MERCURY CONTROL TECHNOLOGIES FOR ELECTRIC UTILITIES BURNING SUBBITUMINOUS COALS

Final Report

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ABSTRACT

The applicability of potential sorbent injection technologies, sorbent enhancement additives (SEAs), elemental mercury (Hg^0) oxidation technologies, and coal pretreatment processes to improve the total mercury (Hg_{total}) removal efficiencies of air pollution control devices (APCDs) was evaluated using a pilot-scale (580-MJ/hr, 550,000-Btu/hr) pulverized coal-fired unit equipped with the following APCDs: an electrostatic precipitator (ESP), fabric filter (FF), ESP and FF (ESP–FF) (e.g., TOXECON®), spray dryer adsorber (SDA) and ESP (SDA–ESP), and SDA and FF (SDA–FF). Short-term ESP testing was also performed on a full-scale (140-MW) unit. The sorbent injection technologies evaluated included NORIT Americas Inc. DARCO® FGD, German carbon, Energy & Environmental Research Center (EERC)-treated carbon, sodium tetrasulfide (Na_2S_4), and ADA Technologies' Amended Silicate™. Two SEAs were evaluated: SEA1 ($CaCl_2$) and SEA2 (confidential EERC oxidizing agent). Solucorp Industries' Molecular Bonding System (MBS®) SDA additive and Washington University's titanium dioxide (TiO_2) injection in the presence of ultraviolet radiation were evaluated as Hg^0 oxidation technologies. Three coal pretreatment processes were tested: Demeter Systems' Inorganic Polymer Electret™ (IPE), Western Research Institute's (WRI's) thermally treated coal, and blending with chlorine-rich bituminous coal. The sorbent injection technologies, SEAs, Hg^0 oxidation additives, and coal pretreatments were evaluated separately, and most were also tested in combination. Caballo and Absaloka subbituminous coals, blends of these coals with Blacksville bituminous coal, and sponsor-treated Caballo coals were fired in the unit, while mercury species (Hg^0, gaseous inorganic mercuric compounds [Hg^{2+}], and fly ash particle-associated mercury [Hg_p]) concentrations were measured using ASTM International Method D6784-02 (Ontario Hydro method) and continuous mercury monitors at various APCD inlets and outlets to evaluate Hg_{total} removal performance. Several of the sorbents, Hg^0 oxidation additives, SEAs, and coal pretreatments, and combinations thereof, enhanced the Hg_{total} removal performance of the APCDs relative to the baseline Hg_{total} control strategy of activated carbon injection (ACI) alone. The relative performance of the pilot-scale APCDs to remove Hg_{total} from the coal combustion flue gases for a given control technology was generally: ESP < SDA–ESP ≈ SDA–FF < FF ≈ ESP–FF (e.g., TOXECON).

An Hg_{total} control cost analysis was performed for the DARCO FGD injection and/or SEA addition technologies for capturing Hg_{total} in an APCD. All estimated costs were based on 2004 U.S. dollars, assuming that a 500-MW subbituminous coal-fired plant was configured with an ESP, FF, ESP–FF (i.e., TOXECON), SDA–ESP, or SDA–FF. The most cost-effective approach for an ESP was the addition of SEA2 at 1.9 lb/MMacf, which resulted in about 70% Hg_{total} removal at an estimated cost of $2.97/kW, or $6967/lb of Hg removed. SEA2 addition upstream of an ESP met the project goal of achieving 50%–90% Hg_{total} removal at costs of one-half to three-quarters of those currently estimated for ACI (e.g., U.S. Department of Energy 2005 baseline cost estimate is $60,000/lb of Hg removed. The TOXECON technology was more cost-effective for Hg_{total} control relative to ACI combined with only a FF, assuming that the ESP ash could be sold. Additions of SEAs increased the costs of TOXECON Hg_{total} removal because they did not significantly improve Hg_{total} capture. SEA2 addition upstream of SDA–ESP and SDA–FF systems was estimated to cost

about $1.00/kW, or $4000/lb Hg, and provide similar Hg_{total} removal efficiencies, 45%–50%, at less cost as those achieved with ACI. SEA2 and SEA1 additions combined with ACI significantly improved SDA–ESP and SDA–FF Hg_{total} capture to 80%–90% and reduced control costs on a per-pound-of-Hg-removed basis relative to ACI alone.

Flue gas sampling using a U.S. Environmental Protection Agency (EPA) Method 29 multimetals train and EPA–Southern Research Institute five-stage cyclone and a fly ash leaching evaluation using ASTM Method D3987-85 were performed to determine the effects of SEAs on trace element gas–particle partitioning, particle-size distributions, and fly ash mobility (i.e., leachability). Fly ashes produced during three test conditions were evaluated: 1) baseline Caballo coal combustion, 2) Caballo coal combustion during SEA1 addition, and 3) Caballo coal combustion during SEA2 addition. The concentrations of ten trace elements (As, Be, Cd, Co, Cr, Mn, Ni, Pb, Sb, and Se) in flue gas, ESP fly ash, and size-fractioned fly ash samples did not vary significantly among the three test conditions. Trace element leaching results were similar, in that for all conditions and leaching periods, trace element concentrations were below regulatory disposal limits. In summary, SEA injections did not significantly affect trace element gas–particle partitioning, particle-size distributions, or fly ash mobility.

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LIST OF ABBREVIATIONS/ACRONYMS

ACI	activated carbon injection
acfm	actual cubic foot per minute
acmm	actual cubic meter per minute
AES	atomic emission spectroscopy
APCD	air pollution control device
APS `	aerodynamic particle sizer
ASTM	ASTM International (formerly American Society for Testing and Materials)
CAIR	Clear Air Interstate Rule
CEM	continuous emission monitor
CMM	continuous mercury monitor
CVAAS	cold-vapor atomic absorption spectroscopy
d	dry
DOE	U.S. Department of Energy
dscm	dry standard cubic meter
EERC	Energy & Environmental Research Center
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ESP	electrostatic precipitator
FF	fabric filter
FGD	flue gas desulfurization
GFAAS	graphite furnace atomic absorption spectroscopy
HAP	hazardous air pollutant
Hg	mercury
Hg^0	gaseous elemental mercury
Hg^{2+}	gaseous inorganic mercuric compounds
Hg_p	particle-associated mercury
Hg_{total}	total mercury, for Ontario Hydro measurements it includes: Hg^0, Hg^{2+}, and Hg(p), whereas for CMM measurements it includes Hg^0 and Hg^{2+}
HHV	higher heating value
ICP	inductively coupled plasma
ICR	information collection request
i.d.	inside diameter
IGCC	integrated gasification combined cycle
IPE	Inorganic Polymer Electret™
IR	infrared
kg	kilogram
lb	pound (0.454 kg)
LOI	loss on ignition
MBS®	Molecular Bonding System
MMacf	million actual cubic feet
MS	mass spectroscopy
MVD	median volume diameter
NETL	National Energy Technology Laboratory

Nm^3	normal cubic meter (dry, 20°C, 3% O_2, at 1 atm)
OH	Ontario Hydro
PAC	powdered activated carbon
pc	pulverized coal
PCD	particulate control device
ppm	parts per million
ppmv	parts per million by volume
PRB	Powder River Basin
PSD	particle-size distribution
PTC	particulate test combustor
QA/QC	quality assurance/quality control
SCR	selective catalytic reduction
SDA	spray dryer absorber
SEA	sorbent enhancement additive
SRI	Southern Research Institute
TOXECON®	An EPRI Hg control technology involving the injection of activated carbon between an ESP and FF
µg	microgram
UV	ultraviolet
WRI	Western Research Institute

MERCURY CONTROL TECHNOLOGIES FOR ELECTRIC UTILITIES BURNING SUBBITUMINOUS COALS

EXECUTIVE SUMMARY

The Energy & Environmental Research Center (EERC) developed a practically oriented, applied research consortium project to test cost-effective mercury (Hg) control technologies for utilities burning subbituminous coals. The project sponsors included the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL), Alliant Energy Corporation, Ameren UE, American Electric Power, Babcock Power Environmental Inc., Babcock & Wilcox Company, Basin Electric Power Cooperative, Demeter Systems LLC, DTE Energy Corporation, Electric Power Research Institute (EPRI), Ontario Power/Kinectrics Inc., Peabody Energy, Solucorp Industries Ltd., Western Research Institute (WRI), and Westmoreland Coal Company. The project goal was to test innovative Hg control technologies that have the potential to reduce total mercury (Hg_{total}) emissions from subbituminous coal-fired power plants by 50% to 90% at costs of one-half to three-quarters of current estimates for activated carbon injection (ACI). Hg_{total} includes gaseous elemental mercury (Hg^0), gaseous inorganic mercuric compounds (Hg^{2+}), and fly ash particle-associated mercury (Hg_p).

Testing was performed using the EERC's particulate test combustor (PTC). The PTC was fired on pulverized coal (pc) at 580 MJ/hr (550,000 Btu/hr) to produce a particulate-laden flue gas stream. The PTC was configured with various air pollution control devices (APCDs), including an electrostatic precipitator (ESP), fabric filter (FF), ESP and FF (ESP–FF), spray dryer absorber (SDA) with an ESP (SDA–ESP), and SDA with a FF (SDA–FF). Short-term ESP testing was also performed on a full-scale (140-MW) unit. In general, the Hg_{total} control technologies investigated as part of this project included Hg^0 oxidation additives, sorbent enhancement additives (SEAs), precombustion thermal treatment of coal, blending with chlorine-rich bituminous coal, sorbent injection, and coal pretreatment processes. Injecting a sorbent downstream from an ESP and upstream of a FF is a technology configuration that has been used by ALSTOM under the designation Filsorption in Europe for Hg_{total} control in waste-to-energy plants and is patented by EPRI in the United States as TOXECON® for controlling Hg_{total} in power plants. The Hg_{total} control technologies that were evaluated are summarized in Table ES-1.

Two Powder River Basin (PRB) subbituminous coals from the Caballo and Absaloka Mines and a bituminous coal from the Blacksville No. 2 Mine were used in evaluating Hg_{total} control. General information on the three coals is presented in Table ES-2. Average Hg concentrations in the Caballo, Absaloka, and Blacksville coals were 0.112, 0.042, and 0.072 ppm on a dry basis, respectively. Chlorine concentrations in the Caballo, Absaloka, and Blacksville coals were 25, 6, and 961 ppm on a dry basis, respectively. ASTM International Method D6784-02 (Ontario Hydro [OH]) and continuous mercury monitoring (CMM) results for the Caballo, Absaloka, Caballo–Blacksville, and Absaloka–Blacksville coal combustion flue gases indicated that although the Hg_{total} concentrations varied from about 4 to 13 $\mu g/Nm^3$, the relative proportions of Hg^0, Hg^{2+}, and Hg_p in the flue gases were similar at >70%, <30%, and <1%, respectively.

Table ES-1. Potential Hg_{total} Reduction Technologies

Sorbent Injection Technologies
NORIT Americas Inc. DARCO® FGD
EERC-treated carbon
Alternative (German) carbon
Sodium tetrasulfide (Na_2S_4)
ADA Technologies Amended Silicate™
Hg^0 Oxidation Technologies
Washington University TiO_2 injection–ultraviolet (UV) radiation
Solucorp Industries Ltd. Molecular Bonding System (MBS®)
Coal Pretreatment Processes
Demeter Systems LLC Inorganic Polymer Electret™ (IPE)
WRI thermally treated coal
Blending with chlorine-rich bituminous coal
Sorbent Enhancement Additives
SEA1 addition – $CaCl_2$
SEA2 addition – Confidential EERC oxidizing agent

Table ES-2. Coal Information

Organization	Mine	Seams Mined	Location	Mine Production,[a] tons
Caballo Coal Co.	Caballo	Smith/Wyodak–Anderson	PRB, Wyoming	25,967,000
Washington Group International	Absaloka	Rosebud–McKay/McKay	PRB, Montana	5,283,532
Consol Energy Inc.	Blacksville No. 2	Pittsburgh	Northern Appalachia, Pennsylvania	4,816,887

[a] *Keystone Coal Industry Manual*; Mining Media: Prairieville, LA, 2004.

ESP Mercury Control Options

Controlling Hg emissions with an ESP was the most challenging of the APCDs tested. DARCO FGD injection provided an ESP Hg_{total} removal of ~50% at a reasonable injection rate of about 5 lb/MMacf. An alternative German carbon provided similar performance. SEA1 addition combined with ACI increased ESP Hg_{total} removal to approximately 60%. Blending with a high-chlorine-content bituminous coal combined with ACI produced results comparable to SEA1 injection, along with the benefit of introducing a higher-heating-value (HHV) fuel. A promising control option was SEA2 addition, which resulted in 70% ESP Hg_{total} removal. Similar removal results occurred during a short-term full-scale (140-MW) test involving SEA2 additions. SEA2 additions combined with ACI at 2.9 lb/MMacf increased Hg_{total} removals to >80%.

The WRI-treated coal combined with moderate DARCO FGD injections (2.5 lb/MMacf) performed the best, with a combined Hg_{total} removal (sum of coal pretreatment removal and ACI

capture) of 84%. EERC-treated carbon injection at 4.8 lb/MMacf resulted in an ESP Hg_{total} removal of 63%. The Amended Silicate, Na_2S_4, and TiO_2–UV technologies provided ESP Hg_{total} removals of <40%. These methods may be improved, but they are currently not viable Hg_{total} control technologies for an ESP.

ESP–FF Mercury Control Options

An ESP–FF system provided the best conditions of the APCDs tested for controlling Hg_{total} emissions. DARCO FGD injection using the TOXECON process provided a high Hg_{total} removal, 90%, at a reasonable injection rate of 4 lb/MMacf. SEA1 or SEA2 addition combined with ACI did not significantly increase the high removal efficiencies attained through ACI alone. Blending high-chlorine-containing Blacksville bituminous coal with Caballo subbituminous coal did not improve ESP–FF Hg_{total} capture and may have actually hindered Hg_{total} removal when combined with ACI. ACI at 1.3 lb/MMacf into WRI-treated Caballo coal combustion flue gas resulted in 80% Hg_{total} removal. When the Hg removed by the WRI coal pretreatment process is included, 93% removal was achieved. EERC-treated carbon injection at about 5 lb/MMacf into Demeter Systems-treated Caballo coal combustion flue gas enhanced TOXECON Hg_{total} capture to 87%; however, the EERC-treated carbon was not as effective as DARCO FGD at similar injection rates. The Demeter Systems coal treatment process resulted in >90% SO_2 capture in the ESP–FF.

FF Mercury Control Options

The Hg_{total} emission control attained with a FF was similar to that achieved with TOXECON. DARCO FGD injections at 2.5 and ~5 lb/MMacf provided 75% to 80% Hg_{total} removal efficiencies. The additional ash collected on the filter bags because of the absence of an ESP did not seem to hinder carbon–Hg_{total} adsorption. Blending Caballo subbituminous coal with high-chlorine-containing Blacksville bituminous coal did not significantly improve FF Hg_{total} removal in the presence of ACI.

SDA–ESP Mercury Control Options

The Hg_{total} control performance of the SDA–ESP was intermediate relative to the ESP and ESP–FF systems. DARCO FGD injection provided a removal efficiency of ~50% at a reasonable injection rate of ~5 lb/MMacf. SEA1 additions combined with ACI resulted in high Hg_{total} removals of 85%. SEA2 addition at relatively low rates of 0.2 and 0.5 lb/MMacf resulted in SDA–ESP Hg_{total} removal efficiencies of about 40% and 50%, respectively. SEA2 combined with DARCO FGD injections at 0.05 and 3.9 lb/MMacf achieved 80%–90% Hg_{total} removal. SEA2 addition combined with ACI was the most promising SDA–ESP control option tested.

SDA–FF Mercury Control Options

SDA–FF Hg_{total} removal performance was intermediate to that achieved with the ESP and ESP–FF and similar to the SDA–ESP. SEA1 addition at about 5 lb/MMacf combined with DARCO FGD injection at about 2 lb/MMacf enhanced SDA–FF Hg_{total} removal performance to 80%. SEA2 addition alone provided a SDA–FF Hg_{total} removal of about 40%, but when combined with ACI at relatively low rates of 0.1 and 1.9 lb/MMacf achieved 90% removal. The Amended Silicate and

Na_2S_4 injections did not significantly improve Hg_{total} capture. The WRI-treated coal also resulted in low SDA–FF Hg_{total} removal performance, but WRI's pretreatment process removed 64% of the Hg in Caballo coal. The Solucorp Industries SDA additive, MBS, slightly improved SDA–FF Hg_{total} capture when the flue gas flow rate to the SDA was reduced by 50%. System limitations inhibited an evaluation of MBS at longer SDA residence times. SEA2 addition combined with ACI was the most promising control option, achieving high removals at moderate injection rates. The Solucorp Industries SDA additive was promising, but further testing at longer SDA residence times should be performed to demonstrate the maximum Hg_{total} removal possible with this technology.

Cost Analysis of Controlling Mercury Emissions Using DARCO FGD Injection and/or SEA Addition

A Hg_{total} control cost analysis was performed for the DARCO FGD injection and/or SEA addition technologies for capturing Hg_{total} in an ESP, FF, ESP–FF (i.e., TOXECON), SDA–ESP, and SDA–FF. Although other emerging technologies, such as WRI's thermal coal treatment and EERC-treated carbon injection, were also effective in controlling Hg_{total} emissions, a cost analysis for implementing these technologies was not performed because of a lack of economic information. All estimated costs were based on 2004 U.S. dollars, assuming that a 500-MW subbituminous coal-fired plant was configured with an ESP, FF, ESP–FF, SDA–ESP, or SDA–FF.

ESP Hg Control Cost Estimate

The most cost-effective approach for an ESP was the addition of SEA2 at 1.9 lb/MMacf, which resulted in about 70% Hg_{total} removal at an estimated cost of $2.97/kW, or $6967/lb of Hg. SEA2 addition is also advantageous because it should not affect fly ash salability. SEA2 addition upstream of an ESP met the project goal of achieving 50%–90% Hg_{total} removal at costs of one-half to three-quarters of those currently estimated for ACI.

FF and TOXECON Hg Control Cost Estimates

The TOXECON technology was more cost-effective for Hg_{total} control relative to ACI combined with only a FF, assuming that the ESP ash can be sold. Additions of SEAs increased the costs of TOXECON Hg_{total} removal because they did not significantly improve Hg_{total} capture.

SDA–ESP and SDA–FF Hg Control Cost Estimates

SEA2 addition upstream of SDA–ESP and SDA–FF systems was estimated to cost about $1.00/kW, or $4000/lb of Hg, and provided similar Hg_{total} removal efficiencies, 45%–50%, at less cost than those achieved with ACI. SEA2 and SEA1 additions combined with ACI significantly improved SDA–ESP and SDA–FF Hg_{total} capture to 80%–90% and reduced control costs on a per-pound-of-Hg-removed basis relative to ACI alone.

Comparison of Pilot- and Full-Scale Testing

To evaluate the reliability and applicability of the pilot-scale testing approach used to evaluate Hg_{total} control technologies, test results obtained on the PTC equipped with an ESP were compared

with results obtained on a full-scale pc-fired boiler also equipped with an ESP. The lignite coal fired in both units was from the same mine. The Hg_{total} control technology tested in both the pilot- and full-scale units included DARCO FGD injections upstream of the ESP and combined ACIs with SEA1 additions. Test results for corresponding conditions performed on the PTC and full-scale unit compared favorably, as illustrated in Figure ES-1.

Effects of SEA Addition on Trace Element Gas–Fly Ash Partitioning and Fly Ash Mobility

A U.S. Environemntal Protection Agency (EPA) Method 29 multimetals train and anEPA–Southern Research Institute (SRI) five-stage cyclone were used to collect gaseous and size-fractioned fly ash samples, respectively, to determine the effects of SEA additions on trace element gas–particle partitioning and particle-size distributions. In addition, the mobility (i.e., leachability) of trace elements in fly ashes was evaluated using ASTM Method D3987-85. Fly ashes produced during three test conditions were evaluated: 1) baseline Caballo coal combustion, 2) Caballo coal combustion during SEA1 addition, and 3) Caballo coal combustion during SEA2 addition. The concentrations of ten trace elements (As, Be, Cd, Co, Cr, Mn, Ni, Pb, Sb, and Se) in flue gas, ESP fly ash, and size-fractionated fly ash samples did not vary significantly among the three test conditions.

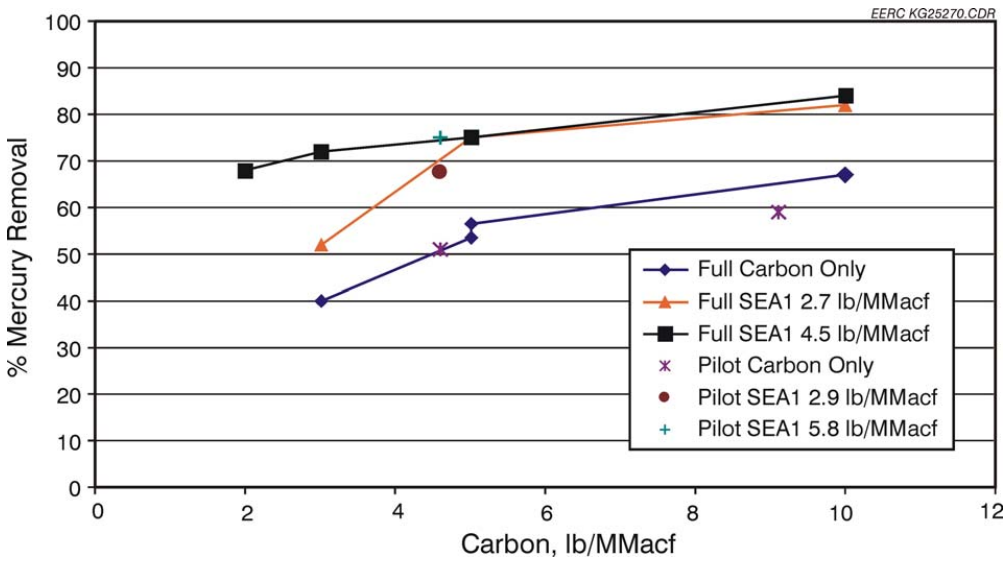


Figure ES-1. Comparison of ESP Hg_{total} removal efficiencies obtained on the pilot-scale PTC and a utility-scale unit during combustion of the same lignite coal.

The majority of trace elements in the flue gases were associated with fly ash particles. In addition to chemical composition, the three fly ash particle-size distributions (PSDs) were very similar, and most of the mass, ~75%, occurred in the coarser, ~7.3-µm, fraction. Trace element leaching results for fly ashes produced during baseline Caballo coal combustion testing and the additions of SEA1 and SEA2 were similar, in that for all conditions and leaching periods, trace element concentrations were below regulatory limits for disposal. In summary, SEAs did not significantly affect trace element gas–particle partitioning, PSDs, or fly ash mobility.

MERCURY CONTROL TECHNOLOGIES FOR ELECTRIC UTILITIES BURNING SUBBITUMINOUS COALS

1.0 INTRODUCTION

The Energy & Environmental Research Center (EERC) developed a practically oriented, applied research consortium project to test cost-effective mercury (Hg) control technologies for utilities burning subbituminous coals. This project was developed in response to the U.S. Environmental Protection Agency (EPA) decision to regulate Hg from utility power plants. EPA based its decision on health, emissions, and scientific data. U.S. power plants burning subbituminous coals generally release greater proportions of elemental mercury (Hg^0) than those burning bituminous coals. Hg^0 is the most difficult chemical species of Hg to remove from flue gas and, therefore, requires an innovative Hg control approach.

The project goal was to test innovative Hg control technologies that could potentially reduce Hg emissions from subbituminous-fired power plants by 50% to 90% at costs of one-half to three-quarters of current estimates (e.g., the U.S. Department of Energy [DOE] 2005 baseline cost estimate is $60,000/lb of Hg removed). Testing was performed using the EERC's particulate test combustor (PTC). Pulverized subbituminous coals were fired in the PTC at 580 MJ/hr (550,000 Btu/hr) to produce particulate-laden flue gas streams. The PTC was configured with various air pollution control devices (APCDs) to simulate configurations of interest to the project sponsors. The APCDs tested included electrostatic precipitators (ESPs), fabric filters (FFs), ESPs and FFs (ESP–FFs), and spray dryer absorbers (SDAs) with an ESP (SDA–ESPs) or a FF (SDA–FFs). Hg removal technologies investigated as part of this project included Hg^0 oxidation agents, activated carbon injection (ACI), sorbent injection, addition of sorbent enhancement agents (SEAs), coal blending, and coal pretreatment. The most promising Hg^0 oxidation agents were added to various coals or a lime slurry in a SDA or injected upstream of an APCD. Potential Hg sorbents were injected upstream of an ESP, FF, in between an ESP and FF, and in between a SDA and ESP or FF. Sorbent injection downstream from an ESP and upstream of a FF has been used by ALSTOM under the designation Filsorption in Europe for controlling Hg emissions from waste-to-energy plants and is patented by the Electric Power Research Institute (EPRI) in the United States as TOXECON® for controlling Hg from power plants.

2.0 BACKGROUND

2.1 Mercury Regulations

In December 2000, EPA decided that the regulation of Hg from coal-fired electric utility steam-generating units was appropriate and necessary under Section 112 of the Clean Air Act (1). EPA determined that Hg emissions from power plants pose significant hazards to public health and must be reduced. The EPA *Mercury Study Report to Congress* (1997) (2) and the *Utility Hazardous Air Pollutant Report to Congress* (1998) (3) both identified coal-fired boilers as the largest single category of atmospheric Hg emissions in the United States, accounting for about one-third of the total anthropogenic emissions.

On March 15, 2005, EPA issued the first-ever federal rule to permanently cap and reduce Hg emissions from coal-fired power plants (a power plant is defined as an electrical generating facility that provides >25 MW_e). The rule is a market-based cap-and-trade program (Section 111 of the Clean Air Act) that is similar to the program in place for SO_2. The rule is to be administered in two phases. The first phase places a cap of 38 tons of mercury beginning in 2010. The second phase sets a final cap of 15 tons by 2018. Currently, the estimate of total mercury (Hg_{total}) emitted from coal-fired power plants is 48 tons; therefore, the 2010 and 2018 reductions are 21% and 69%, respectively.

With the implementation in March 2005 of the Clear Air Interstate Rule (CAIR) to reduce emissions of SO_2 and NO_x in the eastern 28 states, it is expected that the initial phase of the Clean Air Mercury Rule will be met as a cobenefit from the additional wet scrubbers and selective catalytic reduction (SCR) systems that will be installed. However, a cap of 15 tons will require additional mercury-specific controls at many power plants.

For trading purposes, EPA established allocations for each state, the District of Columbia, and Indian Reservations based on their share of the total heat input from coal. These were then adjusted to reflect coal rank and existing air pollution control equipment. For allocation purposes, coals were subcategorized as bituminous, subbituminous, lignite, integrated gasification combined cycle (IGCC), and coal refuse. The total state allocations from 2010 to 2017 are 38 tons and from 2018 and thereafter 15 tons. Each state will decide whether to participate in the trading program.

In addition to the cap-and-trade program, new coal-fired sources will have additional mercury requirements as part of the New Source Performance Standard. The requirements were subcategorized as follows:

- Bituminous units – 21×10^{-6} lb/MWh
- Subbituminous units
  - Wet flue gas desulfurization (FGD) – 42×10^{-6} lb/MWh
  - Dry FGD – 78×10^{-6} lb/MWh
- Lignite units – 145×10^{-6} lb/MWh
- IGCC units – 20×10^{-6} lb/MWh
- Coal refuse units – 1.4×10^{-6} lb/MWh

2.2 Mercury Is a Health Concern

Mercury is a neurological toxin that can cause impairment of mental, sensory, and motor functions in humans, particularly in developing fetuses and children. A congressionally mandated reassessment of the toxicological effects of Hg issued by the National Research Council (1) in August 2000 reaffirmed EPA's low Hg exposure reference dose of 0.1 µg/kg per day as the scientifically justifiable level for the protection of child-bearing women, based on quantifiable findings for low-dose exposure in a large-study population in the Faroe Islands. Prompted by these health concerns, Hg is the chemical contaminant responsible, at least in part, for the issuance of approximately 2000 fish consumption advisories. Almost 68% of all advisories issued in the United States are a result of Hg contamination in fish and shellfish. Freshwater lake advisories have more than doubled in the last 5 years, resulting in over 40 states that have issued fish advisories because of Hg. Furthermore, recently the Food and Drug Administration issued an advisory limiting consumption of certain ocean fish.

2.3 Mercury Emissions from Low-Rank Coals Will Be Difficult to Control

Mercury emissions from utilities burning U.S. coals were determined under EPA's information collection request (ICR), which mandated Hg and chlorine analyses on coal shipped to units larger than 25 MW_e during 1999 and emissions testing on 84 units selected to represent different categories of air pollution control equipment and coal rank. As shown in Table 2-1, subbituminous coals from the western United States, on average, contain significantly lower concentrations of Hg, chlorine, and sulfur than bituminous coals from the eastern U.S., Appalachian, or interior regions.

Western subbituminous coal and lignite are also distinguished by their much higher alkaline earth metal (i.e., magnesium and calcium) contents. Gulf Coast lignites resemble eastern bituminous coals in their high concentrations of Hg and iron, but are similar to western coals in regard to low chlorine and high calcium contents. These compositional differences not only affect the quantities and chemical species of Hg emitted from a boiler but also the effectiveness of different control technologies to remove Hg from flue gas. As indicated by ICR data in Table 2-1, western coals contain about half as much Hg on a weight basis; however, the ICR data in Table 2-2 indicate that they emit almost twice as much Hg.

In general, currently installed ESPs, dry scrubbers, and wet scrubbers do not effectively control Hg emissions from subbituminous coal-fired power plants (4). The lack of Hg control is primarily attributable to the high proportions of Hg^0 present in subbituminous coal combustion flue gases. In pulverized and cyclone subbituminous coal-fired units, Hg^0 generally comprises >85% of the Hg_{total} emissions that average 5.7 lb/10^{12}Btu (4, 5).

In general, subbituminous coals are characterized by their relatively high oxygen, moisture, and alkali and alkaline-earth elemental concentrations and low chlorine contents. Based on the ICR data, Powder River Basin (PRB) coals produce as much as 6 lb Hg/10^{12}Btu compared to 8 lb Hg/10^{12}Btu for North Dakota lignites, 6.5 lb Hg/10^{12}Btu for Illinois Basin bituminous coals, 9.5 lb Hg/10^{12}Btu for Appalachian bituminous coals, and 12.5 lb Hg/10^{12}Btu for Gulf Coast lignites (4). Coal composition has a major impact on the quantity and chemical form of Hg in the flue gas and, as

Table 2-1. Average Coal Compositions and Heating Values from a Select Group of ICR Data, on a dry basis

Parameter	Eastern Appalachian	Western Subbituminous
Hg, ppm	0.126	0.068
Cl, ppm	1064	124
S, wt%	1.67	0.48
Ash, wt%	11.65	7.92
Ca, ppm	2700	14,000
HHV[a], Btu/lb	12,900	9300
Moisture, wt%	2.5	19.4

[a] Higher heating value.

Table 2-2. Mercury Emissions Based on ICR Data

Parameter	Eastern Bituminous	Western Subbituminous
Coal burned, % of U.S.	55	35
Uncontrolled Hg Emissions, lb/10^{12}Btu*	7	5.7
Av Hg Stack Emission, lb/10^{12}Btu*	2.6	4.6
Av Removal, %*	63	20
Particulate Hg Leaving Stack, lb/10^{12}Btu*	0.4	0
Hg^{2+} Leaving Stack, lb/10^{12}Btu*	1.2	0.6
Hg^{0} Leaving Stack, lb/10^{12}Btu*	1	4

* Data presented are based on a total of 81 plants from the ICR sorted by coal region and categorized as eastern and western coals. Note, some plants did not supply adequate information as to the origin of their coal and were not considered.

a result, the effectiveness of APCDs to remove Hg from flue gas. Coals containing greater than about 200 ppm chlorine produce flue gases that are dominated by the more easily removable mercuric compounds (Hg^{2+}), most likely mercuric chloride ($HgCl_2$). Appalachian and Illinois Basin bituminous coals generally have >200 ppm chlorine. Conversely, low-chlorine (<50-ppm) subbituminous and lignite coal combustion flue gases contain predominantly Hg^0, which is substantially more difficult to remove than Hg^{2+} (6). Additionally, the abundance of calcium in subbituminous coal fly ashes may reduce the oxidizing effect of the already low chlorine content by reactively scavenging chlorine species (Cl, HCl, and Cl_2) from the combustion flue gas.

2.4 Mercury Control Options

Options for controlling Hg_{total} emissions are being investigated that have the potential to attain >90% removal of Hg_{total} from flue gas. ICR data and other test data of Hg_{total} control for lignite and

subbituminous coal-fired systems indicate that low Hg^0 reactivity poses technical and economic challenges and that innovative Hg^0 control technologies are needed for subbituminous coals. Hg_{total} control strategies at subbituminous coal-fired power plants have primarily focused on enhancing existing control technologies, while investigating and developing new control technologies is secondary. The strategies include sorbent injection with and without SEAs upstream of an ESP or FF and Hg^0 oxidation upstream of a wet or dry FGD system. New technologies being investigated include Hg_{total} capture using the *Advanced Hybrid ™* filter, gold-coated materials, baghouse inserts, and carbon beds (7). In addition to the postcombustion Hg_{total} control technologies under development, Western Research Institute's (WRI's) precombustion thermal treatment of coal aims at removing a substantial portion of the Hg before the coal is processed for feeding into the combustor.

2.4.1 Activated Carbon Injection

Many potential Hg sorbents have been evaluated (4). These evaluations have demonstrated that the chemical speciation of Hg controls its capture mechanism and ultimate environmental fate. ACI is the most tested technology available for Hg_{total} control. Activated carbons have the potential to effectively adsorb Hg^0 and Hg^{2+}, depending on the carbon characteristics and flue gas composition (4). Most activated carbon research has been performed in fixed-bed reactors that simulate relatively long-residence-time (gas–solid contact times of minutes or hours) Hg_{total} capture by a FF filter cake (8–10). However, it is important to investigate short-residence-time (seconds) in-flight capture of Hg^0 because most of the coal-burning boilers in the United States employ cold-side ESPs for controlling particulate matter emissions.

The projected annual cost for activated carbon adsorption of Hg in a duct injection system is significant. Carbon-to-mercury weight ratios of 3000–18,000 (lb carbon injected/lb Hg in flue gas) have been estimated to achieve 90% Hg_{total} removal from a coal combustion flue gas containing 10 $\mu g/Nm^3$ of Hg_{total} (11). More efficient carbon-based sorbents are required to enable lower carbon-to-mercury weight ratios to be used, thus reducing the costs.

EERC pilot-scale ESP and ESP–FF Hg removal efficiencies for Fort Union lignite coal combustion flue gases from Saskatchewan and North Dakota are compared in Figures 2-1 and 2-2 to those obtained at full-scale utility boilers while injecting activated carbons into a bituminous coal combustion flue gas upstream of a TOXECON (pulse-jet FF) and into bituminous and PRB subbituminous coal combustion flue gases upstream of an ESP. As indicated in Figures 2-1 and 2-2, coal type (i.e., composition) was an important parameter that affected the Hg_{total} removal efficiency of a control device. During the pilot-scale lignite and utility-scale eastern bituminous coal tests, Hg_{total} removal efficiencies increased with increasing ACI rates. Conversely, Hg_{total} removal efficiencies were never greater than 70%, regardless of the ACI rate into the PRB subbituminous coal combustion flue gas. This limitation is probably caused by the low amount of acidic flue gas constituents, such as HCl, that promote Hg-activated carbon reactivity.

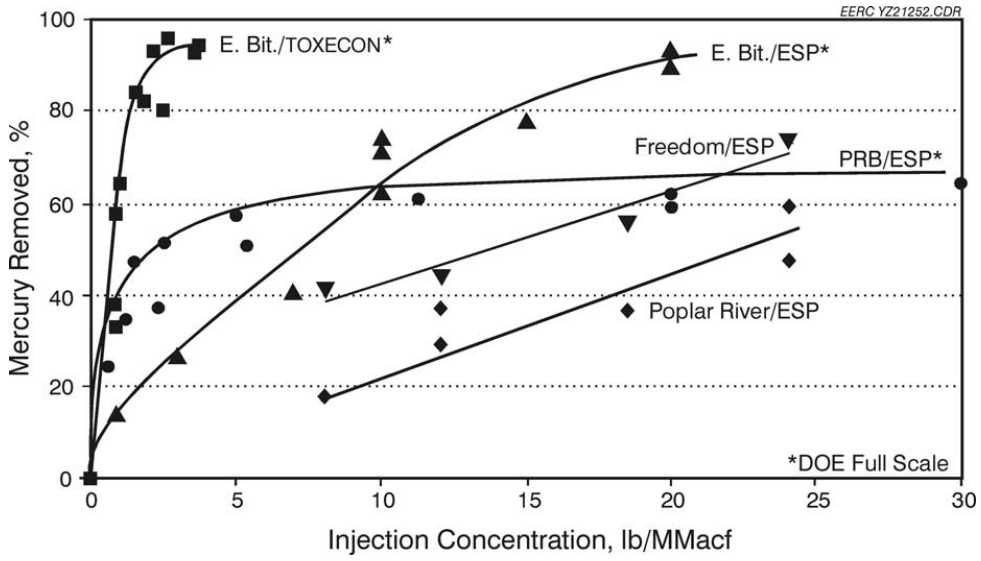


Figure 2-1. Pilot-scale ESP (11) and full-scale ESP (12) Hg_{total} removal efficiencies as a function of ACI rate.

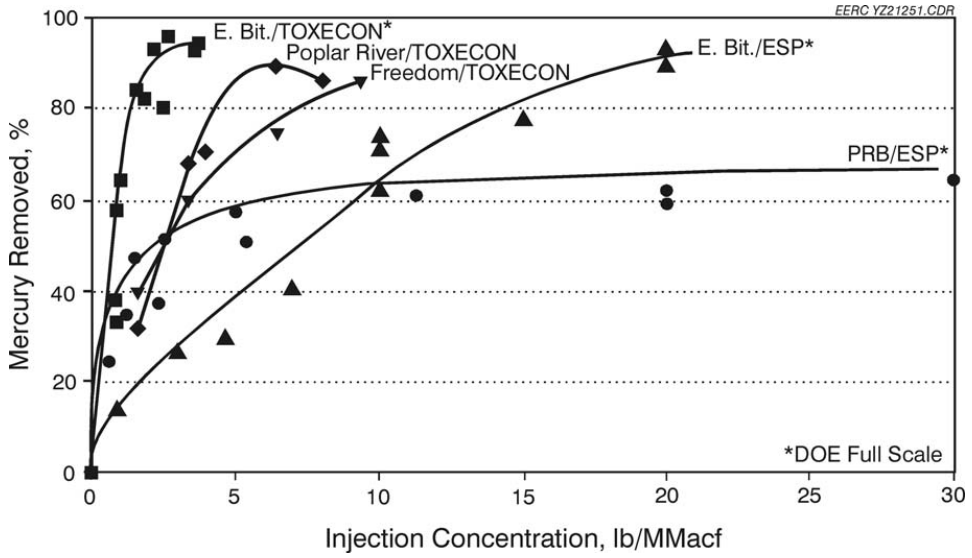


Figure 2-2. Pilot-scale ESP–FF (11) and full-scale TOXECON and ESP (12) Hg_{total} removal efficiencies as a function of ACI rate.

Testing at a power plant firing Fort Union lignite and equipped with a SDA–FF indicated that DARCO FGD and lignite-derived ACIs resulted in Hg_{total} removal efficiencies of <35% (13). The poor performance of ACI was probably the result of low-acid-gas concentrations and high proportion of Hg^0 in the flue gas. An iodine-impregnated activated carbon, however, captured approximately 90% of the Hg_{total}.

Researchers at the EERC and elsewhere are striving to attain a better understanding of Hg species reactions on activated carbon surfaces in order to produce more efficient sorbents. Functional groups containing inorganic elements such as chlorine or sulfur probably have a significant role in bonding Hg (14–16). Recently, detailed analyses of sorbents derived from lignites exposed to flue gas and Hg^0 indicated the key species impacting oxidation and retention of Hg on the carbon surface were chlorine and sulfur (17, 18). Chlorine reacted to form organically associated chlorine on the carbon surface. The organically associated chlorine provided an important site for Hg^{2+} bonding.

Amended Silicate™ injection shows promise in controlling Hg_{total} emissions at coal-fired power plants (19). The Amended Silicates have shown improvement factors of 1.5 to 2 in controlling Hg_{total} emissions over ACI from subbituminous coal testing in a pilot-scale test. In addition, the use of Amended Silicates will not impact the use of fly ash for cement replacement.

2.4.2 Hg^0 Oxidation

Hg^0 oxidation technologies being investigated for Fort Union lignites include catalysis, chemical additives, and cofiring fuels. The catalysts that have been tested include metal-impregnated, oxide-impregnated, noble metal, and SCR catalysts for NO_x reduction. The chemical additives tested are generally halogen-containing salts. The cofired fuels tested contained oxidizing agents (13).

Mercury speciation sampling was conducted upstream and downstream of SCR catalysts at power plants firing bituminous and subbituminous coals (20). Test results indicated evidence of Hg^0 oxidation across SCR catalysts when firing bituminous coals. However, when firing subbituminous coal, the results indicated limited Hg^0 oxidation, and more testing needs to be conducted on low-rank coals. The capability of SCR systems to promote Hg^0 oxidation is coal-specific and probably related to the chlorine, sulfur, and calcium contents of the coal as well as temperature and specific operation of the SCR catalyst including space velocity.

Hg^0 oxidation catalysts were very effective, with >80% conversion of Hg^0 to Hg^{2+} during testing on a North Dakota power plant flue gas slipstream for periods of ≤6 months (13). Tests were also conducted using iron oxides and chromium, with little success of oxidation. Zygarlicke and others (21) conducted short-term pilot-scale testing with maghemite (γ-Fe_2O_3) additions and were able to transform about 30% of the Hg^0 in North Dakota lignite combustion flue gases to Hg^{2+} and/or Hg(p) and, with an injection of a small amount of HCl (100 ppmv), nearly all of the Hg^0 to Hg^{2+}. Theoretically, the use of chloride compounds to oxidize Hg^0 to Hg^{2+} makes sense. The evidence includes chemical kinetic modeling of bench-scale test results, indicating that the introduction of chloride compounds into the high-temperature furnace region will most likely result in the

production of atomic chlorine and/or molecular chlorine, which are generally thought to be the dominant Hg^0 reactants in coal combustion flue gases (7).

Coal additives for Hg^0 oxidation and sorbent enhancement have recently been tested at the EERC. The results of the addition of materials with coal at very low levels along with ACI upstream of a TOXECON, an *Advanced Hybrid* filter, and an ESP are illustrated in Figure 2-3. Baseline Hg emissions ranged from 9 to 12 µg/Nm^3, with 80% to 90% of the Hg_{total} as Hg^0. Coal additives improved the Hg_{total} removal efficiencies of the TOXECON, *Advanced Hybrid* filter, and ESP devices to ≥90% removal. The Hg_{total} control efficiency obtained with the ESP significantly improved compared to the previous ESP results presented in Figure 2-1. The coal additive technology also has the potential to improve SDA–ESP and SDA–FF Hg_{total} control efficiency.

Sorbent enhancement technologies have also been investigated by ALSTOM using a synthetic flue gas and an ESP. The sorbent preparation system enhanced sorbent performance from 68% to >90% Hg_{total} removal by changing the physical and chemical nature of the sorbent. The enhancement approach is expected to be applicable to a significant number of sorbents currently utilized for Hg_{total} control.

ACI and SEA addition upstream of an ESP was evaluated for controlling Hg_{total} emissions associated with North Dakota lignite combustion. The testing was performed using the EERC's PTC equipped with an ESP. Test results are presented in Figure 2-4. DARCO FGD injection at 3.75 and 15 lb/MMacf reduced Hg_{total} emissions by 50% and 60%, respectively. The addition of SEA to the coal and ACI at 3.75 lb/MMacf reduced Hg_{total} emissions by >70%.

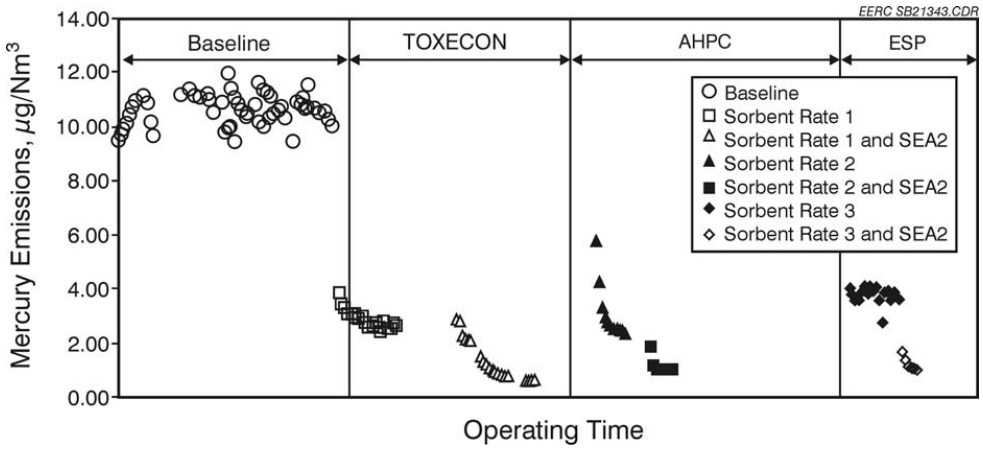


Figure 2-3. Mercury emissions for ACI combined with additives.

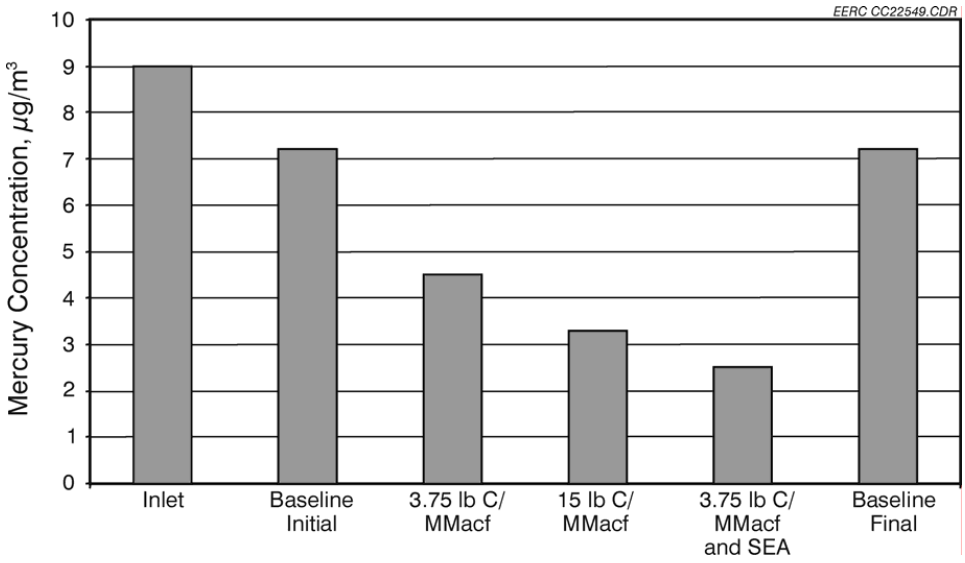


Figure 2-4. ESP inlet and outlet Hg_{total} concentrations as functions of ACI and SEA addition rates into North Dakota lignite combustion flue gases.

3.0 GOALS AND OBJECTIVES

The project goal was to evaluate innovative Hg_{total} control technologies for reducing Hg_{total} emissions from subbituminous coal-fired power plants by 50% to 90% at costs of one-half to three-quarters of current estimates associated with ACI (e.g., DOE 2005 baseline cost estimate is $60,000/lb of Hg removed). Power plants firing subbituminous coals produce flue gases that contain >80% Hg^0 which is difficult to capture. In order to meet the project goal, the following specific objectives were identified: evaluate Hg^0 oxidation additives for improving Hg_{total} capture in wet and dry scrubbers, identify additives and technologies for enhancing Hg_{total} sorbent effectiveness in ESP and FF systems, evaluate Amended Silicate injection for capturing Hg_{total}, evaluate the effects of blending chlorine-containing bituminous coal with subbituminous coal on Hg_{total} emissions, and evaluate coal-cleaning processes for reducing Hg_{total} emissions.

4.0 APPROACH

The project approach consisted of four tasks:

- Task 1 – Mercury Control Enhancement for Unscrubbed Systems Equipped with Only Particulate Control Devices
- Task 2 – Mercury Control in Dry Scrubbers
- Task 3 – Blending of Subbituminous and Bituminous Coals to Enhance Mercury Oxidation
- Task 4 – Reporting and Management

5.0 WORK PLAN

5.1 Task 1 – Mercury Control Enhancement for Unscrubbed Systems Equipped with Particulate Control Devices

This task involved evaluating and furthering the ability to control Hg emissions in subbituminous-fired power systems equipped with an ESP only, as well as performing limited testing with an ESP–baghouse configuration. Testing was performed using sorbent injection on the EERC's PTC (580-MJ/hr [550,000-Btu/hr] pulverized coal [pc]-fired unit) equipped with an ESP and ESP–baghouse to evaluate Hg sorbent effectiveness in coal combustion flue gases.

This task included testing with two subbituminous coals with sorbent and enhanced sorbent additive (SEA) injection. Selection of specific sorbents and sorbent enhancement agents was made with input from project sponsors. Selected sorbents and sorbent enhancements were tested to quantify the improvements in Hg removal with each. The testing involved shorter-term screening tests for evaluation of the sorbent and SEAs at several rates to obtain removal efficiencies as a function of injection rate for the test coals. Throughout testing, two Hg continuous emission monitors (CEMs), also referred to as continuous mercury monitors (CMMs), were used to measure Hg^0 and Hg_{total} concentrations upstream of the injection system and downstream of the APCD(s). Limited Ontario Hydro (OH) sampling was used to validate the CMM measurements and provide ESP particulate capture efficiency and Hg speciation information.

5.2 Task 2 – Mercury Control in Dry Scrubbers

The task involved configuring the PTC with the pilot-scale spray dryer followed by the pilot-scale baghouse. Testing involved injection of sorbents upstream of the SDA, both alone and in combination with SEAs added to the coal. In addition, a proprietary sorbent enhancement technology developed by Solucorp Industries Ltd. was tested as a slurry additive in the SDA. CMMs were used to measure Hg^0 and Hg_{total} at the SDA inlet and baghouse outlet during each test, with limited OH sampling performed to validate the measurements.

5.3 Task 3 – Blending of Subbituminous and Bituminous Coals to Enhance Mercury Oxidation

Combustion testing was conducted to determine the impact of blending a chlorine-containing bituminous coal with a subbituminous coal on the speciation and control of Hg. This testing was conducted in an ESP-only and a spray dryer baghouse system and was similar to the testing conducted in Tasks 1 and 2. The testing also included specific sorbents and SEAs along with the coal blends. WRI's thermally treated coal was tested to demonstrate additional mercury removal potential and speciation behavior in conventional pc-fired combustors with various APCDs.

Throughout testing, two CMMs were used to measure Hg^0 and Hg_{total} concentrations upstream of the carbon injection system and downstream of the ESP and baghouse. Limited OH sampling was used to validate the CMM measurements and provide ESP particulate capture efficiency and Hg speciation information.

5.4 Task 4 – Project Reporting and Management

This task involved coordination of all testing and reporting of results to the project sponsors. Conference calls were scheduled to convey the significant results of each week of the pilot-scale testing. In addition, a meeting of the sponsors was held July 20, 2004, as part of the fourth week of testing to present the results to date. A discussion of all project results is provided hereinafter.

6.0 DESCRIPTION OF PILOT-SCALE TEST FACILITIES

6.1 Particulate Test Combustor

The pilot furnace, shown schematically in Figure 6-1, known as the PTC, is a 550,000-Btu/hr pc-fired unit designed to generate fly ash representative of that produced in a full-scale utility boiler. The burner is oriented vertically to minimize wall deposits. A refractory lining helps to ensure adequate flame temperature for complete combustion and prevents rapid quenching of the coalescing or condensing fly ash. Based on the superficial gas velocity, the mean residence time of a particle in the combustor is approximately 3 seconds. The coal nozzle of the PTC fires axially upward from the bottom of the combustor, and secondary air is introduced concentrically to the primary air with turbulent mixing. Coal is introduced to the primary air stream via a screw feeder and eductor. An electric air preheater is used for precise control of the combustion air temperature.

The PTC instrumentation permits system temperatures, pressures, flow rates, flue gas constituent concentrations, and particulate control device operating data to be monitored continuously and recorded on a data logger.

Flue gas samples can be taken at any combination of two of three available system sample points: the furnace exit, the particulate control device inlet, and the particulate control device outlet. After passing through sample conditioners to remove the moisture, the flue gas is typically analyzed

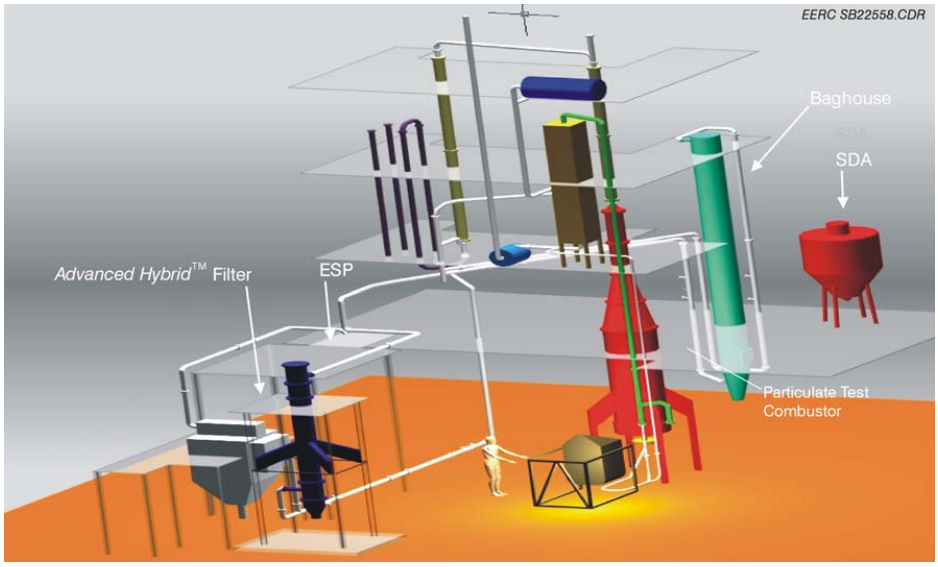


Figure 6-1. Schematic of the EERC PTC 580-MJ/hr (550,000-Btu/hr) combustion unit.

for O_2, CO, CO_2, SO_2, and NO_x. Except for CO and CO_2, each constituent is normally analyzed at both the furnace exit and the outlet of the particulate control device simultaneously using two analyzers. The concentration values from all of the instruments are recorded continuously using circular charts. In addition, data are manually recorded at set time intervals. NO_x is determined using two Thermoelectron chemiluminescent NO_x analyzers. The O_2, CO, and CO_2 analyzers are made by Beckman, and the SO_2 analyzers are manufactured by DuPont. Each of these analyzers is regularly calibrated and maintained to provide accurate flue gas concentration measurements.

6.2 Fabric Filter or Baghouse

The baghouse vessel is a 20-in.-i.d. chamber that is heat-traced and insulated, with the flue gas introduced near the bottom. Since the combustor produces about 200 acfm of flue gas at 300°F, three 13-ft by 5-in. bags provide an air-to-cloth ratio of 4 ft/min. Each bag is cleaned separately with its own diaphragm pulse valve. In order to quantify differences in pressure drop for different test conditions, the bags are cleaned on a time basis, rather than with the cleaning cycle initiated by pressure drop. Once bag cleaning is initiated, all three bags are pulsed in rapid succession online.

6.3 Electrostatic Precipitator

A single-wire, tubular ESP, shown schematically in Figure 6-2, is designed to provide a specific collection area of 125 at 300°F. Gas velocity through the ESP is 5 ft/min. Plate spacing for the unit is 11 in. The ESP has an electrically isolated plate that is grounded through an ammeter, allowing continuous monitoring of the actual plate current to ensure consistent operation of the ESP. The tubular plate is suspended by a load cell and is used to monitor rapping efficiency. In addition, sight ports are located at the top of the ESP to enable online inspection of electrode alignment, sparking, rapping, and dust buildup on the plate. The ESP was designed to facilitate thorough cleaning between tests so that all tests can begin on the same basis.

6.4 Spray Dryer Absorber

The SDA is shown schematically in Figure 6-3. The SDA is a Niro production minor spray dryer designed to operate in conjunction with the PTC and FF. The drying chamber is 1.2 m (3.9 ft) in diameter, with a 0.75-m (2.5-ft) cylindrical height and a 60° conical bottom. The inner shell is constructed of 2-mm stainless steel, Type AISI 316, with a 220-grit finish. A Niro Inc. Type FS-1 rotary atomizer, capable of speeds ranging from 10,500 to 30,000 rpm, was used for atomizing lime slurry. An air disperser, supplied with the rotary atomizer, was used to introduce the proper heated (149°C, 300°F) airflow pattern throughout the chamber. The lime slurry flow rate is nominally 0.17 lb/min. The residence time is approximately 10 seconds. Humidity can increase from inlet 2.6% to outlet 6.1%. For example, for a typical lignite fired in the PTC with ultimate S of 1.1 wt%, a feed rate of 75 lb/hr produces a SDA inlet gas flow rate of 218 acfm at 300°F (SO_2 of 1148 ppmv).

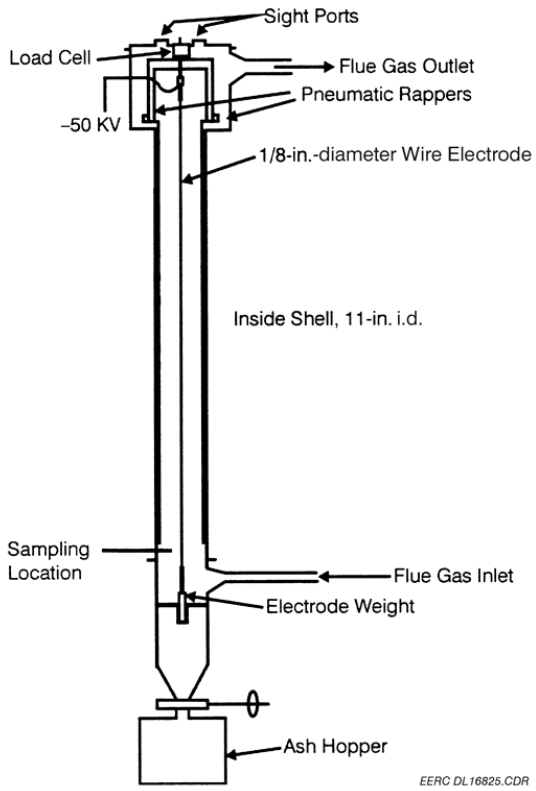


Figure 6-2. Schematic of the pilot-scale ESP.

