greater coverage.

- Some oxidation products of the stainless steel were deposited on the gold foil.

- The gold surface appears to be pitted after four weeks of exposure.
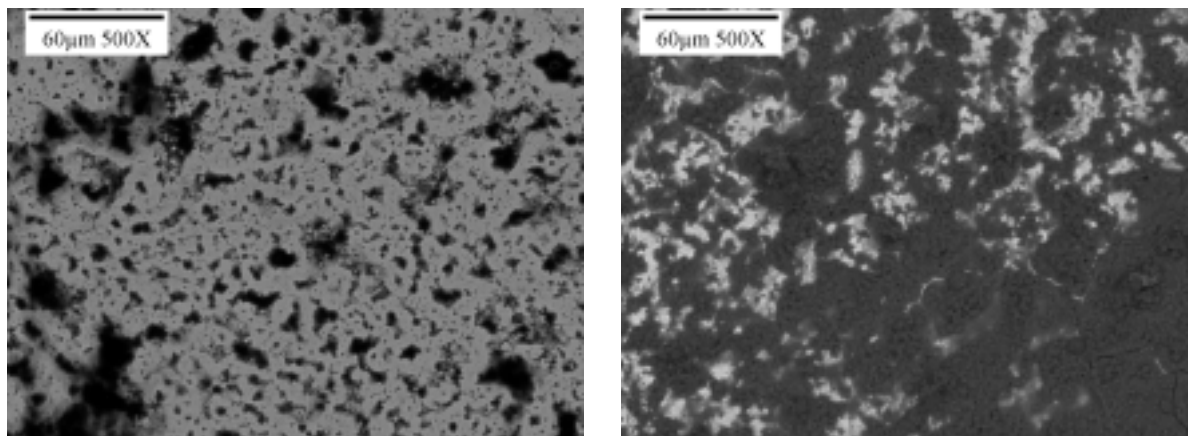
Figure 19. A BEI of gold foil sample exposed to power plant exhaust for 2 weeks (left and four weeks (right).
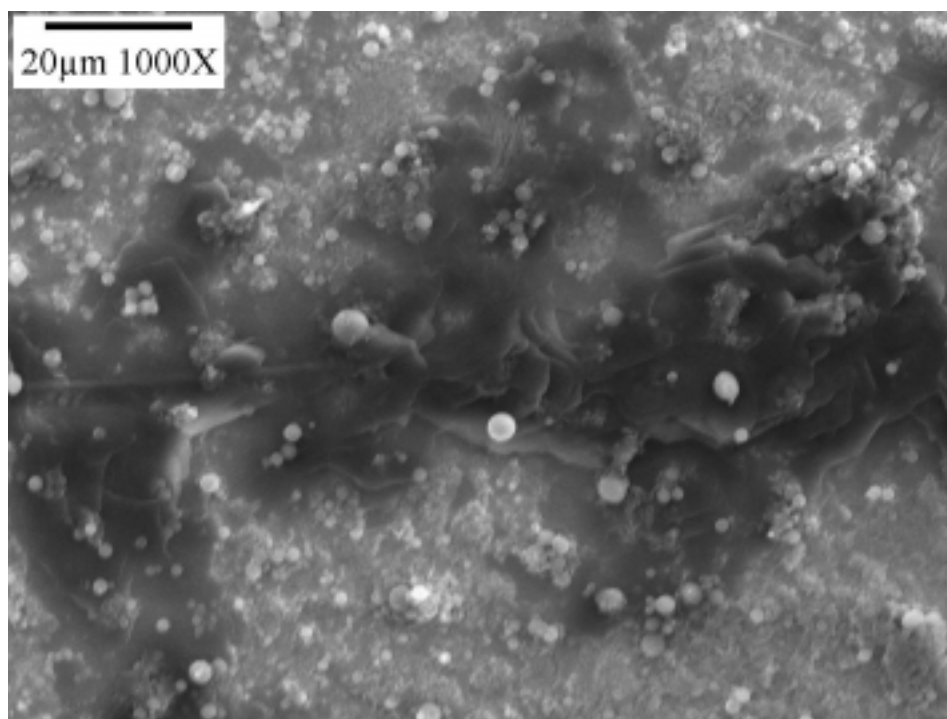
Figure 20. A SEI of dark residue and fly ash observed on sample with a 2 week exposure before cleaning.
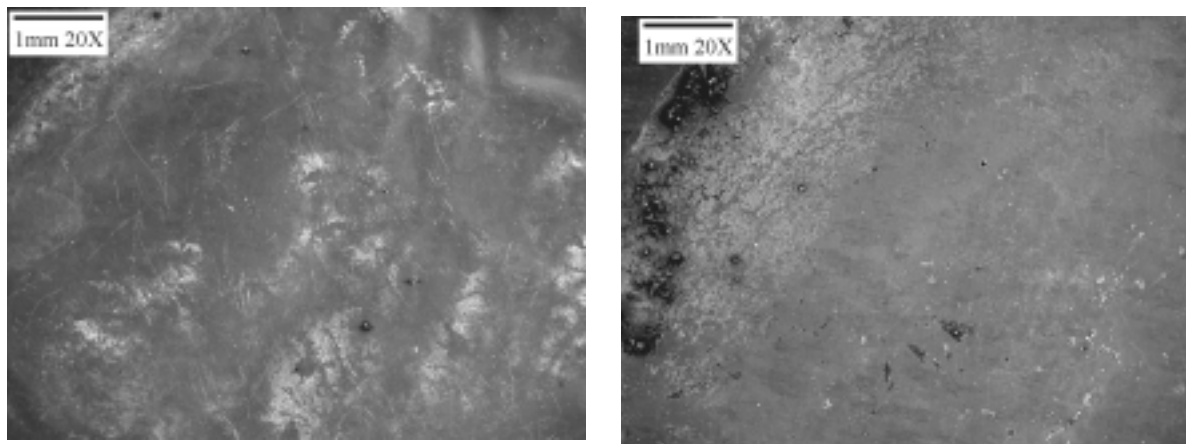
Figure 21. A SEI of a cleaned gold foil sample exposed to power plant exhaust for 2 weeks (left) and for 4 weeks (right).
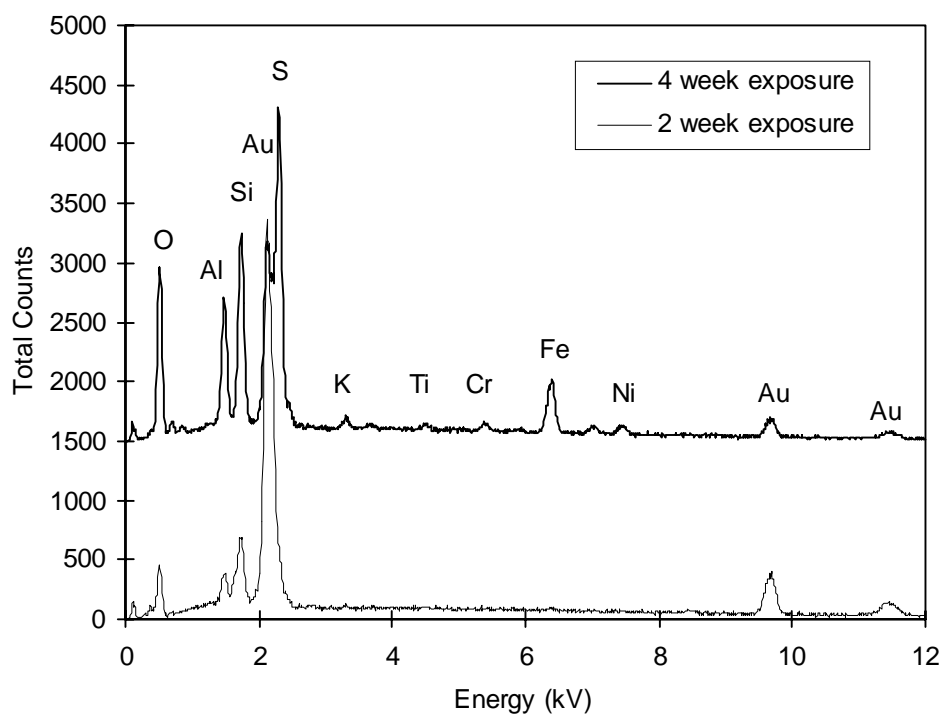
Figure 22. Energy spectrum from a wide region of the surface.

Results from Laboratory Work

Mercuric Chloride vs. Mercury Sorption

The relatively low removal efficiency of the field unit prompted an investigation regarding why the sorbent was performing below expectations. The initial focus was on the speciation of the mercury. The bulk of the prior laboratory sizing tests were carried out with elemental mercury. Historically the mercury speciation at Hudson has been 80% oxidized mercury, a level that was confirmed by the May 1999 Ontario-Hydro sampling. Although Phase I lab testing had shown uptake of $HgCl_2$, this compound is notoriously difficult to work with and the results may have been misleading. ADA undertook a series of experiments to confirm the capture efficiency of $HgCl_2$ with the same sorbent formulation being used at Hudson.

