PRELIMINARY FIELD EVALUATION OF MERCURY CONTROL USING COMBUSTION MODIFICATIONS

Final Report

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Abstract

In this project EER conducted a preliminary field evaluation of the integrated approach for mercury (Hg) and NO_x control. The approach enhanced the "naturally occurring" Hg capture by fly ash through combustion optimization, increasing carbon in ash content, and lowering ESP temperature. The evaluation took place in Green Station Units 1 and 2 located near Henderson, Kentucky and operated by Western Kentucky Energy. Units 1 and 2 are equipped with cold-side ESPs and wet scrubbers. Green Station Units 1 and 2 typically fire two types of fuel: a bituminous coal and a blend of bituminous coals based on availability.

Testing of Hg emissions in Unit 2 without reburning system in operation and at minimum OFA demonstrated that efficiencies of Hg reduction downstream of the ESP were 30-40%. Testing also demonstrated that OFA system operation at 22% air resulted in 10% incremental increase in Hg removal efficiency at the ESP outlet. About 80% of Hg in flue gas at ESP outlet was present in the oxidized form.

Testing of Hg emissions under reburning conditions showed that Hg emissions decreased with LOI increase and ESP temperature decrease. Testing demonstrated that maximum Hg reduction downstream of ESP was 40-45% at ESP temperatures higher than 300^{o}F and 60-80% at ESP temperatures lower than 300^{o}F. The program objective to demonstrate 80% Hg removal at the ESP outlet has been met.

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Executive Summary

In this project EER conducted a preliminary field evaluation of the integrated approach for mercury (Hg) and NO_x control. The integrated Hg/NO_x control method utilized coal reburning (injection of reburning coal and overfire air) and ESP optimization. The approach enhanced the "naturally occurring" Hg capture by fly ash through combustion optimization, increasing carbon in ash content, and lowering ESP temperature. Another benefit of the approach includes reduced NO_x emissions.

The evaluation took place in Green Station Units 1 and 2 located near Henderson, Kentucky and operated by Western Kentucky Energy. Units 1 and 2 are sister units with similar boiler parameters and unit configurations. They are equipped with cold-side ESPs and a wet scrubber. Green Station Units 1 and 2 typically fire two types of fuel: a bituminous coal and a blend of bituminous coals based on availability. Mercury content in coal blend is typically lower than that in the individual coal.

The approach to optimizing reburning for Hg control included pilot-scale testing to determine effects of process conditions and fuel composition on Hg removal, engineering evaluation to determine optimum boiler operation conditions for Hg removal, and a Unit 2 optimization test program for Hg control.

The program focused on optimizing combustion conditions and ESP temperature to maximize Hg reduction across the ESP. The ESP temperature was decreased by decreasing unit load. The project goal was to demonstrate 80% Hg control downstream of the ESP.

Testing of Hg emissions in Unit 2 without reburning system in operation and at minimum OFA demonstrated that Hg reductions downstream of ESP for coal and blend firing were 30-40%. Mercury emissions at the ESP outlet were 5.8-6.9 lb/TBtu and 2.7-3.7 lb/TBtu for coal and blend firing, respectively. Testing demonstrated that OFA system operation at 22% air resulted in 10% incremental increase in Hg removal efficiency at ESP outlet. About 80% of Hg in flue gas at ESP outlet was present in the oxidized form.

Pilot-scale testing in a 300 kW Boiler Simulator Facility was conducted to determine effects of process conditions and fuel composition on Hg removal. Testing focused on determining effects of the following factors on Hg removal: (a) fuel composition, (b) carbon in ash content (also characterized as Loss On Ignition, or LOI), and (c) ESP temperature. Testing demonstrated that Hg removal improved with LOI increase and ESP temperature decrease.

Results of pilot-scale testing suggested that 80% Hg control at ESP outlet could be achieved at LOI ≥8% and ESP temperatures ≤ 300^{o}F.

Testing of Hg emissions in Units 1 and 2 under reburning conditions confirmed that Hg emissions decreased with LOI increase and ESP temperature decrease. Testing demonstrated that maximum Hg reduction downstream of ESP was 40-45% at ESP temperature higher than 300^{o}F and 60-80% at ESP temperatures lower than 300^{o}F. The 80% Hg control downstream of ESP was achieved for blend firing for LOI in the range of 10-11% and ESP temperature in the range of 270-285^{o}F.

Testing also demonstrated that incremental efficiency of Hg removal across the FGD system was in the range of 65-70%. Most Hg at the stack was present in the elemental form. Mercury emissions at the stack were in the range of 1.8-3.0 lb/TBtu and 1.0-1.5 lb/TBtu for coal and blend firing, respectively.

Under optimized reburning conditions NO_x emissions were reduced from 0.44 lb/MBtu to 0.13 lb/MBtu, corresponding to about 70% reduction.

1.0 Introduction

Regulations for controlling mercury (Hg) emissions are currently being developed. In 2004, the EPA promulgated Maximum Achievable Control Technology (MACT) standards for coal-fired *industrial* boilers requiring Hg emissions from existing units to be lower than 9 lb/TBtu. In December 2003, the EPA proposed two frameworks to regulate Hg emissions from coal-fired *utility* boilers. The first proposed framework is consistent with the present regulatory mechanism, requiring MACT standards to be used in formulating regulatory limits. The MACT approach would limit Hg emissions for bituminous coal to 2 lb/TBtu and require less aggressive reductions for low-rank coals. The second "cap-and-trade" framework would provide greater overall reduction in Hg emissions, requiring significant Hg reduction for all coal types. The deadline for adopting a final rule to regulate Hg from power plants was extended to March 15, 2005. Several other frameworks for Hg regulations also have been proposed. The Clear Skies Initiative proposed by President Bush mandates dramatic reductions in power plant SO_2, NO_x, and Hg emissions over the next 15 years. The Clear Skies was proposed on February 14, 2002 and was first introduced to the Congress in 2002, but did not pass that year. The Clear Skies Act 2005 was re-introduced to The Senate Environment and Public Works committee on January 24, 2005. After reviewing the Act the committee will make decision about recommending the Act for the Senate consideration in 2005.

Many utilities are actively seeking efficient, cost-effective technologies for controlling multiple pollutants including Hg emitted from power plants. GE Energy has been developing an integrated multi-pollutant control approach for coal-fired power plants since the late 1990s[1,2,3]. The approach enhances the "naturally occurring" Hg capture by fly ash through combustion optimization and increasing carbon in ash content and may include a polishing step that uses small amounts of activated carbon to further increase Hg removal efficiency. Another benefit of the approach includes reduced NO_x emissions. Depending on coal type, unit configuration, and required level of Hg reduction, this approach may provide compliance with expected Hg regulations without activated carbon injection. If injection is required, the integrated approach requires less activated carbon than does the traditional approach, since optimized combustion staging improves Hg absorption on fly ash and increases the amount of oxidized mercury in flue gas. The approach can be tailored to specific unit configurations and coal types for optimal performance.

1.1 Project Description

In this project General Electric Energy and Environmental Research Corporation (EER), a wholly owned subsidiary of GE Energy, conducted a preliminary field evaluation of the integrated approach for Hg control at Green Station Units 1 and 2 located near Henderson, Kentucky. Green Station is owned and operated by Western Kentucky Energy (WKE). Units 1 and 2 are equipped with cold-side electrostatic precipitators (ESPs) and wet scrubbers.

The integrated Hg/NO_x control method at Green Station utilizes coal reburning (injection of reburning coal and overfire air) and ESP optimization. In reburning technology, most of the coal (70-80%) is burned in the primary combustion zone of the boiler, where NO_x is typically generated. The remaining coal is injected downstream to provide a reburning zone with a fuel-rich environment where about 50-60% of the NO_x from the primary combustion zone is reduced to N_2. During the reburning process, carbon in the reburning coal does not burn out as completely as it would in a boiler environment with a high level of excess air. Thus, coal reburning usually increases the level of unburned carbon in the fly ash. This carbon is used to control Hg emissions. Most of the coal Hg content is transferred to the gas phase in the primary combustion zone of the boiler. Mercury in flue gas is absorbed by carbon present in the fly ash in the ESP. This fly ash can be landfilled or optionally treated in an ash burnout unit to recover heat and generate salable fly ash. A carbon bed can be used to absorb Hg released from fly ash in the burnout unit. Mercury absorption in the carbon bed can be done more economically than in the boiler. Since fly ash generated at Green Station is landfilled, Hg recovery in an ash treatment system could not be investigated in this project.

The program comprised field and pilot-scale tests and engineering studies and consisted of the following five tasks:

1. Baseline field measurements
2. Pilot-scale testing
3. Systems design
4. Preliminary field evaluation
5. Data reduction, management and reporting.

Task #1 provided baseline data on Hg emissions before reburning system retrofit. Data collected in Task #1 were also used to compare with pilot-scale data obtained in Task #2 to

evaluate scalability of pilot-scale data. Pilot-scale facility in Task #2 was configured to match time-temperature profile found in Green Unit 2. The same fuels fired at full-scale were tested in pilot-scale. Baseline data on Hg emissions and pilot-scale results were evaluated in Task #3 to determine optimum conditions for Hg removal in Units 1 and 2 when the reburning system became operational. Armed with the pilot scale information, a field optimization program in Unit 2 was structured in Task #4 to achieve the conditions identified in the pilot-scale tests using the advanced combustion systems. The goal of these tests was to identify stable conditions that yield high Hg capture, low NO_x emissions, low byproducts (CO, LOI) and were acceptable operating conditions for WKE operators.

The following sections present a description of Green Units 1 and 2 and describe in detail project activities.

1.2 Description of Green Units 1 & 2

Western Kentucky Energy's Green Station Units 1 and 2 are nearly identical opposed-wall-fired steam generators manufactured by Babcock and Wilcox. Each unit was originally designed to produce 1,840,000 lb/hr of main steam. At its maximum continuous rating (MCR) each unit has a peak generating capacity of 255 MWe (gross). Excess oxygen is typically 3.0 to 3.5 percent at the economizer exit. As boiler load drops, boiler excess O_2 is increased to maintain reheat steam temperature.

EER retrofitted Units 2 and 1 with reburning systems in 2002 and 2003, respectively. The overfire air system consists of 10 ports located at Elevation 165 m (Figure 1). Five ports are located on the front wall and five ports are located on the rear wall. Heated combustion air is supplied from the secondary air ducts on the hot side of the air heater. The overfire air ports are EER's double concentric design that features an inner and outer nozzle. In most operating modes, the inner nozzle supplies between 12% and 15% of the total air. The remaining air is supplied through the outer nozzle. The air fraction to either nozzle can be controlled automatically from the control room.

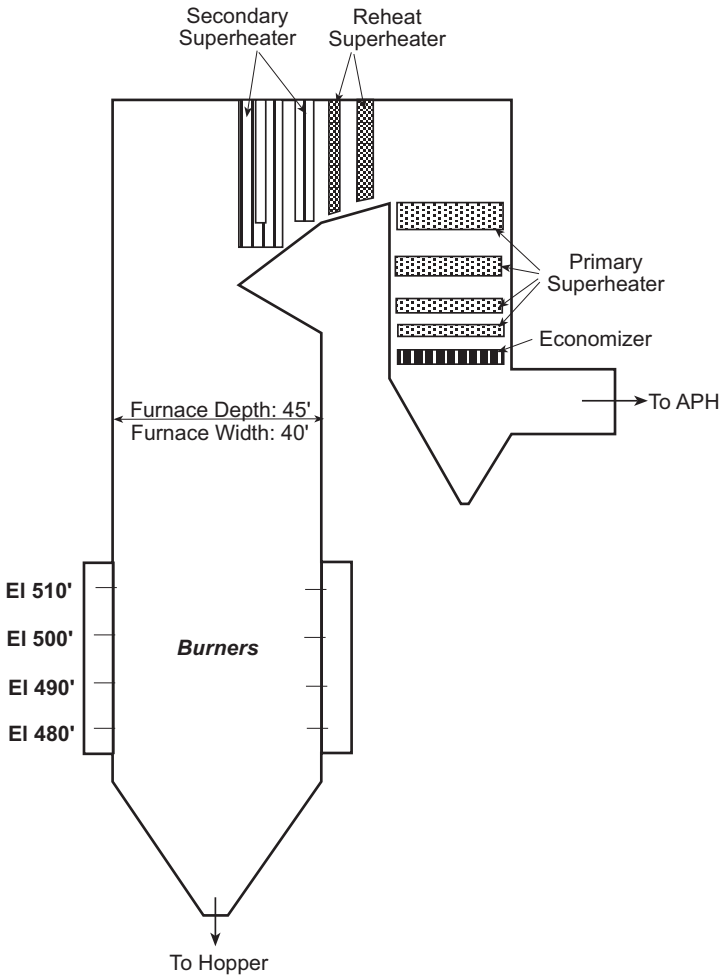

Figure 1. Side elevation of Green Unit 2.

The coal reburning system is comprised of PC piping modifications, furnace penetrations, and controls along with 12 reburning fuel injectors located at Elevation 520 ft 6 inches. Six injectors are located on the front wall and six injectors are located on the rear wall. The system was designed with a capacity to supply between 20 and 30 percent of the heat input as reburning fuel. To accommodate the reburning system, the top row of burners are taken out of service. The installation also included coal line balancing dampers and combustion sensors. The dampers and sensors were used in combustion optimization activities. A schematic of the reburning system on Unit 2 is presented in Figure 2.

WKE usually operates the reburning system only during ozone season (May – September). The OFA portion of the system is part of the normal unit operation during the rest of the year.

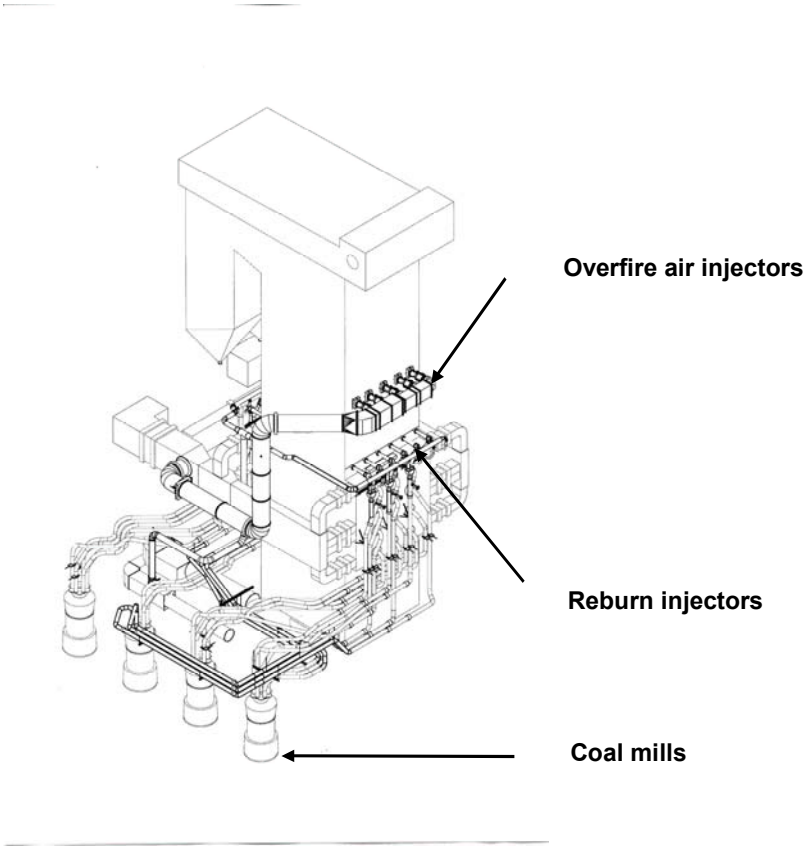

Figure 2. Reburning system on Green Unit 2.

Green Station Units 1 and 2 typically fire two types of fuel: a bituminous coal and a blend of bituminous coals based on availability. Prior to reburning retrofit, loss-on-ignition (LOI) for the fly ash was less than 2 percent when firing bituminous coal.

WKE considers information on fuel properties to be of proprietary nature. Properties of fuels tested in this project are presented in *Appendix I* and should be treated as confidential information.

2.0 Pilot-Scale Testing

The first activity in optimizing Hg reduction in Units 1 and 2 was to test fuels fired at Green Station in pilot-scale. Previous experience with Hg and NO_x studies suggested that pilot-scale testing produced the same trends in the effect of process conditions on Hg and NO_x reduction as in full-scale. Results of pilot-scale testing would be then used to determine optimum conditions for Hg and NO_x reduction at Green Station.

Pilot-scale testing was conducted in Boiler Simulator Facility (BSF) to determine effects of process conditions and fuel composition on Hg removal. Testing focused on determining effects of the following factors on Hg removal 1) fuel composition, 2) carbon in ash content (also characterized as Loss On Ignition, or LOI), and 3) ESP temperature. The following sections give BSF description and present results of pilot-scale testing.

2.1 Boiler Simulator Facility

The BSF (Figure 3) is a down-fired combustion research facility with a nominal firing rate of 300 kW (1 MMBtu/hr). It is designed to simulate the thermal characteristics of a utility boiler. As shown in Figure 3, the BSF consists of a burner, vertical radiant furnace, and horizontal convective pass. The facility's variable swirl diffusion burner is equipped to fire coal, oil, or natural gas. The furnace is constructed of eight modular refractory lined spool sections with access ports. The furnace has an inside diameter of 0.55 m and a height of 5.4 m. The radiant section is equipped with adjustable heat removal panels. Configuration of these panels is adjusted such that the BSF matches the residence time-temperature profile and furnace exit gas temperature of a specific full-scale boiler. The convective pass is equipped with air-cooled tube bundles designed to simulate the superheater and economizer sections of a coal-fired boiler.

