Evaluation of Sorbent Injection for Mercury Control

Final Report for
Sunflower Electric's Holcomb Station
AmerenUE's Meramec Station
American Electric Power's Conesville Station
DTE Energy's Monroe Power Plant
Missouri Basin Power Project's Laramie River Station
and
AmerenUE's Labadie Power Plant
Reporting Period: January 1, 2000 – September 30, 2008

Principal Author: Sharon Sjostrom

Submitted: December 2008

DOE Award Number DE-FC26-03NT41986
Report Number 42307R27

ADA-ES, Inc.
8100 SouthPark Way, Unit B
Littleton, Colorado 80120
(303) 734-1727

DISCLAIMER

This technical report was prepared with the support of the U.S. Department of Energy, under Award No. DE-FC26-03NT41986. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of the DOE.

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ACKNOWLEDGMENTS

This project was made possible through the generous funding of the Department of Energy's National Energy Technology Laboratory and industry partners. There were more than 100 individual team members from 27 organizations participating in this program. The project co-funding was provided by:

ADA-ES, Inc.
ALSTOM
AmerenUE*
American Electric Power*
Arch Coal
Associated Electric Co-op
Babcock & Wilcox
Calgon Carbon Corporation
City of Sikeston
DTE Energy*
Dynegy Generation
Empire District Electric Company
EPCOR
EPRI
Kansas City Board of Public Utilities
Kansas City Power and Light
Kennecott Coal
MidAmerican
Missouri Basin Power Project*
Nebraska Public Power District
Norit Americas Inc.
Ontario Power Generation*
PacificCorp
Peabody Coal
Southern Company
Southern Minnesota Municipal Power Agency
Sunflower Electric Power Corporation*
Tennessee Valley Authority
Tri-State Generation & Transmission
TransAlta Utilities
TransAlta Energy
Westar Energy

Western Fuels Association

Wisconsin Public Service

** Indicates host site*

Key members of the test team included:

ADA-ES, Inc.

Project Manager: Sharon Sjostrom

Site Manager (Holcomb, Meramec, Laramie River, Monroe): Travis Starns

Site Manager (Conesville): Cody Wilson

Site Manager (Labadie): Marty Dillon

Hg CEM Leads: Jerry Amrhein, Erik Zipp, Steve Modrak

QA Coordinator: Andrea Adams

Technical Editor: Cindy Larson

DOE/NETL

Project Manager: Andrew O'Palko

EPRI

Project Manager: Ramsay Chang

American Electric Power

Conesville Power Plant: Gary Spitznogle, Aimee Toole, Gig Hammond

AmerenUE

Meramec Station: Rich Phillips, Tom Hart

Labadie Power Plant: Thomas Orscheln, Steve Wahlert (retired), Larry Illingworth, Brian Griffen

DTE Energy

Monroe Station: Melanie McCoy, Jason Brown, Sam Dubois

Missouri Basin Power Project

Laramie River Station: Bob Boetcher, Myron Singleton

Sunflower Electric

Holcomb Station: Wayne Penrod, Cory Linville

Reaction Engineering International

Coal and byproduct analysis interpretation, flow modeling for Conesville: Connie Senior

ALSTOM

Evaluation of scrubber operation for Holcomb and Laramie River and KNX™ coal additive injection parameters: Leif Lindau

ABSTRACT

ADA-ES, Inc., with support from DOE/NETL, EPRI, and industry partners, studied mercury control options at six coal-fired power plants. The overall objective of the this test program was to evaluate the capabilities of activated carbon injection at six plants: Sunflower Electric's Holcomb Station Unit 1, AmerenUE's Meramec Station Unit 2, Missouri Basin Power Project's Laramie River Station Unit 3, DTE Energy's Monroe Power Plant Unit 4, American Electric Power's Conesville Station Unit 6, and Labadie Power Plant Unit 2. These plants have configurations that together represent 78% of the existing coal-fired generation plants. The financial goals for the program established by DOE/NETL were to reduce the uncontrolled mercury emissions by 50 to 70% at a cost 25 to 50% lower than the target established by DOE of $60,000 per pound of mercury removed. Results from testing at Holcomb, Laramie River, Meramec, Labadie, and Monroe indicate the DOE goal was successfully achieved. However, further improvements for plants with conditions similar to Conesville are recommended that would improve both mercury removal performance and economics.