The sorbent at Hudson involves gold coated onto a 200 cell-per-square-inch ceramic (Corning Cordierite) monolith. The Cordierite monolith is initially wash-coated with alumina to provide a high-surface area for the noble metal. 7.5-inch diameter monoliths are used in the pilot unit and 1-inch diameter by 4-inch long versions of these monoliths were used in the lab tests. The mercury species were transported to the test chamber using nitrogen as the carrier gas at a flow rate of 2.5 L/min. Concentrations of elemental mercury and mercuric chloride in the sorption test gases were 39 $\mu g/Nm^3$ and 156 $\mu g/Nm^3$ (115 $\mu g/Nm^3$ as mercury), respectively.

The first series of tests used a washcoated monolith that had no impregnated metal. These tests established a baseline sorption capacity for the bare monolith (see Figure 23). Tests were conducted at sorbent temperatures of 320°F and 360°F with nitrogen as the carrier gas. Neither elemental mercury nor mercuric chloride were sorbed at 360°F. Elemental mercury passed through the test chamber unchanged at 320°F. Mercuric chloride exhibited some removal at 320°F; after five minutes, the outlet $HgCl_2$ level concentration rose to 50% of the inlet value, and reached 90% in 130 minutes. In several of the tests the response of the ADA continuous mercury analyzer was checked by the use of a Jerome Scientific mercury analyzer. The Jerome instrument is designed as an ambient monitor for elemental mercury. ADA researchers were able to get readings from the Jerome by placing it downstream of the ADA instrument (which cracks $HgCl_2$ to Hg^0). The Jerome cannot be used in simulated flue gas mixtures. ADA also cross-checked some tests with the revamped field CEM.

Loading of gas-phase elemental mercury and mercuric chloride onto the noble metal impregnated monolith was determined at three different temperatures: 300°F, 320°F, and 360°F. Results of the sorption tests using the impregnated monolith are shown on Figure 24. Loadings were based on the time required for the mercury concentration at the test chamber outlet to reach a selected value of 10 $\mu g/m^3$.

Overall the sorbent had a much greater affinity for mercuric chloride. Loading for mercuric chloride and elemental mercury were comparable at 360°F, but differed significantly as temperature decreased (Figure 25). At 300°F, the loading for mercuric chloride was nearly 30 weight percent (weight $HgCl_2$/weight noble metal), roughly 3 times the loading of elemental mercury. In the temperature range studied, the loading for elemental mercury was less than 10 weight percent (weight Hg/ weight noble metal).
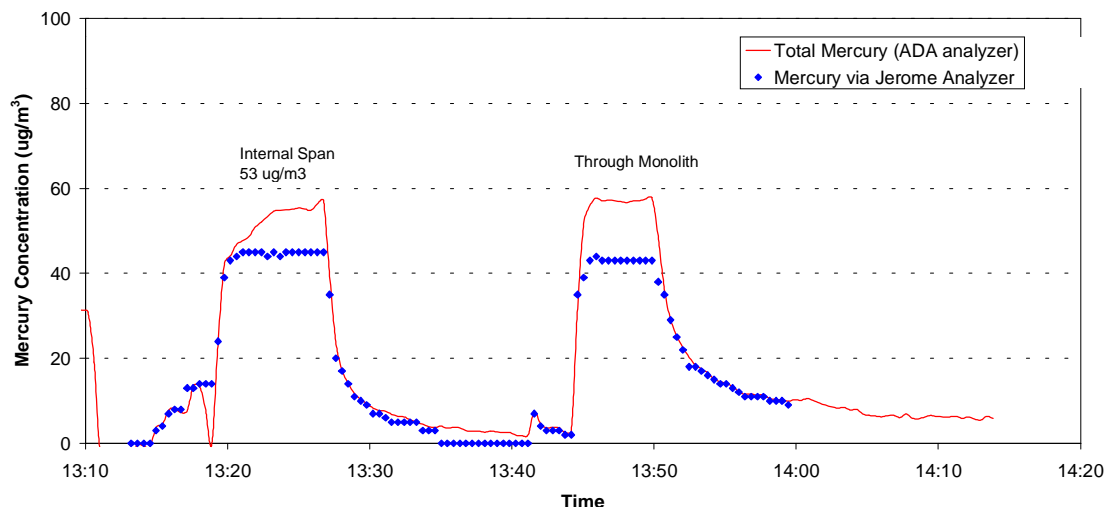
Figure 23. HgCl₂ uptake test over a bare monolith at 360°F. First peak shows feed gas concentration, second is outlet from monolith.
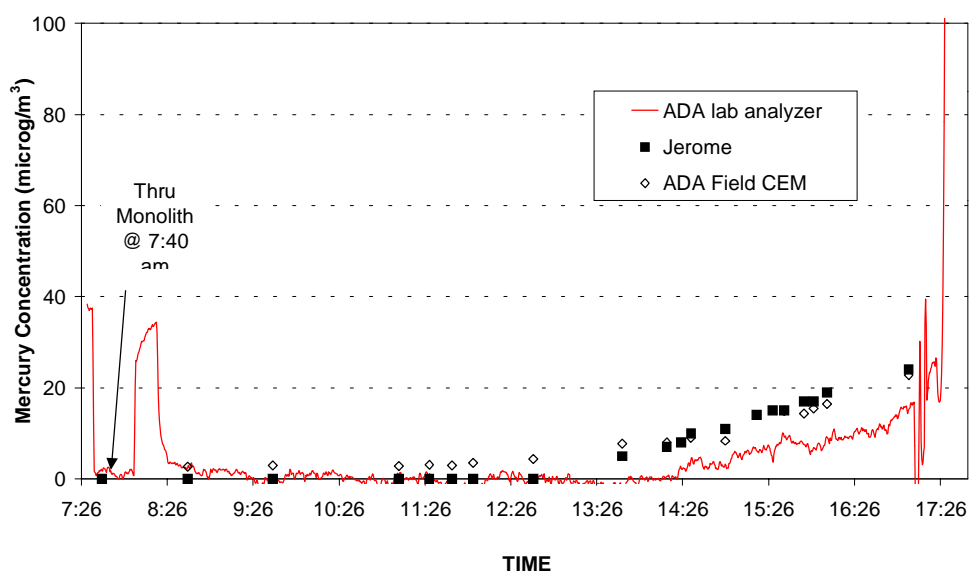
Figure 24. Breakthrough curve for HgCl₂ over a gold-impregnated monolith at 300°F. Trace shows readings from three different mercury analyzers.

Elemental mercury is captured by noble metals through amalgamation. The maximum amount of mercury that can dissolve into the noble metal is defined by the solubility limit at a given temperature. Day and Mathewson (1938) presented solubility data as a function of temperature through phase diagrams. The maximum solubility of mercury in the noble metal at ordinary temperatures has been reported as 15 weight percent. This solubility is a very weak

function of temperature until desorption temperatures are exceeded (>400°F). A 15% loading is consistent with data presented here and earlier work by ADA.

The sorbent's high affinity for mercuric chloride was quite unexpected. Gold is not believed to form an amalgam with mercuric chloride; however, prior ADA research and that of others (Aeschliman and Norton, 1999) has shown that it can capture $HgCl_2$. The sorption mechanism for mercuric chloride is thought to be solely by adsorption onto noble metal crystallites. (Recall that the bare monolith had little capacity for $HgCl_2$.) However, far more mercuric chloride is sorbed onto the sorbent than can be accounted for by a monolayer surface interaction with gold. It may be that sorption of mercuric chloride occurs predominately by physical sorption in which multiple layers of mercuric chloride are formed around the noble metal crystallites. In this case, the noble metal provides nucleation sites for mercuric chloride deposition.
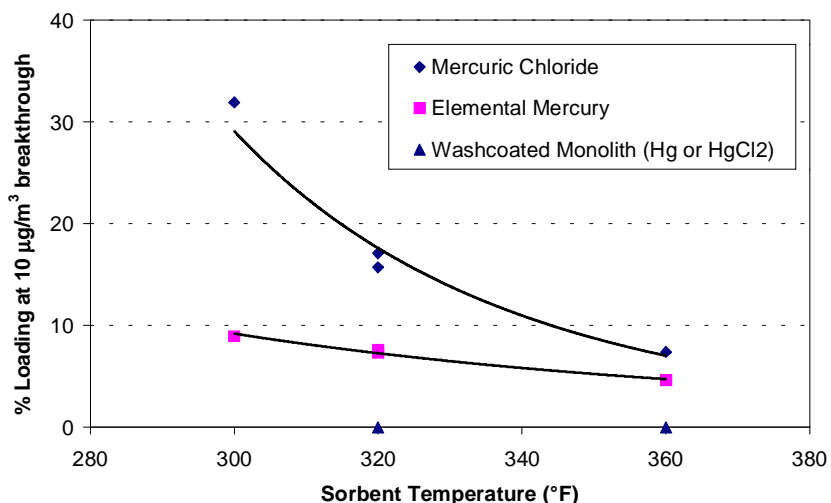
Figure 25. Loading of mercury species on metal-impregnated monolith.