Temperature gradient in BSF was adjusted to simulate thermal environment in Units 1 and 2. Figure 4 compares axial temperature profile in the BSF and Unit 2. Unit 2 temperature profile was calculated using EER's thermal model that was successfully used in the past to predict temperature environment in coal-fired boilers. Figure 4 shows good agreement between full- and pilot-scale temperature profiles at temperatures below 1200 K at which Hg oxidation and adsorption on fly ash is expected to take place.

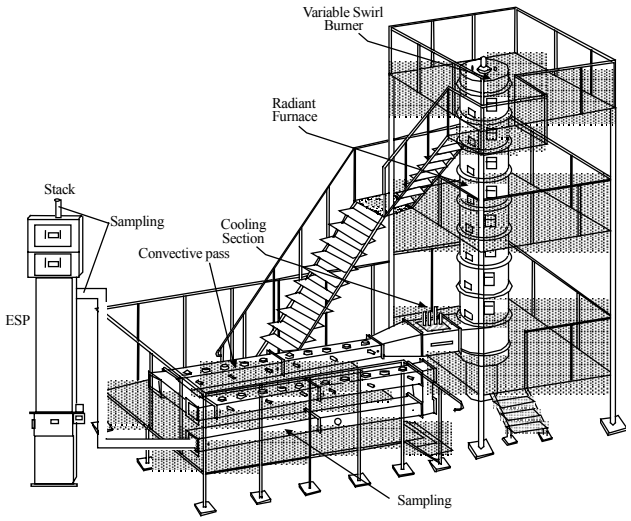

Figure 3. Boiler Simulator Facility (BSF).

The ESP for the BSF is a single-field down-flow cylindrical unit with an axial corona electrode.

Process performance was characterized by continuous emissions monitors (CEMs), which provided an online analysis of flue gas composition. The CEMs consisted of a water-cooled sample probe, sample conditioning system (to remove water and particulate), and gas analyzers. Species analyzed, detection principles, and detection limits were as follows:

- O_2: paramagnetism, 0.1%
- NO_x: chemiluminescence, 1 ppm
- CO: nondispersive infrared, 1 ppm
- CO_2: nondispersive infrared, 0.1%

High purity dry nitrogen was used to zero the analyzers. Certified span gases were used to calibrate and check linearity of the analyzers. A chart recorder was used to obtain a hard copy of analyzer outputs. A personal computer based data acquisition system (LabTech Notebook) was used for storage and analysis of test data.

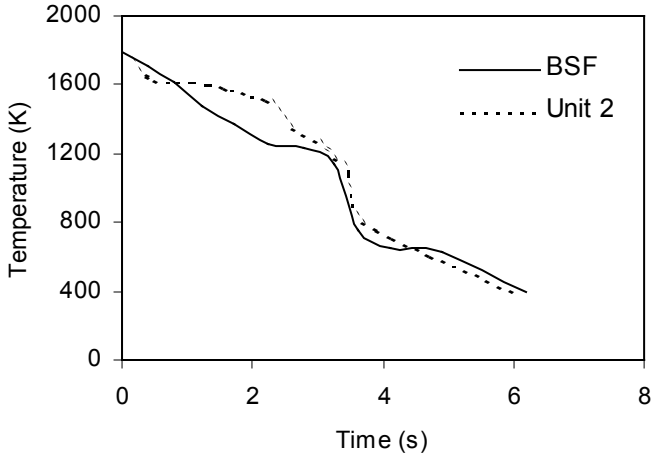

Figure 4. Axial temperature profiles in BSF and WKE Green Unit 2.

2.2 Results of Pilot-Scale Testing

Combustion tests were performed to evaluate effects of process conditions and fuel type on Hg emissions. Characteristics of tested fuels are shown in *Attachment I* Table I-1. At the time of the testing WKE was purchasing coals from two suppliers. Two coals and one coal blend were tested in pilot-scale. Two tested coals were bituminous coals with high sulfur content. Coals had similar compositions except for higher Cl content in coal 2. Concentrations of total Hg and elemental Hg (Hg^0) were measured at ESP outlet using Hg analyzer Sir Galahad from PS Analytical. Concentration of oxidized Hg (Hg^{+2}) was determined as a difference between Hg and Hg^0.

High carbon fly ash was formed using two approaches: air staging and coal reburning. In air staging, part of the combustion air (usually 15-30% of total) is redirected from the main combustion zone into an overfire (OFA) zone. In reburning, part of the fuel (usually 10-30% of total) is injected downstream of the main combustion zone (reburning zone); overfire air is injected downstream of the reburning zone to complete fuel combustion. In both approaches fuel combustion occurs in a more fuel-rich environment than at typical combustion conditions, usually resulting in incomplete fuel combustion and increased carbon in ash content. However, in reburning combustion of secondary (reburning) fuel takes place at lower temperatures than in air staging, which potentially can affect properties of fly ash and its reactivity towards Hg.

Process variables in tests included location of OFA injection, amount of OFA, amount of

reburning fuel, and ESP temperature. The ESP temperature was adjusted by changing facility load.

Figure 5 shows Hg removal and Hg emissions for three tested fuels as a function of LOI at air staging conditions. Figure 5a demonstrates that at air staging conditions efficiency of Hg removal increases as LOI increases from 0% to 5-6%, but then stays about the same as LOI further increases to 16%. Mercury removal efficiencies for all three tested fuels were similar at the same LOI. It should be noted, however, that because of different reactivity of fuels the same combustion conditions generated fly ash with different LOI. Thus, although the air staging data presented in Figure 5a can be used to establish target LOI required to achieve desired Hg removal efficiency, combustion conditions that produce target LOI are affected by fuel properties. Maximum achieved Hg reduction in air staging tests was 60%. The ESP temperature in air staging tests was 350°F (450 K). Due to the lower Hg content in the blend, Hg emissions for blend firing were lower than for coal firing at the same LOI (Figure 5b).

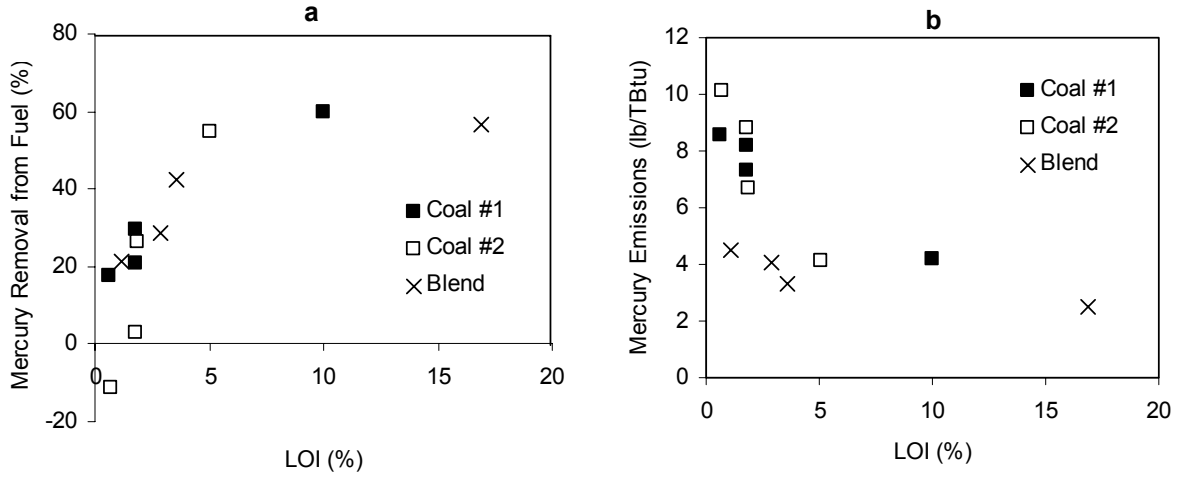

Figure 5. Mercury removal (a) and Hg emissions (b) as a function of LOI at air staging.

Effects of reburning and ESP temperature on Hg removal were evaluated for coal 1 and blend firing. Figure 6 shows Hg removal efficiency and Hg emissions as a function of LOI at ESP temperatures in the range of 310-360°F (427-455 K).

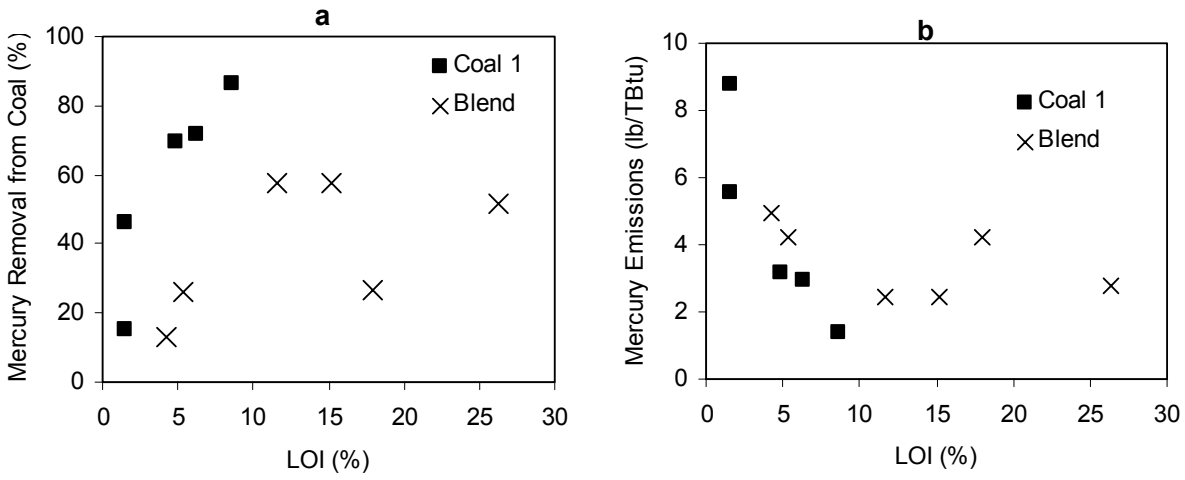

Figure 6. Mercury removal (a) and Hg emissions (b) as a function of LOI at reburning conditions at ESP temperatures of 310-360^{o}F.

Figure 6a demonstrates that Hg removal efficiencies for coal are higher than those for blend firing at the same LOI. Maximum LOI generated in reburning tests with blend was ~26% while for coal it was ~9%. This is result of higher reactivity of coal 1 due to its higher volatiles content (Table I-1). The maximum Hg removal efficiency achieved for coal firing was close to 90% while for blend firing it was 60%. This suggests that in reburning, fuel properties have a significant effect on fly ash reactivity towards Hg. At the same time, Hg emissions for coal and blend firing were similar (Figure 6b).

Figure 7 shows efficiency of Hg removal for coal 1 at reburning conditions at different ESP temperatures. For comparison, data on the effect of LOI and ESP temperature on Hg removal obtained by Consol[4] are also shown. In that project fly ashes obtained from Illinois utility and industrial boilers were injected into 1.5 MM Btu/hr combustor duct and collected in ESP. Mercury removals were measured across the duct and ESP. The flue gas temperature was controlled using both humidification with an in-duct atomization nozzle and the pilot plant heat exchanger. The CONSOL data showed that Hg absorption on fly ash was affected by LOI and improved as ESP temperature decreased. Since data on coal composition in the Consol study[4] were not available, Figures 7 and 8 do not show data on Hg emissions.

Figure 7 demonstrates that ESP temperature has an effect on Hg removal: Hg removal at 250-270^{o}F (394-405 K) at LOI ~5% was ~80% while at 440-490^{o}F (500-505 K) it was only ~20%. This suggests that lowering ESP temperature can be an effective approach to increasing Hg

adsorption on fly ash.

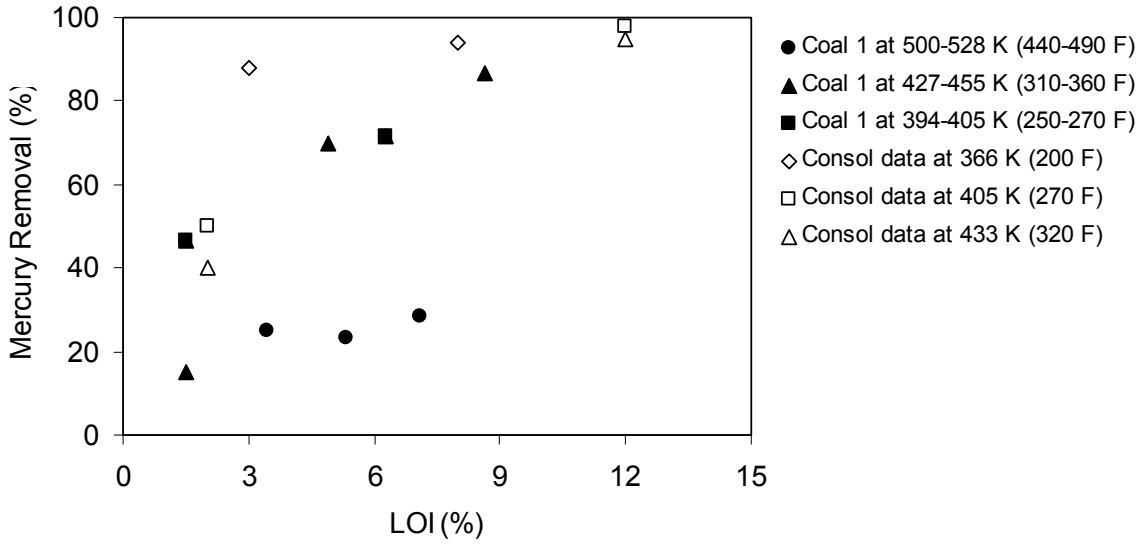

Figure 7. Mercury removal for coal 1 at reburning conditions at different ESP temperatures as a function of LOI. Data obtained by Consol on re-injection of high carbon fly ash are also shown.

Data on effects of LOI and ESP temperatures were used to develop an empirical correlation between Hg removal, LOI, and ESP temperature. Figure 8 shows a comparison between experimental data and correlation predictions. Figure 8 demonstrates good agreement between calculated and experimental data for wide ranges of LOIs and temperatures.

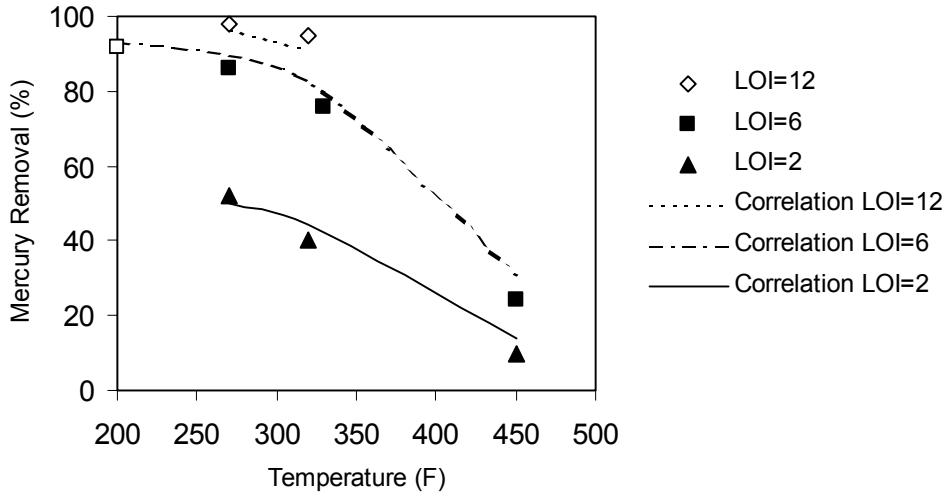

Figure 8. Effect of ESP temperature on Hg removal. Filled symbols represent present data, open symbols Consol data, lines correlation predictions.

Figure 9 shows experimental data on Hg removal obtained in BSF (presented in Figure 7) at ESP temperatures of 250–450°F (390 – 500 K) and adjusted using empirical correlation to the temperature of 350°F (450 K). Figure 9 shows good agreement between experimental data and correlation predictions. It also shows that uncertainty of experimental data is about ±10%.

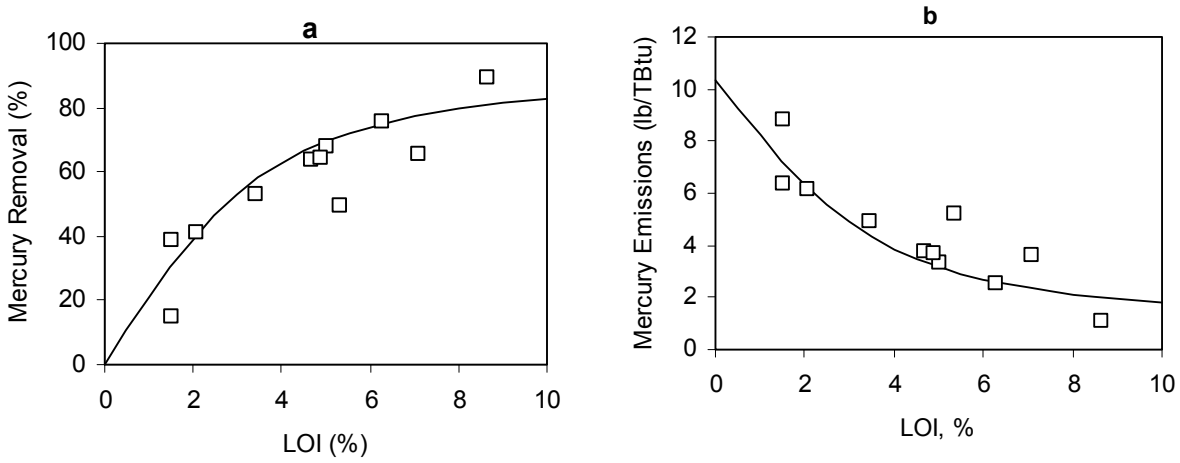

Figure 9. Mercury removal (a) and Hg emissions (b) in reburning as a function of LOI. ESP temperature is 350°F (450 K).