TABLE OF CONTENTS

INTRODUCTION **1**

Description of Overall Program **1**

EXECUTIVE SUMMARY **5**

Low-Sulfur Coal with a Fabric Filter **6**
Low- to Medium-Sulfur Coal with an ESP **7**
Low- to Medium-Sulfur Coal with an ESP and SO_3 Injection **8**
High-Sulfur Coal **10**

PROJECT OBJECTIVES AND TECHNICAL APPROACH **11**

Low-Sulfur Coal with an SDA and Fabric Filter – Holcomb **11**
Low- to Medium-Sulfur Coal with an ESP – Meramec and Laramie River **11**
Low- to Medium-Sulfur Coal with SO_3 Injection – Labadie and Monroe **12**
High-Sulfur Coal – Conesville **13**
Technical Approach **13**

Results and Discussion **15**

Low-Sulfur Coal with a Fabric Filter **15**
Holcomb **15**
Site Description 15
Baseline Mercury Removal 15
Coal Blending 16
Parametric Testing 17
Long-Term Testing 21
Balance-of-Plant Impacts 24
Low- to Medium-Sulfur Coal with an ESP **24**
Meramec **25**
Site Description 25
Baseline Mercury Removal 25
Parametric Testing 25
Long-Term Testing 28
Balance-of-Plant Impacts 30
Laramie River **30**
Site Description 30
Baseline Mercury Removal 31
Parametric Testing 31
Long-Term Testing 34
Balance-of-Plant Impacts 34
Low- to Medium-Sulfur Coal with SO_3 Injection **34**
Labadie **35**
Site Description 35

Baseline Testing 35
Parametric Testing 35
Sorbent Injection 36
KNX™ Testing 39
Trona Injection for Flue Gas Conditioning 39
Long-Term Testing 39
Balance-of-Plant Impacts 41
Monroe 42
Site Description 42
Baseline Testing 42
Parametric Testing 43
Long-Term Testing 46
Balance-of-Plant Impacts 47
High-Sulfur Coal 48
Conesville 48
Site Description 48
Baseline Testing 48
Parametric Testing 48
Long-Term Testing 49
Balance-of-Plant Impacts 49
Cost Analysis 50
Sorbent Injection 50

CONCLUSIONS 54

Low-Sulfur Coal with a Fabric Filter 57
Low- to Medium-Sulfur Coal with an ESP 57
Low- to Medium-Sulfur Coal with SO_3 Injection 58
High-Sulfur Coal 60

REFERENCES 62

APPENDIX: EQUIPMENT DESCRIPTION 63

LIST OF TABLES

Table 1. Host Site Operating Parameters. 2

Table 2. Field-Testing Schedule. 4

Table 3. Task 2 Subtasks. 14

Table 4. Results from Coal Analyses (Dry Basis) Collected during Blend Test Period. 16

Table 5. Summary of Mercury Removal Efficiencies and Costs for Different Air Pollution Control Configurations, Coals, and Sorbents. 51

Table 6. Cost Analysis for Commercial Mercury Removal Systems and Operation. 53

Table 7. Summary of Mercury Removal Efficiencies and Costs for Different Air Pollution Control Configurations, Coals, and Sorbents. 56

LIST OF FIGURES

Figure 1. Compilation of Results from DOE Phase I and Phase II Mercury Control Programs.....6

Figure 2. Summary of Coal Blending Tests at Holcomb.....17

Figure 3. Results of Alternative Sorbent Tests, Holcomb Station, SDA Inlet.....18

Figure 4. Results of Injection Location Tests, Holcomb Station. 19

Figure 5. Impact of the Addition of Coal Additive (KNX™) on Mercury Removal.....21

Figure 6. Mercury Removal during 30-Day Continuous Injection of DARCO® Hg-LH, 2004.....22