For physical adsorption, loading will generally increase with increasing gas-phase concentration. Thus, it may be that the higher $HgCl_2$ concentrations used in these tests (156 $\mu g/m^3$) are responsible for the greater mass loading of $HgCl_2$ relative to elemental mercury. The amalgamation process is more akin to a chemical adsorption, and, as such, its maximum loading is relatively independent of gas-phase concentration. Additional sorption tests at different elemental mercury and mercuric chloride concentrations are needed to determine the relationship between sorption capacity, mercury species concentration and breakthrough time.

Mercuric Chloride Uptake in Simulated Flue Gas

The next series of tests studied the uptake of mercuric chloride by noble metal sorbents in the presence of acid gases. Tests were conducted in a simulated flue gas having sulfur dioxide, hydrogen chloride, and nitrogen dioxide components as shown in Table 7. In these tests, an abbreviated factorial test matrix was carried out to study what the effect various acid gas components have on the sorption capacity of the noble metal sorbent.

Table 7. Simulated flue gas composition.

Flue Gas Composition	
Sulfur Dioxide	1500 ppm
Hydrogen Chloride	40 ppm
Nitrogen Dioxide	200 ppm
Water Vapor	5%
Carbon Dioxide	12%
Oxygen	~1%*
Nitrogen	balance
Mercuric Chloride	156 $\mu g/Nm^3$
Process Conditions	
Pressure	620 mm Hg (absolute)
Temperature	300°F
Gas Flow Rate	2.5 liters/min

* oxygen level fluctuates slightly based on performance of air separator.

The initial tests were run using a monolith with the same noble metal loading as in the prior tests (0.6-mg gold). However mercury breakthrough was detected almost immediately when a full complement flue gas was used. To prolong the onset of breakthrough, a new monolith was prepared that had roughly four times as much gold (2.4 mg).

Sorbent breakthrough tests were conducted with different combinations of acid gas components. All tests had the same baseline gases of oxygen, nitrogen, carbon dioxide and water. Tests were allowed to continue until total breakthrough was detected. At that time, the monolith was regenerated at 700°F for 4 hours. Results of the flue gas sorption tests are given in Table 8. Mercuric chloride loading at total breakthrough was calculated to determine the utilization of the noble metal.

In Table 8, longer breakthrough times correspond to better sorbent capacity. The results indicate that the presence of acid gas components dramatically reduce the sorption capability of the sorbent. The presence of SO_2 alone had only a minor impact on sorbent capacity. Addition of either HCl or NO_2 along with SO_2 led to a marked reduction in sorbent capacity. Finally, the presence of all three gases dropped the capacity by a factor of 35 from that found with only the baseline gases. The loading measured in the control test was lower than the loading reported in the previous section (31 weight percent), possibly due to residual affects from the acid gas tests.

Table 8. Test matrix and results for experiments with $HgCl_2$ in simulated flue gas at 300°F. Baseline gases of CO_2, H_2O, O_2, N_2 present in all cases.

Test No.	HCl in Gas	NO_2 in Gas	SO_2 in Gas	Onset of Break-through (min)	Total Break-through (min)	Total Break-through Loading
Control	No	No	No	889	1171	19.0%
1	No	No	Yes	302	840	13.7%
2	No	Yes	Yes	24	57	0.93%
3	Yes	No	Yes	24	54	0.88%
4a	Yes	Yes	Yes	9	35	0.54%
4b	Yes	Yes	Yes	14	36	0.57%

These results mimic very closely those found by Miller and coworkers (1998) at the University of North Dakota's Energy & Environmental Research Center (EERC). The EERC workers fed elemental mercury through carbon samples and systematically changed the gas composition. They noted a limited impact by SO_2, but a dramatic drop in capacity when HCl or NO_2 were present with SO_2. HCl or NO_2 alone actually improved capacity in the EERC tests, presumably by oxidizing the elemental mercury to a more readily adsorbed form. The tests shown in Table 8 had a $HgCl_2$ feed, so no conversion would be expected. The similarity with the EERC results is striking because the sorbents are very different in form – carbon versus gold on alumina. This implies that the uptake of $HgCl_2$ on gold is a physical adsorption (as is uptake on carbon) and that it is affected in the same fashion by the chemistry occurring in the presence of the flue gas components. This further suggests that, *when dealing with oxidized mercury in flue gas*, noble-metal sorbents may have the same limitations as carbon adsorbents. Further examination of elemental mercury feed streams are required to determine if the same phenomenon occurs in those cases (as it does with carbon).

Mercuric Chloride Uptake in Scrubbed Flue Gas

As seen above, the removal of mercury compounds in an acid gas environment using noble metals is a difficult task due to the interactions of acid gases with the sorbent. With this in mind, tests were designed to pre-treat the flue gas to remove acid gas components prior to the mercury removal step. These tests simulate what might be expected in a plant using acid gas control, such as flue gas desulfurization. The testing apparatus was modified to include a guard bed upstream of the monolith chamber to remove the acid gases from the flue gas mixture. The guard bed contained 100 g of 1/8"-diameter alumina beads impregnated with 20 weight percent sodium carbonate. Sodium carbonate was selected because it is used in several analytical procedures for adsorption of acid gas species.

Initial tests investigated whether the guard bed affected elemental mercury and mercuric chloride concentrations. Data showed that elemental mercury passed through the guard bed unchanged. However, with mercuric chloride the inlet concentration was reduced by 65% by the guard bed alone, indicating that a reaction was occurring between mercuric chloride and sodium carbonate. It is suspected that mercuric chloride is converted to mercuric carbonate and retained on the guard bed support (Figure 26). After several hours of testing, the guard bed was heated to

700°F to remove any mercury compounds. An equivalence of 50 µg of elemental mercury (measured as total mercury) was desorbed from the guard bed.
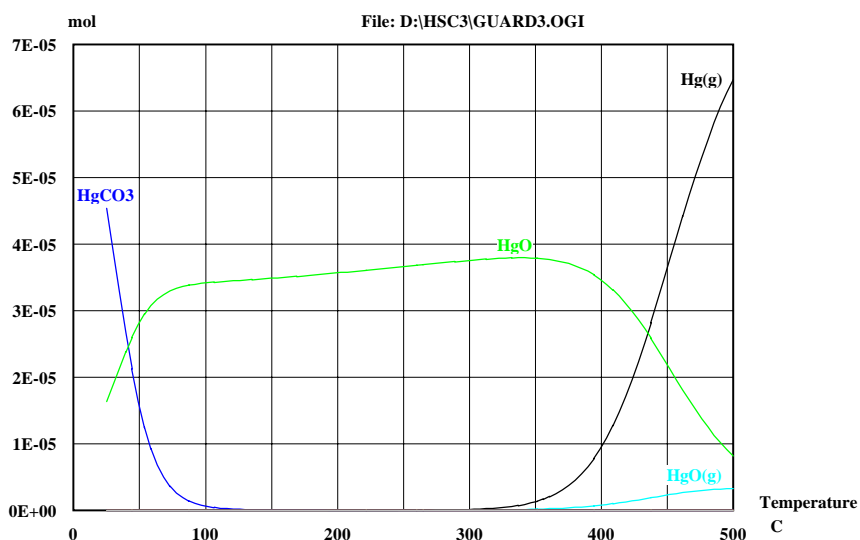
Figure 26. Expected equilibrium of HgCl$_2$ in contact with sodium carbonate in simulated flue gas. HgCO$_3$ and HgO are appreciably less volatile than HgCl$_2$ or Hg^0.

A long-term test was next performed with the guard bed and monolith in series. Flue gas composition and process conditions were the same as those given in Table 7. A fresh batch of sodium carbonate impregnated beads was used for the test. The test was allowed to run until 20 µg/Nm^3 breakthrough. Onset of breakthrough occurred after 1,450 minutes. This breakthrough time exceeds even that seen in the absence of acid gases (Table 8), probably because the guard bed itself removes some of the mercury. The combined guard bed and treated monolith removed 560 µg of mercuric chloride from the flue gas mixture during the test. We were not able to determine the quantity of SO$_2$, NO$_2$, and HCl removed by the guard bed, since the appropriate monitors were not available. The combined use of an acid gas scrubbing material and mercury sorbent is not novel, as co-injection of carbon and lime has been shown to remove mercury better than carbon alone (Butz & Chang, 1999). The implication for multipollutant control is encouraging because acid gases and mercury can be removed simultaneously.