The lime slurry for the SDA was prepared by adding deionized distilled water to slaked lime and fly ash obtained from Basin Electric's Laramie River Power Plant. High-purity water was used to avoid the unintended introduction of chlorine into the system via a chlorinated water supply. Lime slurry compositions are presented in Table 6-1. The solid content of the prepared slurries averaged 30 wt% for the SDA test runs.

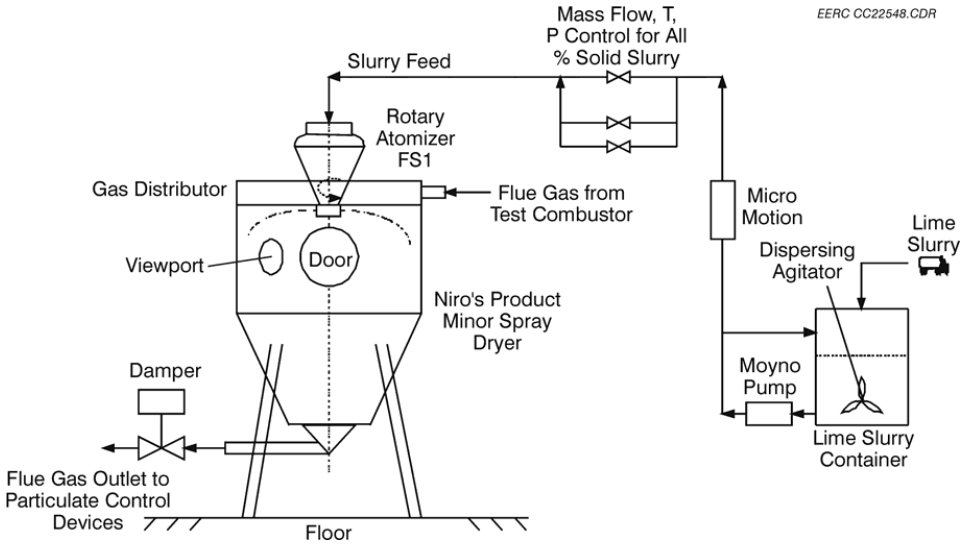


Figure 6-3. Schematic (not drawn to scale) of the Niro Inc. Production Minor SDA.

Table 6-1. Lime Slurry Composition, wt%

Component	SDA
$Ca(OH)_2$	3.8
Fly Ash	26.7
Distilled Water	69.5

7.0 EXPERIMENTAL

Presented in Appendix A are the quality assurance/quality control (QA/QC) procedures that were used during the sampling, analysis, and data reduction activities described in this reporting section.

7.1 Continuous Mercury Sampling and Analysis

Two CMMs were used for determining Hg^0 and Hg_{total} concentrations. The majority of the measurements were made with Tekran analyzers. A Sir Galahad was also used during one of the four weeks of testing. All the CMM results are presented in Appendix B.

The Tekran Model 2537A atomic fluorescence-based Hg vapor analyzer is used in conjunction with a PS Analytical S235C400 wet-chemistry conversion unit. The S235C400 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 S235C400 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 ultra-pure gold sorbent. The amalgamated Hg is then thermally desorbed and detected using atomic fluorescence spectrometry. A dual-cartridge design allows alternate sampling and desorption, resulting in continuous measurement of the sample stream. The Model 2537A allows two methods of calibration: manual injection or automatic permeation source. Permeation source calibration was used to calibrate the instrument daily. Manual injection calibration on both cartridges was performed for verification. The Tekran instrument can measure either Hg_{total} or Hg^0, with one analysis point being obtained approximately every 2.5 minutes. The operation and calibration of the Sir Galahad instrument is similar, but measurements of both Hg_{total} and Hg^0 are obtained approximately every 5 minutes.

7.2 OH Method and Mercury Analysis

For verification of the CMM measurements in the flue gas, ASTM Method D6784-02 (Standard Test Method for Elemental, Oxidized, Particle-Bound, and Total Mercury in Flue Gas Generated from Coal-Fired Stationary Sources – Ontario Hydro Method) was used. Samples were withdrawn from the flue gas stream isokinetically through a probe/filter system, maintained at 120°C or the flue gas temperature, whichever was greater, followed by a series of impinger solutions in an ice bath. Particle-bound mercury was collected on a quartz filter in the front half of the sampling train. Hg^{2+} was collected in impingers containing a chilled aqueous potassium chloride solution. Hg^0 was collected in subsequent impingers (one impinger containing a chilled aqueous acidic solution of hydrogen peroxide and three impingers containing chilled aqueous acidic solutions of potassium permanganate). Samples were recovered and sent to the lab for analysis. The OH samples were typically prepared and analyzed the same day of collection or the following day. Mercury was determined by cold-vapor atomic absorption spectroscopy (CVAAS) using a CETAC M6000A automated Hg analyzer. Results were initially reported as µg/L and then converted to µg/dscm, as indicated in Appendix C.

7.3 Mercury Analyses of Combustion Residues

The particle-bound Hg and Hg_{total} in combustion residues were determined using ASTM Method D6414-01 (Standard Test Method for Total Mercury in Coal and Coal Combustion Residues by Acid Extraction or Wet Oxidation/Cold Vapor Atomic Absorption). Samples were heated in a hot-water bath at 80°C with a mixture of nitric and hydrochloric acids. After digestion, the solutions were cooled, diluted to a known volume, filtered, and analyzed by CVAA using a CETAC M6000A Hg analyzer. Mercury concentrations were reported as µg/g on a dry basis.

7.4 Coal Analyses

Caballo and Absaloka subbituminous coals and a Blacksville bituminous coal for blending purposes were fired in the PTC. In addition, subsamples of the Caballo coal were provided to WRI for heat treatment and to Demeter Systems for addition of an additive. All coals were pulverized to a standard combustion grind (i.e., 70%–80% of the coal particles <75 µm) for analysis and combustion testing purposes. Hourly samples of each coal were collected during testing. During multiple days of testing for a given coal, daily samples were combined to provide a representative composite sample for analysis. During firing of the coal blends, hourly samples were taken only of the major coal component (Caballo or Absaloka). Proximate and ultimate analyses were conducted on the composite coal samples using ASTM Methods D3172, D5142, and D3176. A Mitsubishi Model TOX-100 total chlorine analyzer was used to perform the recently validated ASTM Method D6721-01 (Standard Test Method for Determination of Chlorine in Coal by Oxidative Hydrolysis Microcoulometry). Coal Hg contents were determined in triplicate using CVAAS according to EPA Method 245.1 and EPA SW-846 Method 7470.

7.5 Hydrogen Chloride (HCl) Measurements

A Thermo Environmental Model 15C HCl analyzer was used at the ESP exit to determine HCl concentrations in the flue gas during tests involving SEA1. The Model 10C analyzer uses infrared (IR) spectroscopy to achieve an HCl detection limit of 0.2 ppmv (5-min integration time). The Model 15C analyzer measures only HCl because other chlorine species (Cl and Cl_2) are not IR active.

7.6 EPA Method 29

EPA developed and validated Method 29 for quantifying trace element emissions from stationary sources such as fossil fuel-fired utility boilers. Method 29, also known as the multiple metals stack emission measurement method, was developed for measuring the solid particulate and gaseous emissions of 17 trace elements (antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, lead, manganese, mercury, nickel, phosphorus, selenium, silver, thallium, and zinc). A large database of trace element emissions from fossil fuel-fired utility boilers exists because of the applicability of EPA Method 29.

The EPA Method 29 sampling system, shown schematically in Figure 7-1, is based on the physical entrapment of particle-associated trace elements on a heated quartz filter and the absorption of gaseous trace elements in chilled oxidizing nitric acid (HNO_3)–hydrogen peroxide (H_2O_2) and

sulfuric acid (H_2SO_4)–potassium permanganate ($KMnO_4$) solutions. EPA Method 29 was used for trace element sampling of the flue gas during Week 1 (February 2–4, 2004) testing of Caballo coal. Samples were collected at the ESP inlet upstream of the carbon injection location during three different conditions: baseline and SEA1 and SEA2 additions. The objective was to determine the effects of SEA additions on trace metal concentrations and particle–gas partitioning.

The ash particulate trapped on the quartz filter was prepared for analysis by carefully removing the ash from the filter and thoroughly homogenizing the sample. For all three conditions, there were adequate amounts of ash for analysis (>3 g). The ash was prepared for analysis by heating with a mixture of hydrofluoric (HF), hydrochloric (HCl), and nitric (HNO_3) acids. The digested ash samples and impinger solutions were analyzed by graphite furnace atomic absorption spectroscopy (GFAAS), inductively coupled plasma–atomic emission spectroscopy (ICP–AES), and inductively coupled plasma–mass spectroscopy (ICP–MS). Ten inorganic hazardous air pollutants (HAPs) were determined: As, Be, Cd, Co, Cr, Mn, Ni, Pb, Sb, and Se.

7.7 Leaching Characterization

The same ESP fly ashes that were collected for the flue gas partitioning study during Week 1 testing of Caballo coal were also evaluated for leaching potential using ASTM Method D3987-85 (2004) (Standard Test Method for Shake Extraction of Solid Waste with Water). The three ash samples were leached at a 20:1 liquid-to-solid ratio for 18 hours with distilled deionized

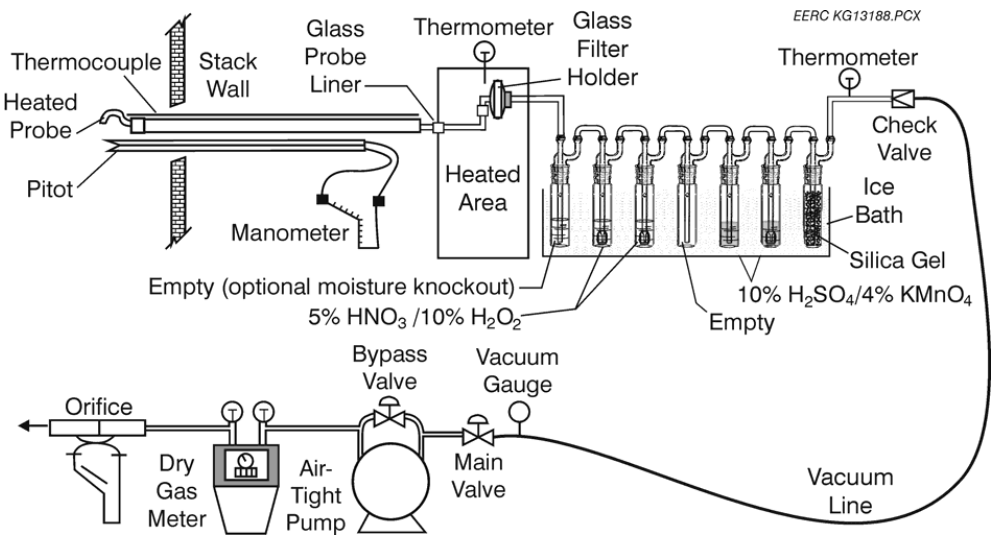


Figure 7-1. Schematic of EPA Method 29 impinger train.

water as stated in the method. However, because of limited amounts of ash, the leaching experiments were scaled down, but the 20:1 liquid-to-solid ratio was still maintained. Two additional leaching times of 30 days and 60 days were selected to compare the mobility of trace elements over time. These longer-term tests help evaluate trace element mobility under disposal conditions or in by-product utilization scenarios. The same ten trace elements identified in the previous section were selected for the leaching studies and were determined using GFAAS, ICP–AES, and ICP–MS.

7.8 Multicyclone Fly Ash Sampling and Analysis

Size-segregated fly ash samples were collected from the Caballo coal combustion flue gas during Week 4 testing (July 19–20, 2004) using a multicyclone. Samples of aerodynamically sized fly ash were collected from the outlet of the PTC using an EPA–Southern Research Institute (SRI) five-stage cyclone sampler. The sized fly ash samples were prepared for GFAAS, ICP–AES, or ICP–MS analysis by heating with a mixture of HF, HCl, and HNO_3 acids. Approximately 100 mg of ash was digested from each of the 5-stage cyclone catches and diluted to a final volume of 14 mL. The small amounts (<100 mg) of ash, collected on the filter catch, could not be removed; therefore, the entire sample with the filter was digested.

7.9 Particle-Size Measurements

Near-real-time particle-sizing measurements were made using a Model 33 aerodynamic particle sizer (APS 33) manufactured by TSI, Inc. The APS is a laser particle counter that measures the concentration of particles ranging in size from 0.7 to 30 µm. Flue gas collected downstream of the ESP was diluted 8:1 with filtered flue gas prior to introduction to the APS to avoid overloading the instrument.

8.0 POTENTIAL MERCURY REDUCTION TECHNOLOGIES

The specific project objectives were focused on determining the feasibility of enhancing Hg^0 oxidation for effectively capturing Hg^{2+} in wet and dry scrubbers, incorporation of additives and technologies that enhance Hg sorbent effectiveness in ESPs and FFs (baghouses), and the use of Hg adsorbents within a baghouse. Table 8-1 summarizes the potential Hg reduction technologies tested during the course of the project. These technologies are described in the subsequent subsections of this report.

8.1 Sorbent Injection Technologies

8.1.1 NORIT Americas Inc. DARCO® FGD

NORIT Americas Inc. DARCO FGD is a lignite-based activated carbon manufactured specifically for the removal of heavy metals and other pollutants typically found in incinerator flue gas streams. It has been proven in numerous incinerator facilities to be highly effective for removing gaseous Hg, dioxins, and furans. Bench-scale tests indicate a Hg^0 sorption capacity of about 100 µg/g (22). Testing in pilot-scale combustion systems indicates that the effectiveness of DARCO FGD to remove Hg from coal combustion flue gases is variable depending on the flue gas composition, residence time, pollution control device, and temperature (23–25). General properties and characteristics of DARCO FGD are presented in Table 8-2. Duplicate Malvern particle-size analyses of the DARCO FGD indicated median volume diameters (MVDs) of 16.2 and 18.1 µm. The inorganic chemical composition of DARCO FGD is presented in Table 8-3.

Table 8-1. Potential Mercury Reduction Technologies

Sorbent Injection Technologies
NORIT Americas Inc. DARCO FGD
EERC-treated carbon
Alternative (German) carbon
Sodium tetrasulfide (Na_2S_4)
ADA Technologies Amended Silicate
Hg^0 Oxidation Technologies
Washington University TiO_2 injection–ultraviolet (UV) radiation
Solucorp Industries Ltd. Molecular Bonding System (MBS®)
Coal Pretreatment Processes
Demeter Systems LLC Inorganic Polymer Electret™ (IPE)
WRI thermally treated coal
Blending with chlorine-rich bituminous coal
Sorbent Enhancement Additives
SEA1 addition – $CaCl_2$
SEA2 addition – Confidential EERC oxidizing agent

Table 8-2. Physical and Chemical Characteristics of DARCO FGD

Property or Characteristic, unit	Value
Moisture, wt% as-received	≤8
Particle Size <325 mesh (45 μm), wt%	≥95
Iodine Number, mg/g	600
Bulk Density, tamped, g/mL	0.53
Surface Area, m^2/g	600
Heat Capacity	0.22
Total Sulfur, wt%	1.8
Ignition Temperature, °C (°F)	450 (842)

Table 8-3. Elemental Oxide Composition of DARCO FGD, ash wt%

Equivalent Oxide	DARCO FGD
SiO_2	38.5
Al_2O_3	15.6
Fe_2O_3	10.6
TiO_2	1.3
P_2O_5	<0.1
CaO	18.1
MgO	4.7
Na_2O	0.7
K_2O	0.6
SO_3	10.0
Total	100.1

The inorganic fraction of DARCO FGD is primarily an Fe_2O_3-, CaO-, and SO_3-rich aluminosilicate material. It lacks alkali metals, Na_2O and K_2O, but contains relatively high alkaline-earth metal, CaO and MgO, content. DARCO FGD carbon is commonly used as a "baseline" sorbent to compare with the Hg removal effectiveness of other Hg control technologies.

8.1.2 EERC Carbon

EERC carbon is the standard DARCO FGD carbon that was treated using a proprietary process to enhance Hg^0 oxidation and increase sorbent performance.

8.1.3 Alternative (German) Carbon

The alternative carbon is a Donau Desorex DX400 FGD carbon with properties similar to the baseline DARCO FGD carbon but available at approximately half the cost.

8.1.4 Sodium Tetrasulfide

Babcock Power Environmental Inc. has undertaken a program to test the effectiveness of Na_2S_4 to control Hg emissions from coal combustion. Na_2S_4 is injected as an aqueous solution into flue gases to react with Hg^0 and Hg^{2+} and form mercuric sulfide (HgS) which is an insoluble, thermally stable solid. The process has the potential to effectively immobilize Hg_{total}, which can then be removed from flue gas by a particulate removal device such as a FF or ESP.

8.1.5 Amended Silicate

ADA Technologies, Inc., through funding from EPA and DOE, developed Amended Silicate sorbents using a commodity substrate material impregnated with a chemical amendment that binds Hg to the particle surface. The Amended Silicate is reportedly cost-competitive with activated carbon and, unlike activated carbon, it does not hinder the salability of fly ash as a concrete additive. Testing on a flue gas slipstream at a power plant burning PRB subbituminous coal indicated that Amended Silicate sorbents provided 70% to 96% Hg removals at injection rates of 1.6-9 lb/MMacf (26).

8.2 Hg^0 Oxidation Technologies

8.2.1 Washington University Titanium Dioxide – UV Technology

The Washington University technology introduces a vapor-phase precursor, titanium isopropoxide, of titanium dioxide (TiO_2) into the combustion chamber, resulting in the formation of nanoparticle agglomerates of TiO_2. In the presence of UV, the photocatalytic properties of TiO_2 are used to oxidize Hg^0 on particle surfaces and strongly bind it. These Hg–TiO_2 agglomerates are readily removed in conventional particle control devices, thus preventing the emission of Hg_{total}. A vapor-phase titanium isopropoxide and fine TiO_2 particles were tested.

8.2.2 Solucorp Industries Ltd. Molecular Bonding System

Solucorp Industries Ltd. developed patented technologies termed MBS® that uses a proprietary sulfide compound to react with Hg^0 to form HgS. In this investigation, MBS was added to a SDA to convert Hg^0 to insoluble HgS that should then be captured in an ESP or FF downstream of the SDA. The additive is not expected to affect fly ash properties.

8.3 Coal Pretreatment Processes

8.3.1 Demeter Systems Inorganic Polymer Electret-Treated Coal

Demeter Systems LLC developed a nonpolluting chemical termed IPE, which combines a chemical compound and a physical process whereby ingredients common in nature (i.e., sand, water, alkali, etc.) are blended in a patented process to yield a solution with properties that are advantageous in many applications. IPE addition to crushed coal reduces the pollutant emissions created during coal combustion and increases combustion efficiency. The primary function of the additive is to reduce the emission of sulfur dioxide and other pollutants.

8.3.2 WRI Heat-Treated Coal

WRI's patented heat treatment process (Patent No. 5,403,365) subjects the coal to heat in a two-stage process in a near-inert atmosphere. During the first stage, the coal is heated to 250°–280°F to remove moisture. The second stage involves heating the coal from 50° to 550°F to volatilize Hg. Guffey and Bland (27) and Bland et al. (28) describe WRI's technology in detail.

8.3.3 Blending with Chlorine-Rich Bituminous Coal

Eastern bituminous coal-burning power plants generally release greater proportions of Hg^{2+} relative to western subbituminous coal-fired power plants. This occurs primarily because of the relatively high chlorine concentrations (200–1000 ppm) in these coals that promote Hg^0 oxidation. In general, Hg^{2+} is more easily captured than Hg^0 in APCDs. Western subbituminous coals have very low chlorine concentrations, hence they release primarily Hg^0 during combustion. Blending western subbituminous coals with eastern bituminous coals may be an effective approach for increasing the proportions of Hg^{2+} in flue gases.

8.4 Sorbent Enhancement Additives

8.4.1 Calcium Chloride ($CaCl_2$)–SEA1

The addition of inorganic chloride compounds such as sodium chloride (NaCl) or $CaCl_2$ (SEA1) to the coal during combustion may promote Hg^0 oxidation. $CaCl_2$ was chosen as the chlorine-containing additive because the addition of small amounts of calcium, ≤4 lb/MMacf, is expected to have little effect on ash slagging or fouling severity because of the relatively high calcium contents of subbituminous coals.

8.4.2 SEA2–Confidential Oxidizing Agent

SEA2 is a proprietary Hg^0 oxidizing agent effective at addition rates on the order of 1/10 of those for SEA1.

9.0 OVERVIEW OF PILOT-SCALE TESTING

9.1 Week 1 Testing: ESP Configuration

ESP Hg removal testing was performed with the PTC firing Caballo subbituminous coal. The SEA addition, sorbent injection, CMM, and OH sampling locations are illustrated in Figure 9-1. The SEAs were added to the coal, and Hg sorbents were injected upstream of the ESP. The CMM and OH samples were obtained at the ESP inlet upstream of the sorbent injection location and at the ESP outlet as shown in Figure 9-1. In addition, EPA Method 29 sampling was performed at the ESP inlet upstream of the carbon sorbent injection point to obtain samples with and without SEAs to determine trace element solid–gas partitioning. The flue gas stream exiting the ESP was sampled with a TSI APS to obtain particle-size distributions (PSDs) of ash and sorbent. A Thermal Environment Model 15C HCl analyzer was used at the ESP exit to determine HCl concentrations in the flue gas during the tests involving SEA1 addition.

The combustor was fired at a nominal rate of 70 lb/hr coal with 4.6 % excess oxygen. The ESP was maintained at a nominal temperature of 300°F and voltage of 50 kV. Flue gas flow was 132 scfm. The average gas composition exiting the combustor is presented in Table 9-1.

Table 9-2 presents the test matrix for Week 1 testing. Baseline testing was conducted to provide information on Hg_{total} control without the use of additives or sorbents. DARCO FGD was used so that test results could be compared to other pilot- and full-scale studies. The DARCO FGD was injected at the ESP inlet and after the CMM and OH sampling locations using a small

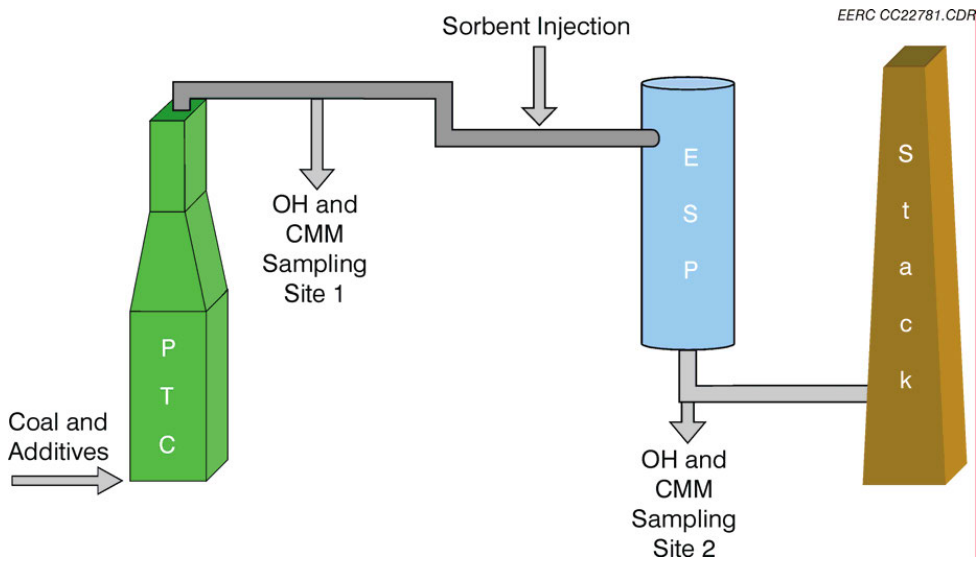


Figure 9-1. Injection and sampling schematic of the PTC with an ESP.

Table 9-1. Week 1 – Average Flue Gas Composition

Gas Component	Combustor Outlet	ESP Outlet
O_2, %	4.64	5.82
CO_2, %	14.4	13.9
CO, ppm	2.78	2.86
SO_2, ppm	311	275
NO_x, ppm	814	770

Table 9-2. Week 1 – Test Matrix

Date	Sampling Inlet	Sampling Outlet	Sorbent	Rate, g/hr	Rate, lb/MMacf	Oxidant	Rate, g/hr	Rate, lb/MMacf
2/2/04	OH	OH	Baseline					
	M-29		Baseline					
			DARCO	25.0	7.03			
			DARCO	28.0	7.84			
			DARCO	32.0	8.96			
		OH	DARCO	45.0	12.60			
			DARCO	69.0	19.20			
2/3/04			Baseline					
						SEA1	15.2	4.28
						SEA1	29.8	8.38
			DARCO	25.0	7.03	SEA1	29.8	8.38
	OH	OH	DARCO	25.0	7.03	SEA1	45.5	12.80
	M-29		DARCO	25.0	7.03	SEA1	59.9	16.73
			DARCO	25.0	7.03	SEA1	15.2	4.28
2/4/04			Baseline					
						SEA2	9.8	2.73
			DARCO	25.0	6.96	SEA2	9.8	2.73
	OH	OH	DARCO	15.0	4.18	SEA2	9.8	2.73
			DARCO	15.0	4.18			
	M-29		DARCO	15.0	4.18	SEA2	6.9	1.92
			DARCO	15.0	4.18	SEA2	4.3	1.20
			DARCO	15.0	4.18			
			DARCO	15.0	4.18	SEA1–SEA2	2.6	0.72
2/5/2004			Baseline					
	OH	OH	EERC carbon	25.0	6.97			
			EERC carbon	35.0	9.76			
			Am. Silicate	25.0	6.91			
			Am. Silicate	50.0	13.82			

Notes:
M-29 = EPA Method 29
EERC carbon = EERC-treated DARCO carbon
Am. Silicate = Amended Silicate
SEA1–SEA2 = 50%–50% blend of SEA1 and SEA2. The total rate for both is given.

screw feeder. The SEA1 and SEA2 additives were each premixed with an aliquot of pulverized Caballo coal for feeding purposes, and the premixed material was added to the coal feed system using a small screw feeder.

SEA1 and SEA2 additions were tested alone and in combination with DARCO FGD injection. In addition, a single test was performed with a 50:50 wt% blend of SEA1 and SEA2 in combination with ACI. A proprietary EERC-treated DARCO FGD carbon and Amended Silicate were also tested.

9.2 Week 2 Testing: SDA–ESP and SDA–FF Configurations

Testing began with the PTC in the SDA–ESP configuration, with CMM and OH sampling performed at the SDA inlet and ESP outlet. After two days of testing, the PTC was reconfigured to the SDA–FF configuration, as shown in Figure 9-2. Caballo subbituminous coal was fired during Week 2 testing.

The combustor was fired at a nominal rate of 66 lb/hr coal with 4.9% excess oxygen. SDA inlet and outlet temperatures were 300° and 170°F, respectively. A SDA slurry was formulated with a 1:7 ratio of lime/high-calcium fly ash, with a total solids loading of 30.5%. The slurry injection rate was 10 kg/hr. When in service, the ESP was maintained at a nominal temperature of 170°F and voltage of 50 kV. The FF temperature was maintained with an external electric heater at 170°F. The FF was

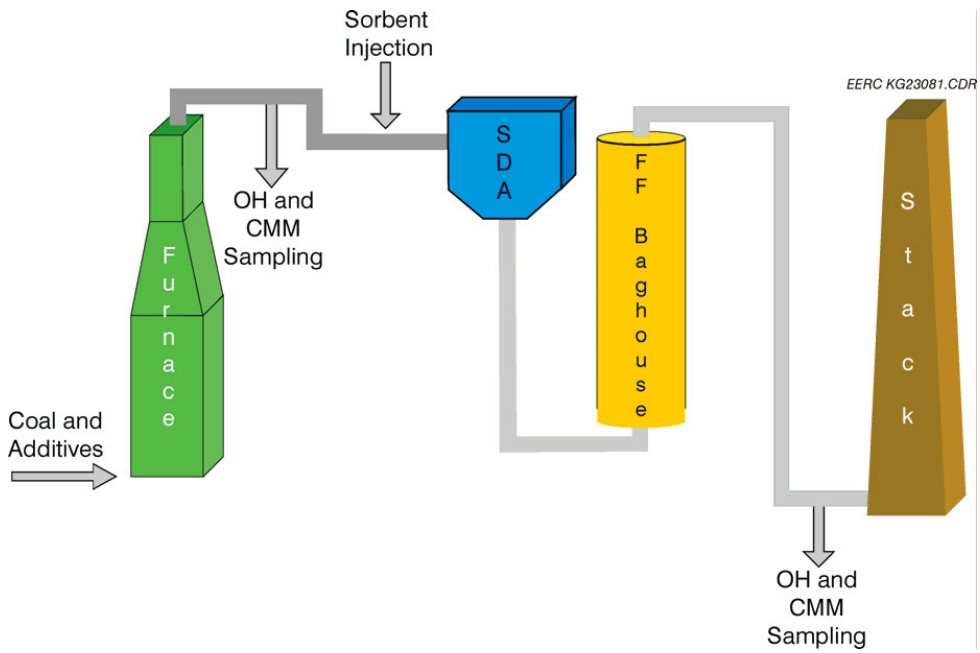


Figure 9-2. Injection and sampling schematic of the PTC with an SDA–FF configuration.

equipped with three Gore 13-ft × 5-in. Teflon bags, providing an air-to-cloth ratio of 3.72 ft/min. The flue gas flow rate was 132.2 scfm. The average gas composition exiting the combustor is given in Table 9-3. O_2 and CO_2 concentrations increased and decreased, respectively, at the ESP and FF exits relative to the furnace location because of air in-leakage. The SDA SO_2 removal efficiency averaged 64% during the ESP and FF testing.

Table 9-4 provides an overview of the test matrix for the Week 2 testing. Similar to the previous testing, DARCO FGD was injected with a small screw feeder at the SDA and FF inlets downstream from the CMM and OH sampling location. The SEA1 ($CaCl_2$) and SEA2 additives were each mixed with an aliquot of pulverized Caballo coal and added to the coal stream fed to the PTC using a small screw feeder. ACI, SEA1, and SEA2 were each tested individually, and combinations of DARCO FGD with SEA1 and SEA2 were tested using the SDA–ESP and SDA–FF configurations at several addition rates. An Amended Silicate was tested at two rates using the SDA–FF configuration.

9.3 Week 3 Testing: Coal Blends, ESP, FF, ESP–FF, SDA–ESP, and SDA–FF Configurations

During the third week of Hg control testing, the Absaloka coal and Caballo–Blacksville and Absaloka–Blacksville coal blends were fired in the PTC system that was configured with an ESP, FF, ESP–FF, and SDA–FF, as summarized in Table 9-5. The combustor was fired at a nominal rate of 70 lb/hr coal, with 5.0% excess oxygen. Coal blending was performed by directing the subbituminous coals to the main feeder and using a smaller screw feeder to introduce the bituminous Blacksville coal into the venturi leading to the burner. SDA inlet and outlet temperatures were 300° and 170°F, respectively. A SDA slurry with a ratio of 1:7 of lime/high-calcium fly ash was formulated, with a total solids loading of 30.5%. Slurry was injected at 10 kg/hr. During ESP, FF, and ESP–FF testing, the ESP and FF were maintained at a nominal temperature of 300°F, whereas during SDA–ESP and SDA–FF testing they were maintained at about 170°F. The FF was fitted with two Gore Teflon bags rather than the normal three bags. This resulted in an air/cloth ratio of 5.6 ft/min that was one-third higher than that used during the second week of testing. Flue gas flow was 132.8 scfm. The average gas composition exiting the combustor is given in Table 9-6. SO_2 concentrations averaged 295 ppmv and ranged from 42–80 ppmv at the SDA inlet and exit, respectively.

Table 9-3. Week 2 – Average Flue Gas Composition

Gas Component	Combustor Outlet	ESP or FF Outlet
O_2, %	4.87	6.39
CO_2, %	14.51	12.88
CO, ppm	1.89	3.58
SO_2, ppm	295	106
NO_x, ppm	804	770

Table 9-4. Week 2 – Test Matrix

Date	Sampling Inlet	Sampling Outlet	Sorbent	Rate, g/hr	Rate, lb/MMacf	Oxidant	Rate, g/hr	Rate, lb/MMacf
SDA–ESP								
2/17/04	OH	OH	Baseline					
			DARCO	25	5.82			
				35	8.14			
				45	10.47			
		OH		55	12.8			
			Baseline					
						SEA1	25	5.82
SDA–ESP								
2/18/04			Baseline					
						SEA1	25	5.82
	OH	OH	DARCO	25	5.82	SEA1	25	5.82
			DARCO	25	5.82	SEA1	35	8.14
			Baseline					
						SEA2	1	0.23
						SEA2	2.5	0.58
		OH	DARCO	10	2.33	SEA2	2.5	0.58
			DARCO	10	2.33	SEA2	5	1.16
SDA–FF								
2/19/04		OH	Baseline					
			DARCO	10	2.33			
	OH	OH	DARCO	25	5.82			
			DARCO	55	12.8			
			Baseline					
						SEA1	10	2.33
		OH	DARCO	10	2.33	SEA1	15	3.49
			DARCO	10	2.33	SEA1	25	5.82
SDA–FF								
2/20/2004			Baseline					
						SEA2	1	0.23
						SEA2	1.5	0.35
		OH	DARCO	10	2.33	SEA2	1.5	0.35
			DARCO	10	2.33	SEA2	0.5	0.12
			Baseline					
			Am. Silicate	15	3.49			
			Am. Silicate	30	6.98			

Notes:
EERC carbon = EERC-treated DARCO carbon
Am. Silicate = Amended Silicate

DARCO FGD injection was tested during the first day when 80:20 wt% and 90:10 wt% Caballo–Blacksville coal blends were being burned and the PTC was equipped with an ESP, FF, and ESP–FF. To minimize configuration changes, the ESP and FF remained in series for these tests. For the ESP-only configuration, sorbent injection was at the ESP inlet downstream of the inlet OH and CMM sampling point. Outlet sampling was performed at the ESP exit upstream of the FF. For the

Table 9-5. Week 3 – Test Matrix

Date	Coal	Configuration	Sampling Inlet	Sampling Outlet	Sorbent	Rate, g/hr	Rate, lb/MMacf	Oxidant	Rate, g/hr	Rate, lb/MMacf
3/29/04	80% Caballo–20% Blacksville	ESP	OH	OH	Baseline					
	80% Caballo–20% Blacksville	FF			Baseline					
	80% Caballo–20% Blacksville	FF			DARCO	25	4.8			
	80% Caballo–20% Blacksville	ESP–FF			Baseline					
	80% Caballo–20% Blacksville	ESP–FF			DARCO	25	4.8			
	80% Caballo–20% Blacksville	ESP			Baseline					
	80% Caballo–20% Blacksville	ESP		OH	DARCO	25	4.8			
	80% Caballo–20% Blacksville	ESP			DARCO	50	9.6			
	90% Caballo–10% Blacksville	ESP			Baseline					
	90% Caballo–10% Blacksville	ESP			DARCO	25	4.8			
	90% Caballo–10% Blacksville	ESP			DARCO	50	9.6			
3/30/04	Absaloka	ESP	OH	OH	Baseline					
	Absaloka	ESP	mod. OH		DARCO	25	4.8			
	Absaloka	ESP			DARCO	25	4.8	SEA2	2.5	0.48
	Absaloka	ESP			Baseline					
	Absaloka	ESP		OH	TiO_2 solution	20	3.84			
	Absaloka	ESP			TiO_2 solution	51.6	9.91			
	Absaloka	ESP			Baseline					
	Absaloka	ESP			TiO_2 solution					
3/31/04	Absaloka	ESP	M-29		Baseline					
	Absaloka	ESP			German carbon	25	4.8			
	Absaloka	ESP			German carbon	50	9.6			
	Absaloka	ESP			Baseline					
	Absaloka	ESP							50*	
	Absaloka	ESP		OH				Na_2S_4	100*	
	Absaloka	ESP						Na_2S_4	100**	
	Absaloka	ESP			DARCO	25	4.8	Na_2S_4	100**	
4/1/04	Absaloka	SDA–FF	OH	OH	Baseline			Na_2S_4	50*	
	Absaloka	SDA–FF						Na_2S_4	100*	
	Absaloka	SDA–FF		OH				Na_2S_4	100*	
	Absaloka	SDA–FF						Na_2S_4	100*	
	80% Absaloka–20% Blacksville	SDA–FF			Baseline					
	80% Absaloka–20% Blacksville	SDA–FF			DARCO	25	4.8			
	80% Absaloka–20% Blacksville	SDA–FF			Baseline					
	80% Absaloka–20% Blacksville	SDA–FF						SEA2	2.5	0.48
	80% Absaloka–20% Blacksville	SDA–FF			DARCO	25	4.8	SEA2	2.5	0.48

Notes:
Mod. OH = Washington University modified OH method
German carbon = Alternative FGD carbon
TiO_2 solution = Titanium isopropoxide
*50 = 50 mg/dry standard cubic meter
*100 = 100 mg/dry standard cubic meter
**100 = 100 mg/dry standard cubic meter, insulation removed from injector nozzle

Table 9-6. Week 3 – Average Flue Gas Composition

Day 1 – 80% Caballo–20% Blacksville		
Gas Component	Combustor Outlet	ESP or FF Outlet
O_2, %	4.83	6.18
CO_2, %	14.41	13.38
CO, ppm	3.41	3.99
SO_2, ppm	540	538
NO_x, ppm	698	643
Day 1 – 90% Caballo–10% Blacksville		
Gas Component	Combustor Outlet	ESP or FF Outlet
O_2, %	5.40	6.31
CO_2, %	14.13	12.77
CO, ppm	3.20	3.33
SO_2, ppm	389	357
NO_x, ppm	644	593
Day 2 – Absaloka		
Gas Component	Combustor Outlet	ESP or FF Outlet
O_2, %	4.93	6.34
CO_2, %	14.52	13.27
CO, ppm	2.86	3.39
SO_2, ppm	519	476
NO_x, ppm	695	712
Day 3 – Absaloka		
Gas Component	Combustor Outlet	ESP or FF Outlet
O_2, %	4.98	6.41
CO_2, %	14.58	13.19
CO, ppm	2.81	3.56
SO_2, ppm	521	439
NO_x, ppm	760	675
Day 4 – Absaloka SDA–FF		
Gas Component	Combustor Outlet	ESP or FF Outlet
O_2, %	5.03	6.18
CO_2, %	14.53	13.57
CO, ppm	2.74	3.90
SO_2, ppm	495	42
NO_x, ppm	793	807
Day 4 – 80% Absaloka–20% Blacksville SDA–FF		
Gas Component	Combustor Outlet	ESP or FF Outlet
O_2, %	4.80	5.18
CO_2, %	14.70	14.01
CO, ppm	3.23	4.30
SO_2, ppm	592	81
NO_x, ppm	813	846

single test in the ESP–FF configuration, sampling was performed at the ESP inlet and FF outlet. It should be noted that the sorbent was injected at the ESP inlet rather than between the ESP outlet and the FF inlet for this test. A FF test was performed with the ESP in-line ahead of the FF, but with the collection field turned off.

Day 2 testing involved combustion of Absaloka coal in the PTC equipped with an ESP configuration (FF in-line, but with CMM and OH sampling performed at the ESP inlet and outlet). SEA2 and SEA2 additions in combination with ACI were tested. Testing was also performed with injection of TiO_2 alone and TiO_2 combined with ACI upstream of the ESP in the presence of two UV lamps. One lamp was mounted in a viewport at the end of the duct leading to the ESP inlet, and a second lamp was mounted in a viewport at the top of the ESP itself. Injections of liquid titanium isopropoxide were also attempted with the feed coal and at the exit of the main furnace combustion zone.

Day 3 testing was conducted using Absaloka coal combustion flue gas with an ESP configuration (FF in-line, but with CMM and OH sampling performed at the ESP inlet and outlet). The alternative German carbon was tested at two injection rates. Aqueous solutions of sodium tetrasulfide (Na_2S_4) were tested with injections upstream of the ESP, both alone and combined with ACI.

The PTC was reconfigured with a SDA–FF for the fourth day of testing. Absaloka coal was fired with Na_2S_4 injection alone and combined with ACI. Na_2S_4 was injected at two locations: upstream of the SDA and after the SDA upstream of the FF. The coal feed was then changed to an 80:20 wt% Absaloka–Blacksville coal blend, and ACI and SEA2 addition were tested alone and in combination.

9.4 Week 4 Testing: ESP, FF, ESP–FF, and SDA–FF Configurations

The fourth week of testing involved testing Caballo coal, Demeter Systems-treated Caballo coal, and WRI heat-treated Caballo coal in the PTC system configured with ESP, FF, ESP–FF, and SDA–FF using several Hg control options, as summarized in Table 9-7. Because of a delay in receiving one of the treated coals, a portion of the testing was delayed a week. The combustor was fired at a nominal rate of 70 lb/hr coal, with 4.7% excess oxygen. SDA inlet and outlet temperatures were 300° and 170°F, respectively. A lime slurry with Solucorp Industries additive as well as a slurry with a ratio of 1:6.9 of lime/high-calcium fly ash with a total solids loading of 30% were used as SDA absorbent. The normal slurry injection rate was 10 kg/hr. When in service, the ESP was maintained at a nominal temperature of 300°F and a voltage of 50 kV. FF temperature was maintained by an external electric heater at a nominal temperature of 300°F. The FF was fitted with two Gore Teflon bags as in Week 3 testing. This resulted in an air/cloth ratio of 5.6 ft/min, which is similar to the Week 3 tests, but one-third higher than during the Week 2 tests. The normal flue gas flow was 131 scfm, except for testing using the Solucorp Industries SDA additive. The average gas compositions exiting the combustor are presented in Tables 9-8 and 9-9.

Table 9-7. Week 4 – Test Matrix

Date	Coal	Configuration	Sampling Inlet	Sampling Outlet	Sorbent	Rate, g/hr	Rate, lb/MMacf	Oxidant	Rate, g/hr	Rate, lb/MMacf
7/19/04	Caballo	ESP–FF	OH	OH	Baseline					
	Caballo	ESP–FF			DARCO	12.7	2.5			
	Caballo	ESP–FF			DARCO	20	3.93			
	Caballo	ESP–FF			Baseline					
	Caballo	ESP–FF						SEA1	12.5	2.46
	Caballo	ESP–FF			DARCO	12.7	2.5	SEA1	12.5	2.46
	Caballo	ESP–FF			DARCO	20	3.93	SEA1	12.5	2.46
7/20/04	Caballo	ESP–FF	OH	OH	Baseline					
	Caballo	FF			DARCO	6	1.18			
	Caballo	FF			DARCO	12.7	2.5			
	Caballo	ESP–FF			Baseline					
	Caballo	ESP–FF			DARCO	6	1.18			
	Caballo	ESP–FF						SEA2	0.5	0.1
	Caballo	ESP–FF						SEA2	1	0.2
	Caballo	ESP–FF			DARCO	6		SEA2	1	0.2
	Caballo	ESP–FF			DARCO	12.5		SEA2	1	0.2
7/21/04	Demeter-treated Caballo	ESP–FF	OH	OH	Baseline					
	Demeter-treated Caballo	ESP–FF			EERC carbon*	12.7	2.48			
	Demeter-treated Caballo	ESP–FF			EERC carbon*	22	4.3			
	Demeter-treated Caballo	ESP–FF			EERC carbon*	26	5.08			
	Demeter-treated Caballo	ESP–FF			EERC carbon*	26	5.08	Demeter soln.(a)		
	Demeter-treated Caballo	ESP–FF			EERC carbon*	26	5.08	Demeter soln.(b)		
	Demeter-treated Caballo	ESP–FF			EERC carbon*	26	5.08	Demeter soln.(c)		
	Demeter-treated Caballo	ESP–FF			EERC carbon*	26	5.08	Demeter soln (d)		
	Demeter-treated Caballo	ESP–FF			EERC carbon*	26	5.08	Demeter soln (e)		
	Demeter-treated Caballo	ESP–FF						Demeter soln (f)		
7/23/04	Caballo	SDA–FF			Baseline					
	Caballo	SDA–FF			Solucorp(g)					
	Caballo	SDA–FF			Solucorp(h)					
	Caballo	SDA–FF			Solucorp(i)					
	Caballo	SDA–FF	OH	OH	Solucorp(j)					
	Caballo	SDA–FF			Solucorp(j)			SEA1	12.5	5.29
	Caballo	SDA–FF			Solucorp(j)			SEA1	25	10.62
8/2/04	WRI-treated Caballo	SDA–FF			Baseline					
	WRI-treated Caballo	SDA–FF			DARCO	6.4	1.26			
	WRI-treated Caballo	SDA–FF			DARCO	12.7	2.5			
	WRI-treated Caballo	ESP–FF	OH	OH	Baseline					
	WRI-treated Caballo	ESP–FF			DARCO	6.4	1.26			
	WRI-treated Caballo	ESP–FF			DARCO	12.7	2.5			

Continued . . .

Table 9-7. Week 4 – Test Matrix (continued)

Date	Coal	Configuration	Sampling Inlet	Sampling Outlet	Sorbent	Rate, g/hr	Rate, lb/MMacf	Oxidant	Rate, g/hr	Rate, lb/MMacf
	WRI-treated Caballo	ESP			Baseline					
	WRI-treated Caballo	ESP			DARCO	6.4	1.26			
	WRI-treated Caballo	ESP			DARCO	12.7	2.5			

EERC carbon = Proprietary EERC-treated DARCO FGD carbon
Demeter soln (a) = 0 1 flow setting, injected before carbon
Demeter soln (b) = 0.3 flow setting, injected before carbon
Demeter soln (c) = 0 1 flow setting, injected before carbon
Demeter soln.(d) = 0.1 flow setting, injected after carbon
Demeter soln. (e) = 0.3 flow setting, injected after carbon
Demeter soln. (f) = 0.6–0.8 flow setting
Solucorp(g) = Solucorp SDA additive
Solucorp(h) = Solucorp SDA additive – 20% bypass
Solucorp(i) = Solucorp SDA additive – 33% bypass
Solucorp(j) = Solucorp SDA additive – 50% bypass

Table 9-8. Week 4 – Average Flue Gas Composition

Day 1 – Caballo		
Gas Component	Combustor Outlet	ESP or FF Outlet
O_2, %	4.59	5.99
CO_2, %	14.87	13.51
CO, ppm	3.80	4.38
SO_2, ppm	317	292
NO_x, ppm	874	771
Day 2 – Caballo		
Gas Component	Combustor Outlet	ESP or FF Outlet
O_2, %	4.38	6.73
CO_2, %	14.99	12.67
CO, ppm	3.82	3.96
SO_2, ppm	313	238
NO_x, ppm	899	741
Day 3 – Baseline Caballo		
Gas Component	Combustor Outlet	ESP or FF Outlet
O_2, %	4.89	6.46
CO_2, %	14.75	13.04
CO, ppm	3.54	3.85
SO_2, ppm	296	269
NO_x, ppm	881	728
Day 3 – Demeter Systems-Treated Caballo		
Gas Component	Combustor Outlet	ESP or FF Outlet
O_2, %	4.61	6.16
CO_2, %	15.11	13.72
CO, ppm	3.67	4.28
SO_2, ppm	1	6
NO_x, ppm	753	671
Day 4 – Caballo SDA–FF, Solucorp Industries SDA Additive		
Gas Component	Combustor Outlet	FF Outlet
O_2, %	4.67	5.40
CO_2, %	14.98	14.47
CO, ppm	3.69	2.43
SO_2, ppm	235	6
NO_x, ppm	954	927
Day 5 – WRI-Treated Caballo SDA–FF		
Gas Component	Combustor Outlet	FF Outlet
O_2, %	4.47	5.43
CO_2, %	14.98	13.98
CO, ppm	3.80	4.23
SO_2, ppm	305	57
NO_x, ppm	665	627
Day 5 – WRI-Treated Caballo ESP–FF		
Gas Component	Combustor Outlet	FF Outlet
O_2, %	4.77	6.28
CO_2, %	14.67	13.17
CO, ppm	3.75	4.09
SO_2, ppm	283	250
NO_x, ppm	589	566

Day 1 testing involved tests firing Caballo coal with the PTC system in the ESP–FF configuration. Tests were performed with ACI and SEA1 addition alone and in combination. ACI occurred between the ESP and FF (i.e., TOXECON).

Day 2 testing was performed firing Caballo coal in the PTC equipped with a FF and an ESP–FF. During the FF tests, the ESP remained in-line upstream of the FF, but the collection field was turned off. Tests were performed with ACI and SEA2 addition alone and in combination. Again, ACI occurred between the ESP and FF (TOXECON).

Day 3 testing involved an ESP–FF configuration and firing Demeter Systems-treated Caballo coal under baseline conditions, with the concurrent injection of EERC-treated carbon upstream of the ESP. Injection of Demeter Systems' additive was also performed upstream of the ESP before and after the carbon injection point.

Day 4 testing involved a SDA–FF configuration firing Caballo coal. Lime slurry with a proprietary Solucorp Industries additive was used in the SDA. Some of the flue gas from the combustor was bypassed around the SDA–FF to increase gas residence time in the SDA. Incremental bypassing of 20%, 33%, and eventually 50% of the flue gas flow was performed to evaluate the effects of residence time on Solucorp Industries additive–Hg interactions. Two tests were also performed with SEA1 addition combined with the Solucorp Industries SDA additive.

Day 5 testing involved firing the WRI thermally treated Caballo coal. The PTC was initially configured with a SDA–FF. Baseline testing and testing at two different DARCO FGD injection rates at the SDA inlet were performed. The system was then reconfigured to an ESP–FF, and similar baseline testing, and testing at two ACI rates was performed. Finally, the FF was turned off, and baseline and ACI testing was conducted with the ESP.

10.0 TEST COALS

Two subbituminous coals from the Caballo and Absaloka Mines and a bituminous coal from the Blacksville No. 2 Mine were utilized in this Hg control evaluation. Information on the three coals is presented in Table 10-1. The two subbituminous coals are part of the same extensive PRB, which is located in northeastern Wyoming and extends into southeastern Montana.

Table 10-1. Coal Information

Organization	Mine	Seams Mined	Location	Mine Production,[a] tons
Caballo Coal Co.	Caballo	Smith/Wyodak–Anderson	PRB, Wyoming	25,967,000
Washington Group International	Absaloka	Rosebud–McKay/McKay	PRB, Montana	5,283,532
Consol Energy Inc.	Blacksville No. 2	Pittsburgh	Northern Appalachia, Pennsylvania	4,816,887

[a] *Keystone Coal Industry Manual*; Mining Media: Prairieville, LA, 2004.

Coal proximate, ultimate, Hg, Cl, and bulk ash elemental oxide analysis results are presented in Tables 10-2–10-4. The Caballo and Absaloka coals possess the general characteristics of the subbituminous coals described in Section 2.3 of this report (i.e., low chlorine and sulfur and high alkaline-earth metal contents) that result in a combustion flue gas containing primarily Hg^0. Conversely, the Blacksville coal has the greater sulfur and chlorine and lower alkaline-earth metal contents that generally result in a combustion flue gas containing Hg^{2+} as the dominant Hg species.

Included in Tables 10-2–10-4 are the compositions of two Caballo coals that were pretreated for Hg_{total} control purposes. As expected, the WRI heat treatment of Caballo coal significantly reduced moisture and Hg contents. The Demeter Systems-treated (i.e., addition of IPE) Caballo coal is distinguished from the untreated Caballo coal by greater ash and chlorine concentrations and a lower sulfur concentration. The addition of chlorine may enhance Hg^0 oxidation during the combustion of the Demeter Systems-treated Caballo coal.

The parent coal compositions in Table 10-5 were used to calculate the chemical compositions of the coal blends that are also presented in Table 10-5. The coal blends contain significantly higher chlorine and sulfur contents relative to the parent subbituminous Caballo and Absaloka coals.

Table 10-2. Proximate and Heating Value Coal Analysis Results

Coal Name:	Caballo Initial Analysis	Caballo Week 1	Caballo Week 4	Caballo WRI-Treated	Caballo Demeter-Treated	Absaloka Week 3	Blacksville Week 3
Proximate Analysis, as-fired, wt%							
Moisture	28.20	28.27	17.60	5.40	18.90	20.70	1.30
Volatile Matter	34.62	34.44	29.45	42.59	38.72	33.36	37.10
Fixed Carbon	32.32	32.57	47.72	45.81	29.24	37.40	53.97
Ash	4.87	4.72	5.22	6.21	13.14	8.54	7.63
Heating Value, Btu/lb	8689	8739	9357	11,084	7648	9020	13,340
Proximate Analysis, dry basis, wt%							
Volatile Matter	48.24	47.92	35.76	45.02	47.73	42.09	37.58
Fixed Carbon	44.98	45.61	57.9	48.42	36.07	47.13	54.69
Ash	6.78	6.47	6.34	6.56	16.2	10.78	7.73
Heating Value, Btu/lb	12,109	12,186	11,361	11,717	9428	11,381	14,645

Table 10-3. Ultimate, Hg, and Cl Coal Analysis Results

Coal Name:	Caballo Initial Analysis	Caballo Week 1	Caballo Week 4	Caballo WRI-Treated	Caballo Demeter-Treated	Absaloka Week 3	Blacksville Week 3
Ultimate Analysis, as-fired, wt%							
Hydrogen	6.61	6.61	5.70	4.85	5.33	5.74	5.00
Carbon	49.37	48.68	54.20	64.97	46.50	52.18	75.32
Nitrogen	0.85	0.89	0.94	1.15	0.81	0.95	1.82
Sulfur	0.36	0.37	0.50	0.49	0.09	0.61	1.88
Oxygen	37.95	38.74	33.44	22.33	34.14	31.97	8.35
Ash	4.87	4.72	5.22	6.21	13.14	8.54	7.63
Ultimate Analysis, dry basis, wt%							
Hydrogen	4.84	4.83	4.54	4.49	3.98	4.34	4.92
Carbon	68.80	67.88	65.80	68.68	57.32	65.84	76.30
Nitrogen	1.18	1.24	1.14	1.22	1.00	1.20	1.84
Sulfur	0.50	0.51	0.61	0.52	0.12	0.78	1.90
Oxygen	17.90	18.96	21.57	18.53	21.38	17.06	7.31
Ash	6.78	6.59	6.34	6.56	16.20	10.78	7.73
Coal Analysis, dry basis, ppm							
Hg	NA	0.0985	0.1255	0.0449	0.099	0.0422	0.0722
Cl	NA	18	32.2	28.4	1150	6	961

Table 10-4. Bulk Coal Ash Chemical Compositions (expressed as weight percent equivalent oxide)

Coal Name:	Caballo Week 1	Caballo Week 4	Caballo WRI-Treated	Caballo Demeter-Treated	Absaloka Week 3	Blacksville Week 3
Oxide, wt%						
SiO_2	26.63	26.70	28.70	23.00	32.40	47.80
Al_2O_3	17.48	15.90	16.60	8.00	20.30	24.10
Fe_2O_3	6.15	5.87	5.84	2.64	3.58	16.26
TiO_2	1.45	1.36	1.46	0.48	0.65	0.96
P_2O_5	1.31	1.19	1.31	0.42	0.75	0.39
CaO	25.85	26.80	26.10	51.10	20.80	3.60
MgO	4.34	3.80	3.92	1.80	2.31	0.87
Na_2O	1.35	2.08	1.96	5.49	3.85	1.47
K_2O	0.23	0.16	0.16	0.48	0.27	1.31
SO_3	15.23	16.13	13.86	6.61	15.80	3.31
Oxide, wt%, sulfur-free basis						
SiO_2	31.43	31.90	33.40	24.70	38.20	49.40
Al_2O_3	20.58	19.00	19.30	8.60	23.90	24.90
Fe_2O_3	7.26	7.00	6.78	2.83	4.22	16.82
TiO_2	1.71	1.62	1.69	0.51	0.76	1.00
P_2O_5	1.55	1.42	1.53	0.45	0.88	0.41
CaO	30.50	31.90	30.30	54.70	24.50	3.70
MgO	5.12	4.53	4.55	1.92	2.72	0.90
Na_2O	1.59	2.48	2.27	5.88	4.53	1.52
K_2O	0.27	0.19	0.19	0.51	0.32	1.36

Table 10-5. Proximate, Heating, and Ultimate Values for the Parent Coals and Coal Blends

Coal Name:	Caballo Week 3	Absaloka Week 3	Blacksville Week 3	Caballo 90%–Blacksville 10%	Caballo 80%–Blacksville 20%	Absaloka 80%–Blacksville 20%
Proximate Analysis, as-fired, wt%						
Moisture	17.60	20.70	1.30	15.97	14.34	16.82
Volatile Matter	29.45	33.36	37.10	30.22	30.98	34.11
Fixed Carbon	47.72	37.40	53.97	48.35	48.97	40.71
Ash	5.22	8.54	7.63	5.46	5.70	8.36
Heating Value, Btu/lb	9357	9020	13,340	9755	10,154	9884
Ultimate Analysis, as-fired, wt%						
Hydrogen	5.70	5.74	5.00	5.63	5.56	5.59
Carbon	54.20	52.18	75.32	56.31	58.42	56.81
Nitrogen	0.94	0.95	1.82	1.03	1.12	1.12
Sulfur	0.50	0.61	1.88	0.64	0.78	0.86
Oxygen	33.44	31.97	8.35	30.93	28.42	27.25
Ash	5.22	8.54	7.63	5.46	5.70	8.36
Coal Analysis, dry basis, ppm						
Hg	0.1255	0.0422	0.0722	0.1202	0.1148	0.0482
Cl	32.25	6	961	125	218	197

11.0 RESULTS AND DISCUSSION

11.1 ESP Mercury Control

11.1.1 Baseline Mercury Speciation and ESP Control

Caballo and Absaloka subbituminous coals as well as 90:10 wt% and 80:20 wt% Caballo–Blacksville coal blends were combusted at a nominal feed rate of 70 lb/hr. Baseline testing was performed to determine Hg species concentrations in the flue gas at the ESP inlet and outlet.

Hg_{total} concentrations in Caballo combustion flue gas as determined with a CMM at the ESP inlet are shown in Figure 11-1. The error bars in Figure 11-1 and all subsequent figures represent plus or minus one standard deviation. Hg_{total} concentrations ranged from 10.4 to 13.2 µg/Nm^3 and generally increased during the testing period, suggesting variability in the coal Hg content. Compared in Figure 11-2 are CMM and OH baseline ESP inlet and outlet Hg_{total} and Hg^0 concentrations. The ESP inlet Hg_{total} and Hg^0 for the two methods are in good agreement; however, the outlet CMM Hg_{total} concentration is approximately 3 µg/Nm^3 higher than the corresponding OH value. Hg^0 was the dominant form, comprising 80%–90% of the Hg_{total} at the ESP inlet. Little Hg_{total} removal or conversion of Hg^0 to Hg^{2+} occurred across the ESP during baseline combustion conditions.