Figure 10 shows the predicted by the transfer function effect of the temperature and LOI on Hg absorption by fly ash.

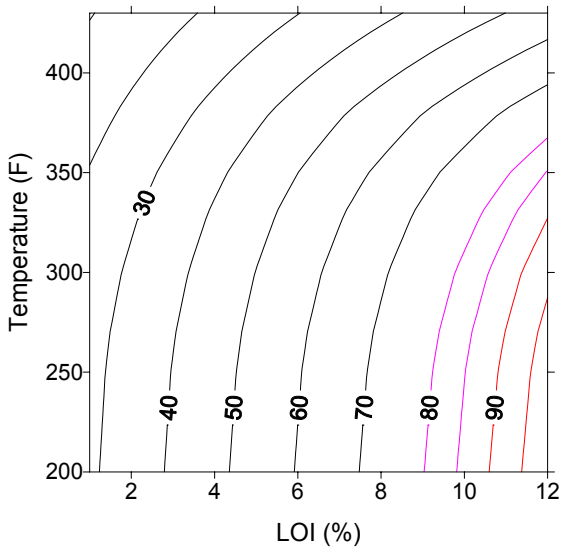

Figure 10. Predicted effect of temperature and LOI on Hg removal (solid lines). Numbers indicate level of mercury removal.

Figure 10 suggests that both temperature and LOI should be considered in selecting optimum conditions for Hg removal. LOI change in the range of 2-8% offers the most significant

effect on Hg removal. LOI increase from 8% to 12% provides only marginal efficiency improvement in Hg reduction. Temperature decrease below the acid dew point can result in sulfuric acid condensation and duct corrosion. While the acid dew point depends on a number of parameters including coal sulfur content, in most cases for bituminous coals it is lower that 290^{o}F. Figure 10 suggests that high Hg removal efficiency is difficult to achieve at temperatures higher than 350^{o}F and that 80-90% Hg removal can be potentially achieved at ESP temperatures of 290-350^{o}F.

Pilot-scale testing suggested that fuel composition affected efficiency of Hg reduction: efficiency of Hg removal at the same LOI was higher for coal firing than for blend firing. However, due to the lower Hg content in the blend, Hg emissions for two fuels were similar. Testing also demonstrated that Hg removal improved with LOI increase and ESP temperature decrease. Based on results of pilot-scale testing it is estimated that 80% Hg control at Green Station at ESP outlet could be achieved at LOI ≥ 8% and ESP temperatures ≤ 300^{o}F (420 K).

3.0 Testing of Baseline Mercury Emissions

Mercury testing at Green Station consisted of four programs. The first program was conducted in September 2003 with the goal to obtain data on baseline Hg emissions in Unit 2. The second and third programs were conducted in January and April 2004, respectively, and were designed to obtain data on Hg emissions while reburning systems in Units 1 and 2 were optimized for NO_x reduction. The fourth program involved final reburning system optimization for Hg and NO_x control in Unit 2 in September 2004. The following sections give a description of the baseline test program.

3.1 Program Description

The test program consisted of 5 tests with the boiler operating under nominal full load conditions. Reburning and OFA systems during baseline testing were not operational. However, minimal air flow through OFA ports was maintained to cool the ports. The total cooling air accounted for 11-12% of the total combustion air. Thus, baseline tests corresponded to Unit 2 operating at slightly air staged conditions.

Table 1 shows a matrix of the baseline test program. The boiler was configured in the normal firing configuration, that is, with the upper row of burners in service and cooling air flowing through the overfire air injectors. Tests 1, 2, and 3 were conducted with the boiler firing the coal blend (see *Attachment I* Table I-2 for details on fuel composition). Tests 4 and 5 were conducted with the boiler firing a single coal. For Test 5, OFA was increased to 22% to measure the impact of a moderate staging on Hg emissions.

Table 1. Test matrix for baseline testing.

		Fuel	OFA	Ontario Hydro Sampling		
Day	Test No			ESP Inlet	ESP Outlet	Stack
30-Sep	1	Blend	11%	X	X	
1-Oct	2	Blend	11%	X		X
1-Oct	3	Blend	11%		X	X
2-Oct	4	Coal	11%		X	X
2-Oct	5	Coal	22%		X	X

Relative Hg measurement locations are shown in Figure 11. Manual Hg sampling using the Ontario Hydro Method was performed at three locations: the ESP inlet, the ESP outlet, and the stack. Fuel samples were collected from the silos and fly ash was collected from the economizer exit duct during each test. EER also performed O_2 profiling at the ESP inlet because of the possibility of O_2 stratification as the flow makes a ninety-degree turn into the ESP. To closely monitor boiler operations, EER also measured O_2 on a dry basis continuously during each test at the economizer exit duct. All measurements were made on the boiler's East side duct.

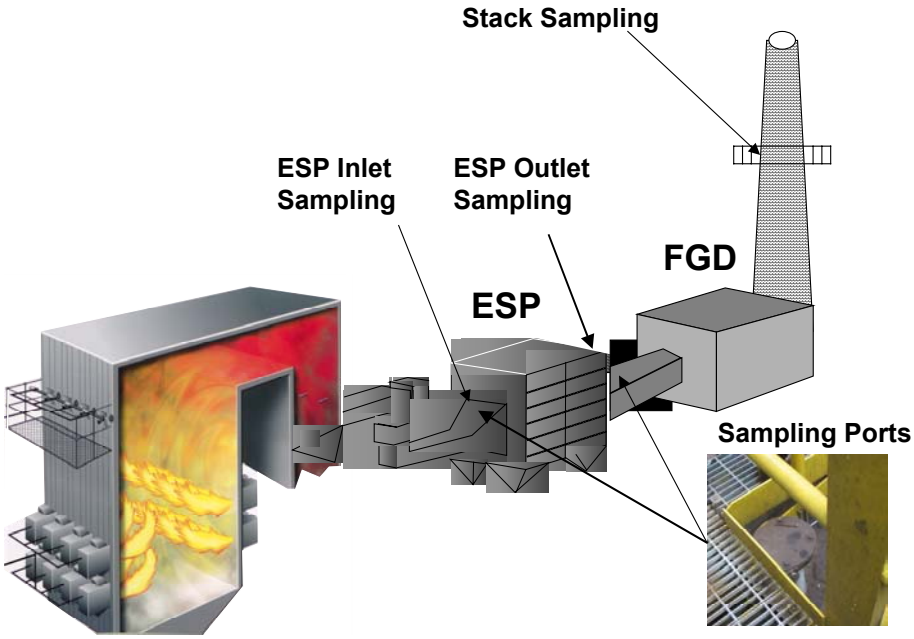

Figure 11. Mercury sampling locations.

3.2 Data Collection and Sampling Procedures

Pertinent data from plant operations were collected to document the operating conditions of the boiler as part of the Hg test program. This section of the report summaries the sampling procedures that were used in the test program, and the data collection protocols that were followed. The following is a summary of the data collected.

- Boiler operating data from the plant information system
- NO_x, CO_2 and SO_2 from the plant CEMS at the stack
- Plant O_2 from plant sensors at the economizer outlet
- O_2 from 12 point sampling grid at the East economizer outlet
- O_2 stratification checks at the East ESP Inlet
- Hg concentrations by Ontario Hydro Method

- Coal samples
- Fly ash samples.

The following sections present a summary of the boiler operating data, O_2 measurements, coal and fly ash sampling, and Hg emissions.

3.2.1 Boiler Operating Data

Boiler operating data were downloaded from the plant's digital information network at the end of each test day. The data points included measured steam, fuel, flue gas, and combustion air flows and properties, power output, CEMS data, and plant O_2 data. Each point was logged by the plant information system at one-minute intervals and averaged across the exact sampling period for each test. A summary of the operating data is included in *Attachment I* Table I-3.

To characterize the operating conditions of the boiler, the data were used to calculate boiler efficiency and the actual fuel and air flows. Boiler efficiency was calculated using the ASME PTC 4.1 Heat Loss Efficiency Method. For these calculations, fuel analysis was provided from the actual samples taken during the tests (Table I-2), and the carbon loss was measured from the actual fly ash samples collected during the tests. A heat balance was then used to calculate the actual fuel flow and the plant O_2 measurements were used to calculate the actual airflow. Stoichiometric values for the burner zone and for the OFA zone as well as the percent OFA are included in the *Attachment I* Table I-3.

3.2.2 Continuous O_2 Monitoring /O_2 Profiling

A 12-point sampling grid was installed in the East duct of the economizer exit duct to monitor O_2 concentrations during the tests. Sintered metal filters were installed on the end of each probe to remove ash particles from the flue gas. The gas extracted from each point was metered to ensure uniform sampling. A moisture knockout device was used to remove moisture from the flue gas sample. The dry flue gas sample was then pumped to the mobile CEMS laboratory for analysis of O_2 concentration. The analyzer was calibrated using an EPA Protocol 1 calibration gas before and after each test. A bias check was performed prior to test number 1 to insure the integrity of the sampling line and leak checks were conducted on a daily basis.

Figure 12 shows oxygen profile across East side duct. Oxygen traversing was done on four occasions: prior to the beginning of the test program and on first three test days. Traversing was

done across distance of 180 cm which comprises half the duct height. Figure 12 demonstrates that relatively small O_2 bias (about 10%) exists across the flow, indicating that flow is well mixed. This suggests that Hg bias at the location of Hg measurements at ESP inlet is also small. Due to the intense flue gas mixing in ESP and wet scrubber, it is expected that Hg bias at the location of Hg measurements at ESP outlet and stack to be even smaller. Velocity traverses made at these three locations during Ontario Hydro sampling confirmed the flow uniformity (see Section 3.2.5).

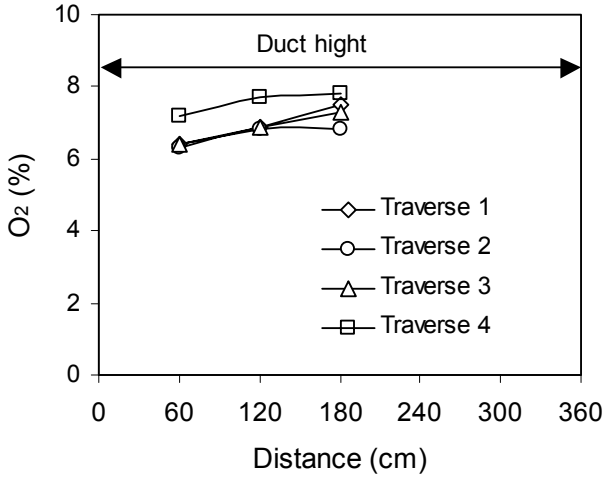

Figure 12. Oxygen profile across East side duct.

3.2.3 Coal Sampling

Coal samples were taken during the second half of each test period. To achieve the most representative sample, coal was acquired from the bottom of the four coal silos. A composite sample was then assembled by combining an equal mass from each of the individual silo samples. The samples were labeled to include the test number, sampling time, and sampling location and sent to an independent laboratory for determinations of ultimate, proximate, and heating value as well as Hg concentration. Table I-2 in *Attachment I* shows composition of tested fuels.

3.2.4 Fly Ash Samples

Fly ash samples were collected in-situ from the East side economizer exit duct. The fly ash sampling system consisted of a multi hole probe that ran the width of the economizer exit duct, a high volume sampler that was used to pull flue gas, and a cyclone to capture the ash into a plastic jar. At the completion of each test, the samples were placed in an airtight container, labeled, and

shipped to a laboratory for analysis. The ash samples were analyzed for LOI using a Hot Foil™ LOI Analyzer. The LOI data for tests 1-5 are shown in *Attachment I* Table I-3.

3.2.5 Mercury Emissions

Mercury emissions were measured by Metco Environmental using the Ontario Hydro Method, Revised July 7, 1999. Two tests were conducted at ESP inlet, four at ESP outlet, and four at the stack. A preliminary velocity traverses were made at each location in order to determine the uniformity and magnitude of the flow prior to testing. Several traverse points at each location were checked for cyclone flow and none was found to be present. Three traverse points were sampled at each of the ESP locations and twelve points were sampled at the stack. For each run at the ESP inlet and outlet, samples of flue gas of 50 min duration were taken isokinetically at each of the traverse points for a total sampling time of 150 min. At the stack samples of 10 min duration were taken isokinetically at each of the twelve traverse points for a total sampling time of 120 min. Tables 2, 3, and 4 show results of Ontario Hydro measurements.

Table 2. Summary of baseline tests for ESP inlet duct.

Test Number	1	2
Duct Flow Rate (acfm)	357,272	384,070
$\%O_2$ (%Vol)	4.6	4.4
Duct Temperature (F)	310	313
Particle Bound Mercury Emissions ($\mu g/m^3$)	0.19	0.079
Elemental Mercury Emissions ($\mu g/m^3$)	0.607	0.735
Oxidized Mercury Emissions ($\mu g/m^3$)	7.122	7.127
Total Mercury Emissions ($\mu g/m^3$)	7.919	7.941

Table 3. Summary of results for ESP outlet duct.

Test Number	1	3	4	5
Duct Flow Rate (acfm)	260,175	271,313	264,213	280,834
$\%O_2$ (%Vol)	4.6	4.6	4.6	4.2
Duct Temperature (F)	316	316	294	299
Particle Bound Mercury Emissions ($\mu g/m^3$)	0.016	0.009	0.005	0.004
Elemental Mercury Emissions ($\mu g/m^3$)	1.145	1.131	2.26	1.958
Oxidized Mercury Emissions ($\mu g/m^3$)	4.909	3.658	9.109	7.527
Total Mercury Emissions ($\mu g/m^3$)	6.070	4.798	11.374	9.489

Table 4. Summary of results for the stack.

Test Number	2	3	4	5
Duct Flow Rate (acfm)	783,470	799,894	816,248	827,442
%O_2 (%Vol)	4.2	4.2	4.6	4.4
Duct Temperature (F)	121	123	121	127
Particle Bound Mercury Emissions ($\mu g/m^3$)	0.026	0.077	0.016	0.081
Elemental Mercury Emissions ($\mu g/m^3$)	1.489	1.278	2.433	2.165
Oxidized Mercury Emissions ($\mu g/m^3$)	0.662	0.481	1.142	0.806
Total Mercury Emissions ($\mu g/m^3$)	2.177	1.836	3.591	3.052

Figures 13 and 14 show Hg concentrations in flue gas for blend and coal firing at different locations. Typical of bituminous coals, most Hg in the gas phase at ESP inlet and outlet is present in the oxidized form. Total mercury at the stack is significantly lower than that before wet scrubber and present mostly in the elemental form.

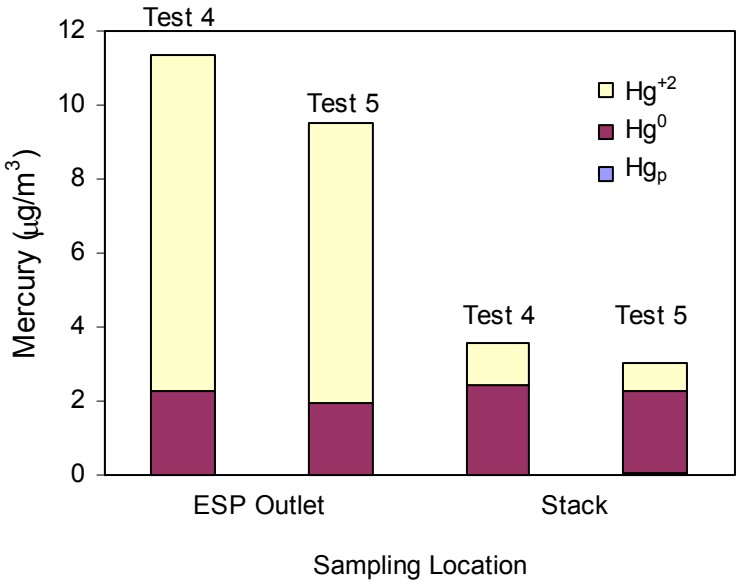

Figure 13. Mercury emissions for blend firing.

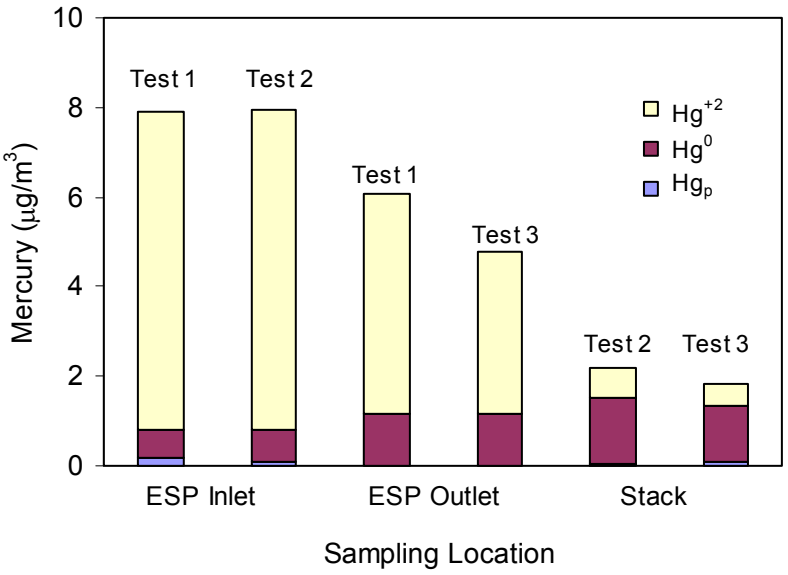

Figure 14. Mercury emissions for coal firing.

