PILOT- AND FULL-SCALE DEMONSTRATION OF ADVANCED MERCURY CONTROL TECHNOLOGIES FOR LIGNITE-FIRED POWER PLANTS

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PILOT- AND FULL-SCALE DEMONSTRATION OF ADVANCED MERCURY CONTROL TECHNOLOGIES FOR LIGNITE-FIRED POWER PLANTS

INTRODUCTION

North Dakota lignite-fired power plants have shown a limited ability to control mercury emissions in currently installed electrostatic precipitators (ESPs), dry scrubbers, and wet scrubbers (1). This low level of control can be attributed to the high proportions of Hg^0 present in the flue gas. Speciation of Hg in flue gases analyzed as part of the U.S. Environmental Protection Agency (EPA) information collection request (ICR) for Hg data showed that Hg^0 ranged from 56% to 96% and oxidized mercury ranged from 4% to 44%. The Hg emitted from power plants firing North Dakota lignites ranged from 45% to 91% of the total Hg, with the emitted Hg being greater than 85% elemental. The higher levels of oxidized mercury were only found in a fluidized-bed combustion system. Typically, the form of Hg in the pulverized and cyclone-fired units was dominated by Hg^0 at greater than 85%, and the average amount of Hg^0 emitted from North Dakota power plants was 6.7 lb/TBtu (1, 2).

The overall objective of this Energy & Environmental Research Center (EERC) project is to develop and evaluate advanced and innovative concepts for controlling Hg emissions from North Dakota lignite-fired power plants by 50%–90% at costs of one-half to three-fourths of current estimated costs. The specific objectives are focused on determining the feasibility of the following technologies: Hg oxidation for increased Hg capture in wet and dry scrubbers, incorporation of additives and technologies that enhance Hg sorbent effectiveness in ESPs and baghouses, the use of amended silicates in lignite-derived flue gases for Hg capture, and the use of Hg adsorbents within a baghouse. The scientific approach to solving the problems associated with controlling Hg emissions from lignite-fired power plants involves conducting testing of the following processes and technologies that have shown promise on a bench, pilot, or field scale: 1) activated carbon injection (ACI) upstream of an ESP combined with sorbent enhancement, 2) Hg oxidation and control using wet and dry scrubbers, 3) enhanced oxidation at a full-scale power plant using tire-derived fuel (TDF) and oxidizing catalysts, and 4) testing of Hg control technologies in the *Advanced Hybrid*™ filter insert.

WORK PLAN

The work plan for this proposed project consists of six tasks outlined as follows:

- Task 1 – Mercury Control Enhancement for Unscrubbed Systems Equipped with ESPs
- Task 2 – Mercury Oxidation Upstream of Wet and Dry Scrubbers
- Task 3 – Field Tests to Determine Impacts of Oxidizing Agents on Mercury Speciation
- Task 4 – Particulate and Mercury Control for North Dakota Lignites Using the *Advanced Hybrid*™ Filter Technology

- Task 5 – Field Testing of Sorbents
- Task 6 – Project Reporting and Management

BACKGROUND

North Dakota lignite-fired power plants have shown a limited ability to control Hg emissions in currently installed ESPs, dry scrubbers, and wet scrubbers (1). This low level of control can be attributed to the high proportions of Hg^0 present in the flue gas. Speciation of Hg in flue gases analyzed as part of the EPA ICR for Hg data showed that Hg^0 ranged from 56% to 96% and the oxidized mercury ranged from 4% to 44%. The Hg emitted from power plants firing North Dakota lignites ranged from 45% to 91% of the total Hg, with the emitted Hg being greater than 85% elemental. The higher levels of oxidized mercury were only found in a fluidized-bed combustion system. Typically, the form of Hg in the pulverized and cyclone-fired units was dominated by Hg^0, being greater than 85% elemental, and the average emitted from North Dakota power plants was 6.7 lb/Btu (1, 2).

The composition of a coal has a major impact on the quantity and form of Hg in the flue gas and, as a result, on the ability of air pollution control devices (APCDs) to remove Hg from flue gas. In general, North Dakota lignitic coals are unique because of a highly variable ash content, ash that is rich in alkali and alkaline-earth elements, high oxygen levels, high-moisture levels, and low chlorine content. Experimental results indicate that low-chlorine (<50 ppm) coal combustion flue gases (typical of North Dakota lignite) contain predominantly Hg^0, which is substantially more difficult to remove than Hg^{2+} (3). The generally high calcium contents of lignite coals may reduce the oxidizing effect of the already low chlorine content by reactively scavenging chlorine species (Cl, HCl, and Cl_2) from the combustion flue gas. The level of chlorine in flue gases of recently tested North Dakota and Saskatchewan lignites ranged from 2.6 to 3.4 ppmv, respectively, while chlorine contents in the coal on a dry basis, ranged from 11 to 18 ppmw, respectively.

Mercury Control Options

The technologies utilized for the control of Hg will ultimately depend upon the EPA-mandated emission limits. Options being investigated have the potential to attain over 90% control of Hg emissions. The Hg control strategies at North Dakota lignite-fired power plants involve, first, the enhancement of existing control technologies and, second, investigation and development of new control technologies. The strategies include sorbent injection with and without enhancements upstream of an ESP or fabric filter (FF) and Hg oxidation upstream of a wet or dry flue gas desulfurization (FGD) system. The new technologies being investigated include Hg capture using the EERC's advanced hybrid particulate collector (AHPC) or the *Advanced Hybrid*™ filter gold-coated materials, baghouse inserts, and carbon beds (4).

Sorbent injection for removing Hg involves adsorption of Hg species by a solid sorbent injected upstream of a particulate control device such as an FF (baghouse) or ESP. Many

potential Hg sorbents have been evaluated (4). These evaluations have demonstrated that the chemical speciation of Hg controls its capture mechanism and ultimate environmental fate.

Activated carbon injection is the most mature technology available for Hg control. Activated carbons have the potential to effectively sorb Hg^0 and Hg^{2+} but depend upon the carbon characteristics and flue gas composition (4). Most activated carbon research has been performed in fixed-bed reactors that simulate relatively long-residence-time (gas–solid contact times of minutes or hours) Hg capture by an FF filter cake (5–7). However, it is important to investigate short-residence-time (seconds) in-flight capture of Hg^0 because most of the coal-burning boilers in the United States employ cold-side ESPs for controlling particulate matter emissions. The projected annual cost for activated carbon adsorption of Hg in a duct injection system is significant. Carbon-to-mercury weight ratios of 3000:18,000 (lb carbon injected/lb Hg in flue gas) have been estimated to achieve 90% Hg removal from a coal combustion flue gas containing 10 $\mu g/Nm^3$ of Hg (8). More efficient carbon-based sorbents are required to enable lower carbon-to-mercury weight ratios to be used, thus reducing the costs. Recent testing conducted at the EERC, as shown in Figures 1 and 2, illustrates the effectiveness of sorbents injected upstream of the ESP and baghouse, respectively.

EERC pilot-scale ESP and ESP–FF Hg removal efficiencies for the Fort Union lignite coals from Saskatchewan and North Dakota (Poplar River and Freedom coals) flue gases are compared in Figures 1 and 2 to those obtained at full-scale utility boilers where activated carbons were injected into a bituminous coal combustion flue gas upstream of a compact hybrid particulate collector (COHPAC) (pulse-jet FF) and into bituminous and Powder River Basin

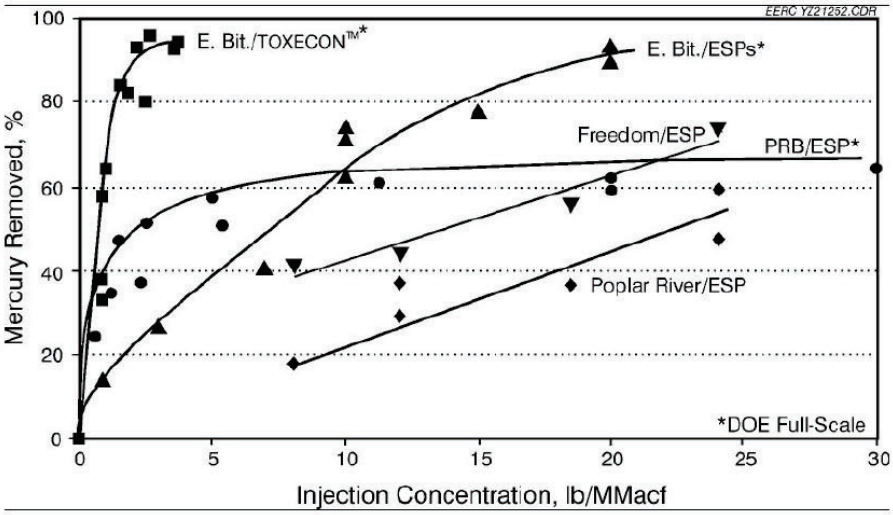

Figure 1. Pilot-scale ESP (8) and full-scale COHPAC and ESP (9) Hg removal efficiencies as a function of the ACI rate.