Mercury Uptake by Thin Gold Films

Gold crystallite size appeared to have a pronounced effect on the capacity of the sorbent. It was not clear if this effect was due to reduced surface area or the diffusion time required for mercury to penetrate the larger crystallites. An experiment was run with gold films of equal surface area but differing depth to evaluate the impact of penetration depth. Gold was sputter-coated onto a set of 1" x 3" glass microscope slides to a thickness of 2.5 nm and 25 nm. These slides were then exposed to mercury vapor in nitrogen at ~280°F (138°C). The flow cell held two slides facing each other with a 2.5-mm slit for gas flow. Total gas flow was 1 L/min, generating a

slit-flow Reynolds number of approximately 65. The cell contained a 25-mm entry zone to allow development of the flow profile over the slides. Figure 27 compares the uptake over the 2.5 nm and 25 nm films.
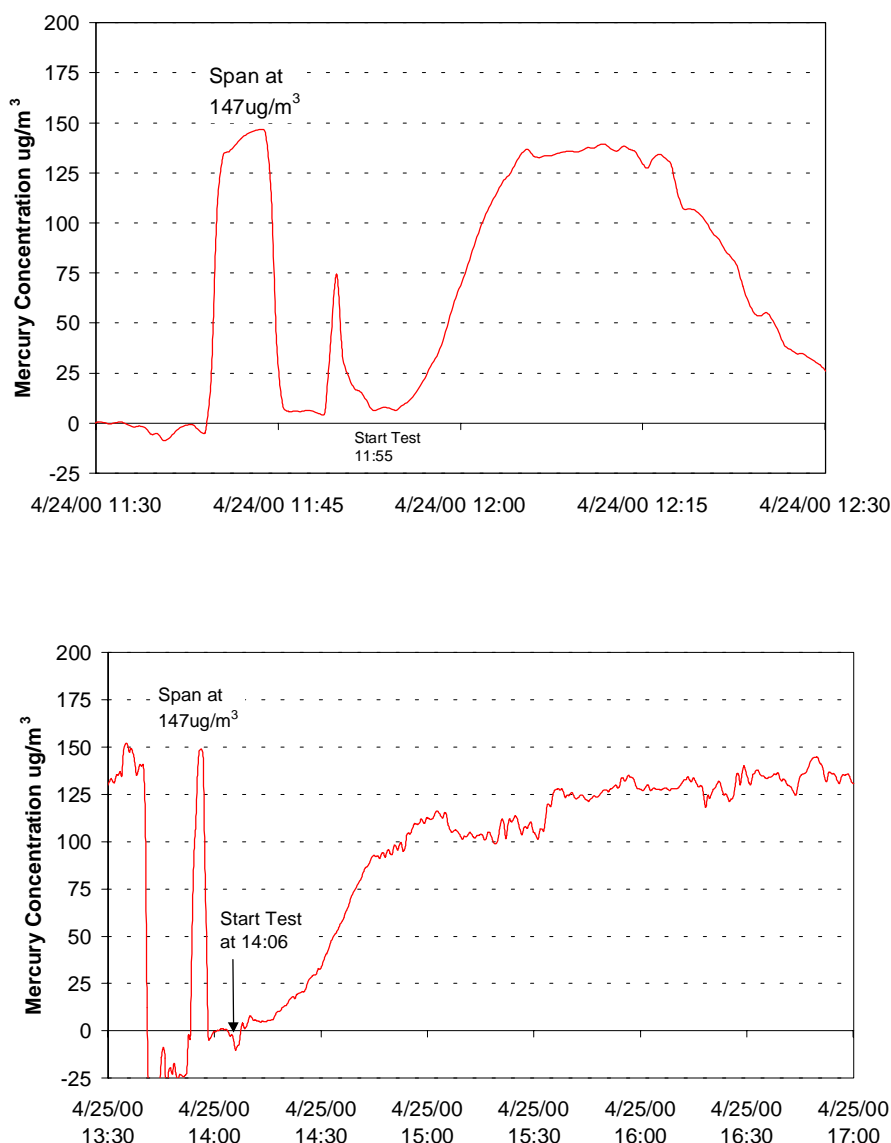
Figure 27. Mercury breakthrough trace over 2.5-nm gold film (top) and 25-nm gold film (bottom).

Measured at 50% breakthrough, the 25-nm film lasted about 33 minutes versus 5 minutes for the 2.5-nm film. This roughly six-fold larger capacity indicates that the mercury is able to diffuse into the gold film during the time period of the test. Thus, crystallites of 25 to 50 nm

diameter in size should be appropriate for sorbent use. This is original size of the crystallites in the regenerable sorbent (Table 5).

Effect of Tubing Material on Mercury Transport

Laboratory testing with mercuric chloride showed a loss of mercury during transfer within the test apparatus when elemental mercury was used in the presence of hydrogen chloride gas. In these tests, mercury concentration decreased from the span value of 39 $\mu g/m^3$ to roughly 18 $\mu g/m^3$ when HCl gas was included in the gas mixture. We first verified that the mercury analyzer was reporting accurate gas-phase concentrations. Runs were made with a impinger containing potassium permanganate solution downstream of ADA's mercury analyzer to capture the vapor-phase mercury. The solution was analyzed for mercury using cold vapor atomic absorption (CVAA). Mercury concentrations reported by the analyzer and determined using wet chemistry were comparable, indicating that the mercury analyzer was able to detect all mercury species in the gas stream.

Given that the analyzer readings appeared accurate, ADA concluded that the mercury was being retained within the tubing of the test system. Tests were run with lengths of PTFE Teflon and electro-polished stainless steel (EPSS) connected directly to the mercury analyzer to see if mercury transport was affected by tubing materials. Elemental mercury (73 $\mu g/m^3$) in nitrogen with and without HCl gas (100 ppm) was sent through equal lengths of PTFE and EPSS tubing. Tubing was heat traced to maintain a temperature of 150°C (300°F). These tests suggested that a 15% to 50% drop in total mercury can be expected in the first few hours after introducing Hg^0 and HCl gases. The readings gradually returned to the feed concentration, presumably as the tubing becomes "conditioned" to the mercury species. Wang and coworkers (1983) attribute the conditioning period with stainless steel to the reaction between $HgCl_2$ and surface H_2 on the tubing wall, forming Hg_2Cl_2.

In a separate test, samples of PTFE and EPSS tubing were subjected to 90 minutes of exposure to mercury in nitrogen and mercury plus 40 ppm HCl in nitrogen. After the exposure the tubes were filled with 10 ml of 1% HCl and bromochloride and allowed to soak overnight to remove mercury sorbed on the tubing material. Rinse solution was analyzed for mercury using CVAA. The results of these tests are shown in Table 9.

Table 9. Results of Transport Tests with Elemental Mercury in N_2/HCl Gas.

Gas Mixture	Hold up on PTFE Tubing	Hold up on EP SS Tubing
Hg^o/N_2	0 ng Hg	66 ng Hg
$Hg^o/N_2/HCl$	44 ng Hg	128 ng Hg

As shown above, little elemental mercury was retained by the PTFE tubing when only nitrogen gas was used, whereas, the EPSS retained a substantial amount of mercury. This was not unexpected since EPSS tubing does require a "conditioning" period to season the material

with mercury. However, when HCl gas was included in the gas mixture, both PTFE and EPSS materials retained mercury, although the EPSS again held more.

Nitrogen gas for these tests was taken from a membrane separation system. Therefore, some oxygen was present in the gas mixture. Additional runs were carried out using bottled nitrogen with no oxygen. Again, when HCl was added to the gas mixture, the mercury concentration was reduced, indicating a loss of vapor-phase mercury in the gas stream.

This brief study suggests that Teflon PTFE may be a better tubing material than stainless steel. Part of this advantage is tempered by the greater care required in heat-tracing the PTFE because of its lower thermal conductivity and lower temperature limits. With regards to EPSS, it was ultimately determined that a longer conditioning time was required in order to avoid this transport loss. The entire test system needs to be conditioned with the mercury/HCl gas mixture for 9 to 24 hours to prevent mercury loss. This is significantly longer than conditioning times required in the absence of the HCl.

Process Economics

The field results impacted the level of effort devoted to the economic assessment of the technology. Rather than undertake an extensive preliminary plant design (an effort involving process flow diagrams, energy and material balances, size and cost of major equipment, estimated costs for ancillary equipment, and total capital and annual O&M costs), we updated the previous estimates to reflect the revised understanding of the process performance. From the Phase I work, we estimated the capital cost of noble-metal agent per unit of flue gas flow, I_s, as

$$I_s = \frac{GC}{\Delta q} * \tau_b \qquad (1)$$

where:

- G = cost of noble metal per unit mass ($22/g),
- C = mercury concentration ($10\mu g/m^3$),
- Δq = difference between the mass ratio of mercury to gold at the end of a sorption cycle and the beginning of a sorption cycle, and
- τ_b = breakthrough time, given by

$$\tau_b = \frac{M_s}{Q} * \frac{\Delta qW}{C} \qquad (2)$$

where additionally:

- W = mass fraction of gold on the sorbent,
- M_s = the total mass of sorbent (support plus noble metal), and
- Q = volumetric flow rate of the flue gas.