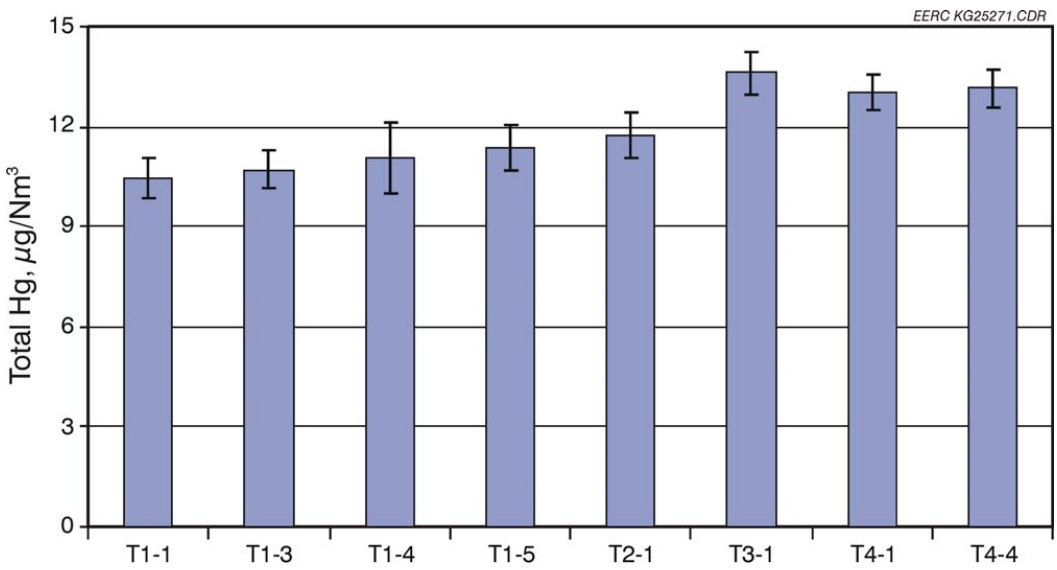


Figure 11-1. Baseline ESP inlet Hg_{total} concentrations measured during Caballo coal combustion.

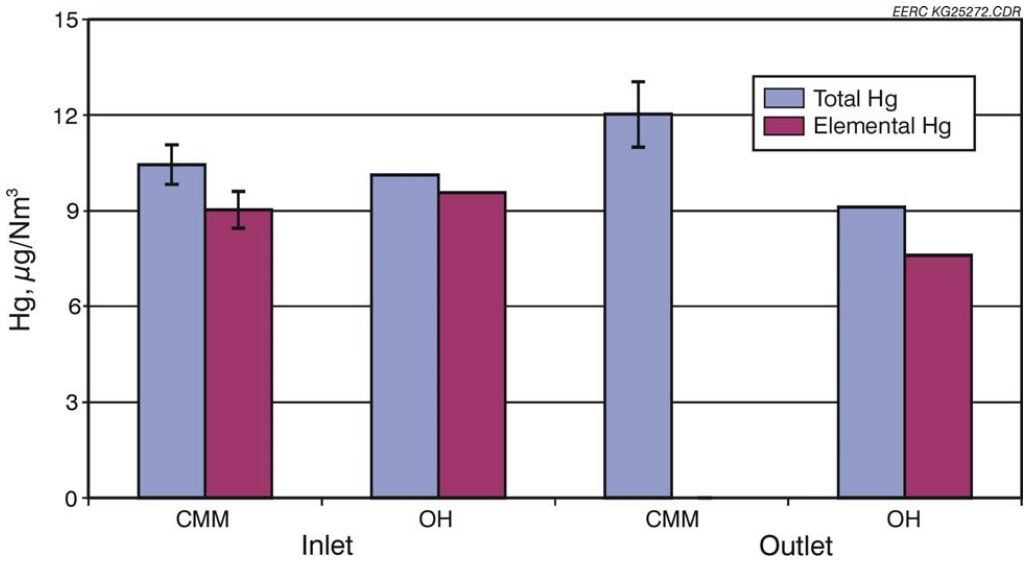


Figure 11-2. Comparison of CMM and OH baseline ESP inlet and outlet Hg_{total} and Hg^0 concentrations measured during Caballo coal combustion.

ESP inlet Hg_{total} concentrations for the test periods when Absaloka coal was fired are shown in Figure 11-3. As expected based on the coal analyses (Table 10-3), Hg_{total} concentration was less than that for the Caballo coal, ranging from 3.87 to 5.75 μg/Nm^3. CMM and OH measurements of Hg_{total} and Hg^0 concentrations at the ESP inlet and outlet compare favorably in Figure 11-4, with 66%–88% of the Hg_{total} as Hg^0 and no significant Hg removal across the ESP.

Figures 11-5 and 11-6 present the baseline ESP inlet Hg_{total} concentrations measured during the combustion of 90:10 wt% and 80:20 wt% blends of Caballo subbituminous coal with Blacksville bituminous coal, respectively. Over the relatively short duration of these tests, the inlet Hg_{total} concentration was consistently about 9.5 μg/Nm^3. Figure 11-7 shows a comparison of CMM and OH ESP inlet and outlet Hg_{total} and Hg^0 concentrations measured during the combustion of an 80:20 wt% Caballo–Blacksville coal blend. The ESP outlet CMM Hg_{total} value is somewhat higher than that of the outlet OH method, but the Hg^0 values are similar. Unfortunately, CMM data were unavailable for inlet Hg concentrations during this test period. OH measurements were not performed during combustion of the 90:10 wt% Caballo–Blacksville blend because of the short test duration.

11.1.2 ACIs and SEA1 Additions into Caballo Coal Combustion Flue Gas

The effects of DARCO FGD injection rate on ESP outlet Hg_{total} concentrations and ESP Hg_{total} removal efficiencies are shown in Figures 11-8 and 11-9, respectively. An injection rate of 5.4 lb/MMacf resulted in 44% Hg_{total} removal, and additional increases in the ACI rate did not substantially improve Hg_{total} capture. Only 58% Hg_{total} removal was achieved at an economically impractical injection rate of 13.4 lb/MMacf.

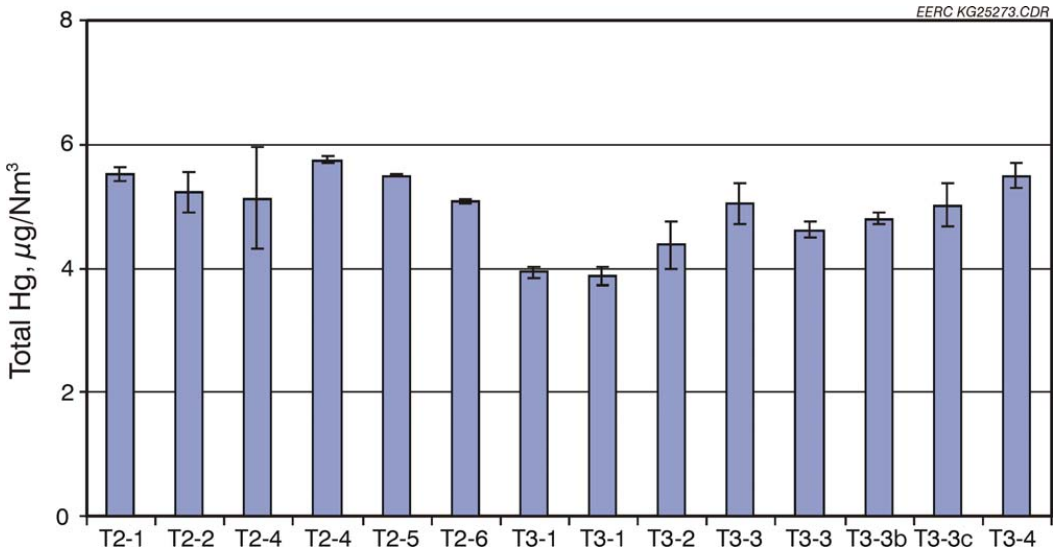


Figure 11-3. Baseline ESP inlet Hg_{total} concentrations measured during Absaloka coal combustion.

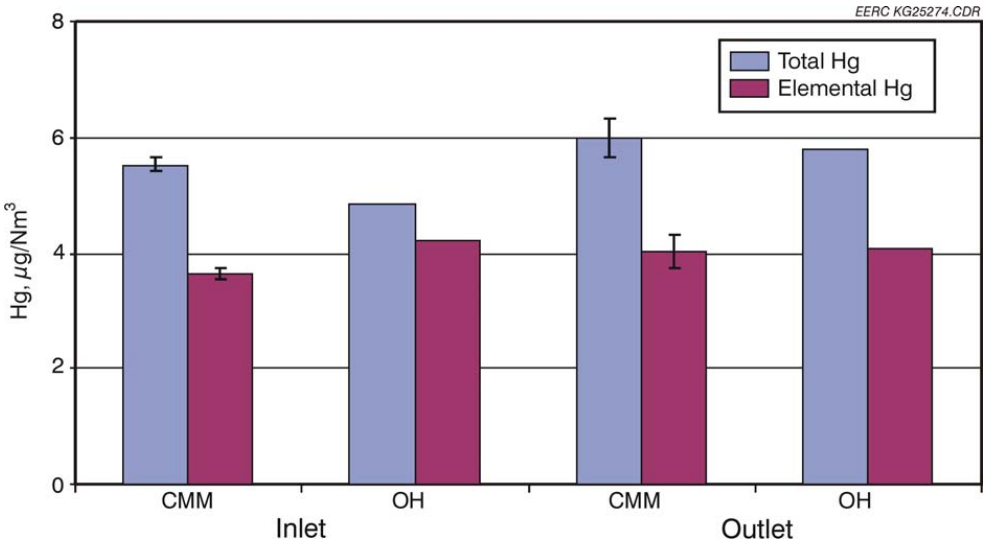


Figure 11-4. Comparison of CMM and OH baseline ESP inlet and outlet Hg_{total} and Hg^0 concentrations measured during Absaloka coal combustion.

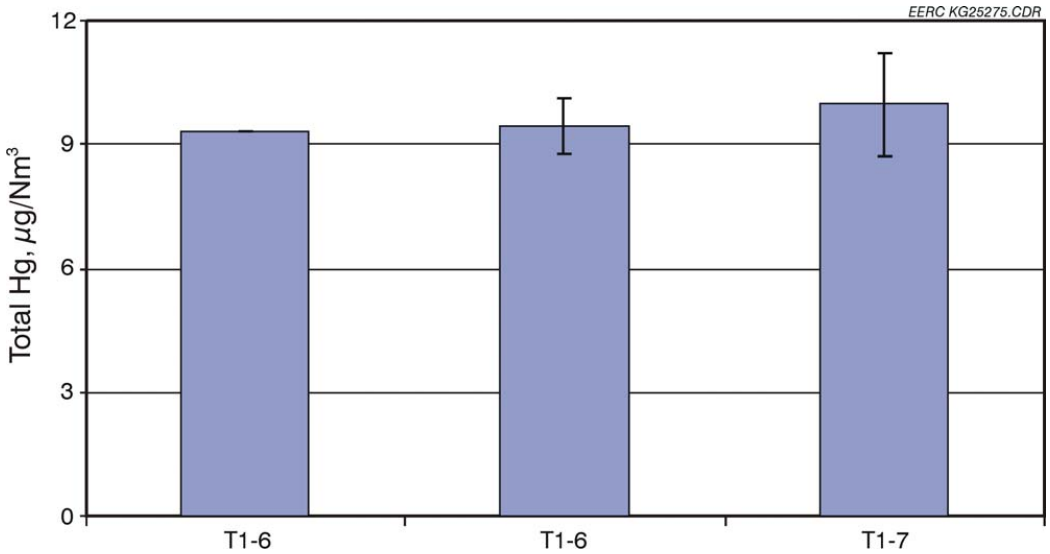


Figure 11-5. Baseline ESP inlet Hg_{total} concentrations measured during 90:10 wt% Caballo–Blacksville coal combustion.

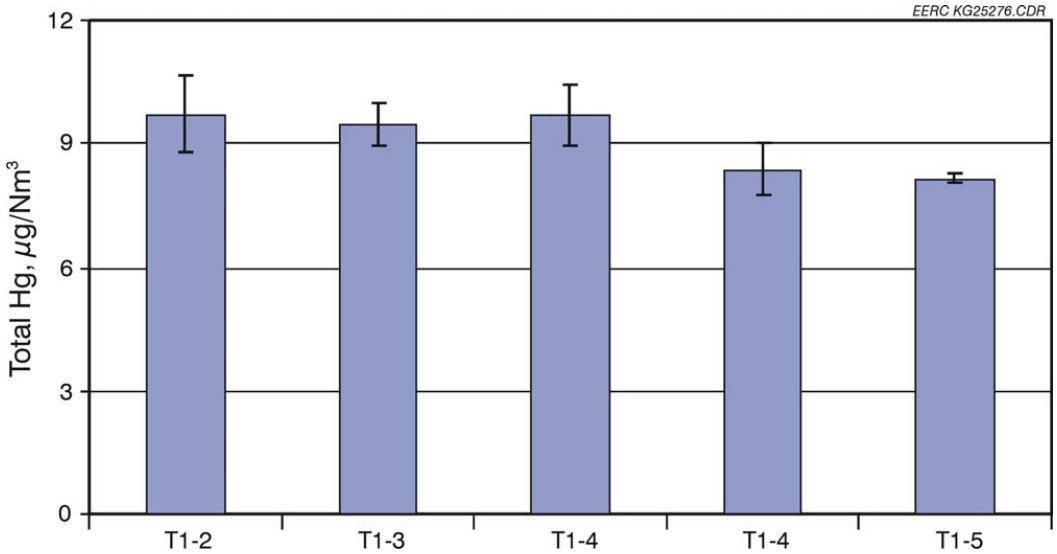


Figure 11-6. Baseline ESP inlet Hg_{total} concentrations measured during 80:20 wt% Caballo–Blacksville coal combustion.

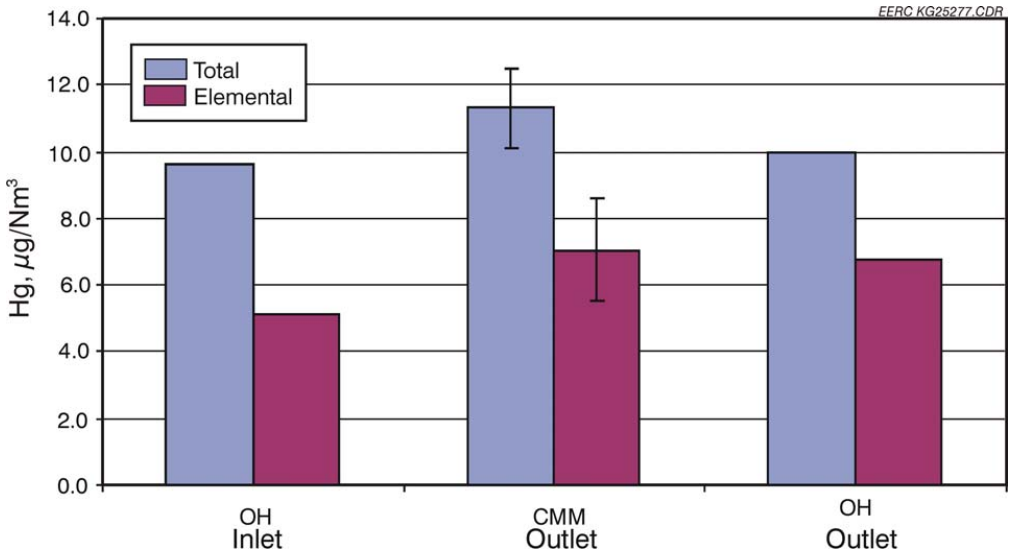


Figure 11-7. Comparison of CMM and OH baseline ESP Hg_{total} and Hg^0 concentrations measured during 80:20 wt% Caballo–Blacksville coal combustion.

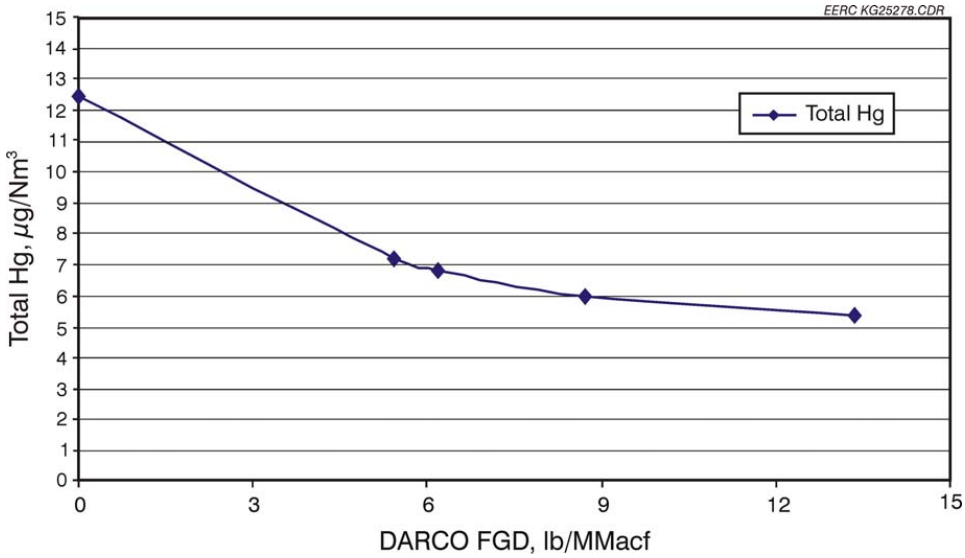


Figure 11-8. Effects of DARCO FGD injection on ESP outlet Hg_{total} concentrations during Caballo coal combustion.

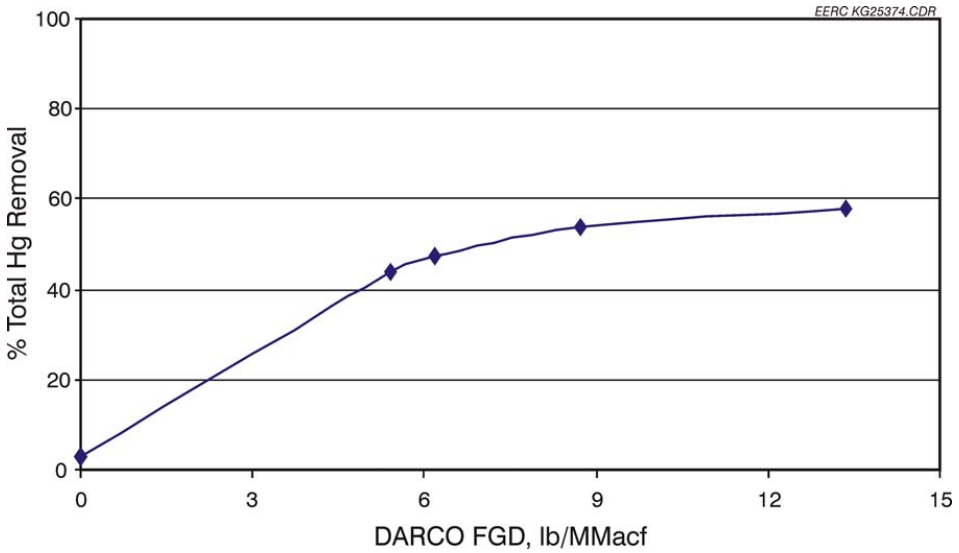


Figure 11-9. ESP Hg_{total} removal efficiency versus DARCO FGD injection rate into the Caballo coal combustion flue gas.

Particle-size and concentration measurements were performed at the ESP exit during baseline testing conditions and ACIs into the Caballo coal combustion flue gas. Results from these measurements are presented in Figure 11-10. The periodic large increases in median mass and number particle sizes and corresponding large decreases in mass concentrations are caused by ESP rapping. During baseline testing conditions, the fly ash mass concentration exiting the ESP was about 10 mg/m^3 and the median mass and number particle diameters were approximately 2.25 and 1 µm, respectively. ACI did not significantly affect particle size and concentration at the lower injection rates, but at 8.7 and 13.4 lb/MMacf the median mass particle size and mass concentration increased slightly, suggesting that the additional particle loading from ACI slightly reduced ESP collection efficiency.

SEA1 was added to the Caballo coal. The relationship between the SEA1 addition rate and HCl concentration in the Caballo coal combustion flue gas downstream of the ESP is shown in Figure 11-11. HCl concentrations gradually increased during the first two SEA1 additions, whereas during the last two higher addition rates, HCl concentrations increased rapidly in the system. Apparently, time was required for surfaces in the system to become saturated with chlorine before steady-state HCl concentrations in the Caballo flue gas could be attained.

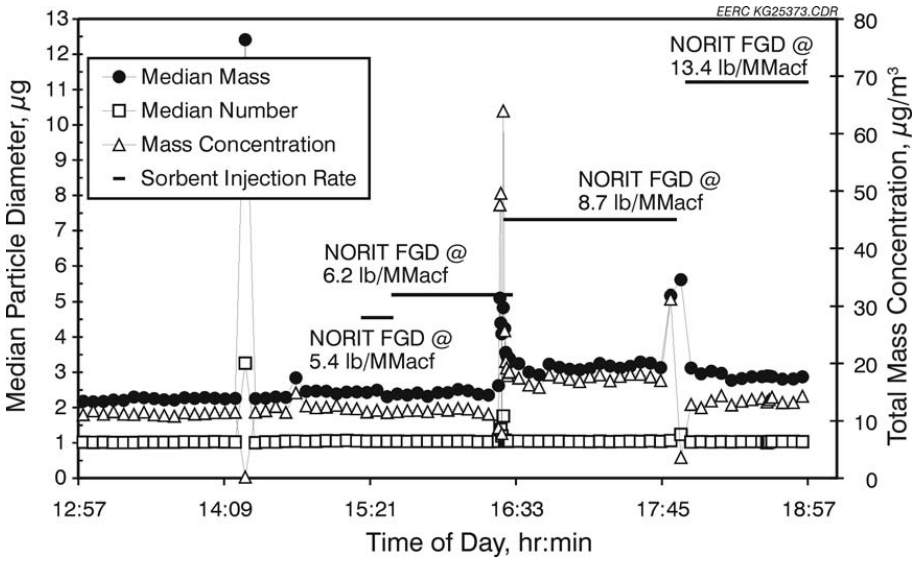


Figure 11-10. Online APS particle-size and concentration measurements during baseline testing conditions and ACI into the Caballo coal combustion flue gas.

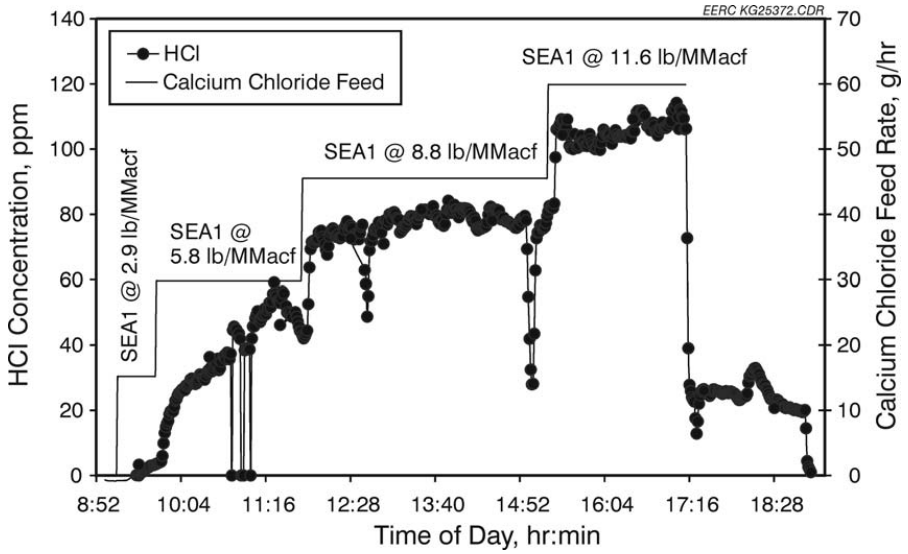


Figure 11-11. Temporal variations in ESP outlet HCl concentrations and SEA1 ($CaCl_2$) addition rates.

As indicated in Figure 11-12, SEA1 addition alone had a negligible effect on ESP Hg_{total} removal. However, SEA1 addition used in conjunction with DARCO FGD injection resulted in higher Hg_{total} removals compared to those obtained with ACI alone. SEA1 addition at a rate of 2.9 lb/MMacf along with 4.8 lb/MMacf ACI resulted in nearly 60% Hg_{total} removal.

The effects of SEA1 addition alone and in combination with DARCO FGD injection on ESP outlet Hg_{total} and Hg^0 concentrations and ESP Hg_{total} removal efficiencies are shown in Figures 11-13 and 11-14, respectively. Even though SEA1 addition alone reduced the proportion of Hg^0, it did not result in significant Hg_{total} removal. SEA1 addition combined with ACI resulted in substantial Hg_{total} removal. Increasing the addition rate of SEA1 above 2.9 lb/MMacf did not significantly increase Hg_{total} removal.

11.1.3 ACIs and SEA2 and SEA2–SEA1 Mixture Additions into Caballo Coal Combustion Flue Gas

The effectiveness of SEA2 addition, SEA2 additions combined with DARCO FGD injection, and a 50:50 wt% SEA1 and SEA2 mixture addition combined with ACI to remove Hg_{total} and Hg^0 from Caballo coal combustion flue gas is shown in Figures 11-15, 11-16, and 11-17. SEA2 addition at 1.9 lb/MMacf reduced the ESP outlet Hg_{total} concentration by 70%. When SEA2 was added during ACI, ESP Hg_{total} capture increased moderately to >80%. The Hg speciation results in Figure 11-16 suggest that in addition to Hg^0, some Hg^{2+} exited the ESP during the SEA2 and SEA2–SEA1 addition and ACI tests. The addition of the SEA1–SEA2 mixture at 0.5 lb/MMacf combined with ACI at 2.9 lb/MMacf resulted in a slightly lower ESP Hg_{total} removal as compared to the SEA2 addition and ACI tests.

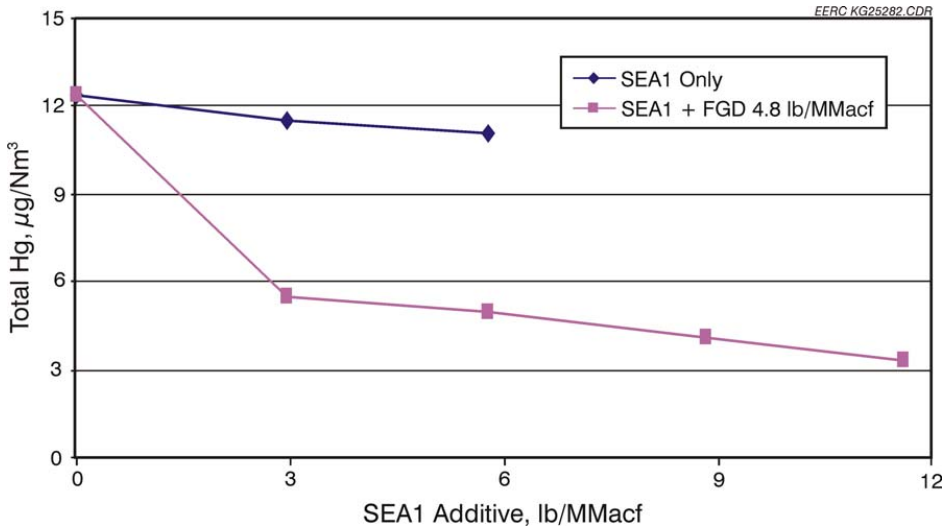


Figure 11-12. ESP outlet Hg_{total} concentrations measured during Caballo coal combustion and SEA1 additions alone and in combination with DARCO FGD injections.

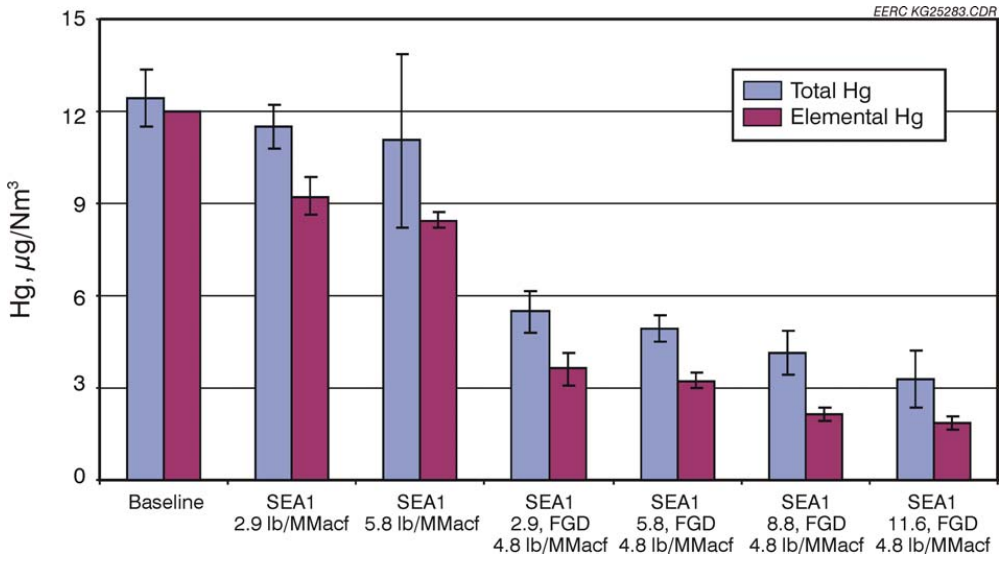


Figure 11-13. ESP outlet Hg_{total} and Hg^0 concentrations during Caballo coal combustion and SEA1 additions alone and in combination with DARCO FGD injections.

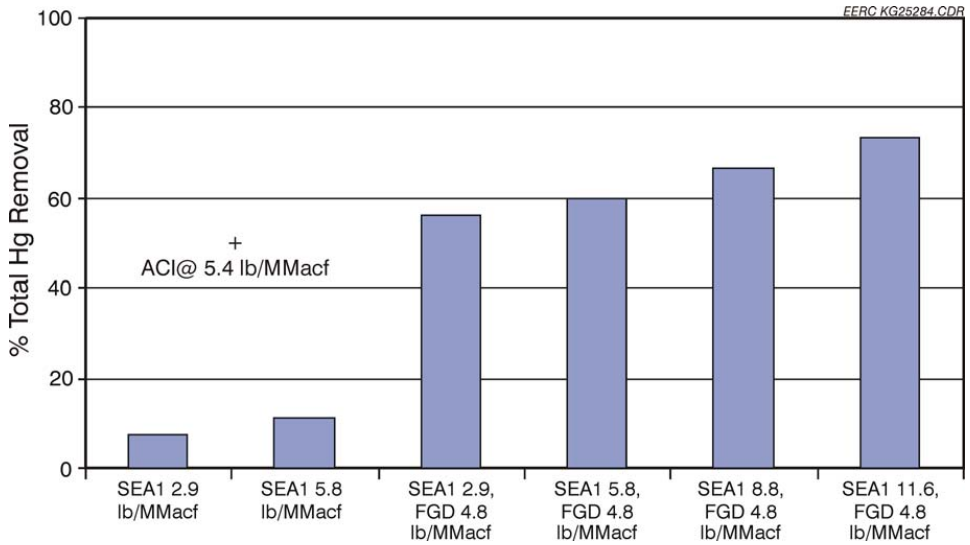


Figure 11-14. ESP Hg_{total} removals during SEA1 additions and DARCO FGD injections into the Caballo coal combustion flue gas.

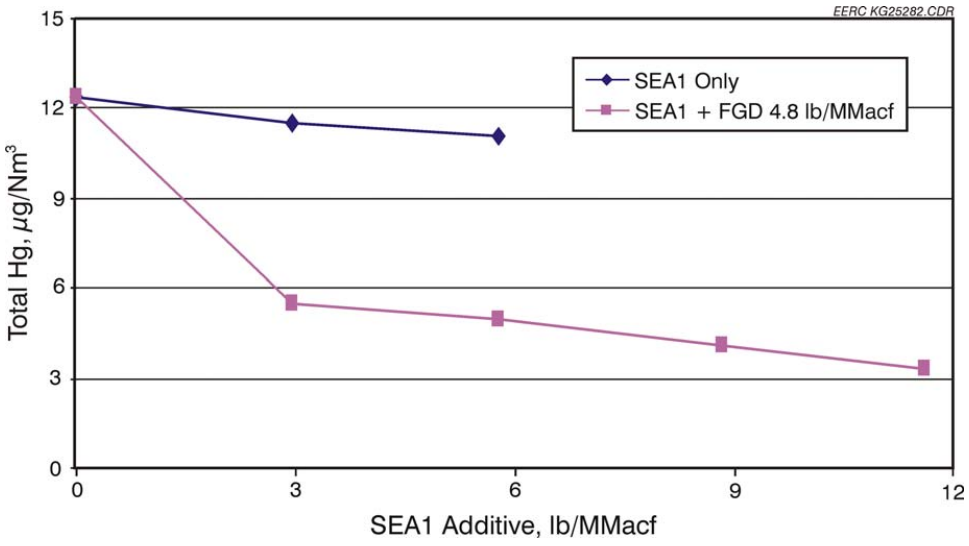


Figure 11-15. ESP outlet Hg_{total} concentrations during SEA2 addition, SEA2 additions and DARCO FGD injections and SEA1 and SEA2 mixture addition combined with DARCO FGD injection into the Caballo coal combustion flue gas.

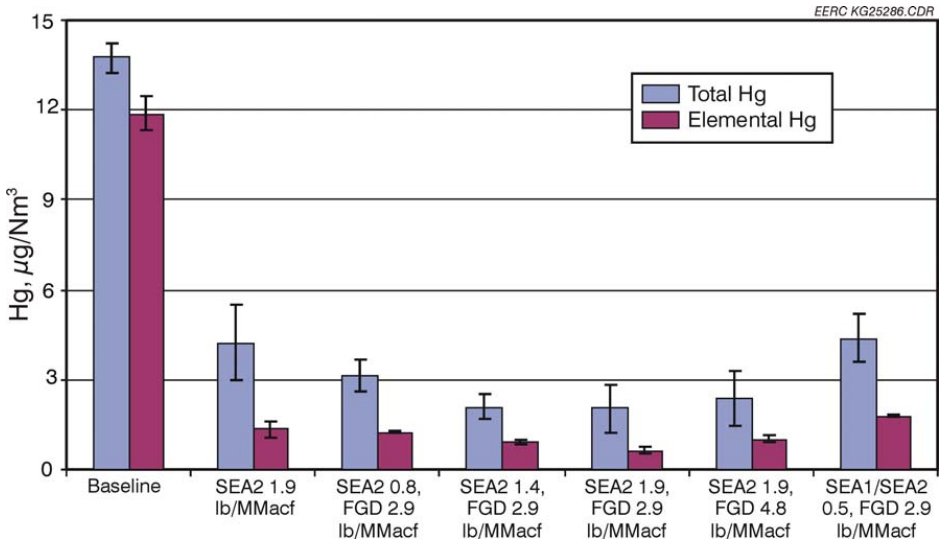


Figure 11-16. ESP outlet Hg_{total} and Hg^0 concentrations during SEA2 addition, SEA2 additions and DARCO FGD injections, and SEA1 and SEA2 mixture addition combined with DARCO FGD injection into the Caballo coal combustion flue gas.

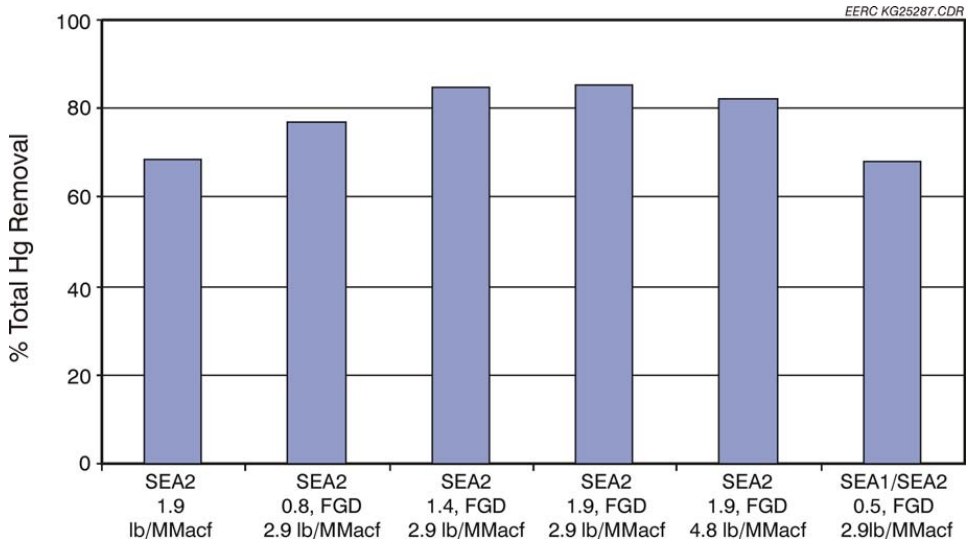


Figure 11-17. ESP Hg_{total} removal efficiencies during SEA2 addition, SEA2 additions and DARCO FGD injections, and SEA1 and SEA2 mixture addition combined with DARCO FGD injection into the Caballo coal combustion flue gas.

11.1.4 EERC-Enhanced Carbon Injections into Caballo Coal Combustion Flue Gas

The EERC treated DARCO FGD with a proprietary process to improve Hg_{total} adsorption. The EERC-enhanced carbon was tested in the ESP test configuration with Caballo coal at two injection rates; Hg_{total} and Hg^0 concentrations at the ESP outlet are presented in Figure 11-18. Unfortunately, no Hg^0 CMM data were available during the 6.8 lb/MMacf injection rate. ESP Hg_{total} removal efficiencies were approximately 60% at 4.8 lb/MMacf and 75% at 6.8 lb/MMacf, as shown in Figure 11-19. The Hg_{total} removal performance of the EERC-enhanced carbon is compared with DARCO FGD in Figure 11-20. At similar injection rates, the EERC-enhanced carbon removed 15%–20% more Hg_{total} relative to untreated DARCO FGD.

11.1.5 Amended Silicate Injections into Caballo Coal Combustion Flue Gas

Amended Silicate was injected into a Caballo coal combustion flue gas upstream of an ESP at 4.8 to 9.7 lb/MMacf. Test results indicating ESP Hg_{total} removal efficiencies of 37% and 40% at Amended Silicate injections of 4.8 and 9.7 lb/MMacf, respectively, are shown in Figures 11-21 and 11-22. Figure 11-23 compares ESP Hg_{total} removals as a function of injection rate for the EERC-enhanced carbon, Amended Silicate, and DARCO FGD. The Amended Silicate is moderately less effective than the DARCO FGD carbon at comparable injection rates. Higher Hg_{total} removal efficiencies have been reported in previous testing with Amended Silicate.

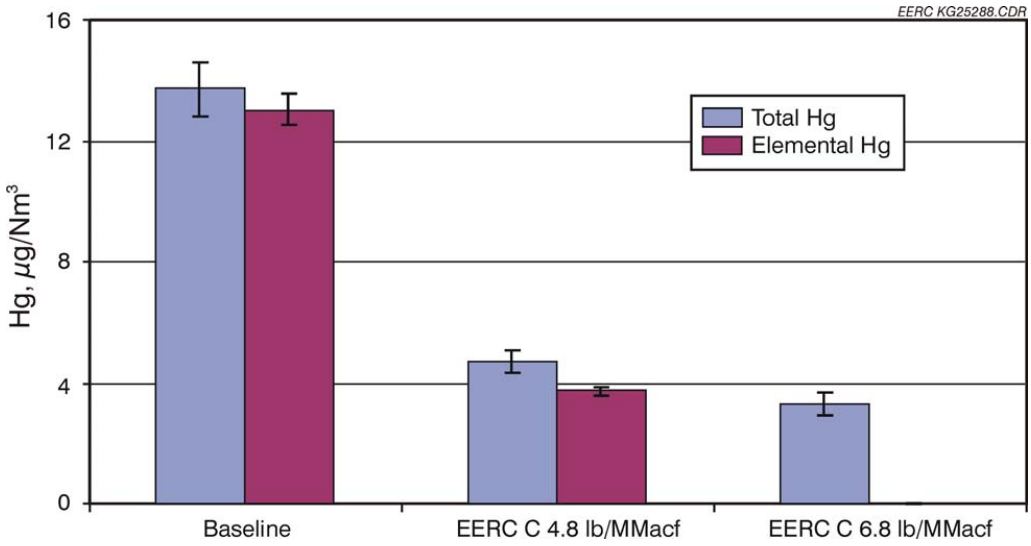


Figure 11-18. Comparison of ESP baseline outlet Hg_{total} and Hg^0 concentrations to those obtained during EERC-enhanced carbon injections into the Caballo coal combustion flue gas.

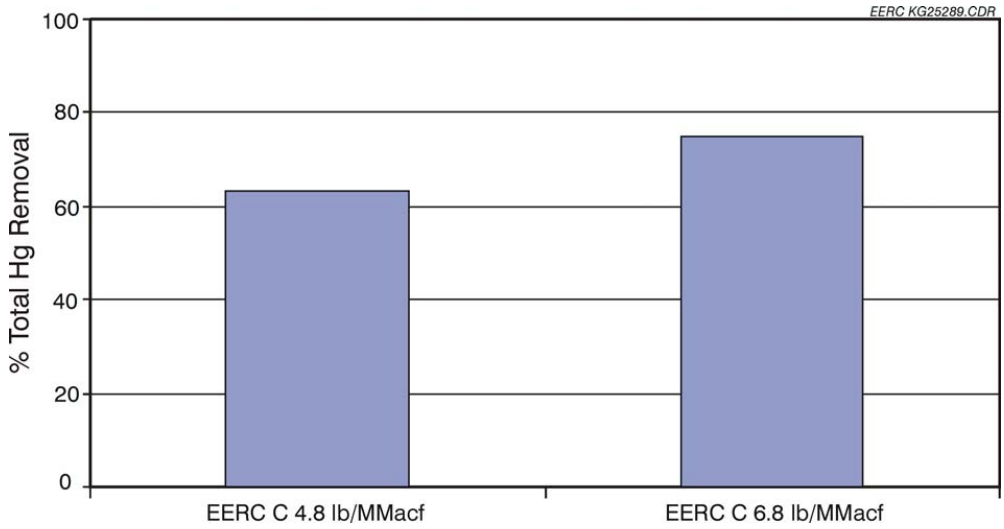


Figure 11-19. ESP Hg_{total} removal efficiencies during EERC-enhanced carbon injections into the Caballo coal combustion flue gas.

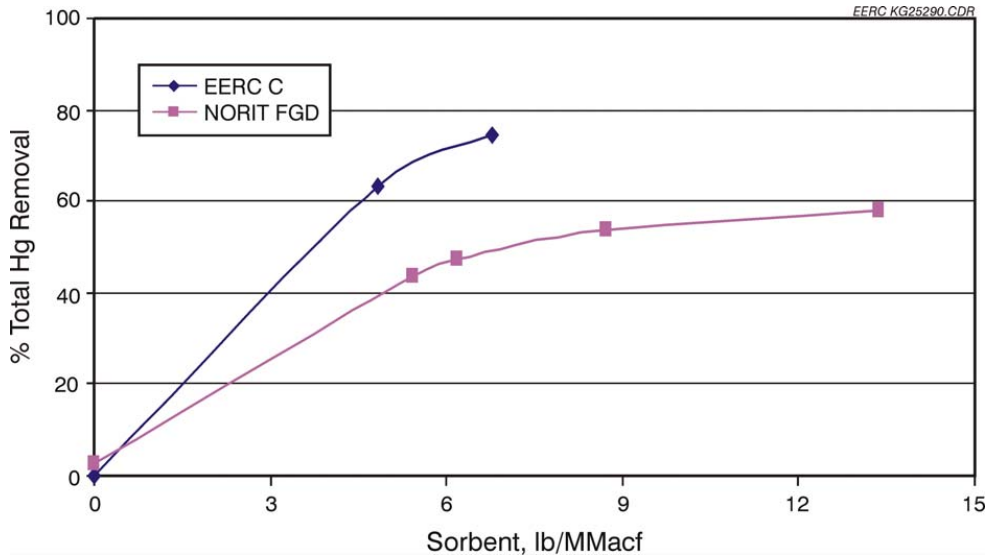


Figure 11-20. Comparison of ESP Hg_{total} removal efficiencies during EERC-enhanced carbon and DARCO FGD injections into the Caballo coal combustion flue gas.

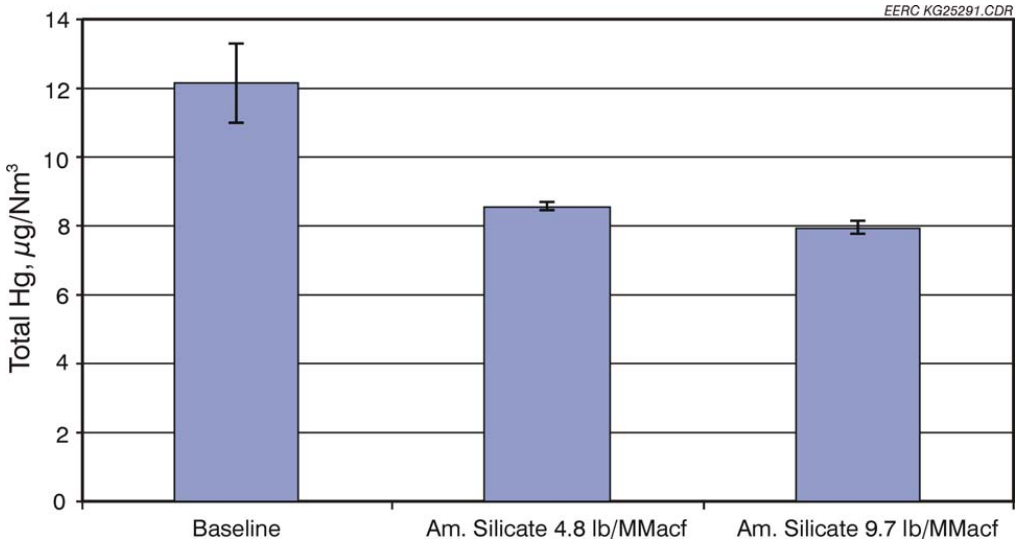


Figure 11-21. ESP outlet Hg_{total} concentrations during baseline conditions and the injection of Amended Silicate into the Caballo coal combustion flue gas.

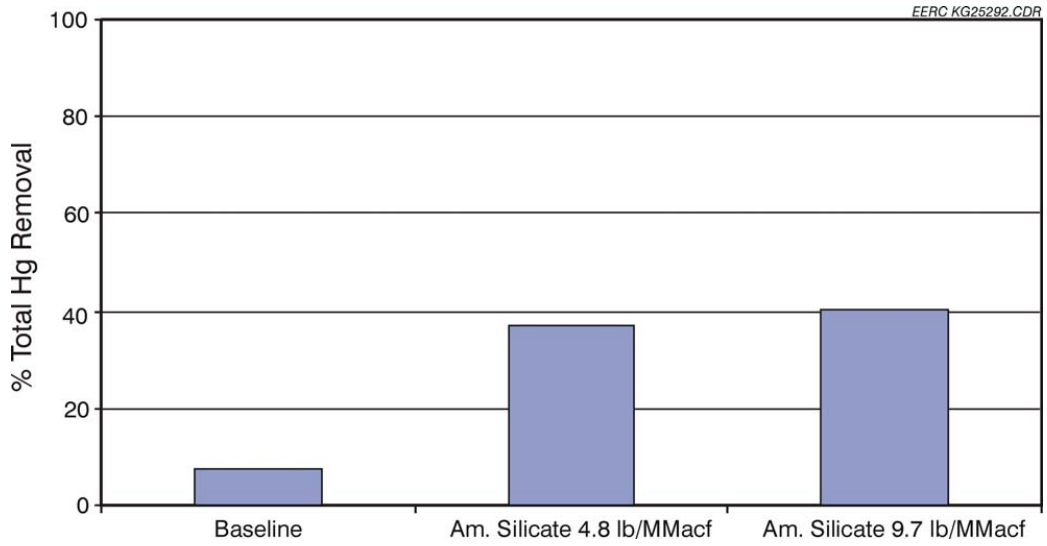


Figure 11-22. ESP Hg_{total} removal efficiencies during baseline conditions and the injection of Amended Silicate into the Caballo coal combustion flue gas.

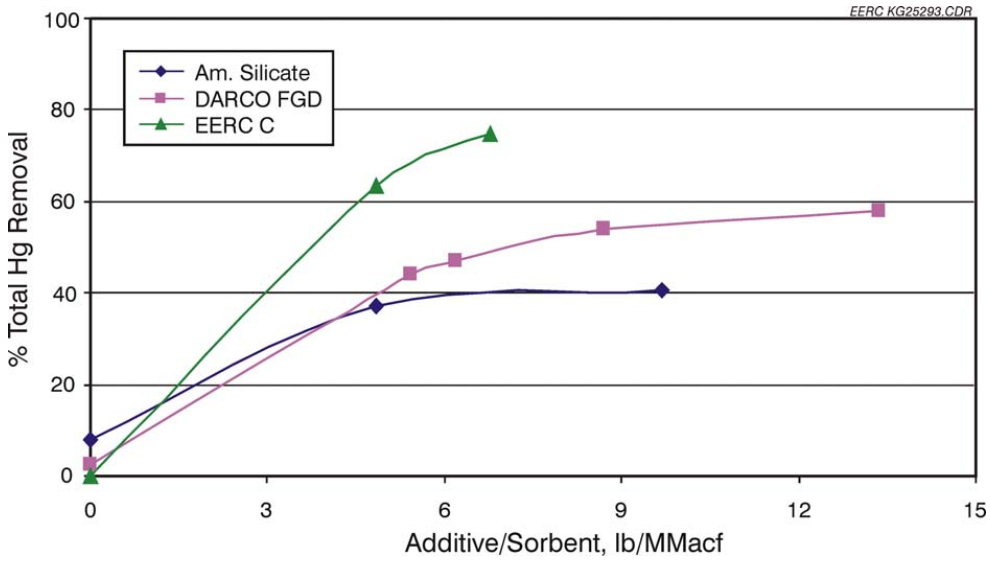


Figure 11-23. Comparison of ESP Hg_{total} removal efficiencies during the injections of Amended Silicate, EERC-enhanced carbon, and DARCO FGD into the Caballo coal combustion flue gas.

11.1.6 ACIs and SEA2 Additions into Absaloka Coal Combustion Flue Gas

DARCO FGD injections alone and in combination with SEA2 addition were tested using an Absaloka coal combustion flue gas. ESP outlet Hg_{total} and Hg^0 concentrations measured during the tests are presented in Figure 11-24, and ESP Hg_{total} removal efficiencies are plotted in Figure 11-25. Most, 67%, of the Hg_{total} in the baseline Absaloka coal combustion flue gas exiting the ESP was Hg^0. ACI at 4.8 lb/MMacf resulted in a 36% Hg_{total} removal efficiency which is similar to the ~40% reduction achieved for the Caballo coal combustion flue gas at a similar injection rate (Figure 11-9). SEA2 addition at 0.5 lb/MMacf combined with ACI at 4.8 lb/MMacf greatly improved ESP Hg_{total} removal to 84%. This level of ESP Hg_{total} removal is comparable to that achieved with similar addition rates of DARCO FGD and SEA2 into the Caballo coal combustion flue gas (Figure 11-17).

11.1.7 German Carbon Injection into the Absaloka Coal Combustion Flue Gas

Results of testing the alternative German carbon at two injection rates with Absaloka coal are shown in Figures 11-26 and 11-27. Total Hg removal at an injection rate of 4.8 lb/MMacf was 35%, which is comparable to the performance achieved with DARCO FGD injection into the Absaloka coal combustion flue gas at the same injection rate. Doubling the alternative carbon injection rate to 9.6 lb/MMacf slightly improved ESP Hg_{total} removal, as shown in Figure 11-27. The alternative carbon provided ESP Hg_{total} removal performance similar to the DARCO FGD carbon.

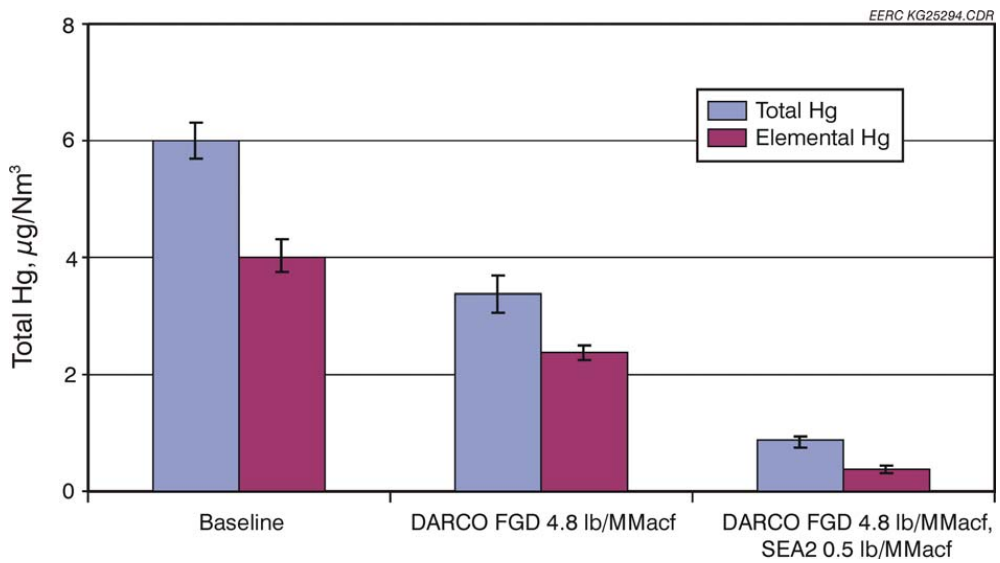


Figure 11-24. ESP outlet Hg_{total} and Hg^0 concentrations during baseline conditions and DARCO FGD injections alone and in combination with SEA2 addition into the Absaloka coal combustion flue gas.

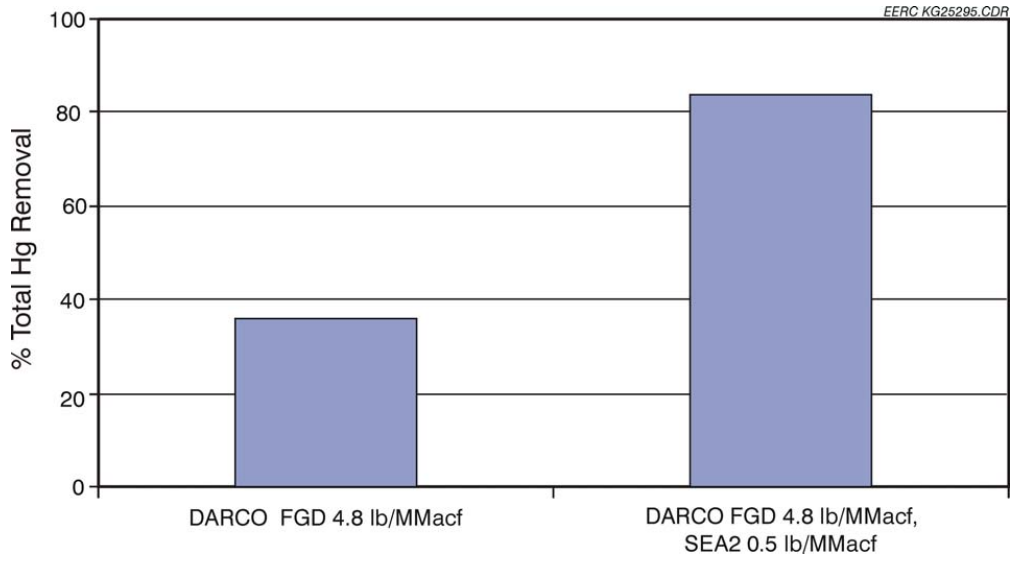


Figure 11-25. ESP Hg_{total} removal efficiencies during DARCO FGD injection alone and combined with SEA2 addition into an Absaloka coal combustion flue gas.

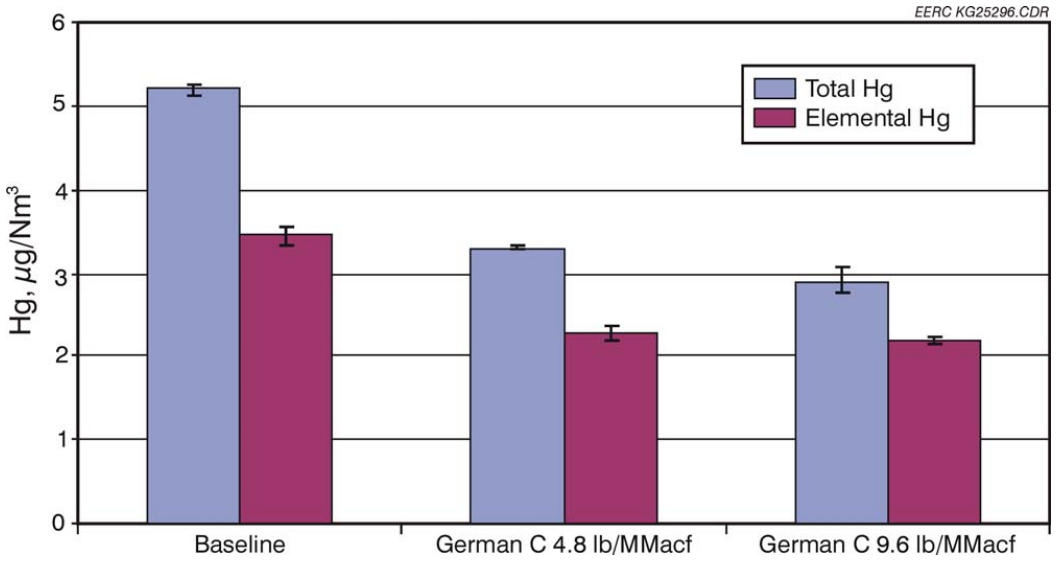


Figure 11-26. ESP outlet Hg_{total} and Hg^0 concentrations during baseline conditions and German carbon injections into Absaloka coal combustion flue gas.