Figures 15 and 16 show efficiencies (defined as the difference between theoretical Hg concentration in the gas phase calculated using fuel feed rate and fuel Hg content and that measured) of Hg removal and Hg emissions for coal and blend firing. Testing showed (Figure 16a) that Hg removal at ESP inlet was small. Mercury emissions at ESP inlet agreed with the theoretical value within ±15% (Figure 16b). This suggests that practically all Hg present in coal is released into flue gas during combustion process and very little Hg if any is absorbed on bottom ash. Mercury removal at ESP outlet and at the stack was 30-45% and 70-80%, respectively. These data agree well with average Hg removal efficiencies of 46% and 81% reported by utilities for bituminous coal for similar configurations in respond to EPA Information Collection Request[5].

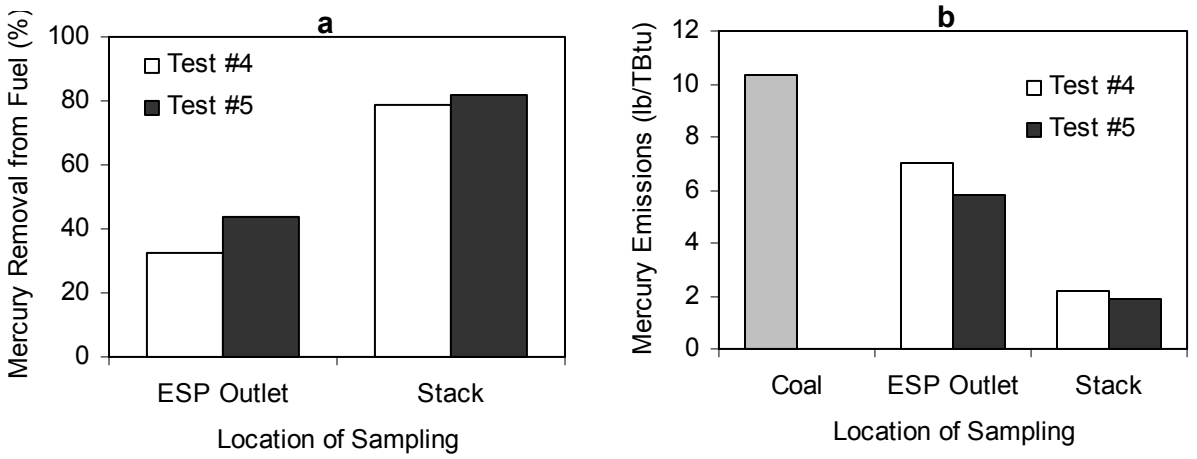

Figure 15. Mercury removal efficiencies (a) and Hg emissions (b) for coal firing.

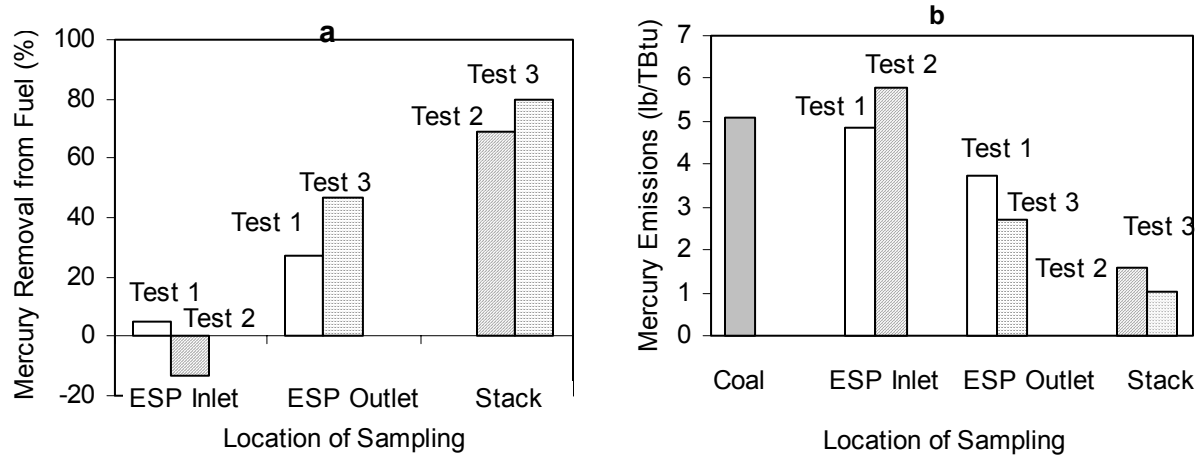

Figure 16. Mercury removal efficiencies (a) and Hg emissions (b) for blend firing.

Incremental efficiency of Hg removal across FGD (defined as the difference between Hg concentration at ESP outlet and stack) was in the range of 65-70% (Figures 15a and 16a). Reduction in concentration of the oxidized Hg was about 90%. However, about 20% of the oxidized Hg was reduced to elemental across the scrubber. As a result, elemental Hg at the stack was about 70% of total Hg emissions (figures 13 and 14).

3.3 Comparison of Pilot-Scale and Baseline Measurements

Figures 17 and 18 show comparison of Hg removal efficiencies measured at ESP outlet in full- and pilot-scale for coal and blend firing. Figures 17 and 18 show that full-scale data are in agreement with pilot-scale measurements for both fuels suggesting that BSF adequately simulates thermal environment of Green Unit 2. Figure 17 also demonstrates that some improvement in Hg

removal can be achieved for coal firing by increasing LOI to 6-10%. Comparison (Figure 18) of baseline and pilot-scale measurements for blend firing suggests that LOI increase above 8-9% achieved in baseline measurements will result in additional 20-30% Hg removal improvement.

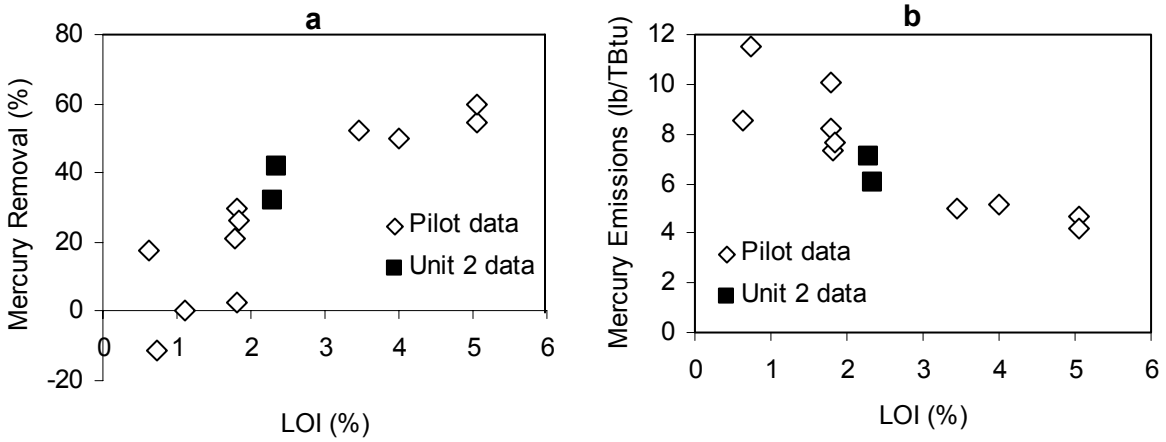

Figure 17. Comparison of pilot- (open symbols) and full-scale (filled symbols) data for OFA tests for Hg removal efficiency (a) and Hg emissions (b) for coal firing.

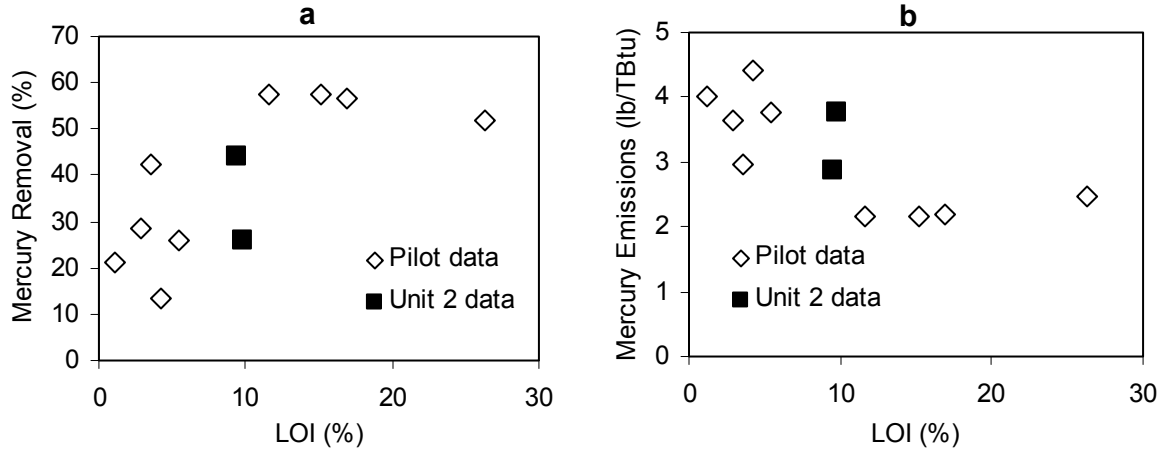

Figure 18. Comparison of pilot- (open symbols) and full-scale (filled symbols) data for OFA tests for Hg removal efficiency (a) and Hg emissions (b) for blend firing.

Figures 19 and 20 show good agreement on Hg partition measured in full- and pilot-scale testing. Data demonstrate that at ESP outlet oxidized Hg comprises about 80% of total Hg.

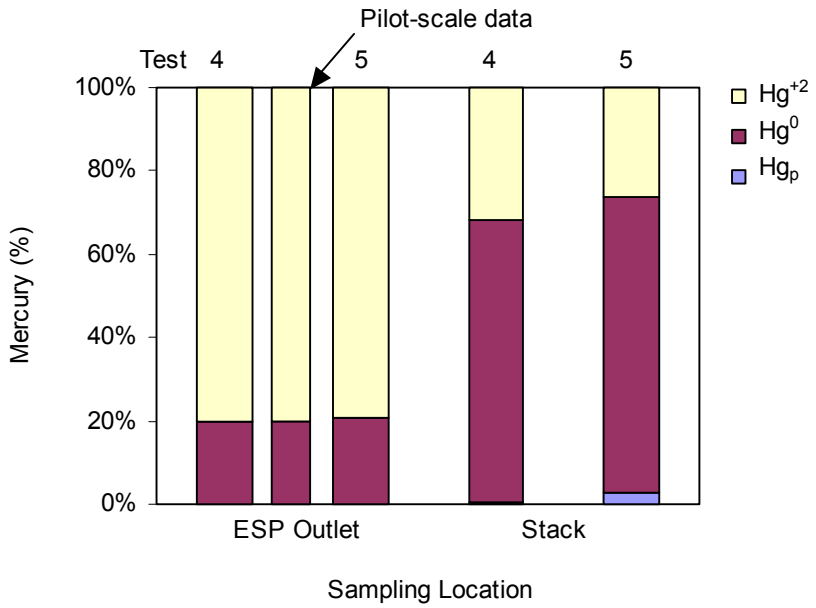

Figure 19. Mercury partition in full- and pilot-scale tests for coal firing.

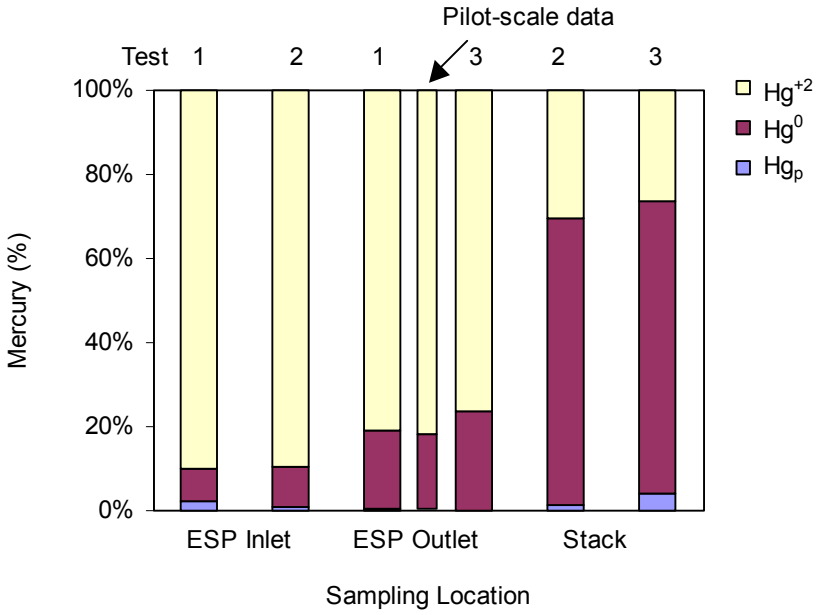

Figure 20. Mercury partition in full- and pilot-scale tests for blend firing.

Baseline testing demonstrated that efficiencies of Hg reduction for coal and blend firing were similar. Mercury reductions at ESP outlet and stack were 30-45% and 70-80%, respectively. However, since Hg content in coal was higher than that in the blend, Hg emissions were lower for blend firing. Mercury emissions at ESP outlet were 5.8-6.9 lb/TBtu and 2.7-3.7 lb/TBtu for coal and blend firing, respectively. Mercury emissions at the stack were 1.8-2.2 lb/TBtu and 1.0-1.5

lb/TBtu for coal and blend firing, respectively. Testing also demonstrated that OFA system operation at 22% air resulted in 10% and 5% incremental increase in Hg removal efficiencies at ESP outlet and stack, respectively. Testing demonstrated that about 80% of Hg at ESP outlet was present in the oxidized form. Most Hg at the stack was present in the elemental form. Results of baseline testing of Hg reduction and speciation in flue gas agree with pilot-scale data.

4.0 Mercury Emissions In Unit 2 Under Reburning Conditions

The next task after characterizing baseline Hg emissions in Unit 2 was to measure Hg emissions under reburning conditions. These tests were conducted in January 2004 and focused on coal firing, although limited data on blend firing were also obtained. Although typically WKE does not operate reburning system during that time of the year, it was activated and made available for the duration of testing.

4.1 Mercury Emissions in Unit 2 In Reburning

The test program consisted of 8 tests with the boiler operating under nominal full and reduced load conditions. Table 5 shows a matrix of the test program. The boiler was configured in the reburning firing configuration. Tests 1 and 2 were conducted with the boiler firing the coal blend (see *Attachment I* Table I-4 for details on fuel composition). Tests 3 through 8 were conducted with the boiler firing 100% coal. For Tests 7 and 8, boiler load was reduced to measure the impact of ESP temperature on Hg emissions.

Manual Hg sampling using the Ontario Hydro Method was performed by Metco Environmental at three locations: the ESP inlet, the ESP outlet, and the stack. Fuel samples were collected from each mill, fly ash was collected from the economizer exit duct, and hopper ash was collected from the ESP hoppers during each test. To closely monitor boiler operations, EER also measured CO and O_2 on a dry basis continuously during each test at the economizer exit duct. All measurements were made on the boiler's East side duct. Data collection and sampling procedure was the same as in the baseline testing (Section 3.2). A summary of the operating data is included in *Attachment I* Table I-5. Table I-5 also includes data on CO emissions, O_2 concentrations and LOI.

Mercury emissions were measured using the Ontario Hydro Method, Revised July 7, 1999. Three tests were conducted at ESP inlet, eight at ESP outlet, and five at the stack. Tables 6 - 9 show results of Ontario Hydro measurements.

Table 5. Coal reburning mercury test matrix.

Test		Fuel	Load (MW)	Reburn Fuel	Reburn Fuel (%)	OH Sampling		
Date	Test No	Coal				ESP Inlet	ESP Outlet	Stack
21-Jan-04	1	Blend	242	Blend	30%	X	X	
	2	Blend	242	Blend	30%		X	X
22-Jan-04	3	Coal	242	Coal	30%	X	X	
	4	Coal	242	Coal	30%		X	X
23-Jan-04	5	Coal	242	Coal	30%		X	X
	6	Coal	242	Coal	30%		X	X
25-Jan-04	7	Coal	180	Coal	30%		X	X
	8	Coal	180	Coal	30%	X	X	

Figure 21 shows Hg concentrations in flue gas at different locations for blend firing. Typical of bituminous coals, most Hg in the gas phase at ESP inlet and outlet is present in the oxidized form. Total mercury at the stack is significantly lower than that before the wet scrubber and present mostly in the elemental form. Surprisingly, very little particulate bound Hg was measured at ESP inlet.

Table 6. Summary of results for ESP inlet duct.

Test Number	1	3	8
$\%O_2$ (%Vol)	6.6	3.8	4
Duct Temperature (F)	301	297	279
Particle Bound Mercury Emissions ($\mu g/m^3$)	0.053	0.585	1.197
Elemental Mercury Emissions ($\mu g/m^3$)	0.706	0.681	0.544
Oxidized Mercury Emissions ($\mu g/m^3$)	6.063	10.327	7.403
Total Mercury Emissions ($\mu g/m^3$)	6.822	11.593	9.144

Table 7. Summary of results for ESP outlet duct.