In Phase I we assumed a Δq value of 10%, on the basis of those laboratory tests. The data of Phase II indicates that this number was optimistic for flue gas containing acid gas components (compare results in the final column of Table 8). Assuming we maintain the desire for a 24-hour sorption cycle, the loading of noble metal on the support monolith needs to be increased by a factor of approximately twenty. Plugging in $\Delta q=0.005$ and other reasonable values into Equations (1) and (2), yields:

$$I_s = (\$22/g)*(10\mu g/m^3)/(0.005) * (24hr)*(60min/hr)/(10^6 \, \mu g/g) = \$63/(m^3/min).$$

Converting from cubic meters to cubic feet yields a gold cost of \$1.80/acfm.

For a 1,000,000 ACFM unit with the desired contact time of 1.0 seconds, the volume of sorbent monoliths required is 16,666 cubic feet. Assuming three beds with one always regenerating, the total required volume is $16,666/(2/3) = 25,000$ ft^3. Cost for the monolith support runs \$248/ft^3 in quantities of several thousand (5.9" x 5.9" x 12", 230-cpsi monoliths, Corning Environmental, Erwin, NY, August 2000). Impregnation costs, exclusive of the cost of gold itself, run \$110/ft^3. Thus, the cost for the coated sorbent monoliths to treat one million acfm is approximately $\$1.80/(2/3)*10^6 + 25,000*(\$248+\$110) = \$11.6M$.

Selective catalytic reduction (SCR) catalysts are made of similar materials to those being considered here for mercury sorption, namely an active metal on ceramic monoliths. These catalysts normally last from three to four years when installed downstream of the particulate control device (Heck & Farrauto, 1995). For this exercise it is assumed that the mercury sorbent life will be comparable.

Using our basis of 10^6 acfm and 10 $\mu g/m^3$ of mercury, and further assuming a 60% plant availability, a total of 62 kg (135 lb) of mercury is captured annually. Using *only the cost for the sorbent* and its anticipated three-year life, the cost for mercury recovery is estimated at \$29,600/lb Hg. This value is comparable to the *total cost* estimated for other, more developed treatment options (Brown et al. 1999). Given the additional costs not accounted for in this estimate (sorbent vessel, ducting, regeneration system, operating costs, etc.) and the uncertainties in the performance of the process, the economics of the regenerable sorbent look poor for use in flue gas containing acid gases.

The sorbent's higher capacity when treating scrubbed flue gas holds more promise for its use downstream of acid-gas scrubbers and in industrial applications that do not involve NOx- or HCl-bearing acid-gas streams. Within the utility sector, such an application is the capture of mercury downstream from a flue-gas desulfurization (FGD) system. Approximately 20% of coal-fired power plants use some form of FGD. Recent mercury monitoring data indicates that wet FGD systems capture 85% to 95% of oxidized mercury but virtually none of the elemental mercury (DeVito & Rosenhoover, 1999). Depending on the mercury speciation, this "slip" can allow several $\mu g/m^3$ of mercury in the stack gas – possibly more than would be allowed should limitations be promulgated. A polishing step with a regenerable sorbent is attractive because no particulate capture is required, as with injected sorbents.

Mercury Analyzer Upgrades

As ADA began Phase II of this project, the intention was to utilize the continuous mercury analyzer developed under DOE and ADA funding during the mid-1990s. However, the analyzer was unable to provide stable values during the initial testing at CONSOL, and sampling with IC-traps was required to track sorbent performance. As described previously, the IC-trap technique turned out to have flaws of its own and long analytical turn-around times hampered efforts to debug the problem in a timely fashion. Although reliable, the Ontario-Hydro method is too costly for routine data tracking.

After consultation with the FETC contract representative (Meeting 3/23/99) the decision was made to invest in improving the reliability of the ADA analyzer. ADA staff had already outlined what changes were needed to improve the analyzer: single furnace operation to reduce complexity and cost, temperature-controlled optics, revamped mercury calibration supply, and isolated detector electronics, among others. Changes to the analyzer were begun in April and completed in June, 1999.

Operation of the CEM was simplified by the following modifications:

- The unit uses a single absorption cell. Consequently, calibration and gas sampling reports only one signal. This signal is typically total mercury concentration, but can be set for elemental mercury if desired. This change reduces system size, cost, and complexity.

- The modes of operation are limited to calibration and gas sampling, thus simplifying plumbing and control logic.

- The mercury concentration is recorded and displayed at the analyzer, with provision for a remote signal out.

- The mercury analyzer is controlled by a small laptop computer, decreasing system size and improving the reliability over the old design

- Optical components are now rigidly mounted to minimize the need for field adjustments

- Smaller, less costly magnets and a focusing lens are used to improve the strength of the UV beam and enhance the Zeeman effect.

- Shielded electrical traces are used to reduce electromagnetic interference.

- The UV source and optics are kept in a temperature-control housing to minimize thermal drift.
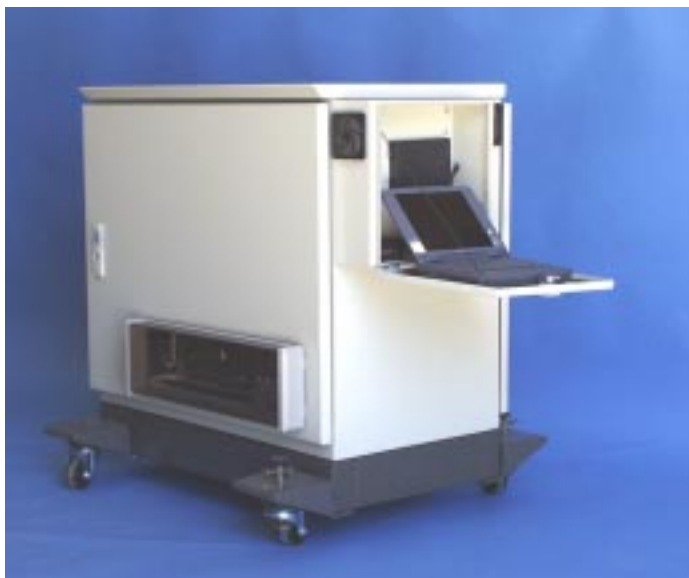
Figure 28.

ADA's redesigned continuous mercury monitor for flue gas.

In addition to the technical improvements, the revamped monitor is about half the size of the previous version and will be significantly less expensive to manufacture. Budget constraints and the changing priorities of other mercury projects did not allow for independent field-testing of the new analyzer in other test programs. The unit was used successfully in laboratory experiments in the current project and provided the data during the June 2000 tests at Hudson Station.

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Appendices

Table A-1. Cumulative hours on flue gas while at CONSOL.

General Comments:
> Actual time on flue gas is ~10% less because of ESP downtime for cleanouts.
> Start and stop times sometimes estimated from prior trends.

Week of	Flue Gas On Date	Flue Gas On Time	Flue Gas Off Date	Flue Gas Off Time	Week Hours	Cumulative Hours	Comments
03-Aug							
10-Aug	8/11	16:15	8/14	0:30	56.3	56.3	
17-Aug	8/18	9:50	8/20	18:10	58.0	114.3	
24-Aug	8/26	6:45	8/27	10:45	28.0	142.3	Unit shut down on 8/27
31-Aug						142.3	Unit down
07-Sep						142.3	Unit down
14-Sep						142.3	Unit down
21-Sep	9/23	2:30	9/25	2:35	48.1	190.3	
28-Sep	9/29	9:25	10/2	9:43	72.3	262.6	
05-Oct	10/6	18:15	10/8	0:00	29.8	292.4	
12-Oct						292.4	Combustor down
19-Oct	10/20	0:00	10/22	13:55	61.9	354.3	
26-Oct	10/27	12:00	10/30	10:50	70.8	425.1	
03-Nov	11/3	21:55	11/6	16:00	90	515.1	
30-Nov	12/2	7:20	12/4	8:40	49	564.1	
07-Dec	12/8	6:24	12/11	8:00	74	637.6	

Table A-2. Summary data of Ontario-Hydro sampling at CONSOL.

December 9, 1998 Inlet

	Hg(II)	Hg$^{\circ}$	Total Hg
Run #1	4.16	1.52	5.68
Run #2	5.67	1.37	7.04
Run #3	5.54	1.29	6.83
Avg	5.12	1.39	6.52
sdev	0.83	0.12	0.73
PRSD	16.3%	8.3%	11.2%

December 9, 1998 R101 Outlet

	Hg(II)	Hg$^{\circ}$	Total Hg
Run #1	9.05	0.27	9.32
Run #2	8.28	0.49	8.77
Run #3	8.44	0.60	9.04
Avg	8.59	0.45	9.04
sdev	0.40	0.17	0.27
PRSD	4.7%	36.9%	3.0%

December 10, 1998 Inlet

	Hg(II)	Hg$^{\circ}$	Total Hg
Run #1	5.85	1.20	7.05
Run #2	5.23	1.34	6.57
Run #3	5.77	0.97	6.74
Avg	5.62	1.17	6.79
sdev	0.34	0.19	0.24
PRSD	6.0%	15.9%	3.6%

December 10, 1998 R102 Outlet

	Hg(II)	Hg$^{\circ}$	Total Hg
Run #1	7.62	0.35	7.97
Run #2	8.23	0.59	8.82
Run #3	8.30	0.69	8.99
Avg	8.05	0.54	8.59
sdev	0.37	0.17	0.54
PRSD	4.6%	32.0%	6.3%

Dec 9 & 10 Inlet Measurements

	Hg(II)	Hg$^{\circ}$	Total Hg
Run #1	4.16	1.52	5.68
Run #2	5.67	1.37	7.04
Run #3	5.54	1.29	6.83
Run #4	5.85	1.20	7.05
Run #5	5.23	1.34	6.57
Run #6	5.77	0.97	6.74
Avg	5.37	1.28	6.65
sdev	0.63	0.19	0.51
PRSD	11.8%	14.5%	7.7%

Table A-3. IC Trap data summary from testing at CONSOL.