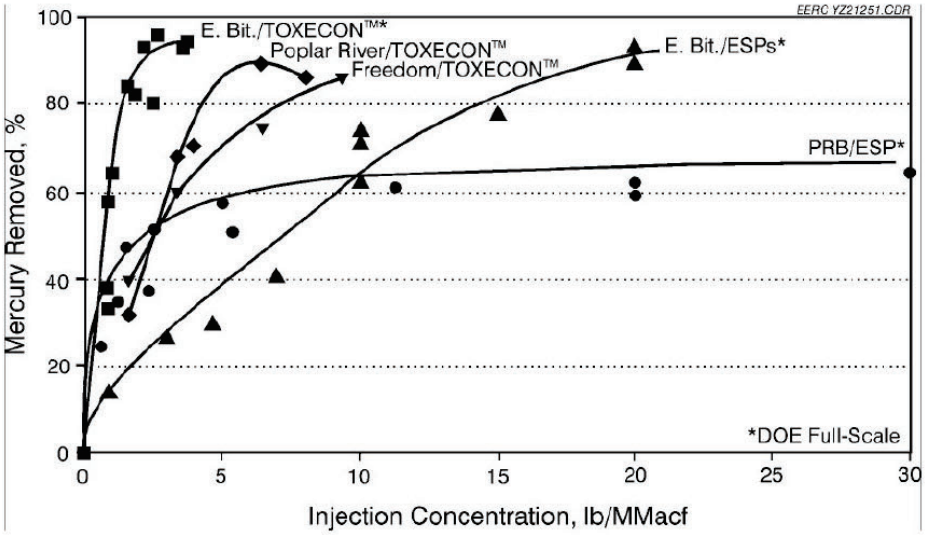

Figure 2. Pilot-scale ESP–FF (8) and full-scale COHPAC and ESP (9) Hg removal efficiencies as a function of the ACI rate.

(PRB) subbituminous coal combustion flue gases upstream of an ESP. Coal type (i.e., composition) is an important parameter that affects the Hg removal efficiency of a control device. During the pilot-scale lignite and utility-scale eastern bituminous coal tests, Hg removal efficiency increased with increasing activated carbon injection rates. Conversely, Hg removal efficiency was never greater than 70%, regardless of the activated carbon injection rate into the PRB subbituminous coal combustion flue gas. This limitation is probably caused by the low amount of acidic flue gas constituents, such as HCl, that promote Hg-activated carbon reactivity.

Testing conducted at lignite-fired power plants equipped with a spray dryer baghouse firing Fort Union lignite indicated poor performance of conventional ACI to control Hg (10). The results indicate control efficiency of less than 35% for DARCO® FGD and lignite-activated carbon (LAC). The poor results are due to the low-acid-gas-containing flue gas and the high proportion of Hg^0 in the flue gas stream. The iodine-impregnated activated carbon (IAC) showed approximately 90% control.

Researchers at the EERC and elsewhere are striving to attain a better understanding of Hg species reactions on activated carbon surfaces in order to produce more efficient sorbents. Functional groups containing inorganic elements such as chlorine or sulfur appear to have a significant role in bonding Hg (11–13). Recently, detailed analysis of sorbents derived from lignites exposed to flue gas and Hg^0 indicated the key species impacting oxidation and retention of Hg on the surface of the carbon contain chlorine and sulfur (14, 15). The chlorine reacts to form organically associated chlorine on the surface, and it appears that the organically associated chlorine on the carbon is the key site responsible for bonding with the Hg^{2+} species.

Amended silicate injection shows promise in controlling Hg emissions at coal-fired power plants (16). The amended silicates have shown improvement factors of 1.5–2 in controlling Hg emissions over activated carbon from subbituminous coal testing in a pilot-scale test. The amended silicates have not been tested using North Dakota lignites.

Mercury Oxidation

Mercury oxidation technologies being investigated for Fort Union lignites include catalysts, chemical agents, and cofiring materials. The catalysts that have been tested include a selective catalytic reduction (SCR) catalyst for NO_x reduction, noble metal-impregnated catalysts, and oxide-impregnated catalysts. The chemical agents include chlorine-containing salts and cofiring fuels that contain oxidizing agents (10).

SCR catalysts were tested for their ability to oxidize Hg; results were mixed. Mercury speciation sampling conducted upstream and downstream of SCR catalysts at power plants that fire bituminous and subbituminous coals (17) showed evidence of mercury oxidation across SCR catalysts when firing bituminous coals. However, when firing subbituminous coals, the results indicate limited oxidation. More testing needs to be conducted on low-rank coals. The ability of the SCR system to contribute to oxidation appears to be coal-specific and is related to the chloride, sulfur, and calcium content of the coal, as well as temperature and specific operation of the SCR catalyst including space velocity.

Mercury oxidation catalysts have shown high potential to oxidize Hg^0. Results in testing a slipstream at a North Dakota power plant indicated over 80% conversion to oxidized mercury for periods of up to 6 months (10). Tests were also conducted using iron oxides and chromium, with little success of oxidation. Galbreath and others (18) have conducted short-term pilot-scale testing with maghemite (γ-Fe_2O_3) additions and were able to transform about 30% of the Hg^0 in North Dakota lignite combustion flue gases to Hg^{2+} and/or Hg(p) and, with an injection of a small amount of HCl (100 ppmv), nearly all of the Hg^0 to Hg^{2+}. Theoretically, the use of chloride compounds to oxidize Hg^0 to Hg^{2+} makes sense. The evidence includes chemical kinetic modeling of bench-scale test results, indicating that the introduction of chloride compounds into the high-temperature furnace region will most likely result in the production of atomic chlorine and/or molecular chlorine, which are generally thought to be the dominant Hg^0 reactants in coal combustion flue gases (4).

Fuel additives for mercury oxidation and sorbent enhancement have recently been tested at the EERC. The results of the addition of materials with coal at very low levels along with the ACI upstream of an ESP–FF, *Advanced Hybrid*™, and ESP-only are illustrated in Figure 3. The first part of the figure shows the baseline data for Hg emissions ranging from 9 to 12 $\mu g/Nm^3$, with 80%–90% of the Hg in the elemental form. The second case is ACI followed by the addition of Additive 2, showing a reduction in Hg emissions to 90% removal. The third case is the *Advanced Hybrid*™ filter, which produced nearly 90% control efficiency. The final ESP-only case also indicated up to 90% control. The control efficiency for the ESP-only case showed significant potential improvement over past results obtained with the ESP-only illustrated in Figure 1. This technology also has the potential to improve dry FGD baghouse control efficiency.

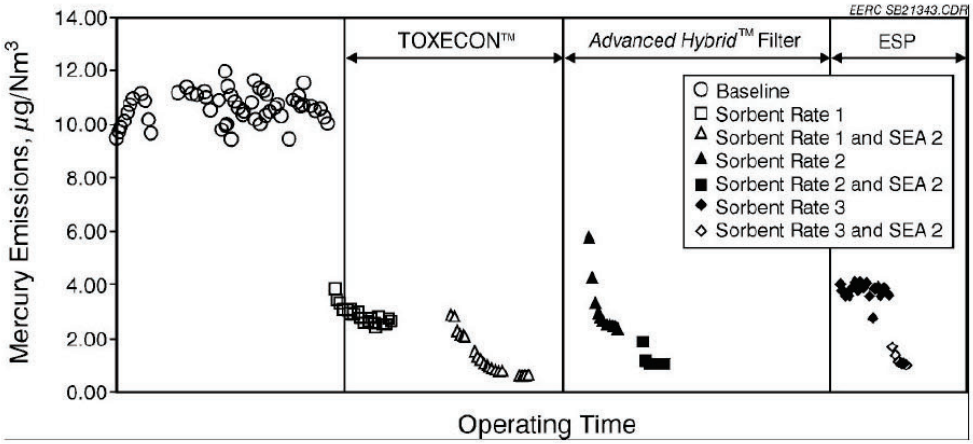

Figure 3. Hg emissions for ACI combined with additives.