Test Number	1	2	3	4
%O_2 (%Vol)	7.8	7.8	7.8	7.8
Duct Temperature (F)	311	312	317	323
Particle Bound Mercury Emissions ($\mu g/m^3$)	0	0.03	0.023	0.037
Elemental Mercury Emissions ($\mu g/m^3$)	1.96	1.453	2.889	2.67
Oxidized Mercury Emissions ($\mu g/m^3$)	5.03	5.329	7.681	10.018
Total Mercury Emissions ($\mu g/m^3$)	6.990	6.812	10.593	12.725

Table 8. Summary of results for ESP outlet duct.

Test Number	5	6	7	8
%O_2 (%Vol)	7.8	7.8	6.8	6.8
Duct Temperature (F)	334	356	307	270
Particle Bound Mercury Emissions ($\mu g/m^3$)	0.023	0.011	0.008	0.013
Elemental Mercury Emissions ($\mu g/m^3$)	3.381	3.413	2.172	1.574
Oxidized Mercury Emissions ($\mu g/m^3$)	12.007	9.654	10.236	8.599
Total Mercury Emissions ($\mu g/m^3$)	15.411	13.078	12.416	10.186

Table 9. Summary of results for the stack.

Test Number	2	4	5	6	7
%O_2 (%Vol)	6.2	4.4	6.6	6.0	6.4
Duct Temperature (F)	126	123	122	125	122
Particle Bound Mercury Emissions ($\mu g/m^3$)	0.032	0.037	0.457	0.08	0.062
Elemental Mercury Emissions ($\mu g/m^3$)	2.176	4.905	3.031	3.883	3.649
Oxidized Mercury Emissions ($\mu g/m^3$)	0.446	0.037	0.021	1.117	0.556
Total Mercury Emissions ($\mu g/m^3$)	2.654	4.979	3.509	5.080	4.267

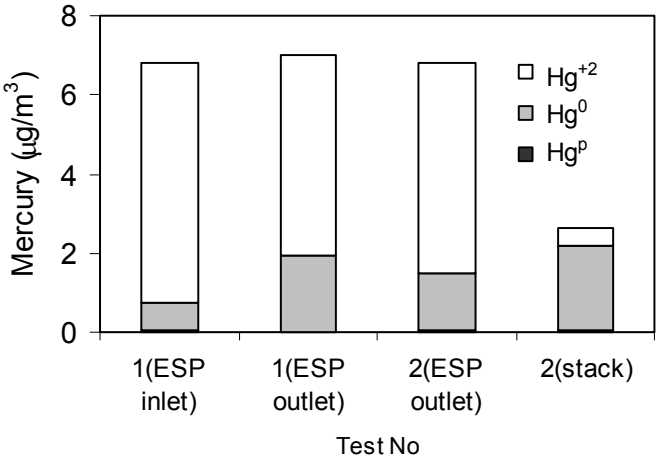

Figure 21. Mercury emissions for blend firing.

Figures 22, 23 and 24 show Hg concentrations in flue gas at different locations for coal firing. As with blend firing, most Hg emissions at ESP inlet and outlet were present in the oxidized form while at the stack they were present mostly in the elemental form.

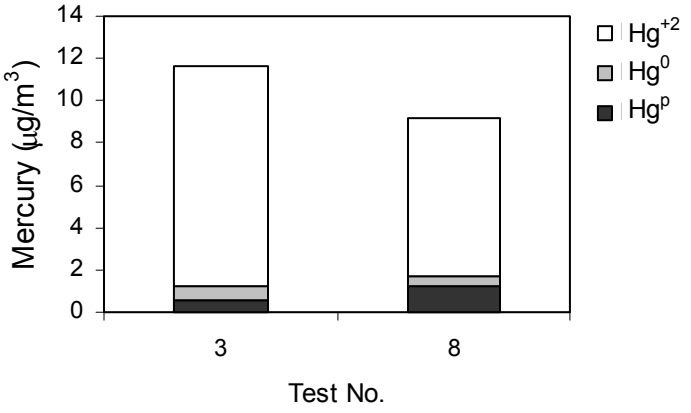

Figure 22. Mercury emissions at ESP inlet for coal firing.

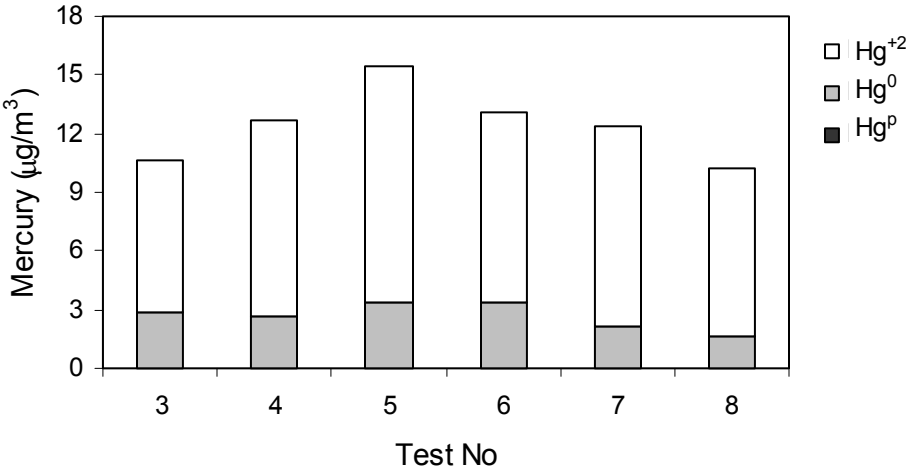

Figure 23. Mercury emissions at ESP outlet for coal firing.

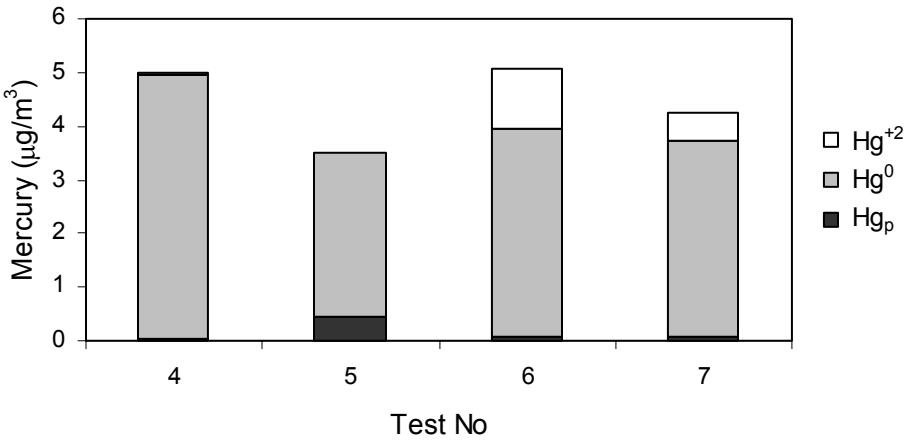

Figure 24. Mercury emissions at the stack for coal firing.

Figures 25 and 26 show efficiencies (defined as the difference between theoretical Hg concentration in the gas phase calculated using coal feed rate and coal Hg content and that measured) of Hg removal and Hg emissions for blend and coal firing.

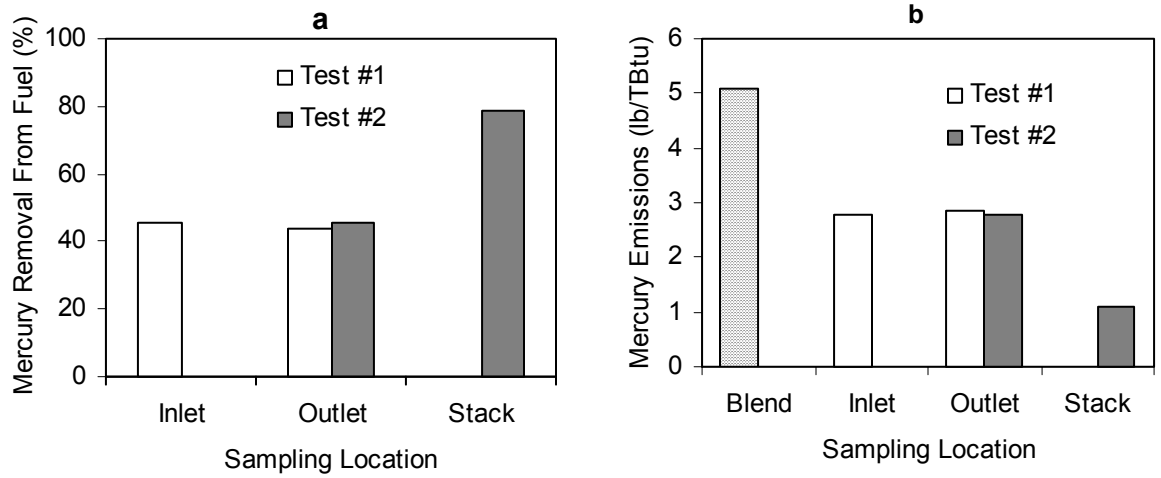

Figure 25. Mercury removal efficiencies for blend firing.

Testing showed that for both fuels efficiency of Hg removal at ESP inlet was about the same as that at ESP outlet, suggesting very low efficiency of Hg removal across ESP. Testing also showed about 30-40% Hg removal at ESP inlet. These observations do not agree with results of baseline measurements of Hg emissions in Unit 2 and pilot-scale data that demonstrated about 30-40% Hg removal across ESP and relatively small Hg removal at ESP inlet at similar LOIs. It is not clear what the reasons are for this disagreement. One possible explanation is that not all Hg

captured by the sampling system at ESP inlet was accounted properly, resulting in higher than expected efficiencies of Hg removal at ESP inlet.

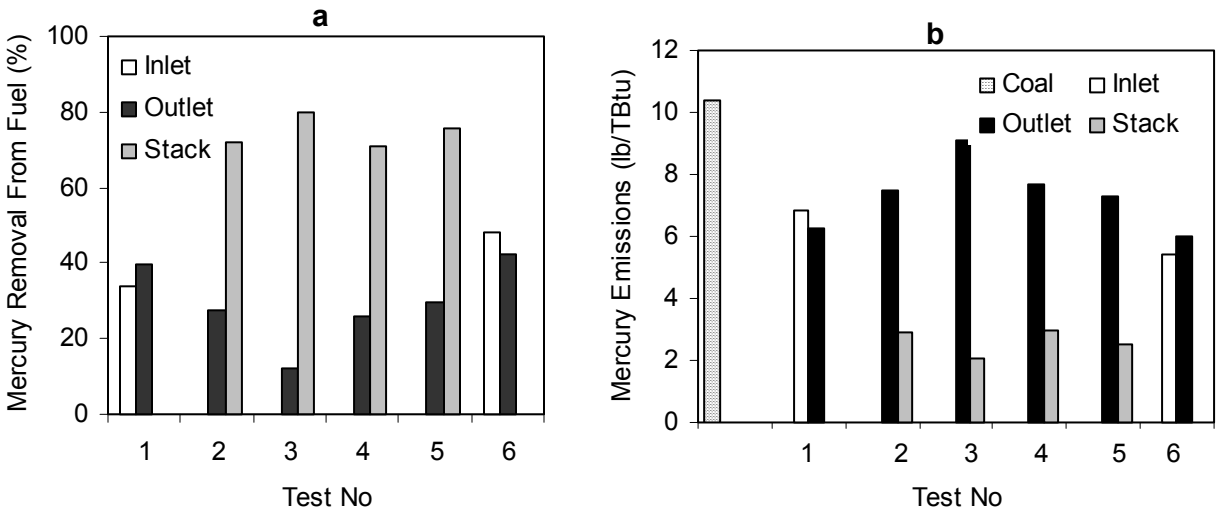

Figure 26. Mercury removal efficiencies (a) and Hg emissions (b) for coal firing.

Although determination of the effect of the ESP temperature on Hg removal was not the primary goal of these tests, variations in the boiler operation conditions and load resulted in changes in flue gas temperature at ESP inlet, providing data on Hg removal efficiencies in the temperature range of 270-350^{o}F. Pilot-scale testing demonstrated that decreasing ESP temperature improved Hg removal. Figure 27 shows data on the effect of temperature on Hg removal and emissions. Figure 27 shows that Hg reduction improved with decrease in ESP temperature.

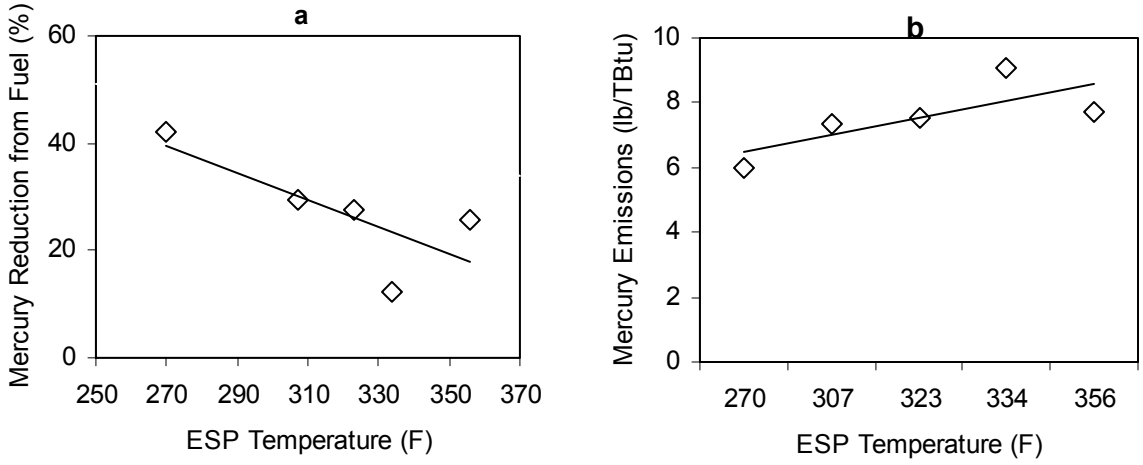

Figure 27. Effect of temperature on Hg removal (a) and Hg emissions (b) for coal firing.

Figure 28 shows dependence of fly ash surface area on carbon in ash content for coal and blend firing. Fly ash surface area is one of the factors that determines fly ash reactivity towards Hg. Figure 28 demonstrates that combustion staging not only improves fly ash reactivity by increasing carbon in ash content, but it also increases fly ash surface area. Figure 28 demonstrates that increase in surface area is affected by fuel properties: it is higher for coal than for the blend.

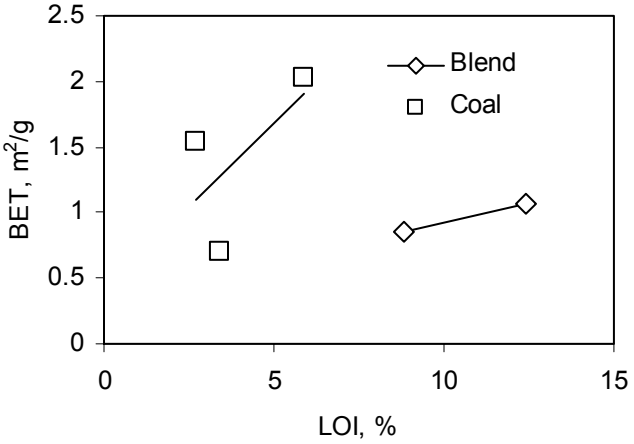

Figure 28. Dependence of fly ash surface area on LOI.

Figure 29 shows results of NO_x measurements under baseline, reburning, and optimized reburning conditions.

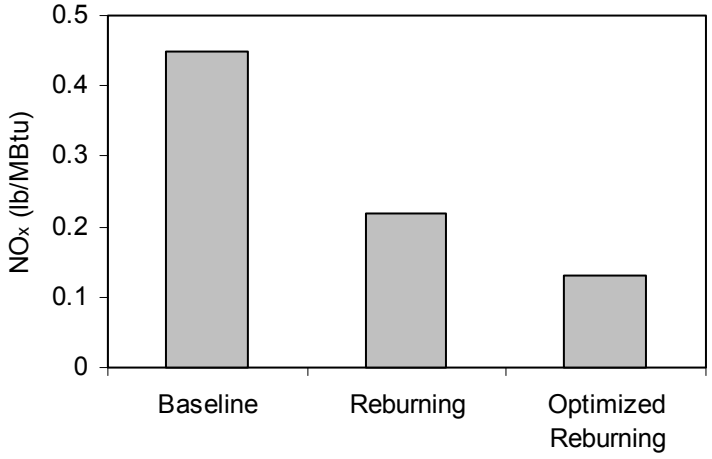

Figure 29. NO_x emissions in Unit 2.

Figure 29 shows that optimized reburning reduced NO_x emissions by almost 70%.

Typically, NO_x reduction efficiency in reburning is in the range of 40-60%. These results demonstrate importance of combustion optimization for reduction of NO_x emissions and improved plant efficiency.

4.2 Comparison with Baseline and Pilot-Scale Data

Figures 30 and 31 show comparison of Hg removal efficiencies and Hg emissions measured at ESP outlet in full- and pilot-scale in reburning for coal and blend firing. Figures 30 and 31 demonstrate that full-scale data are in general agreement with pilot-scale and baseline measurements, although data on Hg removal efficiency under reburning conditions for coal firing (Figure 30) are in the lower range of expected efficiencies. Measurements of Hg content in coal samples collected during testing (Table I-4) show high variability in Hg content (up to 30% variation from the average value for the coal). Proximate and ultimate analyses also showed variability in coal composition. For example, coal ash content varied from ~11% in Test #4 to 15.5% in Test #6. This suggests that theoretical Hg content in flue gas may had varied significantly not only in different tests, but also within 2 hour period required to complete one Ontario Hydro sampling run. Thus, if not all Hg in coal was accounted correctly due to the variability in coal properties, this could explain relatively low efficiencies of Hg removal at ESP outlet.