Iodated Carbon Trap Sampling DATA
Filename: mesadata.xls
Skid located at CONSOL pilot coal-combustor

Std Temperature = 293 K
Std Pressure = 29.92 mm Hg
Meter Y Factor = 1.042

Sample Date	Sample ID	Sample Port	Sorbing Vessel	Dry Gas Vol. (L)	Meter Temp (C)	Barom. (inch Hg)	Gas Vol. (Norm. L)	Hg in Samples Blank-corr'd Total (ng/trap)	Dry-Basis Hg Conc. (ug/Nm³)
12-Aug	8-12-1415	SP-4	R101	29.5	38	29.0	28.1	180	6.4
12-Aug	8-12-1307	SP-4	R101	29.68	36	29	28.4	204	7.2
12-Aug	8-12-1030	SP-4	R101	29.32	30	29	28.6	230	8.0
								Avg/Std Dev. =	**7.2**
13-Aug	8-13-1350	SP-4	R102	30.98	38	29	29.5	124	4.2
13-Aug	8-13-1000	SP-4	R102	29.09	35	29	27.9	72	2.6
13-Aug	8-13-0900	SP-4	R102	29.56	29	29	29.0	51	1.8
								Avg/Std Dev. =	**2.8**
18-Aug	8-18-1300	SP-4	R101	30.21	40	28.9	28.5	253	8.9
18-Aug	8-18-1130	SP-4	R101	29.95	36	28.9	28.6	283	9.9
18-Aug	8-18-0830	SP-4	R101	31.2	31	28.9	30.3	270	8.9
								Avg/Std Dev. =	**9.2**
19-Aug	8-19-1100	SP-4	R102	29.61	36	29.1	28.5	135	4.7
19-Aug	8-19-1000	SP-4	R102	29.6	31	29.1	28.9	118	4.1
19-Aug	8-19-0830	SP-4	R102	28.34	22	29.1	28.5	72	2.5
								Avg/Std Dev. =	**3.8**
26-Aug	8-26-1100	SP-1a	R102	11.14	34	29.2	10.8	1393	128.8
26-Aug	8-26-0930	SP-4	R102	31.63	29	29.1	31.1	197	6.3
27-Aug	8-27-1050	SP-1a	R101	13.99	38	29.1	13.4	1416	106.0
	8-27-0930	SP-1a	R101	12.92	31	29.2	12.7	502	39.6
								Avg/Std Dev. =	**72.8**
27-Aug	8-27-1000	SP-4	R101	17.82	36	29.1	17.1	114	6.7
27-Aug	8-27-0820	SP-4	R101	30.19	25	29.1	30.1	183	6.1
								Avg/Std Dev. =	**6.4**
28-Aug	8-28-1000	SP-4		0			0.0	0	na
	Trip Blank	blank						1.2	
29-Sep	9-29-1000	SP-4	R102	30.33	24	29.1	30.3	763.47	25.2
29-Sep	9-29-1100	SP-4	R102	31.02	32	29.1	30.2	1107.89	36.7
29-Sep	9-29-1220	SP-1a	R102	9.5	34	29.1	9.2	436.39	47.5
29-Sep	ICA-TB	blank						1.19	
30-Sep	9-30-0800	SP-1a	R101	8.95	19	28.97	9.1	415.53	45.9
30-Sep	9-30-0848	SP-4	R101	31.89	26	28.97	31.5	317.88	10.1
30-Sep	9-30-1000	SP-4	R101	31.18	34	28.97	30.0	318.49	10.6
07-Oct	10-07-0830	SP-1a	R102	12.43	22	29.23	12.6	1261.03	100.3
07-Oct	10-07-1020	SP-4	R102	30.56	29	29.22	30.2	137.94	4.6
07-Oct	10-07-1300	SP-4	R102	30.47	33	29.16	29.6	137.17	4.6
20-Oct	10-20-1220	SP-4	R101	30.49	30	29.25	30.0	1083.4	36.1
20-Oct	10-20-1048	SP-1a	R101	13.16	22	29.25	13.3	310.8	23.3
20-Oct	10-20-1445	SP-4	R101	30.8	31	29.23	30.2	664	22.0
20-Oct	10-20-1330	SP-1a	R101	9.43	32	29.3	9.2	536	58.0
21-Oct	10-21-0830	SP-4	R102	30.54	20	29.22	31.1	0	0.0
21-Oct	10-21-0830	SP-4	R102	30.54	20	29.22	31.1	715	23.0
21-Oct	10-21-0940	SP-1a	R102	8.33	27	29.21	8.3	408.8	49.4
21-Oct	10-21-1015	SP-4	R102	30.48	29	29.23	30.1	527.4	17.5
21-Oct	10-21-1120	SP-1a	R102	9.28	30	29.23	9.1	367.7	40.3
27-Oct	10-27-1515	SP-4	R102	30.72	32	29.25	30.1	324.4	10.8
27-Oct	10-27-1725	SP-1a	R102	9.96	30	29.25	9.8	379.8	38.7
27-Oct	10-27-1618	SP-4	R102	31.3	34	29.25	30.4	330.9	10.9
28-Oct	10-28-0840	SP-4	R101	30.39	26	29.06	30.1	349.3	11.6
28-Oct	10-28-0945	SP-1a	R101	9.3	32	29.06	9.0	303.6	33.6
28-Oct	10-28-1015	SP-4	R101	30.82	35	29.06	29.7	367.8	12.4
29-Oct	10-29-1000	blank					0.0	1.25	
29-Oct	10-29-0850	blank					0.0	2.48	

Table A-3. continued.

Sample Date	Sample ID	Sample Port	Sorbing Vessel	Dry Gas Vol. (L)	Meter Temp (C)	Barom. (inch Hg)	Gas Vol. (Norm. L)	Hg in Samples Blank-corr'd Total (ng/trap)	Dry-Basis Hg Conc. (ug/Nm^3)
03-Nov	11-03-1300	SP-4	R101	31.57	34	29.03	30.5	334.79	11.0
03-Nov	11-03-1440	SP-1a	R101	11.67	32	29.01	11.3	288.62	25.5
03-Nov	11-03-1500	SP-4	R101	32.91	32	29	31.9	305.91	9.6
06-Nov	11-06-0800	SP-4	R102	30.8	26	29.12	30.6	301.67	9.9
06-Nov	11-06-0900	SP-1a	R102	9.7	30	29.12	9.5	289.08	30.4
06-Nov	11-06-0945	SP-4	R102	30.65	31	29.12	30.0	299.02	10.0
06-Nov	11-06-0915	perm tube	na					11,416	
09-Nov	11-09-0915	perm tube	na						
09-Nov	11-09-1259	perm tube	na					987.58	
09-Nov	11-09-1331	perm tube	na					1021.93	
09-Nov	11-09-1403	perm tube	na					1083.68	
02-Dec	12-2-1025	SP-1a	R101	9.8	32	29.25	9.6	223.44	23.3
02-Dec	12-2-0910	SP-4	R101	31.25	29	29.25	30.9	287.87	9.3
02-Dec	12-2-1200	SP-4	R101	23.57	31	29.2	23.1	180.4	7.8
02-Dec	12-2-1430	SP-1a	R102	8.68	36	29.14	8.4	209.31	25.1
02-Dec	12-2-1500	SP-4	R102	24.73	36	29.11	23.8	149.24	6.3
02-Dec	12-2-1550	SP-4	R102	24.58	36	29.11	23.6	222.19	9.4
02-Dec	12-2-1315	P-1a/Room A	R101	35	35	29.16	33.8	29.17	0.9
02-Dec	12-2-0800	blank	na				0.0	1.46	
09-Dec	12-9-0930	SP-1a	R101	9.68	32	29.39	9.5	231.84	24.4
09-Dec	12-9-1000	SP-1a	R101	9.59	32	29.38	9.4	203.99	21.6
09-Dec	12-9-1405	SP-1a	R101	9.68	35	29.38	9.4	183.44	19.5
09-Dec	12-9-0845	SP-4	R101	31.32	26	29.36	31.4	195.88	6.2
09-Dec	12-9-1100	SP-4	R101	29.93	35	29.4	29.2	185.15	6.4
09-Dec	12-9-1250	SP-4	R101	31.17	31	29.39	30.7	193.3	6.3
09-Dec	12-9-1857	ESP outlet	R101	15.95	24	29.41	16.1	1464.65	90.9
09-Dec	12-9-1936	ESP outlet	R101	15.95	27	29.41	16.0	692.42	43.4
09-Dec	12-9-2015	ESP outlet	R101	15.72	28	29.41	15.7	670.02	42.8
09-Dec	12-9-1530	blank	na				0.0	1.39	
10-Dec	12-10-1021	SP-1a	R102	8.94	29	29.41	8.9	142.59	16.1
10-Dec	12-10-1227	SP-1a	R102	8.04	34	29.41	7.9	239.81	30.5
10-Dec	12-10-0830	blank	na				0.0	1.44	
10-Dec	12-10-0830	SP-4	R102	40.3	24	29.41	40.7	266	6.5
10-Dec	12-10-1048	SP-4	R102	36.06	33	29.41	35.4	259.7	7.3
10-Dec	12-10-1256	SP-4	R102	34.7	35	29.41	33.8	245.8	7.3

Table A-4. Ontario-Hydro sampling data from Hudson Station.

