# JV TASK 122 – ASSESSMENT OF MERCURY CONTROL OPTIONS FOR THE SAN MIGUEL ELECTRIC COOPERATIVE POWER PLANT

Final Report

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# JV TASK 122 – ASSESSMENT OF MERCURY CONTROL OPTIONS FOR THE SAN MIGUEL ELECTRIC COOPERATIVE POWER PLANT

## ABSTRACT

In the United States, testing has been under way at electric coal-fired power plants to find viable and economical mercury control strategies to meet pending regulations. San Miguel Electric Cooperative (SMEC) engaged the Energy & Environmental Research Center (EERC) through a request for proposal (RFP) to perform research tests to evaluate sorbent-based technologies at its coal-fired San Miguel Generating Station to identify possible technology options that could be used by SMEC to meet the mercury reduction requirements of future U.S. federal standards. The goal of the testing was to target a mercury removal of ≥90%.

The EERC has successfully field-tested several sorbent-based technologies in previous projects that offer promise and potential to achieve a target removal of ≥90%. Based on these field test results, yet recognizing that fuel type and plant operating conditions affect mercury capture significantly, the EERC proposed research tests to evaluate potential sorbent-based technologies provided by Norit Americas and the EERC that could potentially meet SMEC's mercury control objectives. Over the period of May through mid-June 2008, the EERC tested injection of both treated and nontreated activated carbon (AC) provided by Norit Americas and sorbent enhancement additives (SEAs) provided by the EERC. Tests were performed at San Miguel Unit 1 (450 MW) and included injection at the inlet of the air heater (AH) (temperature of 720°F). The test coal was a Texas lignite fuel with an average moisture content of 31.19%, an ash content of 26.6%, a heating value of 5,094 Btu/lb, a sulfur content of 2.7%, and a mercury concentration of 0.182 ppm, all reported on an as-received basis.

Pilot-scale testing results identified DARCO® Hg-LH, SEA2 + DARCO® Hg, and the ChemMod sorbents as technologies with the potential to achieve the target mercury removal of ≥90% at the full-scale test.

Mercury concentrations were tracked with continuous mercury monitors (CMMs) at the electrostatic precipitator (ESP) inlet (ESP In), scrubber inlet, and scrubber outlet of San Miguel Unit 1, and a dry sorbent trap method was used to take samples periodically to measure mercury concentrations at the each of the CMM sampling locations described above. A limited number of Ontario Hydro (OH) measurements were also conducted. Removal efficiencies were calculated from mercury-in-coal values to scrubber out CMM values. Sorbent trap samples taken at the each sampling location outlet were found to be fairly consistent with CMM values.

A maximum mercury removal of 78.5% was achieved with the SEA2 + DARCO Hg sorbent combination at injection rates of 50 ppm and 4 lb/Macf, respectively. An injection rate of 4 lb/Macf for DARCO Hg-LH and DARCO Hg resulted in mercury removals of 70.0% and 64.2%, respectively. These mercury reduction values were achieved at full load and at stable plant operating conditions. Scrubber reemission was observed during sorbent injection and had a significant effect on coal to scrubber out mercury removal values.

When the sorbents were injected into San Miguel Unit 1 at the AH inlet, no effects on unit operations were observed. ESP performance throughout the test period was fairly steady, with only one minor breakdown. However, it should be noted that test durations were short.

# TABLE OF CONTENTS

Continued . . .

## TABLE OF CONTENTS (continued)

# LIST OF FIGURES

Continued . . .

## LIST OF FIGURES (continued)

# LIST OF TABLES

## NOMENCLATURE

| | |
|---|---|
| AC | Activated carbon |
| AH | Air heater |
| APCD | air pollution control device |
| BOP | Balance of plant |
| CMM | Continuous mercury monitor |
| CVAA | Cold-vapor atomic absorption |
| CVAFS | Cold-vapor atomic fluorescence spectroscopy |
| EERC | Energy & Environmental Research Center |
| EPA | Environmental Protection Agency |
| ESP | Electrostatic precipitator |
| ICP–MS | Inductively coupled plasma mass spectrometry |
| MW | Megawatts |
| OH | Ontario Hydro |
| PRB | Powder River Basin |
| SEA | Sorbent enhancement additive |
| SMEC | San Miguel Electric Cooperative |
| ST | Sorbent trap (for mercury measurement) |
| WFGD | Wet flue gas desulfurization |

# JV TASK 122 – ASSESSMENT OF MERCURY CONTROL OPTIONS FOR THE SAN MIGUEL ELECTRIC COOPERATIVE POWER PLANT

## EXECUTIVE SUMMARY

In the United States, testing has been under way at electric coal-fired power plants to find viable and economical mercury control strategies to meet pending regulations. San Miguel Electric Cooperative (SMEC) engaged the Energy & Environmental Research Center (EERC) through a request for proposal (RFP) to perform research tests to evaluate sorbent-based technologies at its coal-fired San Miguel Generating Station to identify possible technology options that could be used by SMEC to meet the mercury reduction requirements of future U.S. federal standards. The goal of the testing was to target a mercury removal of ≥90%.

The single 450-MW unit at the San Miguel Station is equipped with an electrostatic precipitator (ESP) for particulate control, and a wet flue gas desulfurization (WFGD) system to reduce $SO_x$ emissions. The EERC has successfully field-tested several sorbent-based technologies in previous projects that offer promise and potential to achieve a target removal of ≥90%. Based on these field test results, yet recognizing that fuel type and plant operating conditions affect mercury capture significantly, the EERC proposed research tests to evaluate potential sorbent-based technologies provided by Norit Americas and the EERC that could potentially meet SMEC's mercury control objectives. Over the period of May through mid-June 2008, the EERC tested injection of both treated and nontreated activated carbon (AC) provided by Norit Americas and sorbent enhancement additives (SEAs) provided by the EERC. Tests were performed at San Miguel Unit 1 (450 MW) and included injection at the inlet of the air heater (AH) (temperature of 720°F).

The coal combusted during this project was a Texas lignite which is mined in the land adjacent to the power plant and transported to the plant via dump trucks. Table ES-1 presents the average coal properties on an as-received basis.

Pilot-scale testing results identified DARCO® Hg-LH, SEA2 + DARCO® Hg, and the ChemMod sorbents as technologies with potential to achieve the target mercury removal of ≥90% at the full-scale test. Scrubber reemission was not observed during pilot-scale testing, but the slurry used for the scrubber was not exactly the same as the slurry used at the San Miguel Station.

Mercury concentrations were tracked with continuous mercury monitors (CMMs) at the ESP inlet (ESP In), scrubber inlet, and scrubber outlet of San Miguel Unit 1 and a dry sorbent trap method was used to take samples periodically to measure mercury concentrations at each of the CMM sampling locations described above. Removal efficiencies were calculated from mercury-in-coal values to scrubber out CMM values. Sorbent trap samples taken at the each sampling location outlet were found to be fairly consistent with CMM values.

**Table ES-1. Average Coal Values for the Test Coal**

| | As-Received Basis | |
|---|---|---|
| Parameter | Average[a] | Std. Dev |
| Hg, ppm | 0.182 | 0.027 |
| Cl, ppm | 843 | 37 |
| Br, ppm | 4.2 | 0.3 |
| Proximate Analysis, wt% | | |
| Moisture | 31.1 | 0.4 |
| Volatile Matter | 23.7 | 0.56 |
| Fixed Carbon | 18.5 | 0.68 |
| Ash | 26.6 | 1.21 |
| Ultimate Analysis, wt% | | |
| Hydrogen | 6.1 | 0.06 |
| Carbon | 29.6 | 0.93 |
| Nitrogen | 0.5 | 0.02 |
| Sulfur | 2.7 | 0.16 |
| Oxygen | 34.4 | 0.67 |
| Heating Value, Btu/lb | 5094 | 181 |

[a] Average values are based on 17 samples.

Baseline and parametric tests were completed over a 1-month period while combusting the coal noted above. To determine baseline emissions and technology effectiveness, mercury removal efficiencies were calculated using mercury-in-coal values compared to scrubber outlet CMM values. Baseline results with no sorbent injection showed a native mercury removal of 34.4%, with most of the mercury removal occurring across the scrubber.

Parametric testing entailed the injection of sorbents into the AH inlet (temperature of 720°F). When SEA2 was introduced, it was combined with the DARCO Hg on the ground and then injected into the flue gas at the AH inlet injection location. Two Norit Americas products, a standard AC, DARCO Hg and a brominated treated AC, and DARCO Hg-LH were evaluated for mercury control at the San Miguel station. A proprietary EERC SEA named SEA2 was also tested with DARCO Hg. Parametric tests of 0.5–4 hours in duration were performed using these test materials by varying the injection rates and evaluating their effectiveness to capture mercury, as measured by the scrubber outlet mercury concentration. Mercury removal efficiencies for these options varied from 51% to 78.5%.

When the sorbents were injected into San Miguel Unit 1 at the AH inlet, no effects on unit operations were observed. ESP performance throughout the test period was fairly steady, with only one minor breakdown. However, it should be noted that test durations were short.

Figure ES-1 displays the maximum mercury removals obtained with each of the sorbents tested. At 4 lb/Macf, DARCO Hg, and DARCO Hg-LH achieved mercury removals of 64.2% and 70.0%, respectively. At 50 ppm and 4 lb/Macf, the SEA2 + DARCO Hg combination achieved a mercury removal of 78.5%. Scrubber reemission was observed and had a significant impact on the mercury removal results that were obtained.

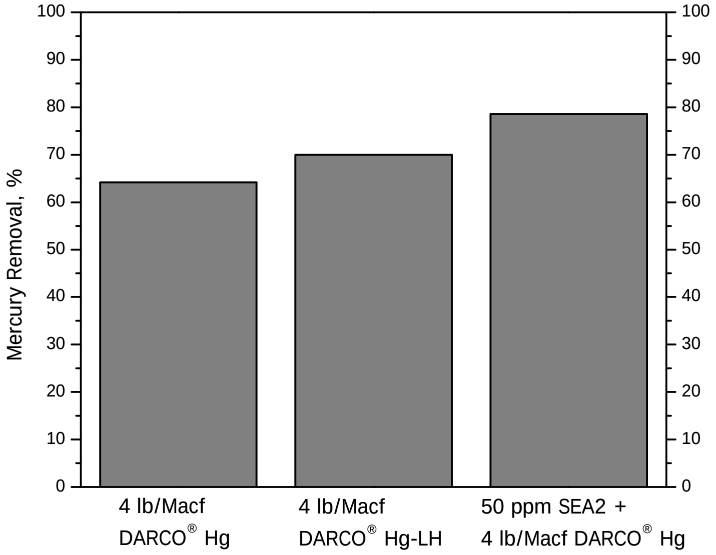


Figure ES-1. Maximum mercury removals obtained with each technology tested.

Scrubber reemission was very pronounced during the injection of DARCO Hg-LH and during the SEA2 + DARCO Hg tests. At the highest DARCO Hg-LH and SEA2 + DARCO Hg injection rates, the $Hg^0$ concentration increased by approximately 4–5 μg/Nm$^3$ across the scrubber. At the Scrubber In sampling location, $Hg^0$ concentrations as low as 2.8 μg/Nm$^3$ were measured during sorbent injection. These results show that ≥90% mercury removal may be possible if scrubber reemission does not occur during sorbent injection.

# JV TASK 122 – ASSESSMENT OF MERCURY CONTROL OPTIONS FOR THE SAN MIGUEL ELECTRIC COOPERATIVE POWER PLANT

## INTRODUCTION

In the United States, testing has been under way at electric coal-fired power plants to find viable and economical mercury control strategies to meet the requirements of the Clean Air Act Amendments. Despite the fact that both the U.S. Clean Air Mercury Rule and the Clean Air Interstate Rule have recently been overturned, state limits are generally quite stringent and call for greater limits than those that were expected at the federal level. The Energy & Environmental Research Center (EERC) has been fully involved in these discussions and in technology development and testing efforts for over 15 years. The technology that presently holds the most promise to meet U.S. regulations for mercury control is injection of activated carbon (AC) into the flue gas stream—both with and without enhancement additives. San Miguel Electric Cooperative (SMEC) engaged the EERC to perform research tests to evaluate sorbent-based technologies at SMEC's coal-fired San Miguel Generating Station to identify possible technology options that could be used by SMEC to meet the mercury reduction requirements of the future U.S. federal standards, with mercury removals targeted at ≥90%.

To achieve this reduction goal, an intensive research project was initiated in January 2008 to perform mercury sampling and measurement while evaluating a number of mercury control technologies at the pilot-scale at the EERC and full-scale testing at the San Miguel Station, which is located near Christine, Texas, and owned/operated by SMEC. The single 450-MW unit at the San Miguel Station is equipped with a cold-side electrostatic precipitator (ESP) for particulate control, and a wet flue gas desulfurization (WFGD) system to reduce $SO_x$ emissions. The EERC has successfully field-tested several sorbent-based technologies in previous projects that offer promise and potential to achieve a target removal of ≥90%. Based on these field test results, yet recognizing that fuel type and plant operating conditions affect mercury capture significantly, the EERC proposed research tests to evaluate potential sorbent-based technologies provided by Norit Americas and the EERC that could potentially meet SMEC's mercury control objectives. Over the period of May through mid-June 2008, the EERC tested injection of both treated and nontreated AC provided by Norit Americas and sorbent enhancement additives (SEAs) provided by the EERC. Tests were performed at San Miguel Unit 1 (450 MW) and included injection at the inlet of the air heater (AH) (temperature of 720°F).

Baseline and parametric tests were completed over a 1-month period while combusting the coal noted above. To determine baseline emissions and technology effectiveness, mercury removal efficiencies were calculated using mercury-in-coal values compared to scrubber outlet continuous mercury monitor (CMM) values.

### Project Participants

To execute the project, several organizations were involved, requiring a very collaborative approach. Their roles in the project are briefly described below:

- SMEC assembled the project team and contracted organizations to perform the research project. Managed corporate and plant activities, communications, and interfaced with and directed project team.

- San Miguel Generating Station is owned and operated by SMEC; served as host site for testing.

- The EERC is a U.S.-based research, development, demonstration, and commercialization research organization. Contracted by SMEC to serve as project lead. Oversaw and managed research program and provided test and measurement equipment and SEA2. Coordinated and performed tests, data reduction, and reporting.

- Norit Americas Inc. is a commercial provider of ACs, which provided both treated and untreated ACs for the project.

- Nol-Tec is a provider of commercial injection feed systems. The EERC owns the Nol-Tec system that was installed and operated by the EERC for this project.

## BACKGROUND

Since the U.S. Environmental Protection Agency (EPA) announced its intention to regulate mercury in 2000, utilities have been seeking to develop and test possible technology options for mercury control. The U.S. government has provided funds, as have many utilities, to assess various strategies that would provide the best economics with optimal mercury control.

Although several mercury control technologies have been developed and tested at various scales, sorbent-based technologies, specifically AC technologies, have been identified as the most mature, consistent, and economical approach for mercury removal. During early testing in the United States, it became apparent that coal type and plant configuration were the two biggest factors affecting the possible removal of mercury, as illustrated in Table 1.

**Table 1. Mercury Removal as a Function of Coal Type and Plant Configuration**

| Control Tech. (no. plants) | Bituminous | Subbituminous | Lignite | All Coals |
|---|---|---|---|---|
| Cold-Side ESP (*640*) | 30–40 | 0–20 | 0–10 | 0–40 |
| Cold-Side ESP + WFGD (*129*) | 60–80 | 15–35 | 0–40 | 0–80 |
| Dry FGD + Cold-Side ESP (*4*) | 35–50 | 10–35 | 0–10 | 0–50 |
| Fabric Filter (*58*) | 40–90 | 20–75 | 0–10 | 0–90 |
| Fabric Filter + WFGD (*15*) | 75–95 | 30–75 | 10–40 | 10–95 |
| Dry FGD + Fabric Filter (*37*) | 65–95 | 20–40 | 0–20 | 0–95 |
| Coal Cleaning | 20–40 | ? | ? | 0–40 |

* Typical values based on EPA notice of data availability (NODA), information collection request (ICR) data, field tests, and observations. Some values are based on single data points and may not reflect removal for all plants.

In the past, low-chlorine coals (below 500 ppm) were considered to be most problematic and challenging for mercury control. This is partly because the lack of chlorine results in a low ratio of oxidized mercury in the flue gas compared to the total mercury concentration. Through extensive research, the EERC has developed a complex mercury–sorbent–flue gas interaction model, shown in Figure 1, that shows the role and impact that various flue gas components have on chemisorption (1).

The EERC model further shows that mercury oxidation (whether in the gas phase or on/within the carbon structure) must occur before the basic sites on the carbon can chemisorb the mercury. The basis of this model provides much insight into why the mercury must be oxidized, how to enhance mercury oxidation on the carbon through the use of sorbent enhancement additives, and why and how $NO_x$ and $SO_x$ ($SO_2$ and $SO_3$) impact the carbon's ability to capture mercury. For example, for low-chlorine coals that produce predominantly elemental mercury, an oxidant such as a halogen is needed to promote oxidation of the mercury on/within the carbon, which is then subsequently captured on basic sites within the carbon structure. In contrast, for coals that produce high amounts of $SO_3$, the $SO_3$ will bind to these basic sites preferentially, limiting the sites available for mercury chemisorption. This is of significant importance when $SO_3$ injection is used to condition fly ash to improve ESP collection.

For the reasons stated above, plain (untreated) ACs have often yielded poor capture for plants burning low-halogen coals, such as lignite and Powder River Basin (PRB) coals. In these cases, the carbon has low reactivity unless SEAs or treated ACs are used. However, results for

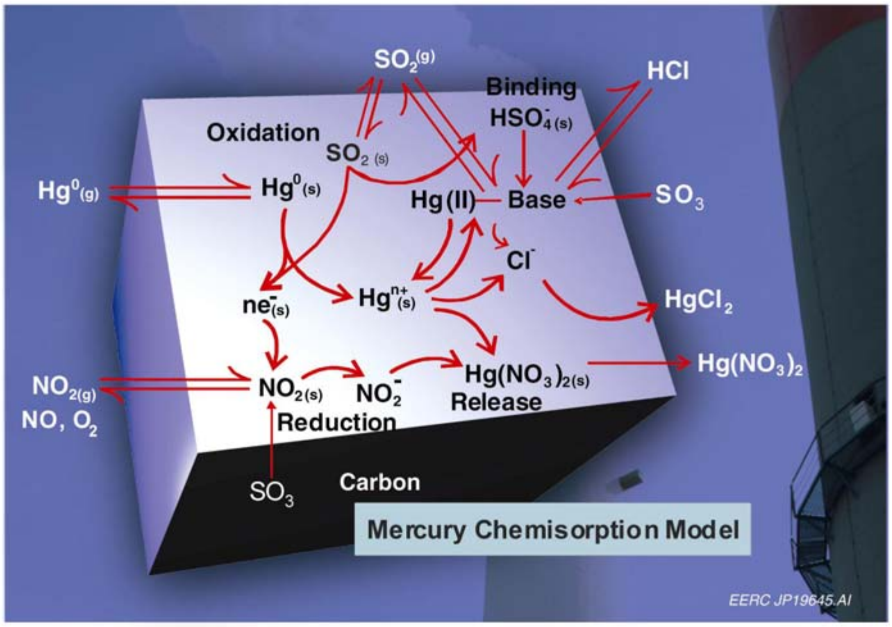


Figure 1. Chemisorption model for mercury–flue gas interactions with AC sorbents.

both approaches are very site-specific, as several field tests have shown varying rates of effectiveness depending on plant configuration, operating conditions, and coal type (or blends of coal).

Several economic analyses have shown that the AC cost is the largest ongoing factor when AC injection is used as a mercury control strategy. Additives and/or treatments as shown in Figure 2 can be used to lower the total amount of injected material which can lessen the balance-of-plant (BOP) impacts on air pollution control devices (APCDs), while often promoting mercury capture at a reduced price. If these technologies can lessen the total amount of AC injected, utility by-product sales may also be maintained, thereby preserving a valuable revenue stream and lessening the amount of material to be landfilled.

## GOALS AND OBJECTIVES

The goal of the project was to identify and evaluate the most promising technology options that could be used by SMEC to meet the mercury reduction requirements of the future U.S. regulations, with mercury removals targeted at ≥90%. The objectives of the field testing activities were to gather data (technology effectiveness, preliminary economics, etc.) to guide future test and installation decisions and support the development of SMEC's mercury control strategy.

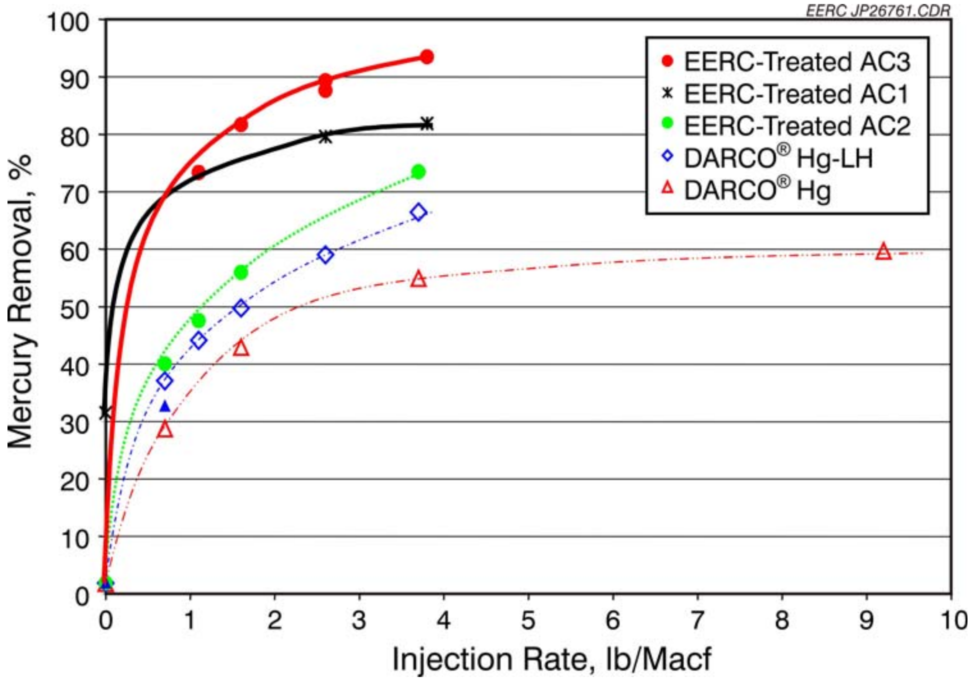


Figure 2. Pilot-scale data showing the mercury removal of plain and treated/enhanced carbon on an ESP-only configuration.

The coal burned at San Miguel presents a challenge to control mercury on several fronts. First, the coal mercury concentration exhibits a high degree of variability on a daily and hourly basis. Secondly, the high ash content of the coal makes analytical measurements challenging. Finally, the high volume of coal being combusted, approximately 480 ton/hr, results in high lb/hr sorbent injection rates compared to plants of similar MW size. The high lb/hr injection rates increase the cost per pound for mercury captured.

To meet these challenges and the overall project goal, the EERC and SMEC identified the following pretest objectives and activities to adequately prepare for the test program:

- EERC personnel conducted a site visit to assess potential sorbent injection locations, site needs, and possible impediments to testing.

- The test team determined the best injection schemes by performing flow modeling, and the subsequent design of injection lances, splitters, and necessary ports for good dispersion of the injected sorbents.