Sorbent enhancement technologies (also referred to as additives [SEAs]) have also been investigated by ALSTOM Power, Inc. The sorbent preparation system enhances sorbent performance by changing the physical and chemical nature of the sorbent. The enhancement is expected to be applicable to a significant number of sorbents currently utilized for Hg control. The potential for sorbent enhancement has shown an increase from 68% to over 90% capture of Hg. These tests evaluated the performance of baseline and enhanced sorbents in entrained flow. Sorbents were injected in a duct with synthetic flue gas followed by an ESP.

Cofiring TDF at Otter Tail Power Company's Big Stone Plant has been suspected to contribute to very high reactivity of Hg with fly ash and also with carbon sorbents while firing a low-chlorine PRB coal (19). During periods of operation that coincide with cofiring TDF, enhanced Hg oxidation and removal of Hg by a particulate control device (PCD) have been observed. When about 3%–5% (Btu basis) TDF was cofired with coal at the power plant, measurements showed that the average PCD inlet Hg speciation was 55% particulate bound, 38% oxidized, and 6.4% elemental. Without carbon injection to the PCD, the natural Hg capture efficiency of the PCD was 49%. Furthermore, a carbon injection rate of 24 kg carbon/million m^3 flue gas resulted in a 91% total Hg capture efficiency at the PCD. These field test results indicate that cofiring TDF has the effect of changing the speciation of Hg at the inlet to the PCD, which facilitates Hg collection at the PCD.

Since 1995, DOE has supported development of a new concept in particulate control called the AHPC (19). The AHPC has been licensed to W.L. Gore & Associates, Inc., and is now marketed as the *Advanced Hybrid*™ filter by Gore. The *Advanced Hybrid*™ combines the best features of ESPs and baghouses in a unique configuration, providing major synergism between the two collection methods, both in the particulate collection step and in the transfer of dust to the hopper. The *Advanced Hybrid*™ filter provides ultrahigh collection efficiency, overcoming the problem of excessive fine-particle emissions with conventional ESPs, and it solves the

problem of reentrainment and re-collection of dust in conventional baghouses. The *Advanced Hybrid*™ filter appears to have unique advantages for Hg control over baghouses or ESPs as an excellent gas–solid contactor. The *Advanced Hybrid*™ filter technology can be a very cost-effective retrofit technology for plants with existing ESPs.

EXPERIMENTAL

Objective and Goals

The goal of this work is to develop advanced, innovative mercury control technologies to reduce mercury emissions by 50%–90% in flue gases typically found in North Dakota lignite-fired power plants at costs of one-half to three-fourths of current estimated costs. Power plants firing North Dakota lignite produce flue gases that contain >85% elemental mercury, which is difficult to collect. The specific objectives are focused on determining the feasibility of the following technologies: mercury oxidation for increased mercury capture in dry scrubbers and the use of mercury adsorbents within a baghouse.

PLANNED SCOPE OF WORK

Task 1 – Mercury Control Enhancement for Unscrubbed Systems Equipped with ESPs

This task will evaluate and further the ability to control Hg emissions in lignite-fired power systems equipped with an ESP, as well as provide valuable information for enhancing Hg control in other unscrubbed systems. Testing will be performed using sorbent injection on the EERC's particulate test combustor (PTC) equipped with an ESP to evaluate Hg sorbent effectiveness in coal combustion flue gases.

This task will include testing for a full week with up to two North Dakota lignite coals with one activated carbon and ADA Technologies, Inc's Amended Silicate™. In addition, a sorbent enhancement technology developed by ALSTOM Power, Inc., will be used to enhance a sorbent for injection in the flue gas duct upstream of the ESP. During ACI, several additives and sorbent enhancements will be tested to quantify the improvements in Hg removal with each. The initial testing will involve shorter-term screening tests for evaluation of the sorbent enhancement additives (roughly two per day). A final full-day test will be performed to obtain longer-term results on the performance of a selected additive. This final additive will be selected based on performance during screening tests and with consideration of cost, availability, and any issues associated with use in a utility system. Based on the test results, initial economic evaluations will be performed to determine the cost savings per pound of Hg removal in comparison to the baseline case of ACI without additives.

Task 2 – Mercury Oxidation Upstream of Wet and Dry Scrubbers

Task 2.1 – Elemental Mercury Oxidation Additives

Potential Hg^0 oxidation additives will be evaluated using the PTC equipped with the refurbished spray dryer absorber (SDA) and AHPC. Pilot-scale testing will involve a North Dakota lignite coal with short-term (1- to 2-h) screening tests of several oxidation additives including chloride compounds (e.g., sodium chloride, hydrogen chloride, calcium chloride) and potassium iodide, followed by longer-term (8- to 10-h) evaluations of two or more of the most promising additives. In most cases, the additives will be blended with the coals. Gaseous HCl will be injected into the PTC.

Hg^0 and total Hg levels will be measured on a nearly continuous basis using a continuous mercury monitor (CMM) at the inlet and outlet locations of the SDA. Slaked lime slurry feed and the SDA product solids will be analyzed for Hg content. Additive blend ratios and injection rates will be varied to evaluate the effectiveness of additives to oxidize Hg^0. Economic analyses will be performed for the additives that are most effective.

Task 2.2 – Sorbent Injection

NORIT Americas Inc., DARCO® FGD, and lignite-based activated (steam activated at 800°C, 1472°F) Luscar char (derived from Fort Union lignite) will also be injected upstream of the SDA while burning a North Dakota lignite in the PTC. One of the sorbents will be pretreated with an EERC proprietary material to enhance its sorption capacity. FGD, activated Luscar char, and the pretreated sorbent will be injected in the absence and presence of the most effective Hg^0 oxidation additive identified in Task 2.2. In addition, a proprietary sorbent enhancement technology developed by ALSTOM will be tested. CMMs will be used to measure Hg^0 and total Hg at the inlet and outlet of the SDA during each test. After each test, slaked lime slurry feed and the SDA product solids will be analyzed for Hg and carbon contents.

Task 3 – Field Tests to Determine Impacts of Oxidizing Agents on Mercury Speciation

Task 3.1 – Impacts of Cofiring on Tire-Derived Fuels

The efforts in this subtask involve testing the ability of cofiring TDF with North Dakota lignite to increase the oxidized and particulate forms of mercury at a fluid bed-fired power plant (Montana–Dakota Utilities Heskett Station Unit 2, 85 MW, ESP). Testing will include a baseline run firing 100% lignite at full load and up to 10% TDF (Btu basis). Hg and Cl species levels in the flue gas phase will be measured at the inlet and the outlet of the ESP with and without cofiring the TDF. Coal and TDF will be analyzed for basic proximate, ultimate, sulfur, and ash compositional analysis, Cl, Zn, and Hg. Total Hg collection efficiency of the ESP and the Hg speciation information will be determined.

Task 3.2 – Impacts of Oxidation Catalysts – Coyote Station Slipstream Testing

This task involves testing a Hg oxidation agent. Maghemite combined with very small amounts of HCl has been shown to oxidize Hg^0 in simulated flue gases. Currently, a slipstream reactor to test NO_x reduction catalysts is being installed at Otter Tail Power's Coyote Station in North Dakota under an existing EERC project. In Task 3.2, maghemite will be incorporated into a catalyst matrix by Haldor Topsoe, Inc. and placed into the reactor. Small amounts of HCl will be added, and the impact on Hg speciation will be measured across the reactor.

Task 4 – Particulate and Mercury Control for North Dakota Lignites Using the *Advanced Hybrid*™ Filter Technology

This task includes reconfiguring the PTC with an ESP followed by the *Advanced Hybrid*™ filter system to simulate a full-scale retrofit system. The single-wire tubular ESP will be operated at slightly reduced power to simulate the first one or two ESP fields in a full-scale system, with a goal of removing approximately 90% of the fly ash. Flue gas exiting the ESP with a reduced fly ash level will be routed to the pilot-scale (200-acfm) *Advanced Hybrid*™ filter unit.