Figure 7. Mercury Speciation during Long-Term Testing at Holcomb, 2004. 23

Figure 8. Mercury Measurements from Five Extraction Locations at Holcomb. 24

Figure 9. Mercury Removal Trends during Long-Term Testing Series. 29

Figure 10. Comparison of DARCO® Hg-LH Results from Parametric and Long-Term Tests.....29

Figure 11. ESP Power during Injection of Activated Carbon at Brayton Point.....30

Figure 12. Summary of DARCO® Hg Results on Cold-Side ESPs.....32

Figure 13. Results from Sorbent Injection Tests at Laramie River.....33

Figure 14. Labadie Fall 2006 Parametric Test Results from Downstream of the Air Preheater and SO_3 Injection.....36

Figure 15. Labadie Parametric Test Results from Hg-LH injected Upstream and Downstream of the Air Preheater. 38

Figure 16. Labadie Parametric Test Results from Upstream of the Air Preheater and the SO3 Injection Location.....38

Figure 17. Averaged As-Received vs. Unenhanced PAC Removal at > 600 MW with SO_3 at 5.2 ppm.....41

Figure 18. Results of Parametric Testing: Mercury Removal due to Sorbent.....44

Figure 19. Summary of DARCO® Hg Results at Monroe, Meramec, and Brayton Point.....45

Figure 20. Comparison of Parametric Test Results at St. Clair and Monroe Stations. 46

Figure 21. Thirty-Day DARCO® Hg Injection Test Results from Monroe Compared to Parametric Results. Removal shown includes both Native Capture and Sorbent Capture. 47

Figure 22. Parametric Results for Full Scale Testing at Conesville Unit 6. 49

Figure 23. Comparison of Projected Annual Sorbent Costs for ESP, COHPAC® Fabric Filter, and SDA+FF Configurations based on Results from NETL Full-Scale Tests. 52

Figure 24. Compilation of Results from DOE Phase I and Phase II Mercury Control Programs.....55

INTRODUCTION

Description of Overall Program

The power industry in the U.S. is faced with meeting state imposed regulations, as well as expected federal legislation, to reduce the emissions of mercury compounds from coal-fired plants. Regulations are directed at the existing fleet of nearly 1,100 boilers. These plants are relatively old with an average age of more than 40 years. Although most of these units are capable of operating for many additional years, there is a desire to minimize large capital expenditures because of the reduced (and unknown) remaining life of the plant to amortize the project. Injecting a sorbent such as powdered activated carbon into the flue gas represents one of the simplest and most mature approaches to controlling mercury emissions from coal-fired boilers.

The overall objective of this test program was to evaluate the capabilities of activated carbon injection (ACI) at plants with configurations that together represent 78% of the existing coal-fired generation plants. Activated carbon injection was successfully evaluated in NETL's Phase I tests at scales up to 150 MW on plants burning subbituminous, bituminous and blends of coals and with fabric filters (FF) and electrostatic precipitators (ESP). These tests identified issues that still needed to be addressed, such as evaluating performance on other configurations, optimizing sorbent usage (costs), and gathering longer-term operating data to address concerns about the impact of activated carbon on plant equipment and operations. A summary of the key descriptive parameters for the host sites included in this program can be found in Table 1. Holcomb, Meramec and Conesville were included as part of the original project with Ontario Power's Nanticoke Station. Testing at DTE's Monroe Station was substituted for Nanticoke Station testing. Laramie River Station was added as the fifth site in the program during 4Q04 with support from the cost-share participants funding tests at Holcomb Station. Due to lower than expected mercury removal achieved at Conesville, no long-term tests were conducted at this site. During this quarter (4Q06), DOE approved transferring funds budgeted for long-term testing at Conesville for baseline, parametric, and extended testing at AmerenUE's Labadie Power Plant. These six sites represent configurations for most coal-fired plants in the U.S.