ADA Hg Sampling Program - Ontario Hydro Analysis Spreadsheet
Testing Conducted on May 19, 1999

Date	5/19	5/19	5/19	5/19	5/19	5/19
Time	1300-1440		1540-1730		1745-1920	
Location	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
dscf	52.8	53.42	62.23	63.01	55.55	58.97
dsm3	1.495	1.513	1.762	1.784	1.573	1.670
% O2	7.1	7.1	6.9	7.0	11.2	11.3
KCl						
liq. vol. mL	590	591	635	639	617	625
ppb Hg	9.55	8.97	8.48	7.93	6.88	8.3
$\mu g/m^3$	3.77	3.50	3.06	2.84	2.70	3.11
HNO3/H2O2						
liq. vol. mL	175	175	175	175	175	177
ppb Hg	3.79	3.61	3.76	5.06	4.31	3.84
$\mu g/m^3$	0.44	0.42	0.37	0.50	0.48	0.41
KMnO4						
liq. vol. mL	241	244	241	241	247	248
ppb Hg	0.60	1.22	0.70	1.07	1.47	1.04
$\mu g/m^3$	0.10	0.20	0.10	0.14	0.23	0.15
HCl Rinse						
liq. vol. mL	100	100	100	100	100	100
ppb Hg	1.56	0.48	0.64	0.11	0.69	0.49
$\mu g/m^3$	0.10	0.03	0.04	0.01	0.04	0.03
Oxidized	3.77	3.50	3.06	2.84	2.70	3.11
Elemental	0.64	0.65	0.51	0.65	0.75	0.59
Total $\mu g/m^3$	4.41	4.15	3.56	3.49	3.45	3.70
% oxidized	85%	84%	86%	81%	78%	84%

	INLET	OUTLET
Avgerage	3.81	3.78
Std.Dev.	0.52	0.34
PRSD	14%	9%

Table A-5. IC Trap summary from testing at Hudson Station, 05/99-07/99.

Iodated-Carbon Trap (IC Trap) Sampling DATA

Filename: Hudson Sample Analyses.xls Std Temperature = 530 R
Skid located at Hudson Station Std Pressure = 29.92 mm Hg
R101 is the sorbing vessel Meter Y Factor = 1

Sample Date	Sample ID	Sample Port	Dry Gas Vol. (L)	Meter Temp (F)	Barom. (inch Hg)	Gas Vol. (Norm. L)	Blank corrected Total Hg (ng/trap)	B-trap Hg (ng/trap)	Dry-Basis Hg Conc. (ug/Nm^3)	Removal Effic.	
19-May	051999-1305-SP1A	SP-1a	48.33	86	29.82	46.8	967		20.7		
19-May	051999-1512-SP1A	SP-1a	61.38	90	29.82	59.0	937		15.9		
19-May	051999-1748-SP1A	SP-1a	48.62	89	29.82	46.8	529	1.8	11.3		
19-May	051999-1304-SP4	SP-4	46.62	85	29.82	45.2	104	2.6	2.3	89%	
19-May	051999-1510-SP4	SP-4	59.32	90	29.82	57.0	177	1.5	3.1	80%	
19-May	051999-1744-SP4	SP-4	49.8	90	29.82	47.8	104		2.2	81%	
								Avg/Std Dev. =		83%	5%
19-May	051999-1330-B	blank					nondetect	1.1			
08-Jun	060899-0900-B	blank	0				3.63				
08-Jun	060899-0946-SPIA	SP-1A	56.26	94	29.92	53.8	535.4		9.9		
08-Jun	060899-1056-SPIA	SP-1A	58.93	101	29.92	55.7	396.96		7.1		
08-Jun	060899-1201-SPIA	SP-1A	59.1	101	29.92	55.8	320.78	2.75	5.7		
08-Jun	060899-0945-SP4	SP-4	59.36	95	29.92	56.7	184.33	1.3	3.3	67%	
08-Jun	060899-1200-SP4	SP-4	54.5	102	29.92	51.4	133.33		2.6	64%	
08-Jun	060899-1055-SP4	SP-4	59.87	103	29.92	56.3	161.81	1.58	2.9	50%	
								Avg/Std Dev. =		60%	9%
16-Jun	061699-1821-b	blank	0.0				1.16				
16-Jun	061699-1822-sp1a	SP-1A	31.45	94.8	29.92	30.01	750.91		25.0		
16-Jun	061699-1928-sp1a	SP-1A	31.54	94.2	29.92	30.12	1071.88		35.6		
16-Jun	061699-2032-sp1a	SP-1A	28.87	91.0	29.92	27.73	367.22	1.74	13.2		
16-Jun	061699-1821-sp4	SP-4	29.28	96.6	29.92	27.84	144.32	2.7	5.2	79%	
16-Jun	061699-1927-sp4	SP-4	29.08	95.5	29.92	27.71	154.61		5.6	84%	
16-Jun	061699-2031-sp4	SP-4	28.66	92.0	29.92	27.48	142.27		5.2	61%	
								Avg/Std Dev. =		75%	12%
28-Jun	062899-1200-B	blank	0				0.21				
28-Jun	062899-1105-SPIA	SP-1A	32.19	78	29.92	31.7	665.22		21.0		
28-Jun	062899-1210-SPIA	SP-1A	28.78	82	29.92	28.1	175.06	1.89	6.2		
28-Jun	062899-1315-SPIA	SP-1A	29.63	83	29.92	28.9	148.56		5.1		
28-Jun	062899-1104-SP4	SP-4	26.7	81	29.92	26.1	45.89		1.8	92%	
28-Jun	062899-1209-SP4	SP-4	30.22	84	29.92	29.4	50.4	1.89	1.7	72%	
28-Jun	062899-1314-SP4	SP-4	29.83	85	29.92	29.0	57.68		2.0	61%	
								Avg/Std Dev. =		75%	15%
07-Jul	070799-1215-B	blank	0				0.32				
07-Jul	070799-905-SPIA	SP-1A	29.38	77	29.92	29.0	175.06		6.0		
07-Jul	070799-1011-SPIA	SP-1A	28.54	79	29.92	28.1	118.09		4.2		
07-Jul	070799-1119-SPIA	SP-1A	30.82	80	29.92	30.2	137.97		4.6		
07-Jul	070799-906-SP4	SP-4	27.9	82	29.92	27.3	73.05		2.7	56%	
07-Jul	070799-1012-SP4	SP-4	31.4	82	29.92	30.7	71.73		2.3	44%	
07-Jul	070799-1120-SP4	SP-4	28.95	83	29.92	28.3	84.97		3.0	34%	
								Avg/Std Dev. =		45%	11%
13-Jul	071399-615-B	blank	0				0.44				
13-Jul	071399-620-SPIA	SP-1A	29.62	75.5	29.92	29.3	85.32		2.9		
13-Jul	071399-725-SPIA	SP-1A	29.19	82.5	29.92	28.5	84.48	0.75	3.0		
13-Jul	071399-831-SPIA	SP-1A	31.61	84.2	29.92	30.8	86.57		2.8		
13-Jul	071399-621-SP4	SP-4	30.2	77.5	29.92	29.8	42.19		1.4	51%	
13-Jul	071399-726-SP4	SP-4	28.46	89.1	29.92	27.5	54.55		2.0	33%	
13-Jul	071399-832-SP4	SP-4	29.99	90.8	29.92	28.9	49.94	1.27	1.7	38%	
								Avg/Std Dev. =		41%	9%
14-Jul	071499-040-B	blank	0				0.69				
14-Jul	071499-040-SPIA	SP-1A	28.58	75	29.92	28.28	98.98	0.55	3.5		
14-Jul	071499-147-SPIA	SP-1A	31.05	76.5	29.92	30.63	72.51		2.4		
14-Jul	071499-252-SPIA	SP-1A	29.24	77	29.92	28.82	73.67		2.6		
14-Jul	071499-041-SP4	SP-4	30.28	75	29.92	29.96	40.65		1.4	61%	
14-Jul	071499-148-SP4	SP-4	30.48	78	29.92	29.99	47.73		1.6	33%	
14-Jul	071499-253-SP4	SP-4	29.21	77	29.92	28.79	54.28	0.61	1.9	26%	
								Avg/Std Dev. =		40%	19%

Table A-5. continued.