Two sorbents (activated carbon and silicate-based sorbent) will be injected near the *Advanced Hybrid*™ filter inlet. Both continuous and batch injection modes will be tested at a flue gas temperature of 300°F. Specific sorbent injection rates will be determined based on the measured Hg concentration in the flue gas. For continuous injection, the feed rate will be varied from 2500–12,000 lb sorbent/lb Hg, and for batch injection the ratio will be set at 6000:1. The sorbent that shows the best performance will be tested at a higher flue gas temperature of 400°F, both in continuous and batch injection modes. CMMs will be used to measure Hg^0 and total Hg vapor at the ESP inlet, *Advanced Hybrid*™ filter inlet, and *Advanced Hybrid*™ filter outlet. Mercury sampling with the Ontario Hydro (OH) method will be conducted to provide Hg species information, dust loading, and particulate collection efficiencies for the retrofit *Advanced Hybrid*™ filter unit. EPA Method 26A sampling will be carried out at the *Advanced Hybrid*™ filter inlet to determine the chloride level in flue gas entering into the *Advanced Hybrid*™ filter unit. Results from the tests will be reduced, compiled, interpreted, and reported. Mercury removal efficiencies for both sorbents will be calculated, compared, and reported across the ESP, the *Advanced Hybrid*™ filter, and the ESP–*Advanced Hybrid*™ filter.

Task 5 – Field Testing of Sorbents (Revised January 2004)

This task will test how effectively Hg can be captured by using a sorbent-based technology in conjunction with a pulse-jet baghouse (PJBH) at a power plant in North Dakota. This task's work plan formerly included evaluation of a Gore technology consisting of a proprietary baghouse insert downstream of the FF that has shown a high potential to control Hg. However, Gore's recent decision to abandon their mercury research program has resulted in elimination of its inclusion in the planned scope of work. Additional sorbent evaluations will fill the void. An existing baghouse will be skid-mounted and transported to a power plant in North Dakota and connected in slipstream fashion to allow for testing actual flue gases. Additions to the existing baghouse unit for remote field application will include a control room for remote operation, piping and flanges for connection to plant ductwork, a variable-speed fan, and a sorbent injection

system for Hg control. The PJBH can operate for much longer periods of time than can the pilot-scale AHPC.

The skid-mounted baghouse will be installed downstream of an existing PCD such as an ESP. CMMs will be used to measure Hg^0 and total Hg vapor at various monitoring ports in the system. Mercury sampling with the OH method will be conducted to provide Hg species information, dust loading, and particulate collection efficiencies. In certain cases, EPA Method 101A may be used to determine the total Hg (only) removed across the baghouse system.

RESULTS AND DISCUSSION

Task 1 – Mercury Control Enhancement for Unscrubbed Systems Equipped with ESPs

Pilot-Scale Facility and Test Plan

The pilot-scale test was started on September 8, 2003, and was completed on September 19, 2003. A 550,000-Btu/hr pulverized coal (pc)-fired unit, known as the PTC, was used to fire lignites and test mercury control options. The coal combustion flue gas exiting the PTC was cooled down to a nominal temperature of 149°C (300°F) and then was introduced into a single-wire tubular ESP unit. Figure 4 shows the schematic diagram of the system. Furnace additives were added to coal prior to introduction to the furnace. Mercury sorbents were fed with a K-Tron dual-screw feeder upstream of the ESP.

CMMs were used to monitor mercury vapor concentrations at the ESP inlet (Site 1) and outlet (Site 2) 24 h per day for the entire testing period. Several OH method samples (ASTM D6784 Standard Test Method for Elemental, Oxidized, Particle-Bound and Total Mercury in Flue Gas Generated from Coal-Fired Stationary Sources) were collected at the ESP inlet and outlet throughout the testing period as verification of the CMM data.

Fourteen tests were completed to evaluate various sorbent and mercury oxidant performance on mercury removal across the ESP as functions of feed rate. A detailed test matrix is listed in Table 1. Ten additional tests were performed to evaluate mercury control with the *Advanced Hybrid*™ filter and are summarized under Task 4 Results and Discussion.

Coal and Combustion Flue Gas Analyses

North Dakota Freedom lignite was tested in the PTC at the EERC. The proximate and ultimate analysis data for the Freedom lignite are reported in Table 2, showing a concentration of mercury in the range of 0.0503–0.0515 µg/g (dry basis), with a mean value of 0.0508 µg/g. Based on the proximate and ultimate analysis data, it was calculated that 1 lb of coal would produce 89 scf of dry flue gas normalized to a 3.0% oxygen level. From the mercury content in raw coal, the total mercury concentration in flue gas was expected to be 7.2 $\mu g/m^3$ of dry flue gas (at a 3% oxygen level).

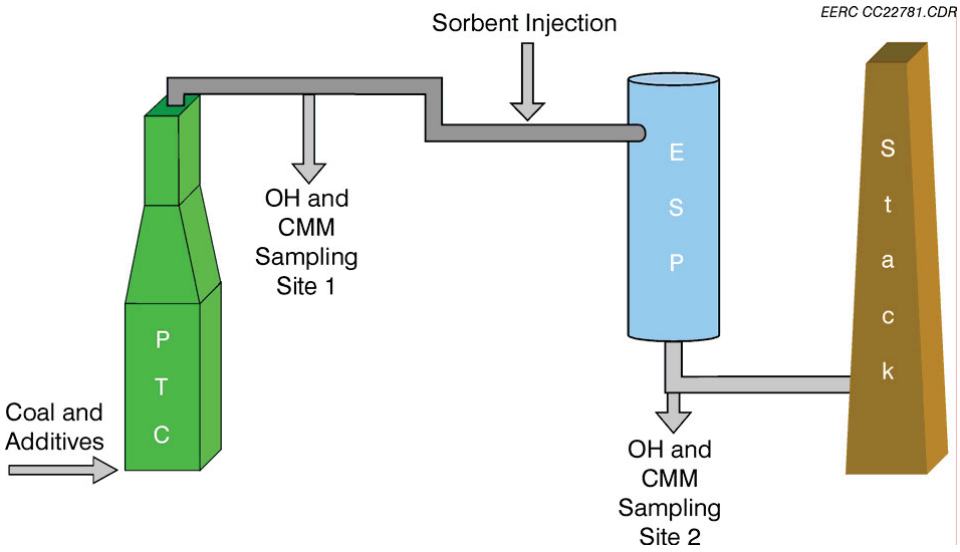

Figure 4. Injection and sampling schematic of the PTC with an ESP.

Table 1. Test Matrix for Unscrubbed Systems Equipped with ESPs

Test No.	Mercury Oxidant Additive		Sorbent	
	Category	Injection Rate, lb/Macf	Category	Injection Rate, lb/Macf
T1-1(Baseline)	None	NA	None	NA
T1-2	None	NA	DARCO® FGD	2.75–18.4
T1-3	NaCl	3.76–14.7	None	NA
T1-4	NaCl	3.76–14.7	DARCO® FGD	2.75–4.59
T1-5	SEA 2	1.84–7.34	None	NA
T1-6	SEA 2	1.84	DARCO® FGD	2.57
T1-7	NaCl	7.34–11.0	HCl-Treated FGD	2.57–4.59
T1-8	None	NA	EERC-Treated Carbon	1.84–2.75
T1-9	SEA 2	1.84	EERC-Treated Carbon	2.75
T1-10	Zn	7.34	None	NA
T1-11	Zn and NaCl	7.34–11.0	None	NA
T1-12	None	NA	Na_2S_4 (solution)	0.89–6.67
T1-13	$CaCl_2$	11	DARCO® FGD	0–4.59
T1-14	None	NA	ALSTOM Sorbent	1.1–3.1

Table 2. Coal Analysis of Freedom Lignite for Run PTC-FM-639

Proximate Analysis, %	As Sampled	Moisture Free
Moisture Content	31.90	NA
Volatile Matter	30.70	45.05
Fixed Carbon	29.12	42.79
Ash	8.29	12.16
Ultimate Analysis, %		
Hydrogen	6.33	4.10
Carbon	41.26	60.55
Nitrogen	0.78	1.15
Sulfur	0.73	1.07
Oxygen	42.61	20.97
Ash	8.29	12.16
Mercury Concentration in Coal, µg/g		
Sample 1		0.0503
Sample 2		0.0507
Sample 3		0.0515
Sample 4		0.0505
Mean		0.0508

The flue gas compositions, O_2, CO_2, CO, NO_x, and SO_2, at the combustor outlet were monitored during the entire testing period, and hourly average values were calculated and plotted as a function of operating time. The CO concentration was in the range 3–6 ppm for most of the testing period, indicating complete coal combustion. CO spikes were observed on September 10–12, 2003, showing somewhat incomplete coal combustion at that time. The SO_2 concentration in the flue gas ranged from 300 to 1200 ppm, depending on the coal feed rate, while the theoretical value of the SO_2 concentration was calculated at 1026 ppm, based on sulfur content and proximate and ultimate coal analyses. The NO_x concentration in the flue gas was 221–770 ppm. The HCl concentration in flue gas was also measured using EPA Method 26, showing 0.58–1.45 ppm. Because of the low levels of CO, NO_X, SO_2, and HCl and historical data, most mercury in the Freedom lignite flue gas was expected to be in the elemental vapor phase (Hg^0).