Laboratory studies conducted over the past 15 years by URS Group, UNDEERC, and others, indicate that HCl and SO_x in the flue gas can significantly affect the mercury adsorption capacity of fly ash and activated carbon.[1] These studies suggest that SO_2 and SO_3 reduce the equilibrium mercury capacity of activated carbon and fly ash because activated carbon tends to catalyze SO_2 to H_2SO_4. In turn, these sulfur compounds occupy surface sites on the carbon that normally are available to adsorb and oxidize mercury. Hence, the mercury adsorption capacity is dependant on the SO_2 and SO_3 concentration, which is orders of magnitude greater than the mercury concentration. For native removal or removal by sorbent injection, low SO_3 and high halogen levels are optimal. High SO_3 levels can be caused by burning high-sulfur coal, oxidation of SO_2 to SO_3 in a selective catalytic reduction (SCR) unit, or by injecting SO_3 for flue gas conditioning. Halogens can be used to promote mercury removal by increasing levels through high-halogen coals, coal additives, or by treating sorbents with a halogen-based material. Based on the SO_3 level and the

particulate control, the six host sites can be divided into four groups. These categories (and the corresponding host site) are as follows:

1. Low-sulfur coal with a fabric filter (Holcomb)
2. Low- to medium-sulfur coal with an electrostatic precipitator (Meramec and Laramie River)
3. Low- to medium-sulfur coal with SO_3 injection (Monroe and Labadie)
4. High-sulfur coal (Conesville)

As can be seen in Table 1, this program addressed many of the areas of interest specified by NETL. The key descriptive information for the final six sites is included in the following table:

Table 1. Host Site Operating Parameters.

	Holcomb	Meramec	Laramie River	Monroe	Conesville	Labadie
Test Period	3/04–8/04	8/04–11/04	2/05–3/05	3/05–6/05	3/06–5/06	11/06–1/07
Unit	1	2	3	4	6	2
Size (MW_E)	360	140	550	785	400	600
Test Portion (MW_E)	180 and 360	70	140	196	400	600
Coal	PRB	PRB	PRB	PRB/Bit. Blend	Bituminous	PRB
NO_x Control	First Generation Low-NO_x Burners	Low-NO_x Burners and SOFA	None	SCR	None	LNB, LNCFS Level III, SOFA
Particulate Control	Joy Western Fabric Filter	American Air Filter ESP	ESP	ESP	Research-Cottrell ESP	ESP (three in parallel)
SCA (ft2/kacfm)	NA	320	599	258	301	279 combined
FGC		None	None	SO_3	None	SO_3
Sulfur Control	Spray Dryer Niro Joy Western	Compliance Coal	Spray Dryer	Compliance Coal	Wet Lime FGD	Compliance Coal
SO_3 ppm	~ <1	~ <1	~ <1	~ 1–2	20–30	0–10
Ash Reuse	Disposal	Sold for Concrete	Disposal	Disposal	FGD Sludge Stabilization	Sold for Concrete
Typical Inlet Hg ($\mu g/dNm^3$)	10–12	10–12	10–12	5–10	15–30	10–12
Typical Native Hg Removal	<15%	<30%	<20%	10–30%	50%	<30%

Table 2 shows the field test schedule for the final program.

Table 2. Field-Testing Schedule.

Site	2004			2005				2006				2007		
	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
Holcomb														
Meramec														
Laramie River														
Monroe														
Conesville														
Labadie														

EXECUTIVE SUMMARY

The power industry in the U.S. is faced with meeting state imposed regulations, as well as expected federal legislation, to reduce the emissions of mercury compounds from coal-fired plants. Regulations are directed at the existing fleet of nearly 1,100 boilers. These plants are relatively old with an average age of more than 40 years. Although most of these units are capable of operating for many additional years, there is a desire to minimize large capital expenditures because of the reduced (and unknown) remaining life of the plant to amortize the project. Injecting a sorbent such as powdered activated carbon into the flue gas represents one of the simplest and most mature approaches to controlling mercury emissions from coal-fired boilers.

The overall objective of this Phase II test program was to evaluate the capabilities of activated carbon injection and other mercury control options at six host sites with configurations that together represent 78% of the existing plants. The ultimate goals for the Phase II program were to reduce the uncontrolled mercury emissions by 50 to 70% at a cost 25 to 50% lower than the benchmark established by DOE of $60,000 per pound of mercury removed.