- A site-specific test plan (SSTP) that included baseline and parametric testing was prepared by the EERC with the guidance and assistance of SMEC.

- A temporary sorbent injection system was installed to allow testing at the AH inlet location.

Testing activities included the following objectives for the San Miguel Station:

- A site-specific test plan was prepared, updated, and submitted to all team members as needs evolved over the course of testing.

- The injection location was upstream of the existing cold-side ESP on this unit, with the planned primary location upstream of the AH, which allowed for increased residence time and maximized sorbent effectiveness.

- To obtain outlet mercury concentrations data for Unit 1, a CMM was installed at the scrubber outlet duct, just prior to the entrance into the stack.

- Sorbent trap (ST) testing was used to verify the CMM results.

- On-site mercury analysis of ST samples was conducted in the EERC's mobile laboratory in order to obtain rapid feedback to evaluate mercury removals and to support ongoing testing decisions.

- Coal and ash samples were obtained and analyzed off-site to support evaluation of mercury removals.

- Quality measures were implemented to ensure accurate measures of mercury in coal, fly ash, and flue gas to accurately evaluate mercury removal effectiveness.

## DESCRIPTION OF TEST UNIT

The San Miguel Generating Station, owned and operated by SMEC, is composed of one 450-MW unit and is located near Christine, Texas. The physical plant address is as follows:

San Miguel Station
6200 FM 3387
Christine, TX 78012

Other features of the plant include:

- Boiler: Unit 1, 450 MW – the boiler was manufactured by Babcock & Wilcox (B&W) and is tangentially fired and equipped with over-fire air and low $NO_x$ burners for reduced $NO_x$ emissions.

- Seven coal feeders.

- Seven MPS-89 mills for coal grinding.

- Fuel: 5,000–5,500 Btu (as-received) Texas lignite. Coal is mined approximately 3 miles from the plant in the San Miguel Mine.

- Low-$NO_x$ burners.

- ESPs for particulate control.

- WFGD for $SO_x$ emissions.

A schematic of Unit 1 with sampling and injection locations is shown in Figure 2, in the following section of the report.

## TEST PLAN

To address the project objectives, the EERC assisted SMEC in planning for and proceeding with testing of sorbents and SEAs for mercury removal to target a ≥90% mercury removal rate. Tests were performed at San Miguel Unit 1 (450 MW) and included injection into the inlet of the AH (temperature of 670°F), location 2 as shown in Figure 3. Sorbents were injected into the primary and both of the secondary air heaters. Note that injection of SEAs and sorbents was performed on the entire unit, with flue gas sampling limited to Side B to minimize duplication of sampling effort and associated costs, as shown in Figure 3.

A test matrix was developed as part of the SSTP to evaluate potential sorbent-based technologies provided by Norit Americas and the EERC that could potentially meet a ≥90% mercury removal target. Over the 1-month period, the EERC tested injection of both treated and nontreated AC provided by Norit Americas and a proprietary SEA provided by the EERC at locations shown in Figure 3. Baseline and parametric tests were completed with a variety of SEAs and sorbents according to the schedule shown in Table 2.

### ACs from Norit Americas

Two types of ACs from Norit Americas were used in this test regime. The first was the standard DARCO Hg, which is a “plain,” nontreated carbon that was used for baseline comparisons. The second was a brominated treated carbon, referred to as DARCO Hg-LH, which is typically used with low-halogen coals to enhance mercury capture. All ACs provided by Norit are readily available in large quantities adequate to supply SMEC.

**Table 2. Test Schedule for San Miguel Unit 1**

| Date | Activities |
|---|---|
| 5/18/08 – 5/23/08 | Travel, equipment mobilization, safety orientation, system installation, setup, and shakedown |
| 5/24/08 – 5/26/08 | Baseline sampling |
| 5/26/08 – 6/5/08 | Parametric testing |
| 6/5/08 – 6/7/08 | Equipment teardown, packing, and travel back to the EERC |

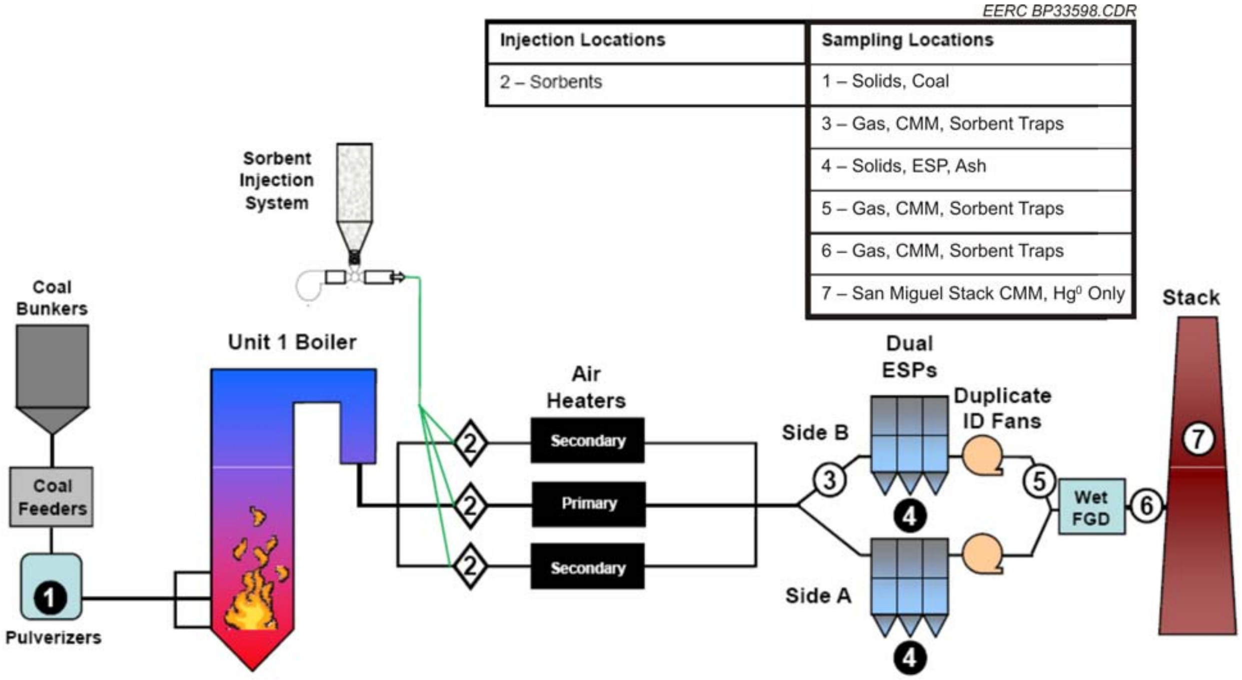


Figure 3. Schematic of San Miguel Unit 1, showing injection and sampling locations.

### SEA2 from the EERC

SEA2 is a proprietary SEA developed at the EERC. This technology is introduced into the AC stream and changes the AC properties, thereby increasing mercury capture compared to AC by itself. SEA2 is generally introduced with a plain AC such as DARCO Hg. The EERC anticipates that the technology will be commercially available with quantities adequate to supply SMEC in the future.

### Flue Gas Sampling

To determine baseline emissions and technology effectiveness, mercury removal efficiencies were calculated using mercury-in-coal values compared to scrubber outlet CMM values. The EERC installed and operated a CMM at the ESP inlet, scrubber inlet, and scrubber outlet throughout the duration of testing to measure gaseous mercury concentrations in the flue gas. The CMMs were used primarily to monitor total gas-phase mercury.

The CMMs used during this project were PSA Analytical Sir Galahad instruments. The PSA Sir Galahad is a CMM for the determination of both Total Hg and elemental Hg speciation in the flue gas stream. This instrument provides a simple and reliable system for the routine determination of Hg emissions from duct work, emission control devices, and stacks. The Sir Galahad analyzer utilizes an integrated sampling, conditioning, and analysis system to determine the mercury concentration in a flue gas stream. In high ash loading areas, the sample gas is extracted from the duct using a heated inertial separation probe (ISP). The sample is then transported to a wet-chemical system where the sample stream is split into two streams, an elemental stream and a total stream. The elemental stream is mixed with a KCl solution to remove the oxidized mercury from the sample gas stream. The gas passes through a chilled gas–liquid separator to remove moisture. It is then sent to the Sir Galahad analyzer for determination of mercury concentration. The total gas stream is mixed with a reducing solution that reduces all of the mercury in the sample gas stream to elemental mercury. It also passes through a chilled gas–liquid separator to remove moisture before being sent to the analyzer. A switching box is used upstream of the analyzer to select between sampling total Hg or $Hg^0$ and sending either zero gas or a span gas to the probe tip. The span gas is generated by the CavKit, which is similar to a permeation device. The Sir Galahad analyzer utilizes gold amalgamation and a cold-vapor atomic fluorescence spectroscopy (CVAFS) to determine the mercury concentration in the sample gas stream. A source of compressed mercury-free argon and clean, dry air is required for operation of the analyzer. If the mercury concentrations are high, mercury-free nitrogen can be substituted for the argon. Calibration of the system is done using $Hg^0$ as the primary standard. It is contained in a closed vial held in a thermostatic bath. The temperature of the mercury is monitored, and the amount of mercury is calculated using vapor pressure calculations. Typically, the calibration of the unit has proven to be stable over a 24-hr period. The sample cycle time is typically 6 minutes, and the nominal measurement range is 0.001–2500 $\mu g/m^3$.

Coal and ash sampling was used to determine inlet and outlet mercury flows and compare them to flue gas measurements. In addition, Ontario Hydro (OH) and ST samples were periodically collected to verify CMM instrumentation. The ST and OH samples were analyzed in the on-site laboratory to provide for rapid turnaround and feedback regarding the effectiveness of the sorbent methodology used. ST and OH sampling has been shown to be appropriate and accurate for short-term mercury measurement in pulverized coal-fired combustion units and was successfully carried out for this project. The ST samples were collected with dual two-stage traps and were recovered and analyzed for mercury in the EERC mobile lab set up on-site. The OH sampling was performed according to ASTM Method D6784-02. Appropriate spikes and blanks were also analyzed for quality assurance/quality control (QA/QC) purposes.

The EERC's mobile laboratory trailer was taken on-site to support both injection and sampling activities. The on-site analysis allowed a quick turnaround on analyses of OH and ST samples and included blanks and spikes to ensure proper QA/QC and confidence in the results obtained. Analysis of the ST samples was performed in the field with an OhioLumex mercury analyzer. This instrument is designed for on-site "direct" testing of sorbent traps. The method is a thermal decomposition procedure validated by EPA. The analyzer uses cold-vapor atomic absorption spectroscopy (CVAAS) to measure the mercury concentration. Analysis of the OH samples was performed in the field with a Leeman Labs Hydra AA spectrometer in accordance with the OH ASTM Method D6784-02. The system features dual-beam optics, a 30-cm absorption cell, built-in autosampler, an integrated gas–liquid separator, and over-range protection. The Hydra AA has a lower detection limit of 1 part per trillion (ppt).

The QA/QC program for analyzing the sorbent traps using the OhioLumex consisted of an initial periodic analysis of blanks, calibration, and check standards as a continuing check on performance and, finally, maintaining performance records that define the quality of the data that are generated. The EERC chemist who performed the analysis is well trained and understands the procedures for using the OhioLumex for doing this analysis both in the laboratory and in the field. The following outlines the calibration standards and QA/QC procedures that were followed:

- Calibration standards were prepared from NIST traceable standards to span the range of sample values; the generated calibration curve was required to have an $r^2$ value greater than 0.99. If these requirements were not met, then the instrument was recalibrated with remade standards if necessary.

- A QC standard was made from a NIST traceable standard from a different lot than the calibration standards, and analyzed to compare to the calibration curve. This standard was required to be within ±5% of its expected value. If it was not, then either the QC standard was remade and analyzed again, or the instrument calibration was rechecked. It should be noted that, for this project, all QC standards fell within the ±5% specification.

- Analyzer calibrations are usually very stable and may be used for several days; the EERC either made or verified the calibration curve each day. QC checks at the high and low calibration on the curve were done a minimum of twice a day (once after generating and verifying the calibration curve and once near the end of the day).

- A QA check at a concentration close to that being analyzed was made for every ten samples or at least twice a day. If these values were within ±10% of the known standard, the calibration was still valid.

- If a calibration had to be repeated after the samples were analyzed, the data for all the samples analyzed since the last valid calibration were recalculated based on the new calibration curve. Because the samples were completely desorbed, it was not possible to run them again; therefore, a recalculation was done using computational processes based on the manufacturer's instructions for the calculation of data. It should be noted that for this project, all check standards fell within the ±10% specification.

- Failure to meet the performance criteria may require any or all of the following: remaking calibration and check standards, recalibration of the analyzer, or recalculation of the data.

- All documentation was recorded in project notebooks and/or on the computer. Data records stored on a computer were maintained and backed up. Following testing, all data sheets and log books were initialed by the person completing the analysis and reviewed for completeness and accuracy. Any changes or corrections that needed to be made were initialed, dated, and noted.

### Solids Sampling and Analysis

To evaluate mercury input into the system, numerous coal samples were collected throughout the test period; two composite coal samples were collected and archived each day: in the morning and again in the afternoon. Analysis of these samples was performed by the EERC at its laboratories. The coal samples were analyzed for Hg, Br, Cl, proximate–ultimate, and higher heating value (HHV) analyses using standard ASTM International (ASTM) and/or EPA methods. ESP ash samples were also periodically collected throughout the test period.

### Plant Data

Operational data as shown in Appendix D were monitored and recorded, including unit load, coal flow, mills in service, flue gas temperatures (for the AH inlet and ESP outlet), and CMM readings (Stack gas flow, boiler $SO_2$, boiler CO, boiler $NO_x$, and boiler $O_2$).

## TEST EQUIPMENT

Sorbent injection was performed with the EERC's pneumatic conveying system manufactured by Nol-Tec Systems, Inc. All back-end sorbents were stored on-site in 1000-lb capacity bulk bags and transported to the injection system via forklift. The control system was integrated with plant load and emergency shutdown signals to allow for load following and plant control in case of a unit shutdown. The injection system dispenses sorbents via a loss-in-weight rotary valve into the transport line. Motive air is provided by a roots-type blower to convey the sorbent through the transport lines, splitters, and injection lances.

Calibration of the Nol-Tec system was completed on-site via measurement of weight versus time. Calibration verification took place after setup and periodically during parametric and extended testing. The data collection system recorded the loss-in-weight-determined feed rate when applicable for the entire test period, along with the load signal from the plant. The sorbent feed rates in lb/Macf were calculated based on the lb/hr feed and flue gas flow calculated from coal combustion.

The AH inlet injection location was in the duct upstream of the AH and downstream of the split in the ductwork coming out of the boiler as shown in Figure 3. The primary AH had two lances and each secondary AH also had two lances with a total of six lances. Entrained sorbent from the Nol-Tec skid was transported to the injection location with 3-inch-i.d. convey hose to a 6-way line splitter to distribute the sorbent to the six ports.

## RESULTS AND DISCUSSION, PILOT-SCALE

### Introduction

Two weeks of testing occurred on the EERC's combustion test furnace (CTF) unit. The goal of the tests was to determine a cost-effective mercury control technology capable of achieving 90% removal. During Week One, ACs with and without the addition of SEA4 were tested upstream of an ESP. Mercury measurements were taken at the outlet of the ESP. Different control technologies, injection rates, and injection locations were all tested. During Week Two, a wet scrubber was added to the system to simulate the ESP–wet scrubber of the San Miguel Power Plant. During Week Two, ChemMod, SEA1, SEA2, and SEA2 + powdered activated carbon (PAC) were tested at various locations and rates. Mercury measurements were taken at the ESP outlet and the scrubber outlet.

### Description of the Combustion Test Facility (CTF)

An isometric drawing of the EERC CTF is shown in Figure 4. The furnace capacity is approximately 100 lb/hr (550,000 Btu/hr) of a moderately high-Btu-content fuel. The combustion chamber is 30 inches in diameter, 8 feet high, and refractory-lined and has been used for combustion testing of fuels of all rank. The furnace can be configured in many different arrangements which allow the CTF to be utilized for a variety of tests.

The furnace diameter may be reduced to 26 inches to elevate the temperature entering the convective pass. Furnace exit gas temperatures (FEGTs) as high as 2550°F have been achieved during combustion testing in this mode. Two Type S thermocouples, located at the top of the combustion chamber, are used to monitor the FEGT. They are situated 180° apart at the midpoint of the transition from vertical to horizontal flow. Excess air levels are controlled manually by adjusting valves on the primary and secondary airstreams. The typical distribution is 15% primary and 85% secondary to achieve the specified excess air level, which is typically 25% or higher for combustion of biomass fuels.

When solid fuels are fired, the fuel is normally pulverized remotely in a hammer mill pulverizer, targeted to a size of 70% less than 200 mesh. It is then charged to a microprocessor-controlled weight loss feeder from a transport hopper. Combustion air is preheated by an electric

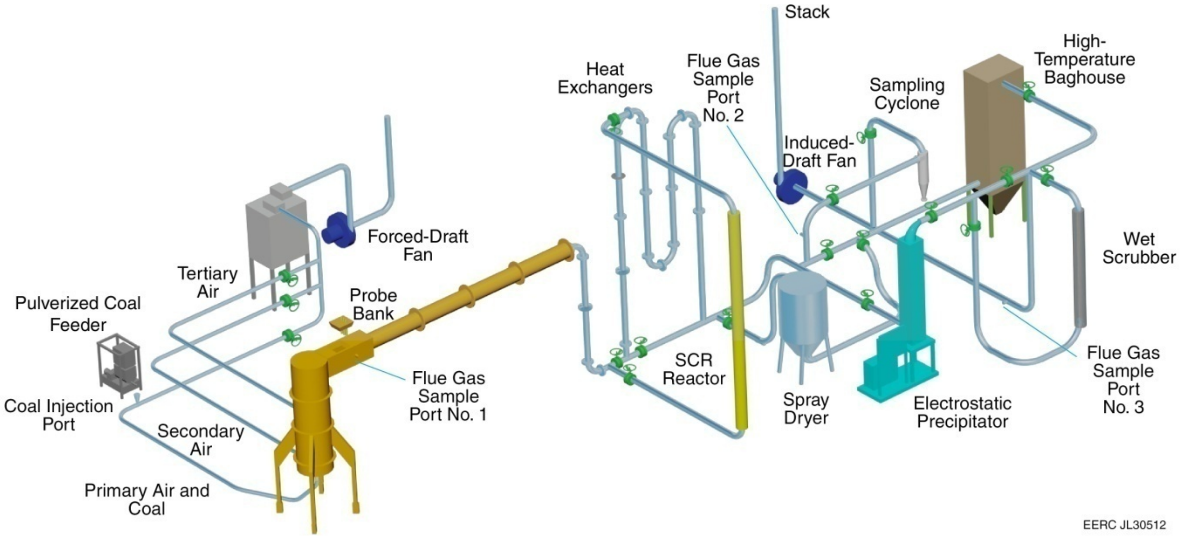


Figure 4. CTF and auxiliary systems.

air heater. The pulverized fuel is screw-fed by the gravimetric feeder into the throat of a venturi section in the primary air line to the burner. Heated secondary air is introduced through an adjustable swirl burner, which uses only primary and secondary air. Flue gas passes out of the furnace into a 25-cm (10-inch)-square duct that is also refractory-lined. Located in the duct is a vertical probe bank designed to simulate superheater surfaces in a commercial boiler. After leaving the probe duct, the flue gas passes through a series of water-cooled, refractory-lined heat exchangers and a series of air-cooled heat exchangers before being discharged through either an ESP or a baghouse.

### *Gas Analyses*

The CTF utilizes two banks of Rosemount NGA gas analyzers to monitor $O_2$, CO, $CO_2$, and $NO_x$. Sulfur dioxide ($SO_2$) is monitored by analyzers manufactured by Ametek. The analyzers are typically located at the furnace exit and the particulate control device exit. The gas analyses are reported on a dry basis. Baldwin Environmental manufactures the flue gas conditioners used to remove water vapor from each gas sample. The flue gas constituents are constantly monitored and recorded by the CTF’s data acquisition system.

### *Continuous Mercury Monitoring*

Throughout the pilot-scale testing, mercury continuous emission monitor (CEMs), also referred to as CMMs, were used to measure the Hg concentrations and to periodically determine the vapor-phase speciation.

The Tekran Model 2537A atomic fluorescence-based Hg vapor analyzer was used in conjunction with a PS Analytical S235C400 wet-chemistry conversion unit to continuously monitor $Hg^0$ and total Hg concentrations at the inlet of the particulate control device and at the outlet. For all of the testing except the last test day in February was done on the PS Analytical. The PS Analytical uses two separate liquid flow paths, one to continuously reduce $Hg^{2+}$ to $Hg^0$, resulting in a total gas-phase Hg sample and the other to continuously scrub out $Hg^{2+}$, resulting in an $Hg^0$ sample. The PS Analytical also uses a Peltier thermoelectric cooler module to cool and dry the sample gases prior to analysis.

The Tekran instrument traps the Hg vapor from the conditioned sample onto a cartridge containing an ultrapure gold sorbent. The amalgamated Hg is then thermally desorbed and detected using atomic fluorescent spectrometry. A dual-cartridge design allows alternate sampling and desorption, resulting in continuous measurement of the sample stream. The Model Tekran allows two methods of calibration: manual injection or an automatic permeation source. The permeation source was used to calibrate the instrument daily. Manual injection calibration on both cartridges was performed for verification. The Tekran instrument can either measure total Hg or $Hg^0$, with one analysis point being obtained approximately every 2.5 minutes.

### Analyses of Combustion Residues

The baseline coal deposit will be analyzed using x-ray diffraction (XRD) to determine the chemical composition of the deposit. The ash samples were also analyzed for carbon, hydrogen, and nitrogen (CHN) to characterize the combustion and determine if there were any effects from the injection sorbent and PAC injection.

#### *Coal Analyses*

Coal samples were analyzed for mercury and chlorine, and a select number of samples also underwent proximate and ultimate analyses and Btu determination. The coal Hg content provided the basis for determining native Hg capture for each control technology and the percent mercury removal achieved during parametric sorbent testing.

## RESULTS AND DISCUSSION

The results from the testing of the lignite used at the San Miguel Power Plant are presented below. During each testing period, the CTF unit was allowed to reach baseline conditions before any sorbents were tested. During the 2-week testing period, the following sorbents were tested: DARCO Hg, DARCO Hg-LH, B-PAC, Envergex Esorb 11, Envergex Esorb 21, Envergex Esorb 19A, SEA4, PAC + SEA4, ChemMod, SEA1, SEA2, and SEA2 + DARCO Hg. The baseline Hg concentration was measured before the ESP via a CMM and averaged 43.4 $\mu g/Nm^3$.

### ACs

The first set of tests focused on utilizing ACs. The ESP was the only pollution control device used for this testing. The ACs work by providing a binding location for gas-phase mercury species. The mercury that is bound to the AC is removed in the ESP. The following ACs were tested: DARCO Hg, DARCO Hg-LH, B-PAC, Envergex Esorb 11, Envergex Esorb 21, and Envergex Esorb 19A. Figure 5 shows the percent Hg removal for various activation rates of the injected carbons. The Hg concentration measurement was taken at the ESP outlet. All of the ACs tested had similar mercury removal percentages. The best two ACs were Envergex Esorb 21 and Envergex Esorb 11. At 10 lb/Macf, the Envergex Esorb 21 had a 62.85% Hg removal. This was the best percent removal for the ACs. Appendix A shows sample calculations, which includes sample calculations that show how mercury removals were calculated.