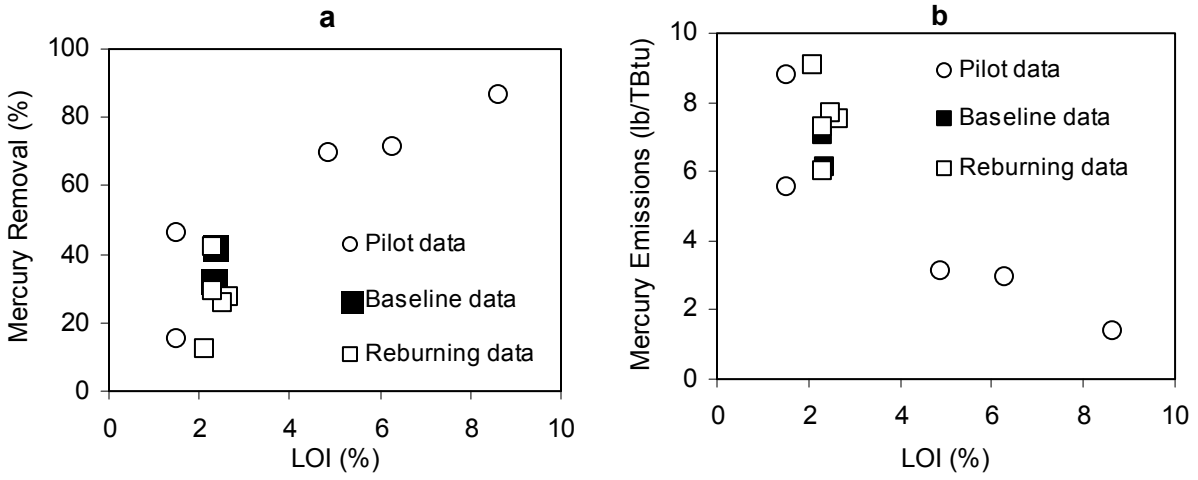

Figure 30. Comparison of Hg removal efficiencies measured in pilot- scale, baseline testing and reburning for coal firing.

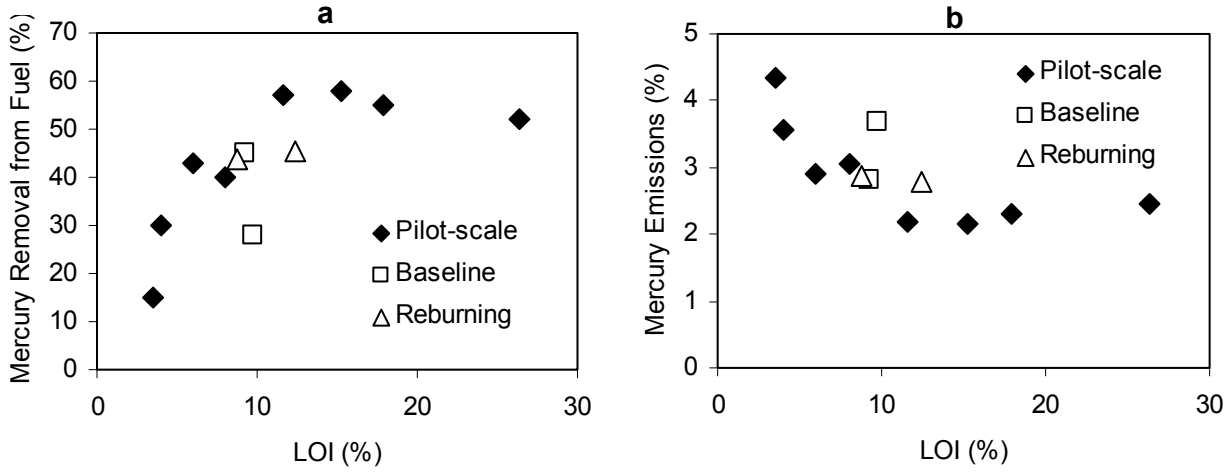

Figure 31. Comparison of Hg removal efficiencies (a) and Hg emissions (b) measured in pilot-scale, baseline testing and in reburning for blend firing.

Testing of Hg emissions under reburning conditions demonstrated that Hg emissions decreased with LOI increase and ESP temperature decrease. LOI in reburning tests with coal and blend firing was about the same as in baseline firing. As a result, no significant improvement in Hg removal over baseline levels was measured. Mercury reduction at the ESP outlet under reburning conditions was in the range of 10-40% and 40-45% depending on LOI and ESP temperature for coal and blend firing, respectively. Efficiency of Hg removal with blend firing was higher due to significantly higher LOI in blend firing tests. Mercury reduction at the stack under reburning conditions was in the range of 70-80% for both fuels. Mercury emissions in general were lower for blend firing due to the lower Hg content in the blend. Mercury emissions at the stack were 2-3 lb/TBtu and about 1 lb/TBtu for coal and blend firing, respectively. Mercury emissions at the ESP outlet were 6-9 lb/TBtu and about 3 lb/TBtu for coal and blend firing, respectively.

5.0 Mercury Emissions In Unit 1 Under Reburning Conditions

Mercury testing in Unit 1 while firing coal blend was conducted to characterize Hg emissions at higher LOI. Since coal blend is less reactive than individual coal, LOI in blend firing is typically higher than that in coal firing. Mercury testing in Unit 1 was conducted in April 2004 when reburning system underwent NO_x compliance testing.

The test program consisted of 13 tests (Table 10) with the boiler operating under nominal full load conditions at different reburning conditions. Table I-6 in *Attachment I* shows fuel composition and Table I-7 shows operational conditions for each test. Samples 13 a,b,c were collected while Unit 1 underwent 24 hour compliance test at constant operating conditions. Manual Hg sampling using the Fluegas Adsorbent Mercury Speciation (FAMS) and Frontier Total Mercury (FSTM) methods was performed by EER personnel at the ESP outlet. FAMS method is an alternative to the expensive and labor-intensive Ontario Hydro method. Extensive studies[6,7,8] conducted to compare FAMS method with the ASTM promulgated Ontario Hydro Method demonstrated reasonably good agreement between these methods. FSTM is a simplified version of FAMS method that measures total Hg.

Table 10. Test matrix for Unit 1 reburning tests.

Test No	Main and Reburning Fuel	Reburn Heat input, %	Notes
1	Blend	0	Other test variables included burners SR and SR in the primary combustion zone
2	Blend	30	
3	Blend	30	
4	Blend	30	
5	Blend	30	
6	Blend	25	
7	Blend	30	
8	Blend	28	
9	Blend	29	
10	Blend	25	
11	Blend	30	
12	Blend	22	
13	Blend	30	

During testing, fuel samples were collected from each mill and fly ash was collected from the economizer exit duct. Fly ash samples were analyzed to determine loss on ignition (LOI). Results of LOI measurements as well as summary of boiler operating conditions at each test are presented in Table I-7 *Attachment I*. To closely monitor boiler operations, EER also measured CO and O_2 on a dry basis continuously during each test at the economizer exit duct. Solid sample

collection procedure was the same as in baseline tests (Section 3.2). All measurements were made on the boiler's East side duct.

5.1 Mercury Emissions

Table 11 shows results of FAMS and FSTM measurements. Figures 32 and 33 show results of Hg measurements in a graphic form. FAMS results in Figure 32 for the total mercury are shown in black. Figure 32 demonstrates that Hg concentration in flue gas at ESP outlet varies from 6 to 10 μg/m^3. FSTM and FAMS results for total Hg agree reasonably well. Except for Test 2 (Figure 33), FAMS measurements demonstrate that most Hg in flue gas is present in the oxidized form. Surprisingly, very little particulate bound Hg was measured at ESP inlet.

Table 11. Results of mercury measurements.

		FAMS Speciation Results			FSTM Total Hg Results		
Test No		Hg^p	Hg^{+2}	Hg^0	Hg^p	Hg^{+2}	Hg^0
		(μg/m^3)	(μg/m^3)	(μg/m^3)	(μg/m^3)	(μg/m^3)	(μg/m^3)
1		NA	NA	NA	0.00	5.79	5.79
2		0.01	2.23	7.41	NA	NA	9.64
3		NA	NA	NA	0.00	9.81	9.81
4		NA	NA	NA	0.00	8.38	8.38
5		NA	NA	NA	0.00	6.97	6.97
6		NA	NA	NA	0.01	6.79	6.80
7		NA	NA	NA	0.01	7.49	7.50
8		0.01	5.13	1.88	NA	NA	7.02
9		NA	NA	NA	0.00	6.66	6.66
10		NA	NA	NA	0.00	6.62	6.62
11		0.00	5.97	2.02	NA	NA	7.99
12		NA	NA	NA	0.01	7.30	7.31
13a		NA	NA	NA	0.00	7.57	7.57
13b		NA	NA	NA	0.01	7.26	7.28
13c		0.00	6.00	1.42	NA	NA	7.42

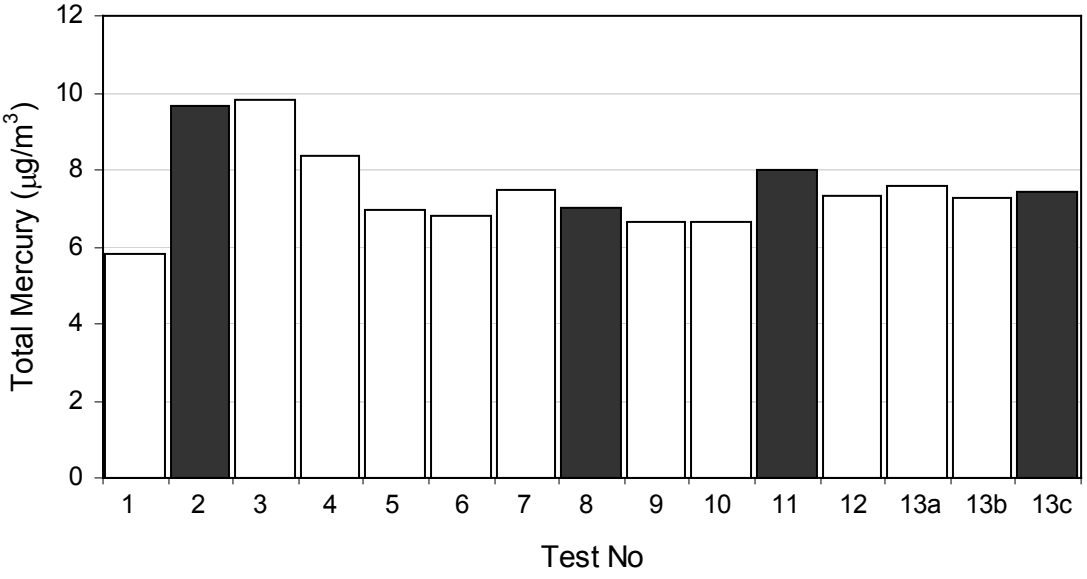

Figure 32. FAMS (filled bars) and FSTM (open bars) results for total Hg at ESP outlet.

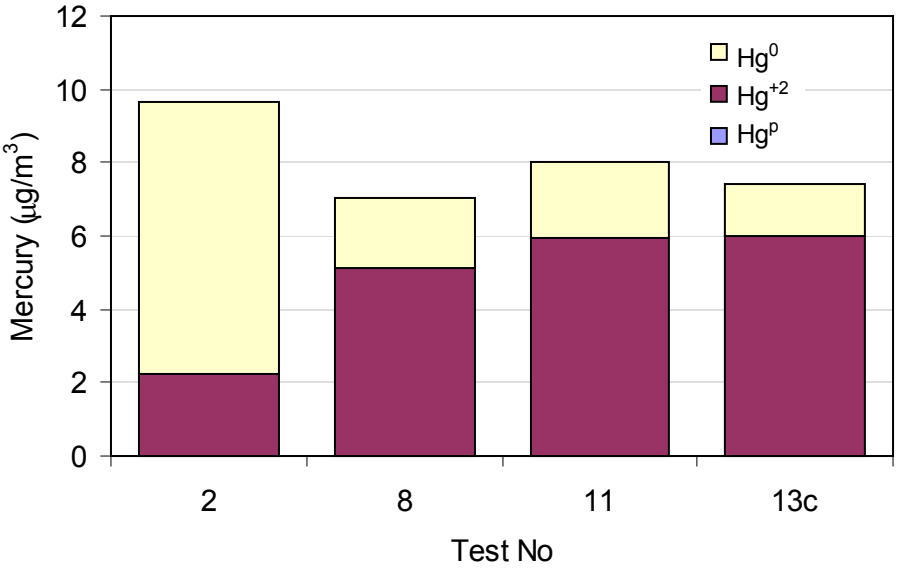

Figure 33. FAMS results for speciated Hg at ESP outlet.

Figure 34 shows efficiencies (defined as a difference between theoretical Hg concentration in the gas phase calculated using coal feed rate and coal Hg content and that measured) of Hg removal at ESP outlet. Testing showed that efficiency of Hg removal varied from 6% to 36%. Efficiencies of Hg removal less than 10% were measured in tests 2 and 3, all other tests showed efficiency of Hg removal 20% or greater. Table I-6 shows that Hg content in coal varies from 63

ppb to 81 ppb, about 30% variation. Coal samples were taken from the mills during each test. Because of the time difference between coal sampling and actual delivery of the same coal batch to the furnace, and because the duration of each Hg test was only about 20 minutes, this high variability in coal Hg content may have resulted in relatively high uncertainty in Hg removal efficiencies.

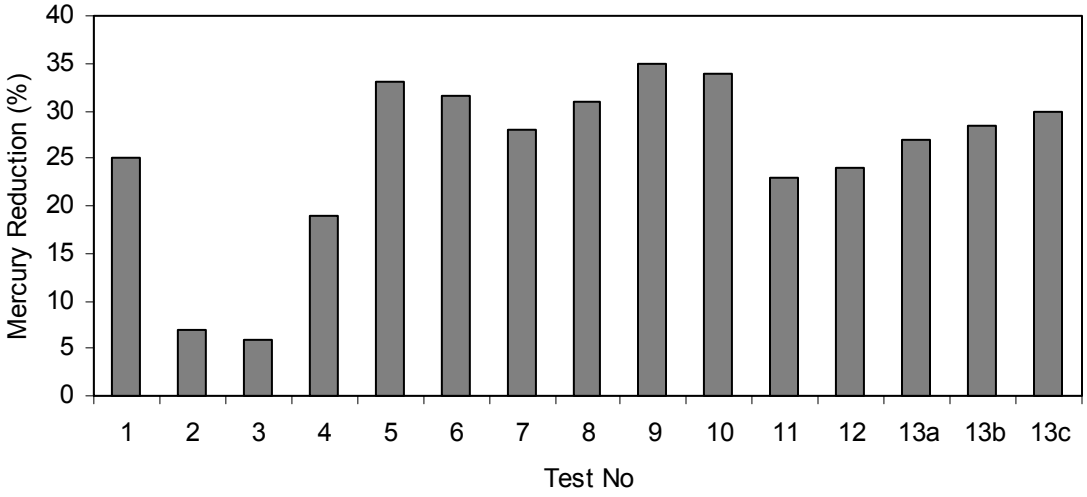

Figure 34. Mercury reduction at ESP outlet.

Figure 35 shows Hg emissions at ESP outlet in Unit 1 reburning tests. Average Hg emissions during tests were 4.8 lb/TBtu.

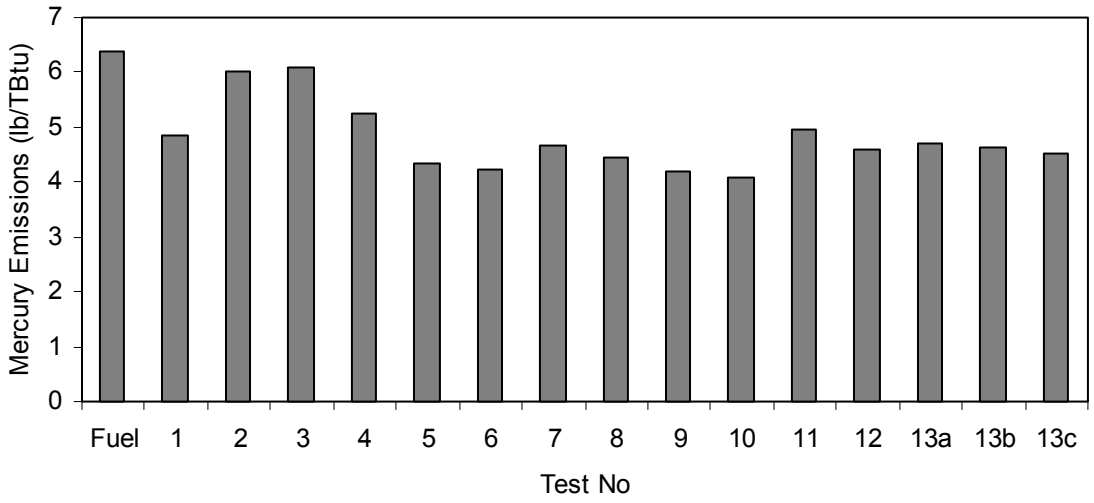

Figure 35. Mercury emissions at ESP outlet.

5.2 Comparison With Previously Obtained Data

Figure 36 shows a comparison of Hg removal efficiencies in reburning measured at ESP outlet in Unit 1 and 2 and pilot-scale measured previously. Figure 36 shows that Unit 1 data are in general agreement with pilot-scale and Unit 2 measurements.