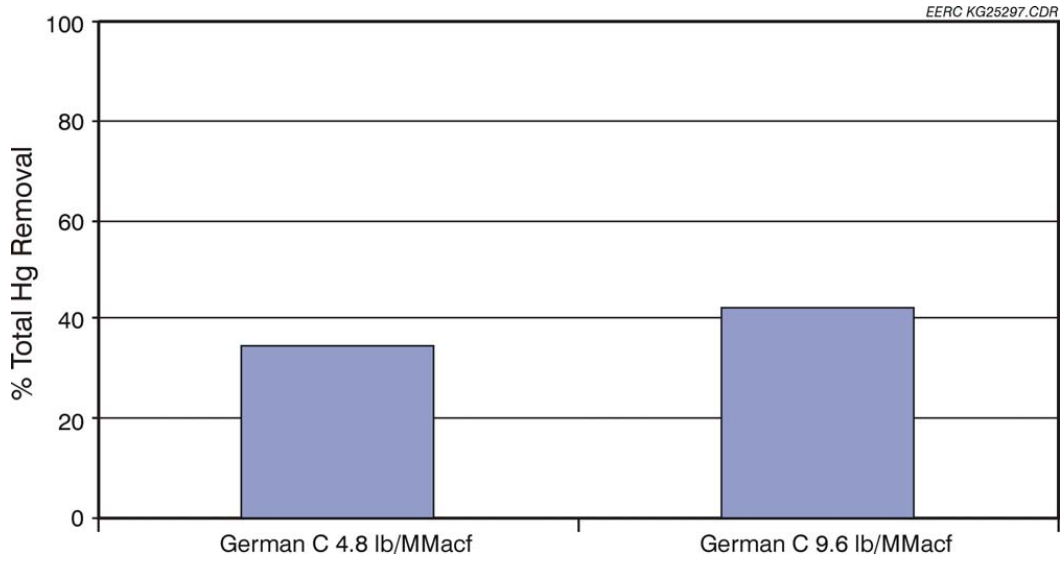


Figure 11-27. ESP Hg_{total} removal efficiencies during German carbon injections into Absaloka coal combustion flue gas.

11.1.8 Washington University TiO_2/UV Technology for Capturing Hg_{total} from the Absaloka Coal Combustion Flue Gas

Fine TiO_2 particles were injected upstream of the ESP, and liquid titanium isopropoxide was injected at the combustor exit into an Absaloka coal combustion flue gas. The liquid titanium isopropoxide injection rate was uncertain and, therefore, is not reported. Two UV light sources were used: one in a port shining down the ductwork upstream of the ESP and the second in a port shining down the length of the ESP itself. CMM ESP outlet Hg_{total} and Hg^0 concentrations and ESP removal efficiencies for the tests are presented in Figures 11-28 and 11-29, respectively. The TiO_2 particle and liquid titanium isopropoxide injections did not significantly affect ESP outlet Hg_{total} and Hg^0 concentrations and, thus, ESP Hg_{total} removal performance. The lack of ESP Hg_{total} removal during the TiO_2 injections was probably caused by insufficient UV lamp intensity, light losses because of the dusty flue gas environment, and short residence time in the light path.

11.1.9 Na_2S_4 Additions and DARCO FGD Injection into Absaloka Coal Combustion Flue Gas

ESP outlet Hg_{total} and Hg^0 concentrations measured during baseline testing conditions and aqueous Na_2S_4 injections alone and combined with DARCO FGD injection into Absaloka coal

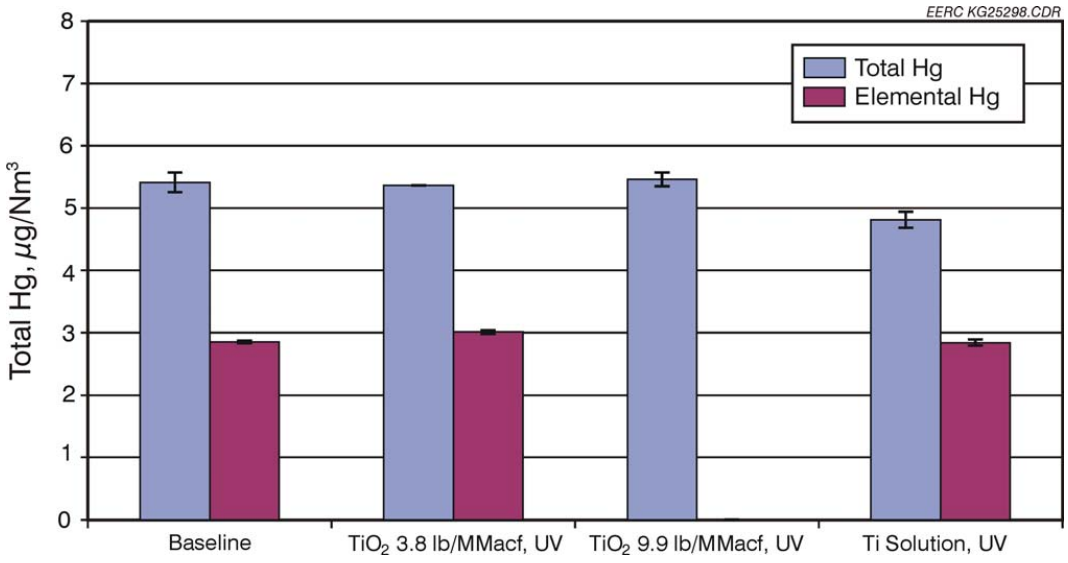


Figure 11-28. EPS outlet Hg_{total} and Hg^0 concentrations during baseline conditions and TiO_2 particle and liquid titanium isopropoxide injections into the Absaloka coal combustion flue gas.

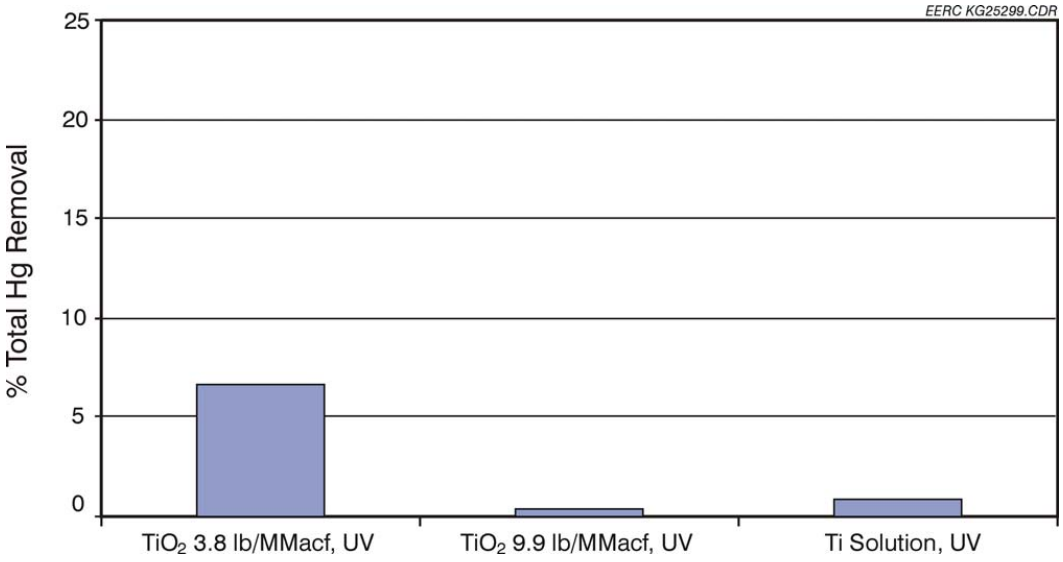


Figure 11-29. ESP Hg_{total} removal efficiencies during TiO_2 particle and liquid titanium isopropoxide injections into the Absaloka coal combustion flue gas.

combustion flue gas are presented in Figure 11-30. Na_2S_4 was injected at rates resulting in flue gas Na_2S_4 concentrations of 50 or 100 mg/Nm^3. During one of the 100 mg/Nm^3 Na_2S_4 injection tests, insulation from the injection nozzle was removed and is so denoted in Figure 11-30. ESP outlet Hg_{total} concentrations and the Hg_{total}–Hg^0 ratio decreased during Na_2S_4 additions. As indicated in Figure 11-31, Na_2S_4 injection alone resulted in <30 % ESP Hg_{total} removal. Na_2S_4 and 4.8-lb/MMacf ACI resulted in an ESP Hg_{total} removal efficiency of 32%, which was about equivalent to similar tests involving ACI into Absaloka coal combustion flue gas (Figures 11-24 and 11-25).

11.1.10 ACIs into Caballo–Blacksville Coal Blend Combustion Flue Gases

A potential method for increasing the Hg^{2+}–Hg^0 ratio in subbituminous coal combustion flue gases is coal blending with a high-chlorine-content bituminous coal. As opposed to SEA1 addition, bituminous coal blending has the added benefit of increasing the fuel heating value. A subbituminous Caballo coal and blends of 80:20 wt% and 90:10 wt% Caballo coal–bituminous Blacksville coal were fired in the PTC equipped with an ESP. In addition to coal blending, DARCO FGD was injected at several different rates into flue gases produced from firing the Caballo and two coal blends.

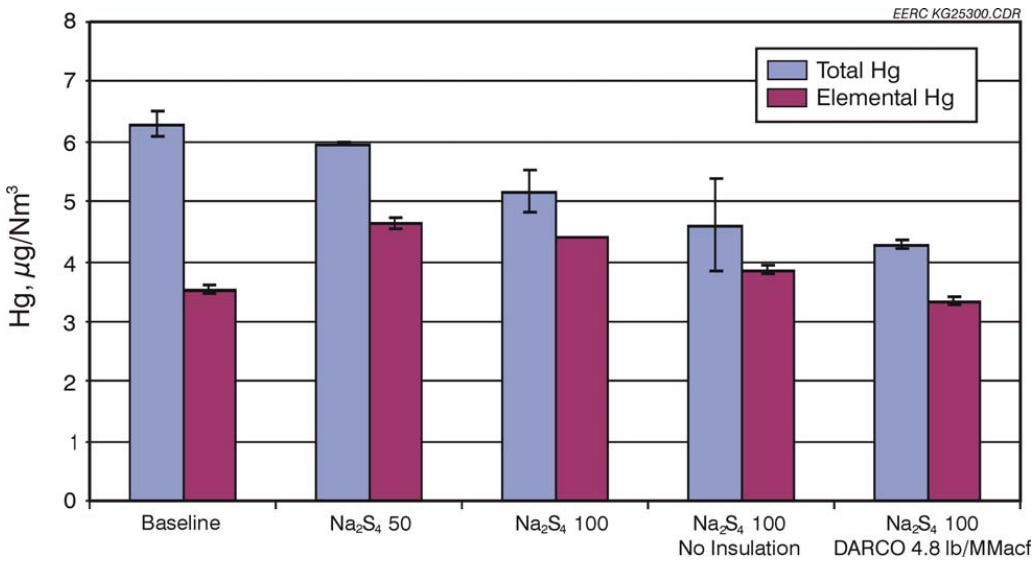


Figure 11-30. ESP outlet Hg_{total} and Hg^0 concentrations during baseline testing conditions and during Na_2S_4 additions alone and in combination with DARCO FGD injection into Absaloka coal combustion flue gas.

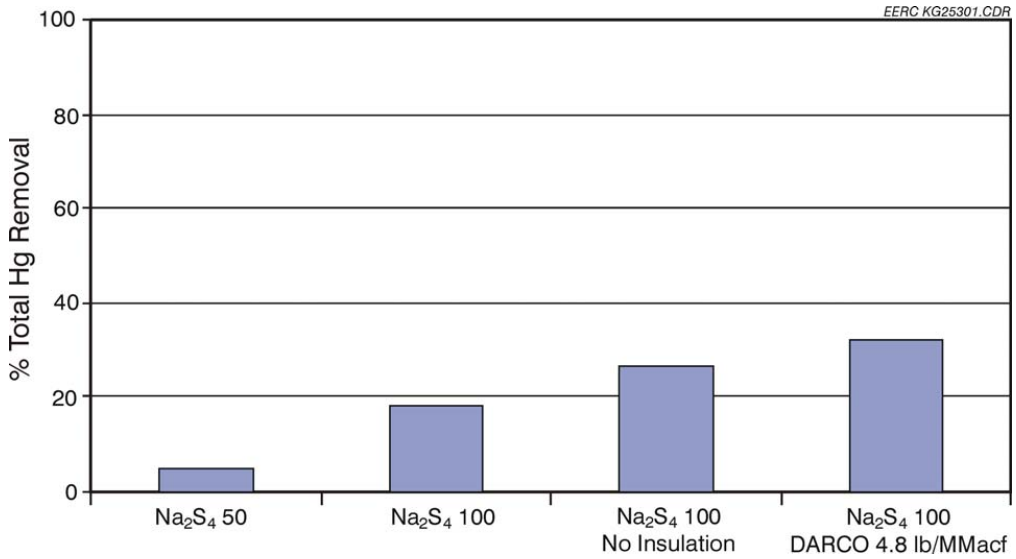


Figure 11-31. ESP Hg_{total} removal efficiencies during Na_2S_4 additions alone and in combination with DARCO FGD injection into Absaloka coal combustion flue gas.

ESP outlet Hg_{total} concentrations and ESP Hg_{total} removal efficiencies during combustion of the Caballo coal and coal blends are presented in Figures 11-32 and 11-33, respectively. Results are also presented in Figures 11-32 and 11-33 that indicate the effects of ACI on ESP outlet Hg_{total} concentrations and ESP Hg_{total} removal efficiencies. ESP Hg_{total} removal during 4.8 lb/MMacf ACI into the 80:20 wt% Caballo–Blacksville coal blend was 54%. ESP Hg_{total} removal results for the 90:10 wt% Caballo–Blacksville coal blend were essentially identical to those obtained during the combustion of the 80:20 wt% blend, suggesting that a sufficient amount of chlorine was made available to react with Hg^0 even at the lower blend level. The effects of coal blending on ESP Hg_{total} removal are comparable to those described for SEA1 addition combined with DARCO FGD injection (Figures 11-12 and 11-13). Blending with a high-chlorine-content bituminous coal appears to be an alternative to SEA1 addition to enhance Hg^0 oxidation and improve Hg_{total} capture by a sorbent.

11.1.11 ACI into WRI Heat-Treated Caballo Coal Combustion Flue Gas

The effects of injecting DARCO FGD into WRI-treated Caballo coal combustion flue gas on ESP Hg_{total} removal performance are presented in Figures 11-34 and 11-35. Duplicate tests are presented for the baseline testing condition and during ACI at 2.50 lb/MMacf. Also presented in Figure 11-34 are the baseline testing results for the untreated Caballo coal combustion flue gas. The WRI treatment reduced the Hg_{total} concentration by about 60%. During baseline testing, the ESP did not capture Hg_{total}. ACI at 1.26 lb/MMacf resulted in an ESP Hg_{total} removal of 29%. Increasing the ACI rate to 2.5 lb/MMacf improved the Hg_{total} removal to 52%–57%.

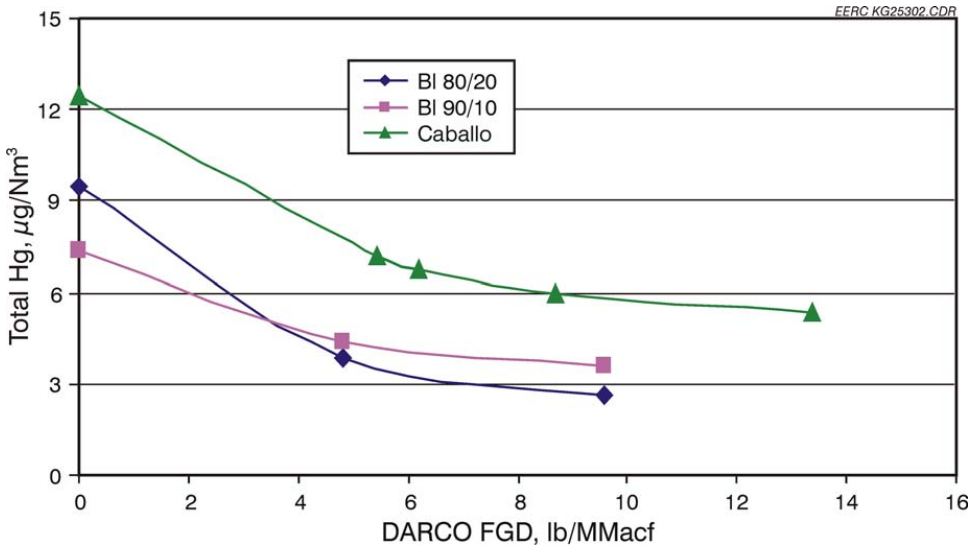


Figure 11-32. ESP outlet Hg_{total} concentrations during Caballo–Blacksville coal blend combustion and DARCO FGD injections.

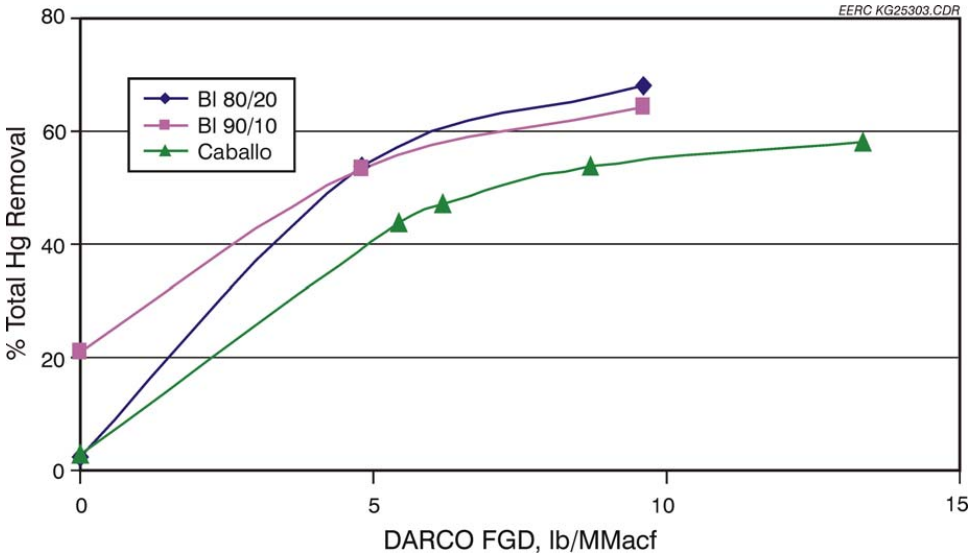


Figure 11-33. ESP Hg_{total} removal efficiencies during Caballo–Blacksville coal blend combustion and DARCO FGD injections.

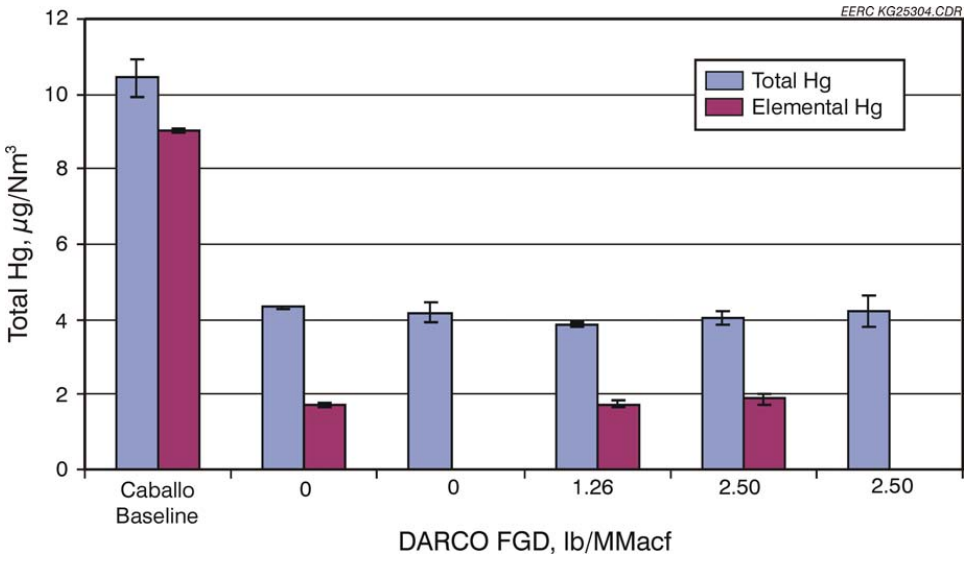


Figure 11-34. ESP inlet and outlet Hg_{total} concentrations during baseline testing conditions and DARCO FGD injections into WRI-treated Caballo coal combustion flue gas.

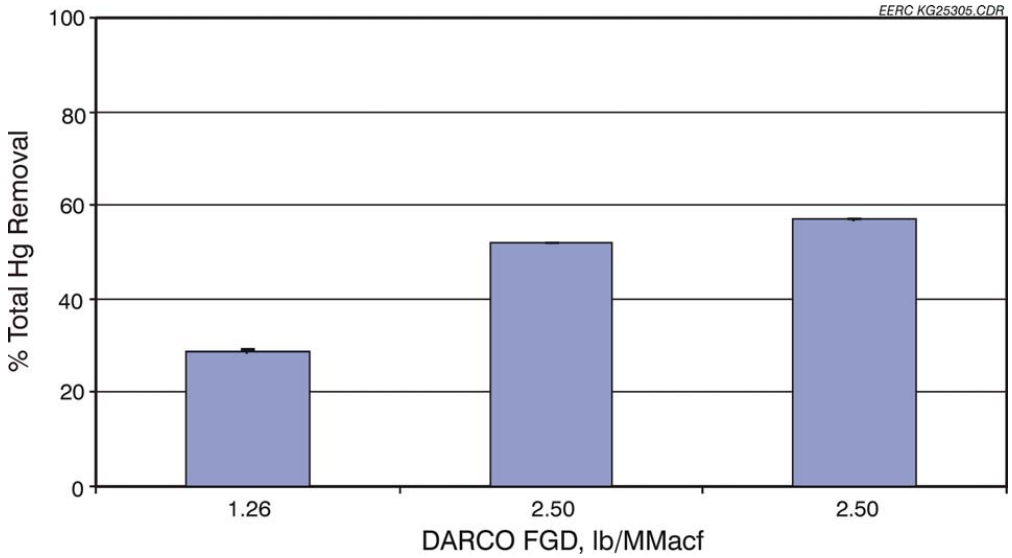


Figure 11-35. ESP Hg_{total} removal efficiencies during DARCO FGD injections into WRI-treated Caballo coal combustion flue gas.

11.2 ESP–FF Mercury Control

The PTC was configured with the pilot-scale ESP followed by a FF as shown in Figure 11-36. Testing involved SEA addition to the coal being fired as well as ACIs between the ESP and FF (i.e., TOXECON). The coal combustion flue gas exiting the PTC was cooled to a nominal temperature of 149°C (300°F) before entering the ESP and FF. The ESP was operated at 40–60 kV, with a corona current of 4.0 mA. FF temperature was maintained by an external electric heater at a nominal temperature of 300°F. The FF was equipped with two Gore Teflon bags, giving an air/cloth ratio of 5.6 ft/min. Additives were added to coal prior to introduction to the furnace. Mercury sorbents were fed with a K-Tron dual-screw feeder upstream of the FF. The feeder was calibrated prior to the start of sorbent injection. CMMs were used to monitor Hg_{total} and Hg^0 concentrations at the ESP inlet and FF outlet. Selected OH sampling was performed at the ESP inlet and FF outlet during the testing period to verify CMM results.

11.2.1 Baseline Test Results for Caballo Coal

Baseline Caballo coal combustion flue gas Hg_{total} concentrations measured at the ESP inlet are presented in Figure 11-37. Concentration values were very consistent at approximately 10 µg/Nm^3. Figure 11-38 compares CMM and OH baseline ESP inlet and FF outlet Hg_{total} and Hg^0 measurement results. ESP inlet Hg^0 CMM results are not plotted in Figure 11-38 because the measurements were inadvertently not made. The inlet Hg_{total} values compare well, but the outlet OH Hg^0 and Hg_{total} values are higher than the corresponding CMM measurements. The outlet OH Hg_{total} value is also

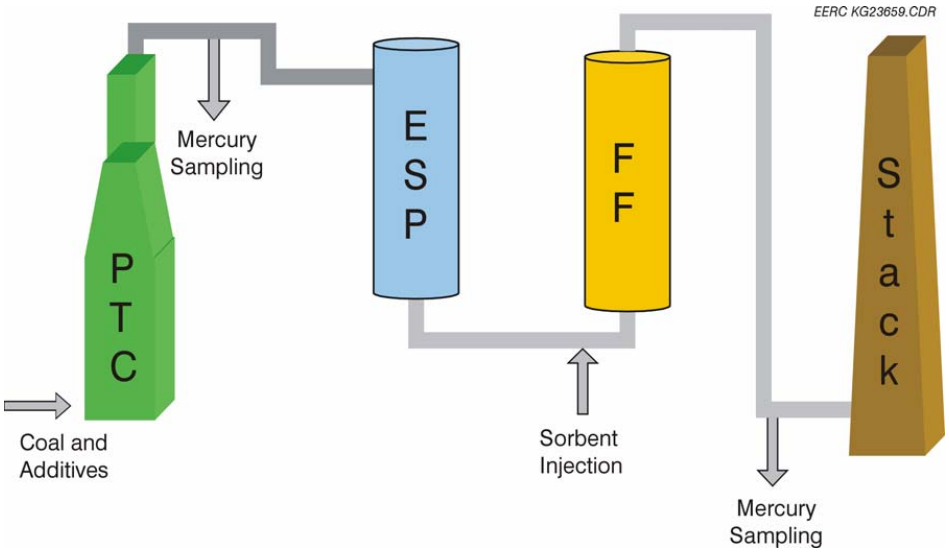


Figure 11-36. EERC PTC combustion unit configured with an ESP followed by a baghouse (FF).

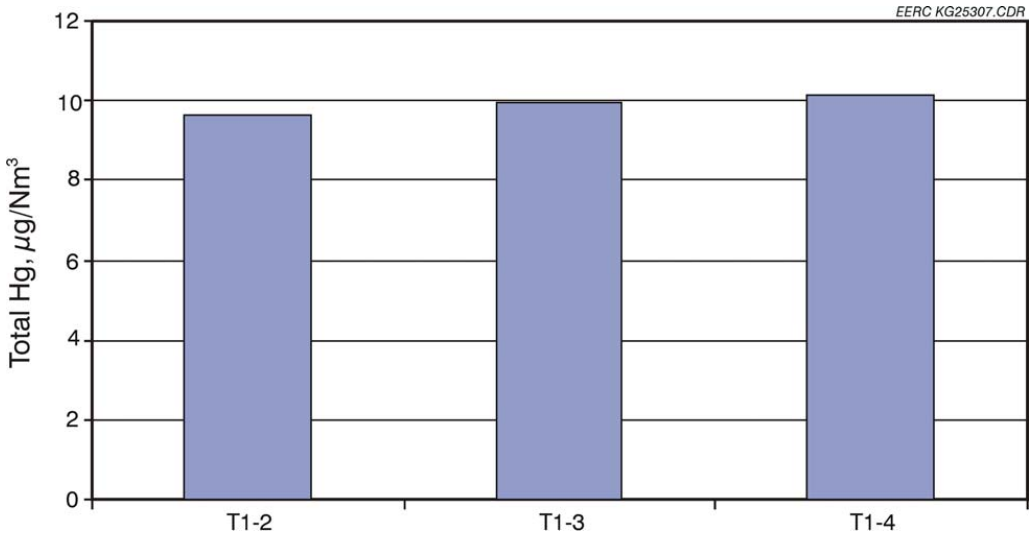


Figure 11-37. ESP inlet Hg_{total} concentrations in Caballo coal combustion flue gas.

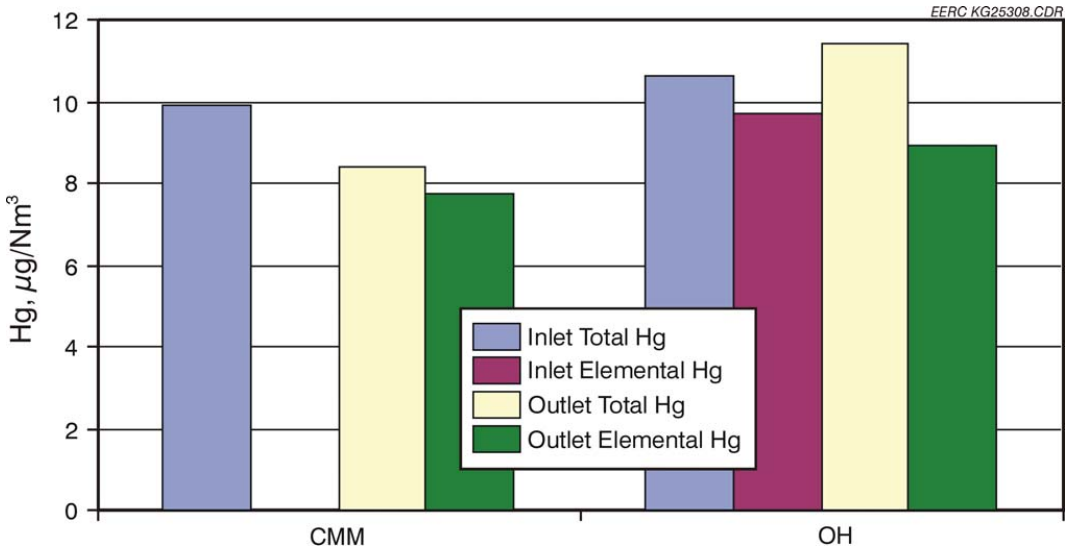


Figure 11-38. Comparison of CMM and OH ESP inlet and FF outlet Hg_{total} and Hg^0 concentrations in the Caballo coal combustion flue gas.

somewhat higher than the corresponding inlet OH value. Regardless of the differences in CMM and OH measurement results, the results in Figure 11-38 indicate that the ESP–FF was ineffective in capturing Hg_{total} from the Caballo coal combustion flue gas.

11.2.2 DARCO FGD Injection and SEA1 Addition into Caballo Coal Combustion Flue Gas

ESP inlet Hg_{total} and FF outlet Hg_{total} and Hg^0 concentrations and ESP–FF Hg_{total} removal efficiencies are plotted as a function of DARCO FGD injection rate into the Caballo coal combustion flue gas in Figures 11-39 and 11-40, respectively. ESP inlet Hg^0 concentrations are not plotted in Figure 11-39 because the appropriate CMM measurements were inadvertently not made. ACI upstream of the FF was very effective in removing Hg_{total}; approximately 80% removal was achieved at an injection rate of 2.5 lb/MMacf. Removal increased moderately to 91% when the injection rate was increased to 3.9 lb/MMacf.

Figures 11-41, 11-42, and 11-43 show the Hg speciation and removal for SEA1 addition and SEA1 addition combined with ACI at two rates. SEA1 addition at a rate of 2.5 lb/MMacf resulted in a dramatic decrease in the proportion of Hg^0, but only a modest increase in Hg_{total} removal efficiency to 31%.

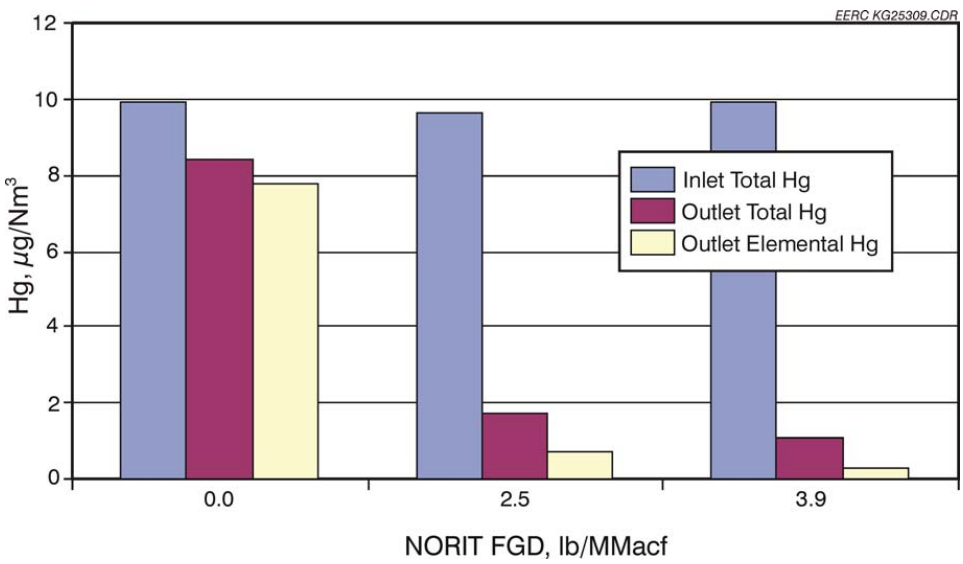


Figure 11-39. ESP inlet Hg_{total} and FF outlet Hg_{total} and Hg^0 concentrations as a function of DARCO FGD injection rate into the Caballo coal combustion flue gas.

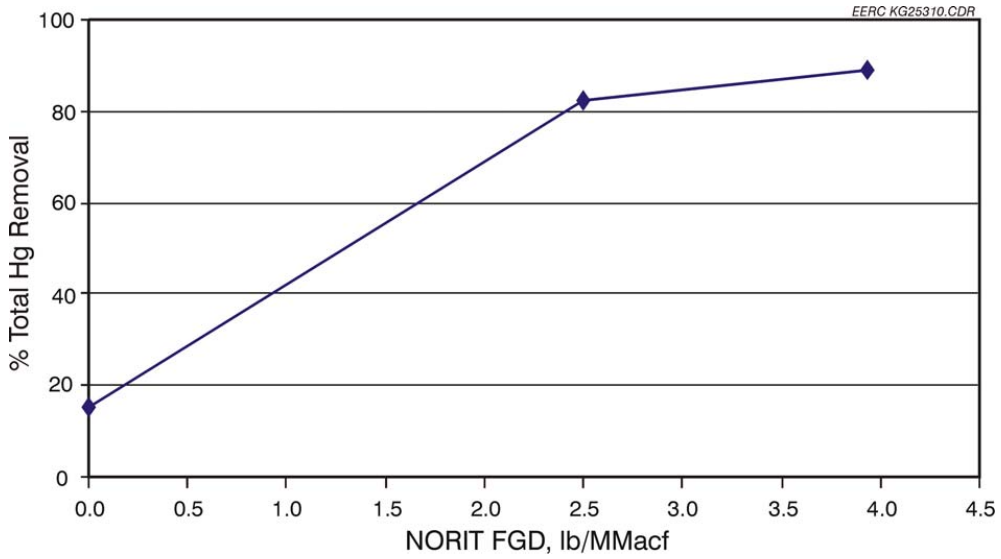


Figure 11-40. ESP–FF Hg_{total} removal efficiencies as a function of DARCO FGD carbon injection rate into the Caballo coal combustion flue gas.

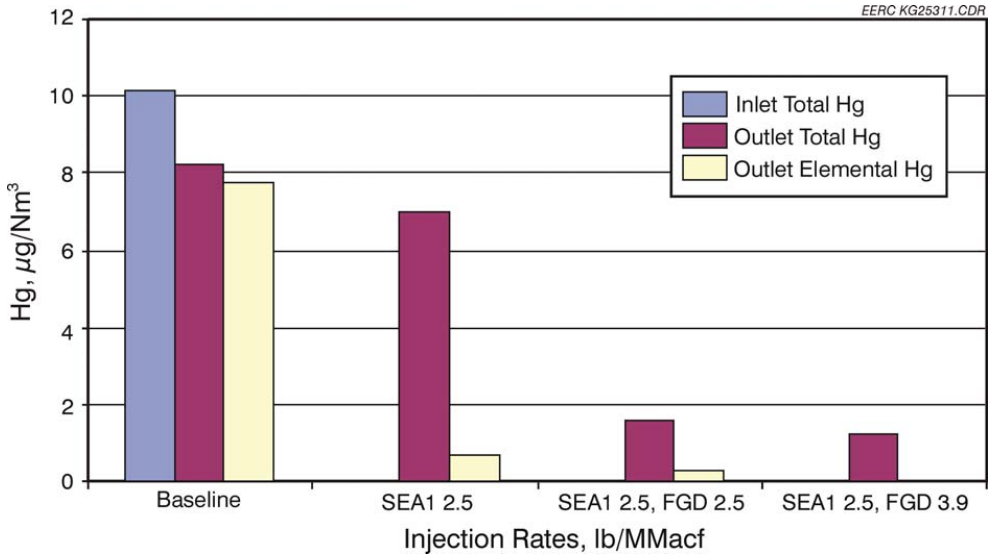


Figure 11-41. ESP inlet Hg_{total} and FF outlet Hg_{total} and Hg^0 concentrations during baseline testing conditions and SEA1 addition alone and in combination with DARCO FGD injection into the Caballo coal combustion flue gas.

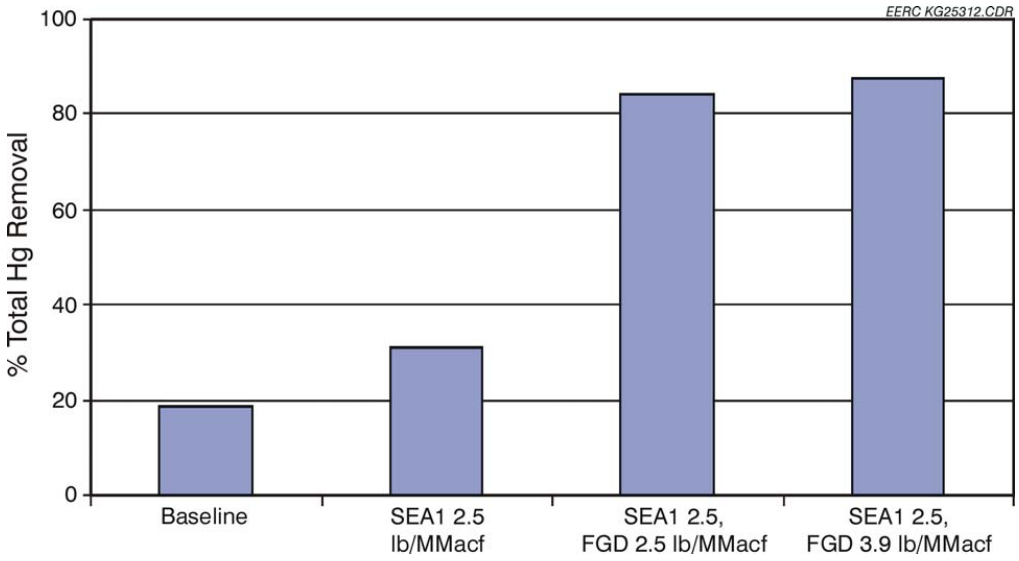


Figure 11-42. ESP–FF Hg_{total} removal efficiencies during baseline testing conditions and SEA1 addition alone and combined with DARCO FGD injection into Caballo coal combustion flue gas.

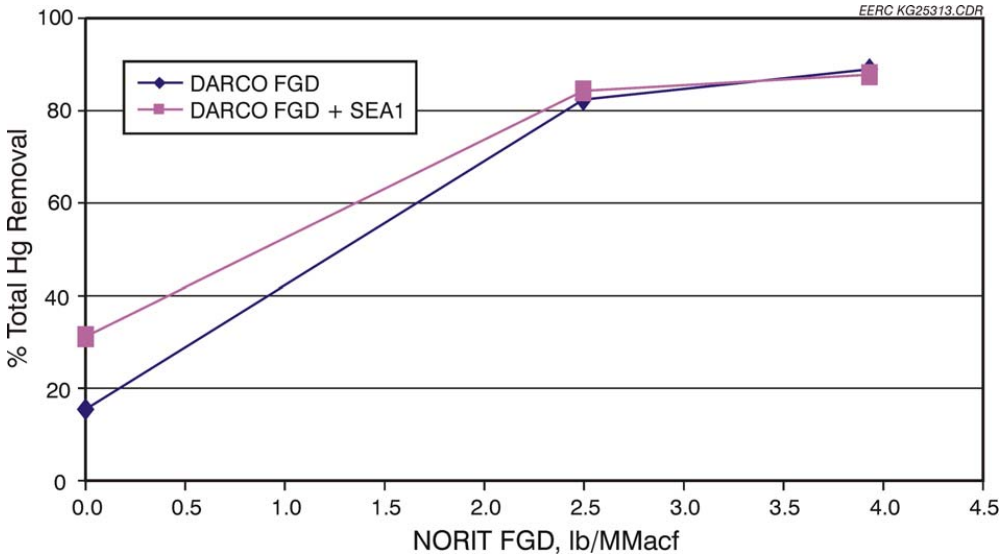


Figure 11-43. Comparison of ESP–FF Hg_{total} removal efficiencies during DARCO FGD injections and SEA1 additions combined with DARCO FGD injection into the Caballo coal combustion flue gas.

Injection of DARCO FGD at a rate of 2.5 lb/MMacf in combination with 2.5 lb/MMacf SEA1 resulted in very high Hg_{total} capture, greater than 80%. Increasing the ACI rate to 3.9 lb/MMacf resulted in a modest increase in capture effectiveness. However, SEA1 addition did not significantly improve on the relatively efficient removal achieved with ACI alone.

11.2.3 ACI and SEA2 Addition into Caballo Coal Combustion Flue Gas

ESP–FF inlet Hg_{total} concentrations during DARCO FGD injections and SEA2 additions were very stable at approximately 10 µg/Nm^3, as indicated in Figure 11-44. ESP inlet Hg_{total} and FF outlet Hg_{total} and Hg^0 concentrations and Hg_{total} removal efficiencies during baseline testing conditions, ACI, SEA2 additions, and ACIs combined with SEA2 additions into Caballo coal combustion flue gas are presented in Figures 11-45 and 11-46, respectively. Hg^0 measurements were limited, thus Hg^0 results are only reported for two test conditions in Figure 11-45. SEA2 addition at 0.1 and 0.2 lb/MMacf did not significantly affect Hg_{total} removal. The SEA2 addition rates were approximately 1/10 the rates used during the ESP testing when 69% Hg_{total} removal was achieved. ACI at 1.2 lb/MMacf resulted in a Hg_{total} removal of 66%. ACIs combined with SEA2 addition at 0.2 lb/MMacf did not significantly enhance Hg_{total} removal as compared to ACI alone. SEA2 was not effective in enhancing Hg_{total} removal at the low addition rates of ≤0.2 lb/MMacf either alone or combined with ACI.

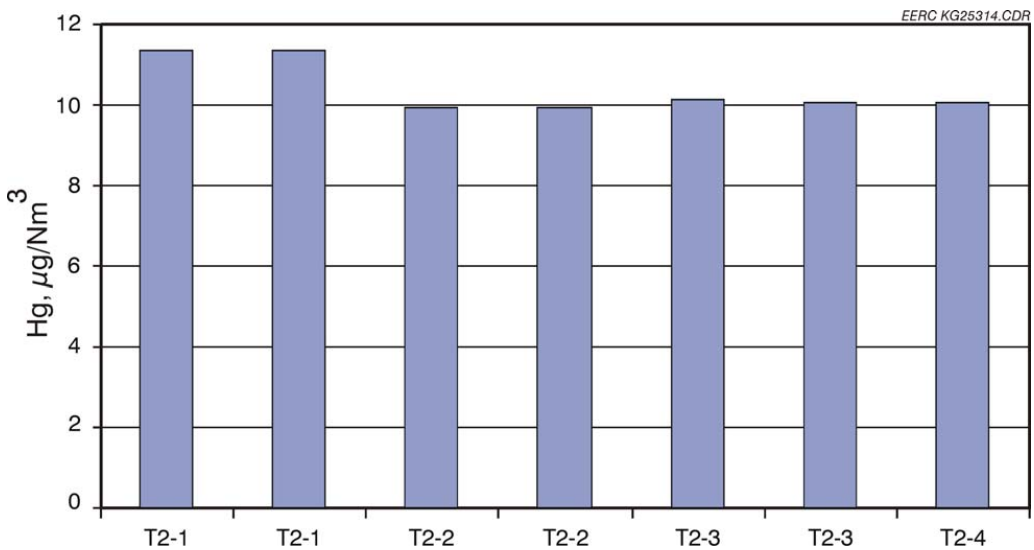


Figure 11-44. ESP–FF inlet Hg_{total} concentrations for Caballo coal combustion flue gas.

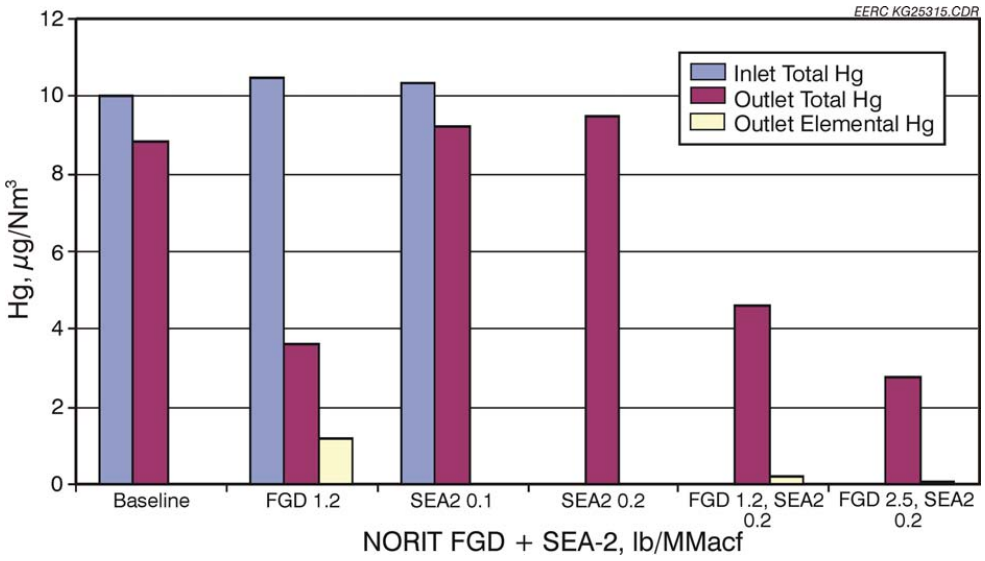


Figure 11-45. ESP inlet Hg_{total} and FF outlet Hg_{total} and Hg^0 concentrations during baseline testing conditions, DARCO FGD injection, SEA2 additions, and DARCO FGD injection combined with SEA2 addition into Caballo coal combustion flue gas.

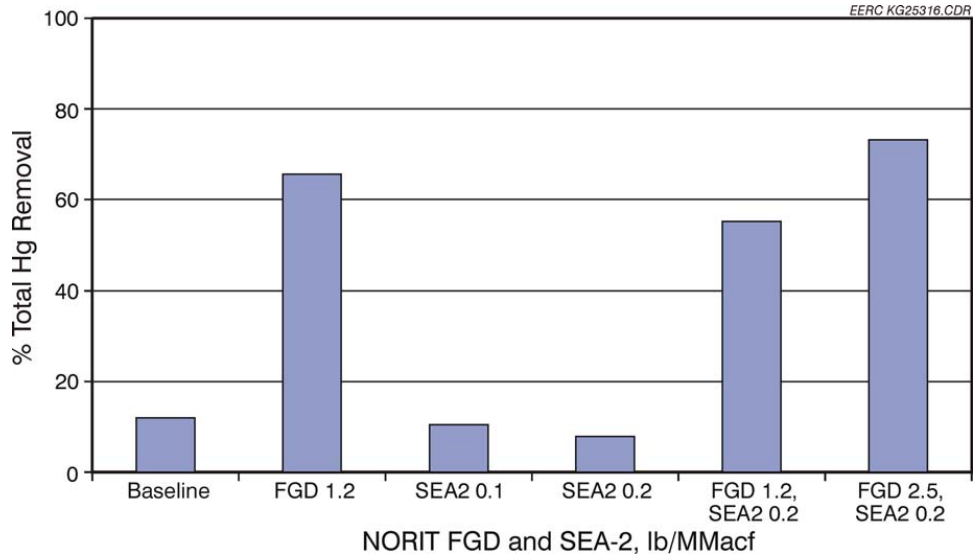


Figure 11-46. ESP–FF Hg_{total} removal efficiencies during baseline testing conditions, DARCO FGD injection, SEA2 additions, and DARCO FGD injections combined with SEA2 additions into Caballo coal combustion flue gas.

11.2.4 EERC-Treated Carbon and Demeter Systems Solution Injections into Demeter Systems-Treated Caballo Coal Combustion Flue Gas

Demeter Systems has developed a chemical, IPE, that when applied to crushed coal reduces pollutant emissions, primarily SO_2, during combustion and increases combustion efficiency. A Demeter Systems-treated Caballo coal was fired in the PTC to evaluate whether IPE would reduce Hg_{total} emissions. At Demeter Systems' request, IPE was also injected upstream of the ESP. An EERC-treated carbon was also injected upstream of the ESP.

Figures 11-47 and 11-48 show the ESP inlet SO_2 and NO_x concentrations, respectively, as the coal feed was changed from untreated Caballo coal to the Demeter Systems-treated Caballo coal. The flue gas SO_2 concentration was effectively reduced to zero, whereas NO_x decreased by about 150 ppmv while firing the Demeter Systems-treated coal. A sulfur analysis of the ESP hopper ash indicated that it contained significant sulfur, probably in the form of sulfate, thus confirming the high degree of SO_2 removal.

Compared in Figure 11-49 are ESP inlet and FF outlet Hg_{total} and Hg^0 concentrations measured with the OH method and a CMM during the combustion of Demeter Systems-treated coal. The ESP inlet Hg_{total} and Hg^0 concentrations measured with the OH method are lower than the corresponding CMM measurements; however, the FF outlet Hg_{total} and Hg^0 concentrations compare favorably.

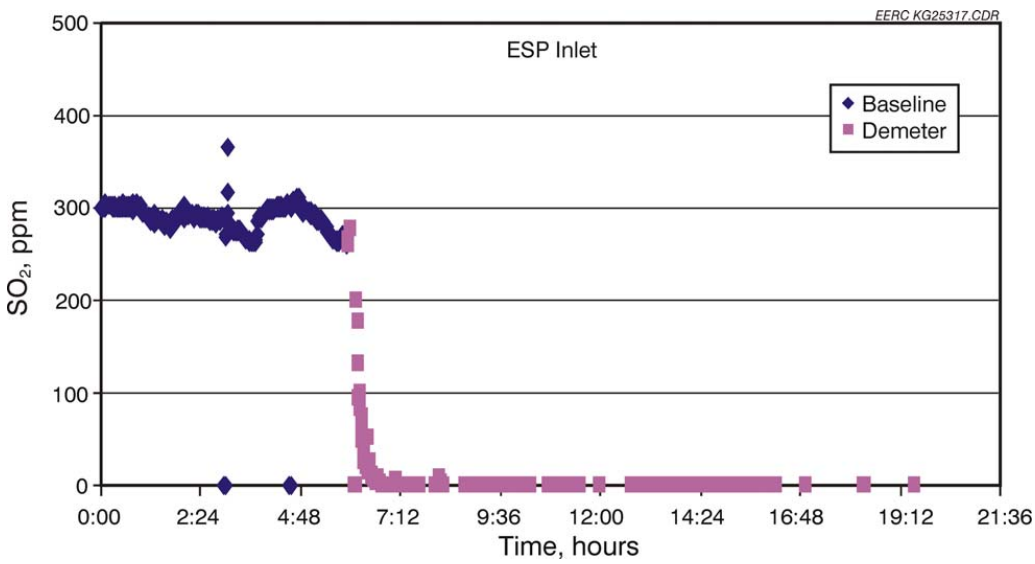


Figure 11-47. Measured SO_2 concentrations for flue gas derived from baseline Caballo coal and Demeter Systems-treated Caballo coal.

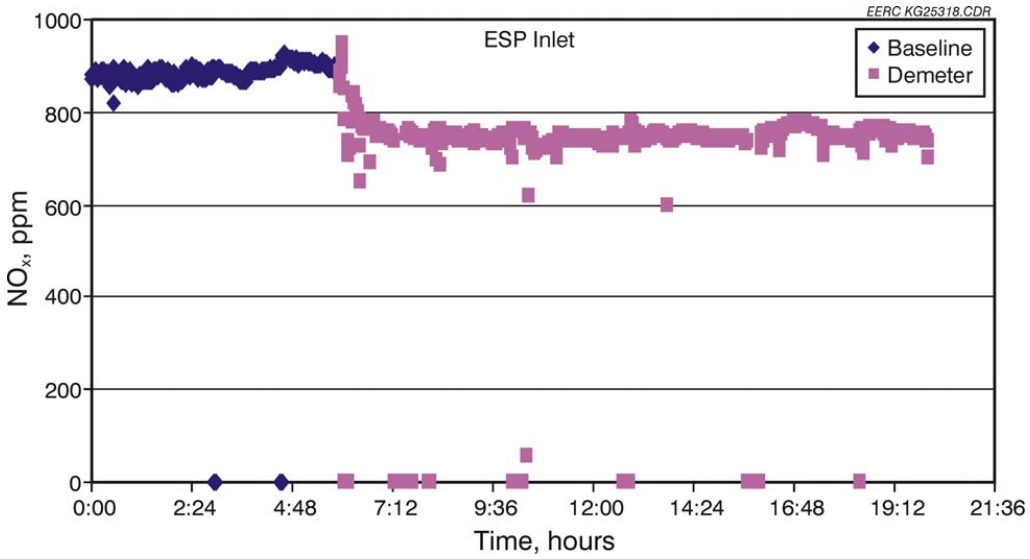


Figure 11-48. Measured NO_x concentrations for flue gas derived from baseline Caballo coal and Demeter Systems-treated Caballo coal.

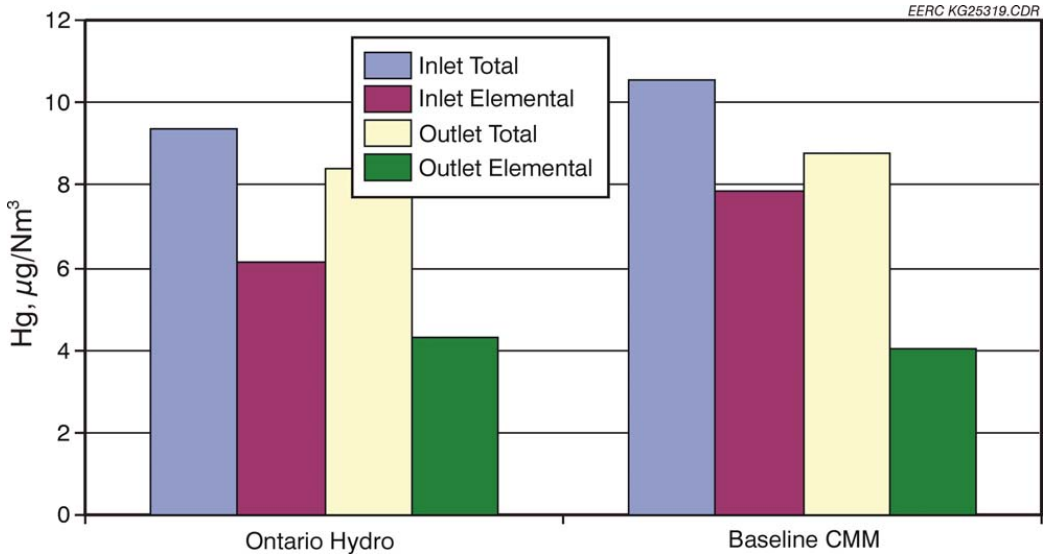


Figure 11-49. Comparison of CMM and OH Hg_{total} and Hg^0 concentrations measured at the ESP inlet and FF outlet during Demeter Systems-treated Caballo coal combustion.

Figure 11-50 presents the inlet CMM Hg concentrations and speciation during the testing with the Demeter Systems-treated coal. Hg^0 values were unavailable for all of the test intervals shown. The inlet Hg_{total} concentrations remained relatively constant at 10.3–11.6 µg/Nm^3. However, there was some variability in the Hg^0 concentrations.

The effects of EERC-treated carbon injection upstream of the ESP on Hg_{total} concentrations and ESP–FF Hg_{total} removal efficiencies are shown in Figures 11-51 and 11-52, respectively. EERC-treated carbon injection at 2.5 lb/MMacf resulted in an ESP–FF Hg_{total} capture efficiency of about 70%. Increasing the injection rate of the EERC-treated carbon from 2.5 lb/MMacf to 4.3 and 5.1 lb/MMacf moderately increased Hg_{total} capture in the ESP–FF.

IPE and EERC-treated carbon were injected upstream of the ESP into the Demeter Systems-treated Caballo coal combustion flue gas. Controlling the IPE injection rate was problematic because of solution evaporation and injector nozzle clogging. As a result, the IPE injection rate was unknown. The EERC-treated carbon injection rate, however, was maintained at 5.1 lb/MMacf. As indicated in Figure 11-53, the IPE injections did not enhance the ESP–FF Hg_{total} removal of the EERC-treated carbon injection.

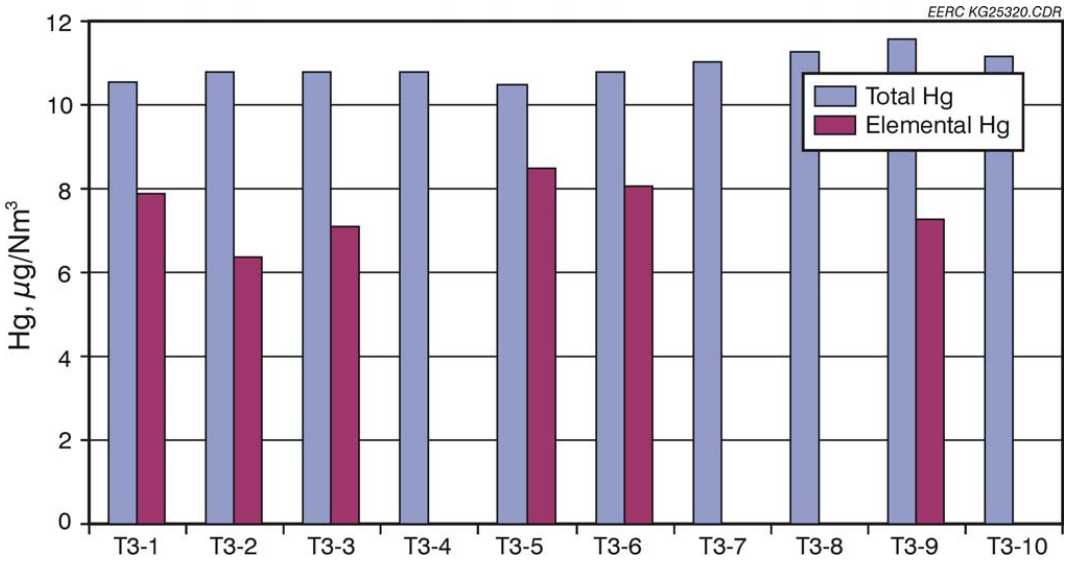


Figure 11-50. Inlet Hg concentrations for flue gas derived from Demeter Systems-treated Caballo coal fired in the PTC configured with ESP–FF as measured by CMM.