Holcomb, Meramec, Laramie River, Labadie, Monroe, and Conesville were the six testing host sites that together represent configurations for most coal-fired plants in the U.S. During the program, the project team identified the significant impact of SO_3 and halogens on mercury removal. For native removal or sorbent injection, low SO_3 and high halogen levels are optimal. High SO_3 levels can be caused by burning high-sulfur coal, oxidation of SO_2 in an SCR, or by SO_3 injection for flue gas conditioning. Halogens can be used to promote mercury removal by increasing levels through high-halogen coals, coal additives, or by treating sorbents with a halogen-based material. Based on the SO_3 level and the particulate control, the six host sites can be categorized as follows:

1. Low sulfur with a SDA and fabric filter (Holcomb)
2. Low to medium sulfur with an electrostatic precipitator (Meramec and Laramie River)
3. Low to medium sulfur flue gas with SO_3 injection (Labadie and Monroe)
4. High sulfur (Conesville)

Results from field tests indicated that different levels of mercury removal can be achieved depending on the air pollution control equipment and flue gas conditions. Data collected from the Phase I DOE tests at Gaston indicate mercury removal levels of up to 90% were obtained with COHPAC® (a baghouse) and DARCO® Hg sorbent injection. At Pleasant Prairie, 50–70% removal while injecting DARCO® Hg was the maximum achievable mercury control, with the configuration of an ESP collecting PRB ash. At Brayton Point, with an ESP and SO_3 injection for flue gas conditioning, 90% removal was achieved with injection of DARCO® Hg.

Several options for removing mercury from flue gas were evaluated. Coal blending was the most costly of all the options if used for mercury control alone, although it was effective for the site with an SDA and FF. Coal additives can be used to increase halogen content. However, it was concluded that the coal additive KNX™ must be paired with

sorbent injection to increase mercury removals, and for plants with higher halogen flue gas, such as those that burn coal with > 0.03% chlorine (by weight), no benefit is expected. Activated carbon injection will be the simplest, most cost-effective mercury control option for coal-fired power plants firing western fuels or low-sulfur eastern fuels. ACI was evaluated during both parametric testing and long-term testing during this DOE Phase II project. The results were highly specific to the plant configuration and operating conditions. Figure 1 summarizes the results of the Phase I and Phase II test programs. The control costs presented in Figure 1 and throughout this report are identical to those presented in the respective Topical Reports. Details on the control costs are included in the respective Topical Reports.