Sample Date	Sample ID	Sample Port	Dry Gas Vol. (L)	Meter Temp (F)	Barom. (inch Hg)	Gas Vol. (Norm. L)	Blank corrected Total Hg (ng/trap)	B-trap Hg (ng/trap)	Dry-Basis Hg Conc. (ug/Nm³)	Removal Effic.	
23-Jul	072399-0759-B	blank	0								
23-Jul	072399-753-sp1a	SP-1A	31.35	84.6	29.92	30.47	155.07		5.1		
23-Jul	072399-900-sp1a	SP-1A	30.69	83.2	29.92	29.91	77.08		2.6		
23-Jul	072399-1010-sp1a	SP-1A	30.93	81.1	29.92	30.26	65.63		2.2		
23-Jul	072399-754-sp4	SP-4	30.28	77.8	29.92	29.80	28.59	0.36	1.0	81%	
23-Jul	072399-901-sp4	SP-4	30.84	90.5	29.92	29.65	36.02		1.2	53%	
23-Jul	072399-1011-sp4	SP-4	30.65	90.23	29.92	29.48	33	0.55	1.1	48%	
								Avg/Std Dev. =		61%	18%
30-Jul	073099-1640-B	blank	0		29.92		0.15	0.15			
30-Jul	073099-1642-SP1A	SP-1A	61.71	83	29.92	60.2	122.51		2.0		
30-Jul	073099-1847-SP1a	SP-1A	59.97	78	29.92	59.1	141.49		2.4		
30-Jul	073099-2051-SP1A	SP-1A	60.03	77	29.92	59.2	133.98		2.3		
30-Jul	073099-1641-SP2	SP-2	59.71	83	29.92	58.3	170.69		2.9	-44%	
30-Jul	073099-1846-SP2	SP-2	60.85	78	29.92	59.9	258.23		4.3	-80%	
30-Jul	073099-2050-SP2	SP-2	60.03	76	29.92	59.4	118.42		2.0	12%	
								Avg/Std Dev. =		-37%	46%
11-Aug	081199-0545-B	blank	0		29		0.08	0.15			
11-Aug	081199-0550-SP2	SP-2	56.01	72.7	29	54.0	209.52	0.96	3.9		
11-Aug	081199-0758-SP2	SP-2	61.18	78	29	58.4	225.64		3.9		
11-Aug	081199-1004-SP2	SP-2	59.03	79	29	56.3	167.74		3.0		
11-Aug	081199-0551-SP4	SP-4	57.32	74	29	55.2	193.39		3.5	10%	
11-Aug	081199-0759-SP4	SP-4	60.93	80	29	58.0	221.24		3.8	1%	
11-Aug	081199-1005-SP4	SP-4	59.61	80	29	56.7	159.68		2.8	6%	
								Avg/Std Dev. =		5%	4%
18-Aug	081899-0605-B		0								
18-Aug	081899-0607-SP2	SP-2	60.32	75.3	29	57.9	146.49		2.5		
18-Aug	081899-0815-SP2	SP-2	56.79	78.7	29	54.2	133.3	0.51	2.5		
18-Aug	081899-1021-SP2	SP-2	59.87	79.8	29	57.0	90.79	0.86	1.6		
18-Aug	081899-0608-SP4	SP-4	60.81	75.8	29	58.3	129.63		2.2	12%	
18-Aug	081899-0816-SP4	SP-4	57.38	82.8	29	54.3	115.71	0.43	2.1	13%	
18-Aug	081899-1022-SP4	SP-4	59.82	81.9	29	56.7	103.25		1.8	-14%	
								Avg/Std Dev. =		4%	16%
16-Sep	091699-0726-B		0				0.09				
16-Sep	091699-0725-SP2	SP-2	59.66	72.3	29.8	59.2	240.83		4.1		
16-Sep	091699-0931-SP2	SP-2	59.65	75	29.7	58.7	196.27		3.3		
16-Sep	091699-1136-SP2	SP-2	29.72	77	29.6	29.0	94.78	0.87	3.3		
16-Sep	091699-0724-SP4	SP-4	59.7	72.8	29.8	59.1	264.39		4.5	-10%	
16-Sep	091699-0930-SP4	SP-4	59.84	75.8	29.7	58.8	195.68		3.3	0%	
16-Sep	091699-1135-SP4	SP-4	30.05	77.6	29.6	29.3	85.94		2.9	10%	
								Avg/Std Dev. =		0%	10%
22-Sep	092299-0711-B		0				-0.13				
22-Sep	092299-0715-SP2	SP-2	60.88	74.8	29.7	59.9	254.58		4.3		
22-Sep	092299-0921-SP2	SP-2	60.1	75.8	29.75	59.1	260.46		4.4		
22-Sep	092299-1125-SP2	SP-2	58.55	76.2	29.75	57.5	240.83		4.2		
22-Sep	092299-0716-SP4	SP-4	60.45	75.2	29.74	59.5	195.68	1.35	3.3	23%	
22-Sep	092299-0922-SP4	SP-4	60.07	76.3	29.75	59.0	284.02	2.1	4.8	-9%	
22-Sep	092299-1126-SP4	SP-4	59.77	76.8	29.75	58.7	229.05		3.9	7%	
								Avg/Std Dev. =		7%	16%
05-Oct	100599-0600-B		0				0.12				
05-Oct	100599-0603-SP2	SP-2	55.01	76.5	30.09	54.7	350.77	0.88	6.4		
05-Oct	100599-0810-SP2	SP-2	61.1	80.5	30.1	60.3	276.17		4.6		
05-Oct	100599-1020-SP2	SP-2	59.32	80.8	30.1	58.5	276.17		4.7		
05-Oct	100599-0604-SP4	SP-4	58.75	77.8	30.09	58.2	374.32	1.21	6.4	0%	
05-Oct	100599-0811-SP4	SP-4	59.57	82	30.1	58.6	231.02	1.55	3.9	14%	
05-Oct	100599-1021-SP4	SP-4	60.1	82.3	30.1	59.1	248.69		4.2	11%	
								Avg/Std Dev. =		8%	7%

Table A-6. Coal analyses for Hudson Station feedstock.

	ECS Lab Analyses				Frontier Lab Analyses			
Sample Date	**Mercury (mg/kg)**	**Chloride (Wt %)**	**Moisture (Wt %)**	**Sulfur (Wt %)**	**Mercury (mg/kg)**	**Chloride (Wt %)**	**Moisture (Wt %)**	**Sulfur (Wt %)**
06/08/99	ND	ND	7.2	0.92	0.050	0.140	7.48	0.89
06/16/99	ND	1.3	5.8	0.83				
06/28/99	ND	ND	7.9	0.91				
07/07/99	ND	0.93	5.9	0.82	0.076	0.130	5.48	0.89
07/13/99	0.048	1.3	8.4	0.83	0.041	0.144	7.52	0.82
07/14/99	ND	1.3	8.3	0.85	0.067	0.139	8.37	0.93
07/23/99	ND	1.2	6.3	0.92				
07/30/99	<0.049	1.3	8.5	0.82				
08/11/99	<0.093	17	7.7	0.78				
08/24/99	<0.095							
09/16/99	0.043	3.8	11	0.90				
09/22/99	0.029	0.8	10	0.88				
10/05/99?	0.034	0.86	10	0.82				
Averages	**0.056**	**2.98**	**8.08**	**0.86**	**0.059**	**0.138**	**7.21**	**0.88**
Std. Dev.	0.027	5.00	1.66	0.05	0.016	0.006	1.23	0.05

Table A-7. Flue gas characteristics during testing at Hudson Station.

Mercury Sampling Date	SO$_2$ (ppm)	Oxygen (%, dry)	NOx (ppm)	Moisture (%)	Unit Load MW	Stack Flow (kscfm)
			Daily average values			
05/19/99	458	9.2%	187	3.8%	398	1315
06/08/99	367	7.8%	295	7.8%	541	1534
06/16/99	493	8.3%	208	5.6%	394	1284
06/28/99	430	7.6%	225	4.6%	528	1583
07/07/99	389	7.5%	237	7.3%	532	1599
07/13/99	350	10.0%	171	4.9%	210	976
07/23/99	330	8.0%	186	8.4%	494	1532
07/30/99	292	7.0%	208	1.4%	572	1723
08/11/99	391	7.4%	256	7.4%	465	1485
08/18/99	417	7.0%	220	7.4%	432	1444
09/16/99	420	8.6%	300	3.4%	347	1262
10/05/99	450	9.4%	262	4.5%	360	1258
Overall average	**399**	**8.2%**	**230**	**5.5%**	**439**	**1416**
Std. Dev.	58	1.0%	42	2.1%	104	204