Mercury Speciation Across the ESP in the Baseline Test

During the pilot-scale test, Freedom lignite with a mean mercury content of 0.05 µg/g (dry basis) was combusted at a nominal feed rate of 87 lb/hr. The coal combustion flue gas exiting the PTC was cooled down to a nominal temperature of 149°C (300°F) and then was introduced into a single-wire tubular ESP unit. The ESP was operated at 40–60 kV with a corona current of 4.0 mA. The collection plates and electrodes were rapped every 120 min. The hopper ash was emptied between tests. Two CMMs were used to monitor mercury vapor concentrations at the ESP inlet and outlet. OH method samples were collected to verify the CMM data. The purpose of the baseline test (T1-1) was to establish speciated mercury concentrations in Freedom lignite flue gas and determine whether there was a change in speciation across the ESP unit. Based on CMM data, the daily average mercury vapor concentrations in Freedom lignite combustion flue gas, both total and speciated, are shown in Figure 5. The error bars represent plus or minus one

standard deviation. No particulate mercury for the CMM is shown because the flue gas was sampled through a filter. Oxidized mercury vapor in the flue gas was in the range of 0.09–1.30 μg/Nm^3, while elemental mercury (Hg^0) vapor was dominant, in the range of 5.52–8.13 μg/Nm^3. The total mercury vapor concentration (Hg^{gas}) in the flue gas varied from 6.8 to 9.2 μg/Nm^3 (dry flue gas, 3% O_2), showing an average mercury level of 7.57 μg/Nm^3, compared to the theoretical value of 7.2 μg/Nm^3 obtained from the coal combustion calculation based on the coal analysis. The above CMM data indicate that most of the mercury released from Freedom lignite combustion was in vapor phase before it entered into the ESP, and elemental mercury vapor was the dominant species.

To determine inherent mercury capture by fly ash across the ESP, mercury concentrations were measured with CMM's and the OH method both at the ESP inlet and outlet, and the results are plotted in Figure 6. Both methods indicate that the majority of mercury was present as elemental mercury vapor, with a small fraction (10.9%–12.9%) of oxidized mercury and nearly no particulate associated mercury at the ESP inlet. The total mercury concentration at the ESP outlet was almost the same as the ESP inlet, showing virtually no mercury capture across the ESP due to the low level of particulate mercury in the flue gas, which is very typical for North Dakota lignite with the ESP configuration. Comparison between the two sampling methods shows consistent results, with the OH method measurement slightly higher than the CMM results. ESP hopper ash was collected to analyze mercury content, loss on ignition (LOI), and chlorine and sodium concentrations. The results are listed in Table 3. The mercury content in the ESP hopper ash was 0.0139 μg/g, close to the 0.003–0.00783 μg/g at the ESP inlet, as indicated by the OH method data. This was not surprising based on the low levels of LOI (0.35%) and chlorine (206 μg/g) in the ESP hopper ash.

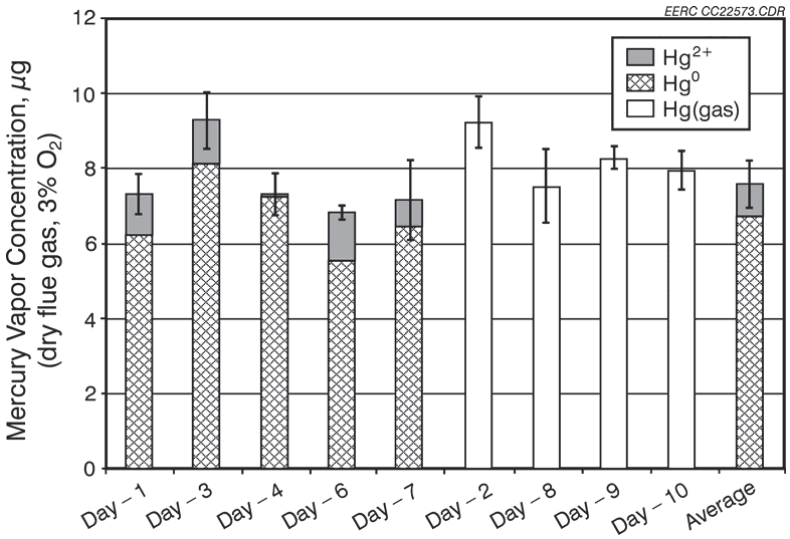

Figure 5. Mercury vapor concentration in Freedom coal flue gas – baseline.

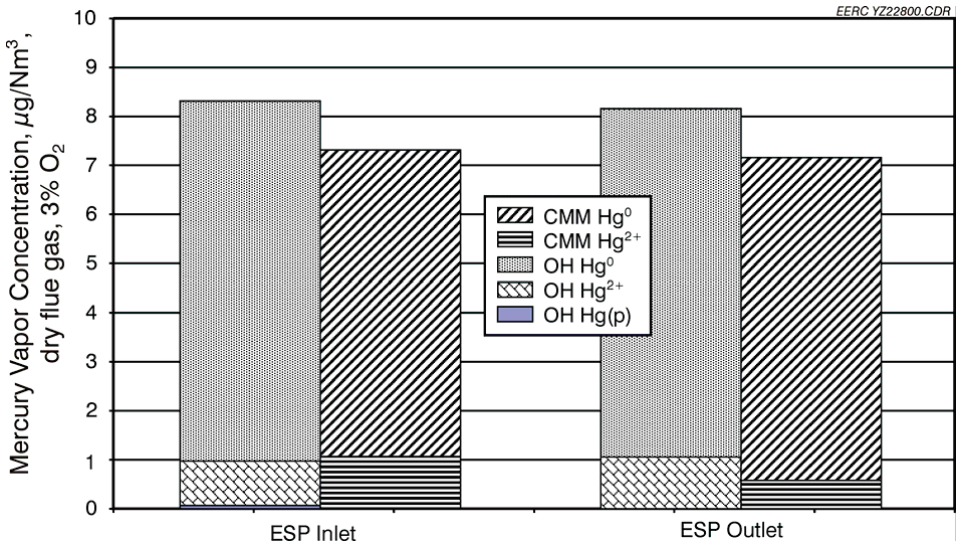

Figure 6. Mercury speciation across the ESP baseline data for Freedom coal, 300°F.

Table 3. ESP Hopper Ash Analysis Results – NaCL/FGD Injection

	Baseline	DARCO® FGD	NaCl	NaCl + DARCO® FGD
LOI, %	0.35	1.28	0.46	0.94
Mercury, µg/g	0.0139	0.189	0.198	0.381
Chlorine, µg/g	206	NA	3820	5440
Sodium, µg/g	11,200	NA	12,200	18,700

Draft copies of the results of Task 1 have been submitted to the commercial sponsors for their review prior to submission as part of a DOE quarterly or final report.

Task 2 – Mercury Oxidation Upstream of Wet and Dry Scrubbers

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As part of the effort to obtain information on possible mercury control technology options for North Dakota lignite-fired power plants, several short-term pilot-scale tests involving Tasks 2.1 and 2.2 were performed during a 4-day test period. Some preliminary results are presented here.