### SEA4

SEA4 is a proprietary control technology under development at the EERC. SEA4 and SEA4 + PAC were tested to determine if SEA4 can effectively reduce the $SO_2$ levels in the flue gas. It is known that high-sulfur coal decreases the Hg removal efficiency of ACs. The SEA4 was introduced with the AC and upstream of the AC. Figure 6 shows the AC results from Figure 5 plus two SEA4 + PAC tests. For these tests, the SEA4 was mixed with the PAC in a 19:1 SEA4:PAC ratio and injected at the same location. As the PAC injection rate increased, the SEA4 rate also increased. When the SEA4 is introduced, the 5-lb/Macf injection rate shows over a 20% increase in Hg removal. The 10-lb/Macf injection rate also shows approximately a 20% increase in Hg removal. The Envergex Esorb 19A with SEA4 was able to achieve a 84.83 % Hg

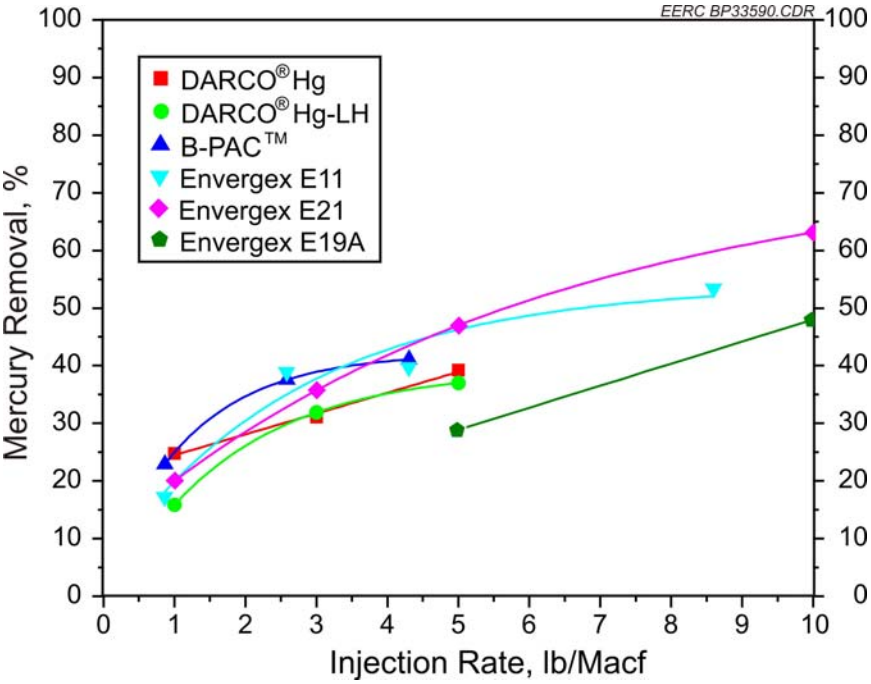


Figure 5. Hg AC control technology results during the firing of San Miguel coal.

removal with a PAC injection rate of 10-lb/Macf. At the 10-lb/Macf PAC injection rate, there is also 190 lb/Macf of SEA4 being introduced with the AC.

In Figure 7, the effect of increasing the amount of SEA4 at a steady PAC injection rate was examined. For this test, the SEA4 was injected upstream of the PAC to provide the SEA4 additional resonance time to interact with $SO_3^-$ and $SO_2$ so that their flue gas concentrations are reduced at the PAC injection location. Envergex Esorb 19A was injected at a constant rate of 5 lb/Macf, and the amount of SEA4 injected varied from 6.05 to 50 lb/Macf. The independent SEA4 injection location and lower injection rates were examined to see if a high percent Hg removal could be obtained at more cost-effective SEA4 injection rates. The 50-lb/Macf injection rate is slightly lower than the initial rate of 57 lb/Macf used in Figure 6. Although Figure 7 shows an increase in Hg removal, the percentage is only 56.44% at the highest rate tested. This indicates that a high SEA4-to-AC ratio is required for a high Hg removal. The high SEA4 rates prevent this method from being a cost-effective Hg control option.

## Wet Scrubber

During the Week Two testing, a wet scrubber was added to the CTF unit. The wet scrubber consisted of two columns and was located after the ESP. The wet scrubber was added to match the pollution control devices and their configuration at the San Miguel Power Plant. The wet scrubber reduces the amount of sulfur emitted and will also remove most of the oxidized Hg present in the flue gas. Figure 8 shows the change in the Hg concentration when the scrubber is brought online. Before the scrubber is brought online, the total Hg concentration is

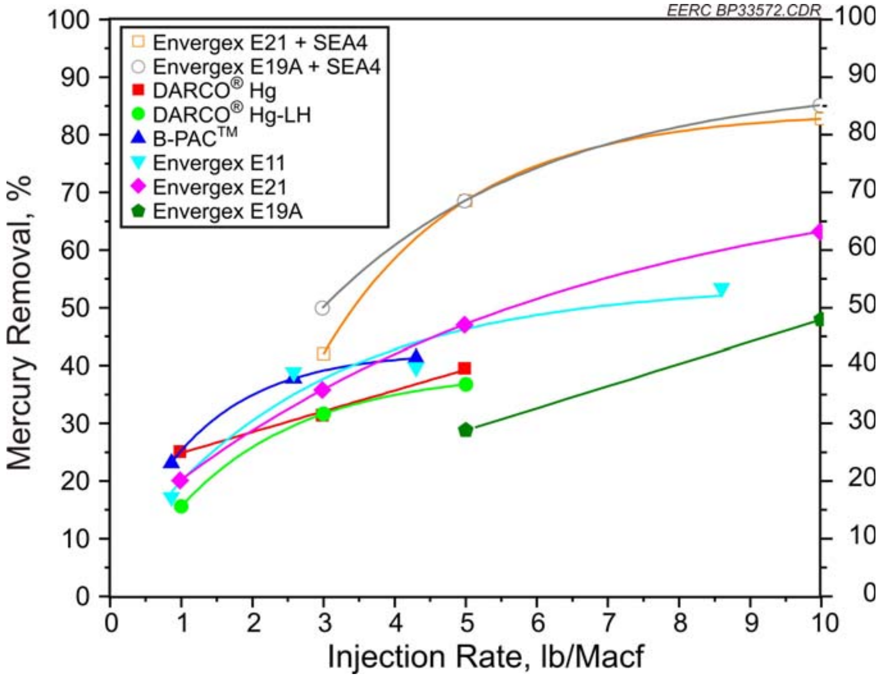


Figure 6. Effect of adding SEA4 to PAC.

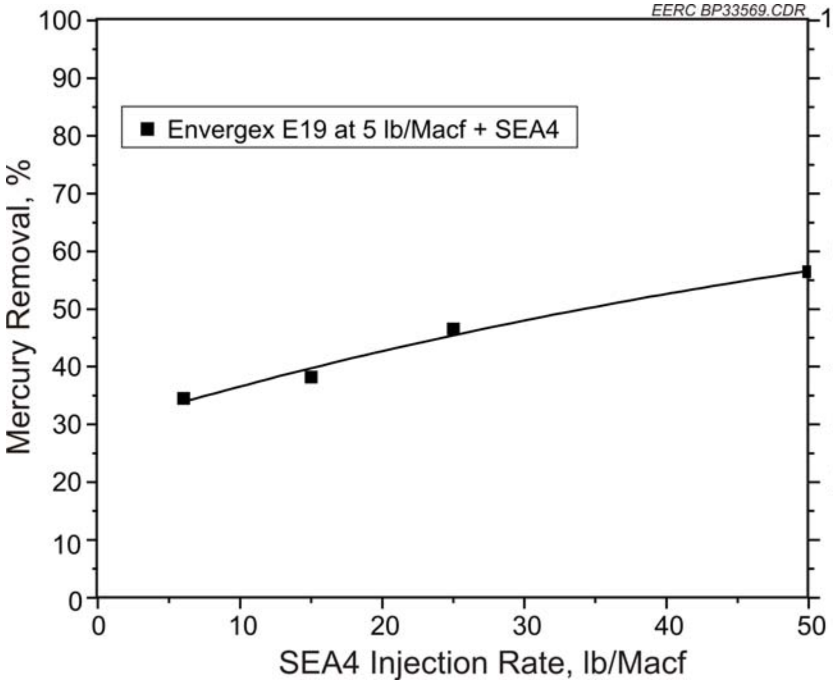


Figure 7. SEA4 effect on percent Hg removal at 5 lb/Macf PAC.

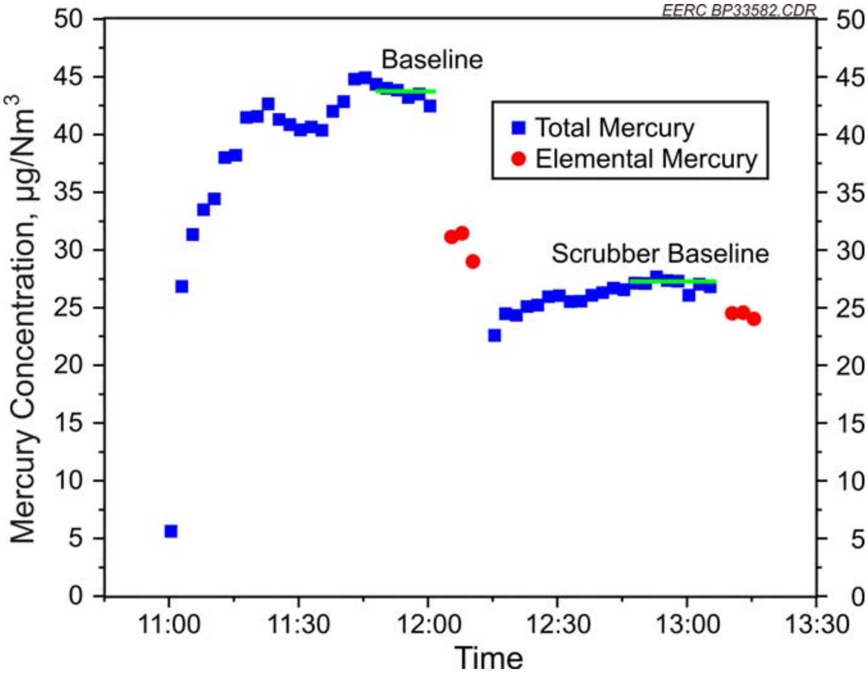


Figure 8. Baseline and scrubber baseline Hg concentrations.

approximately 43 μg/Nm$^3$, and the elemental Hg concentration is approximately 30 μg/Nm$^3$. When the scrubber is brought online, the total and elemental Hg concentrations decrease to approximately 25 and 23 μg/Nm$^3$, respectively. This shows that the scrubber alone removes 41.22% of the Hg present in the flue gas. The data also show that the scrubber must be oxidizing about 7 μg/Nm$^3$ of Hg because the elemental number decreased from 30 to 23 μg/Nm$^3$. The scrubber is also very efficient at removing the oxidized Hg as only 2 μg/Nm$^3$ remains after the flue gas passes through the scrubber.

The plant data show a significant decrease in the flue gas $SO_2$ concentration when the scrubber is brought online. Figure 9 plots the $SO_2$ concentration in ppm versus time. The baseline $SO_2$ concentration decreases from ~4500 ppm to ~232 ppm when the scrubber is brought online. This represents a 95% decrease in the flue gas $SO_2$ concentration.

### SEA1, SEA1 + SEA2

The next control technology tested was an EERC proprietary technology called SEA1. During this testing run, SEA1 was introduced into the coal feed just before the boiler. SEA1 was tested at three rates: 300, 600, and 1000 ppm. SEA1 was ineffective at reducing the Hg concentration further than the scrubber baseline level. The elemental Hg concentrations were also consistent with the scrubber baseline concentrations.

In another test, SEA1 and SEA2 were simultaneously introduced into the coal feed just before the boiler. The two sorbents were mixed together in a 10:1 SEA1:SEA2 ratio. The test

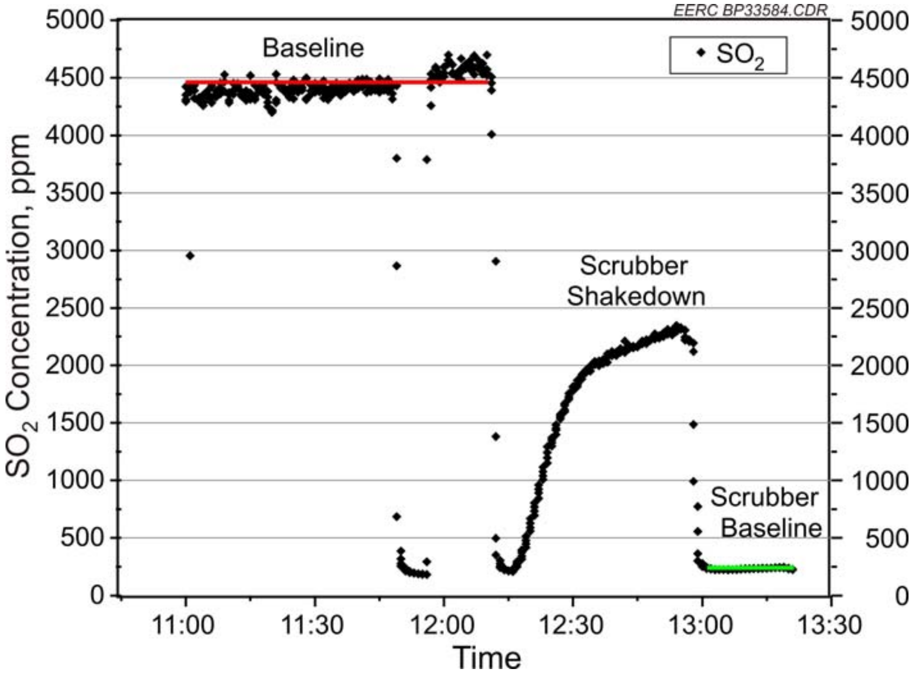


Figure 9. Plant $SO_2$ data collected during baseline and scrubber baseline conditions.

rates were 500:50 and 1324:132 ppm (SEA1: SEA2). Injection at the 500:50 ppm rate produced a 56.63% Hg removal. The higher injection rate removed 62.53% of the Hg present in the flue gas.

### ChemMod

The ChemMod technology utilizes two different sorbents, the M-Sorb and S-Sorb. The M-Sorb is a liquid solvent designed to oxidize the flue gas Hg. The S-Sorb is a powder sorbent designed to reduce sulfur flue gas concentrations and increase the Hg removal efficiency of the M-Sorb. During the ChemMod testing, the M-Sorb was injected directly into the boiler, and the S-Sorb was injected downstream of the boiler at 1400°–1200°F. The injection locations give the sorbents a long resonance time in the flue gas stream which increases the probability that the sorbent will interact with Hg present in the flue gas. The M-Sorb and S-Sorb injection rates are percents based on the coal feed rate. Figure 10 represents the effect of the ChemMod sorbents on Hg removal. Three different M-Sorb rates and two different S-Sorb rates were tested. The S-Sorb rates were 3% and 6%. When the rate was increased from 3% to 6%, the percent Hg removal increased from 78.88% to 79.85% at a M-Sorb rate of 0.125%. Only tests with a 6% S-Sorb rate are present in Figure 10. As the M-Sorb rate was increased, the percent Hg removal increased. A 93.19% Hg removal was obtained at a M-Sorb rate of 0.5%. The next lower rate of 0.25% produced a Hg removal of 92.05%.

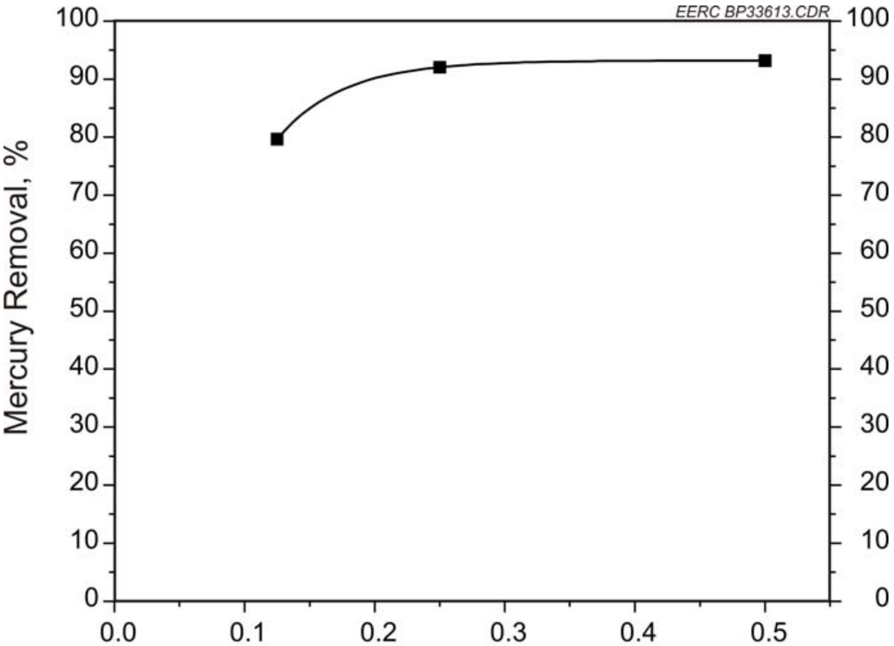


Figure 10. Effect of ChemMod on Hg removal. The three M-Sorb injection rates were 0.125%, 0.25%, and 0.5%. The S-Sorb rate was held constant at 6%.

Figure 11 shows the ChemMod testing time line. When the ChemMod is introduced into the system, it reacts quickly with the Hg present in the flue gas. The Hg elemental numbers show that almost all of the oxidized Hg is being removed by the scrubber. The low Hg elemental numbers also show that the ChemMod technology is oxidizing all but ~3 $\mu g/Nm^3$ of the Hg present in the flue gas. The time line clearly shows that the M-Sorb is the sorbent that has the largest effect on Hg concentrations. The S-Sorb had a minimal effect on the Hg concentration.

### SEA2, SEA2 + PAC

The final control technology tested was EERC's proprietary SEA2 control technology. This technology is injected before the ESP at a flue gas temperature of approximately 300°F. The SEA2 feed rates used were 50, 75, and 100 ppm. At a feed rate of 50 ppm, 81.30% of the mercury was removed. Increasing the rate of SEA2 created only a marginal improvement in the amount of mercury removed.

When the SEA2 + PAC control technology was tested, the SEA2 was injected in the same location as described above. DARCO Hg was the PAC used, and it was injected just before the ESP. DARCO Hg was used because the enhanced PACs had similar Hg removal during the Week 1 testing. The injection rates for the DARCO Hg were 1, 3, and 5 lb/Macf. During this test, both the injection rate of SEA2 and DARCO Hg were varied. The results for this test are depicted in Figure 12. In Figure 8, the SEA2 injection rate is 50 ppm, and the amount of DARCO Hg injected is varied. When 50 ppm SEA2 and 1 lb/Macf DARCO Hg were injected,

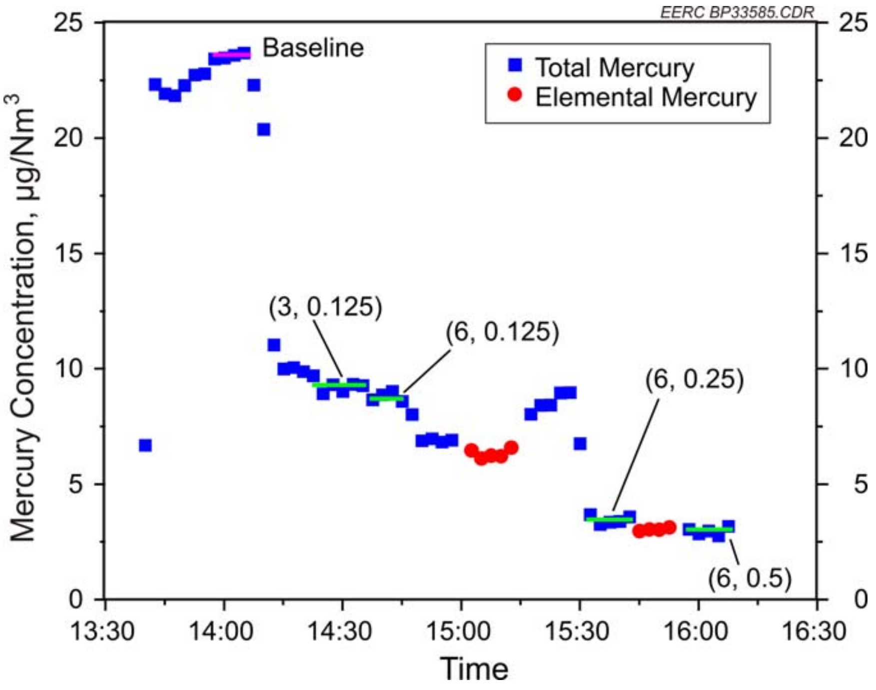


Figure 11. ChemMod testing time line. The first number in the parenthesis represents the S-Sorb injection rate, and the second number represents the M-Sorb injection rate.

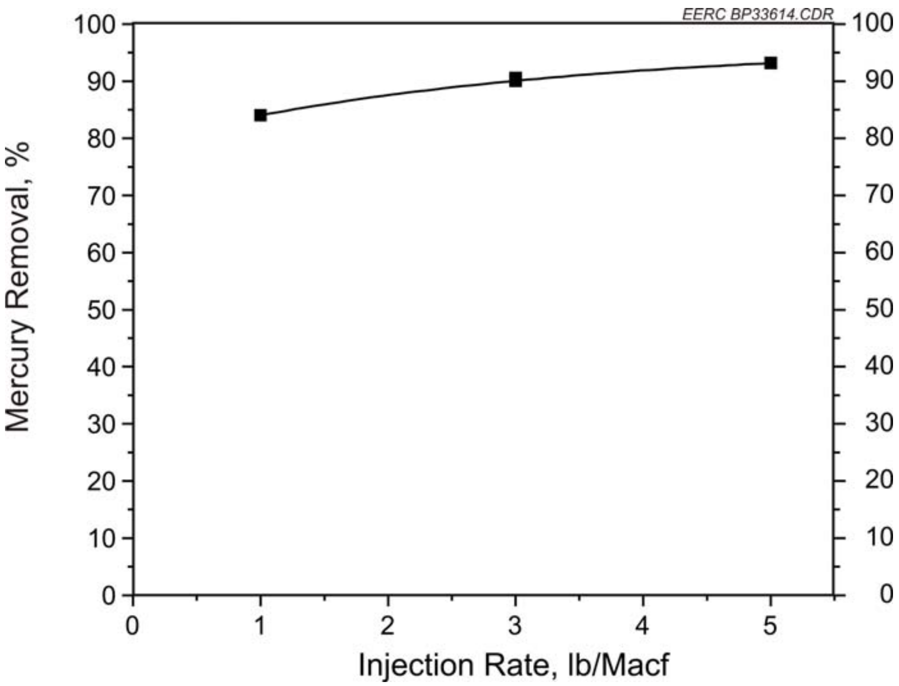


Figure 12. SEA2 + DARCO Hg effect on flue gas Hg concentration. The SEA2 injection rate is 50 ppm.

84.01% of the Hg was removed. When the DARCO Hg injection rate was increased to 3 lb/Macf, 90.07% of the Hg was removed from the flue gas. The CMM after the ESP outlet recorded an average Hg concentration of 10 µg/Nm$^3$. The ESP is removing approximately 33 µg/Nm$^3$ of the Hg present in the flue gas, which accounts for the majority of the Hg removed. The majority of the Hg is removed through the ESP with this control technology.