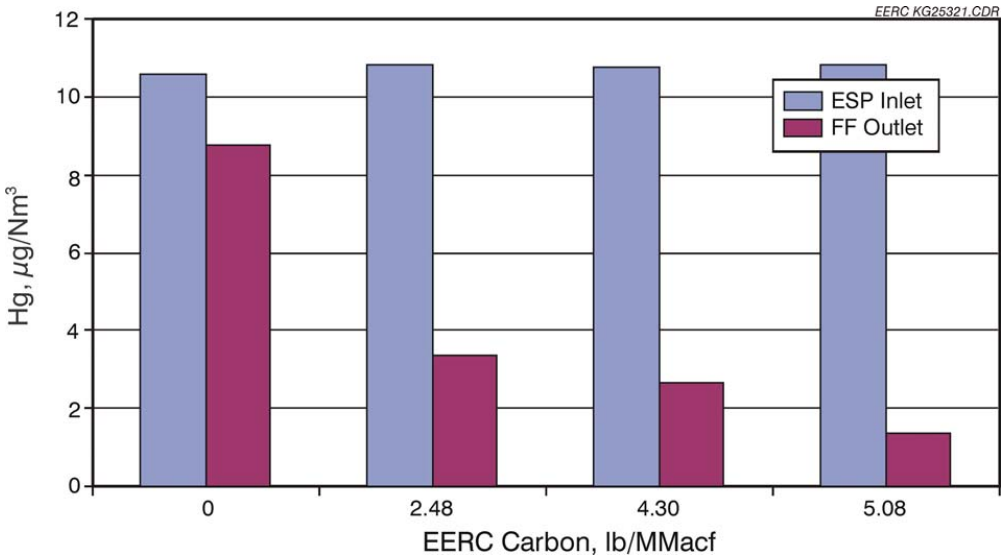


Figure 11-51. ESP inlet and FF outlet Hg_{total} concentrations during EERC-treated carbon injections into Demeter Systems-treated Caballo coal combustion flue gas.

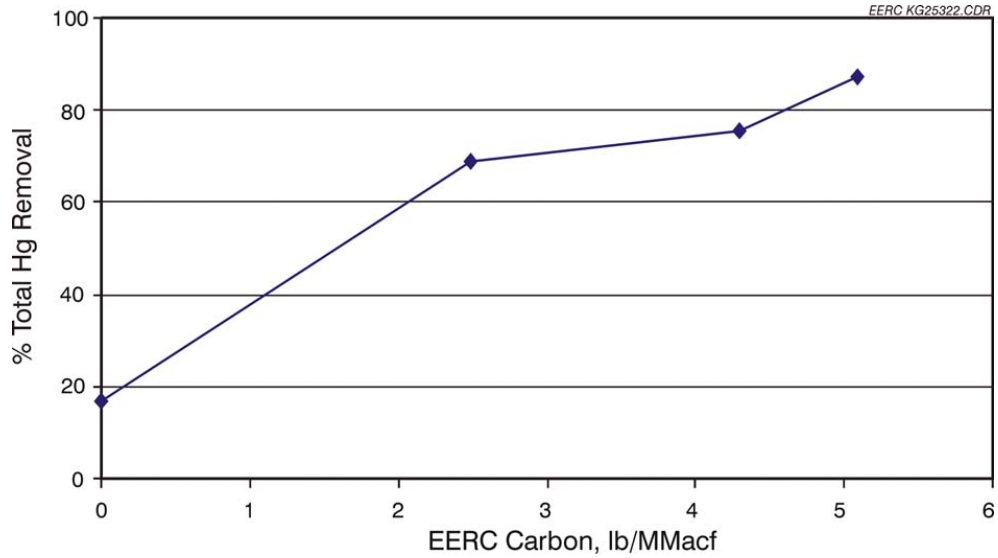


Figure 11-52. ESP–FF Hg_{total} removal efficiencies plotted as a function of EERC-treated carbon injection rate into the Demeter Systems-treated Caballo coal combustion flue gas.

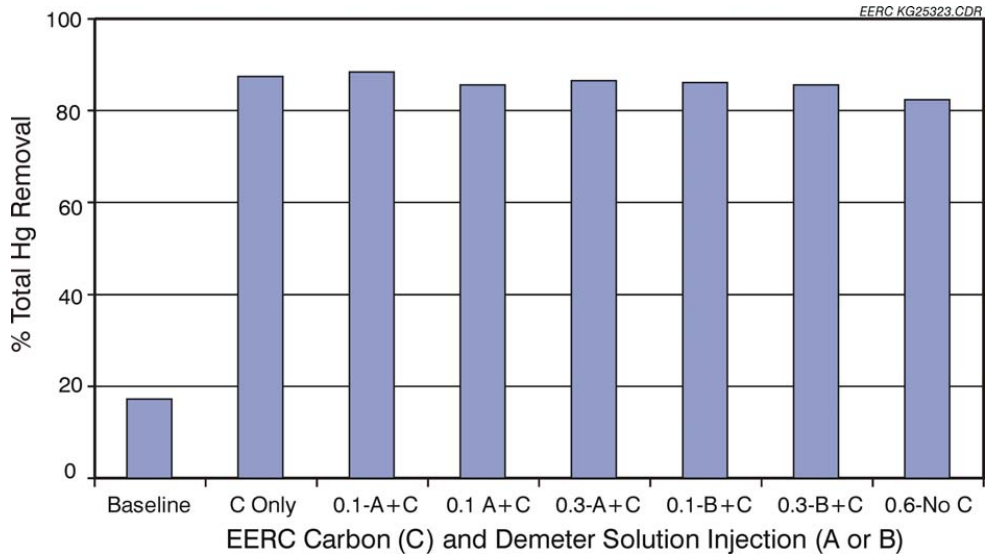


Figure 11-53. ESP–FF Hg_{total} removal efficiencies during EERC-treated carbon and IPE injections into Demeter Systems-treated Caballo coal combustion flue gas.

11.2.5 ACI into WRI Heat-Treated Caballo Coal Combustion Flue Gas

CMM ESP inlet Hg_{total} and Hg^0 concentrations measured during WRI thermally treated Caballo coal combustion are presented in Figure 11-54. Hg^0 values are lacking in Figure 11-54 because Hg^0 was not analyzed during portions of the test period. Hg_{total} concentrations generally ranged from 4 to 5 µg/Nm^3 as compared to the approximate value of 10 µg/Nm^3 for untreated Caballo coal (Figures 11-1 and 11-2). As indicated in Figure 11-55, Hg^0 comprised approximately 40% of the Hg_{total} which is significantly lower than the 80%–90% Hg^0 observed during combustion of the untreated coal (Figure 11-2). Comparison of ESP inlet and FF outlet CMM and OH measurement results when firing the WRI-treated Caballo coal are compared in Figure 11-56. Hg^0 results were unavailable during one of the CMM measurement periods. The ESP inlet CMM Hg_{total} concentrations compare well with the OH results, but both ESP inlet and FF outlet CMM Hg^0 values are consistently lower relative to OH measurements. Both the CMM and OH outlet Hg_{total} concentrations were higher than the inlet Hg_{total} values, suggesting that some residual Hg may have remained on the FF from previous testing. Nevertheless, the results in Figures 11-54–11-56 indicate that the WRI process increased the proportion of Hg^{2+} at the expense of Hg^0 and reduced the Hg_{total} concentration in Caballo coal combustion flue gas.

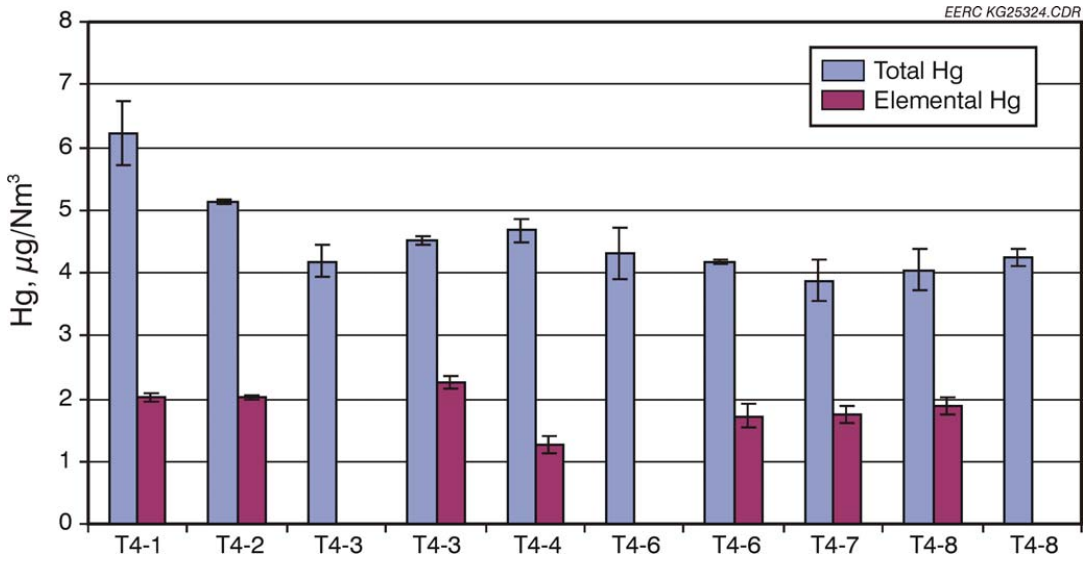


Figure 11-54. ESP inlet Hg_{total} and Hg^0 concentrations in WRI-treated Caballo coal combustion flue gas.

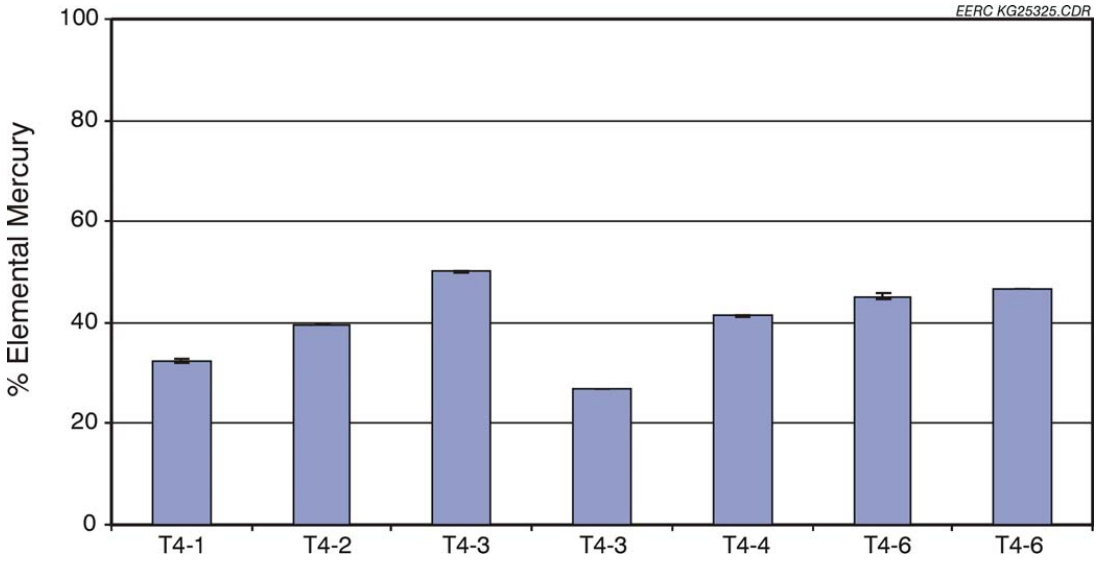


Figure 11-55. Percent Hg^0 of total inlet Hg concentration for flue gas derived from WRI-treated Caballo coal fired in the PTC configured with ESP–FF as measured by CMM.

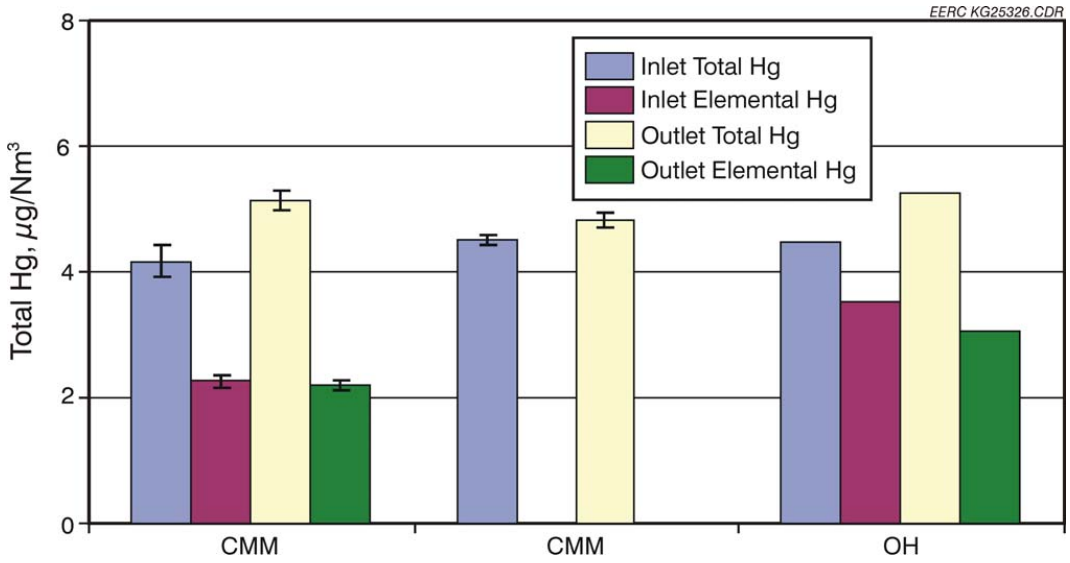


Figure 11-56. Comparison of CMM and OH measurements of ESP inlet and FF outlet Hg_{total} and Hg^0 concentrations for WRI-treated Caballo coal combustion flue gas.

Figures 11-57 and 11-58 show the effects of DARCO FGD injection at 1.26 lb/MMacf on Hg_{total} concentrations and Hg_{total} removal efficiencies, respectively. Duplicate Hg_{total} results are presented in Figure 11-57 for baseline testing conditions and ACI. An inlet Hg_{total} concentration was unavailable for the second set of ACI data. As with previous tests, ACI ahead of the FF (TOXECON) resulted in high Hg_{total} removals of approximately 80% even though the Hg_{total} concentration in the WRI-treated Caballo coal combustion flue gas was very low. Considering that the WRI thermal treatment process removed 64% of the Hg from Caballo coal, the overall Hg_{total} removal was 93%.

11.2.6 ACI into an 80:20 wt% Caballo–Blacksville Coal Blend

Figure 11-59 shows the effect of DARCO FGD injection at 4.8 lb/MMacf upstream of the ESP on FF outlet Hg_{total} concentrations during the combustion of an 80 wt% Caballo and 20 wt% Blacksville coal blend. ESP inlet Hg_{total} concentrations were not measured during this test because of the ACI location upstream of the ESP. ACI resulted in a 55% lower FF outlet Hg_{total} concentration relative to the baseline FF outlet Hg_{total} concentration. The Hg_{total} removal was substantially less than that observed during ACIs using the TOXECON process (Figures 11-39 and 11-40).

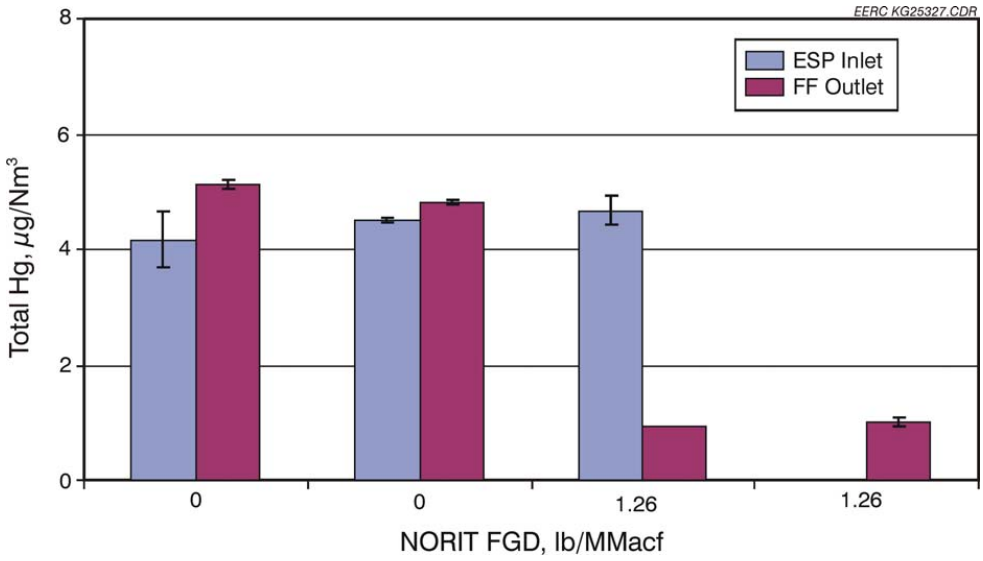


Figure 11-57. ESP inlet and FF outlet Hg_{total} concentrations in WRI-treated Caballo coal combustion flue gas during baseline testing conditions and DARCO FGD injection.

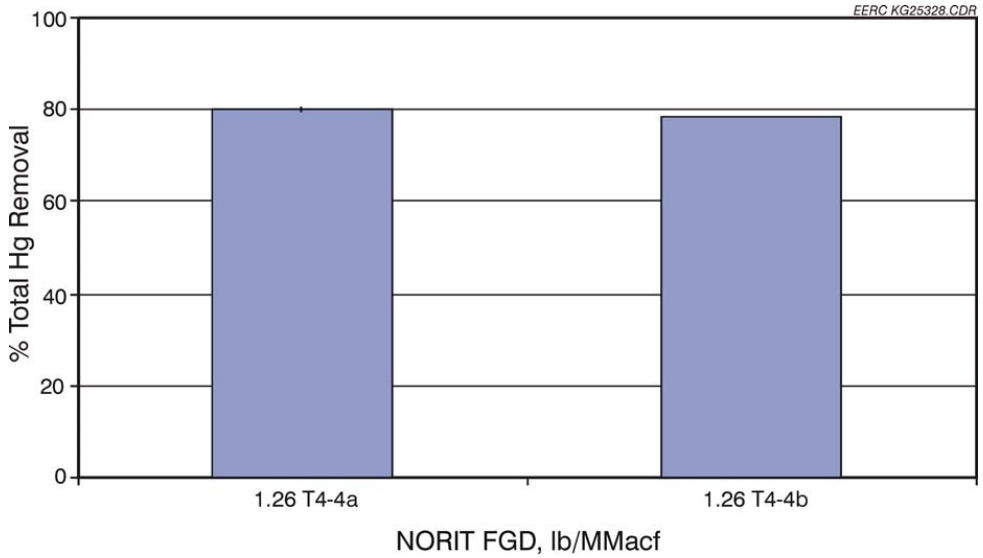


Figure 11-58. ESP–FF Hg_{total} removed efficiencies during DARCO FGD carbon injection into WRI-treated Caballo coal combustion flue gas.

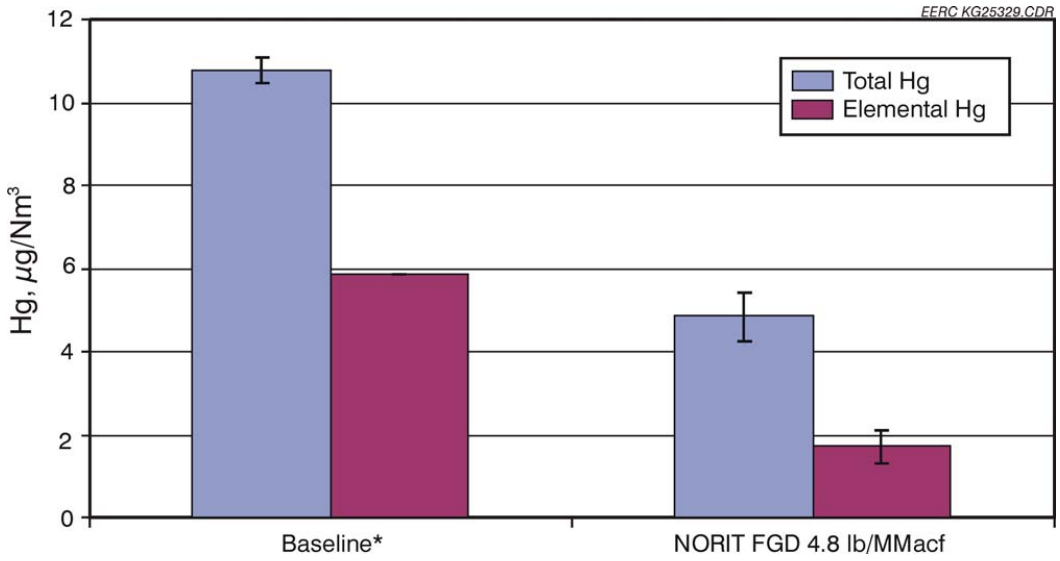


Figure 11-59. FF outlet Hg_{total} and Hg^0 concentrations in an 80 wt% Caballo and 20 wt% Blacksville coal combustion flue gas during DARCO FGD injection at 4.8 lb/MMacf.

11.3 FF Mercury Control

For the FF-only tests, the ESP remained in-line upstream, but with the collection field turned off. The FF consisted of two Gore Teflon bags operating at an air: cloth ratio of 3.08. Carbon injection was performed between the inactive ESP and FF.

11.3.1 ACI into Caballo Coal Combustion Flue Gas

Figures 11-60 and 11-61 show the effects of DARCO FGD injection at 2.49 lb/MMacf on FF outlet Hg_{total} concentrations and removal efficiencies during the combustion of Caballo coal. In the absence of ACI, the FF removed 12% of the Hg_{total}. ACI resulted in slightly more than 80% Hg_{total} removal which is very similar to that observed for the ESP–FF configuration at the same ACI rate (Figure 11-40). The presence of additional fly ash in the FF filter cake because of the lack of an ESP did not hinder the effectiveness of activated carbon to capture Hg_{total}.

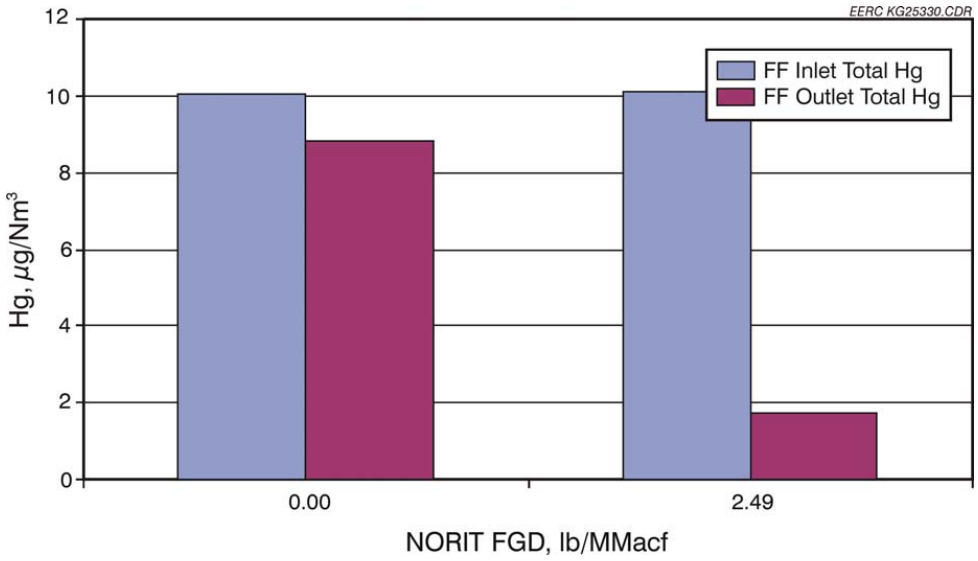


Figure 11-60. FF inlet and outlet Hg_{total} concentrations in Caballo coal combustion flue gas during baseline testing conditions and DARCO FGD injection at 2.49 lb/MMacf.

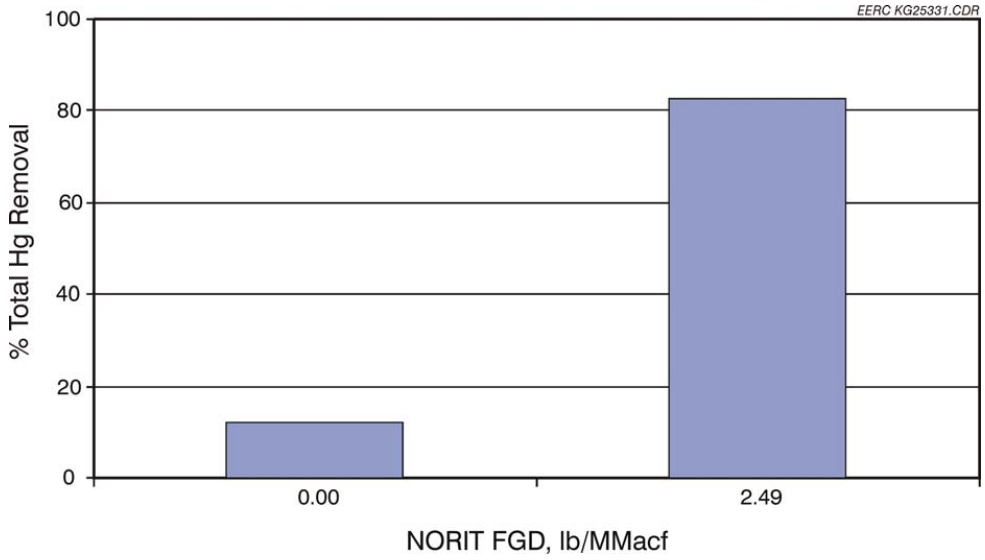


Figure 11-61. FF Hg_{total} removal efficiencies during baseline Caballo coal combustion testing and DARCO FGD injection at 2.49 lb/MMacf.

11.3.2 ACI into an 80:20 wt% Caballo–Blacksville Coal Blend

FF inlet and outlet Hg_{total} and Hg^0 concentrations and FF removal efficiencies determined during the combustion of an 80:20 wt% Caballo–Blacksville coal blend and the injection of DARCO FGD at 4.8 lb/MMacf are presented in Figures 11-62 and 11-63, respectively. Hg^0 was not analyzed for at the FF outlet during the baseline 80:20 wt% Caballo–Blacksville coal blend combustion testing; hence, this Hg^0 result is absent from Figure 11-62. Blending with the high-chlorine Blacksville bituminous coal reduced the proportion of Hg^0 in the Caballo coal combustion flue gas from 80%–90% to approximately 40%. Nevertheless, only about 11% of the Hg_{total} was removed during the baseline testing. ACI at 4.8 lb/MMacf into the 80:20 wt% Caballo–Blacksville coal combustion flue gas removed 75% of the Hg_{total}.

11.4 SDA–ESP and SDA–FF Mercury Control

The PTC was configured with a pilot-scale SDA followed by an ESP or FF as shown in Figure 9-2. Testing involved SEA addition to the coal as well as ACI upstream of the SDA. The coal combustion flue gas exiting the PTC was cooled to a nominal temperature of 149°C (300°F) before entering the SDA. A 1:7 slurry of lime/high-calcium fly ash with a total solids loading of 30.5% was used as the SDA absorbent. The normal slurry injection rate was 22–26.5 lb/hr (10–12 kg/hr). Gas exiting the SDA was at a nominal temperature of 170°F (77°C), which was then introduced

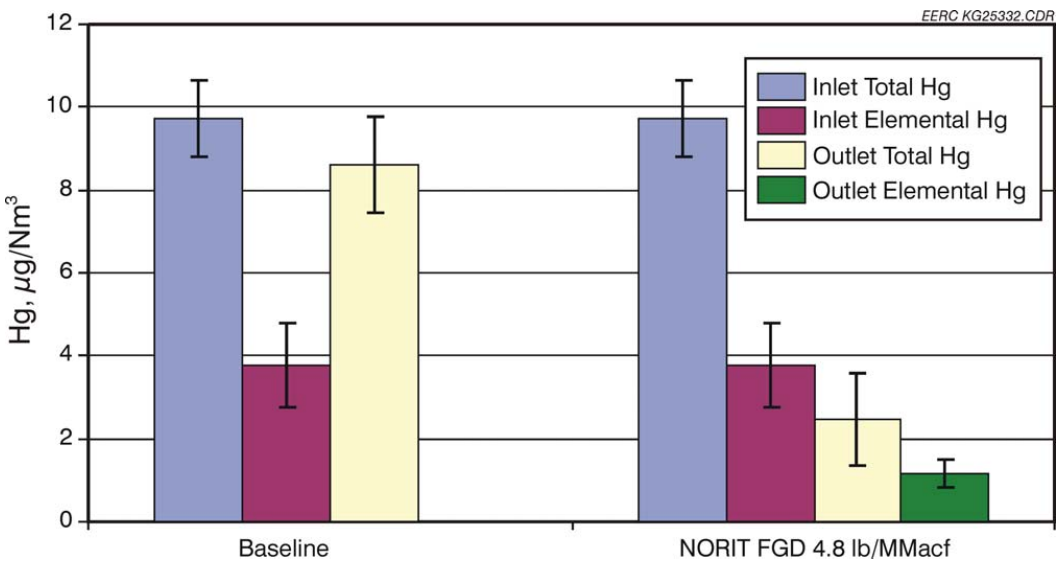


Figure 11-62. FF inlet and outlet Hg_{total} and Hg^0 concentrations in an 80:20 wt% Caballo–Blacksville coal blend combustion flue gas during baseline testing conditions and DARCO FGD injection at 4.8 lb/MMacf.

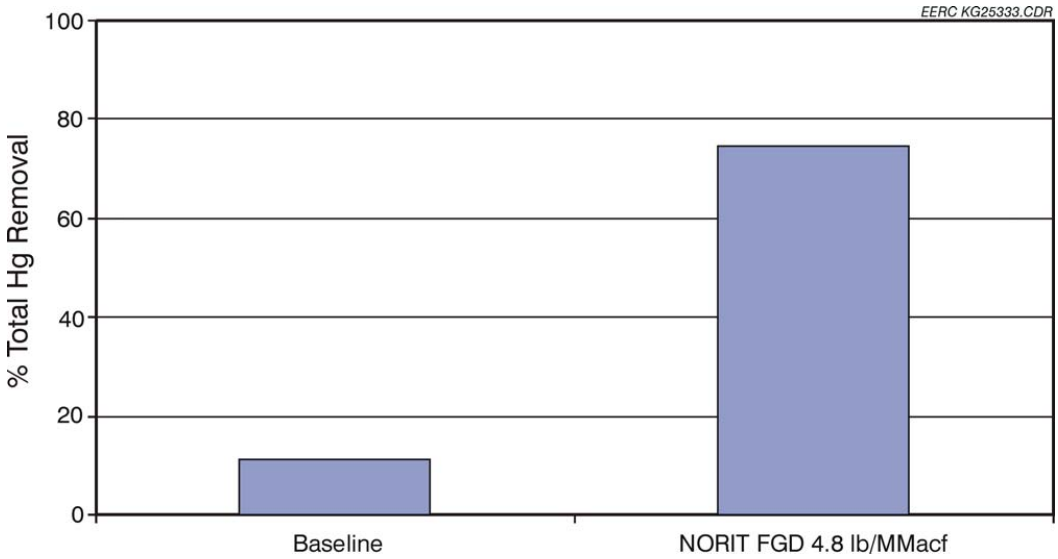


Figure 11-63. FF Hg_{total} removal efficiencies during baseline testing conditions and DARCO FGD injection at 4.8 lb/MMacf into an 80:20 wt% Caballo–Blacksville coal blend combustion flue gas.

into a single-wire tubular ESP unit or a FF. The ESP was operated at 40–60 kV, with a corona current of 4.0 mA. When in service, the ESP was maintained at a nominal temperature of 170°F (77°C) and a voltage of 50 kV. Flue gas in the baghouse was maintained at 170°F (77°C) using an external electric heater. The FF was equipped with three Gore Teflon bags, providing an air:cloth ratio of 3.08. Furnace additives were added to coal prior to introduction to the furnace. Mercury sorbents were fed with a K-Tron dual-screw feeder upstream of the SDA. CMMs were used to monitor Hg_{total} and Hg^0 concentrations at the SDA inlet and ESP or FF outlet. Selected OH sampling was performed at the SDA inlet and ESP or FF outlet during the testing period to verify the CMM results.

Caballo and Absaloka subbituminous coals, as well as an 80:20 wt% blend of Absaloka and Blacksville coals were combusted at a nominal feed rate of 70 lb/hr. Testing was also performed with WRI thermally treated Caballo coal in the SDA–FF configuration.

11.4.1 SDA–ESP Mercury Control: Baseline Caballo Coal Combustion Flue Gas

CMM measurements of Hg_{total} concentrations in Caballo coal combustion flue gas at the SDA inlet are presented in Figure 11-64. The error bars represent plus or minus one standard deviation. Hg_{total} concentrations ranged from 9.9 to 11.5 µg/Nm^3 during the test period. Compared in Figure 11-65 are CMM and OH measurement results for SDA inlet and ESP outlet locations. ESP outlet CMM and OH measurement results are also included in Figure 11-65 for a SEA1 injection test. SDA inlet and outlet Hg_{total} and Hg^0 concentrations measured with the OH method are consistently higher

than those measured with the CMM. Hg^0 was the dominant form, comprising 80%–90% of the Hg_{total}. Hg_{total} removal and Hg^0 oxidation across the ESP was insignificant during baseline testing conditions. Although the measurements for the SEA1 test are more consistent, the outlet OH values were also a little higher than those for the CMM instrument.

11.4.2 SDA–ESP Mercury Control: SEA1 and SEA2 Additions and/or DARCO FGD Injection into Caballo Coal Combustion Flue Gas

DARCO FGD was injected into the Caballo coal combustion flue gas at four different rates upstream of the SDA. Plotted in Figures 11-66 and 11-67 are the ESP outlet Hg_{total} concentrations and SDA–ESP Hg_{total} removal efficiencies versus the DARCO FGD injection rates. Approximately 45% of the Hg_{total} was removed at an ACI rate of 4.8 lb/MMacf.

Presented in Figures 11-68 and 11-69 are SDA–ESP outlet Hg_{total} and Hg^0 concentrations and Hg_{total} removal efficiencies, respectively, plotted as functions of SEA1 addition and/or ACI rates into Caballo coal combustion flue gas. Hg^0 results during the addition of SEA1 at 6.8 lb/MMacf are absent from Figure 11-69 because the measurements were not performed. The SDA–ESP Hg_{total} removal was 17% during the baseline testing conditions. SEA1 addition resulted in a 38% SDA–ESP

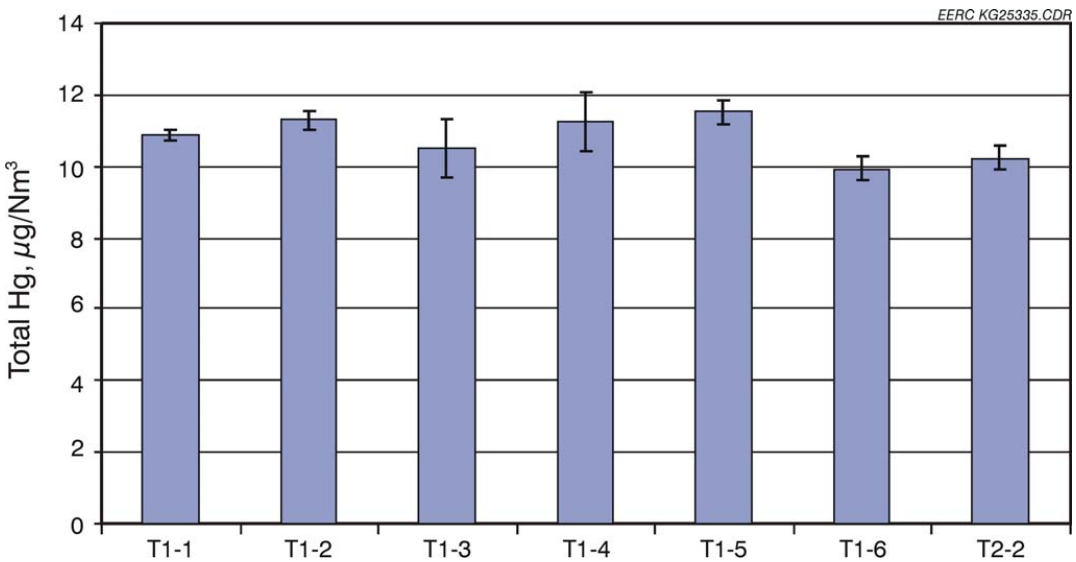


Figure 11-64. SDA inlet Hg_{total} concentrations in Caballo coal combustion flue gas.

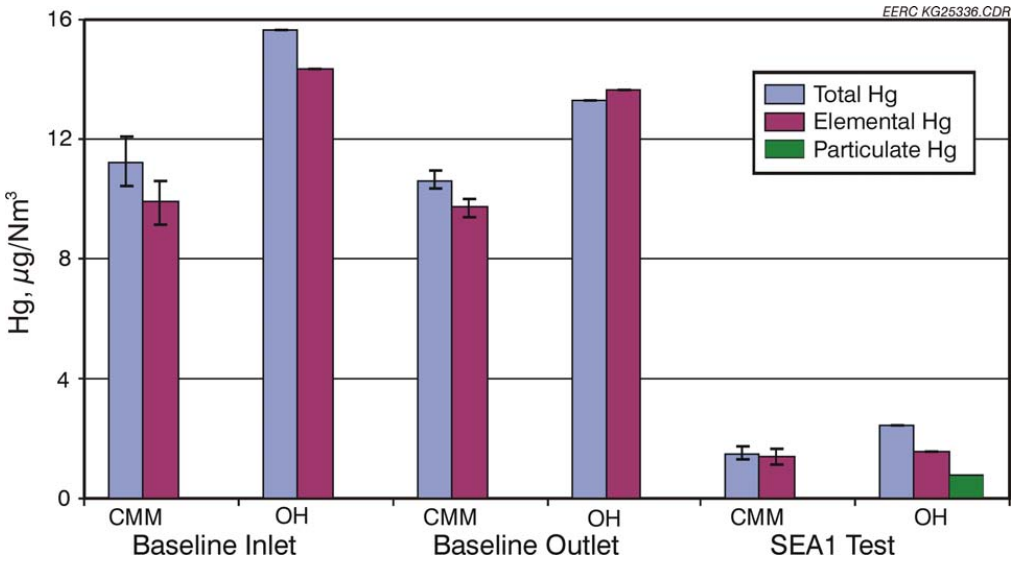


Figure 11-65. Comparison of CMM and OH measurements of SDA inlet and ESP outlet Hg_{total} and Hg^0 concentrations in Caballo coal combustion flue gas during baseline testing conditions and the addition of SEA1.

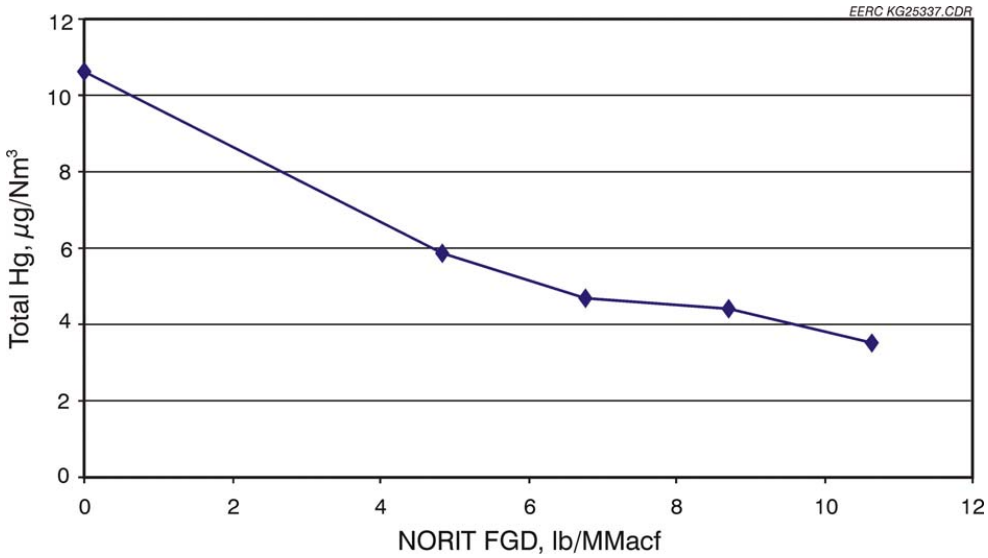


Figure 11-66. SDA–ESP outlet Hg_{total} concentrations versus DARCO FGD injection rates into Caballo coal combustion flue gas.

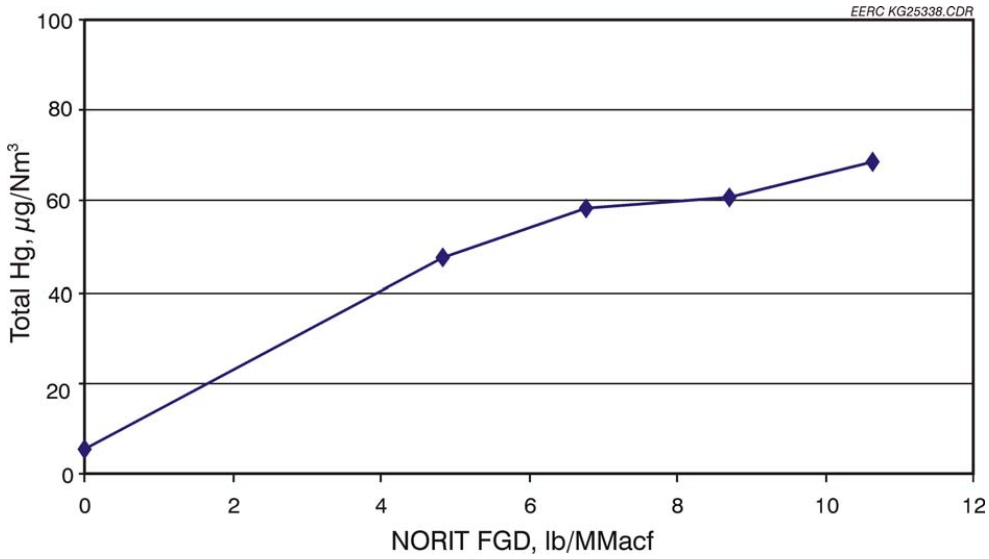


Figure 11-67. SDA–ESP Hg_{total} removal efficiencies plotted as a function of the DARCO FGD injection rate into Caballo coal combustion flue gas.

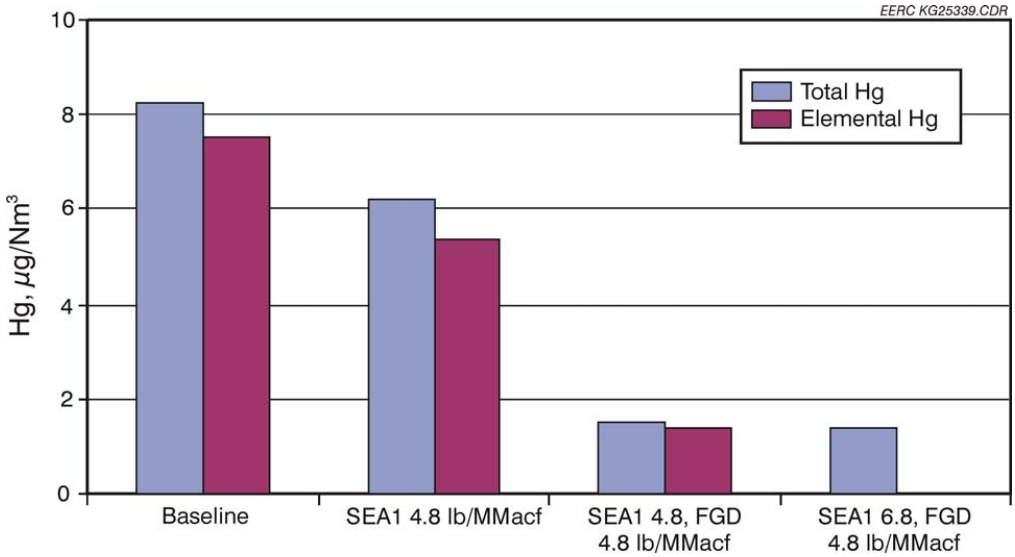


Figure 11-68. SDA–ESP outlet Hg_{total} and Hg^0 concentrations during baseline Caballo coal testing conditions and SEA1 addition at 4.8 lb/MMacf and SEA1 addition at 6.8 lb/MMacf combined with DARCO FGD injection at 4.8 lb/MMacf into Caballo coal combustion flue gas.

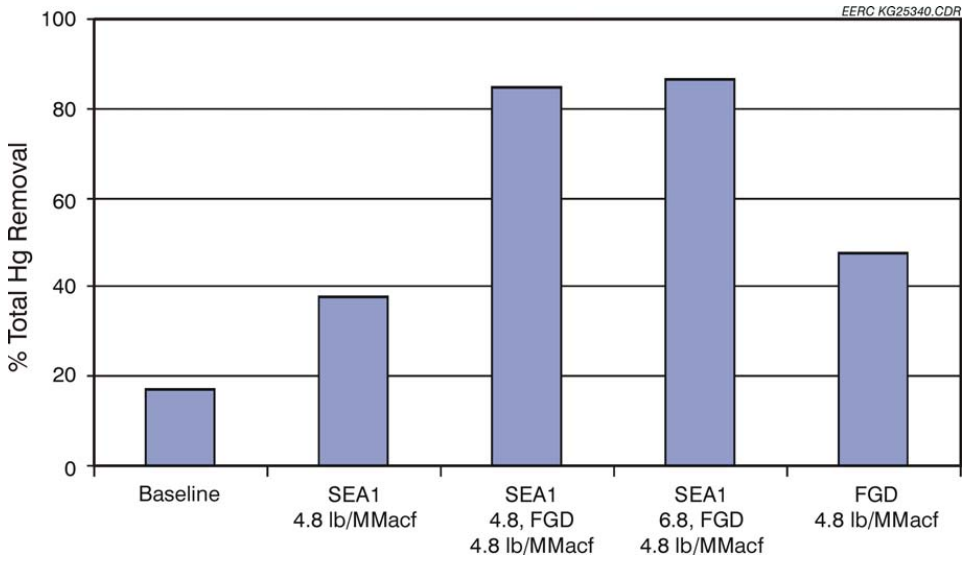


Figure 11-69. SDA–ESP Hg_{total} removal efficiencies during baseline Caballo coal testing conditions and SEA1 addition at 4.8 lb/MMacf, SEA1 additions at 4.8 and 6.8 lb/MMacf combined with DARCO FGD injection at 4.8 lb/MMacf, and DARCO FGD injection at 4.8 lb/MMacf into Caballo coal combustion flue gas.

Hg_{total} removal, which is comparable to the 44% removal achieved with ACI at the same rate of 4.8 lb/MMacf. The combination of SEA1 addition and ACI at similar rates (4.8 lb/MMacf) resulted in a SDA–ESP Hg_{total} removal of >80%. Increasing the SEA1 addition rate to 6.8 lb/MMacf did not significantly affect Hg_{total} removal.

Presented in Figures 11-70 and 11-71 are SDA–ESP outlet Hg_{total} and Hg^0 concentrations and Hg_{total} removal efficiencies, respectively, plotted as functions of SEA2 addition and/or DARCO FGD injection rates into Caballo coal combustion flue gas. Hg^0 results for the baseline test are absent from Figure 11-70 because the measurements were not performed. The SDA–ESP Hg_{total} removal was 30% during the baseline testing conditions. SEA2 additions at 0.2 and 0.5 lb/MMacf resulted in SDA–ESP Hg_{total} removals of 37% and 54%, respectively, that were comparable to that attained with ACI at 4.8 lb/MMacf. SEA2 at 0.5 lb/MMacf combined with ACI at 3.9 lb/MMacf removed >80% of Hg_{total}. Doubling the SEA2 addition to 1.0 lb/MMacf did not significantly improve SDA–ESP Hg_{total} capture. The combination of SEA2 addition, at 1/10 the rate of SEA1 addition, and ACI was very effective for controlling Hg_{total} emissions with the SDA–ESP.

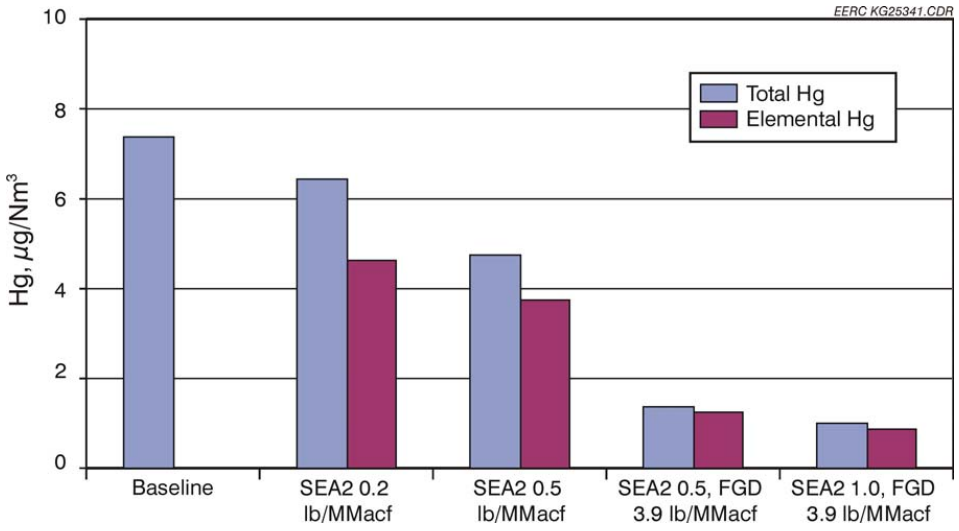


Figure 11-70. SDA–ESP outlet Hg_{total} and Hg^0 concentrations during baseline Caballo coal testing conditions and SEA2 additions at 0.2 and 0.5 lb/MMacf and SEA2 additions at 0.5 and 1.0 lb/MMacf combined with DARCO FGD injection at 3.9 lb/MMacf into Caballo coal combustion flue gas.

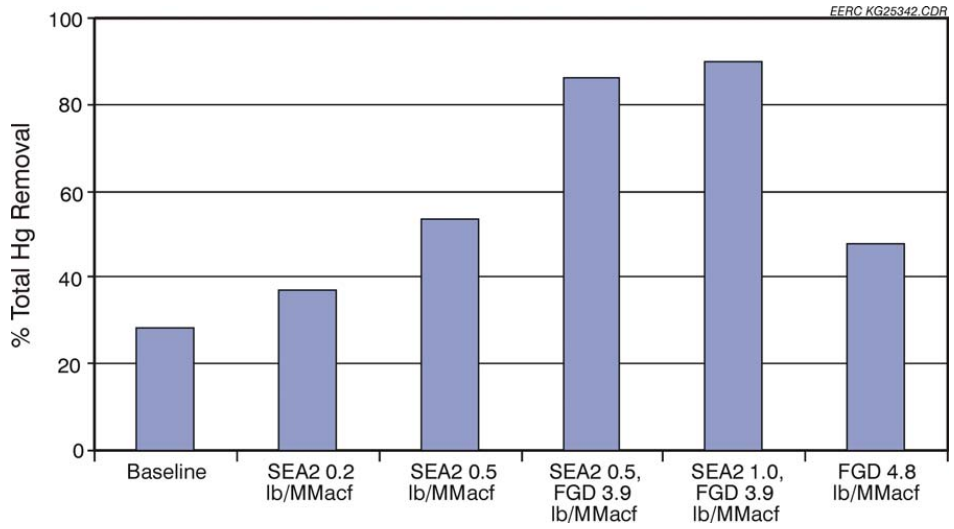


Figure 11-71. SDA–ESP Hg_{total} removal efficiencies during baseline Caballo coal testing conditions and SEA2 additions at 0.2 and 0.5 lb/MMacf, SEA2 additions at 0.5 and 1.0 lb/MMacf combined with DARCO FGD injection at 3.9 lb/MMacf, and DARCO FGD injection at 4.8 lb/MMacf into Caballo coal combustion flue gas.

11.4.3 SDA–FF Mercury Control: SEA1 and SEA2 Additions and DARCO FGD and Amended Silicate Injections into Caballo Coal Combustion Flue Gas

Compared in Figure 11-72 are SDA–FF outlet OH and CMM measurement results made during baseline testing conditions and selected DARCO FGD injection and SEA1 and SEA2 addition tests. The OH Hg_{total} and Hg^0 results were consistently higher than the corresponding CMM results, suggesting that the CMM measurements are biased low. Both methods indicated that Hg^0 is the dominant chemical species, comprising 80%–90% of the Hg_{total}.

Figures 11-73 and 11-74 show the effects of adding SEA1 alone or in combination with injecting DARCO FGD into the Caballo coal combustion flue gas on SDA–FF outlet Hg_{total} concentrations and Hg_{total} removal efficiencies, respectively. During baseline Caballo coal testing, the SDA–FF removed about 27% of the Hg_{total}. SEA1 addition at 1.9 and 2.9 lb/MMacf did not significantly improve Hg_{total} capture in the SDA–FF. In combination with 1.9 lb/MMacf ACI, SEA1 additions of 1.9 and 2.9 lb/MMacf resulted in 67% and 80% Hg_{total} removals.

Figures 11-75 and 11-76 indicate the effects of adding SEA2 alone or combined with injecting DARCO FGD into the Caballo coal combustion flue gas on SDA–FF outlet Hg_{total} concentrations and Hg_{total} removal efficiencies, respectively. Hg^0 results for the SEA2 addition at 0.3 lb/MMacf are lacking because the CMM measurements were not made. SEA2 addition resulted in slightly over 40% Hg_{total} removal, which is comparable to the SDA–ESP Hg_{total} removals achieved with SEA2 addition (Figure 11-71). SEA2 addition at 0.1 lb/MMacf combined with ACI at 1.9 lb/MMacf

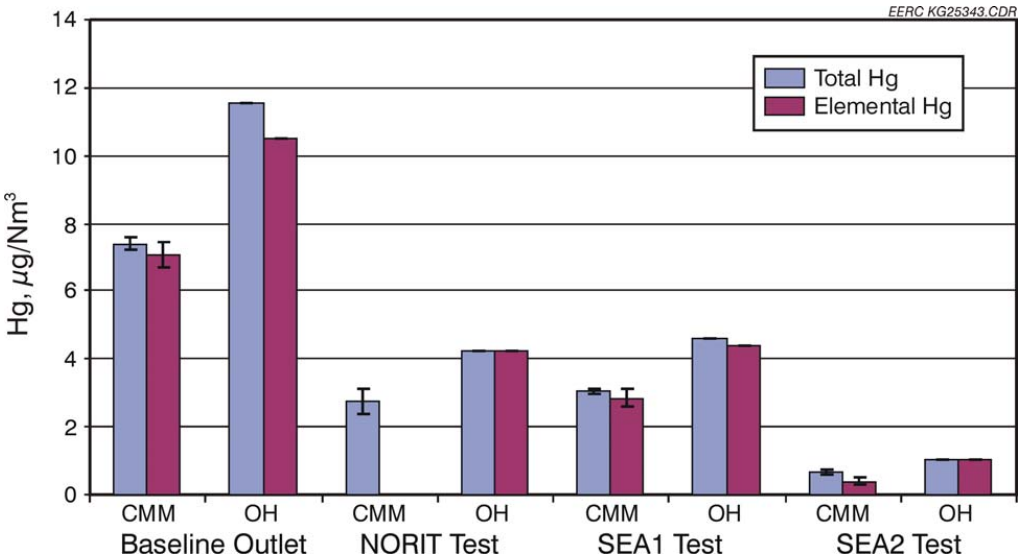


Figure 11-72. Comparison of CMM and OH measurements of SDA–FF outlet Hg_{total} and Hg^0 concentrations in Caballo coal combustion flue gas during baseline testing conditions, DARCO FGD injection, SEA1 addition, and SEA2 addition.

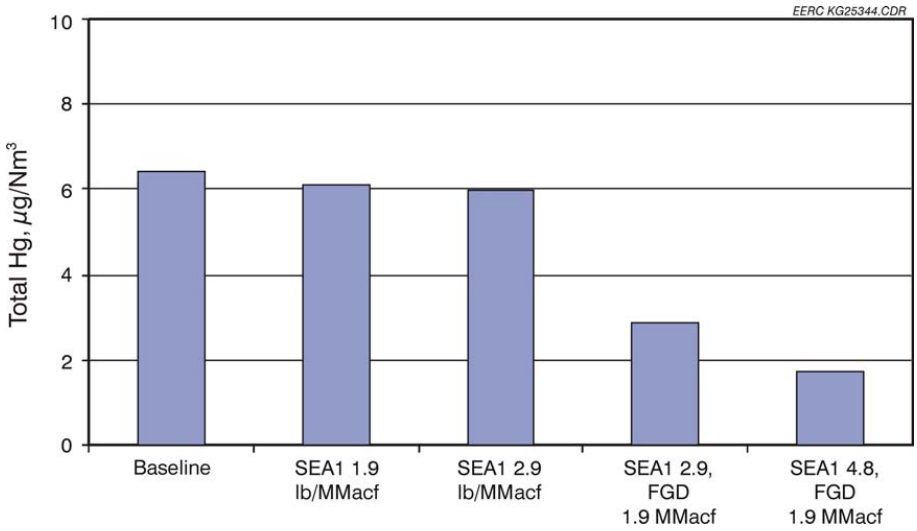


Figure 11-73. SDA–FF outlet Hg_{total} concentrations during baseline Caballo coal testing conditions and additions of SEA1 at 1.9 and 2.9 lb/MMacf and additions of SEA1 at 2.9 and 4.8 lb/MMacf combined with DARCO FGD injection at 1.9 lb/MMacf into Caballo coal combustion flue gas.

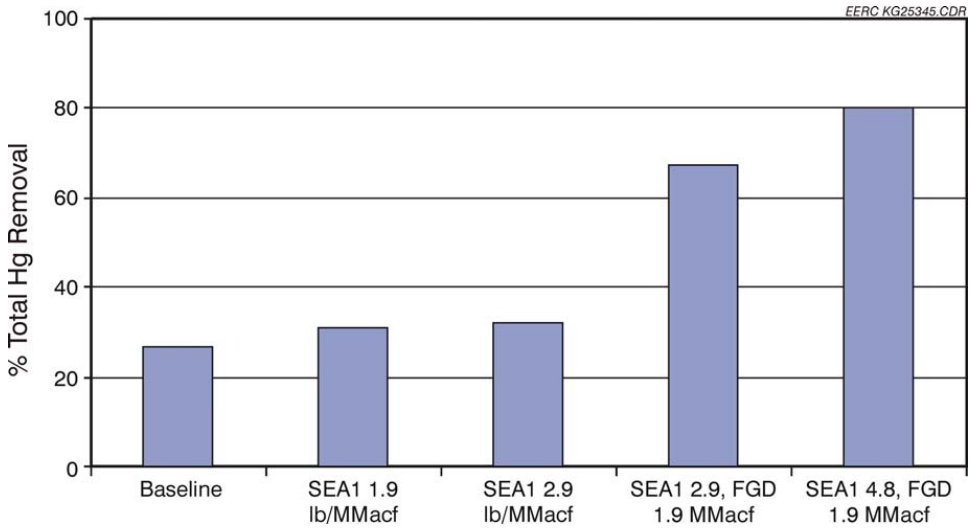


Figure 11-74. SDA–FF Hg_{total} removal efficiencies during baseline Caballo coal testing conditions and SEA1 additions at 1.9 and 2.9 lb/MMacf and SEA1 additions at 2.9 and 4.8 lb/MMacf combined with DARCO FGD injection at 1.9 lb/MMacf into Caballo coal combustion flue gas.