Task 2.1 – Elemental Mercury Oxidation Additives

One week of short-term sorbent (Task 2.2) and furnace additive testing was accomplished in December 2003 to demonstrate mercury removal by sorbent injection combined with various oxidizing additives to simulate a scrubbed baghouse system. The 580 MJ/h (550,000 Btu/h) pulverized coal PTC unit was equipped with a Niro Inc. Produciton Minor Spray Dryer Model I

and baghouse and fired with Center lignite coal. Table 4 summarizes the test matrix for the spray dryer–baghouse configuration. Based on previous pilot-scale testing results of ESP mercury removal effectiveness, three additives (NaCl, $CaCl_2$, and another for which the EERC is assessing the intellectual property issues) were evaluated. CMMs were set up at the inlet to the spray dryer upstream of the sorbent injection port at the outlet of the baghouse to monitor mercury vapor concentrations continuously throughout the 4-day test. Six OH method samples were collected at the same locations to verify CMM measurements and performance of the sorbents and additive injection. A Thermo Environmental Model 15C HCl analyzer was colocated with the CMMs upstream of the spray dryer inlet to measure changes in the chloride levels of the flue gas resulting from chlorine-containing furnace additives. Figure 7 shows the simultaneous HCl and mercury levels for the second day of testing. A preliminary review of the data indicates increased HCl content in the flue gas with increasing NaCl addition in the furnace. This is the first time, to our knowledge, that HCl and mercury concentrations have been measured simultaneously in a coal combustion flue gas. The experimental data are being reduced and interpreted. The results will be reported in an upcoming quarterly report as well as in the project final report.

Table 4. Spray Dryer Test Sample Matrix (December 2004 run)

Mercury Oxidation Additive		Sorbent	
Type	Feed Rate, lb/Macf	Type	Injection Rate, lb/Macf
None	NA	None	NA
None	NA	DARCO® FGD	1.84 – 11.02
None	NA	EERC-Treated FGD	1.84 – 7.35
None	NA	Amended Silicate™	7.35
NaCl	3.67 – 11.02	None	NA
NaCl	3.67 – 11.02	DARCO® FGD	3.67
SEA 2	1.84 – 3.67	None	NA
SEA 2	1.84 – 3.67	DARCO® FGD	1.84
$CaCl_2$	3.67 – 11.02	None	NA
$CaCl_2$	3.67 – 11.03	DARCO® FGD	3.67

Task 2.2 – Sorbent Injection

As described in Task 2.1 and Table 4, one week of short-term sorbent and furnace additive testing (Task 2.1) was accomplished in December 2003. Based on previous pilot-scale testing results of ESP mercury removal effectiveness, three different sorbents (DARCO® FGD activated carbon, supplied by NORIT Americas, Inc.; an EERC-treated activated carbon; and Amended Silicate™ developed by ADA Technologies, Inc.) were selected for evaluation in the PTC with a spray dryer–baghouse pollution control configuration. Preliminary results for the DARCO® FGD sorbent injection, presented in Figure 8, suggest that the efficiency of the DARCO® FGD for mercury capture neared maximum when the injection rate reached 4.35 lb/Macf. At the top rate, the activated carbon sorbed nearly 57% of the mercury in the pilot-scale flue gas. The experimental data are being reduced and interpreted, and the results will be reported in an upcoming quarterly report and/or the final project report.

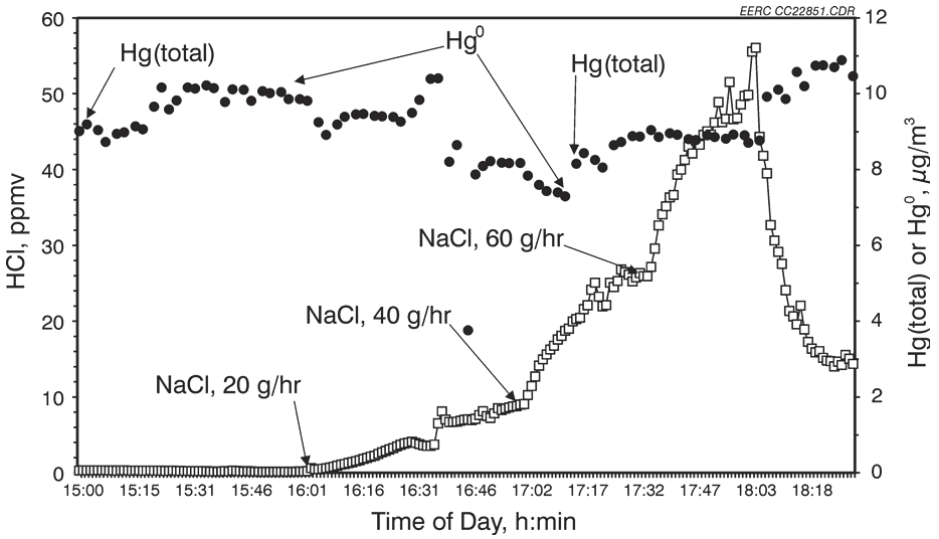

Figure 7. Variability of HCl and mercury (Hg[total] or HgO) levels in a pilot-scale flue gas stream in a spray dryer–baghouse configuration during chlorine additions into a Center lignite coal-fed furnace.

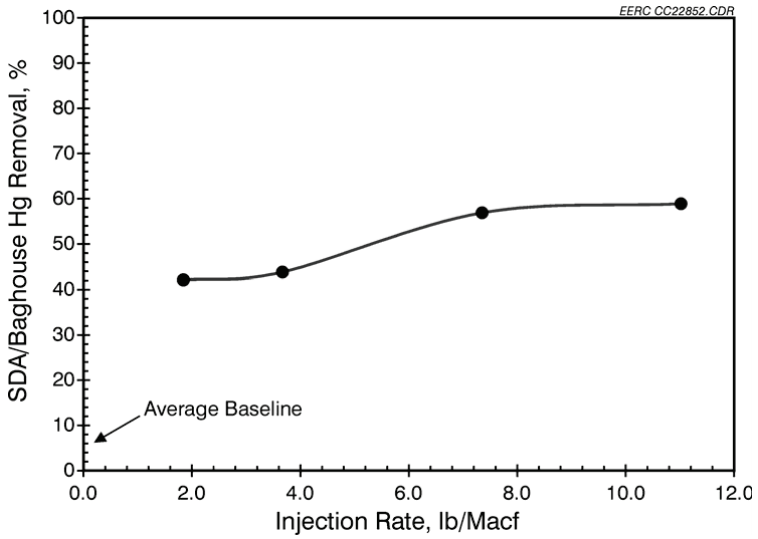

Figure 8. Mercury removal efficiency of DARCO® FGD sorbent injection into a pilot-scale Center lignite coal combustion flue gas stream in a spray dryer–baghouse configuration.

Task 3 – Field Tests to Determine Impacts of Oxidizing Agents on Mercury Speciation

Task 3.1 – Impacts of Cofiring on Tire-Derived Fuels

The activities this quarter involved finding a supplier for the TDF. The testing is scheduled to begin this spring at Montana–Dakota Utilities Heskett Station. Conversations have begun with Montana–Dakota Utilities. A field trip is being planned to the Heskett Station. This activity will begin in the next quarter.

Task 3.2 – Impacts of Oxidation Catalysts – Coyote Station Slipstream Testing

A catalyst has been acquired from Haldor Topsoe for this activity. The reactor is installed at the Coyote Station under a current contract. The testing is scheduled to begin in April 2004.

Task 4 – Particulate and Mercury Control for North Dakota Lignites Using the *Advanced Hybrid*™ Filter Technology

The *Advanced Hybrid*™ filter, which was developed by the EERC with the support of DOE and W.L. Gore & Associates Inc., combines electrostatic and fabric filtration into the same vessel. Extensive pilot-scale testing indicates that the *Advanced Hybrid*™ filter provides high >99.99% particle collection efficiency under high air-to-cloth ratio and long bag-cleaning intervals with reasonable pressure drop. The *Advanced Hybrid*™ filter has unique advantages for mercury control since it provides excellent gas–solid contact in a sorbent injection application, and the gas–solid contact is expected to be further improved under a low dust-loading environment. Figure 9 shows the schematic diagram of the system. The first stage of the ESP removes approximately 90% of fly ash in the flue gas before entering into the retrofitted *Advanced Hybrid*™ filter. Selected sorbents were fed with a K-tron dual-screw feeder downstream of the ESP before the flue gas entered into the retrofitted *Advanced Hybrid*™ filter. Both continuous and batch injection modes were tested as functions of the flue gas temperature (300°F and 400°F) and injection rate. Mercury oxidants were fed into the furnace with the Freedom lignite. Three CMMs were used to monitor mercury vapor concentrations at the combustor outlet (Site 1) and the *Advanced Hybrid*™ filter inlet (Site 2) and outlet (Site 3) continuously during the testing period. OH method sampling was also performed to verify the CMM data. OH method measurements also provide information on particle collection efficiency for the retrofitted *Advanced Hybrid*™ filter.