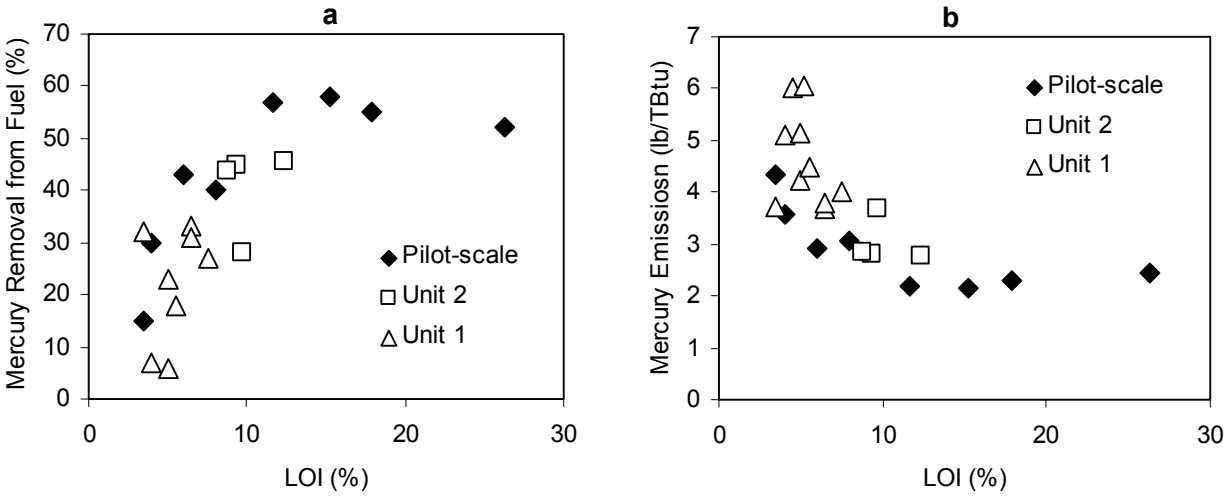

Figure 36. Comparison of pilot-scale and data on Hg removal (a) and Hg emissions (b) in reburning in Units 1 and 2 for blend firing.

Testing in Unit 1 demonstrated that Hg reduction improved with LOI increase. At LOI in the range of 4-7% Hg reduction was in the range of 6-35%. Average Hg emissions at ESP outlet during Unit 1 reburning tests were 4.8 lb/TBtu.

6.0 Optimization of Mercury Emissions in Unit 2

Baseline testing of Hg emissions in Unit 2 demonstrated that Hg reduction was below 40% at minimum OFA and was about 45% at 22% OFA. Testing under reburning conditions demonstrated 40-45% Hg removal depending on LOI. Testing also demonstrated that Hg removal improved as ESP temperature decreased. Both baseline and reburning results were in a good agreement with pilot-scale data suggesting that pilot-scale testing gave reasonable representation of full-scale conditions. It confirmed that the design methodology adopted in this project – optimizing Hg reduction in pilot-scale tests and then using pilot-scale data to define optimum conditions for Hg removal in full-scale – was successful. Pilot-scale data (Section 2.2) suggested that 80% Hg removal in coal reburning could be achieved for LOI in the range of 8-12% and ESP temperatures less that 300^{o}F. These conditions were targeted in the final reburning optimization tests that were conducted in September 2004.

Variables for the Hg optimization tests included fuel type, excess O_2, amount of the reburning fuel, air distribution between main combustion and OFA zones, and ESP temperature. Changes in ESP temperatures were achieved by changing Unit 2 load. Goal of the testing was to achieve 80% Hg reduction at ESP outlet.

The test program consisted of 17 tests with the boiler operating under nominal full and reduced load conditions. Table 12 shows a matrix of the test program. The boiler was configured in the reburning firing configuration. Tests 1-10 were conducted with the boiler firing the coal blend (see *Attachment I* Table I-8 for details on fuel composition). Tests 11-13 were conducted with the boiler transitioning from the coal blend to 100% coal and tests 14-17 were conducted with the boiler firing 100% coal. For a number of tests boiler load was reduced to measure the impact of ESP temperature on Hg emissions. Because of Unit 2 outage on September 19 and 20, tests on September 21 were conducted while bringing boiler to normal operational conditions resulting in ESP temperatures less than 300^{o}F at full load.

Mercury measurements were conducted using a Sir Galahad Hg analyzer from PS Analytical. The analyzer was equipped with the wet chemistry conversion modules and inertia separation probe from Baldwin Inc. The probe was designed to reduce interference between fly ash and Hg in flue gas and was intended to be used for sampling upstream of ESP. Distances between locations of Hg sampling upstream and downstream of ESP and location of the analyzer were 400 ft and 80 ft, respectively.

Table 12. Mercury optimization program test matrix.

Test #	Test Date	Fuel	Load, MW_{gross}	Reburning Parameters		CEMS Data			LOI		
				Reburn Fuel Heat Input (of total)	OFA (of total)	O_2, % dry	NO_X, lb/MMBtu	CO, ppm dry	LOI West location, %	LOI East location, %	LOI Average
1	9/21/2004	Blend	241	34.6%	25.5%	2.6	0.19	80	9.8	10.3	10.1
2	9/21/2004	Blend	241	32.9%	27.6%	2.7	0.19	125	9.2	10.3	9.7
3	9/22/2004	Blend	241	33.2%	27.6%	3.1	0.19	115	10.2	13.0	11.6
4	9/23/2004	Blend	180	26.2%	26.1%	4.0	0.15	68	8.6	8.2	8.4
5	9/23/2004	Blend	180	31.9%	29.1%	4.1	0.16	76	7.4	9.4	8.4
6	9/23/2004	Blend	180	32.2%	28.5%	3.6	0.18	62	7.3	7.5	7.4
7	9/23/2004	Blend	241	32.0%	27.4%	3.2	0.19	124	10.3	10.8	10.5
8	9/24/2004	Blend	198	32.3%	29.2%	3.6	0.18	70	8.7	8.6	8.6
9	9/24/2004	Blend	198	23.0%	23.6%	2.7	0.15	56	11.4	14.2	12.8
10	9/24/2004	Blend	198	23.0%	21.5%	2.7	0.18	55	12.6	11.4	12.0
11	9/24/2004	Blend/coal	200	35.6%	27.1%	3.5	0.17	70	5.1	4.3	4.7
12	9/25/2004	Blend/coal	200	24.7%	23.2%	2.7	0.15	68	5.9	4.9	5.4
13	9/25/2004	Blend/coal	200	23.9%	22.3%	2.3	0.16	80	5.0	5.3	5.1
14	9/25/2004	Coal	240	33.7%	23.7%	n/a	n/a	n/a	4.0	4.0	4.0
15	9/25/2004	Coal	176	25.5%	26.7%	3.0	0.13	30	3.1	4.5	3.8
16	9/25/2004	Coal	150	29.0%	28.1%	4.3	0.12	25	2.0	1.9	2.0
17	9/26/2004	Coal	200	35.4%	31.3%	3.4	0.17	56	2.3	2.1	2.2

To ensure that no significant Hg losses occurred in the sampling system, the ESP upstream and downstream probes were equipped with spanning systems that allowed introduction of a known concentration of elemental Hg at the tip of the sampling probe. The Teflon line between sampling probe and the module was maintained at 400^{o}F to minimize Hg losses. The conversion module at the ESP upstream location was located within 20 ft of the sampling probe such that only elemental Hg was transferred over 400 ft to the analyzer. This arrangement was designed to reduce Hg losses before sampling gas reached the analyzer. Initial testing, however, showed that Hg concentration at ESP inlet was about half of that measured at ESP outlet. Spanning sampling system at the ESP upstream location resulted in about 50% Hg recovery in the analyzer. Based on these initial tests, decision was made not to sample upstream of ESP and focus sampling efforts on the ESP downstream location. Spanning probe at ESP downstream location with elemental Hg showed close to 100% Hg recovery.

Manual Hg sampling using the Frontier Total Mercury (FSTM) method was performed at the stack. Fuel samples were collected from each mill, fly ash was collected from the economizer exit duct, and hopper ash was collected from the ESP hoppers during each test. To closely monitor boiler operations, EER also measured CO and O_2 on a dry basis continuously during each test at the economizer exit duct. All measurements were made on the boiler's East side duct. Data collection procedure was the same as in the baseline testing (Section 3.2). A summary of the

operating data is included in *Attachment I* Table I-9. Table 11 shows data on CO emissions, O_2, and LOI.

6.1 Mercury Measurements

Both tested fuels (See Table I-8) had high sulfur content. Since it is known that SO_2 can reduce efficiency of Hg^{+2} reduction in the analyzer speciation module, a dilution system was used to reduce SO_2 concentration in the sampling gas. Bottled N_2 was introduced into the sampling line upstream of the speciation module. Mass flow of N_2 was about two times larger than that of sample gas, resulting in factor of 3 reduction in SO_2 concentration. The dilution factor was controlled by measuring CO_2 concentrations in the sampling gas before and after dilution N_2 flow was introduced.

Sampling arrangement also allowed for introduction of a known concentration of elemental Hg from the analyzer CavKit at the sampling probe. Figure 37 shows the sampling arrangement.

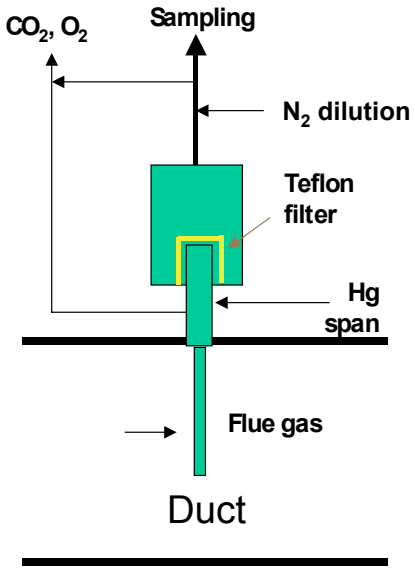

Figure 37. Sampling arrangement.

Comparison between introduced and measured Hg concentrations allowed quantification of Hg losses in the sampling system. Spanning was conducted at the beginning of each testing day. Figure 38 shows Hg recovery factors (defined as the amount of Hg measured as a percent of Hg introduced) for each testing day. Since the analyzer is capable of operating in modes that measure total and elemental Hg, it allowed to determine recovery factor for total and elemental Hg. Figure 38 demonstrates that the average recovery factor for total Hg was 97% suggesting that no

significant Hg losses occurred in the system. Average recovery factor for elemental Hg was 81% suggesting that about 20% of elemental Hg was oxidized in the system. Most likely oxidation took place on the Teflon filter containing traces of fly ash. The filter was replaced every day to reduce potential Hg oxidation in the sampling system.

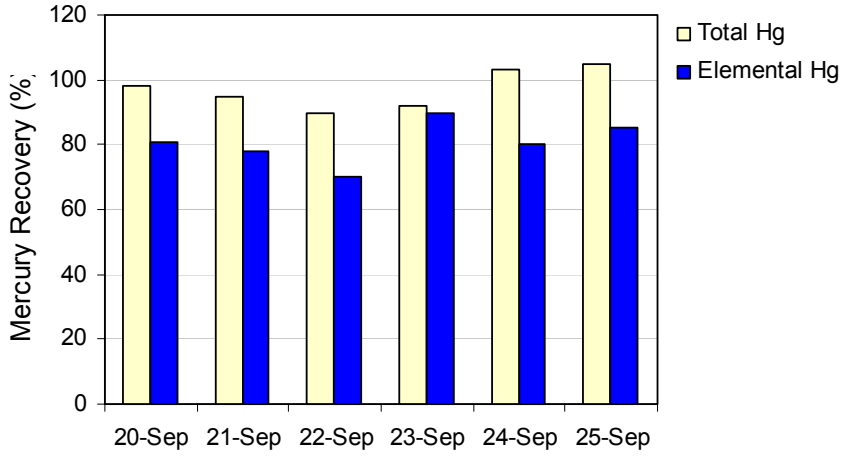

Figure 38. Recovery factors for total and elemental Hg.

Table 13 shows a summary of the Hg optimization tests including Hg removal efficiencies, Hg emissions, and ESP temperatures.

Figure 39 shows measured and theoretical (calculated from Hg in coal content and excess O_2 data) Hg concentration in flue gas for blend firing tests on September 20-24. On September 22 the Hg CEM had to be taken off line for unscheduled maintenance. As a result, Hg data for tests 3-6 were not collected. Only total Hg was measured on September 21 due to problems with the speciation module. The ESP temperature in Tests #1 and 8-10 was below 300^{o}F while in Tests #2 and 3 it was higher than 310^{o}F.

Table 13. Summary of Hg optimization tests.

Test No	Fuel	Hg Removal Efficiency (%)	Hg Emissions (lb/TBtu)	ESP Temperature (F)
1	Blend	77.0	1.9	270
2	Blend	61.0	3.8	303
7	Blend	62.0	3.3	306
8	Blend	75.0	2.1	290
9	Blend	82.0	1.5	285
10	Blend	75.0	2.1	280
11	Blend/coal	9.5	11.7	295
12	Blend/coal	38.1	8.0	293
13	Blend/coal	38.0	8.0	297
14	Coal	16.7	10.8	303
15	Coal	13.8	11.2	289
16	Coal	13.6	11.2	280
17	Coal	26.1	9.6	297

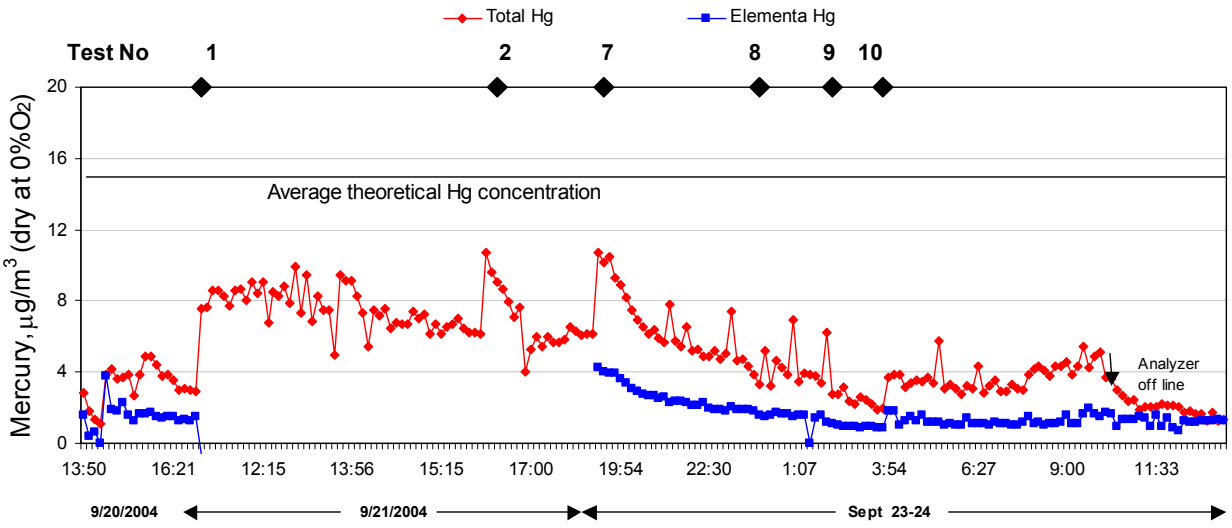

Figure 39. Results of CEM measurements for blend firing on September 20-24.

Figure 40 shows Hg reduction efficiencies and Hg emissions as determined in testing during September 20-24 for blend firing. Mercury reduction is defined as a difference between theoretical Hg concentration in flue gas calculated from Hg content in coal and unit operational conditions, and measured Hg concentration. Figure 40 demonstrates that Hg reduction was about 80% at ESP temperatures of 270-290^{o}F (Tests #1, 8-10) and was about 60% at ESP temperatures 300^{o}F and higher (Tests #2 and 7).

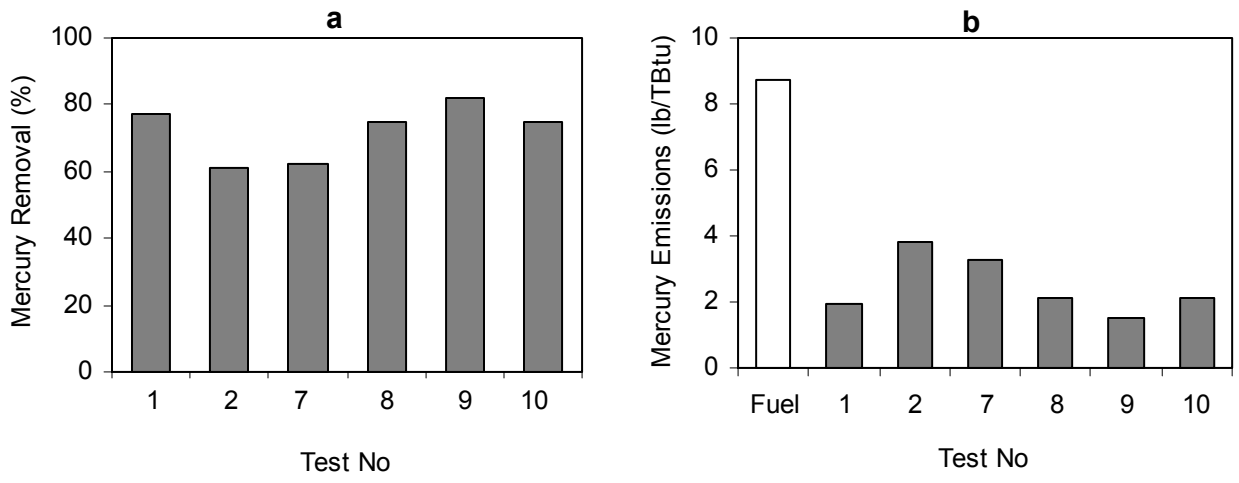

Figure 40. Mercury reduction efficiencies (a) and Hg emissions (b) during testing on September 20-24.