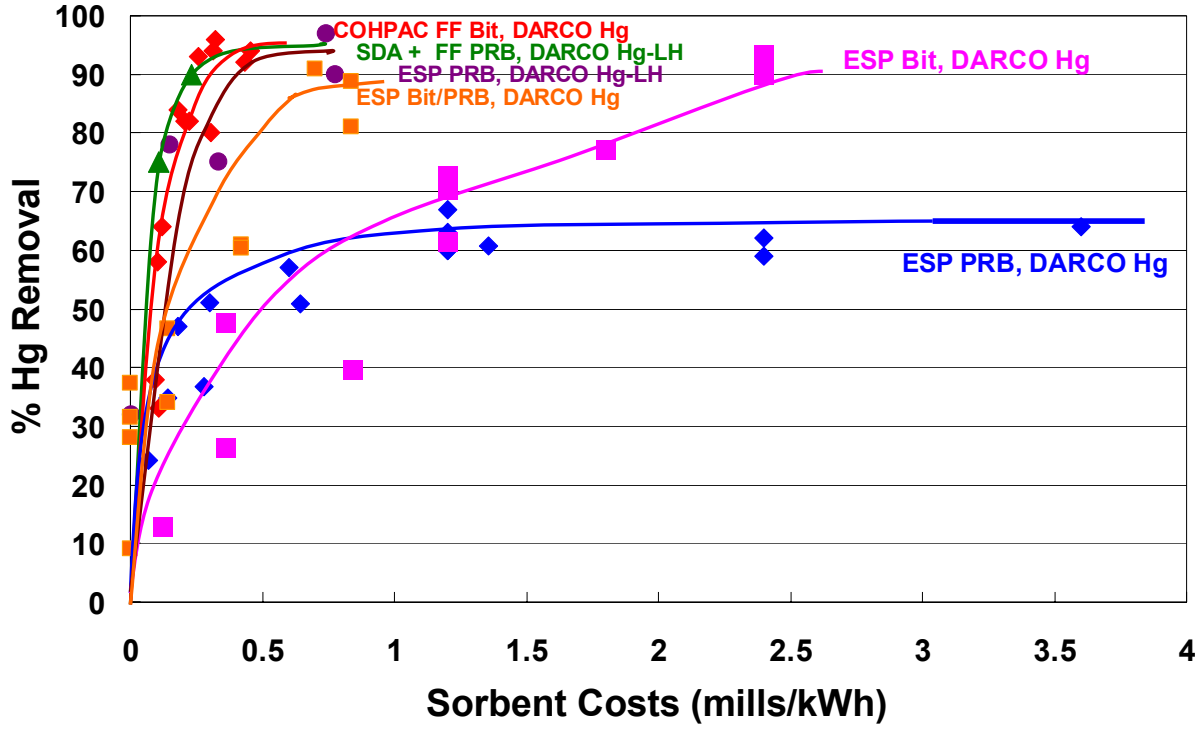


Figure 1. Compilation of Results from DOE Phase I and Phase II Mercury Control Programs.

Low-Sulfur Coal with a Fabric Filter

New units burning PRB coal are likely to consider installing a spray dryer absorber (SDA) and fabric filters (FF) for combined SO_2 and particulate control. However, past results indicated that power plants that burn Powder River Basin (PRB) coal and have SDA-FFs for air pollution control systems represent a challenging application for controlling mercury emissions. Information Collection Request (ICR) measurements and subsequent full-scale field tests have confirmed that the spray dryer removes halogens that are critical for the adsorption of vapor-phase mercury onto solid surfaces such as native fly ash or activated carbon-based mercury sorbents. This results in very low levels of native mercury removal, typically < 20%, at plants with this configuration and greatly diminished effectiveness of standard activated carbon for mercury control.

The test program at Holcomb was designed to provide a full-scale evaluation of different technologies that can overcome the limited mercury removal achievable with native fly ash or standard activated carbon. Several tests were based on supplementing halogens that were not available in sufficient quantities in the PRB coal. The most significant conclusions from testing at Holcomb were:

- Baseline
  - Native removal was less than 15%.
- Coal Blending
  - Blending the PRB with western bituminous coal led to an increase in mercury removal. At 15% western bituminous coal, native mercury removal was nearly 80%.
- Coal Additive
  - The combination of coal additive KNX™, and DARCO® Hg achieved the same mercury removal levels as injection of DARCO® Hg-LH alone.
- Activated Carbon Injection
  - At the same injection concentration, the brominated DARCO® Hg-LH performed better than DARCO® Hg.
  - Mercury removal levels of more than 90% were obtained while injecting DARCO® Hg-LH at 1.2 lb/MMacf.
  - The projected cost for mercury removal by ACI at Holcomb was 0.44 mills/kWh
- Balance-of-Plant Impacts
  - No balance-of-plant impacts were observed at Holcomb.

Low- to Medium-Sulfur Coal with an ESP

Both Meramec and Laramie River sites fire PRB coal and are equipped with a cold-side ESP for particulate control. This configuration is becoming more common in the industry as many U.S. utilities are fuel-switching to lower-sulfur western coals. Testing prior to this program at plants with this configuration (PRB/CESP) using sorbents available at the time indicated that the mercury removal was limited to about 70%. One important difference in the configuration of these two plants is the SDA utilized by Laramie River for SO_2 control, which was expected to further complicate mercury control, since the SDA is known to remove halogens. The most significant conclusions from the tests at Meramec and Laramie River were:

- Baseline
  - Native removal was < 30% at Meramec and < 20% at Laramie River.
- Coal Additive
  - KNX™ increased the amount of mercury captured by the flue gas up to 88% (coal to stack).
  - Combining KNX™ and DARCO® Hg injection led to an increase in the measured vapor-phase mercury removal of 84% at Meramec and 94% at Laramie River (inlet

CEM compared to outlet CEM). The overall mercury removal at Meramec was higher because some of the mercury was already associated with the particulate at the inlet CEM location.