The Hg is oxidized by SEA2, and bonds to the DARCO Hg. The Hg/DARCO Hg complex is then removed by the ESP. When a SEA2 rate of 75 ppm is used with a DARCO Hg injection rate of 3 lb/Macf, the Hg removal rate is 90.58%. This is only a 0.51% increase over the 50 ppm SEA2 injection rate at the same DARCO Hg injection rate. When the DARCO Hg injection rate was increased to 5 lb/Macf and SEA2 was held at 50 ppm, 93.16% of the Hg was removed from the flue gas. At this rate, the ESP outlet Hg concentration was 5.88 µg/Nm$^3$.

## CONCLUSIONS

The two technologies that performed the best were ChemMod and SEA2 + DARCO Hg. At their highest injection rates, ChemMod and SEA2 + DARCO Hg achieved Hg removal percentages of 93.19% and 93.16%, respectively. Table 3 shows the injection rates and percent Hg removals for these two control technologies. The Hg concentrations for the ESP outlet and Scrubber outlet represent corrected Hg concentrations. At the middle injection rate, both ChemMod and SEA2 + PAC were able to achieve 90 % Hg removal. This injection rate is a very

**Table 3. Hg Data for the ChemMod and SEA2 + PAC Pilot-Scale Testing**

| Test Condition | PAC Injection, lb/Macf | SEA2 Injection, ppm | ChemMod S-Sorb, % | ChemMod M-Sorb, % | ESP Outlet, μg/Nm$^3$ | Scrubber Outlet, μg/Nm$^3$ | Hg Removal, % |
|---|---|---|---|---|---|---|---|
| ChemMod | | | 3 | 0.125 | 25.62 | 9.16 | 78.88 |
| ChemMod | | | 6 | 0.125 | 26.39 | 8.83 | 79.65 |
| ChemMod | | | 6 | 0.25 | 25.10 | 3.45 | 92.05 |
| ChemMod | | | 6 | 0.5 | | 2.96 | 93.19 |
| SEA2 + DARCO Hg | 1 | 50 | | | 16.85 | 6.94 | 84.01 |
| SEA2 + DARCO Hg | 3 | 50 | | | 10.00 | 4.31 | 90.07 |
| SEA2 + DARCO Hg | 3 | 75 | | | 9.29 | 4.09 | 90.58 |
| SEA2 + DARCO Hg | 5 | 50 | | | 5.88 | 2.97 | 93.16 |

cost-effective rate for both technologies. The scrubber removes most of the Hg with the ChemMod technology, while the ESP removes the majority of the Hg with the SEA2 + PAC sorbent.

During the full-scale testing at the San Miguel Power Plant, the ChemMod sorbent, and the SEA2 + PAC sorbents will be tested. Both technologies performed well at the pilot-scale level and are expected to also perform well at the full-scale level. It is expected that each technology will be tested for 1 week so that long-term data can be collected.

## RESULTS AND DISCUSSION, FULL-SCALE

### Coal Characteristics

A total of 17 coal samples were analyzed for Hg, Cl, proximate–ultimate, and Btu analyses using standard ASTM or EPA methods. Proximate and ultimate analyses were conducted on composite coal samples using ASTM Methods D3172, D5142, and D3176. A Mitsubishi Model TOX-100 total halogen analyzer was used to perform ASTM Method D6721-01 (Standard Test Method for Determination of Chlorine in Coal by Oxidative Hydrolysis Microcoulometry). This method actually measures all halogens in the coal, not just chlorine. Coal bromine concentrations were determined via a coal combustion method followed by off-line inductively coupled plasma mass spectrometry (ICP–MS) detection. Coal mercury content was determined using CVAAS according to EPA Method 245.1 and EPA SW-846 Method 7470.

Averages of the test coal analyses are present in Table 4. The complete coal data set is presented in Appendix B. The analyses represent the average of all 17 coal samples collected during the test period. The proximate and ultimate analyses' standard deviations are very small which indicates little change between the coal samples. The chlorine and bromine coal concentrations also remained consistent throughout the coal samples. The mercury concentration varied greatly and will be discussed in the next section.

**Table 4. Average Coal Values for the Test Coal**

| | As-Received Basis | |
|---|---|---|
| Parameter | Average[a] | Std. Dev. |
| Hg, ppm | 0.182 | 0.027 |
| Cl, ppm | 843 | 37 |
| Br, ppm | 4.2 | 0.3 |
| Proximate Analysis, wt% | | |
| Moisture | 31.1 | 0.4 |
| Volatile Matter | 23.7 | 0.56 |
| Fixed Carbon | 18.5 | 0.68 |
| Ash | 26.6 | 1.21 |
| Ultimate Analysis, wt% | | |
| Hydrogen | 6.1 | 0.06 |
| Carbon | 29.6 | 0.93 |
| Nitrogen | 0.5 | 0.02 |
| Sulfur | 2.7 | 0.16 |
| Oxygen | 34.4 | 0.67 |
| Heating Value, Btu/lb | 5094 | 181 |

[a] Average values are based on 17 samples.

### Mercury in Coal

The coal mercury concentration was determined for all samples submitted for analysis, and the average mercury concentration was presented in Table 4. Estimates of mercury concentration levels on a flue gas basis and a heating value basis have been prepared using a combustion calculation method which is based on the proximate analysis, ultimate analysis, and coal Btu value. These values are summarized in Table 5.

Figure 13 is a plot of the coal mercury concentration for each coal sample collected. The coal mercury concentration shows a high degree of day to day variability with a range of 22.52–42.19 µg/Nm$^3$. This range shows the high variability in the coal mercury concentration, which correlates with the high standard deviations in Table 5. Coal samples collected on the same day but at different times also show a significant variation in mercury concentration. Because of the variation, mercury percent removals were calculated based on a daily coal mercury concentration average.

**Table 5. Calculated Hg Flue Gas Concentrations Based on Hg Coal Concentrations**

| Parameter | Average[a] | Std. Dev. |
|---|---|---|
| Hg, ppm (in coal, as-received basis) | 0.182 | 0.027 |
| Hg, µg/Nm$^3$ (calculated from coal) | 32.21 | 4.80 |
| Hg, lb Hg/TBtu (calculated from coal) | 24.67 | 3.58 |

[a] Average values are based on 17 samples.

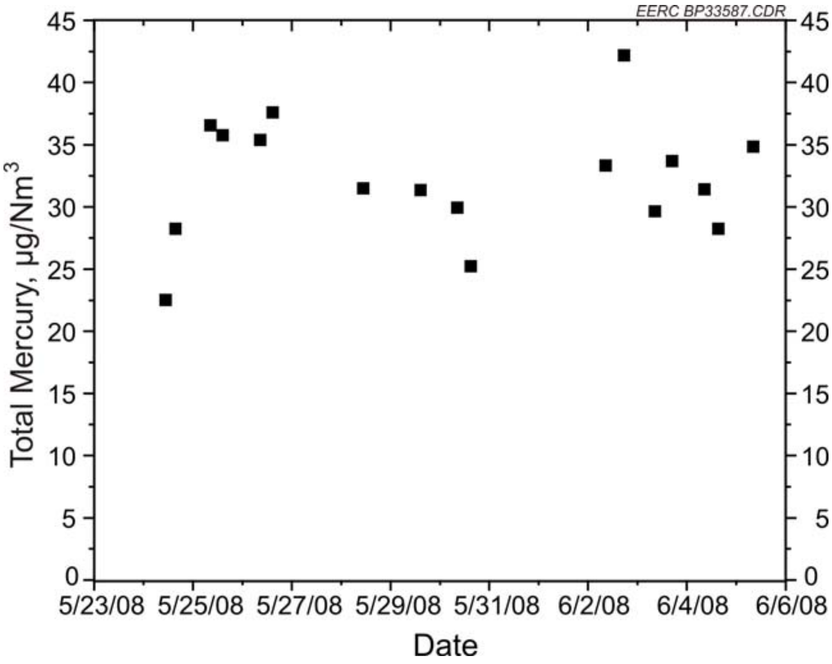


Figure 13. Coal sample calculated mercury flue gas concentrations.

**Baseline Conditions**

The first 3 days of testing consisted of baseline testing. During baseline testing, the plant conditions and Hg concentrations were measured to determine if there are any periodic changes associated with normal plant operations. Coal and ash samples were taken during baseline testing, and sorbent trap and OH measurements were also carried out during baseline testing. The following baseline discussion is broken down by sampling location because each sampling location is significantly different. Appendix C presents the complete CMM, OH, and sorbent data sets.

Figure 14 shows the CMM, sorbent trap, and OH data collected at the ESP In sampling location for the baseline testing period. The CMM data at the ESP In sampling location exhibited the greatest degree of variability with Hg total values ranging from 36.2–56.2 µg/Nm$^3$. The Hg$^0$ values ranged from 25.2–45.8 µg/Nm$^3$ during the baseline testing period. The average CMM total Hg and Hg$^0$ concentrations are 45.7 and 38.3 µg/Nm$^3$, respectively. Based on these averages, 83.7% of the mercury in the flue gas is in the elemental form.

The ESP In sorbent trap collected on 5/23/2008 yielded a total Hg concentration of 35.0 µg/Nm$^3$. The average CMM total Hg concentration at the same time and location averaged 42.4 µg/Nm$^3$. The total Hg concentration of the ESP In sorbent trap collected on 5/25/2008 was 46.2 µg/Nm$^3$. During the sorbent trap sampling time, the ESP In average total Hg concentration was 52.7 µg/Nm$^3$. Both sorbent trap Hg concentrations were 6–7 µg/Nm$^3$ lower than the corresponding CMM Hg total values. It is likely that both the CMM and sorbent trap data are affected by the high ash loading at the ESP In sampling location. The nature and extent of the

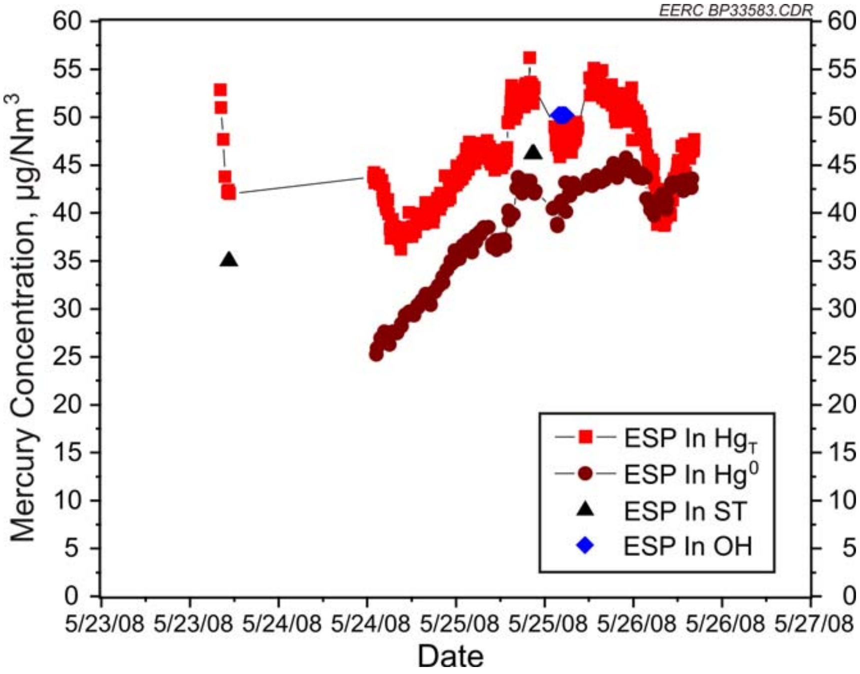


Figure 14. CMM, sorbent trap, and OH data collected during the baseline testing period at the ESP In sampling location. The red and wine-colored data represent the Hg total and $Hg^0$ CMM instrument data, respectively. Sorbent trap and OH data are represented by colored triangles and diamonds, respectively.

bias will be different for the CMM and sorbent trap measurements, thus making direct comparisons difficult.

An OH measurement was also performed on 5/25/2008. The OH measurement yielded a total Hg concentration of 50.0 µg/Nm$^3$. Of the 50.0 µg/Nm$^3$, 16.0 µg/Nm$^3$ was in the particulate phase ($Hg^P$), 26.9 µg/Nm$^3$ was in the oxidized form ($Hg^{2+}$), and 7.0 µg/Nm$^3$ was in the elemental form ($Hg^0$). While the total mercury concentration matches well with the CMM values, the breakdown clearly shows that the ash loading is affecting the OH measurements. The $Hg^0$ value is significantly lower than expected based on the CMM measurements.

At the Scrubber In sampling location, CMM data were collected during the baseline testing period. Figure 15 plots the CMM baseline data at the Scrubber In sampling location. At this sampling location, the CMM total Hg data averaged 31.0 µg/Nm$^3$ with a range of 14.7–46.4 µg/Nm$^3$. The CMM $Hg^0$ data correlated well with the CMM total Hg data and averaged 17.9 µg/Nm$^3$ with a range of 26.1–10.0 µg/Nm$^3$. The total Hg and $Hg^0$ data trends correlate well at this sampling location throughout the baseline testing period. At this sampling location, 57.7% of the Hg in the flue gas is in the elemental form.

The 57.7% $Hg^0$ is a 53.2% decrease in the amount of $Hg^0$ present in the flue gas compared to the ESP In sampling location. Based on these results, it is likely that a significant amount of

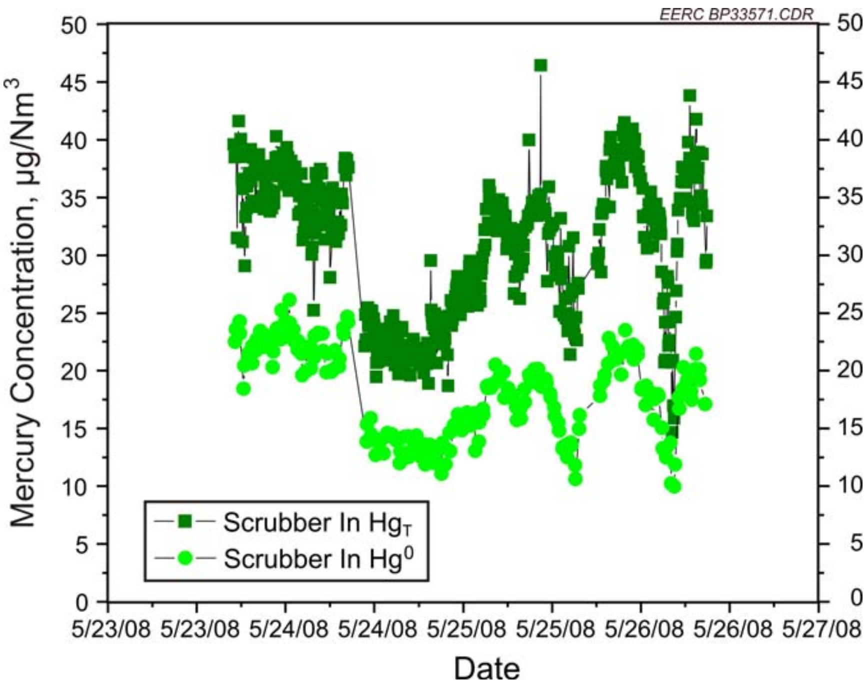


Figure 15. CMM data collected during the baseline testing period at the Scrubber In sampling location. The olive squares and green circles represent the Hg total and $Hg^0$ CMM instrument data, respectively.

$Hg^0$ is being converted to $Hg^{2+}$ in the ESP by using the fly ash as a reaction/catalyst site. As the flue gas enters the ESP, the flow pattern changes, causing significant mixing of the flue gas. This mixing increases the probability of a $Hg^0$ atom interacting with a fly ash particle in a favorable manner to induce its oxidation to $Hg^{2+}$. This is the most likely scenario to explain the reduced percentage of $Hg^0$ present.

The third baseline sampling location was the Scrubber Out sampling location. This sampling location was located about 100 feet before the flue gas enters the base of the stack. At this sampling location, CMM, sorbent trap, and OH measurements were taken. Figure 16 depicts the Hg concentrations from the three measurement methods. At the Scrubber Out sampling location, the baseline Hg total concentration averaged 20.4 µg/Nm$^3$ with a range of 15.2–26.7 µg/Nm$^3$. At this sampling location, the $Hg^0$ concentration averaged 16.2 µg/Nm$^3$ with a range of 12.5–22.4 µg/Nm$^3$. The Hg total and $Hg^0$ concentrations correlate well with one another, and the percent of $Hg^0$ remains fairly constant during the baseline test period. At this sampling location, 79.4% of the Hg in the flue gas is in the elemental form. This represents a significant increase in the percent $Hg^0$ relative to the Scrubber In sampling location because a significant portion of the $Hg^{2+}$ present in the flue gas is being removed by the scrubber. The scrubber removed 34% of the $Hg^{2+}$ from the flue gas, but only 9.9% of the $Hg^0$ present was removed. A native capture of 38.2% was calculated by using the coal to Scrubber Out Hg concentrations.

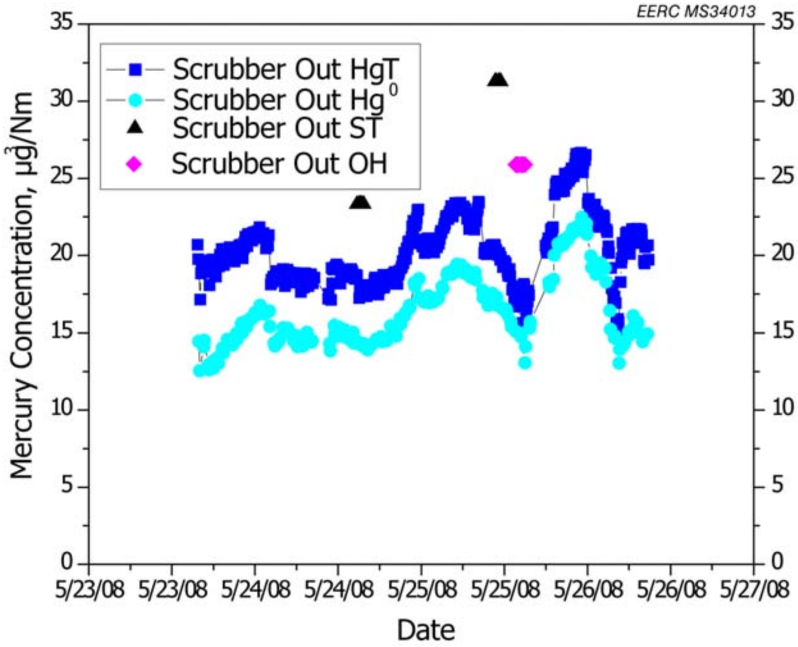


Figure 16. CMM, sorbent trap, and OH data collected during the baseline testing period at the Scrubber Out sampling location. The blue and cyan-colored data represent the Hg total and Hg$^0$ CMM instrument data, respectively. Sorbent trap and OH data are represented by colored triangles and diamonds, respectively.

OH and sorbent trap measurements conducted at the Scrubber Out sampling location showed a fair amount of variability when compared to the CMM data. Both sorbent traps analyzed at this sampling location had higher Hg total values than the CMM values. The average sorbent trap Hg total concentration was 27.2 µg/Nm$^3$, with the two values being 23.2 and 31.2 µg/Nm$^3$, respectively. On average, the sorbent trap Hg total concentrations were 6.8 µg/Nm$^3$ higher than the CMM Hg total concentrations, which corresponds to an average difference of 24%.

The OH measurement conducted on 5/25/2008 resulted in a Hg total concentration that was significantly higher than the CMM Hg total concentration during the OH testing period. The OH Hg total concentration was 25.8 µg/Nm$^3$, with 23.0 µg/Nm$^3$ in the Hg$^0$ form. Based on these numbers, 89% of the Hg present at the Scrubber Out sampling location is present as Hg$^0$. The CMM data indicate that 79% of the Hg is present as Hg$^0$ at the same sampling location. During the OH sampling time, the CMM Hg total concentration averaged 17.2 µg/Nm$^3$. The percent difference between the CMM and OH Hg total concentrations is 33%, which shows a high amount of variation between the two values.

During baseline testing, the Scrubber Out CMM data was compared to the plant's CMM data. The plant's CMM was located about halfway up in the stack. Only the Hg$^0$ data were compared because of trouble with the plant's total Hg conversion system. As can be seen in

Figure 17, the data for the Stack CMM show excellent agreement with the Scrubber Out CMM. The two sets of data overlie each other most of the baseline test period.

During baseline conditions, the plant operating conditions remained fairly constant. The load output was fairly constant and averaged 435 MW. The baseline boiler $NO_x$ and boiler $SO_2$ concentrations were 64.6 ppm and 2378.8 ppm, respectively. The boiler $O_2$ and $CO_2$ percent averages were 2.13% and 7.72%, respectively.

**DARCO Hg**

The first sorbent to be tested was Norit Americas DARCO Hg. DARCO Hg is an untreated PAC and is often used as a "benchmark" for PAC injections. DARCO Hg was injected at rates of 1, 3, and 4 lb/Macf. Higher rates were unattainable due to the high feed rates required to treat the whole plant. Figure 18 displays the percent Hg total removal results for each injection rate. The percent removals are based on a coal-to-Scrubber Out basis. At 1 lb/Macf, the percent Hg removal increased to 45.9% from the baseline value of 38.2%. At 3 lb/Macf, the Hg percent removal increased to 52.4%, and further increased to 65.4% at 4 lb/Macf. Sorbent injection with DARCO Hg was repeated at 3 and 4 lb/Macf with the two separated test runs having similar Hg removal percentages. The curve appears as if it is leveling off at 3 lb/Macf but then exhibits a significant increase at 4 lb/Macf.

During DARCO Hg injection at 1 lb/Macf, sorbent traps were collected at all three sampling locations. The sorbent trap Hg total concentrations at the ESP In, Scrubber In, and Scrubber Out were 55.3 µg/Nm$^3$, 32.5 µg/Nm$^3$, and 24.9 µg/Nm$^3$, respectively. During these test

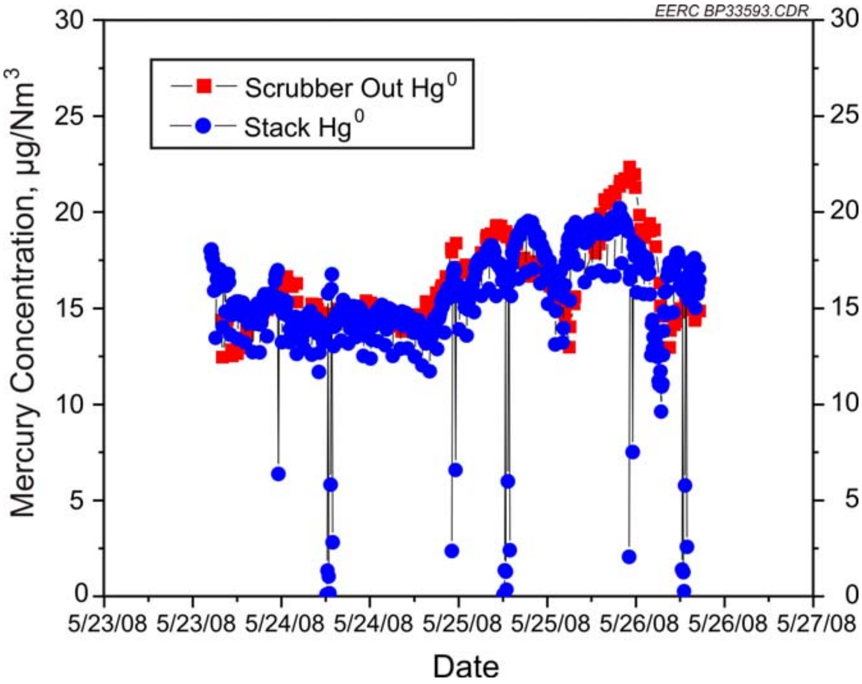


Figure 17. Comparison of the Scrubber Out and Stack CMM Hg$^0$ data.