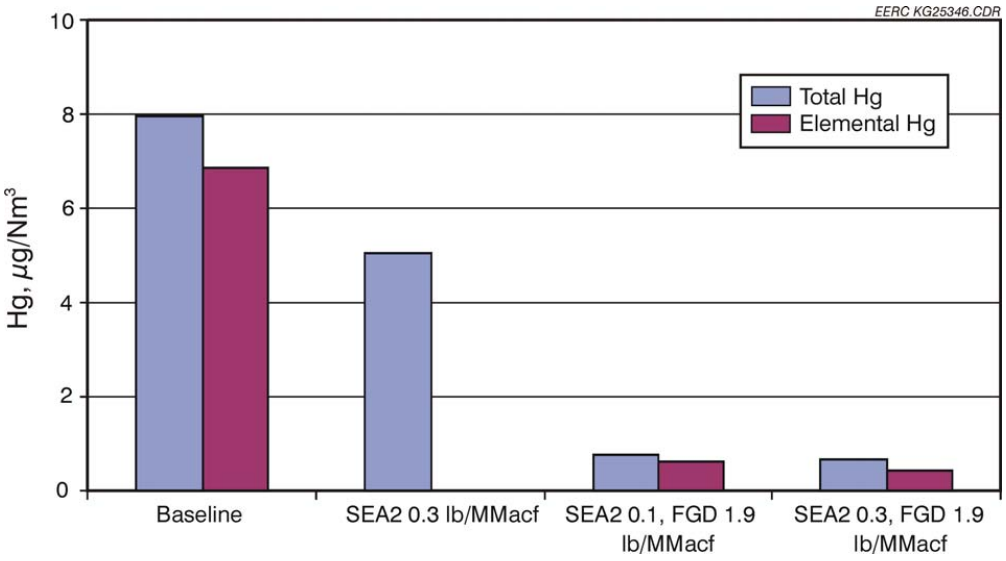


Figure 11-75. SDA–FF outlet Hg_{total} and Hg^0 concentrations during baseline Caballo coal testing and SEA2 addition at 0.3 lb/MMacf and SEA2 additions at 0.1 and 0.3 lb/MMacf combined with DARCO FGD injection at 1.9 lb/MMacf into Caballo coal combustion flue gas.

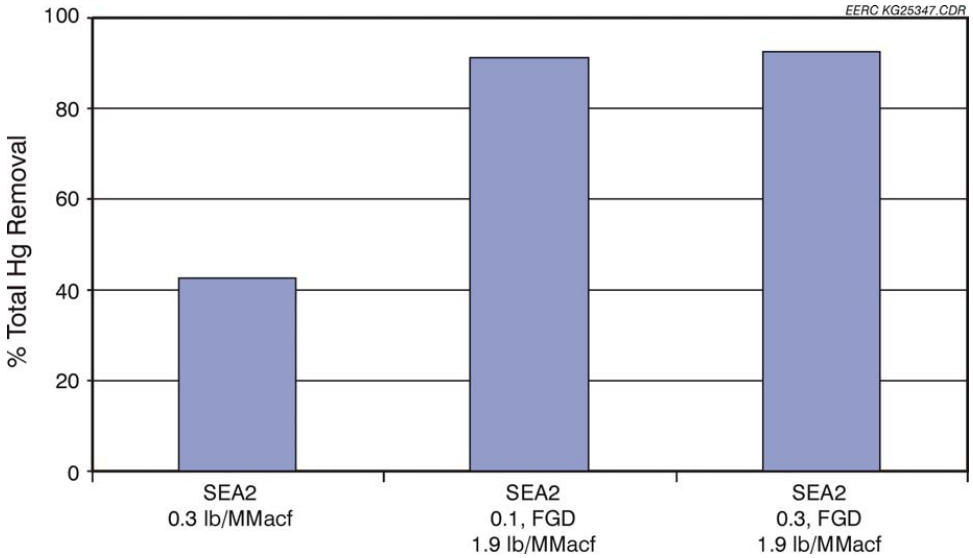


Figure 11-76. SDA–FF Hg_{total} removal efficiencies during SEA2 addition at 0.3 lb/MMacf and SEA2 additions at 0.1 and 0.3 lb/MMacf combined with DARCO FGD injection at 1.9 lb/MMacf into Caballo coal combustion flue gas.

enhanced SDA–FF Hg_{total} removal to approximately 90%. Increasing the SEA2 addition to 0.3 lb/MMacf combined with ACI at 1.9 lb/MMacf did not significantly affect SDA–FF Hg_{total} removal. Similar to the SDA–ESP results, SEA2 addition was very effective at enhancing Hg_{total} removal in the SDA–FF.

As indicated in Figures 11-77 and 11-78, Amended Silicate injections at 2.9 and 5.8 lb/MMacf did not enhance Hg_{total} capture in the SDA–FF during the combustion of Caballo coal. Much better removal rates have been reported in previous testing with Amended Silicates. The lack of Hg_{total} removal observed during the EERC tests may be related to the particular formulation of the Amended Silicate sample used.

11.4.4 SDA–FF Mercury Control: Na_2S_4 Injections into Absaloka Coal Combustion Flue Gas

The potential benefit of Na_2S_4 injection to enhance SDA–FF Hg_{total} capture was evaluated using an Absaloka coal combustion flue gas. Presented in Figure 11-79 are average SDA inlet Hg_{total} concentrations measured during the beginning and ending of the Na_2S_4 injection evaluations. Hg_{total} concentrations inexplicably increased during the testing.

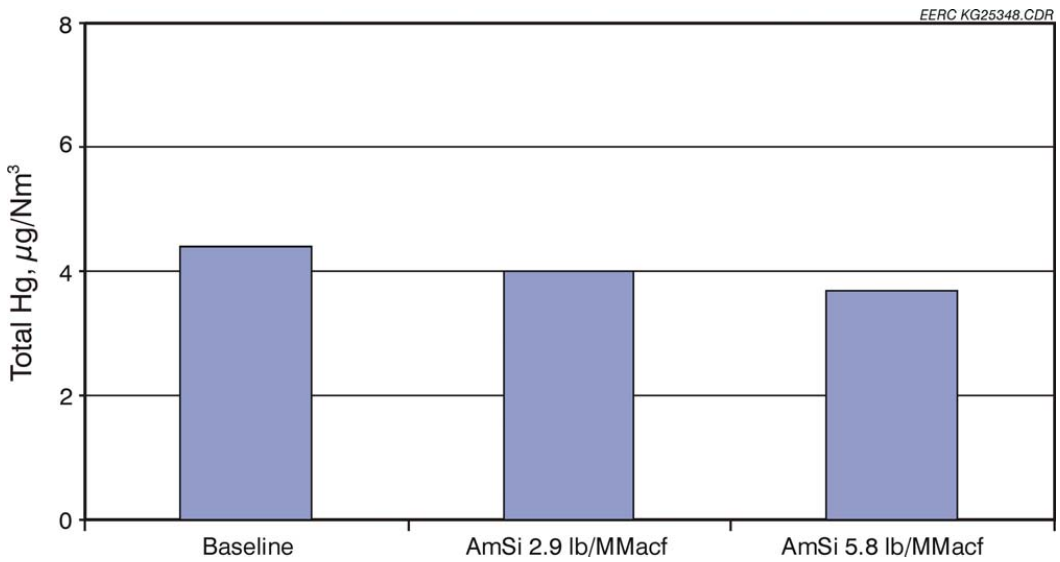
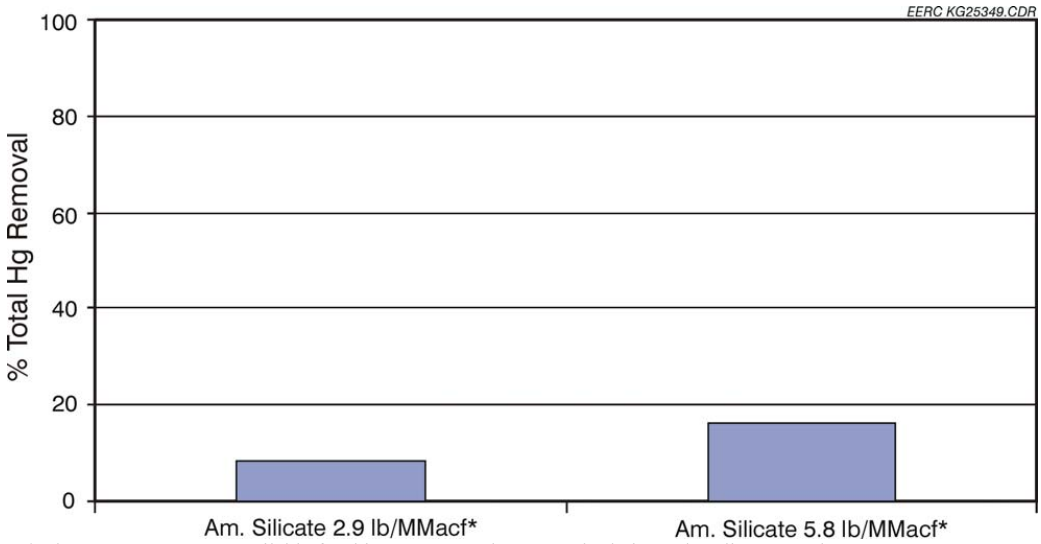


Figure 11-77. SDA–FF outlet Hg_{total} concentrations during baseline Caballo coal testing and Amended Silicate injections at 2.9 and 5.8 lb/MMacf into the Caballo coal combustion flue gas.



*Inlet measurements unavailable for this test; removal expressed relative to baseline FF outlet.

Figure 11-78. SDA–FF Hg_{total} removal efficiencies during Amended Silicate injections of 2.9 and 5.8 lb/MMacf into the Caballo coal combustion flue gas.

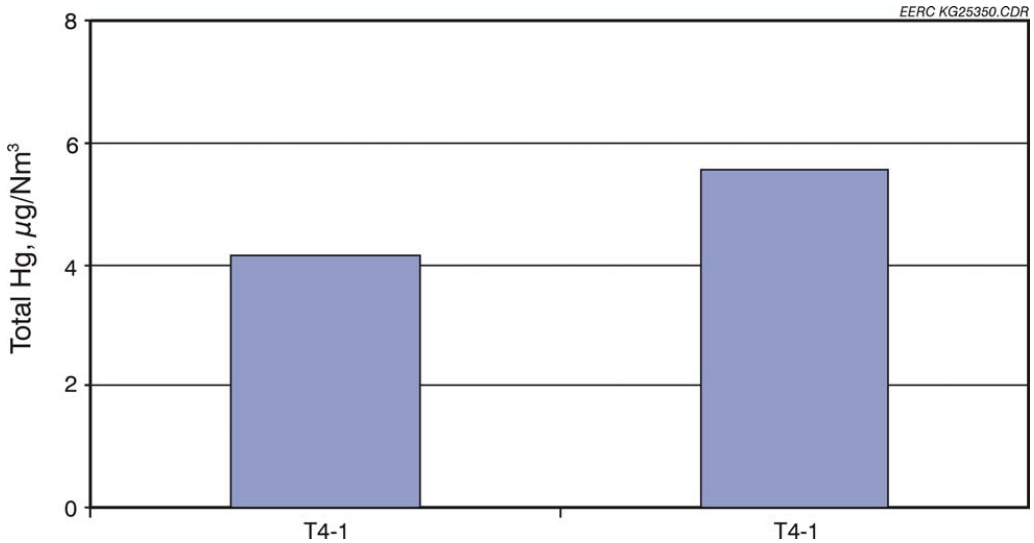


Figure 11-79. SDA–FF inlet Hg_{total} concentrations during Absaloka coal combustion.

Na_2S_4 was injected at the SDA inlet and outlet. SDA–FF outlet Hg_{total} and Hg^0 concentrations measured during the baseline Absaloka coal testing and the Na_2S_4 injections are presented in Figure 11-80. Na_2S_4 injection concentrations are reported in Figure 11-80 as 50 and 100 µg/Nm^3. "Outlet1" and "Outlet2" in Figure 11-80 denote differences in atomizer air pressure at the SDA outlet. The Na_2S_4 injections did not significantly improve Hg_{total} capture in the SDA–FF.

11.4.5 SDA–FF Mercury Control: ACI and SEA2 Addition into an 80:20 wt% Absaloka–Blacksville Coal Blend Combustion Flue Gas

As indicated in Figure 11-81, SDA inlet Hg_{total} concentrations were consistently at about 4.5 µg/Nm^3 during the combustion of an 80:20 wt% Absaloka–Blacksville coal blend. Presented in Figures 11-82 and 11-83 are the SDA–FF outlet Hg_{total} and Hg^0 concentrations and Hg_{total} removal efficiencies, respectively, during baseline 80:20 wt% Absaloka–Blacksville coal testing and during DARCO FGD injection alone at 4.8 lb/MMacf and combined with SEA2 addition at 0.5 lb/MMacf into an 80:20 wt% Absaloka–Blacksville coal combustion flue gas.

The SDA–FF outlet Hg_{total} concentration in Figure 11-82 for the 80:20 wt% Absaloka–Blacksville coal combustion flue gas is very similar to the corresponding SDA inlet Hg_{total} concentrations in Figure 11-81, indicating essentially no Hg_{total} capture in the SDA–FF. Thus blending the Blacksville coal with the Absaloka coal did not significantly improve Hg_{total} capture in the SDA–FF relative to the combustion of Absaloka coal alone. ACI at 4.8 lb/MMacf resulted in a SDA–FF Hg_{total} removal of about 47%. The addition of 0.5 lb/MMacf SEA2 combined with ACI at 4.8 lb/MMacf substantially improved SDA–FF Hg_{total} removal to >80%.

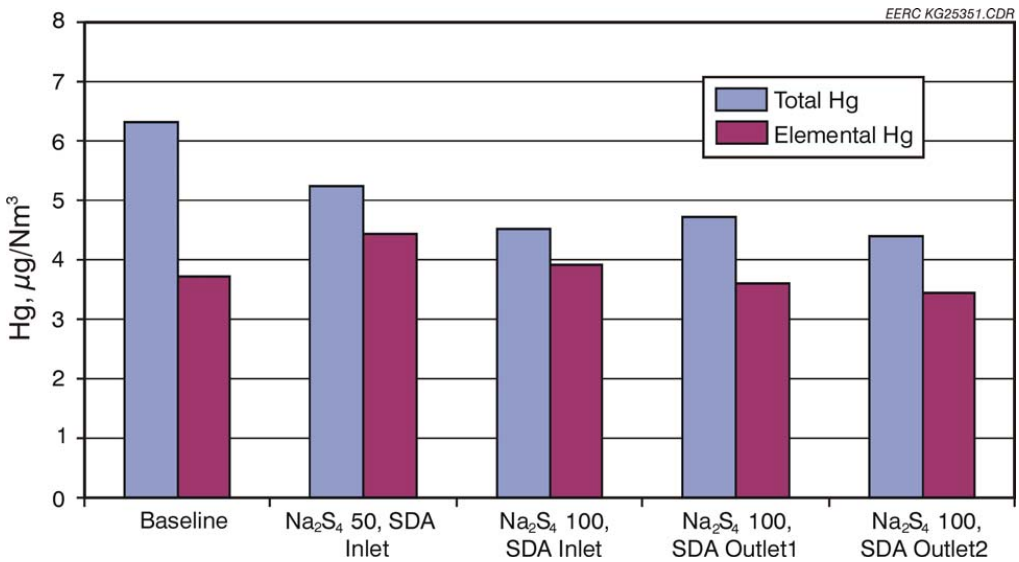


Figure 11-80. SDA–FF outlet Hg_{total} and Hg^0 concentrations during baseline Absaloka coal testing and Na_2S_4 injections at the SDA inlet and outlet into Absaloka coal combustion flue gas.

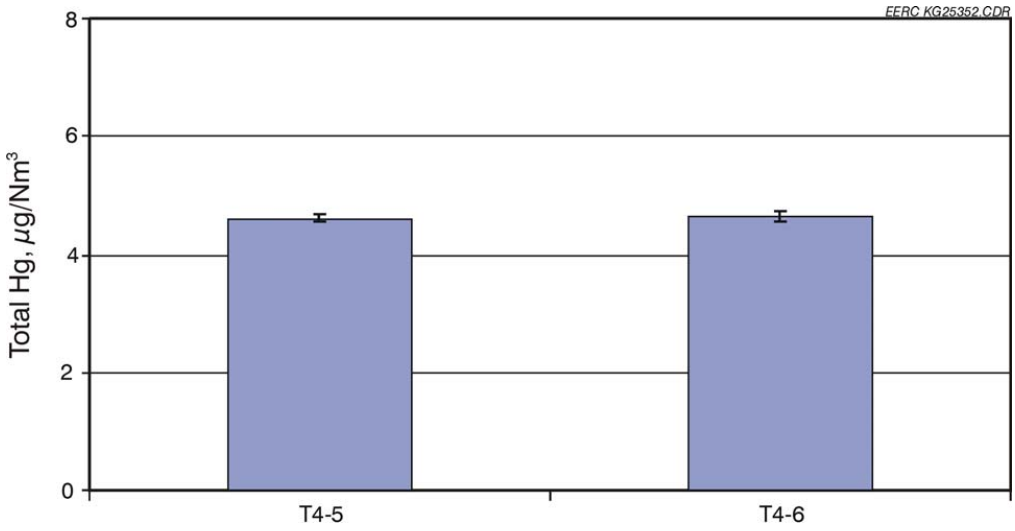


Figure 11-81. SDA inlet Hg_{total} concentrations during 80:20 wt% Absaloka–Blacksville coal combustion.

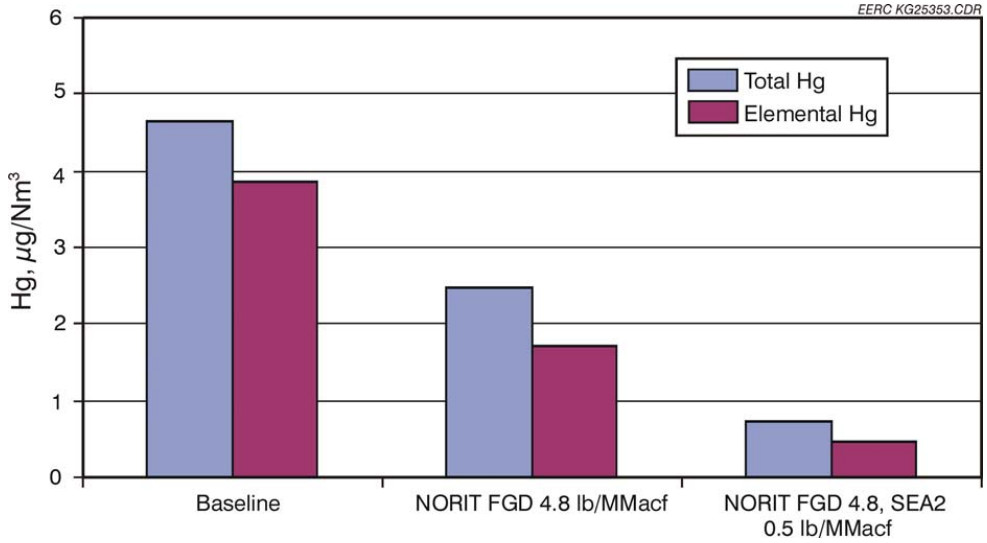
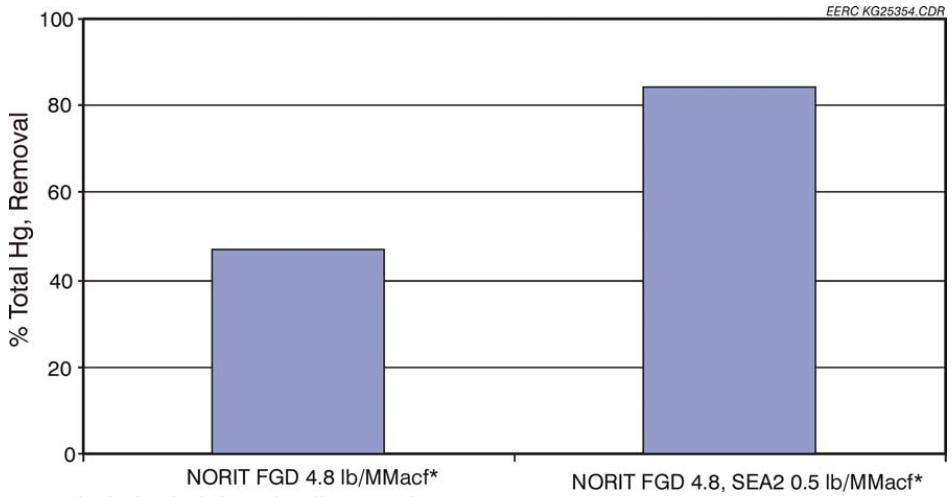


Figure 11-82. SDA–FF outlet Hg_{total} and Hg^0 concentrations during baseline 80:20 wt% Absaloka–Blacksville coal testing and during DARCO FGD injection alone at 4.8 lb/MMacf and combined with SEA2 addition at 0.5 lb/MMacf into an 80:20 wt% Absaloka–Blacksville coal.



*Hg removal calculated relative to baseline FF outlet.

Figure 11-83. SDA–FF Hg_{total} removal efficiencies during DARCO FGD injection alone at 4.8 lb/MMacf and combined with SEA2 addition at 0.5 lb/MMacf into an 80:20 wt% Absaloka–Blacksville coal combustion flue gas.

11.4.6 SDA–FF Mercury Control: ACI into a WRI Heat-Treated Caballo Coal Combustion Flue Gas

Average SDA inlet and FF outlet Hg_{total} concentrations and SDA–FF Hg_{total} removal efficiencies during WRI-treated Caballo coal combustion and the injection of 1.33 lb/MMacf of DARCO FGD into the WRI-treated Caballo coal flue gas are presented in Figures 11-84 and 11-85, respectively. The average results from two baseline measurements are shown in the figures. A SDA inlet Hg_{total} result is lacking in Figure 11-84 because the measurement was not made. The WRI thermal treatment reduced the SDA inlet Hg_{total} concentration from 9.9–11.5 μg/Nm^3 for the untreated Caballo coal to approximately 6 μg/Nm^3. SDA–FF Hg_{total} removal efficiencies were 41% and 57% for the WRI-treated Caballo coal combustion flue gas, suggesting that about half the Hg_{total} was present as Hg^{2+}. The injection of 1.33 lb/MMacf DARCO FGD into the WRI-treated Caballo coal combustion flue gas did not significantly enhance the efficiency of the SDA–FF to remove the small amount of Hg_{total} remaining.

11.4.7 SDA–FF Mercury Control: Solucorp Industries MBS SDA Additive and SEA1 Addition Test Results with Caballo Coal Combustion Flue Gas

A slurry composed of 8.9 wt% lime, 8.8 wt% Solucorp Industries Additive A, and 2.3 wt% Solucorp Industries Additive B was evaluated in the SDA for capturing Hg_{total} in a FF located downstream from the SDA. To increase flue gas residence time in the SDA, a portion of the Caballo coal combustion flue gas was bypassed around the SDA–FF. Incremental bypassing of 20%, 33%, and eventually 50% of the flue gas flow gradually improved SDA–FF Hg_{total} removal as indicated in

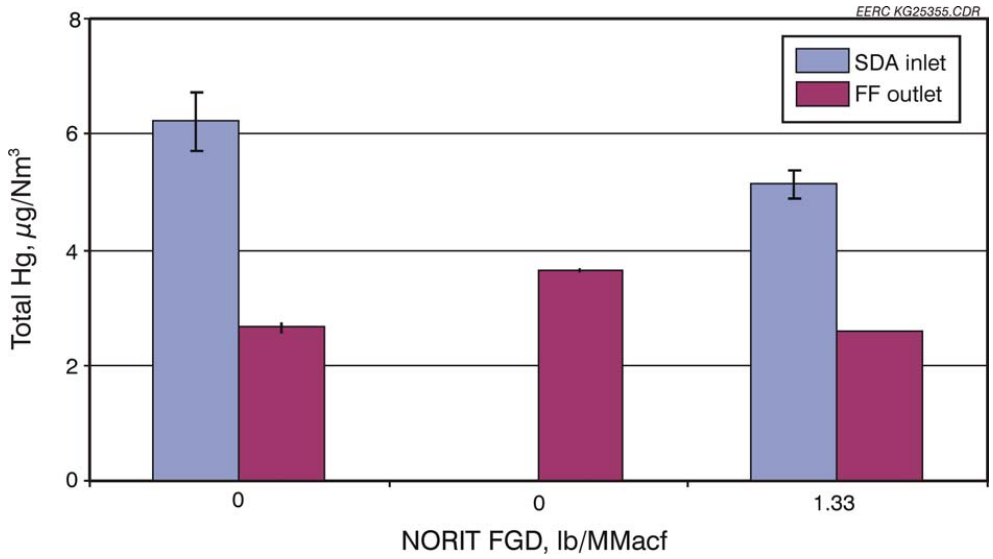


Figure 11-84. SDA inlet and FF outlet Hg_{total} concentrations during baseline WRI-treated Caballo coal testing and DARCO FGD injection at 1.33 lb/MMacf into the WRI-treated Caballo coal combustion flue gas.

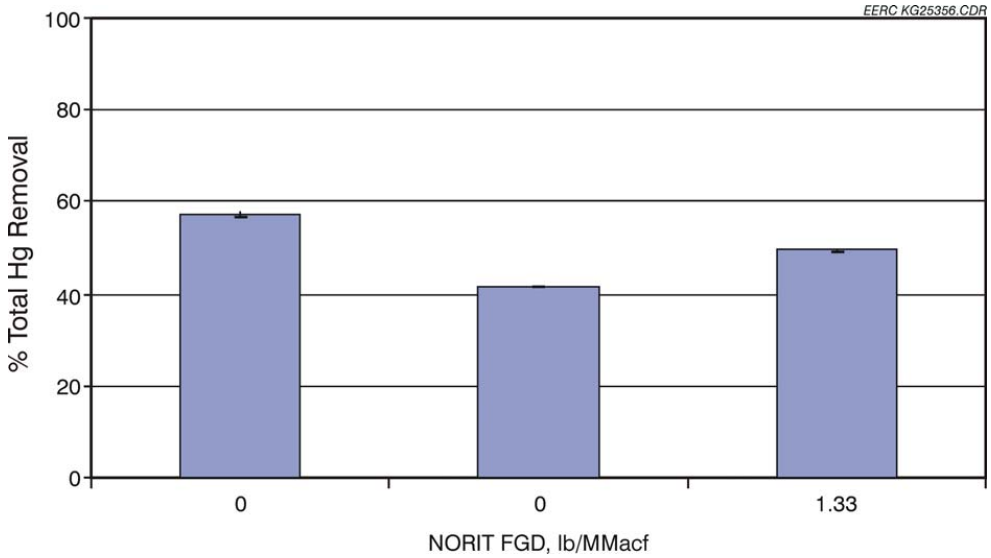


Figure 11-85. SDA–FF Hg_{total} removal efficiencies during WRI-treated Caballo coal combustion and the injection of 1.33 lb/MMacf of DARCO FGD into the WRI-treated Caballo coal flue gas.

Figures 11-86 and 11-87. Thus SDA–FF Hg_{total} removal was restricted by system limitations (i.e., gas residence time in the SDA) rather than the intrinsic ability of the Solucorp Industries additive to enhance Hg_{total} capture.

Compared in Figure 11-88 are CMM and OH Hg_{total} and Hg^0 measurement results for the 50% gas bypass condition. The SDA inlet CMM values are somewhat higher and show less Hg^0 than do the corresponding inlet OH values. The FF outlet CMM and OH measurements are in good agreement.

Two tests were also performed to evaluate the effects of SEA1 addition in conjunction with the Solucorp Industries SDA additive on SDA–FF Hg_{total} capture. Test results are presented in Figure 11-89. The addition of SEA1 did not significantly improve SDA–FF Hg_{total} removal, even at the very high injection rate of 10.6 lb/MMacf.

11.5 Mercury Emissions Control Through Coal Blending

A potential method for increasing the Hg^{2+}:Hg^0 ratio in subbituminous coal combustion flue gases is coal blending with a high-chlorine-content bituminous coal. As opposed to SEA1 addition, bituminous coal blending has the added benefit of increasing the fuel heating value.

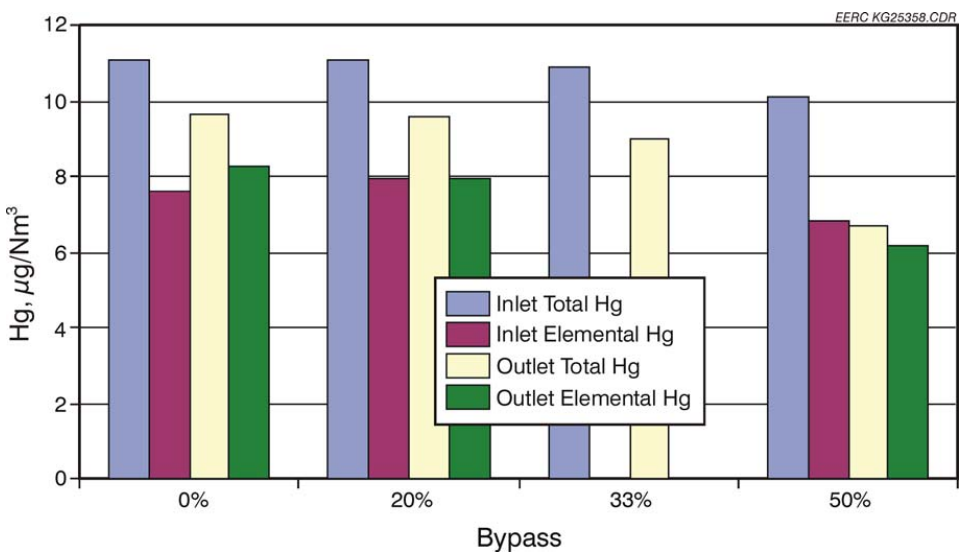


Figure 11-86. SDA additive SDA inlet and FF outlet Hg_{total} and Hg^0 concentrations during Solucorp Industries slurry additions at various degrees of Caballo coal combustion flue gas bypass.

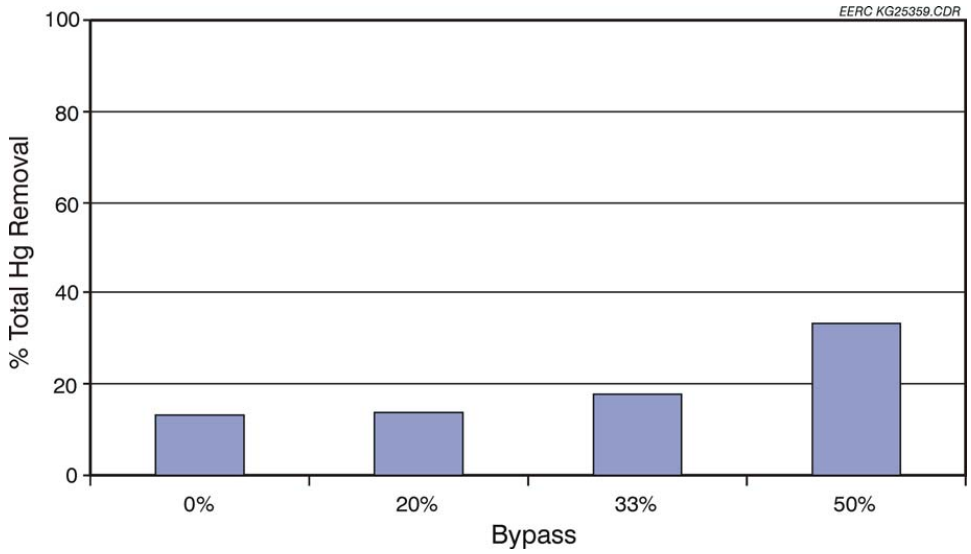


Figure 11-87. SDA–FF Hg_{total} removal efficiencies during Solucorp Industries slurry additions at various degrees of Caballo coal combustion flue gas bypass.

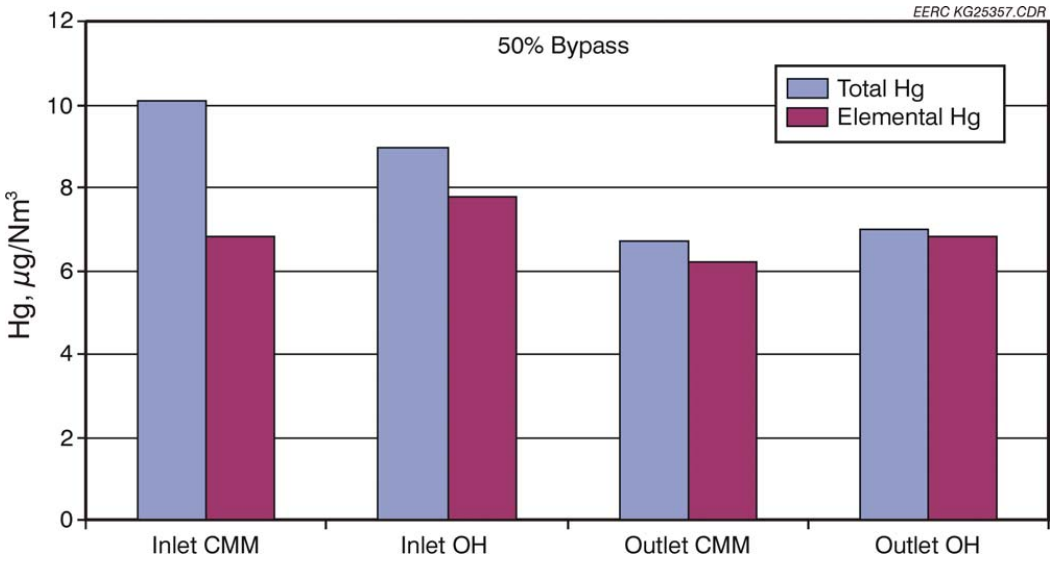


Figure 11-88. Comparison of CMM and OH SDA inlet and FF outlet Hg_{total} and Hg^0 concentration measurement results for Caballo coal combustion flue gas during the testing of a Solucorp Industries SDA additive.

11.5.1 Baseline Mercury Speciation for Coal Blend Combustion Flue Gases

Figures 11-90 and 11-91 present the baseline ESP inlet Hg_{total} concentrations measured during the combustion of 90:10 wt% and 80:20 wt% blends of Caballo subbituminous coal with Blacksville bituminous coal, respectively. Over the relatively short duration of these tests, the inlet Hg_{total} concentrations were consistently about 9.5 µg/Nm^3. Figure 11-92 compares CMM and OH ESP inlet and outlet Hg_{total} and Hg^0 concentrations measured during the combustion of an 80:20 wt% Caballo–Blacksville coal blend. The ESP outlet CMM Hg_{total} value is somewhat higher than that of the outlet OH method, but the Hg^0 values are similar. Unfortunately, CMM data were unavailable for inlet Hg concentrations during this test period. OH measurements were not performed during combustion of the 90:10 wt% Caballo–Blacksville blend because of the short test duration.

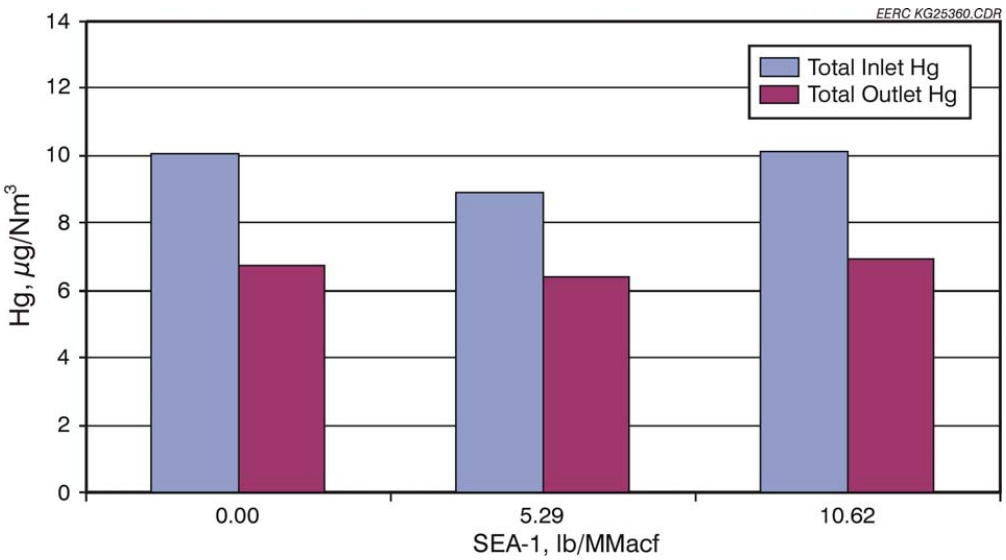


Figure 11-89. Average SDA inlet and FF outlet Hg_{total} concentrations in Caballo coal combustion flue gas during baseline testing conditions and Solucorp Industries SDA addition and SEA1 coal additions.

11.5.2 ACIs into Caballo–Blacksville Coal Blend Combustion Flue Gases

A subbituminous Caballo coal and blends of 80:20 wt% and 90:10 wt% Caballo coal–bituminous Blacksville coal were fired in the PTC equipped with an ESP. In addition to coal blending, DARCO FGD was injected at several different rates into flue gases produced from firing the Caballo and two coal blends.

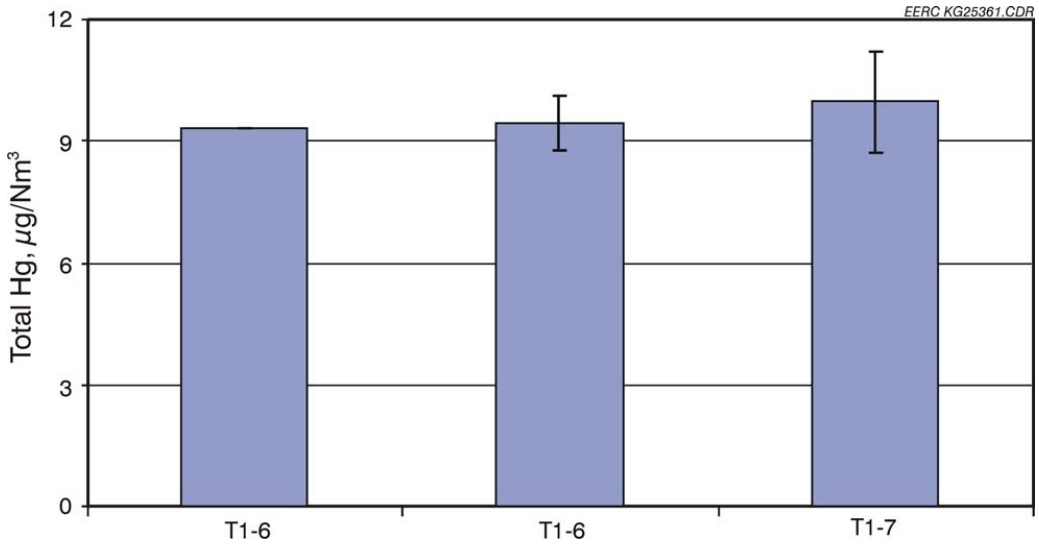


Figure 11-90. Baseline ESP inlet Hg_{total} concentrations measured during 90:10 wt% Caballo–Blacksville coal combustion.

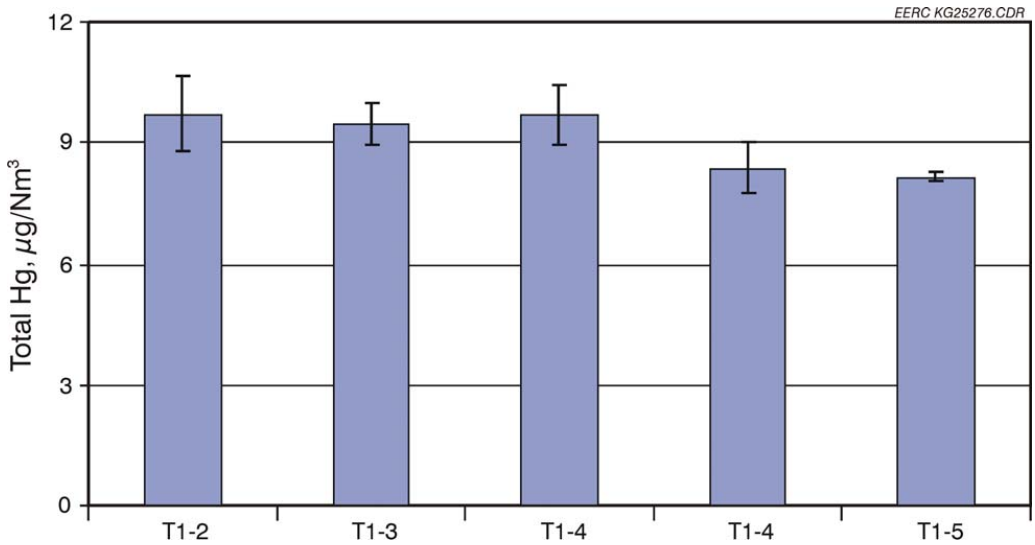


Figure 11-91. Baseline ESP inlet Hg_{total} concentrations measured during 80:20 wt% Caballo–Blacksville coal combustion.

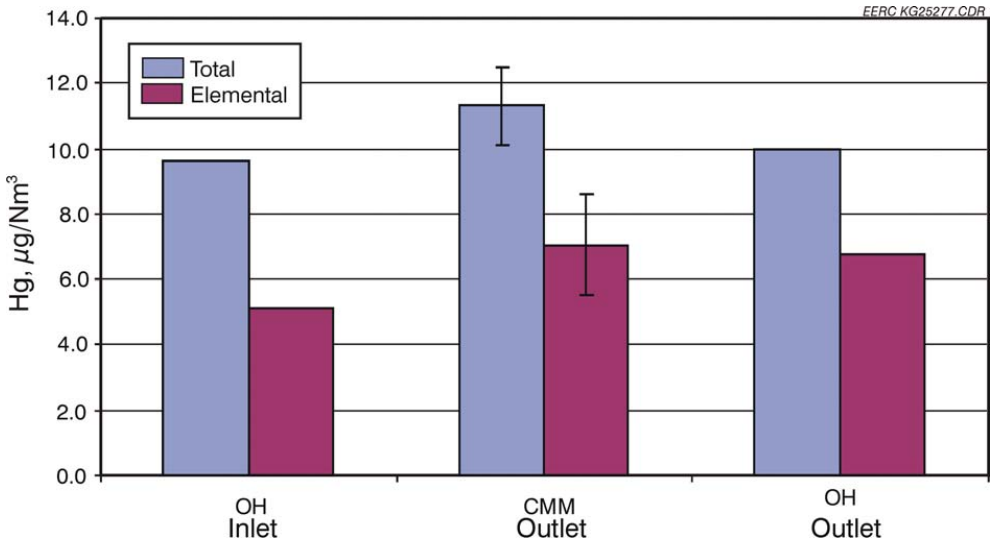


Figure 11-92. Comparison of CMM and OH baseline ESP Hg_{total} and Hg^0 concentrations measured during 80:20 wt% Caballo–Blacksville coal combustion.

ESP outlet Hg_{total} concentrations and ESP Hg_{total} removal efficiencies during combustion of the Caballo coal and coal blends are presented in Figures 11-93 and 11-94, respectively. Results are also presented in Figures 11-93 and 11-94 that indicate the effects of DARCO FGD injection on ESP outlet Hg_{total} concentrations and ESP Hg_{total} removal efficiencies.

ESP Hg_{total} removal during 4.8 lb/MMacf ACI into the 80:20 wt% Caballo–Blacksville coal blend was 54%. ESP Hg_{total} removal results for the 90:10 wt% Caballo–Blacksville coal blend were essentially identical to those obtained during the combustion of the 80:20 wt% blend, suggesting that a sufficient amount of chlorine was made available to react with Hg^0 even at the lower blend level. The effects of coal blending on ESP Hg_{total} removal are comparable to those described for SEA1 addition combined with ACI (Figures 11-12 and 11-13). Blending with a high-chlorine-content bituminous coal may be an alternative to SEA1 addition to enhance Hg^0 oxidation and improve Hg_{total} capture by a sorbent.

11.5.3 ESP–FF Mercury Control: ACI into an 80:20 wt% Caballo–Blacksville Coal Blend Combustion Flue Gas

Figure 11-95 shows the effect of DARCO FGD injection at 4.8 lb/MMacf upstream of the ESP on FF outlet Hg_{total} concentrations during the combustion of an 80 wt% Caballo and 20 wt% Blacksville coal blend. ESP inlet Hg_{total} concentrations were not measured during this test because of the ACI location upstream of the ESP. ACI resulted in a 55% lower FF outlet Hg_{total} concentration relative to the baseline FF outlet Hg_{total} concentration. The Hg_{total} removal was substantially less than that observed during ACIs using the TOXECON process (Figures 11-39 and 11-40).

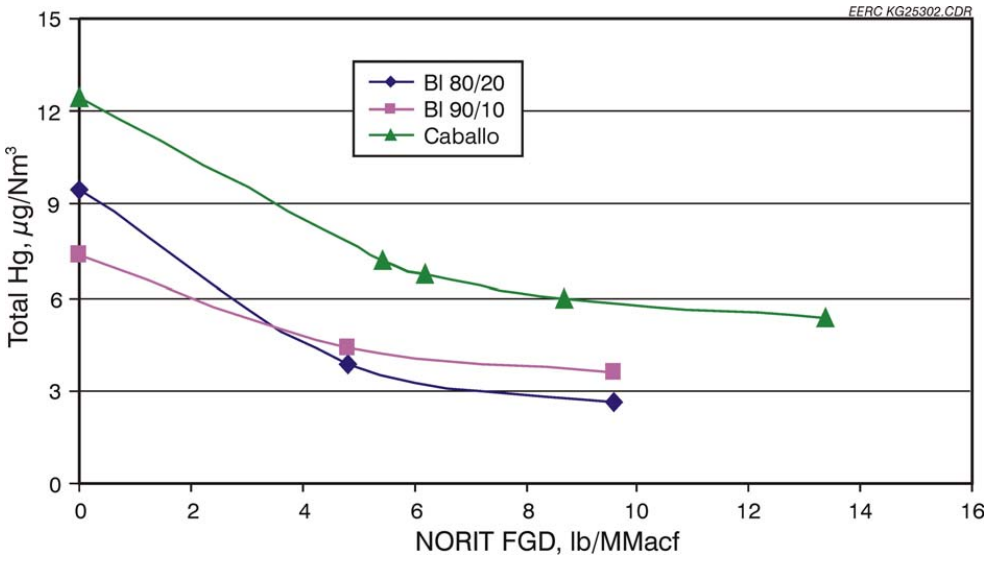


Figure 11-93. ESP outlet Hg_{total} concentrations during Caballo–Blacksville coal blend combustion and DARCO FGD injections.

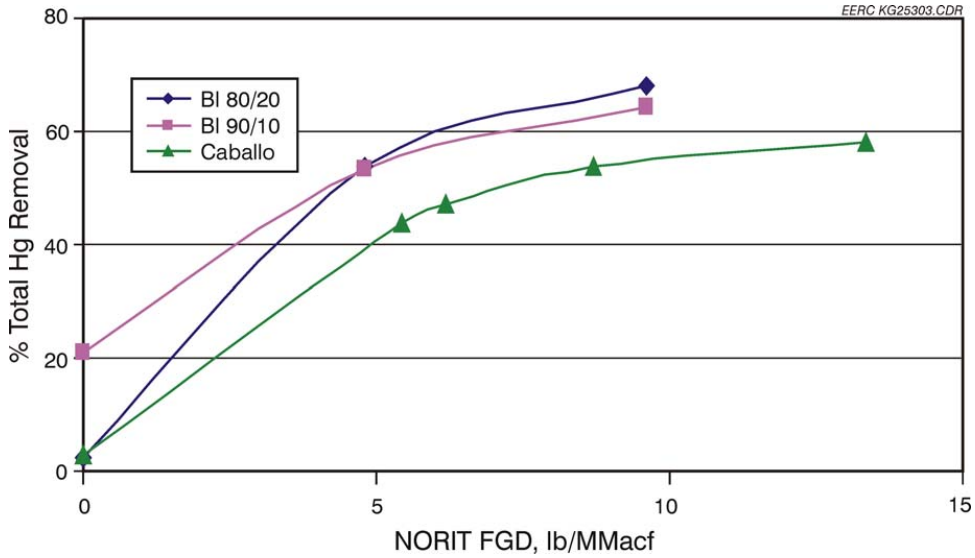


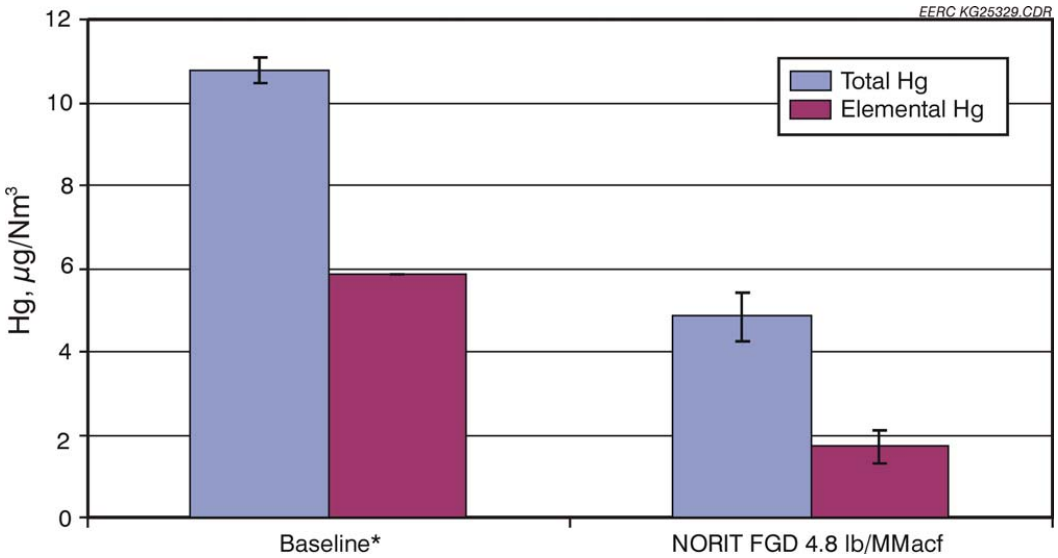
Figure 11-94. ESP Hg_{total} removal efficiencies during Caballo–Blacksville coal blend combustion and DARCO FGD injections.

11.5.4 FF Mercury Control: ACI into an 80:20 wt% Caballo–Blacksville Coal Blend

FF inlet and outlet Hg_{total} and Hg^0 concentrations and FF removal efficiencies determined during the combustion of an 80:20 wt% Caballo–Blacksville coal blend and the injection of DARCO FGD at 4.8 lb/MMacf are presented in Figures 11-96 and 11-97, respectively. Hg^0 was not analyzed for at the FF outlet during the baseline 80:20 wt% Caballo–Blacksville coal blend combustion testing, hence, this Hg^0 result is absent from Figure 11-96. Blending with the high-chlorine Blacksville bituminous coal reduced the proportion of Hg^0 in the Caballo coal combustion flue gas from 80%–90% to approximately 40%. Nevertheless, only about 11% of the Hg_{total} was removed during the baseline testing. ACI at 4.8 lb/MMacf into the 80:20 wt% Caballo–Blacksville coal combustion flue gas removed 75% of the Hg_{total}.

11.5.5 SDA–FF Mercury Control: ACI and SEA2 Addition into an 80:20 wt% Absaloka–Blacksville Coal Blend Combustion Flue Gas

As indicated in Figure 11-98, SDA inlet Hg_{total} concentrations were consistently at about 4.5 µg/Nm^3 during the combustion of an 80:20 wt% Absaloka–Blacksville coal blend. Presented in Figures 11-99 and 11-100 are the SDA–FF outlet Hg_{total} and Hg^0 concentrations and Hg_{total} removal efficiencies, respectively, during baseline 80:20 wt% Absaloka–Blacksville coal testing and during DARCO FGD injection alone at 4.8 lb/MMacf and combined with SEA2 addition at 0.5 lb/MMacf into an 80:20 wt% Absaloka–Blacksville coal combustion flue gas.



*Inlet baseline Hg values were unavailable for this test. Baseline values reported from FF outlet.

Figure 11-95. FF outlet Hg_{total} and Hg^0 concentrations in an 80 wt% Caballo and 20 wt% Blacksville coal combustion flue gas during DARCO FGD injection at 4.8 lb/MMacf.

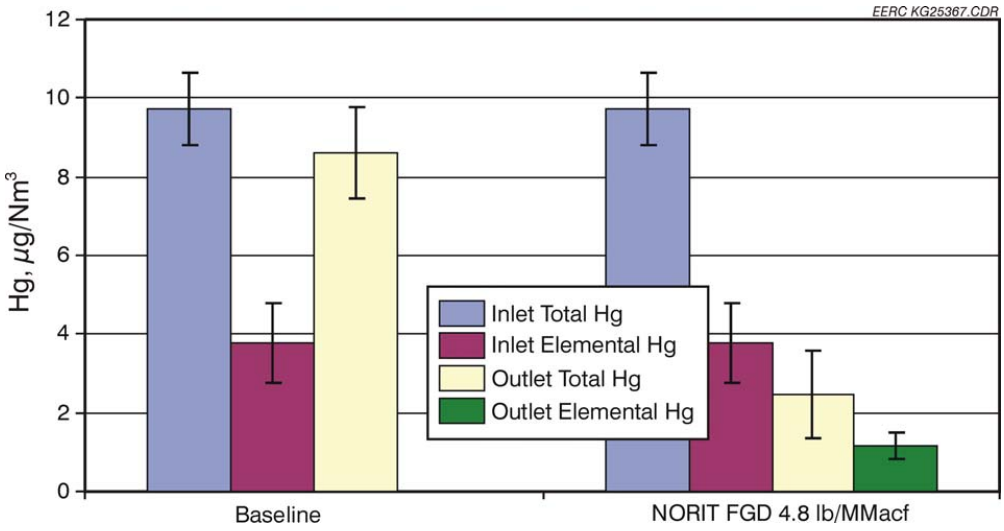


Figure 11-96. FF inlet and outlet Hg_{total} and Hg^0 concentrations in an 80:20 wt% Caballo–Blacksville coal blend combustion flue gas during baseline testing conditions and DARCO FGD injection at 4.8 lb/MMacf.

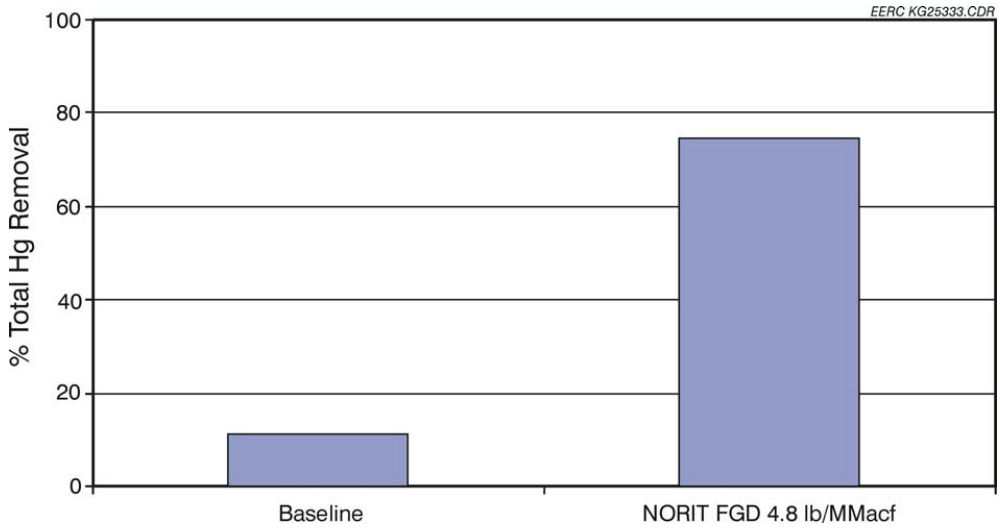


Figure 11-97. FF Hg_{total} removal efficiencies during baseline testing conditions and DARCO FGD injection at 4.8 lb/MMacf into an 80:20 wt% Caballo–Blacksville coal blend combustion flue gas.

The SDA–FF outlet Hg_{total} concentration in Figure 11-99 for the 80:20 wt% Absaloka–Blacksville coal combustion flue gas is very similar to the corresponding SDA inlet Hg_{total} concentrations in Figure 11-98, indicating essentially no Hg_{total} capture in the SDA–FF. Thus blending the Blacksville coal with the Absaloka coal did not significantly improve Hg_{total} capture in the SDA–FF relative to the combustion of Absaloka coal alone. DARCO FGD injected at a rate of 4.8 lb/MMacf resulted in a SDA–FF Hg_{total} removal of about 47%. The addition of 0.5 lb/MMacf SEA2 combined with injecting 4.8 lb/MMacf of DARCO FGD substantially improved SDA–FF Hg_{total} removal to >80%.