Results of Hg CEM measurements on September 24-27 for coal firing are shown in Figure 41. On September 26 at about 4 am Unit 2 was brought down for emergency repairs. Unit 2 was brought back on line at about 10 am.

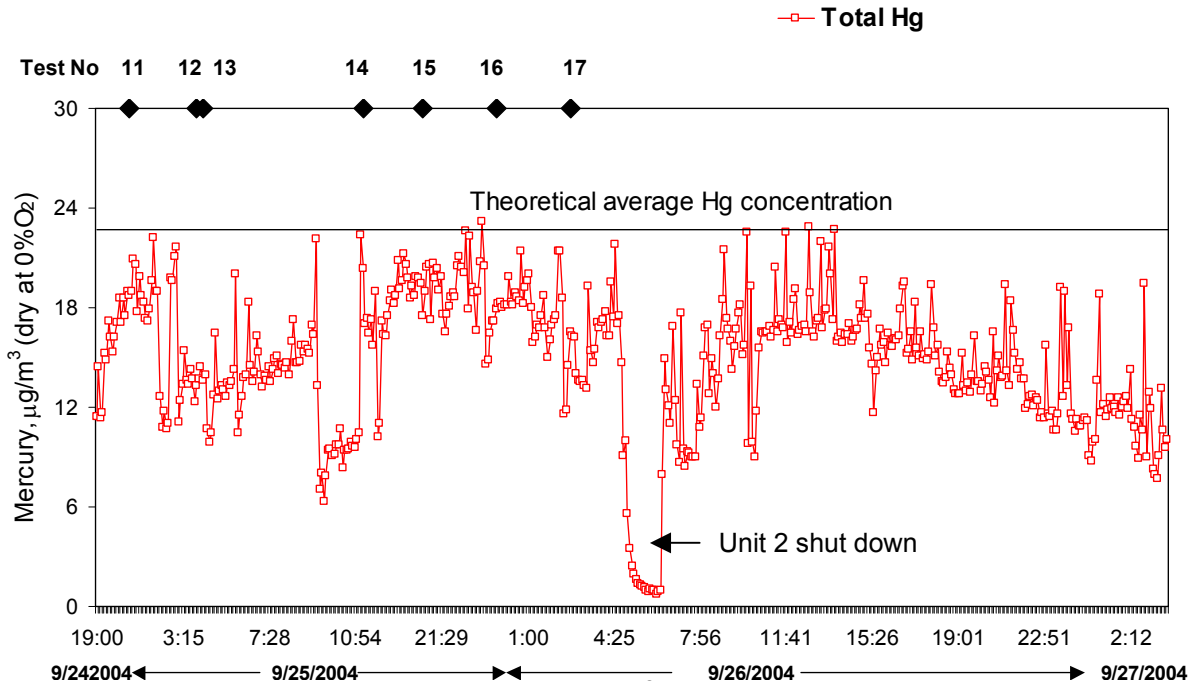

Figure 41. Results of CEM measurements for coal firing on September 24-27.

Figure 42 shows Hg reduction and Hg emissions for coal firing. Figure 42 demonstrates that Hg reduction for coal firing was less than 40%. It should be noted that the lowest ESP temperature in the coal firing tests was 280°F, while in blend firing tests it was 270°F. The highest LOI in coal firing was 5.4%, about 50% of that in blend firing.

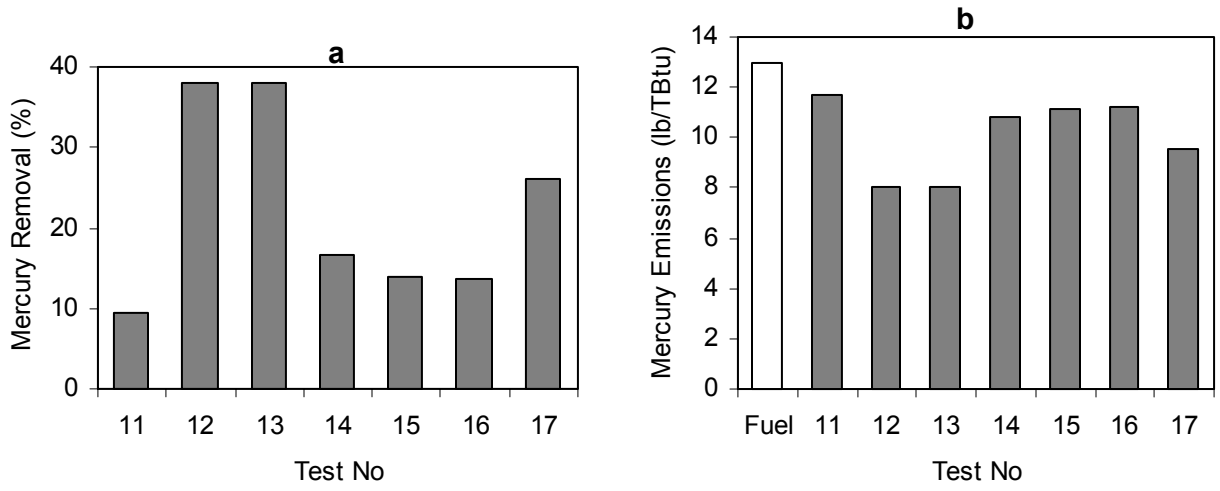

Figure 42. Mercury reduction efficiencies (a) and Hg emissions for coal firing.

Figure 43 shows Hg reduction and Hg emissions at the stack for coal firing measured by the FSTM method. Figure 40a demonstrates that combined Hg reduction across ESP wet FGD in Unit 2 is about 80%. Figure 43b shows uncontrolled Hg emissions calculated from Hg content in coal and Hg emissions at the stack. Figure 43b demonstrates that Hg emissions at the stack for coal firing are below 2.6 lb/TBtu.

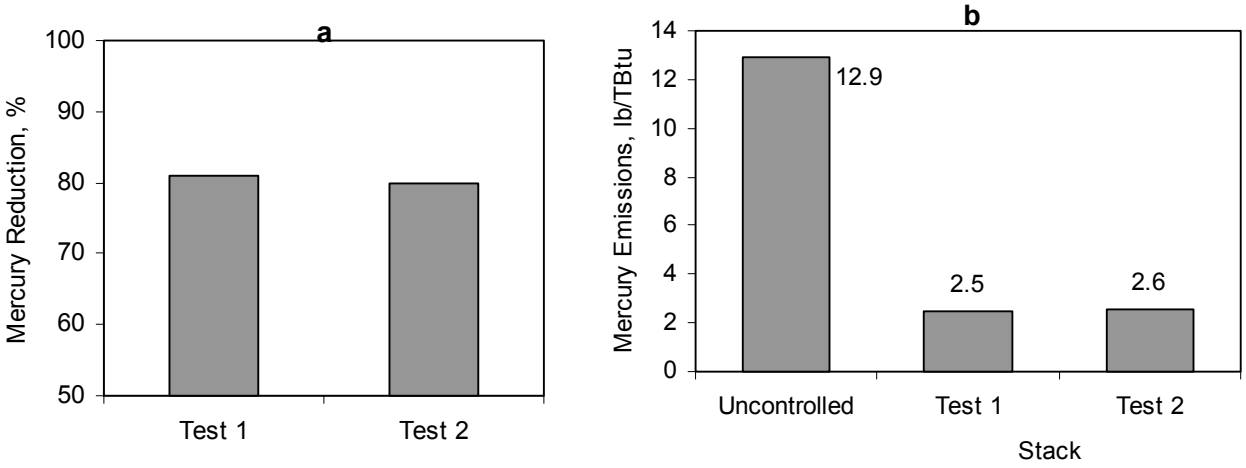

Figure 43. Mercury reduction efficiencies (a) and Hg emissions (b) at the stack for coal firing.

Reburning optimization also improved the efficiency of NO_x reduction. NO_x emissions in Unit 2 prior to reburning retrofit were 0.44 lb/MBtu. Typically, NOx emissions in Unit 2 under reburning conditions were 0.18-0.20 lb/MBtu, about 57% reduction. Table 12 shows that under deep staging conditions which were implemented to increase LOI minimum NO_x emissions were 0.12-0.13 lb/MBtu, a 71% reduction from uncontrolled emissions.

6.2 Discussion and Comparison with Previous Data

Testing suggested that ESP temperature had a significant effect on Hg removal. Figures 44 and 45 show the dependence of Hg removal efficiency on temperature for blend and coal firing as determined in Hg optimization and reburning tests described in Section 4.0. LOI in tests presented in Figures 44 and 45 was in the range of 9.5-10.5% and 2-3% for blend and coal firing, respectively. Testing demonstrated that ESP temperature reduction from 310^{o}F to 270^{o}F resulted in improvement in Hg reduction efficiency from about 40% to about 80% for blend firing. These results clearly demonstrate that controlling ESP temperature can improve the effectiveness of Hg absorption on high carbon fly ash.

Figure 46 shows dependence of Hg content in fly ash collected in ESP in Hg optimization tests on fly ash surface area. Figure 46 demonstrates that increase in fly ash surface area results in increase in fly ash Hg content. At the same fly ash surface area, Hg content in fly ash was higher for coal firing suggesting that fuel properties also affect Hg removal. Figure 46 also demonstrates

that dependence of Hg content in fly ash on surface area is steeper for coal than that for blend firing.

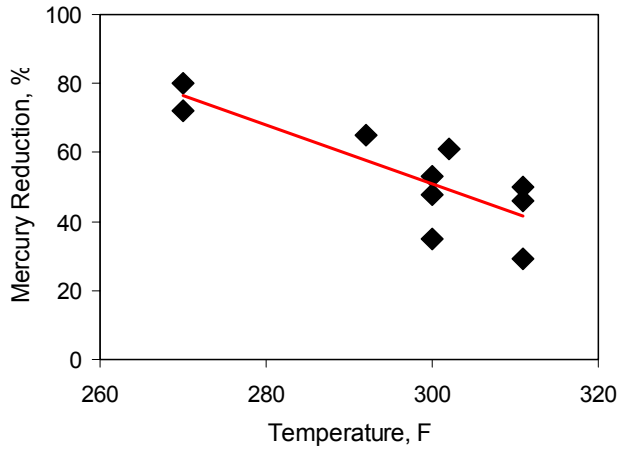

Figure 44. Dependence of Hg removal efficiency on temperature for blend firing.

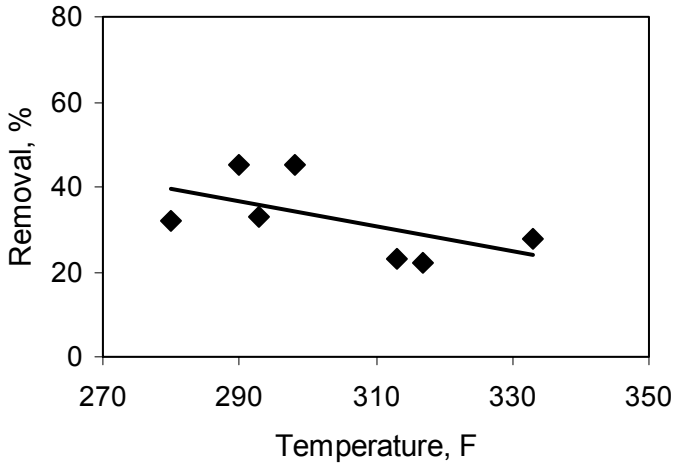

Figure 45. Dependence of Hg removal efficiency on temperature for coal firing.

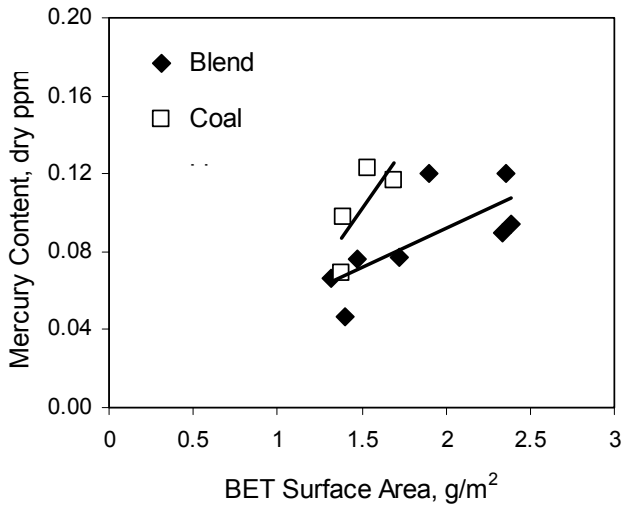

Figure 46. Dependence of Hg concentration in fly ash on fly ash surface area.

Testing demonstrated that under optimized reburning conditions Hg removal by fly ash was in the range of 60-80% for blend firing. Thus, project goal of 80% Hg control was demonstrated. The two most important parameters that affect efficiency of Hg removal are carbon in ash content and ESP temperature. The 80% Hg control was achieved for LOI in the range of 10-11% and ESP temperature in the range of 270-285^{o}F. Since carbon in ash content is affected by combustion conditions and fuel reactivity, fuel properties should be also considered when evaluating potential efficiency of "naturally occurring" Hg capture on fly ash.

7.0 Project Summary

In this project EER conducted a preliminary field evaluation of the integrated approach for Hg and NO_x control. The integrated Hg/NO_x control method utilized coal reburning (injection of reburning coal and overfire air) and ESP to capture the fly ash. The approach enhanced the "naturally occurring" Hg capture by fly ash through combustion optimization, increasing carbon in ash content, and lowering ESP temperature. Other benefits of the approach included reduced NO_x emissions, improved boiler performance, increased heat efficiency, and minimized CO emissions as a result of combustion optimization.

The evaluation took place in Green Station Units 1 and 2 located near Henderson, Kentucky and operated by Western Kentucky Energy. Units 1 and 2 are sister units with similar boiler parameters and unit configurations. They are equipped with cold-side ESPs and a wet scrubber. Green Station Units 1 and 2 typically fire two types of fuel: a bituminous coal and a blend of bituminous coals based on availability. Mercury content in the individual coal is typically higher than that in the blend.

The program focused on optimizing combustion conditions and ESP temperature to improve Hg removal across the ESP. No efforts were made to improve Hg reduction across the wet scrubber. Project goal was to demonstrate 80% Hg control downstream of ESP.

The program comprised field and pilot-scale tests and engineering studies, and consisted of five tasks. The approach to optimizing the reburning system for Hg control included pilot-scale testing to determine effects of process conditions and fuel composition on Hg removal, engineering evaluation to determine boiler operating conditions that would allow to achieve optimum conditions for Hg removal, and Unit 2 optimization for Hg control. Pilot-scale testing demonstrated that Hg removal improved with LOI increase and ESP temperature decrease. Testing of Hg emission in Unit 2 confirmed pilot-scale observations and demonstrated 80% Hg reduction downstream of ESP at optimized conditions.

Project results can be summarized as follows:

1. Testing of Hg emissions in Unit 2 without reburning system in operation and at minimum OFA demonstrated that efficiencies of Hg reductions downstream of ESP for coal and blend firing were 30-40%. However, since Hg content in the blend was lower than that in the coal, Hg emissions were lower for blend firing. Mercury emissions at the ESP outlet were 5.8-6.9 lb/TBtu and 2.7-3.7 lb/TBtu for coal and blend firing, respectively.

2. Testing demonstrated that OFA system operation at 22% air resulted in 10% incremental increase in Hg removal efficiency at ESP outlet.
3. Testing demonstrated that about 80% of Hg at the ESP outlet was present in the oxidized form.
4. Pilot-scale testing in a 300 kW Boiler Simulator Facility was conducted to determine effects of process conditions and fuel composition on Hg removal. Testing focused on determining effects of the following factors on Hg removal: (a) fuel composition, (b) carbon in ash content, and (c) ESP temperature. Testing demonstrated that Hg removal improved with LOI increase and ESP temperature decrease. Results of pilot-scale testing suggested that 80% Hg control could be achieved at LOI ≥8% and ESP temperatures ≤ 300^{o}F (420 K).
5. Testing of Hg emissions in Units 1 and 2 under reburning conditions confirmed that Hg emissions decreased with LOI increase and ESP temperature decrease. Testing demonstrated that maximum Hg reduction downstream of ESP was 40-45% at ESP temperature higher than 300^{o}F and 60-80% at ESP temperatures lower than 300^{o}F.
6. The 80% Hg control downstream of ESP in Unit 2 was achieved for blend firing for LOI in the range of 10-11% and ESP temperature in the range of 270-285^{o}F.
7. Maximum LOI achieved with coal firing was 6%, about half that of blend firing. As a result of lower LOI, maximum Hg reduction downstream of ESP for coal firing was 40%. Since carbon in ash content is affected not only by combustion conditions but also by fuel reactivity, fuel properties should be also considered when evaluating efficiency of "naturally occurring" Hg capture on fly ash.
8. Testing demonstrated that efficiency of Hg removal across the FGD was in the range of 65-70%. Reduction in concentration of the oxidized Hg was about 90%. However, about 20% of the oxidized Hg was reduced to elemental Hg across the scrubber. Most Hg at the stack was present in the elemental form.
9. Mercury emissions at the Unit 2 stack were lower for blend firing due to the lower Hg content in the blend. Mercury emissions at the stack at tested conditions were in the range of 1.8-3.0 lb/TBtu and 1.0-1.5 lb/TBtu for coal and blend firing, respectively.
10. Under optimized reburning conditions NO_x emissions were reduced from uncontrolled 0.44 lb/MBtu to 0.13 lb/MBtu.

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