The pilot-scale test using Freedom lignite was carried out from September 8, 2003, to September 19, 2003. The ADA Amended Silicate™ sorbent was not available during the test because of a product quality problem at ADA. A summary of the test matrix for this task is listed in Table 5. DARCO® FGD and regenerated FGD were tested for mercury removal in the *Advanced Hybrid*™ filter in 300°F and 400°F flue gas with both continuous and batch injection modes. Also, mercury oxidants including NaCl, SEA 2, and zinc were examined for their impacts on mercury removal.

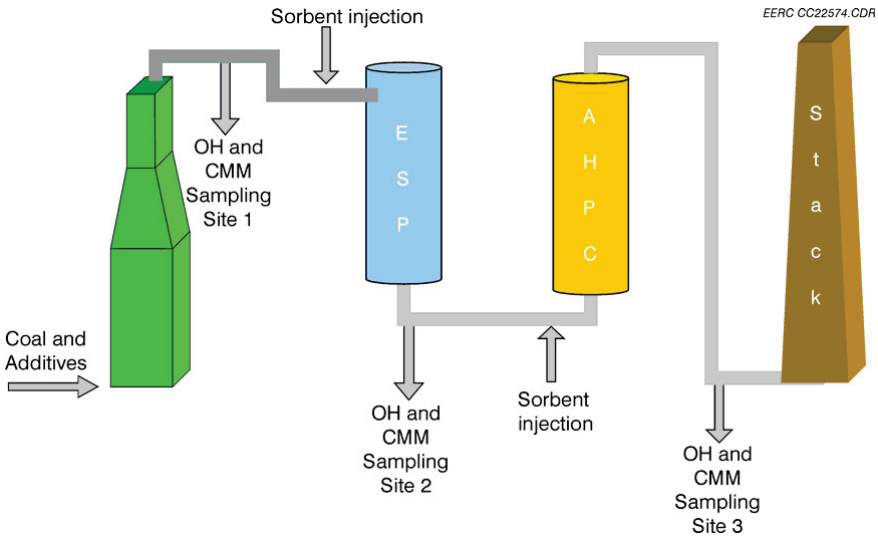

Figure 9. Injection and sampling schematic of the PTCD with an ESP and *Advanced Hybrid*™ filter.

Table 5. Test Matrix for Retrofitted *Advanced Hybrid*™ filter – Task 4

	Mercury Oxidant		Sorbent		Sorbent Injection Mode	Temperature, °F
	Category	Injection Rate, lb/Macf	Category	Injection rate, lb/Macf		
T4-1	None	NA	None	NA	NA	300
T4-2	None	NA	DARCO® FGD	0–8.08	Continuous	300
T4-3	None	NA	DARCO® FGD	0–8.08	Batch	300
T4-4	None	NA	DARCO® FGD	0–4.59	Continuous	400
T4-5	None	NA	DARCO® FGD	2.02	Batch	400
T4-6	NaCl	0–11	NA	None	NA	300
T4-7	SEA 2	0–7.34	NA	None	NA	300
T4-8	Zn/NaCl	7.34–11	NA	None	NA	300
T4-9	NaCl	3.67–7.34	DARCO® FGD	1.22–2.57	Batch/Cont.	300
T4-10	None	NA	Re-gen.	2.2	Batch	300

Task 1 and Task 4 were commingled to produce maximum results with minimum testing days. The Freedom coal flue gas compositions and mercury levels are the same as in Task 1 and are described in Task 1.

Advanced Hybrid™ Filter Operation

The first stage of the ESP was operated at 2B3 mA corona current levels to remove 90%–95% fly ash in the flue gas. The retrofitted *Advanced Hybrid*™ filter was operated under 40–60 kV with 4 mA corona current. The A/C ratio was set at 12 ft/min. Pressure drop across the filter bags started at 2.5 in. W.C. with cleaning bags, and slowly rose because of the particle accumulation on the bag surface. The sorbent injection prior to the *Advanced Hybrid*™ filter and mercury oxidant additions into the furnace did not cause any operating difficulties in electrostatic precipitation control or bag cleanability. Particulate matter emission out of the *Advanced Hybrid*™ filter was 0–0.0002 g/scf according to the OH method dust loading measurements at the *Advanced Hybrid*™ filter outlet, indicating an extremely high particle collection efficiency >99.9% based on the 0.148–0.22 g/scf dust loading at the combustor outlet.

Mercury Speciation Across the Advanced Hybrid™ Filter in Baseline Test

During the pilot-scale test, Freedom lignite with a mean mercury content of 0.05 µg/g (dry basis) was combusted at a nominal feed rate of 87 lb/hr. The coal combustion flue gas exiting the PTC was cooled down to a designated temperature of 149°C (300°F) and was then introduced into the single-wire tubular ESP unit followed by the *Advanced Hybrid*™ filter. Three CMMs were used to monitor mercury vapor concentrations at the combustor outlet and the *Advanced Hybrid*™ filter inlet and outlet. OH method samples were collected at the three locations to verify the CMM data. The purpose of the baseline test (T4-1) was to establish speciated mercury concentrations in Freedom lignite flue gas and determine whether there were changes in mercury speciation across the overall unit. CMM and OH method measurements are plotted in Figure 10, and both methods indicate most mercury from Freedom lignite combustion presented as elemental vapor, with 10.9%–12.9% oxidized mercury and virtually no particle-associated mercury. The total mercury concentrations at the *Advanced Hybrid*™ filter inlet and outlet are almost the same as the combustor outlet, indicating no further mercury capture across the unit.

Mercury removal across the *Advanced Hybrid*™ filter was evaluated with sorbent injection, mercury oxidant addition, and combinations of sorbent and mercury oxidant. The sorbents were injected upstream of the *Advanced Hybrid*™ filter, while the mercury oxidants were added to the coal prior to introduction to the furnace. Draft copies of the results of Task 4 have been submitted to the commercial sponsors for their review prior to submission as part of a DOE quarterly or final report.

Task 5 – Field Testing of Sorbents

Modifications to the existing baghouse chamber were nearly completed during this quarter. The baghouse will be mounted on a flatbed trailer for ease of transport and installation at any location. The trailer was purchased and is being modified so that the baghouse will remain stable

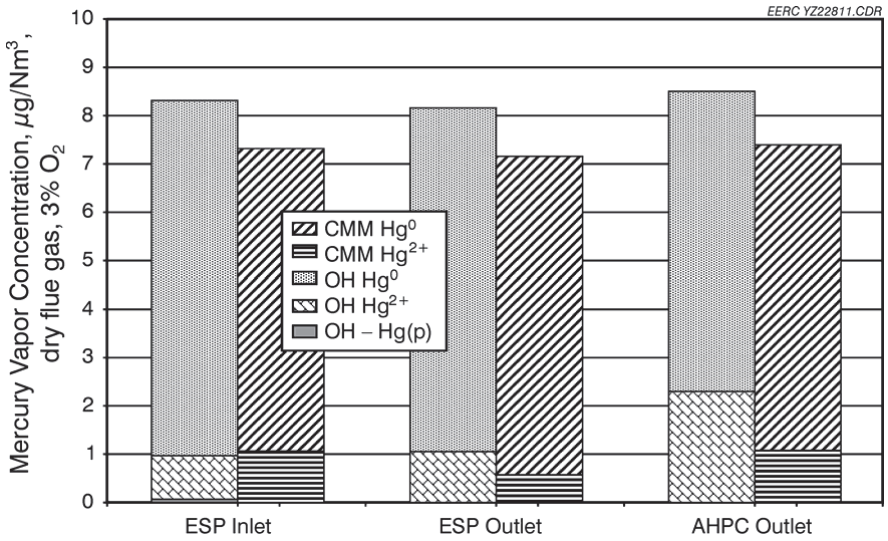

Figure 10. Mercury speciation across the ESP and *Advanced Hybrid*™ filter in Freedom coal flue gas (baseline, 300°F).

during long-term operation at a host utility. The baghouse under construction still needs to bemounted on the trailer. This is expected to be completed by the end of February. Purchase orders for the fan, control room, piping, and auxiliary equipment have been issued, and the majority of the equipment is on-site.

The field test plan was completed. Installation in the field is scheduled for March. Test plan objectives are:

- To demonstrate that mercury can be effectively captured by injecting a sorbent upstream of a slipstream baghouse drawing flue gas at the exit of an ESP.
- To compare the mercury removal performance of sorbent-based and furnace additive technologies.