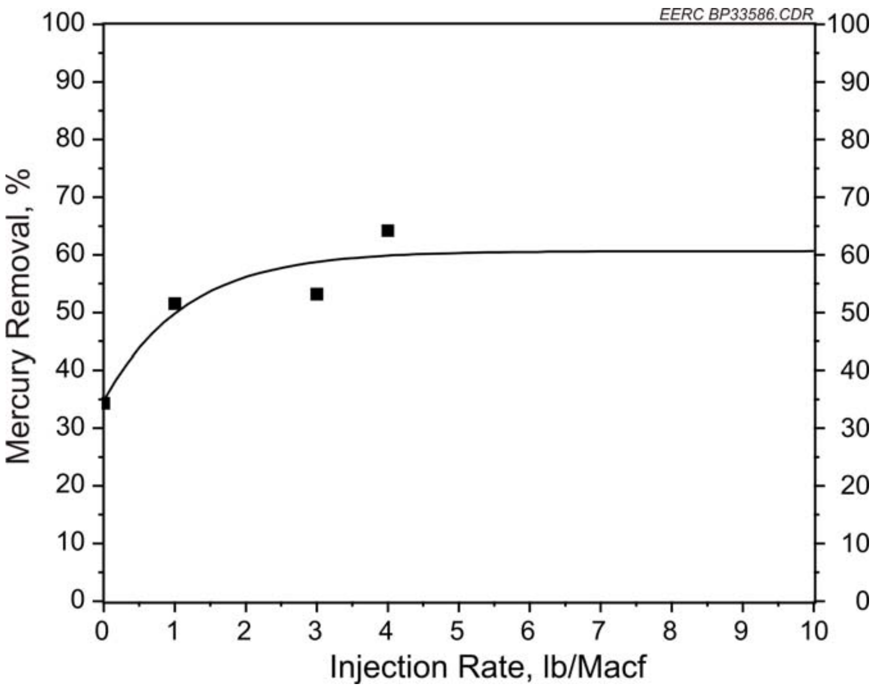


Figure 18. Percent Hg total removals for during the injection of DARCO Hg.

periods, the Scrubber In and Scrubber Out CMM values were 27.2 and 17.9 µg/Nm$^3$. Based on these results, the ST values are slightly higher than the CMM values.

The curve fit plotted in Figure 18 was obtained from the data point in the graph. The curve fit was extrapolated beyond the last data point to provide insight as to how higher injection rates may perform. The extrapolated part of the curve fit shows that DARCO Hg levels off at injection rates above 4 lb/Macf with a maximum predicted removal of approximately 61%. This is far from the targeted removal rate of ≥90%.

### DARCO Hg-LH

A brominated AC, DARCO Hg-LH was also tested at the San Miguel Power Plant. DARCO Hg-LH was injected at rates of 1, 3, and 4 lb/Macf. Figure 19 displays the mercury removal results obtained during DARCO Hg-LH parametric testing. The trend of the curve is similar to when DARCO Hg was injected with a significant increase between 3 and 4 lb/Macf. At each injection rate, the mercury removal was approximately 4% higher than the DARCO Hg results. A maximum mercury removal of 70% was obtained at the 4 lb/Macf injection rate. This is a 6% increase in mercury removal compared to when DARCO Hg was injected at an equivalent rate.

Sorbent trap sampling at the Scrubber In and Scrubber Out was conducted while injecting DARCO Hg-LH at rates of 1, 3, and 4 lb/Macf. The sorbent traps collected at a DARCO Hg-LH injection rate of 1 lb/Macf yielded mercury concentrations of 24.4 µg/Nm$^3$ and 21.1 µg/Nm$^3$ at the Scrubber In and Scrubber Out, respectively. These values compare reasonably well with the average CMM values of 20.7 µg/Nm$^3$ and 15.5 µg/Nm$^3$. At the 3 lb/Macf injection rate, the sorbent trap mercury concentrations were 22.6 µg/Nm$^3$ and 20.1 µg/Nm$^3$ at the Scrubber In and Scrubber Out, respectively. The CMM mercury concentrations averaged 17.9 µg/Nm$^3$ and 14.0 µg/Nm$^3$ during the ST sampling time periods. At a DARCO Hg-LH injection rate of 4 lb/Macf, the ST mercury concentrations were 10.0 µg/Nm$^3$ and 10.6 µg/Nm$^3$ at the Scrubber In and Scrubber Out sampling locations, respectively. The CMM concentrations averaged 9.2 and 8.8 µg/Nm$^3$ during the same time periods. All of the ST data agreed within 15% of the CMM data during the DARCO Hg-LH parametric tests.

The curve fit plotted in Figure 19 was obtained from the data point in the graph. The curve fit was extrapolated beyond the last data point to provide insight as to how higher injection rates may perform. The extrapolated portion of the curve shows a steady increase with the mercury removal rate beginning to level off at 10 lb/Macf. The extrapolated portion of the graph indicates that 80% mercury removal can be obtained at approximately 8.6 lb/Macf. Based on the extrapolated curve, the maximum mercury removal is expected to be around 82%–85%.

### DARCO Hg + SEA2

The last set of parametric testing involved testing DARCO Hg with SEA2. The SEA2 is added to an AC to increase the probability of mercury interacting with the AC surface which increases mercury removal. SEAs also reduce sorbent cost by decreasing the amount of sorbent required to achieve target mercury removals. SEA +AC injection also allows for higher mercury removals to be obtained than with AC injection only. Various SEA2 concentrations and DARCO

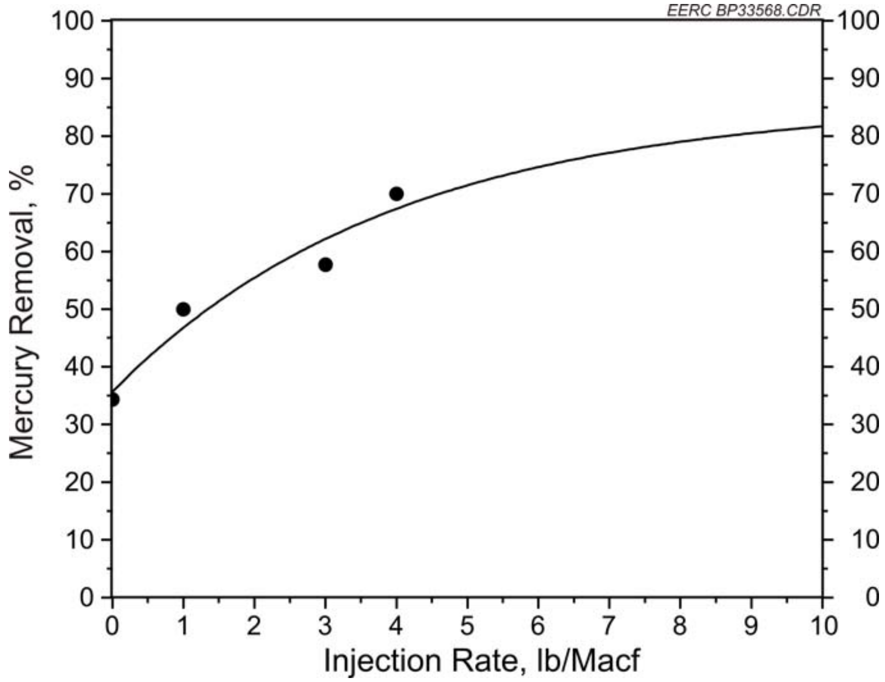


Figure 19. Mercury removal results obtained during parametric testing of DARCO Hg-LH.

Hg injection rates were tested in order to determine the effectiveness of the SEA2 plus DARCO Hg combination.

Figure 20 displays mercury removal as a function of SEA2 + DARCO Hg injection rate. The SEA2 injection rates tested ranged from 10–50 ppm. When Figure 20 is compared to Figures 18 and 19, it is clear that the SEA2 technology has a significant impact on mercury removal. At a SEA2 injection rate of 50 ppm and a DARCO Hg injection rate of 3 lb/Macf, a mercury removal of 71.7% was obtained. This represents a 18.5% improvement compared to DARCO Hg at 3 lb/Macf, and a 14% improvement compared to DARCO Hg-LH at 3 lb/Macf. A maximum mercury removal of 78.5% was obtained at DARCO Hg and SEA2 injection rates of 4 lb/Macf and 50 ppm, respectively. The 78.5% was the maximum mercury removal obtained for all of the parametric tests.

The curve fit plotted in Figure 20 was obtained from the data point in the graph. The curve fit was extrapolated beyond the last data point to provide insight as to how higher injection rates may perform. The extrapolated portion of the curve shows that SEA2 + DARCO Hg reaches a maximum of approximately 88% at 10 lb/Macf DARCO Hg and 50 ppm SEA2. Of the technologies tested, this was the highest extrapolated mercury removal obtained.

### Summary of Parametric Test Results

Figure 21 displays the maximum mercury removal results obtained with each of the technologies tested. The maximum mercury removals for DARCO Hg, DARCO Hg-LH and

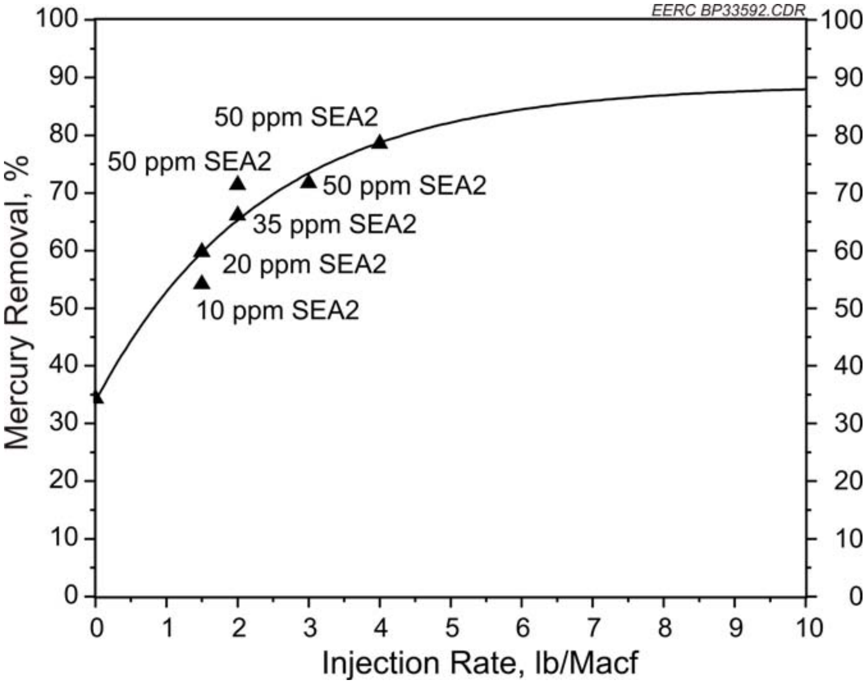


Figure 20. Mercury removal results obtained during the parametric testing of SEA2 + DARCO Hg.

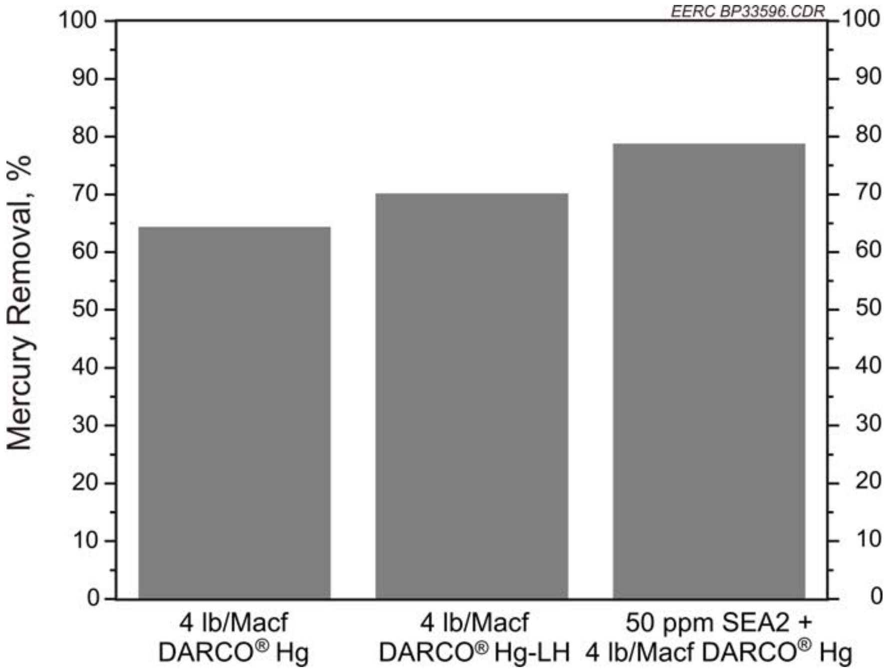


Figure 21. Maximum mercury removals obtained with each technology tested.

SEA2 + DARCO Hg were 64.2%, 70.0%, and 78.5%, respectively. These results show that the SEA2 + DARCO Hg option offers the highest mercury removal. There is a 14.3% difference between the DARCO Hg and SEA2 + DARCO Hg control technologies. This shows that the SEA2 technology demonstrates a significant improvement in mercury removal.

### Scrubber Reemission

During the parametric testing, scrubber reemission was noticed during injection of each sorbent tested. The scrubber reemission significantly impacted the coal-to-Scrubber Out mercury percentages and prevented the 90% mercury removal goal from being obtained. The Scrubber In elemental mercury concentrations provide an indication of obtainable Scrubber Out total mercury concentrations because scrubbers typically remove most or all of the oxidized mercury present in the flue gas (2). An increase in $Hg^0$ concentration across the scrubber indicates that mercury reemission is occurring. Figures 22a–c clearly show that scrubber reemission had a significant impact on the mercury removals obtained during the test period.

Figures 22a–c plot the Scrubber In and Scrubber Out $Hg^0$ concentrations for the sorbents and injection rates tested. The baseline Scrubber In and Scrubber Out $Hg^0$ values are nearly identical, which shows that little or no reemission is occurring. When DARCO Hg was injected, Figure 22a, there was no reemission until the 4 lb/Macf injection rate. The 1 and 3 lb/Macf injection rates showed Scrubber In and Scrubber Out $Hg^0$ concentrations similar to the baseline conditions. At the 4 lb/Macf injection rate, the Scrubber In $Hg^0$ concentration was 6.0 $\mu g/Nm^3$ and the Scrubber Out $Hg^0$ concentration was 10.0 $\mu g/Nm^3$. This indicates a 166% increase in the $Hg^0$ concentration across the scrubber. When DARCO Hg-LH was injected, mercury reemission was observed at each of the injection rates tested. Figure 22b shows that the amount of Hg reemission increases from 1 to 3 lb/Macf but appears to level off between 3 and 4 lb/Macf. At 4 lb/Macf, the $Hg^0$ concentration increased by 224% from the Scrubber In to Scrubber Out sampling locations.

Figure 22c focuses on scrubber reemission when DARCO Hg + SEA2 was injected. Elemental mercury measurements were not collected at every injection rate, so curve fits were generated to allow for the different injection rates to be compared. At the first injection rate of 1.5 lb/Macf, with 10 ppm SEA2, no reemission was occurring across the scrubber. Based on the curve fits, when the SEA2 concentration was increased from 10 to 20 ppm, a small amount of scrubber reemission started to occur. The amount of mercury reemission appears to be consistent at DARCO Hg + SEA2 injection rates of 2 lb/Macf and 35 ppm, respectively. At injection rates greater than 2 lb/Macf and 35 ppm, the amount of $Hg^0$ scrubber reemission is approximately 4 $\mu g/Nm^3$.

Scrubber inlet elemental mercury concentrations provide an indication of possible mercury removals if scrubber reemission does not occur. During baseline conditions, the scrubber outlet mercury concentration was 81.7% of the mercury present in the flue gas. Provided that this value is relatively constant, mercury removals without scrubber reemission can be estimated based on this constant and the scrubber inlet elemental mercury concentrations. Figures 23 and 24 plot the DARCO Hg-LH and SEA2 + DARCO Hg estimated mercury removals based on the scrubber inlet elemental mercury concentrations and the percentage of elemental mercury at the scrubber outlet during baseline conditions. In Figure 23, a DARCO Hg-LH injection rate of 4 lb/Macf results in a mercury removal of 85.5% if there is no scrubber reemission. When scrubber reemission was present, the same 4 lb/Macf injection rate achieved a mercury removal of 70%.

Figure 24 shows the estimated mercury removal results in the absence of scrubber reemission for SEA2 + DARCO Hg. At SEA2 and DARCO Hg injection rates of 50 ppm and 4 lb/Macf, an estimated mercury removal of 91% is calculated. This represents a 12.5% increase over the parametric test results when scrubber reemission was occurring. This estimated removal also would reach the target goal of ≥90% mercury removal. The curve also indicates that higher injection rates will yield slightly higher mercury removals.

## ECONOMIC ANALYSIS

### Economic Background

To gain an understanding of the cost of removing mercury from coal combustion flue gases, the U.S. Department of Energy (DOE) has sponsored many large-scale demonstration activities and has set economic goals for the cost of control. The DOE has put together an economic summary of these demonstration activities in terms of the incremental cost of Hg control. Since the cost of Hg control is very site specific and is based on the best available technology and its subsequent required injection rates to achieve the desired removals, the results vary significantly between sites. The DOE's cost target for the removal of Hg is ≤$45,000/lb of

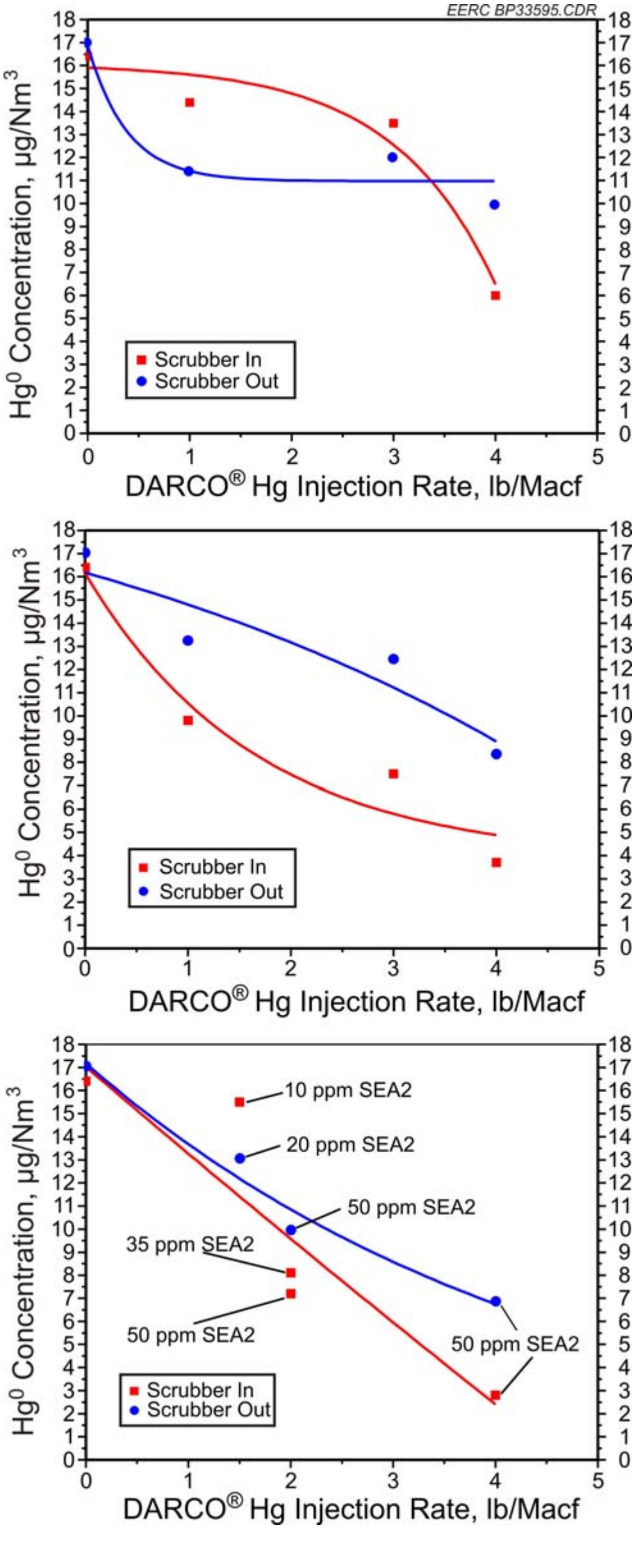


Figure 22 a–c. Scrubber In and Scrubber Out Hg$^0$ concentrations for each sorbent and injection rate tested. Figures 22a–c represent DARCO Hg, DARCO Hg-LH, and SEA2 + DARCO Hg, respectively.

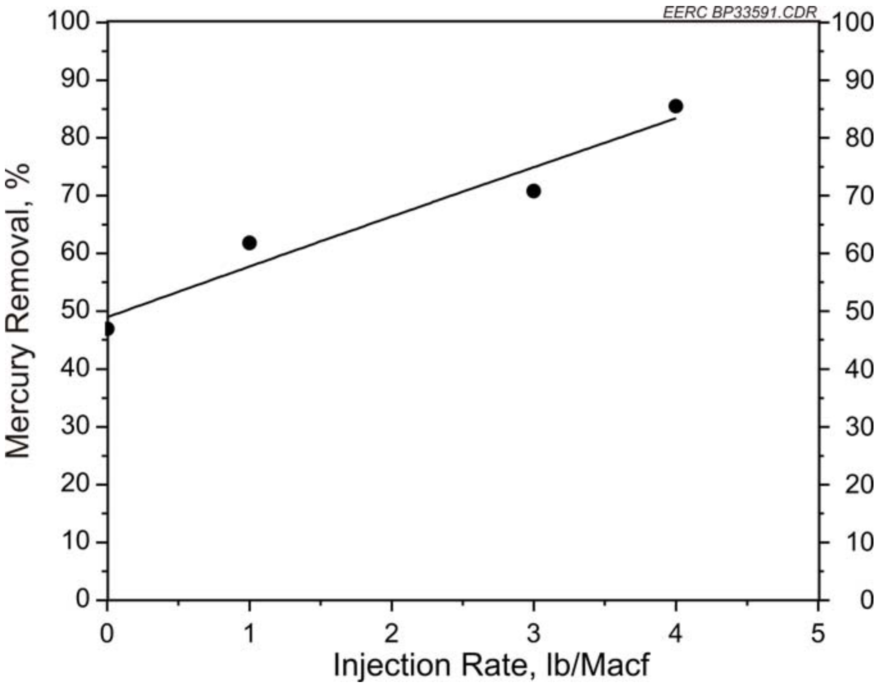


Figure 23. DARCO Hg-LH estimated mercury removals, assuming no scrubber reemission.