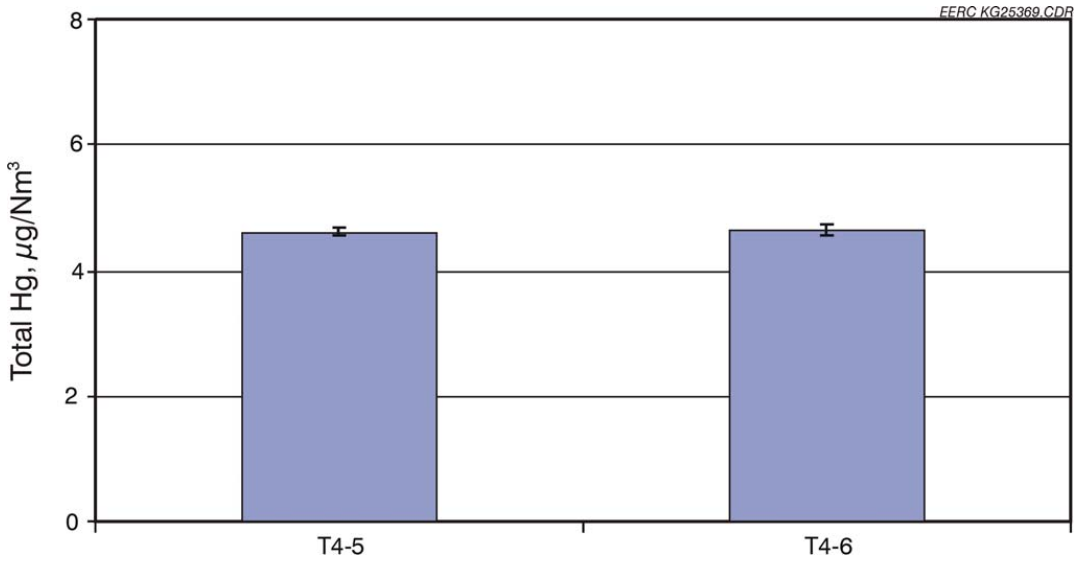


Figure 11-98. SDA inlet Hg_{total} concentrations during 80:20 wt% Absaloka–Blacksville coal combustion.

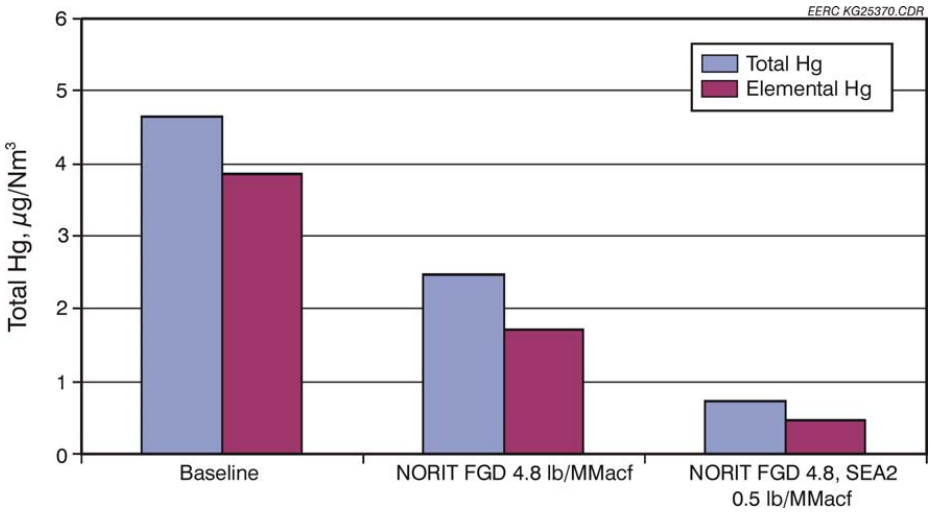
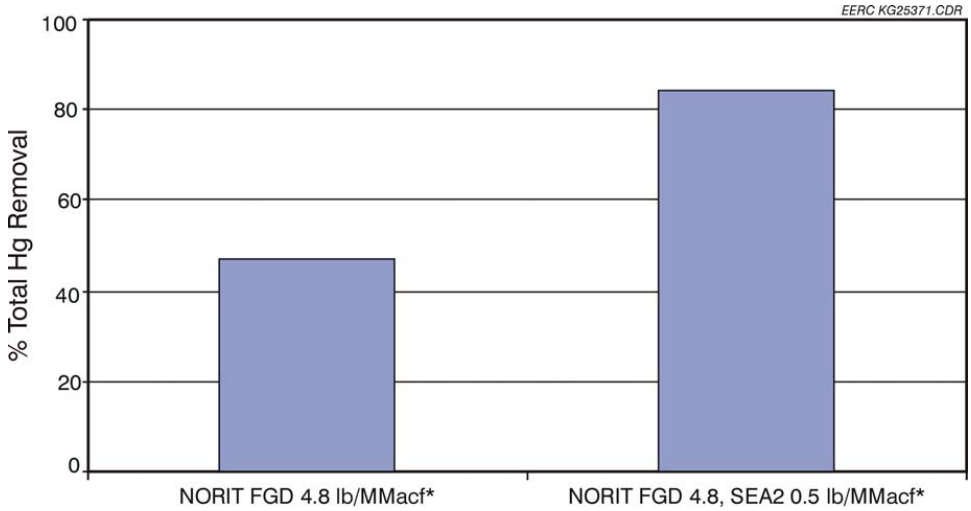


Figure 11-99. SDA–FF outlet Hg_{total} and Hg^0 concentrations during baseline 80:20 wt% Absaloka–Blacksville coal testing and during DARCO FGD injection alone at 4.8 lb/MMacf and combined with SEA2 addition at 0.5 lb/MMacf into an 80:20 wt% Absaloka–Blacksville coal.



*Hg removal calculated relative to baseline FF outlet.

Figure 11-100. SDA–FF Hg_{total} removal efficiencies during DARCO FGD injection alone at 4.8 lb/MMacf and combined with SEA2 addition at 0.5 lb/MMacf into an 80:20 wt% Absaloka–Blacksville coal combustion flue gas.

12.0 COST ANALYSIS OF CONTROLLING MERCURY EMISSIONS USING DARCO FGD INJECTION AND/OR SEA ADDITION

A Hg_{total} control cost analysis was performed for the DARCO FGD injection and/or SEA addition technologies for capturing Hg_{total} in an ESP, FF, ESP–FF (i.e., TOXECON), SDA–ESP, and SDA–FF. Although other emerging technologies, such as WRI's thermal coal treatment and EERC-treated carbon injection, were also effective in controlling Hg_{total} emissions, a cost analysis for implementing these technologies was not performed because of a lack of economic information. The assumptions used in estimating Hg_{total} control costs are summarized in Table 12-1. In addition to the assumptions in Table 12-1, the following was assumed:

- All costs are based on 2004 U.S. dollars (±20%).
- A 500-MW plant was already equipped with an ESP, FF, ESP–FF, SDA–ESP, or SDA–FF.
- Hg_{total} removal performance is based on EERC pilot-scale testing reported herein.
- The cost of a SEA coal addition system is similar to an ACI system.
- ESP and FF capacity are adequate to handle ACI and/or SEA additions.
- During ACI, as part of the TOXECON process, 50 wt% of the ash collected by the ESP is sold, whereas none of the ash collected in the FF is sold.
- When the pilot-scale unit is configured with an ESP, FF, SDA–ESP, or SDA–FF, 50 wt% of the ashes and slurry sludges are sold except those produced during ACI.
- The costs associated with permitting and Hg_{total} emisions monitoring were not included.
- The costs associated with retrofitting a plant were not considered.

Hg_{total} control cost estimates for the various APCDs and selected coals used during the pilot-scale testing are summarized in Table 12-2.

12.1 ESP Mercury Control Cost Estimate

The most cost-effective approach for an ESP was the addition of SEA2 at 1.9 lb/MMacf, which resulted in about 70% Hg_{total} removal at an estimated cost of $2.97/kW, or $6967/lb of Hg. SEA2 addition is also advantageous because it should not affect fly ash salability. SEA2 addition upstream of an ESP met the project goal of achieving 50%–90% Hg_{total} removal at costs of one-half to three-quarters of those currently estimated for ACI.

12.2 TOXECON and FF Mercury Control Cost Estimates

DARCO FGD injection at 2.5 lb/MMacf provided about 80% Hg_{total} removal in the FF and TOXECON systems at similar costs when assuming that the collected ash was not sold. In the TOXECON process, however, the ash collected in the ESP may be salable because the ACI is performed downstream between the ESP and FF. The TOXECON technology is more cost-effective for Hg_{total} control relative to ACI combined with only a FF, assuming that the ESP ash can be sold. Additions of SEAs increased the costs of TOXECON Hg_{total} removal because they did not significantly improve Hg_{total} capture.

Table 12-1. Hg_{total} Control Cost Analysis Assumptions

Parameter	Assumption
Plant Size	500 MW
Capacity Factor	85%
Flue Gas Hg_{total} Concentration	Calculated from coal composition
Heat Rate	11,000 Btu/kWh
Discount Rate[1]	10%
Plant Life[1]	20 y
DARCO FGD Cost	$0.45/lb
SEA1 Cost	$0.08/lb
SEA2 Cost	$0.68/lb
Operation Labor	$20/hr
Maintenance Labor	$25/hr
Additive and/or Injection Labor	0.5 hr/shift
Waste Disposal	$20/ton
Lost Revenue from Ash Sales	$20/ton
ESP Collection Efficiency	98%
FF Collection Efficiency	99%
Fly Ash:Bottom Ash	80:20 wt%

[1] Discount rate and plant life were used to calculate a capital recovery factor.

12.3 SDA–ESP and SDA–FF Mercury Control Cost Estimates

As indicated in Table 12-2, SEA2 addition upstream of the SDA–ESP and SDA–FF systems was relatively inexpensive and provided Hg_{total} removal efficiencies, 45%–50%, similar to those achieved with ACI. SEA2 and SEA1 additions combined with ACI significantly improved SDA–ESP and SDA–FF Hg_{total} capture to 80%–90% and reduced control costs on a per-pound-of-Hg-removed basis relative to ACI alone. Blending bituminous Blacksville coal with subbituminous Caballo coal significantly increased Hg_{total} control costs associated with the SDA–FF.

12.4 Comparison of Mercury Control Cost Estimates

Initial cost projections for achieving 90% Hg emission control using ACI were estimated by EPA (2) to range from $5000 to $28,000/lb Hg removed, whereas DOE (29) estimated $25,000 to

$70,000/lb Hg removed. More recently, DOE estimated that if utilities were required to use today's technologies to meet 90% Hg emission control, it would cost as much as $86,000/lb Hg removed (30). Most of the cost estimates in Table 12-2 are generally on the low end of EPA and DOE cost estimates primarily because they are based on the actual Hg removal achieved for a given pilot-scale test rather than the 90% Hg removal criterion. Undoubtedly, most of the cost estimates in Table 12-2 would increase significantly if ACI rates and/or SEA addition rates were increased to attain 90% Hg removal and, in some cases, 90% removal is probably unachievable regardless of the injection rates of activated carbon and/or SEA.

Table 12-2. Estimated Costs for Hg_{total} Control

						Without Lost Ash Sales			With Lost Ash Sales		
APCD	Coal	ACI Rate, lb/MMacf	SEA	SEA Addition Rate, lb/MMacf	Hg_{total} Removal, %	$/kW	mills/ kWh	$/lb Hg	$/kW	mills/ kWh	$/lbHg
ESP	Caballo	7.1	NA[1]	NA	50	6.45	0.87	21,506	9.90	1.33	33,023
ESP	90:10[2]	4.2	NA	NA	50	4.07	0.55	14,353	7.56	1.02	26,656
ESP	Caballo	4.8	1	2.9	55	5.59	0.75	16,795	9.05	1.22	27,163
ESP	Caballo	0.0	2	1.9	69	2.97	0.40	6,967	2.97	0.40	6,967
ESP	Caballo	2.9	2	0.8	77	4.54	0.61	9,481	8.00	1.07	16,685
FF	Caballo	2.5	NA	NA	83	2.68	0.36	5,170	6.17	0.83	11,893
TOXECON	Caballo	1.2	NA	NA	66	1.62	0.22	3,989	1.65	0.22	4,075
TOXECON	Caballo	2.5	NA	NA	82	2.68	0.36	5,240	2.72	0.36	5,308
TOXECON	Caballo	2.5	1	2.5	84	3.63	0.49	6,920	3.67	0.49	6,986
TOXECON	Caballo	2.5	2	0.2	73	3.48	0.47	7,698	3.52	0.47	7,776
SDA–ESP	Caballo	4.8	NA	NA	48	4.57	0.61	15,932	8.02	1.08	27,984
SDA–ESP	Caballo	4.8	1	4.8	85	5.91	0.79	11,091	9.36	1.26	17,576
SDA–ESP	Caballo	0.0	2	0.5	54	1.25	0.17	3,827	1.25	0.17	3,827
SDA–ESP	Caballo	3.9	2	0.5	86	5.00	0.67	9,263	8.45	1.13	15,668
SDA–FF	Caballo	1.9	NA	NA	45	2.19	0.29	8,229	5.68	0.76	21,331
SDA–FF	Caballo	4.8	NA	NA	66	4.57	0.61	11,250	8.06	1.08	19,845
SDA–FF	Caballo	1.9	1	2.9	67	3.22	0.43	7,807	6.71	0.90	16,263
SDA–FF	Caballo	1.9	1	4.8	80	3.53	0.47	7,081	7.02	0.94	14,073
SDA–FF	Caballo	0.0	2	0.3	43	1.00	0.13	3,968	1.00	0.13	3,968
SDA–FF	Caballo	1.9	2	0.1	91	2.87	0.38	5,010	6.36	0.85	11,108
SDA–FF	80:20[3]	4.8	NA	NA	47	4.59	0.62	32,059	10.04	1.35	70,067
SDA–FF	80:20[3]	4.8	2	0.5	84	5.76	0.77	21,395	11.21	1.51	41,613

[1] Not applicable.
[2] 90 wt% Caballo–10 wt% Blacksville coal blend.
[3] 80 wt% Absaloka–20 wt% Blacksville coal blend.

13.0 EFFECTS OF SEA ADDITION ON TRACE ELEMENT GAS–FLY ASH PARTITIONING AND FLY ASH MOBILITY

13.1 Trace Element Gas–Fly Ash Partitioning

Sampling using the EPA Method 29 multimetals train for selected trace elements was conducted during Week 1 and Week 4 pilot-scale testing. The goal was to determine the effects of SEA addition on trace element gas–particle partitioning and fly ash mobility (i.e., leachability). The three conditions that were evaluated were 1) baseline, Caballo coal combustion without additives; 2) Caballo coal with SEA1 addition; and 3) Caballo coal with SEA2 addition. Concentrations of ten HAPs in fly ashes collected from an ESP during the three test conditions are presented in Table 13-1. Except for Cd and Sb, trace element concentrations did not vary significantly among the three test conditions. Similar to the trace element fly ash results in Table 13-1, total flue gas concentrations for the 10 HAPs, presented in Figures 13-1 and 13-2, did not vary significantly. As indicated in Figure 13-3, the majority of trace elements in the flue gases were associated with fly ash particles. The relatively high gas-partitioning concentrations for Be and Sb in Figure 13-3 are misleading because they were actually below analytical detection in the impinger solutions and were reported as one-half the instrument detection limit. Other elements reported as nondetectable in the impinger solutions were As, Cd, Co, Ni, and Se. The only elements detected in the gas phase were Cr, Mn, and Pb; however, the proportion was less than 1% for all three elements and represented less than 9 µg/dscm in the gas phase of the flue gas.

13.2 Fly Ash Particle-Size and Chemical Composition Distributions

Samples of aerodynamically sized Caballo coal fly ash were collected from the outlet of the PTC during baseline testing conditions and SEA additions using an EPA–SRI five-stage cyclone sampler. Cutoff diameters (d_{50}) and actual flue gas conditions are listed in Table 13-2. The filter catch d_{50} was ~0.4 µm.

Table 13-1. Trace Element Concentrations in ESP Fly Ash, µg/g

	Baseline	SEA1	SEA2
As	24	23	21
Be	3.23	2.71	2.45
Cd	0.57	1.1	1.2
Co	45.5	52.4	56.3
Cr	154	127	128
Mn	897	954	991
Ni	81	80	77
Pb	51	38	38
Sb	1.6	3.53	3.77
Se	21	24	21

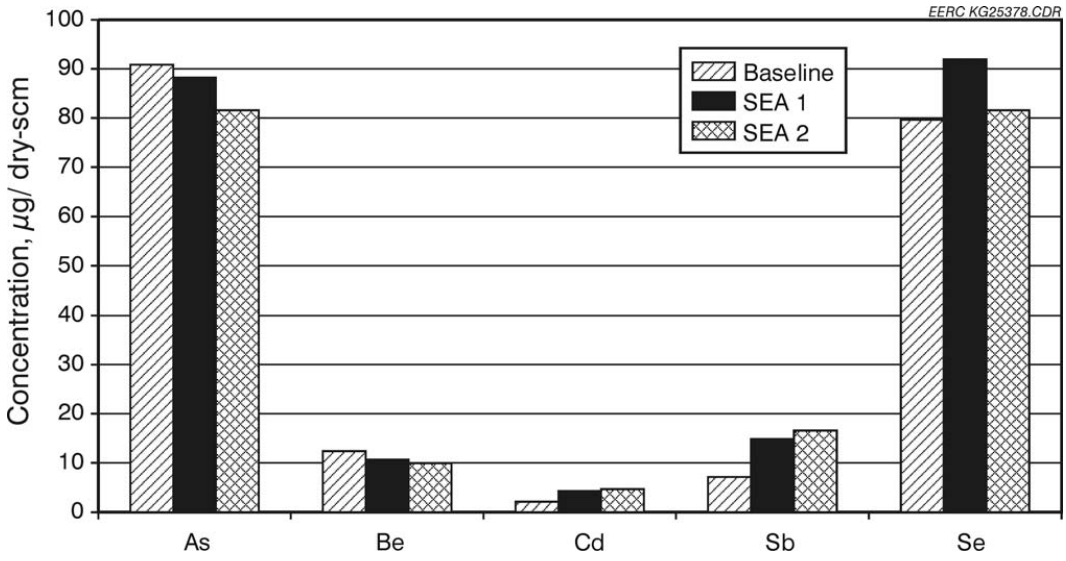


Figure 13-1. Trace element (As, Be, Cd, Sb, and Se) concentrations in Caballo coal combustion flue gas during baseline testing conditions and SEA additions.

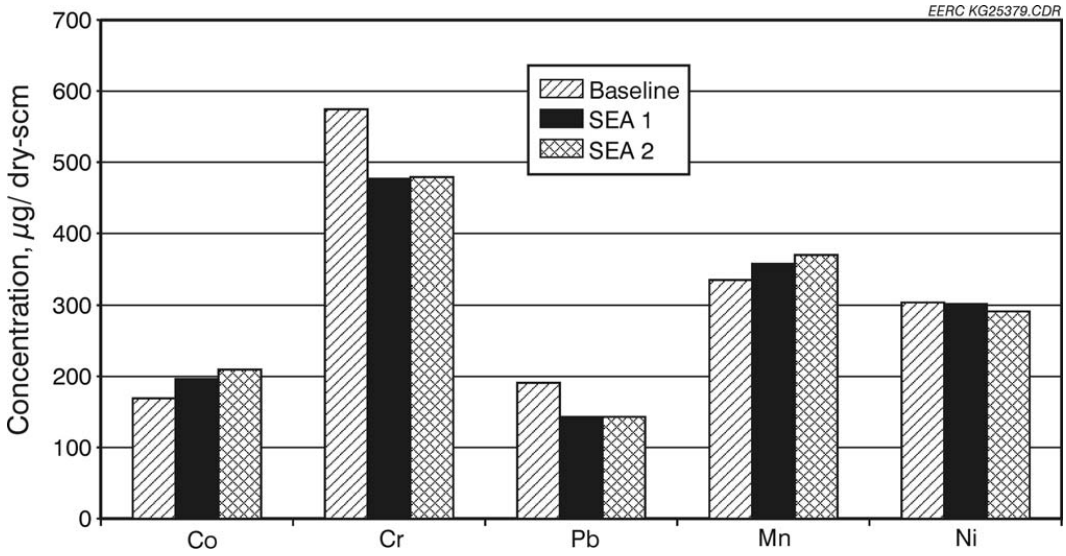


Figure 13-2. Trace element (Co, Cr, Pb, Mn, and Ni) concentrations in Caballo coal combustion flue gas during baseline testing conditions and SEA additions.

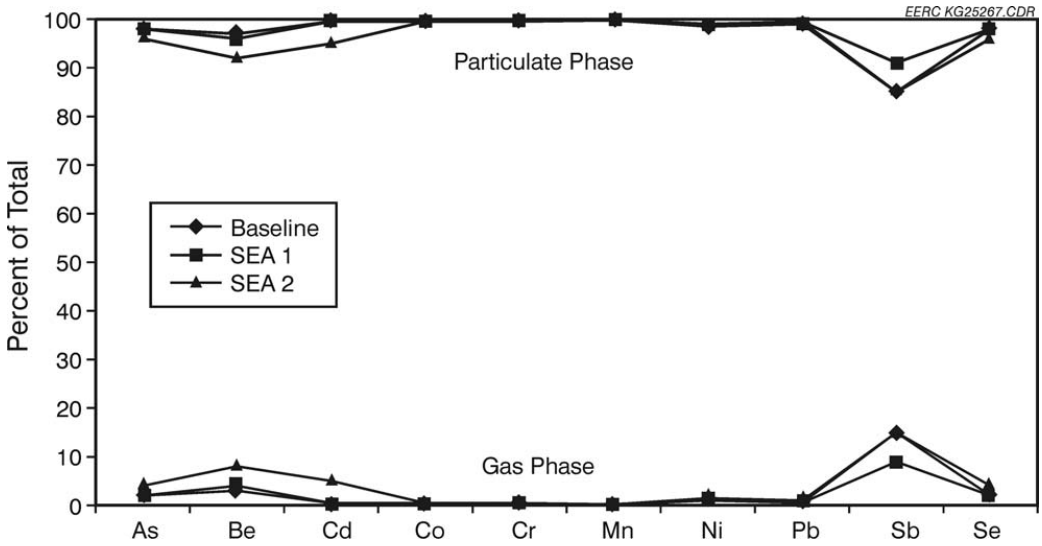


Figure 13-3. Trace element partitioning in Caballo coal combustion flue gas during baseline testing conditions and SEA additions.

Table 13-2. Multicyclone Sampling Conditions

	d_{50}, µm					Gas Composition, %					
	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	O_2	CO	CO_2	H_2O	N_2	Temp., °F
Baseline	7.23	3.97	2.16	1.50	.625	6	0	10	10.4	84	311
SEA1	7.27	4.00	2.18	1.51	.630	6	0	10	10.1	84	314
SEA2	7.45	4.16	2.27	1.57	.656	6	0	10	10.1	84	321

PSDs for the three test conditions are compared in Figure 13-4. The three fly ash PSDs were very similar, and most of the mass, ~75%, occurred in the coarser, ~7.3 µm, fraction.

Trace element concentrations for each cyclone fraction are presented in Tables 13-3, 13-4, and 13-5. Similar to the PSDs in Figure 13-4, trace element-size distributions for the three fly ashes were relatively consistent. Cd, Pb, Se, Co, Mn, and Sb concentrations increased with decreasing particle size, as exemplified in Figures 13-5 and 13-6. Ni and Cr concentrations did not vary with size systematically probably because of contaminants introduced by the stainless steel components of the five-stage multicyclone sampler. Further testing with an alternate sampler would be needed to determine whether the Ni and Cr variability was from contamination or the effects of the Hg control additives.

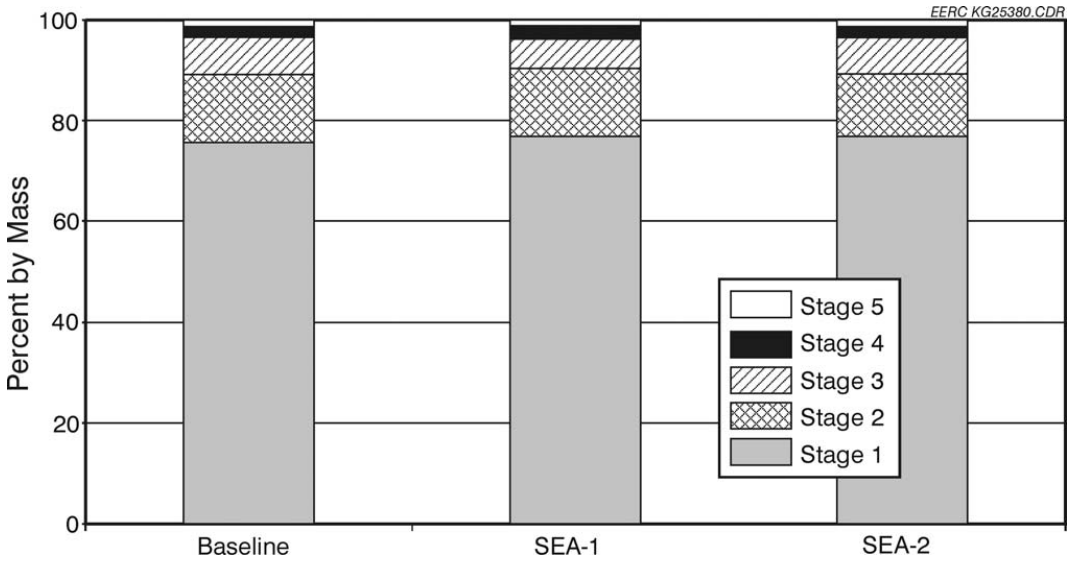


Figure 13-4. Caballo coal fly ash particle-size distributions.

Table 13-3. Trace Element Compositions of Multicyclone Samples from Baseline Caballo Coal Fly Ash, ppm

	Caballo Baseline					
	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Filter
d_{50}, µm	7.23	3.97	2.16	1.5	0.625	~0.4
As	20.5	46.9	36.8	30.8	25.3	17.5
Be	3.0	2.3	3	4.9	5.3	1.95
Cd	0.33	0.62	0.9	1.71	2.75	9.55
Co	49	122	132	137	89	31.2
Cr	96.8	204	158	1500	355	197
Mn	868	1196	1250	1376	1060	505
Ni	78	200	184	723	468	253
Pb	34	57	92	118	132	546
Sb	3.1	7.7	6.9	6.1	9.4	1.95
Se	11.2	24	37.8	58.4	86.3	226

Table 13-4. Trace Element Compositions of Multicyclone Samples from SEA1-Containing Caballo Coal Fly Ash, ppm

	Caballo + SEA1 Addition					
	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Filter
d_{50}, µm	7.27	4.00	2.18	1.51	0.630	~0.4
As	21.6	43.6	35.2	27.6	24.2	15.3
Be	2.7	2.2	3.1	3.3	5.1	1.3
Cd	0.40	0.81	1.3	1.34	2.28	10.9
Co	81	115	131	117	88	20.5
Cr	93.0	108	110	198	285	56.3
Mn	1000	1150	1270	1020	1090	316
Ni	85	122	255	177	227	53.7
Pb	29	56	92	97	111	269
Sb	3.6	7.1	6.7	9.5	4.5	1.3
Se	12.4	20.5	33.6	43	86.8	138

Table 13-5. Trace Element Compositions of Multicyclone Samples from SEA2-Containing Caballo Coal Fly Ash, ppm

	Caballo + SEA2 Addition					
	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Filter
d_{50}, µm	7.45	4.16	2.27	1.57	0.656	~0.4
As	19.7	41.5	35.4	31.1	27.5	17.1
Be	3.1	2.3	2.8	5.2	4.9	2.4
Cd	0.59	1.01	1.42	1.67	2.67	22.0
Co	86	124	143	144	91	25.6
Cr	116	116	124	289	150	48.7
Mn	964	1220	1370	1015	966	396
Ni	89	105	117	219	165	59.7
Pb	30	55	94	107	132	280
Sb	3.5	7.2	7.1	6.0	7.2	1.2
Se	9.5	19.1	32.0	52.0	94.5	246

13.3 Trace Element Fly Ash Mobility

Trace element leaching results for fly ashes produced during baseline Caballo coal combustion testing and the addition of SEAs are shown in Figures 13-7, 13-8, and 13-9. For all conditions and leaching times, trace element concentrations were below regulatory limits for disposal. Cr, Mn, and Se concentrations, however, increased with time, from 18 hours to 60 days, for the baseline- and SEA2-containing fly ashes, indicating that longer leaching times may be required to determine the maximum release of these elements.

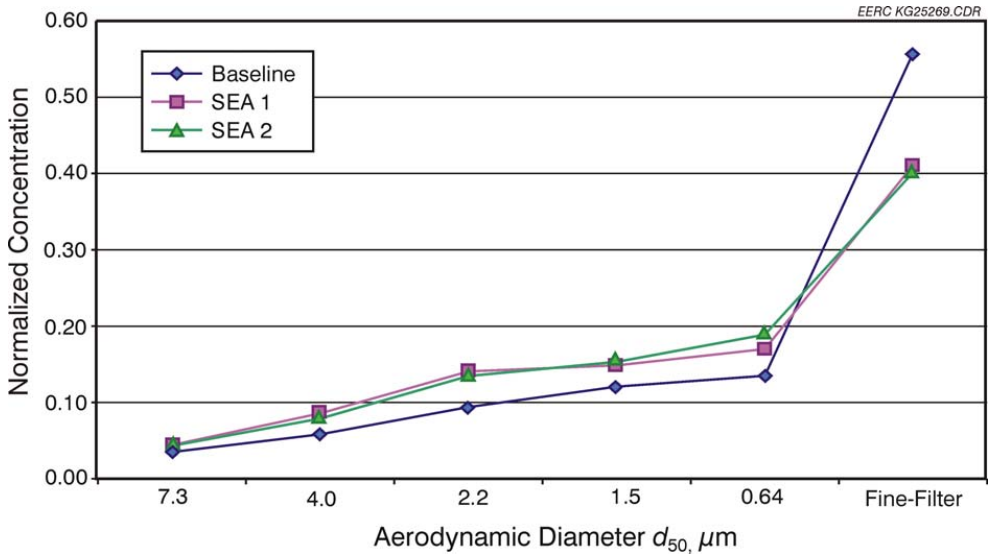


Figure 13-5. Pb concentrations as a function of particle size.

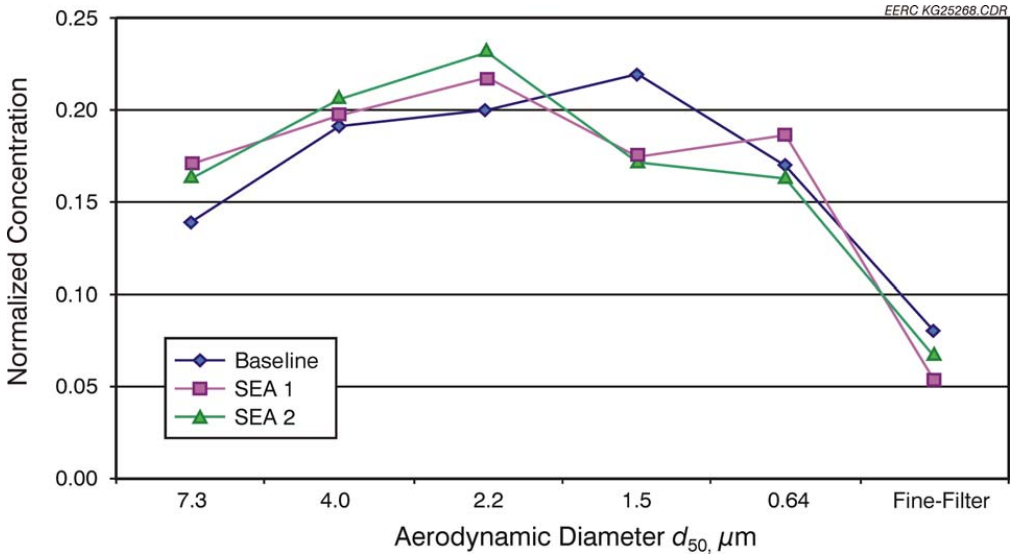


Figure 13-6. Mn concentrations as a function of particle size.

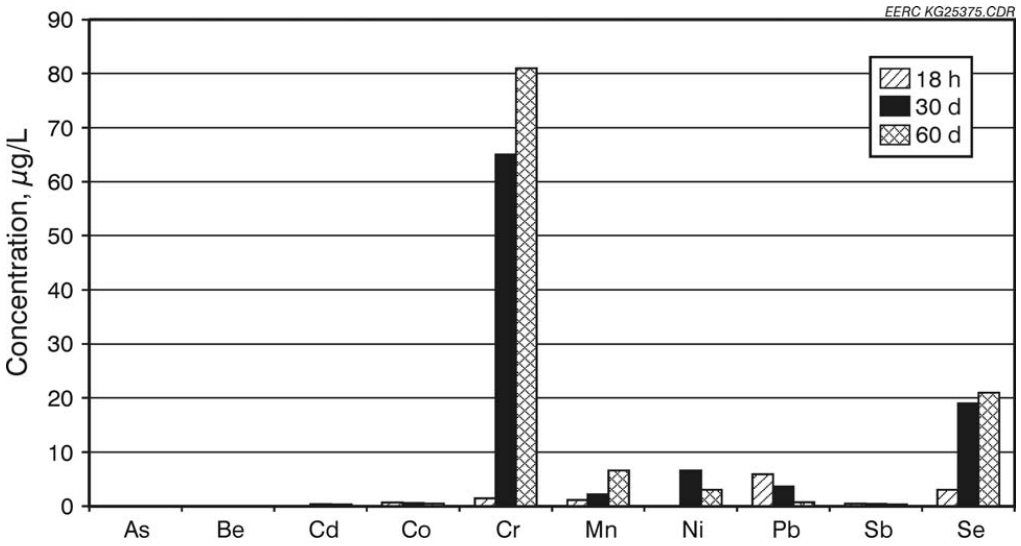


Figure 13-7. Trace element leachate concentrations for Caballo coal fly ash as a function of leaching duration.

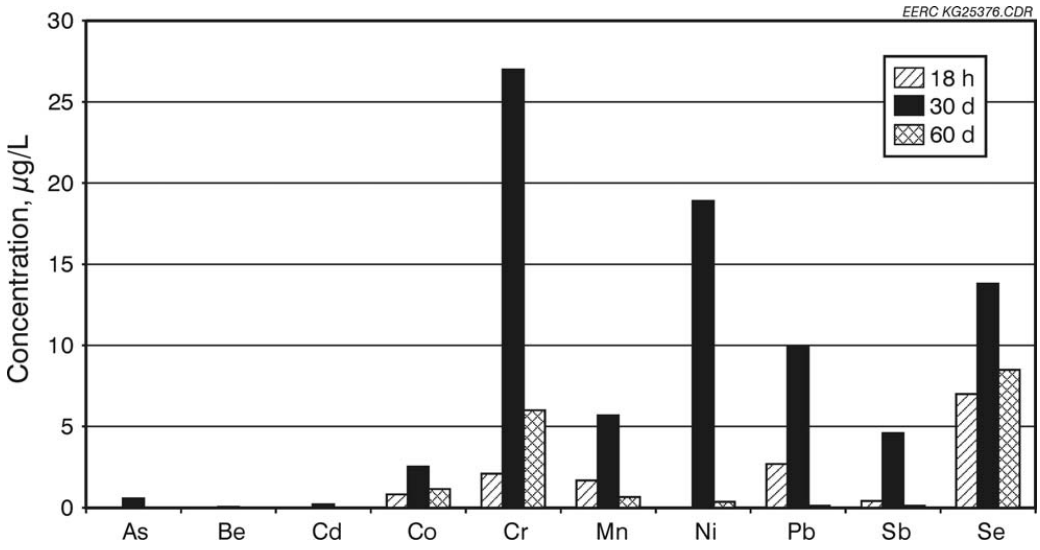


Figure 13-8. Trace element leachate concentrations for SEA1-containing Caballo coal fly ash as a function of leaching duration.

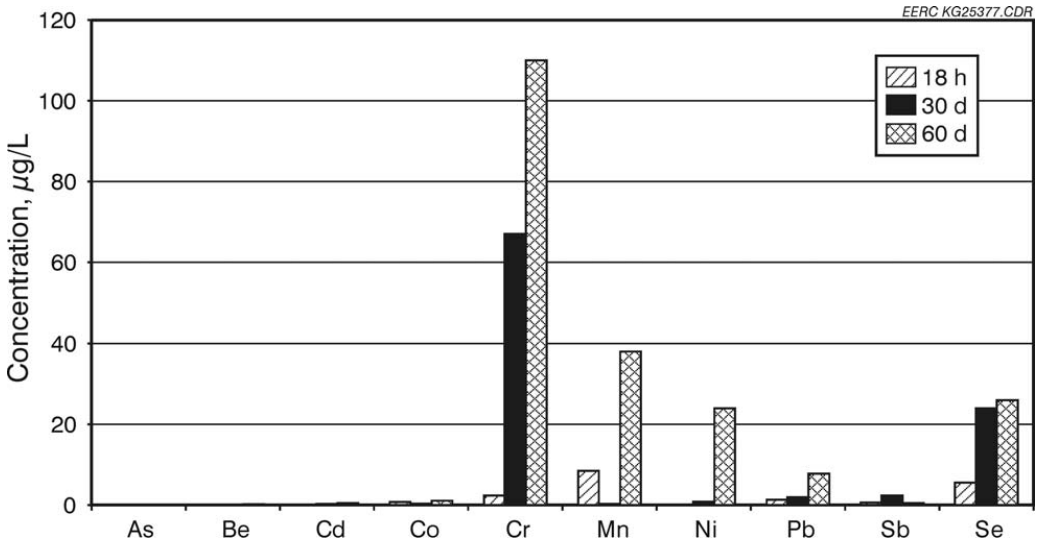


Figure 13-9. Trace element leachate concentrations for SEA2-containing Caballo coal fly ash as a function of leaching duration.

14.0 COMPARISON OF PILOT- AND FULL-SCALE MERCURY CONTROL TESTING

Hg_{total} control technology test results obtained on the PTC equipped with an ESP were compared with results obtained on a full-scale pc-fired boiler also equipped with an ESP. The lignite coal fired in both units was from the same mine. The Hg_{total} control technology tested in both the pilot- and full-scale units included DARCO FGD injections upstream of the ESP and combined DARCO FGD injections with SEA1 additions. Test results for corresponding conditions performed on the PTC and full-scale unit compared favorably, as illustrated in Figure 14-1.

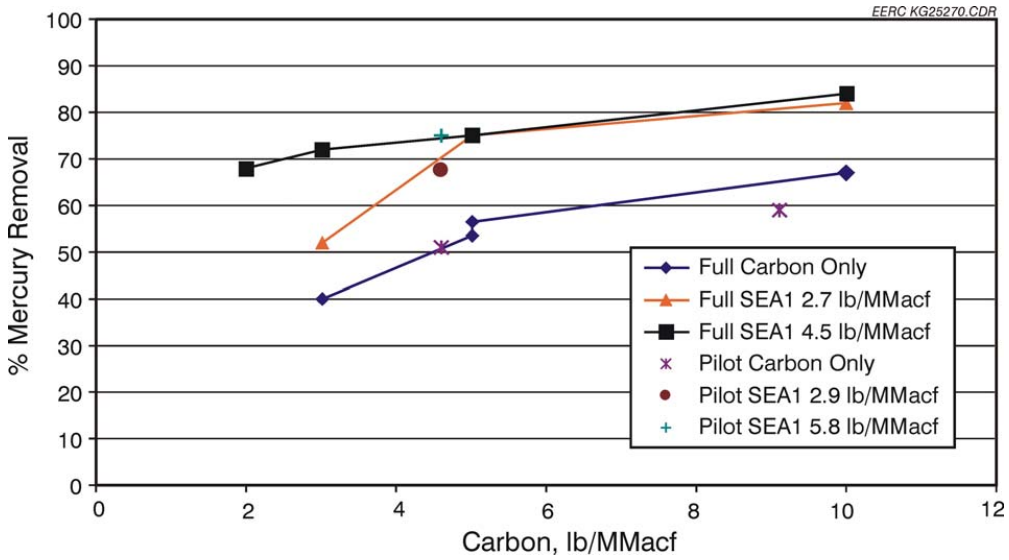


Figure 14-1. Comparison of ESP Hg_{total} removal efficiencies obtained on the pilot-scale PTC and a utility-scale unit during combustion of the same lignite coal.

15.0 FULL-SCALE TESTING OF SEA2 ADDITION AT AMEREN UE'S MERAMEC STATION

At the request of Ameren UE, the program work scope was expanded to include full-scale testing of SEA2 addition at the Meramec Station where ADA–ES was performing powdered activated carbon (PAC) injection for Hg_{total} emission reduction. Ameren UE and NETL provided funding for EERC personnel to travel to the Meramec Station and conduct the SEA2 injection during a 1-week test period. ADA–ES conducted all other site monitoring, measurements, and injections of PAC. Testing was conducted from September 27 – October 1, 2004.

15.1 Facility

Ameren UE's Meramec Station is located in St. Louis County, Missouri. The units at Meramec were originally designed to burn bituminous coal; however, they are now burning 100% PRB subbituminous coal. The test unit (Unit 2) is a load-following subcritical 140-MW (gross) pc, tangentially fired, electric generating unit equipped with a cold-side ESP for particulate removal; in the spring of 2004, the unit was retrofitted with low-NO_x burners and separated overfire air for control of NO_x emissions. Hg measurements for the test period were made on one-half of the 140-MW flue gas stream.

15.2 Mercury Measurements

During testing, Hg_{total} concentrations were measured at the ESP inlet and outlet using two CMMs. Oxygen measurements were made at the ESP inlet and outlet to determine the amount of air in-leakage across the ESP. At full-load conditions, O_2 levels were approximately 4.0% at each location, indicative of minimal leakage across the ESP. Thus the Hg_{total}, Hg^0, and Hg^{2+} concentrations were not normalized to a certain O_2 level in the flue gas. Hg concentrations are presented at normal reference conditions (i.e., dry, 0°C, and 760 mmHg). A cyclone was used to collect in situ samples of fly ash upstream of the ESP to monitor Hg_p concentrations. The fly ash samples were sent off-site and analyzed for Hg content.

15.3 Test Plan

The test matrix for Meramec is presented in Table 15-1. On the first day, CMM measurements were made at the ESP inlet and outlet to establish baseline Hg_{total}, Hg^0, Hg^{2+}, and Hg_p concentrations. During the next two days, SEA2 was added at the Unit 2-C coal feeder just upstream of the coal pulverizer for several hours during each day. It was estimated that the SEA2 would reach the boiler within 60 seconds after being added to the coal. During the final two test days, PAC was injected upstream of the ESP while SEA2 was introduced into the coal. The unit was maintained at high load (nominally ~140 MW) during baseline testing and Hg_{total} control testing.

Table 15-1. Meramec Unit 2 Test Matrix

Test Day	SEA2 Injection Rate, lb/hr	ACI Rate, lb/hr (lb/MMacf)	Test Duration, hr
1	0	0	9
2	1.9	0	5
3	2	0	3.5
	2.4	0	2
	5	0	2
4	5	0	1.5
	5	47 (2.9)	4
5	5	15 (1)	3

15.4 Results

During the initial day of baseline testing conditions, ESP inlet and outlet Hg_{total} concentrations were 5.3 µg/Nm^3 and 3.1 µg/Nm^3, respectively, indicative of an ESP Hg_{total} removal efficiency of 42%. The loss on ignition (LOI) for fly ash collected during the test varied between 0.9 and 1.4 wt%, indicating the presence of unburned carbon. On the second test day, SEA2 was added at 1.9 lb/hr into the 360-scfh flue gas flow. SEA2 addition resulted in ESP Hg_{total} inlet and outlet reductions from 4.5 µg/Nm^3 and 1.9 µg/Nm^3 to 2.7 µg/Nm^3 and 1.5 µg/Nm^3, respectively. After discontinuing the SEA2 addition, ESP inlet and outlet Hg_{total} concentrations returned to their baseline concentrations.

The effects of varying SEA2 addition rates on Hg species concentrations and removals are presented in Figure 15-1. Average ESP inlet and outlet Hg_{total} concentrations prior to SEA2 addition indicated a baseline ESP Hg_{total} removal efficiency of 61%, which was much higher than measured during baseline testing conditions. When the SEA2 was injected into the boiler at a rate of 5.0 lb/hr, ESP inlet and outlet Hg_{total} concentrations were reduced to 2.1 µg/dNm^3 and 1.1 ug/Nm^3, respectively, for an average Hg emission rate of 0.86 lb/10^{12} Btu.

Test results for combined SEA2 addition and PAC injection are presented in Figure 15-2. The SEA2 addition rate was maintained at 5 lb/hr, while the ACI rates ranged from 1.0–2.9 lb/MMacf, or 16–47 lb/hr. In the absence of ACI, SEA2 addition reduced ESP outlet Hg_{total} emissions to ~1.3 µg/Nm^3 (~0.95 lb/10^{12} Btu). Average ESP outlet Hg_{total} emissions were reduced slightly to 1.0 to 1.2 µg/Nm^3 as a result of combining ACI with SEA2 addition. SEA2 addition promoted the conversion of Hg^0 to Hg^{2+}.

Hg^0 oxidation at both the ESP inlet and outlet increased with increasing SEA2 addition rates. At baseline conditions, Hg^{2+} comprised 45% and 32% of the Hg_{total} at the ESP inlet and outlet, respectively. The proportions of Hg^{2+} during baseline conditions were much higher than those observed at Meramec during a previous baseline test period in August 2004 and higher than typically observed by ADA–ES at PRB sites. Nevertheless, Hg^{2+} proportions increased to 90% and 83% at the ESP inlet and outlet, respectively, during the addition of 5 lb/hr of SEA2. Stack opacity did not increase with SEA2 addition or ACI. No change in ESP electrical performance was noted.

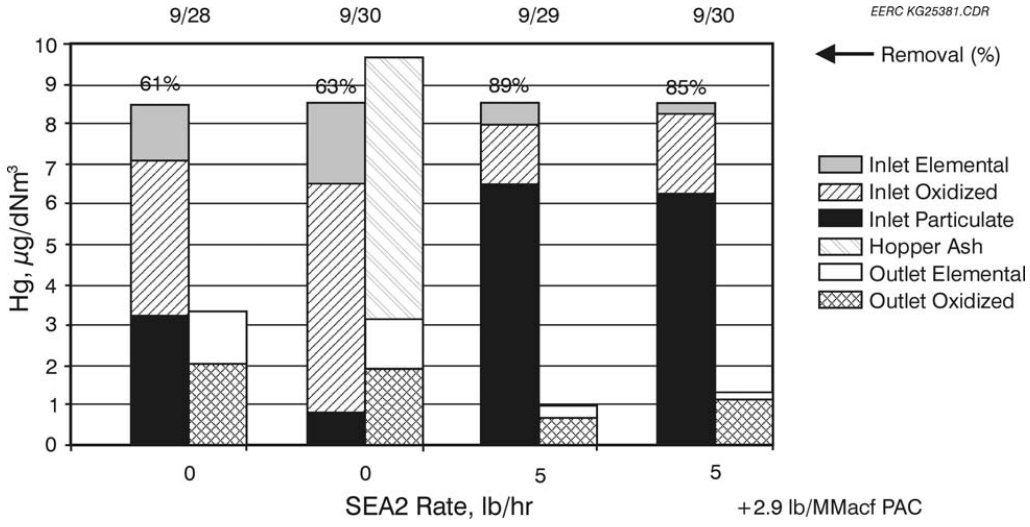


Figure 15-1. ESP inlet and outlet Hg^0, Hg^{2+}, and Hg_p concentrations and Hg_{total} removal efficiencies during baseline testing conditions and SEA2 additions at Meramec's Unit 2.

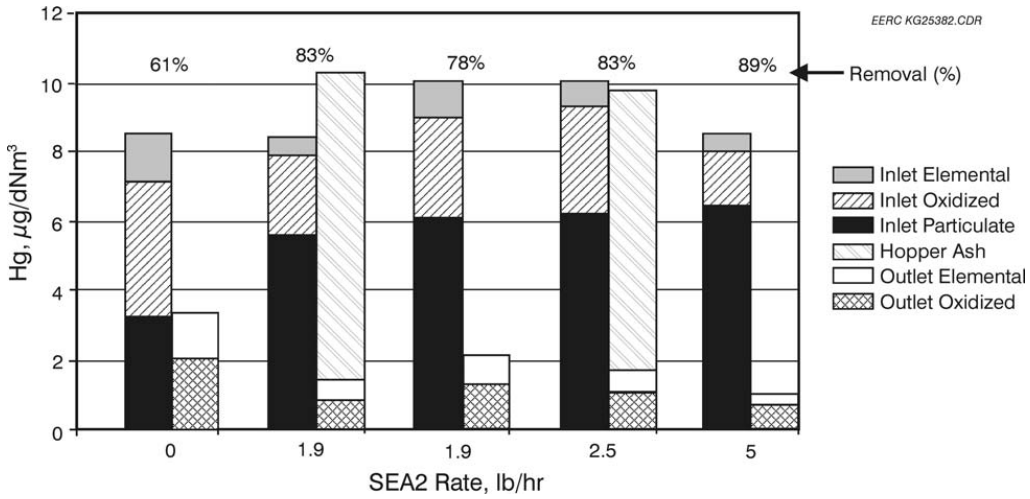


Figure 15-2. ESP inlet and outlet Hg^0, Hg^{2+}, and Hg_p concentrations and Hg_{total} removal efficiencies during duplicate baseline testing conditions and SEA2 addition alone and combined with DARCO FGD injection at Meramec's Unit 2.

15.5 Conclusions

Baseline measurements indicated 42% and 61% ESP Hg_{total} removal efficiencies. These values were higher than observed during previous baseline testing in August at Meramec Unit 2 when nominally 20% Hg_{total} removal was observed. The higher ESP Hg_{total} removal efficiencies are probably the result of relatively high unburned carbon concentrations (LOI ranged from 0.9 to 1.4 wt%) in the fly ash.

Introduction of SEA2 into the PRB coal combustion flue gas at Meramec increased the proportions of Hg^{2+} measured indirectly by CMMs. SEA2 additions increased the ESP Hg_{total} removal efficiency from 61% before injection to a maximum of 89% at an SEA2 addition rate of 5 lb/hr. The unburned carbon in fly ash at Meramec likely contributed to the relatively high ESP Hg_{total} removals.

Coinjection of PAC with SEA2 did not significantly increase ESP Hg_{total} capture relative to SEA2 addition alone. Unburned carbon in the fly ash probably contributed to Hg_{total} removal, and the addition of more carbon did not have a significant impact on Hg_{total} removal.

16.0 SUMMARY AND CONCLUSIONS

The applicability of potential Hg sorbent injection technologies, SEAs, Hg^0 oxidation technologies, and coal pretreatment processes to improve the Hg_{total} removal efficiency of APCDs was evaluated using a pilot-scale (580-MJ/hr, 550,000-Btu/hr) pc-fired unit. The unit was equipped with an ESP, FF, ESP and FF (e.g., TOXECON), SDA and ESP, and SDA and FF. Caballo and Absaloka subbituminous coals, blends of these coals with Blacksville bituminous coal, and sponsor-treated Caballo coals were fired in the unit while Hg species (Hg^0, Hg^{2+}, and Hg_p) concentrations were measured using CMMs and ASTM Method D6784-02 (OH method) at APCD inlets and outlets to evaluate Hg_{total} removal performance. Hg sorbents, Hg^0 oxidation additives, SEAs, and coal pretreatments were evaluated separately, and most were also tested in combination. Test results for various APCDs are summarized in Tables 16-1–16-5. Several of the sorbents, Hg^0 oxidation additives, SEAs, and combinations thereof, enhanced the Hg_{total} removal performance of the APCDs relative to the baseline Hg_{total} control strategy of ACI alone.

16.1 ESP Mercury Control

ESP Hg_{total} removal efficiencies are summarized in Table 16-1. For the WRI-treated Caballo coal, the incremental Hg_{total} removal relative to the baseline-treated coal is presented. In addition, the total removal value including that removed by the WRI pretreatment process is presented in parentheses.

16.1.1 Caballo Coal Combustion Flue Gas

Pilot-scale Caballo coal combustion test results indicated the following:

- The ESP was ineffective in capturing Hg_{total} from Caballo coal combustion flue gas in the absence of ACI or SEA addition.
- DARCO FGD injection provided ESP Hg_{total} removals ranging from 40% to 60% at injection rates of about 5–13 lb/MMacf. Increasing ACI rates gradually improved ESP Hg_{total} removal.
- SEA1 additions alone did not significantly enhance Hg_{total} removal.
- DARCO FGD injection at 4.8 lb/MMacf combined with SEA1 additions ranging from about 3 to 12 lb/MMacf resulted in ESP Hg_{total} removal efficiencies of 50%–70%. Increasing SEA1 addition rates gradually improved ESP Hg_{total} capture.
- In contrast to SEA1 additions alone, SEA2 addition at about 2 lb/MMacf resulted in an ESP Hg_{total} removal efficiency of about 70%. Similar high ESP Hg_{total} removals occurred at a 130-MW PRB coal combustion unit during SEA2 addition.

Table 16-1. Summary of Average ESP Hg_{total} Removal Efficiencies

Caballo Coal Combustion Flue Gas				
Sorbent	Rate, lb/MMacf	SEA	Rate, lb/MMacf	Hg_{total} Removal, %
DARCO FGD	5.4	None	NA[1]	44
DARCO FGD	6.2	None	NA	47
DARCO FGD	8.7	None	NA	54
DARCO FGD	13.4	None	NA	58
None	NA	1	2.9	1.9
None	NA	1	5.8	5.7
DARCO FGD	4.8	1	2.9	53
DARCO FGD	4.8	1	5.8	58
DARCO FGD	4.8	1	8.8	65
DARCO FGD	4.8	1	11.6	72
None	NA	2	1.9	69
DARCO FGD	2.9	2	0.8	77
DARCO FGD	2.9	2	1.4	85
DARCO FGD	2.9	2	1.9	85
DARCO FGD	4.8	2	1.9	82
DARCO FGD	2.9	1 and 2	0.5	68
EERC Carbon	4.8	None	NA	63
EERC Carbon	6.8	None	NA	75
Amended Silicate	4.8	None	NA	37
Amended Silicate	9.7	None	NA	40
Absaloka Coal				
Sorbent	Rate, lb/MMacf	SEA or Hg^0 Oxidant	Rate, lb/MMacf	Hg_{total} Removal, %
DARCO FGD	4.8	None	NA	36
DARCO FGD	4.8	2	1.9	84
German Carbon	4.8	None	NA	35
German Carbon	9.6	None	NA	43
None	NA	TiO_2	3.8	7
None	NA	TiO_2	9.9	0.4
None	NA	Na_2S_4	50 mg/Nm^3	5
None	NA	Na_2S_4	100 mg/Nm^3	18
None	NA	Na_2S_4	100 mg/Nm^3	27
DARCO FGD	4.8	Na_2S_4	100 mg/Nm^3	32
90:10 wt% Caballo–Blacksville Coal Combustion Flue Gas				
Sorbent	Rate, lb/MMacf	SEA	Rate, lb/MMacf	Hg_{total} Removal, %
DARCO FGD	4.8	None	NA	54
DARCO FGD	9.6	None	NA	68

Continued . . .

Table 16-1. Summary of Average ESP Hg_{total} Removal Efficiencies (continued)

80:20 wt% Caballo–Blacksville Coal Combustion Flue Gas				
Sorbent	Rate, lb/MMacf	SEA	Rate, lb/MMacf	Hg_{total} Removal, %
DARCO FGD	4.8	None	NA	54
DARCO FGD	9.6	None	NA	64
WRI-Treated Caballo Coal Combustion Flue Gas				
Sorbent	Rate, lb/MMacf	SEA	Rate, lb/MMacf	Hg_{total} Removal, %
Baseline	NA	None	NA	0 (64)
DARCO FGD	1.3	None	NA	29 (74)
DARCO FGD	2.5	None	NA	55 (84)

[1] Not applicable.

Table 16-2. Summary of Average ESP–FF and TOXECON Hg_{total} Removal Efficiencies

Caballo Coal Combustion Flue Gas				
Sorbent	Rate, lb/MMacf	SEA	Rate, lb/MMacf	Removal, %
DARCO FGD	1.2	None	NA[1]	66
DARCO FGD	2.5	None	NA	82
DARCO FGD	3.9	None	NA	91
None	NA	1	2.5	31
DARCO FGD	2.5	1	2.5	84
DARCO FGD	3.9	1	2.5	88
None	NA	2	0.1	11
None	NA	2	0.2	8
DARCO FGD	1.2	2	0.2	55
DARCO FGD	2.5	2	0.2	73
Demeter-Treated Caballo Coal Combustion Flue Gas				
Sorbent	Rate, lb/MMacf	SEA	Rate, lb/MMacf	Removal, %
EERC Carbon	2.5	None	NA	69
EERC Carbon	4.3	None	NA	75
EERC Carbon	5.1	None	NA	87
WRI-Treated Caballo Coal Combustion Flue Gas				
Sorbent	Rate, lb/MMacf	SEA	Rate, lb/MMacf	Removal, %
None	NA	None	NA	0 (64)
DARCO FGD	1.26	None	NA	79 (93)
80:20 wt% Caballo–Blacksville Coal Combustion Flue Gas				
Sorbent	Rate, lb/MMacf	SEA	Rate, lb/MMacf	Removal, %
DARCO FGD	4.8	None	NA	55*

* Relative to outlet baseline
[1] Not applicable.

Table 16-3. Summary of Average FF Hg_{total} Removal Efficiencies

Caballo Coal Combustion Flue Gas		
Sorbent	Rate, lb/MMacf	Hg_{total} Removal, %
DARCO FGD	2.5	80
DARCO FGD	4.8	75
80:20 wt% Caballo–Blacksville Coal Combustion Flue Gas		
DARCO FGD	4.8	75

Table 16-4. Summary of Average SDA–ESP Hg_{total} Removal Efficiencies

Caballo Coal Combustion Flue Gas				
Sorbent	Rate, lb/MMacf	SEA	Rate, lb/MMacf	Hg_{total} Removal, %
Baseline	NA[1]	None	NA	17
DARCO FGD	4.8	None	NA	48
DARCO FGD	6.8	None	NA	58
DARCO FGD	8.7	None	NA	61
DARCO FGD	10.6	None	NA	69
None	NA	1	4.8	38
DARCO FGD	4.8	1	4.8	85
DARCO FGD	4.8	1	6.8	86
None	NA	2	0.2	37
None	NA	2	0.5	54
DARCO FGD	3.9	2	0.5	86
DARCO FGD	3.9	2	1	90

[1] Not applicable.

- DARCO FGD injection at about 3 lb/MMacf combined with SEA2 additions ranging from about 1 to 2 lb/MMacf enhanced ESP Hg_{total} removal efficiencies to 80%–85%. Increasing the ACI rate to about 5 lb/MMacf in the presence of ~2 lb/hr of SEA2 did not significantly improve on the 80%–85% ESP Hg_{total} capture. The addition of a 50:50 wt% blend of SEA1–SEA2 at 0.5 lb/hr combined with ACI at about 3 lb/hr resulted in an ESP Hg_{total} removal efficiency of about 70%.

- Increasing the EERC-treated carbon injection from about 5 to 7 lb/MMacf improved ESP Hg_{total} removal from approximately 60% to 75%.

- Amended Silicate injections at ~5 and 10 lb/MMacf enhanced the ESP Hg_{total} removal efficiency to about 40%.