Testing will be performed at Basin Electric Cooperative's Leland Olds Unit 1 to determine how effectively mercury can be captured by using sorbent-based and furnace additive technologies in conjunction with a baghouse. A trailer-mounted baghouse will be transported to the Leland Olds Station and connected in slipstream fashion to allow for testing of "real" flue gases under actual operating conditions.

The slipstream baghouse chamber is designed to accommodate twelve 6-in. FFs, with bag lengths up to 12 ft. This equates to approximately 226 ft^2 of filtration area. New bags and cages will be installed in the baghouse as appropriate to meet the objectives of the test. To connect the

slipstream baghouse to the outlet of the ESP at Leland Olds Unit 1, two separate 10-in. flanges will be required, one at the immediate exit of the ESP and the other downstream of this location but upstream of the induced draft (ID) fan. It is assumed that Basin Electric will provide these connections at no charge to the project.

A variable-speed blower is provided as part of the mobile unit and is capable of drawing between 450 and 2700 acfm of flue gas (≈ 300°F) through the slipstream device for a filter face velocity between 2 and 12 ft/min. The blower will be controlled at a rate sufficient to draw gases at or near the maximum system flow of 2700 acfm for all test conditions. An 8-in. baghouse bypass line will be utilized as a flow control mechanism. Flow control will be provided by utilization of an orifice meter on the baghouse effluent stream with a flow control valve inserted in the 8-in. bypass line. Utilization of the bypass line allows for a constant draw of flue gas, maintaining isokinetic flow at the inlet nozzle for all test conditions. In addition, pipe velocities will be maintained near 75 ft/sec for all test conditions, preventing dropout of fly ash particles. The baghouse chamber will utilize between one and three inlet ports (5-in. diameter), depending upon test conditions. Gases will be drawn from an 8-in. header at the baghouse inlet. The baghouse chamber and inlet piping runs will be insulated, with heat-traced lines used to maintain temperatures above a specified minimum, assumed to be 280°F.

Tentatively, the EERC would transport the mobile unit to the Leland Olds Station early next spring. Basin Electric would provide the following:

- Access to the plant
- Assistance and cooperation from plant personnel during planning and while on-site
- Assistance from plant personnel to adjust valve positions, if required, and change out ash collection barrels between site visits
- A site location with level grade to place the trailer and mobile unit
- A 10-in. duct connected near the ESP outlet
- A 10-in. return duct connected upstream of the ID fan
- An adequate source of low-voltage (480-V) three-phase electricity (≈ 60 amps)
- Approximately 120 amps of three-phase (120-V) electricity
- An adequate source of house air (⅜–½-in. line)
- A dedicated phone line for remote control of the system

The EERC would need approximately 1 week for setup and shakedown testing before testing could begin. Once set up, the EERC would begin testing according to the matrix in Table 6. The EERC trailer-mounted sorbent injection system will begin injecting the DARCO®

Table 6. Portable Baghouse Slipstream Test Matrix at Leland Olds Unit 1

Mercury Oxidant		Sorbent		Baghouse
Category	Injection Rate, lb/Macf	Category	Injection Rate, lb/Macf	Face Velocity, ft/min
None	NA	NA	NA	4
None	NA	DARCO® FGD	1 (50% Hg^0 removal)	4
None	NA	DARCO® FGD	3 (70% Hg^0 removal)	4
None	NA	DARCO® FGD	5 (90% Hg^0 removal)	4
Chlorine	TBD	DARCO® FGD	TBD[1]	4
Chlorine	TBD	DARCO® FGD	TBD[1]	7
Chlorine	TBD	DARCO® FGD	TBD[1]	10

[1] To be determined experimentally to achieve a specific mercury removal rate.

FGD activated carbon. This test is planned to last approximately 1 week and will involve injecting the sorbent at various rates at the inlet to the trailer-mounted baghouse. Temperature will be maintained above a specified minimum set point as described above. During the weeklong test, air/cloth ratios will be varied to achieve face velocities between 4 and 10 ft/min to investigate the effect of face velocity on mercury control. Sorbent injection will be performed using a self-contained feed system, injecting sorbent into the 8-in. header at the entrance to the baghouse at an expected rate of 2–10 lb/MMft^3, depending on the level of mercury reduced. Daily activities are outlined as follows:

- Days 1 and 2 – Face velocity maintained at 4 ft/min (905 acfm). Sorbent injection will be varied from 0 to 5 lb/Macf (nominally) to achieve 80%–90% mercury removal.

- Day 3 – Face velocity maintained at 4 ft/min (905 acfm). Chlorine injection in the slipstream (upstream of the sorbent injection) begins. Sorbent injection rate will be adjusted to achieve specific mercury removal as established under the test performed during Days 1 and 2.

- Days 4 and 5 – Face velocity varied from 7 to 10 ft/min (1580 – 2260 acfm). Sorbent injection rate set at same rate as established under the test performed during Days 1 and 2.

During this test period, CMMs will be operated and limited OH sampling will be conducted. CMMs will be installed at the ESP inlet and baghouse outlet. OH Method sampling will take place at the baghouse inlet and outlet. Standard quality assurance/quality control (QA/QC) practices will be followed for all mercury-sampling activities. A field spike and blank will be taken during each sampling period, and all samples will be done in triplicate.

Results from the tests will be reduced, compiled, interpreted, and reported. Mercury removal efficiencies for the sorbent-based and furnace additive technologies will be calculated,

compared, and reported. Data available from mercury CMMs and OH sampling will be adjusted to flue gas conditions and reported, along with other data provided by the plant.

FUTURE WORK – NEXT QUARTER

Work in the upcoming quarter will involve data reduction and interpretation of existing experimental data related to the ESP, *Advanced Hybrid*™ filter, and spray dryer–baghouse test runs; completion and installation of the portable baghouse unit for field testing; and preparations for field testing. Specifically:

- The results from test runs performed under Tasks 1 and 4 have been distributed to the project's commercial sponsors for review and comments. Once comments are received and addressed, the results will be released to DOE.
- The experimental data from test runs performed under Task 2 will be further reduced and interpreted. Ash samples from the pilot-scale activities will be analyzed. Discussion of the results will be included in the next quarterly.
- With field tests for Task 3 expected to begin in the second quarter of 2004, activities in the upcoming quarter will focus on site and field trip preparations for the field tests.
- Construction activities under Task 5 will complete the installation of the baghouse and auxiliary equipment on the trailer bed. Concurrently, site and field trip preparations will begin for the Leland Olds field test scheduled to begin the second quarter of 2004.

An updated milestone chart is presented in Figure 11.

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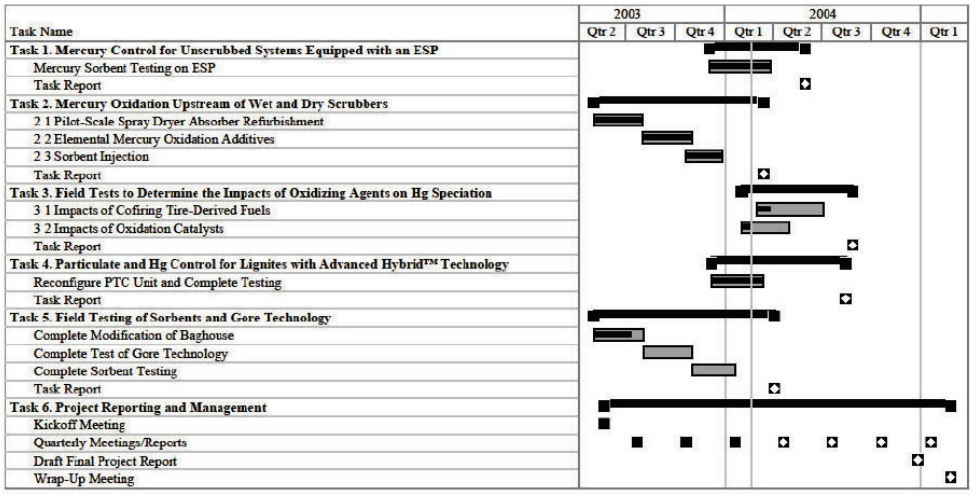

Figure 11. Milestone chart.

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1. Document Title: PILOT- AND FULL-SCALE DEMONSTRATION OF ADVANCED MERCURY CONTROL TECHNOLOGIES FOR LIGNITE-FIRED POWER PLANTS

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