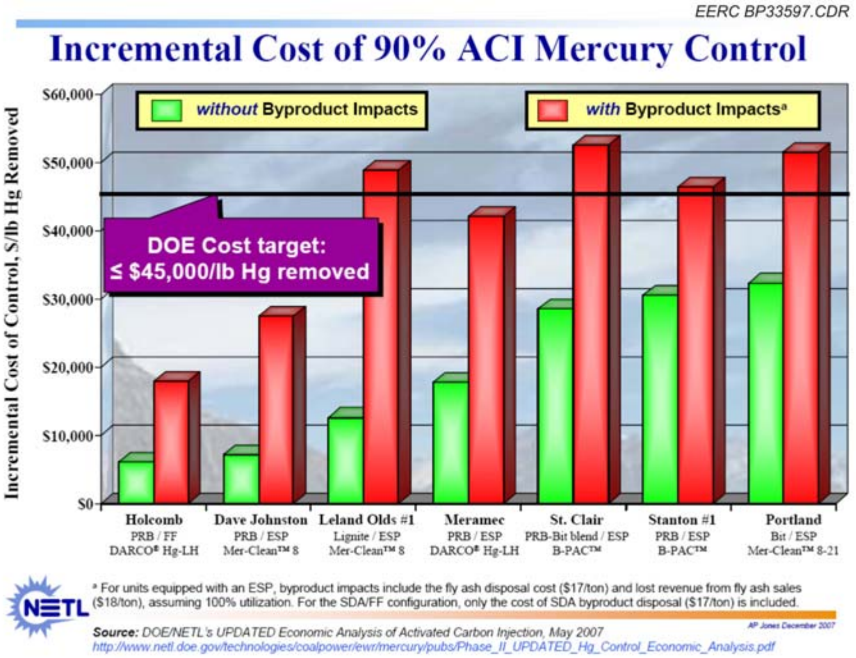
Figure 24. SEA2 + DARCO Hg estimated mercury removals, assuming no scrubber reemission. Assume SEA2 is constant at 50 ppm.

Hg removed. Of the sites presented in DOE's analysis, all units were able to achieve this target when not considering the impacts of being able to sell by-products. If by-product impacts are considered in the analysis, the cost is increased above this target for four out of the seven plants tested. The results of this analysis are summarized in Figure 25. The costs ranged from $5000 to $31,000/lb of Hg removed.

### SMEC Economic Analysis

Based on the results presented above, an economic analysis was performed to give SMEC an example of the estimated cost of Hg removal for different removal rates and technologies. The technologies evaluated during the economic analysis were SEA2 + DARCO Hg and DARCO Hg-LH. Mercury removal rates between 50% and 90% were targeted, based on the removals achieved during full-scale testing. Combustion calculations based on the unit size and coal characteristics were used to determine the flow rate of the flue gas in order to determine the appropriate equipment sizing and pricing to use for the analysis. The results were calculated as the incremental mercury removal cost, which refers to the cost to remove Hg above what is already achieved naturally in the system, which for San Miguel was assumed to be ~34% (based on full-scale test results).

In order to perform the necessary economic analysis assumptions, the maximum removals of each technology had to be included. The test equipment used for the full-scale testing was limited to feeding 4 lb/Macf, and therefore, maximum removals were not determined. Because of this, the trend lines from the plots of injection rate vs. mercury removal were extended to



[a] For units equipped with an ESP, byproduct impacts include the fly ash disposal cost ($17/ton) and lost revenue from fly ash sales ($18/ton), assuming 100% utilization. For the SDA/FF configuration, only the cost of SDA byproduct disposal ($17/ton) is included.

**Source:** *DOE/NETL's UPDATED Economic Analysis of Activated Carbon Injection, May 2007*
*http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/pubs/Phase_II_UPDATED_Hg_Control_Economic_Analysis.pdf*

Figure 25. A comparison of previous economic analysis as performed and presented by the DOE. (ACI is activated carbon injection.)

extrapolate the maximum removal rates that could be expected given higher feed rate capabilities. Because these maximum removals are based on an extrapolation and not actual data, there is no guarantee that the maximum removals can be achieved. The highest achieved Hg removal during the injection of DARCO Hg-LH was 70% (at 4 lb/Macf). If the trend is extrapolated out, it shows that the maximum potential removal rate could be ~80% at an injection rate of 8 lb/Macf. Similarly, for the injection of SEA2 + DARCO Hg, the maximum removal achieved during testing was ~80% (at 50 ppm SEA2 + 4 lb/Macf DARCO Hg). When extrapolated, it was seen that ~90 % could be potentially achieved at the injection rate of 50 ppm SEA2 + 10 lb/Macf DARCO Hg. Because of the reemission of the scrubber, it is thought that increasing the amount of SEA2 alone would not be effective at increasing the Hg removal above the 78.5 % maximum noted during testing, so this extrapolation was not performed.

The results of the economic analysis indicate that the injection of SEA2 + DARCO Hg is significantly cheaper than the injection of DARCO Hg-LH, especially at the higher rates of reduction. Figure 26 shows that the cost for removing 80% of the Hg from the system would be \$4.8 million annually vs. \$14.7 million annually for SEA2 + DARCO Hg and treated PAC (DARCO Hg-LH), respectively. When looking at the cost in terms of \$/lb, it is also noted that the cost associated with the injection of SEA2 + DARCO Hg is significantly lower than that of the injection of DARCO Hg-LH, 8670 \$/lb vs. 26,300 \$/lb, respectively. This trend can be seen in Figure 27. Table 6 shows the results in a tabular form for all of the cases performed in the model. Table 6 also shows the amount of Hg captured and the quantities of material necessary to achieve these removals. Based on these costs, it appears that the incremental cost of mercury removal is similar to that experienced at other plants previously tested by the EERC and DOE.

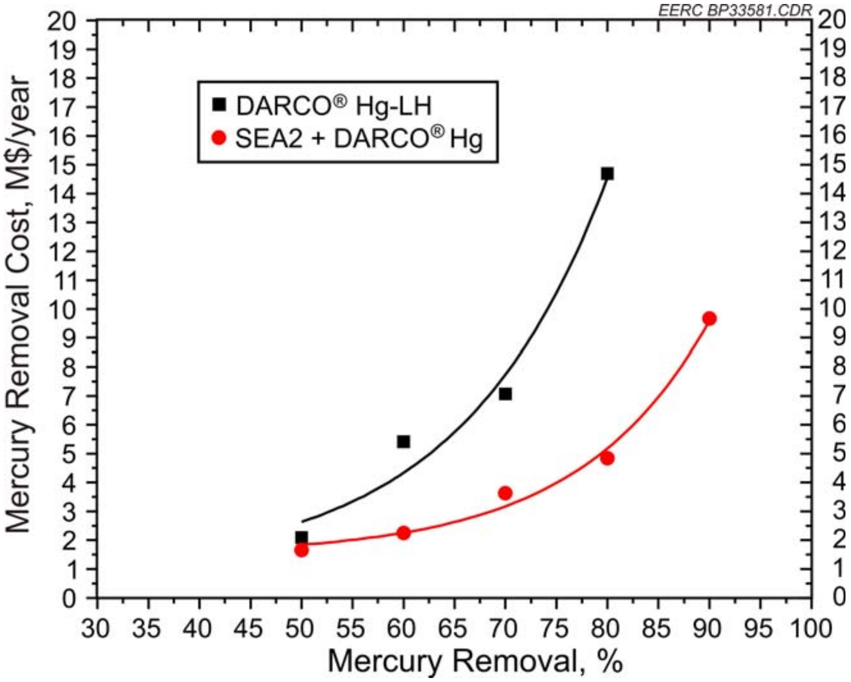


Figure 26. Summary of the economic analysis showing the incremental Hg removal cost in terms of million \$/year.

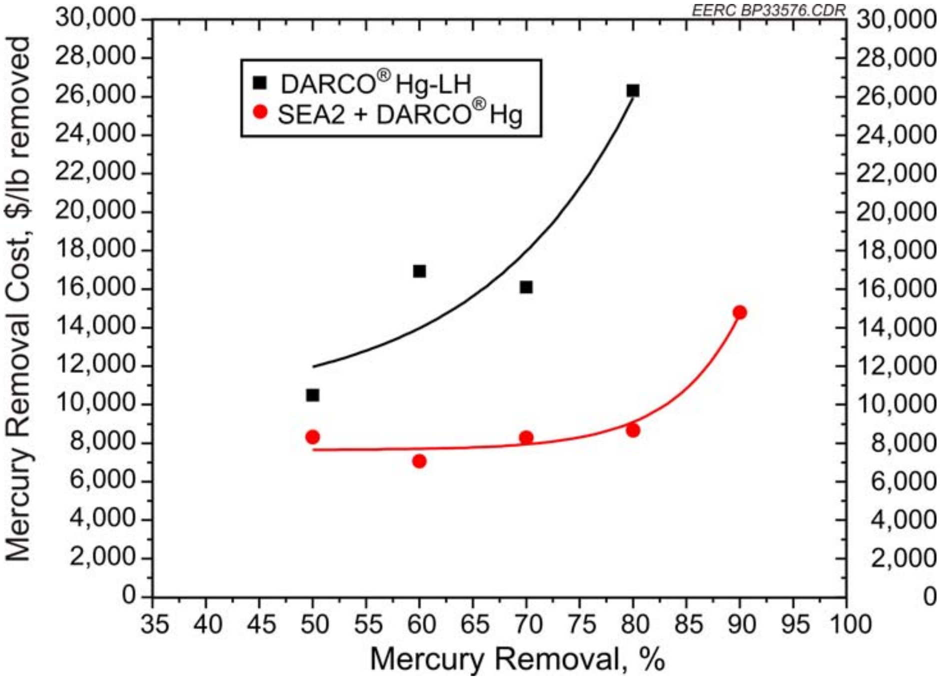


Figure 27. Summary of the economic analysis showing the incremental Hg removal cost in terms of $/lb of Hg removed.

### SMEC Economic Sensitivity Analysis

A sensitivity analysis was performed on certain parameters to determine their effects on the overall cost of incremental Hg removal. The parameters of concern were the cost of the activated carbon, the cost of the SEA2 material, and the cost of the injection equipment. Figure 28 shows the impact of varying the cost of the injection materials. For both the DARCO Hg and the DARCO Hg-LH it was assumed that the cost of the material could vary ± $0.25/lb which would have a huge impact on the overall cost. For example at 80 % control the overall cost for the injection of DARCO Hg-LH could vary from a low of 11.6 to a high of 17.7 million $/year, a difference of 6.1 million $/year. When looking at the effect of the cost of the DARCO Hg with the injection of SEA2 at 80 % control it can be seen that the cost can range from 3.41–6.25 million $/year, with the most likely cost being 4.84 million $/year. The cost is least sensitive when varying the cost of the SEA2 material. When the cost was varied ± $0.50/lb for SEA2, it was seen that the overall cost varied from the mid of 4.84 million $/year to a low and high of 4.60 and 5.07 million $/year, respectively. This analysis indicates that if you can use less DARCO Hg by increasing the amount of SEA2 used and still achieve the same removals, it would be cost advantageous, depending on the contracted price of the PAC.

The last sensitivity analysis performed was the effect of the capital cost associated with the PAC injection system. Several references were used when determining the cost for a PAC injection system for San Miguel. The TCR for the system was determined to be ~1.54 million

# Table 6. SMEC Economic Analysis Results

| Parameter | Plant Name: San Miguel Electric Cooperative | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Scenario | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 | Case 7 | Case 8 | Case 9 |
| Mercury Control Strategy | **DARCO® Hg-LH** | | | | **SEA2+DARCO® Hg** | | | | |
| Total Mercury Reduction, % | 50 | 60 | 70 | 80 | 50 | 60 | 70 | 80 | 88 |
| Unit Size (MW) | 440 | 440 | 440 | 440 | 440 | 440 | 440 | 440 | 440 |
| Flue Gas Flow (dscm/hr, 68 °F) | 2,260,000 | 2,260,000 | 2,260,000 | 2,260,000 | 2,260,000 | 2,260,000 | 2,260,000 | 2,260,000 | 2,260,000 |
| Hg Level Before Injector (µg/dscm, 68 °F) | 32.21 | 32.21 | 32.21 | 32.21 | 32.21 | 32.21 | 32.21 | 32.21 | 32.21 |
| Hg Level After Injector (µg/dscm, 68 °F) | 16.105 | 12.884 | 9.663 | 6.442 | 16.105 | 12.884 | 9.663 | 6.442 | 3.8652 |
| **CAPITAL COST ($)** | | | | | | | | | |
| Purchased Equipment (PE) | 1,198,005 | 1,198,005 | 1,198,005 | 1,198,005 | 1,567,001 | 1,567,001 | 1,567,001 | 1,567,001 | 1,567,001 |
| Installation | 244,921 | 244,921 | 244,921 | 244,921 | 303,960 | 303,960 | 303,960 | 303,960 | 303,960 |
| Indirect | 0 | 0 | 0 | 0 | 153,000 | 153,000 | 153,000 | 153,000 | 153,000 |
| Total Capital Requirement (TCR) | 1,545,374 | 1,545,374 | 1,545,374 | 1,545,374 | 2,167,662 | 2,167,662 | 2,167,662 | 2,167,662 | 2,167,662 |
| **OPERATING AND MAINTENANCE (O&M) ($/yr)** | | | | | | | | | |
| Operating Labor [a] | 19,200 | 19,200 | 19,200 | 19,200 | 28,800 | 28,800 | 28,800 | 28,800 | 28,800 |
| Supervision Labor [b] | 2,880 | 2,880 | 2,880 | 2,880 | 4,320 | 4,320 | 4,320 | 4,320 | 4,320 |
| Operating Materials | 12,270 | 36,811 | 49,081 | 105,525 | 5,868 | 8,803 | 14,671 | 23,474 | 58,684 |
| Maintenance Labor [c] | 16,000 | 16,000 | 16,000 | 16,000 | 32,000 | 32,000 | 32,000 | 32,000 | 32,000 |
| Maintenance Materials [d] | 39,960 | 39,960 | 39,960 | 39,960 | 63,340 | 63,340 | 63,340 | 63,340 | 63,340 |
| Raw Materials (Carbon, Additives, etc)[e] | 1,239,307 | 3,717,920 | 4,957,226 | 10,658,036 | 735,814 | 1,175,272 | 2,197,291 | 3,086,359 | 6,642,630 |
| Utilities (Power, Steam, Water)[f] | 8,775 | 8,775 | 8,775 | 8,775 | 26,787 | 26,787 | 26,787 | 26,787 | 26,787 |
| Additional Disposal [g] | 18,589 | 55,749 | 74,330 | 159,795 | 19,835 | 30,373 | 52,691 | 80,562 | 192,037 |
| Overhead[h] | 7,616 | 7,616 | 7,616 | 7,616 | 13,024 | 13,024 | 13,024 | 13,024 | 13,024 |
| Taxes, Insurance, Administration | 73,661 | 73,661 | 73,661 | 73,661 | 103,323 | 103,323 | 103,323 | 103,323 | 103,323 |
| **Fixed (Capital) Charges [j]** | 273,661 | 273,661 | 273,661 | 273,661 | 383,859 | 383,859 | 383,859 | 383,859 | 383,859 |
| **Total Annual Cost ($/yr) [k]** | **2,097,539** | **5,410,527** | **7,067,023** | **14,686,892** | **1,663,411** | **2,256,005** | **3,631,279** | **4,838,783** | **9,668,790** |
| **mills/kWh** | 0.640 | 1.651 | 2.157 | 4.483 | 0.508 | 0.689 | 1.108 | 1.477 | 2.951 |
| **Mercury Reduction by Technology, %** | 16.75 | 26.75 | 36.75 | 46.75 | 16.75 | 26.75 | 36.75 | 46.75 | 54.75 |
| Mercury Reduction by Technology, (kg/yr) | 91 | 145 | 199 | 253 | 91 | 145 | 199 | 253 | 296 |
| Mercury Reduction by Technology, (lb/yr) | 200 | 319 | 439 | 558 | 200 | 319 | 439 | 558 | 654 |
| Mercury Emission, lb/Tbtu | 16.4 | 13.1 | 9.83 | 6.55 | 16.4 | 13.1 | 9.83 | 6.55 | 3.93 |
| Mercury Emission, lb/GWh | 0.182 | 0.146 | 0.109 | 0.073 | 0.182 | 0.146 | 0.109 | 0.073 | 0.044 |
| Mercury Removal Cost, ($/kg) | 23,127 | 37,354 | 35,514 | 58,019 | 18,340 | 15,575 | 18,248 | 19,115 | 32,614 |
| **Mercury Removal Cost, ($/lb)** | **10,490** | **16,943** | **16,109** | **26,317** | **8,319** | **7,065** | **8,277** | **8,670** | **14,793** |
| a: Based on $/hr operator labor | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| b: Based on % percent of operating labor cost | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| c: Based on $/hr maintenance labor | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| d: Same as maintenance labor plus % of PE for replacement parts | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| e: Based on $/lb of sorbent plus other raw materials | 1.15 | 1.15 | 1.15 | 1.15 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 |
| f: Based on $/kwh of power | 0.045 | 0.045 | 0.045 | 0.045 | 0.045 | 0.045 | 0.045 | 0.045 | 0.045 |
| g: Based on $/ton of nonhazardous waste disposal | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 |
| h: Based on % of labor cost | 20 | 20 | 20 | 35 | 35 | 35 | 35 | 35 | 35 |
| i: Based on % of total capital cost | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| j: Based on a capital recovery factor of | 9.08 | 9.08 | 9.08 | 9.08 | 9.08 | 9.08 | 9.08 | 9.08 | 9.08 |
| at annual percent of | 6.5 | 6.5 | 6.5 | 6.5 | 6.5 | 6.5 | 6.5 | 6.5 | 6.5 |
| for number of years | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| k: Total cost equals fixed charges plus levelized operating costs | | | | | | | | | |

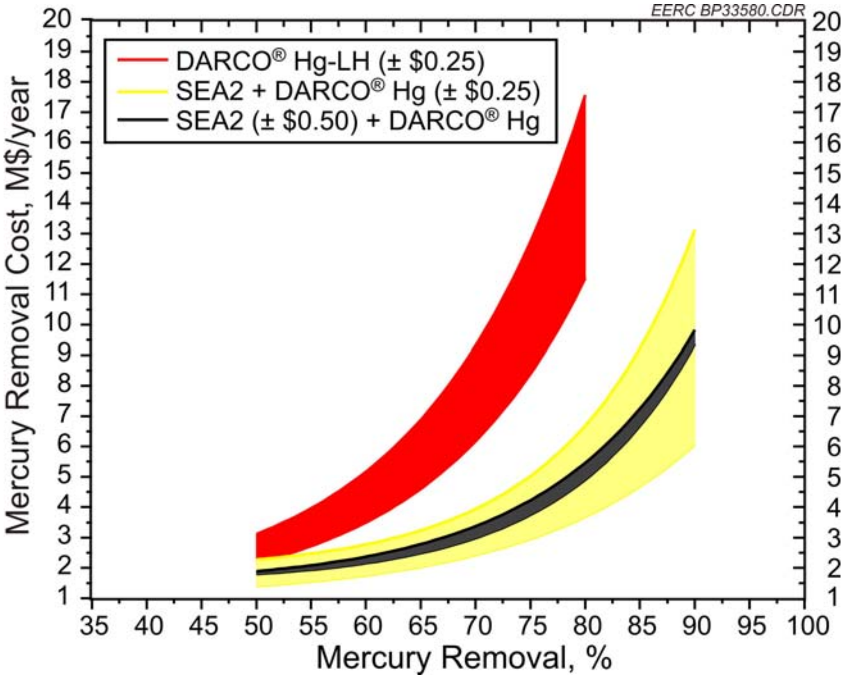


Figure 28. A sensitivity analysis showing the impact of the cost of materials (DARCO Hg, DARCO Hg-LH, and SEA2).

dollars by using the DOE's Integrated Environmental Control Model (IECM) and was similar for a model developed in-house at the EERC. An Internet search yielded a maximum system cost to be 4.64 million dollars for a similar system, also from a DOE report. Therefore, the chosen range for the analysis of the total capital requirement for the PAC injection system was 1.54–4.64 million dollars. Figure 29 shows the range of incremental mercury removal cost when varying the TCR. It can be seen that varying the TCR cost did not have a significant effect on overall cost when compared to the sensitivity of the material cost. At a removal rate of 80% (using SEA2 + DARCO Hg), the total annual cost would increase $690,000 per year if the TCR were 4.64 million dollars rather than 1.54 million dollars.

## CONCLUSIONS

During full-scale testing, scrubber reemission occurred and had a significant impact on mercury removal. Because of scrubber reemission, the highest mercury removal obtained was 78.5% using 50 ppm SEA2 and 4 lb/Macf DARCO Hg. If scrubber reemission were able to be controlled, this injection rate is estimated to achieve approximately 91% mercury removal based on the scrubber inlet elemental mercury concentration. DARCO Hg-LH would also be a technology able to achieve the target removal of ≥90% mercury removal, if scrubber reemission were eliminated.

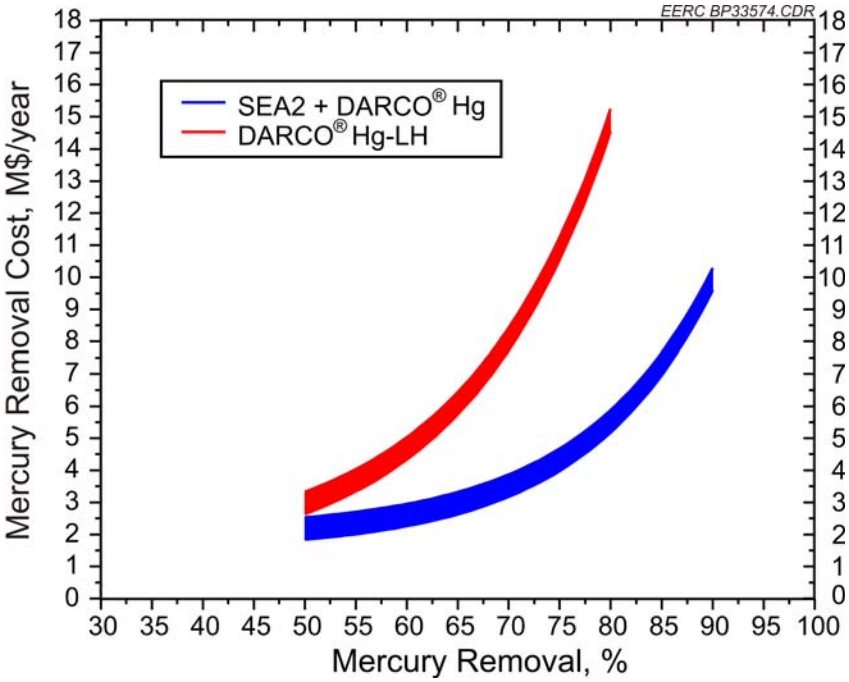


Figure 29. A sensitivity analysis showing the impact of the cost of the PAC injection system ranging from a TCR of 1.54 – 4.64 million dollars.