16.1.2 Absaloka Coal Combustion Flue Gas

Pilot-scale Absaloka coal combustion test results indicated the following:

Table 16-5. Summary of Average SDA–FF Hg_{total} Removal Efficiencies

Caballo Coal Combustion Flue Gas				
Sorbent	Rate, lb/MMacf	SEA	Rate, lb/MMacf	Removal, %
Baseline	NA[1]	None	NA	27
None	NA	1	1.9	30
None	NA	1	2.9	32
DARCO FGD	1.9	1	2.9	67
DARCO FGD	1.9	1	4.8	80
None	NA	2	0.3	43
DARCO FGD	1.9	2	0.1	91
DARCO FGD	1.9	2	0.3	92
None	NA	Amended Silicate	2.9	8
None	NA	Amended Silicate	5.8	16
Absaloka Coal Combustion Flue Gas				
Sorbent	Rate, lb/MMacf	Hg^0 Oxidant	Concentration, mg/Nm^3	Removal, %
None	NA	Na_2S_4	50*	0
None	NA	Na_2S_4	100*	0.8
None	NA	Na_2S_4	100**	4
None	NA	Na_2S_4	100***	0.5
80:20 wt% Absaloka–Blacksville Coal Combustion Flue Gas				
Sorbent	Rate, lb/MMacf	SEA	Rate, lb/MMacf	Removal, %
DARCO FGD	4.8	None	NA	47
DARCO FGD	4.8	2	0.5	84
WRI-Treated Caballo Coal Combustion Flue Gas				
Baseline	NA	None	NA	0 (64)
DARCO FGD	1.3	None	NA	0 (64)
Solucorp Industries SDA Additive, Caballo Coal Combustion Flue Gas				
0% Bypass	NA	None	NA	13
20% Bypass	NA	None	NA	14
33% Bypass	NA	None	NA	18
50% Bypass	NA	None	NA	33
50% Bypass	NA	SEA1	5.29	28
50% Bypass	NA	SEA1	10.62	31

*Injected at SDA inlet.
**Injected at SDA outlet.
***Injected at SDA outlet, second condition.
[1] Not applicable.

- The ESP was ineffective in removing Hg_{total} from Absaloka coal combustion flue gas.

- DARCO FGD injection at about 5 lb/MMacf resulted in an ESP Hg_{total} removal efficiency of about 40%. Similar ESP Hg_{total} removal efficiencies were obtained when injecting German carbon (Donau Desorex DX400 FGD carbon) at about 5 and 10 lb/MMacf.

- DARCO FGD injection at ~5 lb/MMacf combined with SEA2 addition at ~2 lb/hr resulted in a relatively high ESP Hg_{total} removal of about 80%.

- TiO_2 injection along with UV light did not significantly enhance Hg_{total} capture in the ESP, possibly because of insufficient light intensity and/or reaction time.

- Na_2S_4 injections alone and combined with ACI at ~5 lb/hr provided ESP Hg_{total} removals of ≤ 30%.

16.1.3 Caballo–Blacksville Coal Combustion Flue Gases

Pilot-scale Caballo–Blacksville coal combustion test results indicated the following:

- Blending of subbituminous Caballo coal with 10 wt% and 20 wt% Blacksville bituminous coal combined with DARCO FGD injections at ~5 and 10 lb/MMacf resulted in ESP Hg_{total} removals of about 50% and 65%.

- The effects of coal blending on ESP Hg_{total} removal were comparable to those described for ACIs combined with SEA1 additions into the Caballo coal combustion flue gas. Blending with a high-chlorine-content bituminous coal may be an alternative to SEA1 addition for enhancing Hg^0 oxidation and improving Hg_{total} capture by a sorbent.

16.1.4 WRI-Treated Caballo Coal Combustion Flue Gas

Pilot-scale WRI-treated Caballo coal combustion test results indicated the following:

- The WRI coal pretreatment process removed about 60% of the Hg in Caballo coal.

- DARCO FGD injections at about 1 and 2.5 lb/MMacf into WRI-treated Caballo coal combustion flue gas enhanced ESP Hg_{total} capture by 30% and 55%, respectively. When the coal Hg removal as a result of the WRI pretreatment is included, the overall Hg_{total} control efficiency was 82% at a modest ACI rate of 2.5 lb/MMacf.

16.1.5 Summary of ESP Mercury Control Options

Controlling Hg_{total} emissions with an ESP is challenging. DARCO FGD injection provided marginal ESP Hg_{total} removal of ~50% at reasonable injection rates of about 5 lb/MMacf. The German carbon provided somewhat lower performance. Addition of SEA1 in combination with DARCO FGD injection increased ESP Hg_{total} removal moderately to approximately 60%. Blending

with a high-chlorine-content bituminous coal combined with ACI produced results comparable to SEA1 injection, along with the benefit of introducing a HHV fuel. A promising control option was SEA2 addition, which resulted in 70% ESP Hg_{total} removal. Similar removal results occurred during a short full-scale (140-MW) test involving SEA2 additions. SEA2 additions combined with ACI at moderate rates (2.9 lb/MMacf) increased Hg_{total} removals to >80%.

The WRI-treated coal in combination with moderate DARCO FGD injections (2.5 lb/MMacf) performed the best, with a combined Hg removal (sum of pretreatment removal and DARCO FGD capture) of 84%. The EERC-treated carbon also performed well, with 63% removal at an injection rate of 4.8 lb/MMacf. The Amended Silicate, sodium tetrasulfide, and TiO_2/UV light technologies provided ESP Hg_{total} removals of <40%. These methods may be improved, but they are currently not viable control technologies.

16.2 ESP–FF Mercury Control

Hg_{total} removal results with an ESP–FF are presented in Table 16-2. For the WRI-treated Caballo coal, the incremental Hg_{total} removal relative to the baseline-treated coal is presented. In addition, the Hg_{total} removal values including that removed by the WRI pretreatment process are presented in parentheses.

16.2.1 Caballo Coal Combustion Flue Gas

Pilot-scale Caballo coal combustion test results indicated the following:

- In the absence of ACI or SEA addition, an ESP–FF was ineffective in capturing Hg_{total} from the Caballo coal combustion flue gas.
- DARCO FGD injection at ~1 to 4 lb/MMacf enhanced TOXECON Hg_{total} removal efficiencies to about 70%–90%. TOXECON Hg_{total} removal efficiencies increased with increasing ACI rate.
- SEA1 addition at 2.5 lb/MMacf resulted in an ESP–FF Hg_{total} removal efficiency of ~30%.
- SEA1 addition combined with DARCO FGD injection did not significantly improve the already high TOXECON Hg_{total} removal efficiencies achieved with ACI alone.
- SEA2 injections at 0.1 and 0.2 lb/MMacf, an order of magnitude lower than those used during the ESP testing, did not significantly improve Hg_{total} capture in the ESP–FF.
- SEA2 addition at 0.2 lb/MMacf combined with DARCO FGD injections at about 1 and 2.5 lb/MMacf resulted in TOXECON Hg_{total} removal efficiencies that were about 10% lower relative to those obtained using ACI alone at similar rates.

16.2.2 Demeter Systems-Treated Caballo Coal Combustion Flue Gas

Pilot-scale Demeter Systems-treated Caballo coal combustion test results indicated the following:

- EERC-treated carbon injections at 2.5 to about 5 lb/MMacf produced TOXECON Hg_{total} removal efficiencies ranging from 70% to 90%.
- The Demeter Systems coal pretreatment process resulted in an ESP SO_2 removal efficiency of >90% and a small reduction in NO_x emissions.

16.2.3 Caballo–Blacksville Coal Combustion Flue Gas

Pilot-scale Caballo–Blacksville coal combustion test results indicated that:

- DARCO FGD injection at 4.8 lb/MMacf upstream of the ESP into an 80:20 wt% Caballo–Blacksville coal combustion flue gas resulted in an ESP–FF Hg_{total} removal efficiency of 55%.

16.2.4 Summary of ESP–FF Mercury Control Options

An ESP–FF system provided the best conditions for controlling Hg_{total} emissions. DARCO FGD injection provided a high TOXECON Hg_{total} removal, 90%, at a reasonable injection rate of 4 lb/MMacf. SEA1 or SEA2 addition combined with ACI did not significantly increase the high removal efficiencies attained through ACI alone. Blending high-chlorine-containing Blacksville bituminous coal with Caballo subbituminous coal did not improve ESP–FF Hg_{total} capture and may have actually hindered Hg_{total} removal when combined with ACI. DARCO FGD at 1.3 lb/MMacf into WRI-treated Caballo coal combustion flue gas resulted in ~80% removal. When the Hg removed by the WRI coal pretreatment process is included, >90% removal was achieved. EERC-treated carbon injection at about 5 lb/MMacf into Demeter Systems-treated Caballo coal combustion flue gas enhanced ESP–FF Hg_{total} capture to 87%; however, the EERC-treated carbon was not as effective as DARCO FGD at similar injection rates. The Demeter Systems coal treatment process resulted in >90% SO_2 capture in the ESP–FF.

16.3 FF Mercury Control

Hg control test results attained with a FF are presented in Table 16-3.

16.3.1 Caballo Coal Combustion Flue Gas

Pilot-scale Caballo coal combustion test results indicated the following:

- In the absence of DARCO FGD injection, the FF removed 12% of the Hg_{total} from Caballo coal combustion flue gas.

- DARCO FGD injection enhanced FF Hg_{total} capture to slightly more than 80% which is very similar to that observed with the ESP–FF at similar ACI rates.

16.3.2 Caballo–Blacksville Coal Combustion Flue Gas

Pilot-scale 80:20 wt% Caballo–Blacksville coal combustion test results indicated that:

- Blending Caballo coal with 20 wt% Blacksville coal did not significantly affect Hg_{total} adsorption on the injected DARCO FGD.

- The presence of additional fly ash in the FF filter cake because of the lack of an ESP did not hinder the effectiveness of ACI to capture Hg_{total}.

16.3.3 Summary of FF Mercury Control Options

The Hg_{total} emission control attained with a FF was similar to that achieved with an ESP–FF. DARCO FGD injections at 2.5 and ~5 lb/MMacf provided 75% to 80% Hg_{total} removal efficiencies. The additional ash collected on the filter bags because of the absence of an ESP did not seem to hinder carbon–Hg_{total} adsorption. Blending Caballo subbituminous coal with high-chlorine-containing Blacksville bituminous coal did not significantly improve FF Hg_{total} removal in the presence of ACI.

16.4 SDA–ESP Mercury Control

Hg_{total} removal results obtained with the SDA–ESP are presented in Table 16-4.

16.4.1 Caballo Coal Combustion Flue Gas

Pilot-scale Caballo coal combustion test results indicated the following:

- The inherent Hg_{total} removal efficiency of the SDA–ESP was 17%.

- DARCO FGD injections at about 5 to 11 lb/MMacf enhanced SDA–ESP Hg_{total} removal efficiencies to 50%–70%. SDA–ESP Hg_{total} removal efficiencies increased gradually with increasing ACI rates.

- SEA1 addition at ~5 lb/MMacf resulted in a SDA–ESP Hg_{total} removal of 38%.

- DARCO FGD injection at ~5 lb/MMacf combined with SEA1 additions at about 5 and 7 lb/MMacf resulted in high SDA–ESP Hg_{total} removals of 85%. Increasing the SEA1 addition rate did not further improve on the 85% Hg_{total} capture efficiency.

- SEA2 additions at 0.2 and 0.5 enhanced SDA–ESP Hg_{total} removal efficiency to 37% and 54% lb/MMacf, respectively.

- DARCO FGD injection at about 4 lb/MMacf combined with SEA2 additions at 0.5 and 1 lb/MMacf improved SDA–ESP Hg_{total} capture to ~90%.

16.4.2 Summary of SDA–ESP Mercury Control Options

The Hg_{total} control performance of the SDA–ESP was intermediate relative to the ESP and ESP–FF systems. DARCO FGD injection provided marginal removals of ~50% at a reasonable injection rate of ~5 lb/MMacf. SEA1 additions combined with ACI resulted in high Hg_{total} removals of 85%. SEA2 addition at relatively low rates of 0.2 and 0.5 lb/MMacf resulted in SDA–ESP Hg_{total} removal efficiencies of about 40% and 50%, respectively. SEA2 combined with ACIs at 0.05 and 3.9 lb/MMacf achieved 80%–90% Hg_{total} removal. SEA2 addition combined with ACI was the most promising SDA–ESP control option tested.

16.5 SDA–FF Configuration

Hg_{total} removal results obtained with a SDA–FF are summarized in Table 16-5.

16.5.1 Caballo Coal Combustion Flue Gas

Pilot-scale Caballo coal combustion test results indicated the following:

- The inherent Hg_{total} removal efficiency of the SDA–FF was 27%.
- SEA1 additions at about 2 and 3 lb/MMacf did not significantly improve Hg_{total} capture in the SDA–FF.
- DARCO FGD injection at ~2 lb/MMacf combined with SEA1 additions at approximately 3 and 5 lb/MMacf resulted in SDA–FF Hg_{total} removals of 70% and 80%, respectively.
- SEA2 addition alone at 0.3 lb/MMacf enhanced SDA–FF Hg_{total} removal to 43%.
- SEA2 in combination with DARCO FGD injection at about 2 lb/MMacf combined with SEA2 additions at 0.1 and 0.3 lb/MMacf resulted in very high Hg_{total} removals of ~90%.
- Amended Silicate injections did not enhance SDA–FF Hg_{total} removal performance.
- Adding Solucorp Industries additives to the SDA and adjusting the SDA inlet flue gas flow rate slightly improved SDA–FF Hg_{total} removal performance to ~30%.
- SEA1 addition combined with Solucorp Industries MBS additives did not further increase Hg_{total} capture in the SDA–FF.

16.5.2 Absaloka Coal Combustion Flue Gas

Pilot-scale Absaloka coal combustion test results indicated the following:

- Na_2S_4 injections did not enhance SDA–FF Hg_{total} removal performance.

16.5.3 80:20 wt% Absaloka–Blacksville Coal Combustion Flue Gas

Pilot-scale Absaloka–Blacksville coal combustion test results indicated the following:

- DARCO FGD injection at ~5 lb/MMacf produced a SDA–FF Hg_{total} removal of 47%.
- DARCO FGD injection at about 5 lb/MMacf combined with 0.5 lb/MMacf SEA2 addition resulted in a substantial SDA–FF Hg_{total} removal of 84%.

16.5.4 WRI-Treated Caballo Coal Combustion Flue Gas

Pilot-scale WRI-treated Caballo coal combustion test results indicated that:

- The WRI pretreatment process removed approximately 64% of the Hg in Caballo coal.
- DARCO FGD injection at ~1 lb/MMacf did not improve SDA–FF Hg_{total} removal performance.

16.5.5 Summary of SDA–FF Mercury Control Options

SDA–FF Hg_{total} removal performance was intermediate to that achieved with the ESP and ESP–FF and similar to the SDA–ESP. SEA1 addition at about 5 lb/MMacf combined with DARCO FGD injection at about 2 lb/MMacf enhanced SDA–FF Hg_{total} removal performance to 80%. SEA2 addition alone provided a SDA–FF Hg_{total} removal of about 40%, but when combined with ACI at relatively low rates of 0.1 and 1.9 lb/MMacf achieved 90% removal. The Amended Silicate and Na_2S_4 injections did not significantly improve Hg_{total} capture. The WRI-treated coal also resulted in low SDA–FF Hg_{total} removal, but WRI's pretreatment process removed 64% of the Hg in Caballo coal. The Solucorp Industries MBS SDA additives slightly improved SDA–FF Hg_{total} capture when the flue gas flow rate to the SDA was reduced by 50%. System limitations inhibited an evaluation of the MBS additives at longer SDA residence times. Additional testing at longer SDA residence times should be performed to demonstrate the maximum Hg_{total} removal possible with this technology. SEA2 addition combined with ACI was the most promising control option, achieving high removals at moderate injection rates.

16.6 Cost Analysis of Controlling Mercury Emissions Using DARCO FGD Injection and/or SEA Addition

A Hg_{total} control cost analysis was performed for the DARCO FGD injection and/or SEA addition technologies for capturing Hg_{total} in an ESP, FF, ESP–FF (i.e., TOXECON®), SDA–ESP, and SDA–FF. Although other emerging technologies, such as WRI's thermal coal treatment and EERC-treated carbon injection, were also effective in controlling Hg_{total} emissions, a cost analysis for implementing these technologies was not performed because of a lack of economic information.

All estimated costs were based on 2004 U.S. dollars, assuming that a 500-MW subbituminous coal-fired plant was configured with an ESP, FF, ESP–FF, SDA–ESP, or SDA–FF.

16.6.1 ESP Hg Control Cost Estimate

The most cost-effective approach for an ESP was the addition of SEA2 at 1.9 lb/MMacf, which resulted in about 70% Hg_{total} removal at an estimated cost of $2.97/kW, or $6967/lb of Hg. SEA2 addition is also advantageous because it should not affect fly ash salability. SEA2 addition upstream of an ESP met the project goal of achieving 50%–90% Hg_{total} removal at costs of one-half to three-quarters of those currently estimated for ACI.

16.6.2 FF and TOXECON Hg Control Cost Estimates

The TOXECON technology was more cost-effective for Hg_{total} control relative to ACI combined with only a FF because the ESP ash could be sold. Additions of SEAs increased the costs of TOXECON Hg_{total} removal because they did not significantly improve Hg_{total} capture.

16.6.3 SDA–ESP and SDA–FF Hg Control Cost Estimates

SEA2 addition upstream of the SDA–ESP and SDA–FF systems was estimated to cost about $1.00/kW, or $4000/lb Hg, and provided similar Hg_{total} removal efficiencies, 45%–50%, at less cost than those achieved with ACI. SEA2 and SEA1 additions combined with ACI significantly improved SDA–ESP and SDA–FF Hg_{total} capture to 80%–90% and reduced control costs on a per-pound-of-Hg-removed basis relative to ACI alone.

16.7 Effects of SEA Addition on Trace Element Gas–Fly Ash Partitioning and Fly Ash Mobility

An EPA Method 29 multimetals train and EPA–SRI five-stage cyclone were used to collect gaseous and size-fractionated fly ash samples to determine the effects of SEAs on trace element gas–particle partitioning and PSDs. In addition, the mobility (i.e., leachability) of trace elements in fly ash samples was evaluated using ASTM Method D3987-85. Fly ashes produced during three test conditions were evaluated: 1) baseline, Caballo coal combustion; 2) Caballo coal combustion during SEA1 addition; and 3) Caballo coal combustion during SEA2 addition. The concentrations of ten trace elements (As, Be, Cd, Co, Cr, Mn, Ni, Pb, Sb, and Se) in flue gas, ESP fly ash, and size-fractionated fly ash samples did not vary significantly among the three test conditions. The majority of trace elements in the flue gases were associated with fly ash particles. In addition to chemical composition, the three fly ash PSDs were very similar, and most of the mass, ~75%, occurred in the coarser, ~7.3 µm, fraction. Trace element leaching results for fly ashes produced during baseline Caballo coal combustion testing and the addition of SEA1 and SEA2 were similar, in that for all conditions and leaching periods, trace element concentrations were below regulatory limits for disposal. In summary, SEAs did not significantly affect trace element gas–particle partitioning, PSDs, or fly ash mobility.

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APPENDIX A

QUALITY ASSURANCE/QUALITY CONTROL FOR PILOT-SCALE TESTS

QUALITY ASSURANCE/QUALITY CONTROL FOR PILOT-SCALE TESTS

QUALITY ASSURANCE/QUALITY CONTROL

This appendix provides detailed quality assurance/quality control (QA/QC) procedures that were used during the sampling, analysis, and data reduction activities. The most important QA/QC parameter for any sampling activity is the personnel who performed the work. All who participated in the sampling, analysis, data reduction, and reporting activities for this project had extensive training and experience in implementing the proper procedures.

CMM Calibration

Continuous mercury monitors (CMMs) were calibrated using elemental mercury (Hg^0) as the primary standard. Hg^0 was contained in a closed vial held in a thermostatic bath. The amount of Hg^0 delivered to the CMM was determined based on bath temperature and Hg^0 vapor pressure calculations.

Calculated APCD Hg_{total} Removal Efficiencies

CMM data were normalized to dry, 20°C, 3% O_2, at 1 atm conditions so that air pollution control devices (APCD) inlet and outlet CMM results and Ontario Hydro (OH) results could be directly compared on the same basis. CMM data were time-integrated averaged for the duration of the test condition, excluding transition periods when the combustor was obviously responding to a change in test conditions. The inherent mercury capture of a given APCD was calculated for each coal by averaging the data during the baseline period and comparing APCD inlet and outlet Hg_{total} concentrations. Hg_{total} removal efficiencies for each test condition were calculated as a percentage.

OH METHOD

Instrument Set-Up and Calibration

A Cetac M6000A cold-vapor atomic absorption spectroscopy (CVAA) was used for measuring Hg in prepared solutions. The instrument was set up for absorption at 253.7 nm with a carrier gas of nitrogen and a Hg^{2+} reducing solution of 10% $SnCl_2$ and 10% HCl. Each day, the drying tube and acetate trap were replaced and the tubing checked. The rinse container was then cleaned and filled with a fresh solution of 10% $SnCl_2$–10% HCl. After the pump and lamp were turned on and warmed up for 45 min, the aperture was set to the manufacturer specifications. A four-point calibration curve was then completed using matrix-matched standards. The detector response for a given standard was logged and compared to specifications to ensure the instrument had been properly set up. A QC standard of a known analyte concentration was analyzed immediately after the instrument was standardized in order to verify the calibration. This QC standard was prepared from a different stock than the calibration standards. Requirements stated that the values obtained must read within 5% of the true value before the instrument was used. After the initial QC standardization was completed, standards were run

every ten samples to check the slope of the calibration curve. One in every ten samples was run in triplicate and was spiked to verify analyte recovery. A QC chart was also maintained by the Energy & Environmental Research Center (EERC) chemist to monitor the long-term precision of the instrument**.**

Presampling Preparation

All data sheets, volumetric flasks, and petri dishes used for sample recovery were marked with preprinted labels. The liquid samples were recovered into premarked volumetric flasks, logged, and then analyzed on-site. The filter samples were placed in premarked containers and then sent to the lab, where they were analyzed using mixed-acid digestion techniques. The labels contained identifying data, including date, time, run number, and sample port location, which correlate back to the data sheets.

Glassware and Plasticware Cleaning and Storage

All volumetric flasks and transfer pipettes used in the preparation of analytical reagents and calibration standards were designated as "Class A" according to ASTM International specifications. Prior to being used for sampling, all glassware was washed with hot, soapy water, rinsed with deionized water three times, soaked in 10% V/V nitric acid for a minimum of 4 hr, rinsed an additional three times with deionized water, and dried. The glassware was stored in closed containers until it was used.

Analytical Reagents

All acids used for analyzing Hg in solution were trace metal-grade. Other chemicals used in the preparation of analytical reagents were analytical reagent-grade. The calibration standards used for instrument calibration and the QC standards used for calibration verification were purchased commercially and certified to be accurate within ±0.5% and traceable to National Institute of Standards and Technology standard reference materials.

Blanks and Spikes

As part of the QA/QC, a field blank was associated with sampling. A field blank is a complete impinger train, including all glassware and solutions, that is exposed to ambient conditions. These sample trains were then taken apart and the solutions recovered and analyzed in the same manner as those sample trains used for sampling activities. If the field blank showed contamination above instrument background levels, steps were then taken to eliminate or reduce the contamination to below background levels.

As part of the QA/QC, a field spike was also associated with each test condition. A field spike was prepared by the field manager at a level similar to the field samples. These sample trains were then taken apart, and the solution was recovered and analyzed in the same manner as those sample trains used for sampling activities. The target range for recovery of the field spike was ±25%. All blanks were less than 5% of the measured values for the samples and thus within

the error of the method. The results of the spiked samples were all within the 25% range required by the method.

QA/QC CHECKS FOR DATA REDUCTION AND VALIDATION

Data Reduction

Data reduction was performed by sampling and analytical personnel and by the team leaders. Calculations included velocity, moisture, stack gas flow, sample gas volume, percent isokinetic sampling, and flue gas mercury concentrations. Calculations were performed using spreadsheets on a portable computer; some averaging was done with a calculator. Standardized spreadsheets were used. Equations used in the calculations were contained in the method, and example calculations are presented in Appendix B.

Data Validation

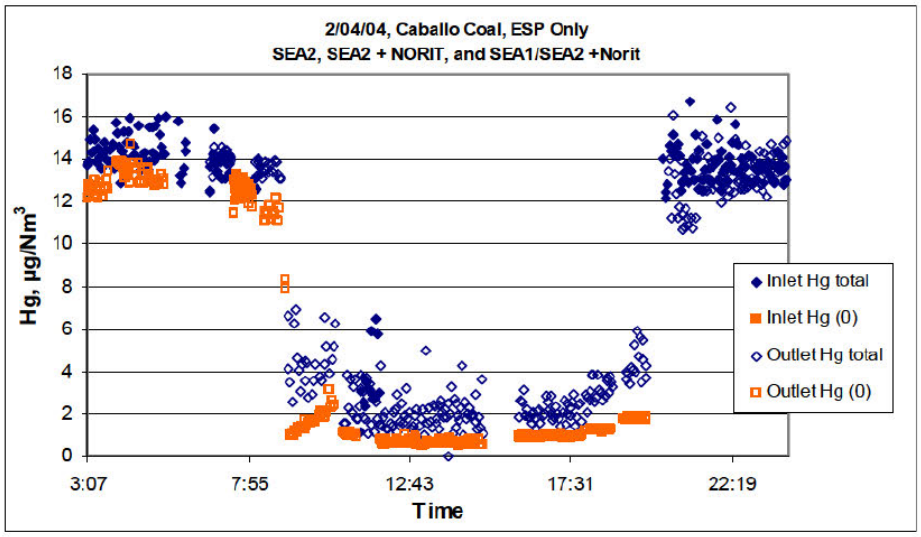
All data, data entry, and calculations were double-checked by the originator and reviewed by a second person. Reviews included recalculation of results, data entry checks, and calculation of known and accepted data sets using the existing spreadsheet.

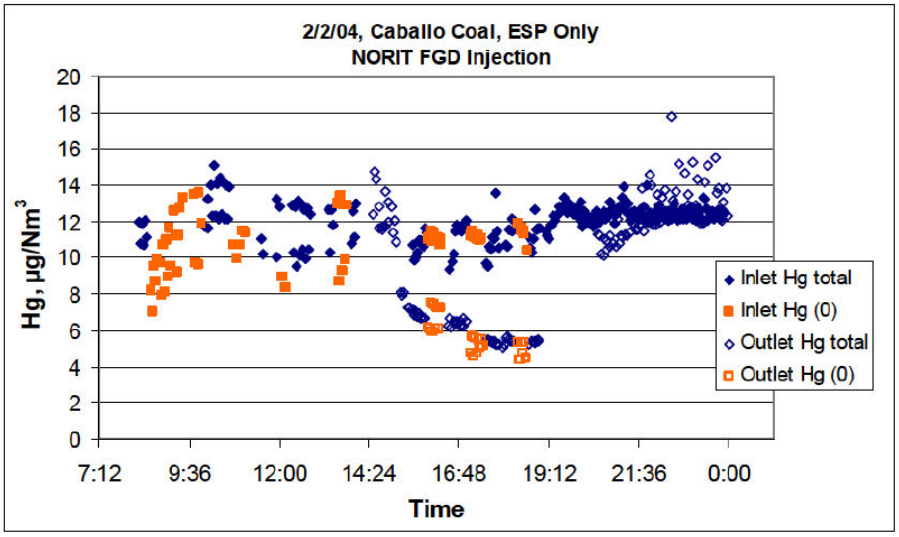
Sample Identification and Chain of Custody

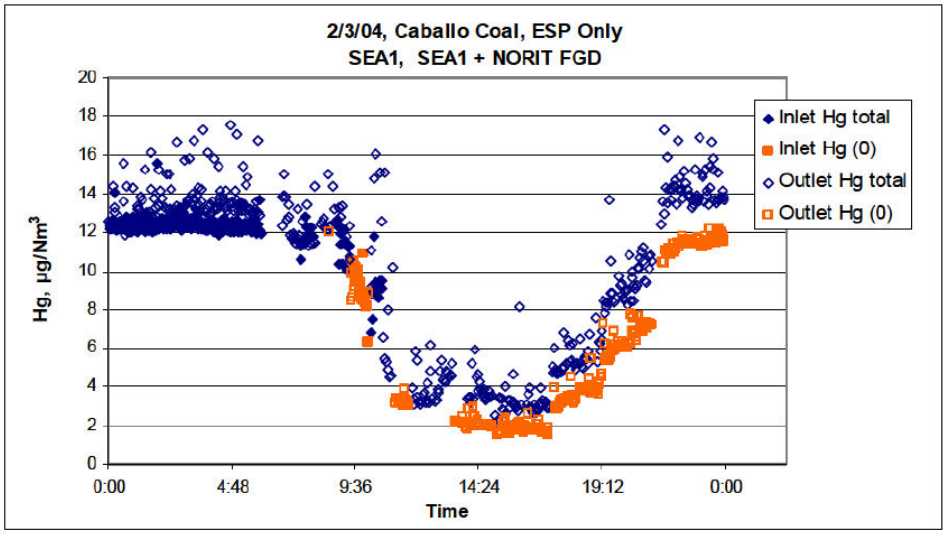
Samples were identified with unique sample numbers and descriptive notations. Sample custody was maintained by EERC personnel. Data sheets were kept in the custody of the originator, the program manager, or team leaders. The original data sheets were used for report preparation, and any additions were initialed and dated.

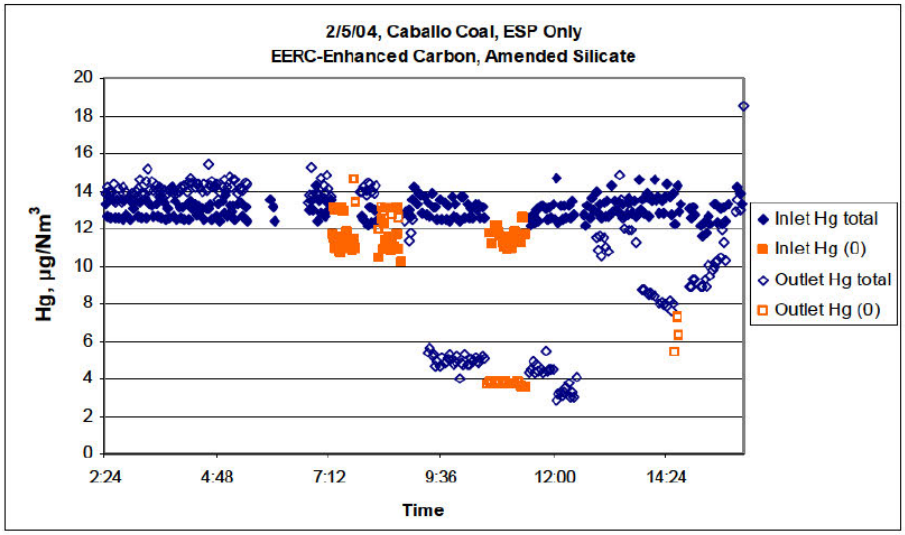
APPENDIX B

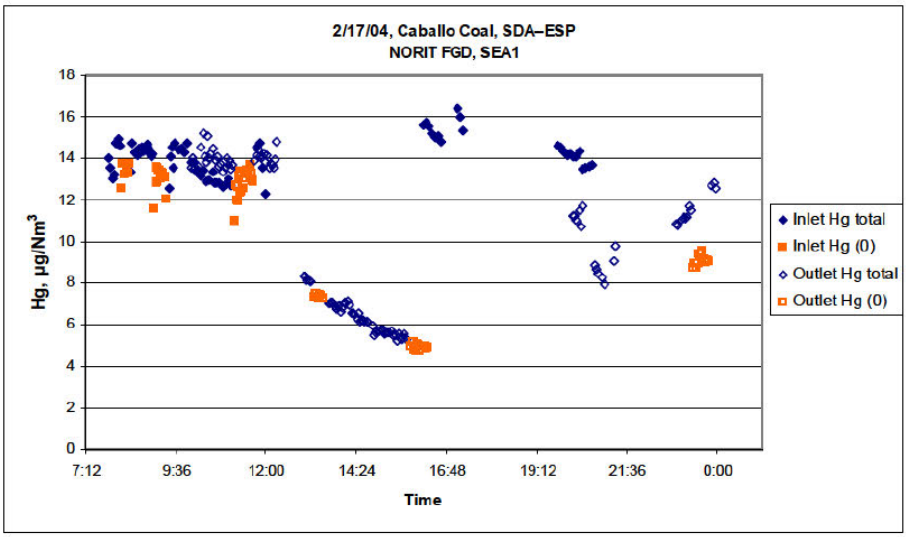
CMM RESULTS

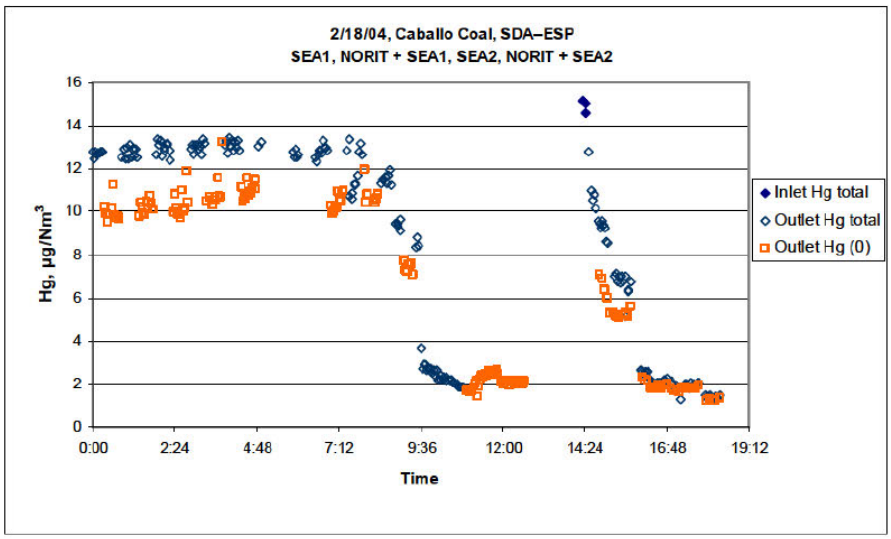

2/04/04, Caballo Coal, ESP Only
SEA2, SEA2 + NORIT, and SEA1/SEA2 +Norit
Hg, µg/Nm3
18
16
14
12
10
8
6
4
2
0
3:07
7:55
12:43
17:31
22:19
Time
Inlet Hg total
Inlet Hg (0)
Outlet Hg total
Outlet Hg (0)

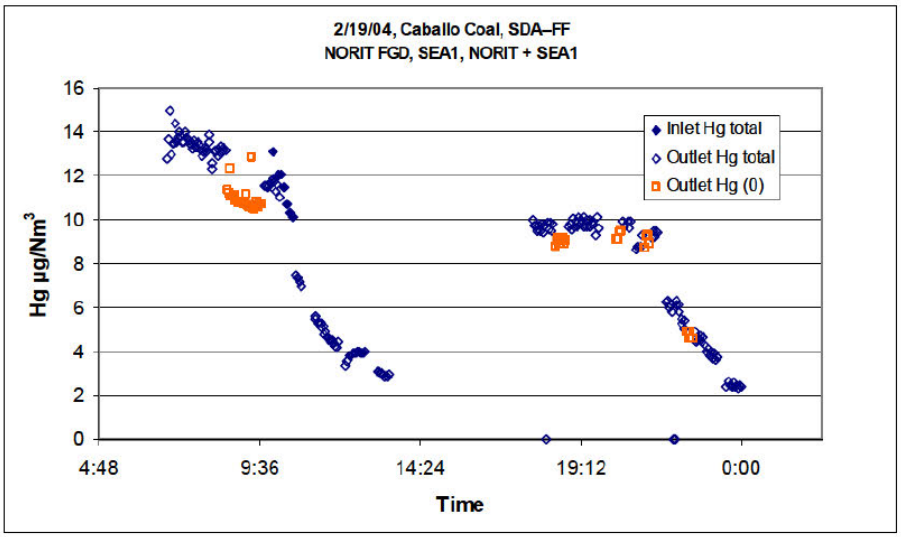

2/2/04, Caballo Coal, ESP Only
NORIT FGD Injection
Hg, µg/Nm3
20
18
16
14
12
10
8
6
4
2
0
7:12
9:36
12:00
14:24
16:48
19:12
21:36
0:00
Time
Inlet Hg total
Inlet Hg (0)
Outlet Hg total
Outlet Hg (0)

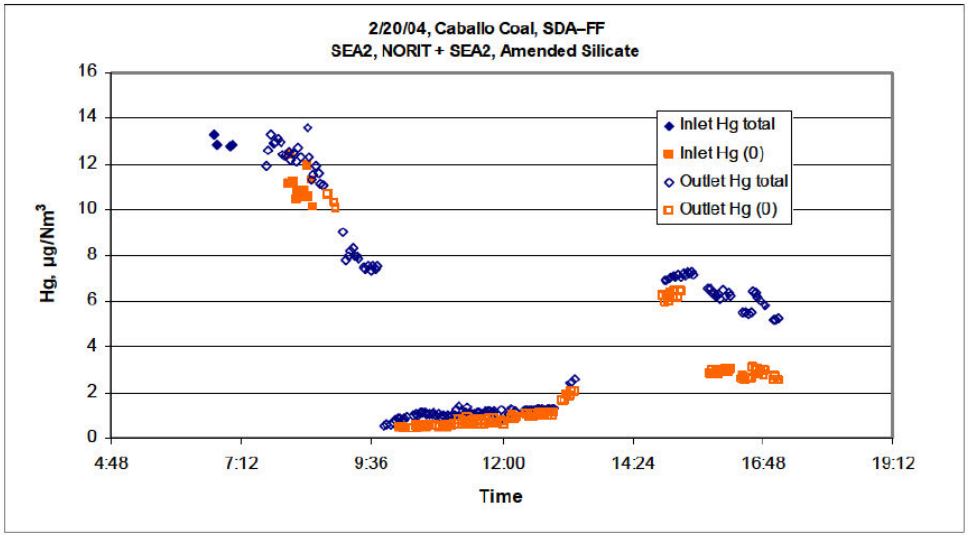

2/3/04, Caballo Coal, ESP Only
SEA1, SEA1 + NORIT FGD
Hg, µg/Nm3
Time
0:00
4:48
9:36
14:24
19:12
0:00
Inlet Hg total
Inlet Hg (0)
Outlet Hg total
Outlet Hg (0)

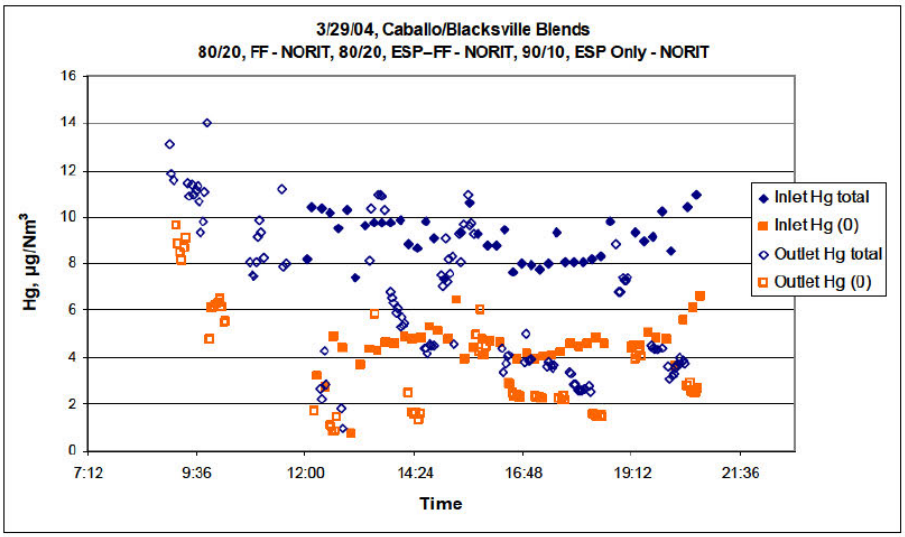

2/5/04, Caballo Coal, ESP Only
EERC-Enhanced Carbon, Amended Silicate
Hg, µg/Nm3
Time
2:24
4:48
7:12
9:36
12:00
14:24
Inlet Hg total
Inlet Hg (0)
Outlet Hg total
Outlet Hg (0)

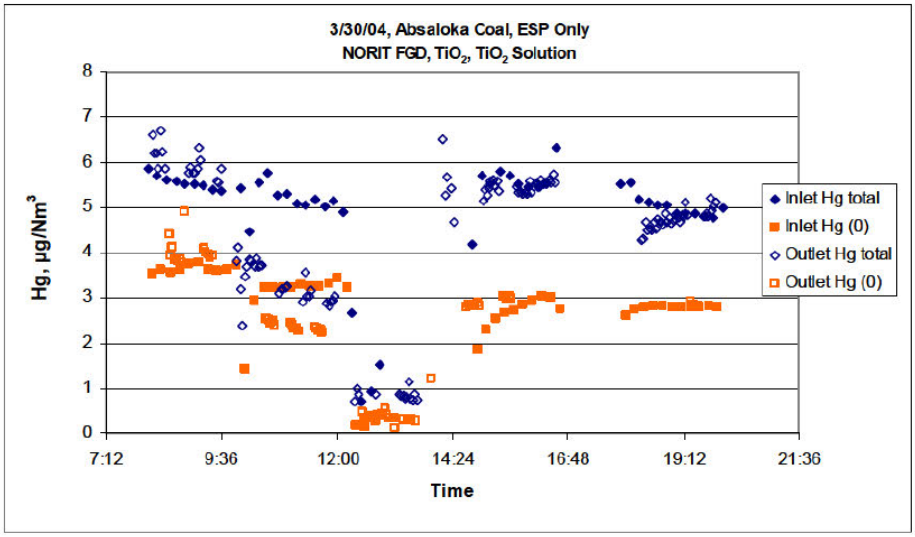

2/17/04, Caballo Coal, SDA–ESP
NORIT FGD, SEA1
Hg, µg/Nm³
Time
Inlet Hg total
Inlet Hg (0)
Outlet Hg total
Outlet Hg (0)

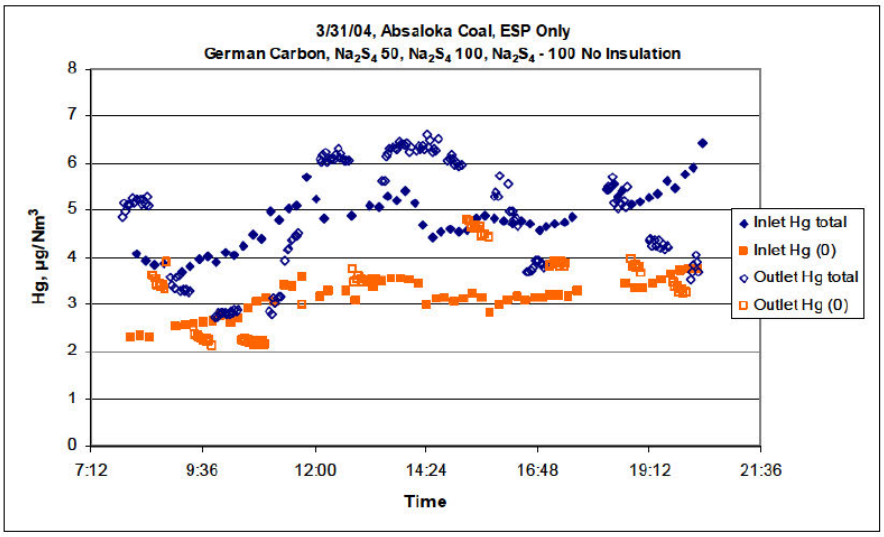

2/18/04, Caballo Coal, SDA–ESP
SEA1, NORIT + SEA1, SEA2, NORIT + SEA2
Hg, µg/Nm³
Time
Inlet Hg total
Outlet Hg total
Outlet Hg (0)

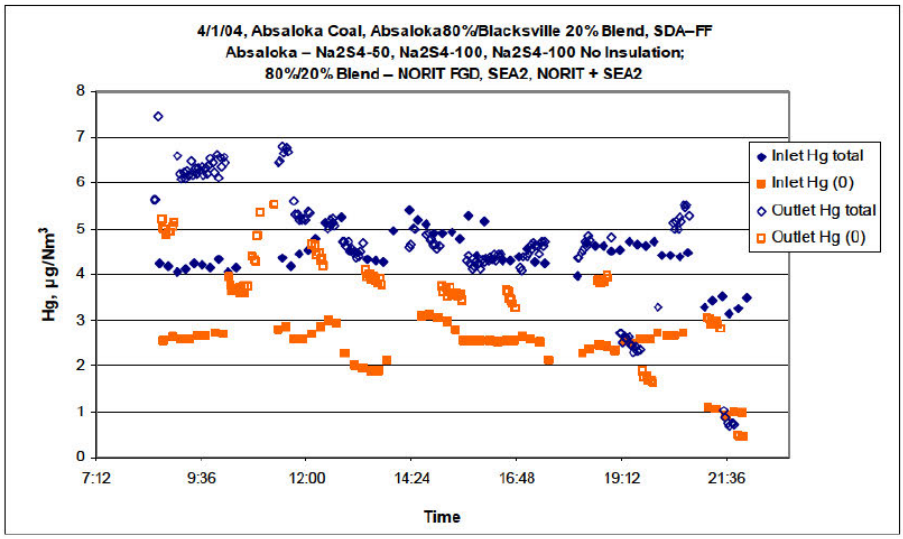

2/19/04, Caballo Coal, SDA–FF
NORIT FGD, SEA1, NORIT + SEA1
Inlet Hg total
Outlet Hg total
Outlet Hg (0)
Hg µg/Nm3
16
14
12
10
8
6
4
2
0
4:48
9:36
14:24
19:12
0:00
Time

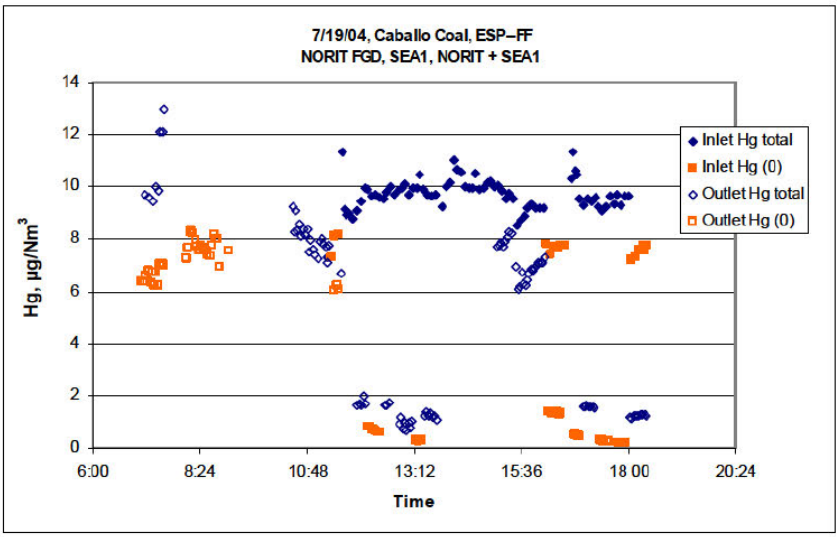

2/20/04, Caballo Coal, SDA–FF
SEA2, NORIT + SEA2, Amended Silicate
Inlet Hg total
Inlet Hg (0)
Outlet Hg total
Outlet Hg (0)
Hg, µg/Nm3
16
14
12
10
8
6
4
2
0
4:48
7:12
9:36
12:00
14:24
16:48
19:12
Time

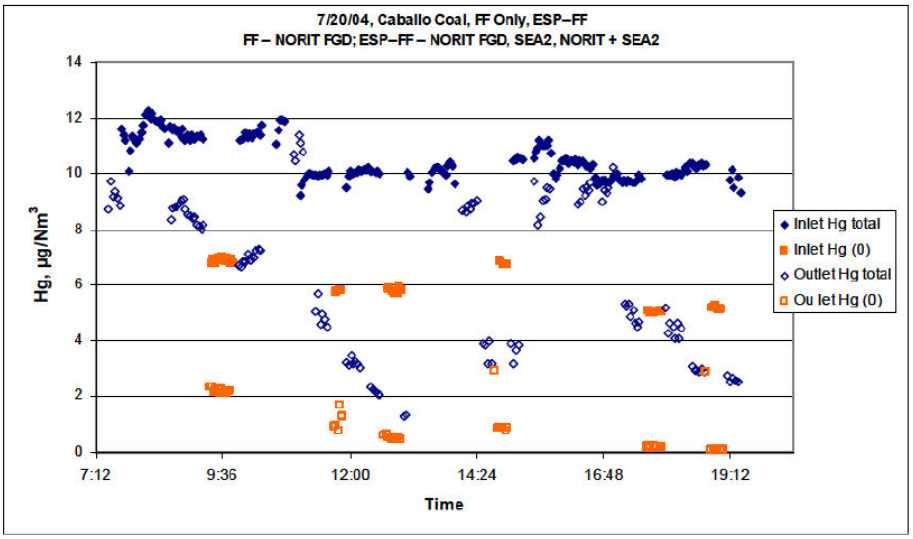

3/29/04, Caballo/Blacksville Blends
80/20, FF - NORIT, 80/20, ESP–FF - NORIT, 90/10, ESP Only - NORIT
Hg, µg/Nm³
Time
Inlet Hg total
Inlet Hg (0)
Outlet Hg total
Outlet Hg (0)

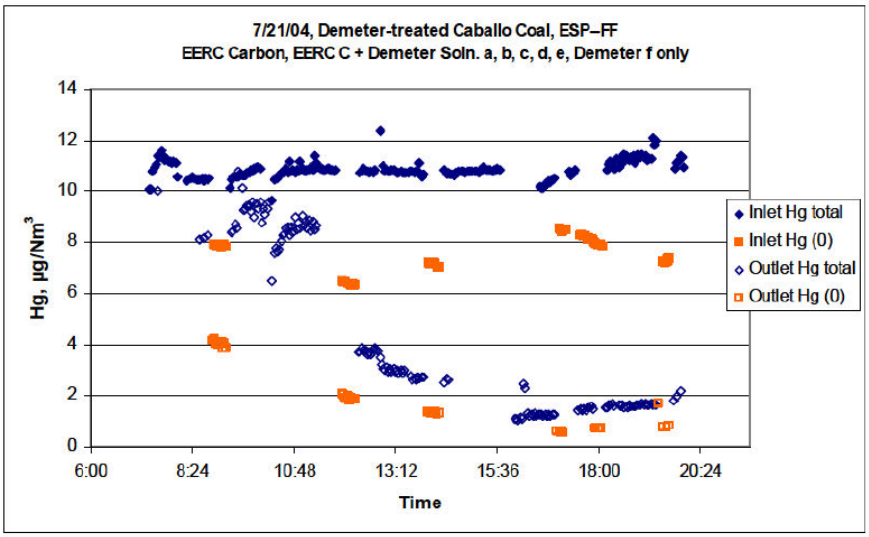

3/30/04, Absaloka Coal, ESP Only
NORIT FGD, TiO2, TiO2 Solution
Hg, µg/Nm³
Time
Inlet Hg total
Inlet Hg (0)
Outlet Hg total
Outlet Hg (0)

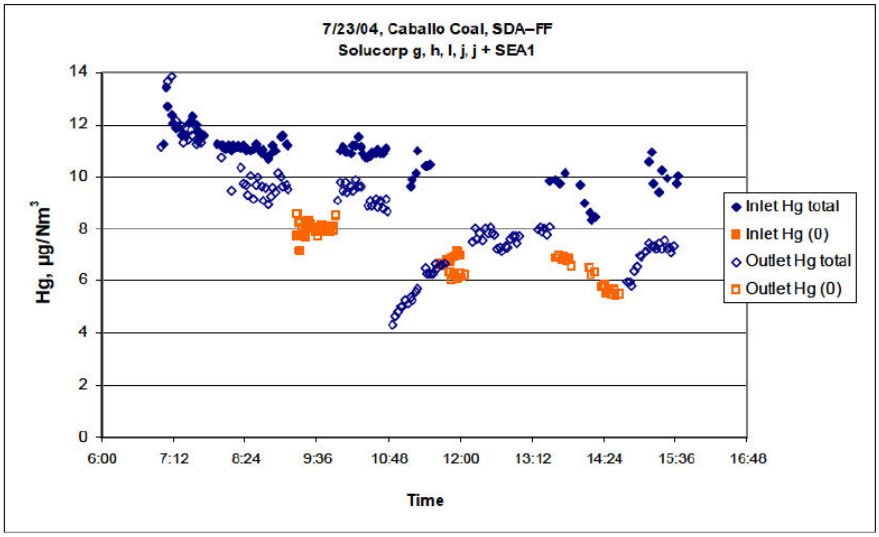

3/31/04, Absaloka Coal, ESP Only
German Carbon, Na_2S_4 50, Na_2S_4 100, Na_2S_4 - 100 No Insulation
Hg, µg/Nm³
Time
7:12
9:36
12:00
14:24
16:48
19:12
21:36
Inlet Hg total
Inlet Hg (0)
Outlet Hg total
Outlet Hg (0)

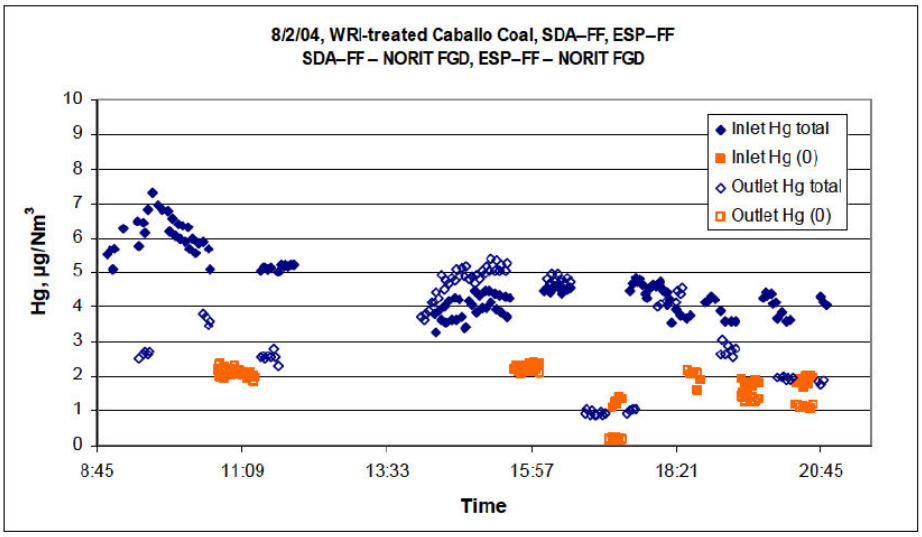

4/1/04, Absaloka Coal, Absaloka80%/Blacksville 20% Blend, SDA–FF
Absaloka – Na2S4-50, Na2S4-100, Na2S4-100 No Insulation;
80%/20% Blend – NORIT FGD, SEA2, NORIT + SEA2
Hg, µg/Nm³
Time
7:12
9:36
12:00
14:24
16:48
19:12
21:36
Inlet Hg total
Inlet Hg (0)
Outlet Hg total
Outlet Hg (0)


7/19/04, Caballo Coal, ESP–FF
NORIT FGD, SEA1, NORIT + SEA1
Hg, µg/Nm³
Time
Inlet Hg total
Inlet Hg (0)
Outlet Hg total
Outlet Hg (0)
0
2
4
6
8
10
12
14
6:00
8:24
10:48
13:12
15:36
18 00
20:24


7/20/04, Caballo Coal, FF Only, ESP–FF
FF – NORIT FGD; ESP–FF – NORIT FGD, SEA2, NORIT + SEA2
Hg, µg/Nm³
Time
Inlet Hg total
Inlet Hg (0)
Outlet Hg total
Ou let Hg (0)
0
2
4
6
8
10
12
14
7:12
9:36
12:00
14:24
16:48
19:12


7/21/04, Demeter-treated Caballo Coal, ESP–FF
EERC Carbon, EERC C + Demeter Soln. a, b, c, d, e, Demeter f only
Hg, µg/Nm3
Time
Inlet Hg total
Inlet Hg (0)
Outlet Hg total
Outlet Hg (0)


7/23/04, Caballo Coal, SDA–FF
Solucorp g, h, l, j, j + SEA1
Hg, µg/Nm3
Time
Inlet Hg total
Inlet Hg (0)
Outlet Hg total
Outlet Hg (0)


8/2/04, WRI-treated Caballo Coal, SDA–FF, ESP–FF
SDA–FF – NORIT FGD, ESP–FF – NORIT FGD
Hg, µg/Nm3
10
9
8
7
6
5
4
3
2
1
0
8:45
11:09
13:33
15:57
18:21
20:45
Time
Inlet Hg total
Inlet Hg (0)
Outlet Hg total
Outlet Hg (0)

APPENDIX C

EXAMPLE CALCULATIONS

EXAMPLE CALCULATIONS

SAMPLE CALCULATIONS

Sample calculations are included for each of the calculated parameters.

Volume of Gas Sample

Vm(std) = Volume of gas sample measured by the dry gas meter, connected 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 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 = $\frac{Vw(std)}{Vm(std)+Vw(std)}$

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-mole) = 0.440 × (%CO_2) + 0.320 × (%O_2) + 0.280 × (%N_2 + %CO)

Md = 0.440 × 15.9 + 0.320 × 3.1 + 0.280 × 81.0 = 30.7 lb/lb-mole

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-mole

Ms (lb/lb-mole) = Md × (1 Bws) + 18.0 × Bws

Ms = 30.7 × (1 0.1332) + 18.0 × 0.1332 = 29.0 lb/lb-mole

Average Stack Gas Velocity

Vs = Average stack gas velocity, ft/sec

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

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

Where:

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

Cp = Pitot tube coefficient, dimensionless

Δp = Velocity head of stack gas (in. Hg)

$(\Delta p)^{1/2}(avg)$ = Average of the square root of Δp values

Ts = Stack gas temperature (°F)

Ps = Stack pressure (in. Hg)

Isokinetric Sampling Rate

I = Percent of isokinetic sampling, %

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

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

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

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

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

Where:

K_5 = 0.02832 m^3/ft^3

Mercury

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

Hg = $\frac{6.99}{1.188}$ = 5.88 μg/Nm^3

Hg_P	=	Sum of mercury from filter and nozzle rinse (note: all nozzle rinse values were nondetects)
Hg^{2+}	=	Sum of mercury from KCl impingers
Hg^0	=	Sum of mercury from H_2O_2 and $KMnO_4$ impingers. Since typically less than 5% of the elemental mercury (Hg^0) is trapped in the H_2O_2 impinger, the less than values were not added to the total Hg^0. Thus the Hg^0 was calculated from the values obtained from the $KMnO_4$ impingers only.