The results of testing at San Miguel indicated that the injection of SEA2 + DARCO Hg was the technology that performed the best based not only on the technical results, but also in terms of the economic analysis. Although this technology performed the best, it is not offered commercially at this time. Efforts to bring this technology to the market place are ongoing, which will make the technology a viable option for plants in the future. Commercial options do exist for San Miguel depending on the levels of control needed. For Hg removals up to 80%, a treated carbon should be effective technically, but it is a more expensive option. Ongoing full- and pilot-scale testing at San Miguel will evaluate the use of another oxidation technology for mercury control and multiple scrubber additives for control of Hg reemission. The alternative oxidation technology is similar to SEA2 in concept but differs in application and is currently available commercially. This technology will be evaluated at the pilot-scale level and compared economically and technically to the results of SEA2 as a commercial option for San Miguel. Two scrubber additives are also being evaluated at the pilot-scale level to determine their potential to mitigate reemission. One reemission technology will be tested at San-Miguel as a full-scale demonstration.

### Comparison of Pilot- and Full-Scale Test Results

The pilot-scale testing was able to parallel the test results obtained during the full-scale test. During the pilot-scale testing with the scrubber online, the baseline removal was found to be 41%, which correlates well with the full-scale baseline removal of 34%. The pilot-scale inlet mercury concentrations were generally higher than the full-scale inlet mercury concentrations, but the pilot-scale inlet concentrations were consistent with some of the higher full-scale inlet concentrations. It is likely that the shipment of coal sent to the EERC for the pilot-scale testing was higher in mercury concentration. The amount of coal combusted for the pilot-scale testing was very small (22 tons over two weeks of operation) compared to the amount of coal that is combusted at the full scale on an hourly basis (480 tons/hr).

The pilot-scale results with SEA2 and DARCO Hg show a mercury removal of 93% and SEA2 and DARCO Hg injection rates of 50 ppm and 5 lb/Macf, respectively. Based on the curve from this data set, a removal of approximately 91% would be obtained at SEA2 and DARCO Hg injection rates of 50 ppm and 4 lb/Macf, respectively. These injection rates to obtain 91% removal are identical to the full-scale extrapolated results in the absence of scrubber reemission.

## REFERENCES

1. Olson, E.S.; Laumb, J.D.; Benson, S.A.; Dunham, G.E.; Sharma, R.K.; Mibeck, B.A.; Miller, S.J.; Holmes, M.J.; Pavlish, J.H. An Improved Model for Flue Gas–Mercury Interactions on Activated Carbons. Presented at the DOE–EPRI–EPA–A&WMA Power Plant Air Pollutant Control “Mega” Symposium, Washington, DC, May 19–22, 2003.

2. Pavlish, J.H.; Sondreal, E.H.; Mann, M.D.; Olson, E.S.; Galbreath, K.C.; Laudal, D.L.; Benson, S.A. Status Review of Mercury Control Options for Coal-Fired Power Plants. *Fuel Process. Technol.* **2003**, *82*, 89–165.

# APPENDIX A

# SAMPLE CALCULATIONS

### Flue Gas Hg Concentration from ST Samples

Hg (µg/dNm$^3$ at 3% O$_2$) = mercury concentration in the flue gas corrected to standard conditions

Hg (µg/dNm$^3$ at 3% O$_2$) = (F + S1 + S2) ÷ Vcorr × 18/(21 – O$_2$)

Vcorr (dNL) = Volume sampled corrected to standard conditions

Vcorr (dNL) = Vm × Cm × (Pb – Elev corr/1000) ÷ 29.92 × 528 ÷ (460 + Tm)

Vcorr (dNL) = 15.0 × 1.070 × (29.94 – 71/1000) ÷ 29.92 × 528 ÷ (460 + 111) = 14.816 dNL

Hg (µg/dNm$^3$ at 3% O$_2$) = (0.4 + 108 + 0.5) ÷ 14.816 × 18/(21 – 4.1) = 7.83 µg/dNm$^3$ at 3% O$_2$

Where:
Vm= Volume of gas sample measured by the dry-gas meter (dL)
Pb = Barometric pressure (in Hg)
Elev corr = Elevation correction for Pb to sampling elevation (ft)
Tm = Meter temperature (°F)
Cm = Meter correction factor (unitless, via calibration)
O$_2$ = Flue gas O$_2$ concentration measured (%)
F = Measured mass of Hg in Front Wool + Plug (ng)
S1 = Measured mass of Hg in Section 1 (ng)
S2 = Measured mass of Hg in Section 2 and plug (ng)

### Hg removal

HgOut = Hg (µg/dNm$^3$ at 3% O$_2$) mercury concentration at the outlet location

HgIn = Hg (µg/dNm3 at 3% O$_2$) coal mercury concentration

% Hg Removal = The percent of mercury removed from the flue gas based on the inlet and outlet mercury concentrations

% Hg Removal = 100 – (HgOut/HgIn × 100)

% Hg Removal = 100 – (2.2/8.1 × 100) = 72.8%

## OH METHOD SAMPLING

### Volume of Gas Sample

Vm(std) = Volume of gas sample measured by the dry-gas meter, corrected to standard conditions, dscf

Vm(std) (dscf) = $$\frac{K_1 \times Vmc \times Pm}{Tm + 460}$$

Vm(std) = $$\frac{17.64 \times 45.472 \times 1 \times 29.665}{104 + 460} = 42.190 \quad \text{dscf}$$

Where:

$K_1$ = 17.64 R/in. Hg
Vmc = Vm × Cm = Volume of gas sample as measured by dry-gas meter, corrected for meter calibration
(Cm = meter calibration coefficient) (dcf)
Pm = Meter pressure (in. Hg)
Tm = Meter temperature (°F)

## Volume of Water Vapor

Vw(std) = Volume of water vapor in the gas sample, corrected to standard conditions, scf
Vw(std) (scf) = $K_2 \times H_2O(g)$
Vw(std) = 0.04715 × 137.5 = 6.483 scf

Where:

$K_2$ = 0.04715 $ft^3/g$
$H_2O(g)$ = Mass of liquid collected in impingers and silica gel (g)

## Water Vapor in the Gas Stream

Bws = Water vapor in the gas stream, proportion by volume

Bws = $$\frac{\text{Vw(std)}}{\text{Vm(std)} + \text{Vw(std)}}$$

Bws = $$\frac{6.483}{42.190 + 6.483} = 0.1332$$

## Dry Molecular Weight

Md = Dry molecular weight of stack gas, lb/lb-mole
Md (lb/lb-mol) = $0.440 \times (\%CO_2) + 0.320 \times (\%O_2) + 0.280 \times (\%N_2 + \%CO)$
Md = 0.440 × 15.9 + 0.320 × 3.1 + 0.280 × 81.0 = 30.7 lb/lb-mol

Where:

%($CO_2$, $O_2$, $N_2$, CO) = Percent ($CO_2$, $O_2$, $N_2$, CO) by volume, dry basis

**Molecular Weight**

Ms = Molecular weight of stack gas, wet basis, lb/lb-mol
Ms (lb/lb-mol) = Md × (1 – Bws) + 18.0 × Bws
Ms = 30.7 × (1 – 0.1332) + 18.0 × 0.1332 = 29.0 lb/lb-mol

**Average Stack Gas Velocity**

Vs = Average stack gas velocity, ft/sec

$$\text{Vs (ft/sec)} = K_3 \times \text{Cp} \times (\Delta \text{p})^{1/2}(\text{avg}) \times \left[\frac{\text{Ts} + 460}{\text{Ps} \times \text{Ms}}\right]^{1/2}$$

$$\text{Vs} = 85.49 \times 0.84 \times 0.4472 \times \left[\frac{685 + 460}{30.49 \times 29.0}\right]^{1/2} = 36.6\,\text{ft/sec}$$

Where:

$$K_3 = 85.49\,\text{ft/sec} \times \left[\frac{\dfrac{\text{lb}}{\text{lb-mole}} \times \text{in. Hg}}{\text{R} \times \text{in. } H_2O}\right]^{1/2}$$

Cp = Pitot tube coefficient, dimensionless
$\Delta$p = Velocity head of stack gas (in. Hg)
$(\Delta \text{p})^{1/2}(\text{avg})$ = Average of the square root of $\Delta$p values
Ts = Stack gas temperature (°F)
Ps = Stack pressure (in. Hg)

**Isokinetic Sampling Rate**

I = Percent of isokinetic sampling, %

$$\text{I (\%)} = \frac{K_4 \times (\text{Ts} + 460) \times \text{Vm(std)} \times 144}{\text{Ps} \times \text{Vs} \times \text{An} \times \theta \times (1 - \text{Bws})}$$

$$\text{I} = \frac{0.09450 \times (685 + 460) \times 42.190 \times 144}{30.49 \times 36.6 \times 0.0707 \times 90 \times (1 - 0.1332)} = 107\%$$

Where:

$K_4$ = $$\frac{0.09450\%(\text{in.Hg})(\text{min})}{\text{R} \times \text{sec}}$$

An = Cross-sectional area of nozzle (in.$^2$)

θ = Total sampling time (min)

**Volume of Gas Sample Corrected to 3% $O_2$**

Vm*(std) = Volume of gas sample measured by the dry-gas meter (Vm[std]), * corrected to 3% oxygen, $Nm^3$

$$\text{Vm*(std)} = K_5 \times \text{Vm(std)} \times \frac{21 - \%O_2}{18}$$

$$\text{Vm*(std)} = 0.02832 \times 42.190 \times \frac{21 - 3.1}{18} = 1.188\,\text{Nm}^3$$

Where:

$K_5$ = 0.02832 $m^3/ft^3$

**Mercury**

$$\text{Hg } (\mu\text{g/Nm}^3) = \frac{\mu\text{g}}{\text{Vm*(std)}}$$

$$\text{Hg} = \frac{6.99}{1.188} = 5.88\ \mu\text{g/Nm}^3$$

Particulate Hg = Sum of mercury from filter and nozzle rinse

Oxidized Hg = Sum of mercury from KCl impingers

Elemental Hg = Sum of mercury from $H_2O_2$ and $KMnO_4$ impingers

# APPENDIX B

# COAL DATA

## Coal Data

Coal samples were subjected to analysis for proximate, ultimate, Btu, Hg, Cl, and Br. Table B-1 contains the complete results of these analyses. Samples are reported on an as-received basis.

**Table B–1. Coal Data May 24 – May 26**

|  | Date | 5/24/08 | 5/24/08 | 5/25/08 | 5/25/08 | 5/26/08 | 5/26/08 |
|---|---|---|---|---|---|---|---|
|  | Time | 10:40 | 15:30 | 8:30 | 14:30 | 8:45 | 14:45 |
| Hg | µg/g | 0.129 | 0.160 | 0.207 | 0.198 | 0.197 | 0.213 |
| Cl | µg/g | 865 |  | 828 | 870 |  |  |
| Br | µg/g | 4.6 |  |  | 4.3 |  |  |
| Proximate |  |  |  |  |  |  |  |
| Moisture | % | 31.4 | 31.1 | 30.7 | 30.2 | 31.4 | 31.1 |
| Volatile Matter | % | 24.03 | 23.75 | 22.67 | 24.54 | 23.62 | 23.75 |
| Fixed Carbon | % | 18.84 | 18.54 | 17.43 | 18.39 | 18.34 | 18.54 |
| Ash | % | 25.73 | 26.64 | 29.20 | 26.87 | 26.64 | 26.64 |
| Ultimate |  |  |  |  |  |  |  |
| H | % | 6.11 | 6.10 | 6.14 | 6.00 | 6.16 | 6.10 |
| C | % | 30.17 | 29.63 | 29.22 | 29.49 | 29.02 | 29.63 |
| N | % | 0.56 | 0.53 | 0.53 | 0.53 | 0.53 | 0.53 |
| S | % | 2.32 | 2.68 | 2.45 | 2.71 | 2.50 | 2.68 |
| O | % | 35.12 | 34.42 | 32.46 | 34.40 | 35.15 | 34.42 |
| Heating Value | Btu/lb | 4798 | 5094 | 4998 | 5183 | 4945 | 5094 |
| Fd | dscf/$10^6$Btu | 11243 | 10522 | 10782 | 10234 | 10607 | 10522 |
| Sulfur, dry | % | 3.38 | 3.89 | 3.54 | 3.88 | 3.64 | 3.89 |
| Heating Value, dry | Btu/lb | 6994 | 7391 | 7212 | 7426 | 7208 | 7391 |
| Hg | µg/$Nm^3$ | 22.52 | 28.25 | 36.55 | 35.77 | 35.37 | 37.60 |
|  | lb/TBtu | 18.44 | 21.65 | 28.70 | 26.66 | 27.33 | 28.82 |

**Table B–2. Coal Data May 28 – June 2**

| | Date<br>Time | 5/28/08<br>10:45 | 5/29/08<br>14:35 | 5/30/08<br>8:30 | 5/30/08<br>15:00 | 6/2/08<br>8:30 | 6/2/08<br>17:30 |
|---|---|---|---|---|---|---|---|
| Hg | µg/g | 0.189 | 0.172 | 0.174 | 0.144 | 0.196 | 0.243 |
| Cl | µg/g | 899 | | 862 | 843 | 841 | 777 |
| Br | µg/g | | | 4.1 | | | |
| Proximate | | | | | | | |
| Moisture | % | 30.9 | 31.0 | 31.6 | 31.4 | 31.0 | 30.6 |
| Volatile Matter | % | 24.15 | 23.46 | 23.75 | 23.97 | 24.56 | 24.29 |
| Fixed Carbon | % | 19.50 | 18.48 | 19.25 | 19.25 | 19.49 | 18.77 |
| Ash | % | 25.45 | 27.06 | 25.41 | 25.37 | 24.95 | 26.34 |
| Ultimate | | | | | | | |
| H | % | 6.14 | 6.03 | 6.22 | 6.12 | 6.13 | 6.04 |
| C | % | 31.49 | 28.85 | 30.12 | 29.95 | 30.84 | 30.32 |
| N | % | 0.57 | 0.50 | 0.55 | 0.52 | 0.52 | 0.53 |
| S | % | 2.65 | 2.68 | 2.74 | 2.69 | 3.03 | 2.96 |
| O | % | 33.70 | 34.88 | 34.96 | 35.34 | 34.53 | 33.81 |
| Heating Value | Btu/lb | 5379 | 5025 | 5278 | 5220 | 5349 | 5261 |
| Fd | dscf/$10^6$Btu | 10580 | 10336 | 10341 | 10297 | 10415 | 10430 |
| Sulfur, dry | % | 3.84 | 3.88 | 4.01 | 3.92 | 4.39 | 4.27 |
| Heating Value, dry | Btu/lb | 7784 | 7283 | 7716 | 7609 | 7752 | 7581 |
| Hg | ug/Nm$^3$ | 31.50 | 31.37 | 29.94 | 25.23 | 33.33 | 42.19 |
| | lb/TBtu | 24.28 | 23.62 | 22.55 | 18.92 | 25.28 | 32.06 |

**Table B–3. Coal Data June 3 – June 5**

| | Date<br>Time | 6/3/08<br>8:30 | 6/3/08<br>16:50 | 6/4/08<br>8:30 | 6/4/08<br>15:15 | 6/5/08<br>8:15 |
|---|---|---|---|---|---|---|
| Hg | µg/g | 0.168 | 0.189 | 0.178 | 0.160 | 0.182 |
| Cl | µg/g | | | | 803 | |
| Br | µg/g | 3.9 | | | 4.1 | |
| Proximate | | | | | | |
| Moisture | % | 31.1 | 31.5 | 31.1 | 31.1 | 31.2 |
| Volatile Matter | % | 23.75 | 23.54 | 23.75 | 23.75 | 22.36 |
| Fixed Carbon | % | 18.54 | 17.75 | 18.54 | 18.54 | 16.95 |
| Ash | % | 26.64 | 27.21 | 26.64 | 26.64 | 29.49 |
| Ultimate | | | | | | |
| H | % | 6.10 | 6.14 | 6.10 | 6.10 | 5.97 |
| C | % | 29.63 | 28.94 | 29.63 | 29.63 | 27.12 |
| N | % | 0.53 | 0.49 | 0.53 | 0.53 | 0.48 |
| S | % | 2.68 | 2.79 | 2.68 | 2.68 | 2.67 |
| O | % | 34.42 | 34.43 | 34.42 | 34.42 | 34.26 |
| Heating Value | Btu/lb | 5094 | 4997 | 5094 | 5094 | 4696 |
| Fd | dscf/$10^6$Btu | 10522 | 10556 | 10522 | 10522 | 10509 |
| Sulfur, dry | % | 3.89 | 4.07 | 3.89 | 3.89 | 3.88 |
| Heating Value, dry | Btu/lb | 7391 | 7295 | 7391 | 7391 | 6826 |
| Hg | ug/Nm$^3$ | 29.66 | 33.70 | 31.43 | 28.25 | 34.83 |
| | lb/TBtu | 22.73 | 25.91 | 24.08 | 21.65 | 26.66 |

# APPENDIX C

# CMM, OH, AND ST DATA

## Continuous Mercury Monitor (CMM), Ontario Hydro (OH), and Sorbent Trap Data

For this project, CMMs were set up at the ESP inlet, scrubber inlet, and scrubber outlet. The plant's CMM was installed in the stack but measured only elemental mercury flue gas concentrations. The quality assurance/quality control and operating parameters were described in the body of this report. For completeness, the raw CMM data is shown here in Figure C-1.

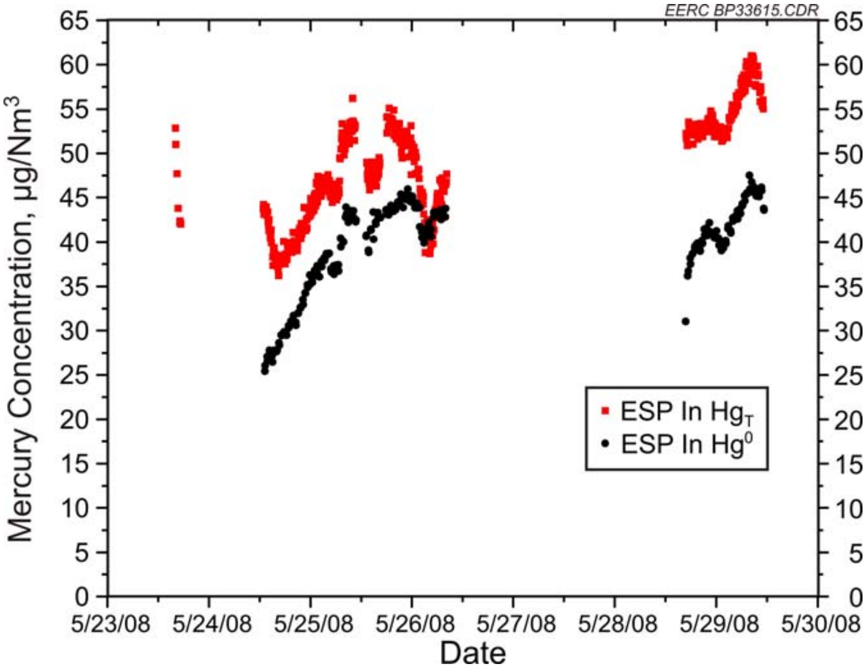


Figure C-1. ESP In CMM data.

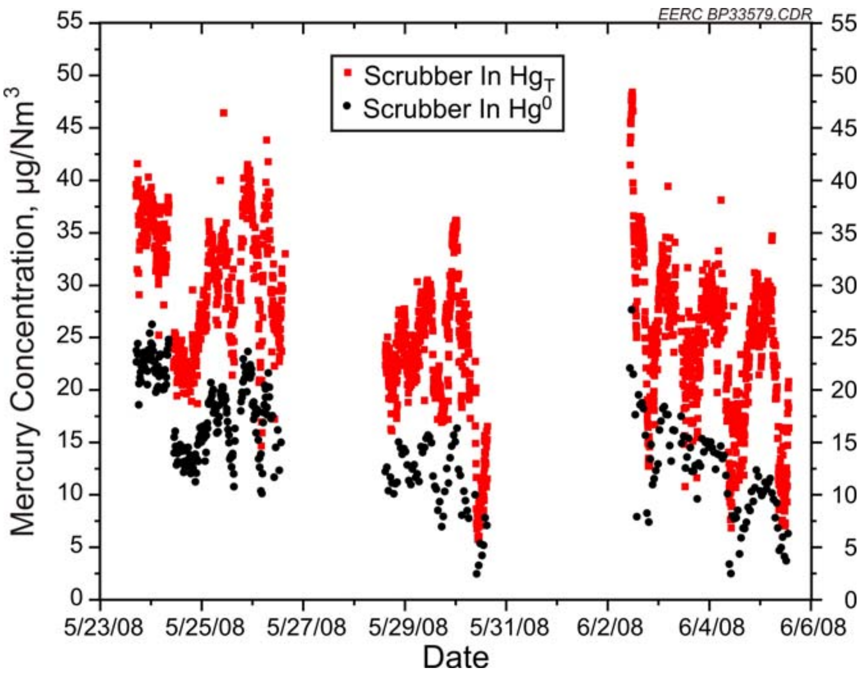


Figure C-2. Scrubber In CMM data.

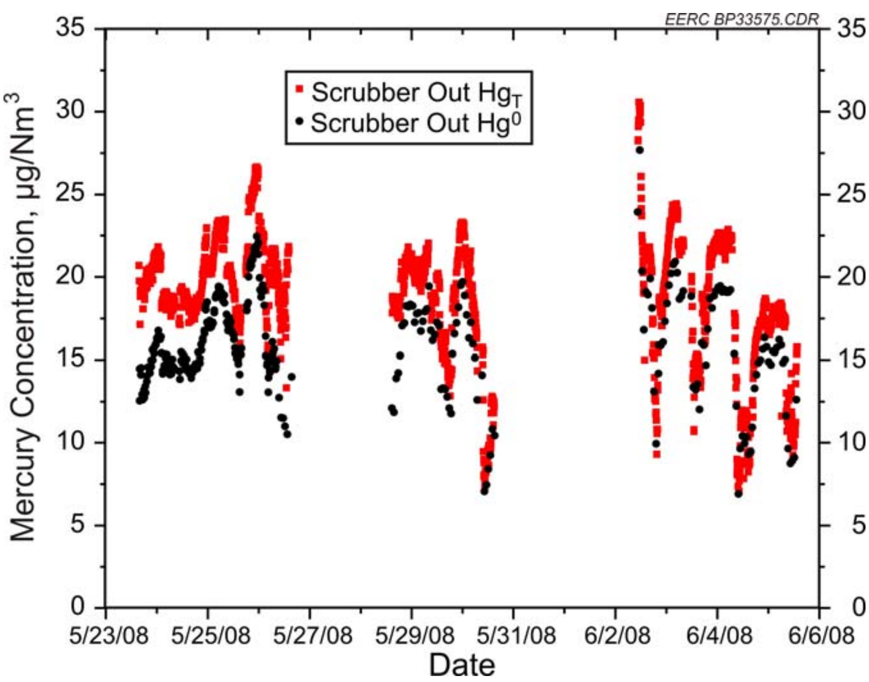


Figure C-3. Scrubber Out CMM data.

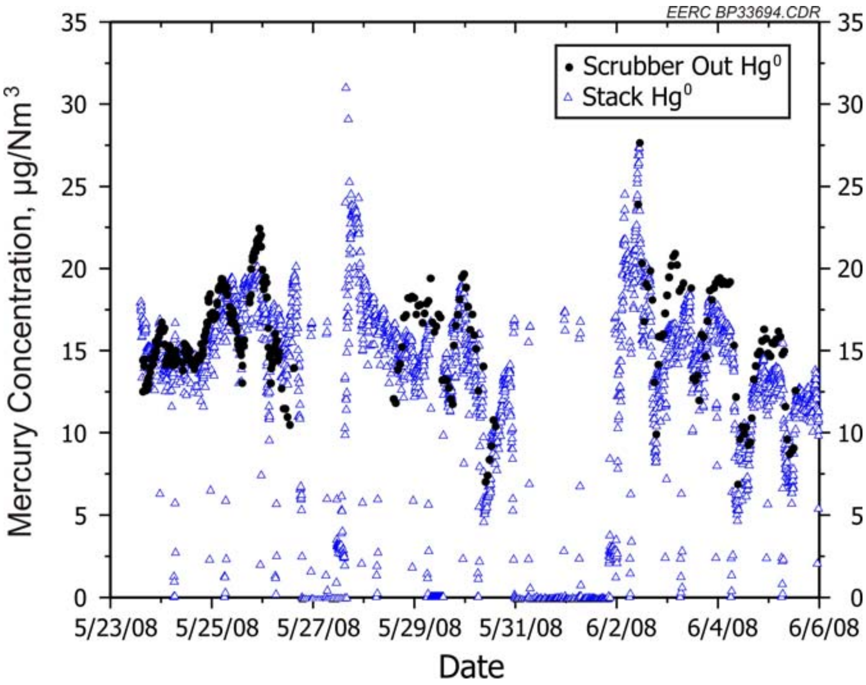


Figure C-4. Scrubber Out and stack $Hg^0$ CMM data.

## Table C–1. Sorbent Trap Sample Data May 24 – May 25

| Sample I.D. | SM-D1-ESP In-ST-1 | SM-D1-STK-ST-1 | SM-D2-ESP In-ST-1 | SM-D2-STK-ST-1 |
|---|---|---|---|---|
| Date | 5/24/2008 | 5/24/2008 | 5/25/2008 | 5/25/2008 |
| Start Time | 16:49 | 14:44 | 10:15 | 10:33 |
| End Time | 17:19 | 15:44 | 10:45 | 11:33 |
| Duration, hr | 0:30 | 1:00 | 0:30 | 1:00 |
| Location | ESPIn | Stack | ESPIn | Stack |
| Trap ID, no. | | | | |
| Vm, dL | 12.5 | 29.1 | 12.8 | 31.7 |
| Pb, in Hg | 29.32 | 29.32 | 29.41 | 29.41 |
| Elev corr, ft | 0 | 0 | 0 | 0 |
| Tm, °F | 91 | 90 | 88.3 | 86.7 |
| Cm | 0.999 | 1.004 | 0.999 | 1.004 |
| Moisture, % | 15.4 | 19.8 | 15.4 | 19.8 |
| $O_2$, % | 10.8 | 10.4 | 11.1 | 10.8 |
| Front Wool + Plug, ng | 18 | 0 | 20 | 0 |
| Sect 1, ng | 241 | 365 | 326 | 536 |
| Sect 2 w/Plug, ng | 0.9 | 1.1 | 3.6 | 2 |
| Back Plug, ng | 0 | 0 | 0 | 0 |
| Breakthrough, % | 0.37 | 0.30 | 1.10 | 0.37 |
| Vcorr, dNL | 11.7 | 27.5 | 12.1 | 30.2 |
| Hg, µg/dNm$^3$ | 20.6 | 13.3 | 27.2 | 17.8 |
| Hg($O_2$corr) at 3% $O_2$ | 36.4 | 22.6 | 49.5 | 31.4 |
| Hg(wet), µg/m$^3$ | 17.9 | 11.1 | 23.6 | 14.9 |

## Table C–2. Sorbent Trap Sample Data May 26 – May 29

| Sample I.D. | SM-D3-ESP In-ST-1 | SM-D3-SCRB In-ST-1 | SM-D3-STK-ST-1 | SM-D4-ESP In-ST-1 | SM-D4-SCRB In-ST-1 | SM-D4-STK-ST-1 |
|---|---|---|---|---|---|---|
| Date | 5/26/2008 | 5/26/2008 | 5/26/2008 | 5/29/2008 | 5/29/2008 | 5/29/2008 |
| Start Time | 11:08 | 11:15 | 10:56 | 14:30 | 14:14 | 14:15 |
| End Time | 11:38 | 12:15 | 11:56 | 15:00 | 15:14 | 15:15 |
| Duration, hr | 0:30 | 1:00 | 1:00 | 0:30 | 1:00 | 1:00 |
| Location | ESPIn | SCRBIn | Stack | ESPIn | SCRBIn | Stack |
| Trap ID, no. | | | | | | |
| Vm, dL | 13.6 | 26.7 | 32.9 | 13.42 | 28.7 | 32 |
| Pb, in Hg | 29.44 | 29.44 | 29.44 | 29.65 | 29.65 | 29.65 |
| Elev corr, ft | 0 | 0 | 0 | 0 | 0 | 0 |
| Tm, °F | 89.3 | 101.3 | 86.5 | 98.5 | 105.7 | 90.6 |
| Cm | 0.999 | 0.976 | 0.994 | 0.999 | 0.976 | 0.994 |
| Moisture, % | 15.4 | 15.4 | 19.8 | 15.4 | 15.4 | 19.8 |
| $O_2$, % | 10.5 | 9.7 | 10.5 | 11 | 9.8 | 10.8 |
| Front Wool + Plug, ng | 11 | 0 | 0 | 0 | 0 | 0 |
| Sect 1, ng | 415 | 514 | 448 | 317 | 415 | 364 |
| Sect 2 w/Plug, ng | 0.4 | 1.5 | 4.4 | 1 | 1.9 | 8.3 |
| Back Plug, ng | 0 | 0 | 0 | 0 | 0 | 0 |
| Breakthrough, % | 0.10 | 0.29 | 0.98 | 0.32 | 0.46 | 2.28 |
| Vcorr, dNL | 12.9 | 24.1 | 31.1 | 12.6 | 25.9 | 30.2 |
| Hg, µg/dNm$^3$ | 32.3 | 21.4 | 14.6 | 25.3 | 16.1 | 12.3 |
| Hg ($O_2$corr) at 3% $O_2$ | 55.4 | 34.0 | 24.9 | 45.6 | 25.9 | 21.7 |
| Hg(wet), µg/m$^3$ | 28.0 | 18.5 | 12.1 | 21.9 | 13.9 | 10.3 |

## Table C–3. Sorbent Trap Sample Data May 29 – May 30

| Sample I.D. | SM-D4-ESP In-ST-2 | SM-D4-SCRB In-ST-2 | SM-D4-STK-ST-2 | SM-D5-ESP In-ST-1 | SM-D5-SCRB In-ST-1 | SM-D5-STK-ST-1 |
|---|---|---|---|---|---|---|
| Date | 5/29/2008 | 5/29/2008 | 5/29/2008 | 5/30/2008 | 5/30/2008 | 5/30/2008 |
| Start Time | 17:40 | 17:36 | 17:38 | 11:25 | 11:18 | 11:07 |
| End Time | 18:10 | 18:36 | 18:38 | 11:55 | 12:18 | 12:07 |
| Duration, hr | 0:30 | 1:00 | 1:00 | 0:30 | 1:00 | 1:00 |
| Location | ESPIn | SCRB In | Stack | ESPIn | SCRB In | Stack |
| Trap ID, no. | | | | | | |
| Vm, dL | 13.4 | 28.1 | 32.7 | 13.1 | 28.7 | 31.8 |
| Pb, in Hg | 29.53 | 29.53 | 29.53 | 29.59 | 29.59 | 29.59 |
| Elev corr, ft | 0 | 0 | 0 | 0 | 0 | 0 |
| Tm, °F | 102 | 105.9 | 90.6 | 88.2 | 95.6 | 89.1 |
| Cm | 0.999 | 0.976 | 0.994 | 0.999 | 0.976 | 0.994 |
| Moisture, % | 15.4 | 15.4 | 19.8 | 15.4 | 15.4 | 19.8 |
| $O_2$, % | 10.3 | 9.7 | 10.6 | 10.2 | 9.6 | 10.7 |
| Front Wool+Plug, ng | 38 | 0 | 0 | 0 | 0 | 0 |
| Sect 1, ng | 250 | 377 | 349 | 162 | 173 | 184 |
| Sect 2 w/Plug, ng | 1.7 | 0.2 | 13 | 2.5 | 0.7 | 3 |
| Back Plug, ng | 0 | 0 | 0 | 0 | 0 | 0 |
| Breakthrough, % | 0.68 | 0.05 | 3.72 | 1.54 | 0.40 | 1.63 |
| Vcorr, dNL | 12.4 | 25.3 | 30.8 | 12.5 | 26.3 | 30.1 |
| Hg, µg/dNm$^3$ | 20.3 | 14.9 | 11.8 | 13.2 | 6.6 | 6.2 |
| Hg($O_2$corr) at 3% $O_2$ | 34.1 | 23.8 | 20.4 | 22.0 | 10.4 | 10.9 |
| Hg(wet), µg/m$^3$ | 17.6 | 12.9 | 9.8 | 11.4 | 5.7 | 5.2 |

## Table C–4. Sorbent Trap Sample Data June 4

| Sample I.D. | SM-D6-ESP In-ST-1 | SM-D6-SCRB In-ST-1 |
|---|---|---|
| Date | 6/4/2008 | 6/4/2008 |
| Start Time | 11:10 | 10:49 |
| End Time | 11:40 | 11:49 |
| Duration, hr | 0:30 | 1:00 |
| Location | ESP In | SCRB In |
| Trap ID, no. | | |
| Vm, dL | 13.3 | 26.3 |
| Pb, in Hg | 29.35 | 29.35 |
| Elev corr, ft | 0 | 0 |
| Tm, °F | 90 | 90.9 |
| Cm | 0.999 | 0.976 |
| Moisture, % | 15.4 | 15.4 |
| $O_2$, % | 10.3 | 9.8 |
| Front Wool+Plug, ng | 54 | 0 |
| Sect 1, ng | 159 | 238 |
| Sect 2 w/Plug, ng | 1.7 | 0.6 |
| Back Plug, ng | 0 | 0 |
| Breakthrough, % | 1.07 | 0.25 |
| Vcorr, dNL | 12.5 | 24.1 |
| Hg, µg/dNm$^3$ | 12.8 | 9.9 |
| Hg($O_2$corr) at 3% $O_2$ | 21.6 | 15.9 |
| Hg(wet), µg/m$^3$ | 11.1 | 8.6 |

## Table C-5. OH Sample Data

| Sample I.D. | SM-D2-ESP In-OH-1 | SM-D2-STK-OH-1 |
|---|---|---|
| Date | 5/25/2008 | 5/25/2008 |
| Start Time | 14:00 | 13:34 |
| End Time | 15:00 | 15:04 |
| Duration, hr | 1:00 | 1:30 |
| HgP, µg/Nm$^3$ | | |
| Filter | 9.44 | 0.00 |
| $Hg^{2+}$, µg/Nm$^3$ | | |
| Probe Rinse | 3.50 | 0.02 |
| KCl | 12.37 | 1.60 |
| $Hg^0$, µg/Nm$^3$ | | |
| $H_2O_2$ | 0.24 | 0.23 |
| $KMnO_4$ | 3.90 | 13.03 |
| Total Hg, µg/Nm$^3$ | 29.45 | 14.89 |
| Total Hg at 3% $O_2$, µg/Nm$^3$ | 50.0 | 25.8 |

# APPENDIX D

# PLANT OPERATING DATA

## Plant Operating Data

Figure D-1 shows the generated megawatts (MW) for the duration of on-site activities. Figure D-2 shows the coal flow during the testing period. The coal flow varied based on fuel properties but was fairly consistent during the testing period. Figure D-3 shows the primary air and secondary air heater differential pressures. The pressures remained constant during the testing period. Figure D-4 plots the primary and secondary air heater temperatures. The inlet temperatures show a rise and fall in temperatures throughout the testing period. The maximum temperatures are in the afternoon of each day, which corresponds to ambient air temperature increase during the heating of the day. Figure D-5 is a stack plot which displays the stack gas flow, boiler $SO_2$, boiler $CO_2$, boiler CO, boiler $NO_x$, and boiler $O_2$ values during the testing period. The boiler $SO_2$ concentrations showed a significant amount of variability, with values ranging from approximately 1800–5000 ppm.

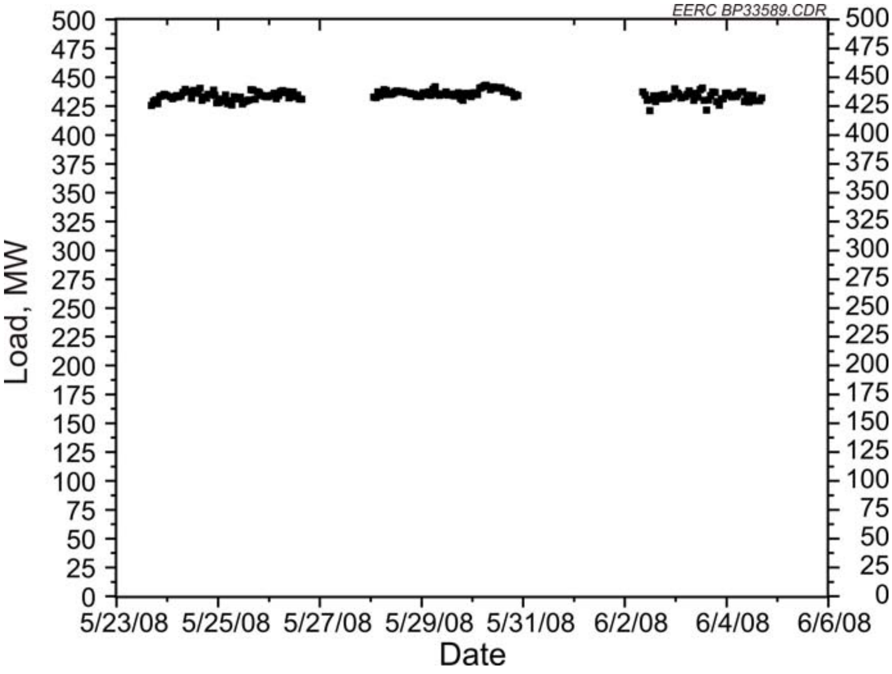


Figure D-1. Generated megawatts for Unit 1.

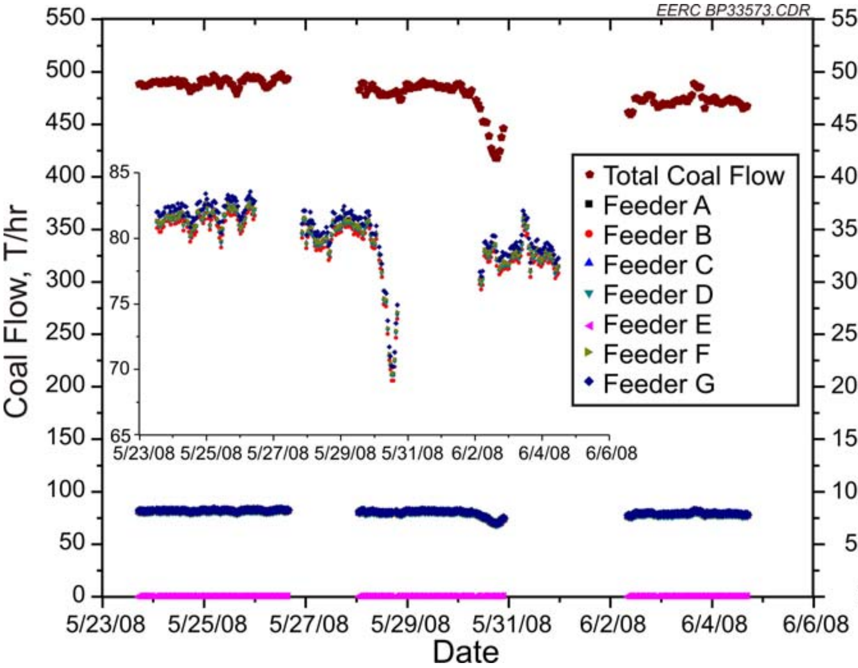


Figure D-2. Total and coal feeder flows. The inset shows the 65–85 T/hr region of the graph.

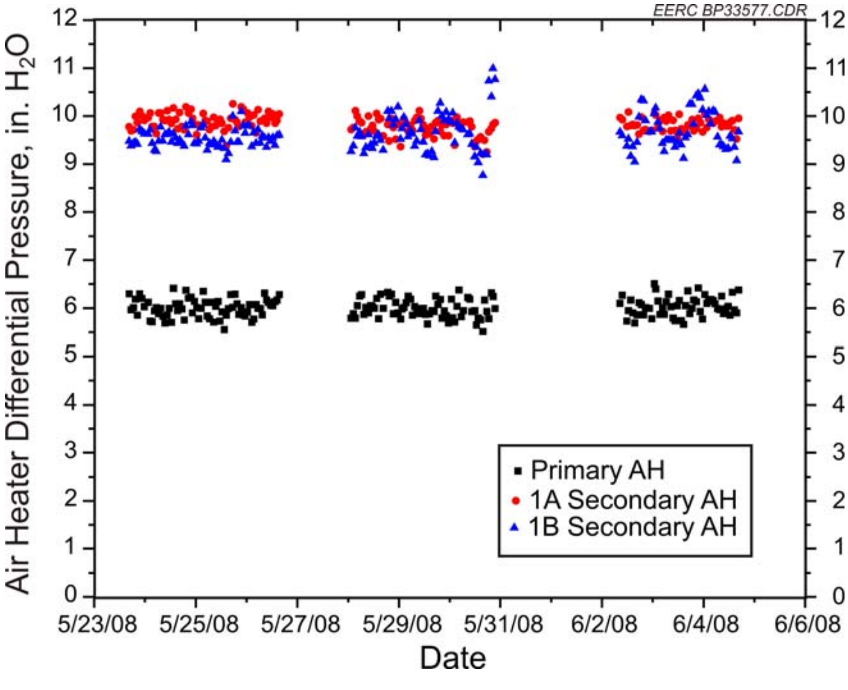


Figure D-3. Primary and secondary air heater differential pressures.

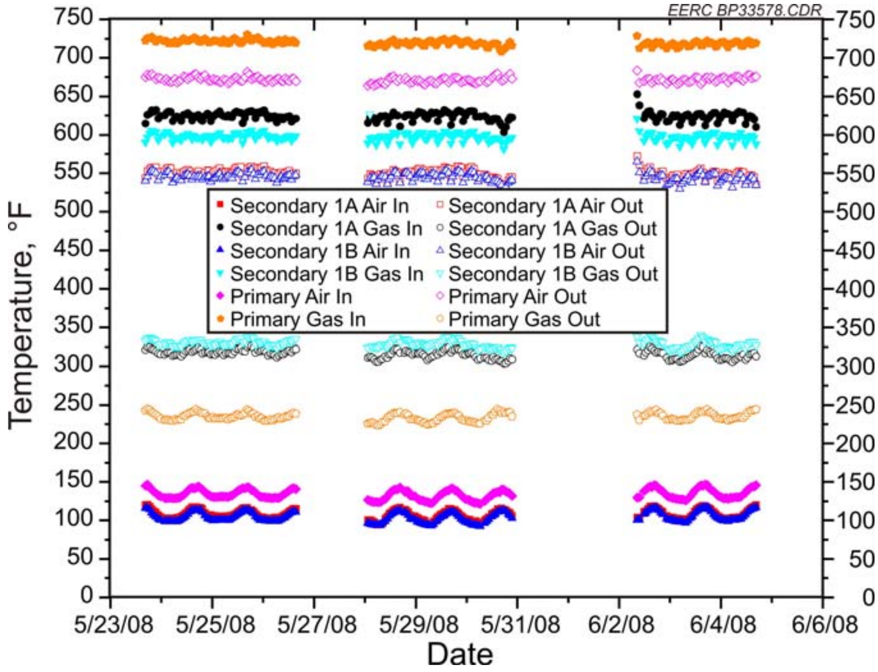


Figure D-4. Primary and secondary air heater temperatures.

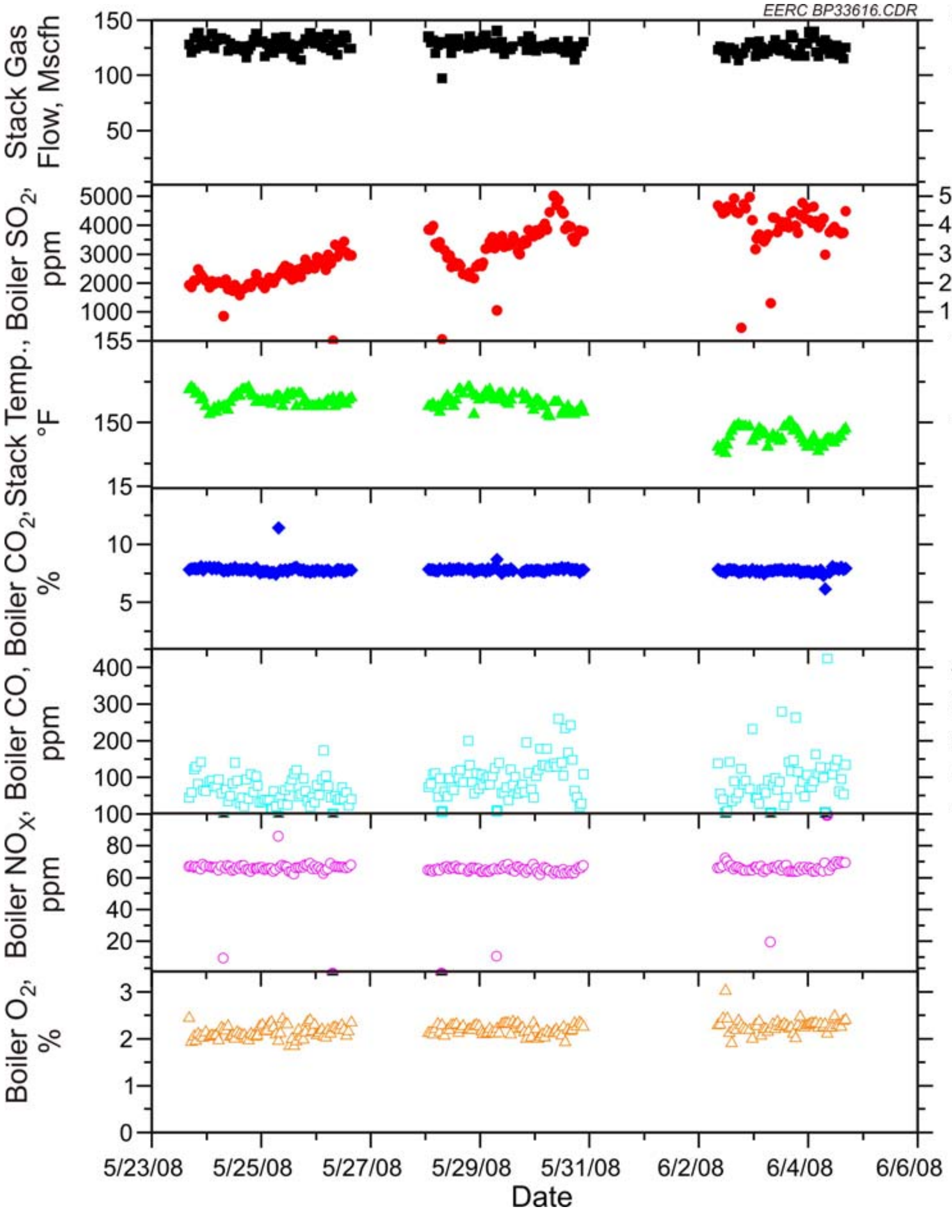


Figure D-5. Additional plant data logged during full-scale baseline and parametric testing.