- Activated Carbon Injection
  - With DARCO® Hg, removal was limited to 74% at 5 lb/MMacf at Meramec and < 45% at 6 lb/MMacf at Laramie River.
  - DARCO® Hg-LH could remove up to 97% at 3.2 lb/MMacf at Meramec and 95% at Laramie River using 6 lb/MMacf.
  - During long-term tests at Meramec with DARCO® Hg-LH, 60–70% of mercury was removed at an injection concentration of 1 lb/MMacf and 90% removal was achieved with 3 lb/MMacf.
  - The cost of mercury removal was $6,500/lb Hg for 90% mercury removal at Meramec and $4,000/lb Hg at Laramie River.
- Balance-of-Plant Impacts
  - No balance-of-plant impacts were observed during testing.

Low- to Medium-Sulfur Coal with an ESP and SO_3 Injection

Similar to Meramec and Laramie River, Labadie also burns PRB coal and is configured with a cold-side ESP. However, Labadie injects SO_3 for flue gas conditioning, which increases ESP performance, but can dramatically decrease mercury removal using PAC. Parametric tests were completed at Labadie with different rates levels of SO_3 injection. Monroe also injects SO_3, and fires a blend of PRB and bituminous coals. Select results from the testing completed under this program at the Labadie and Monroe sites include:

- Baseline
  - Baseline removal was limited to < 15% at Labadie and < 35% at Monroe.
  - Baseline removal was slightly worse when the Monroe SCR was online, rather than bypassed.
- Coal Blending
  - No changes in mercury speciation or removal were observed at Monroe due to coal blending ratio (ratios of 60/40 or 70/30 PRB/bituminous).
  - Brominated PAC did not increase mercury removal levels over those observed from standard PAC, likely due to the halogen contribution from the bituminous coal.
- Coal Additive
  - At Labadie, similar mercury removal levels were observed using both KNX™ and DARCO® Hg to those of using a standard brominated sorbent alone.
- Activated Carbon Injection
  - SCR Effects (Monroe)
    - The inlet mercury during both test weeks was fairly steady, with the SCR was in bypass and 7.6 lb/TBtu while the SCR was in-service.

- DARCO® Hg performed essentially the same whether the SCR was in-service or in bypass.

- Downstream of the APH
  - At Labadie, DARCO® E-26, the bromine-treated carbon with alkali, was the most effective of all sorbents evaluated during parametric testing downstream of the APH. At an injection concentration of approximately 5 lb/MMacf at the APH outlet and nominally 5.2 ppm SO_3, nearly 74% mercury removal was achieved.
  - At Monroe, mercury capture during long-term testing was over 87%, using DARCO® Hg.

- Upstream of the APH
  - Sorbents were more effective when injected upstream of the APH at Labadie, possibly due to more residence time or increased dispersion.
  - In the presence of 5.2 ppm (30%) of SO_3, FLUEPAC®-MC PLUS and DARCO® Hg-LH performed very comparably. At an injection rate of 5.2 lb/MMacf, these sorbents were able to achieve roughly 85% (± 2.5%) vapor-phase mercury removal.

- SO_3 Levels
  - For all the mercury sorbents tested, an increase in SO_3 concentration led to a reduction in the mercury removal at Labadie. The SO_3 concentration was not varied at Monroe.

- ADA-ES Patented On-Site Milling Process
  - Data from the extended testing period suggests significant improvement in PAC performance due to on-site sorbent enhancement. The results indicate that 85% mercury removal can be achieved with either 4 lb/MMacf enhanced PAC or 10 lb/MMacf as-received PAC.

- Cost
  - The cost of mercury removal by injecting DARCO® Hg-LH at Labadie was calculated to be $7,900/lb Hg with as received PAC for 75% control and $5,600/lb Hg with enhanced PAC for 85% control with SO_3 at 5.2 ppm.
  - Mercury removal using ACI at Monroe was projected to cost $18,000/lb Hg for 90% removal.

- Balance-of-Plant Impacts
  - At Labadie, when injecting trona as a possible flue gas conditioning substitute, it was concluded that alkaline materials may absorb some of the SO_3 before it has time to react with the fly ash. The removal of SO_3 increases ash resistivity, which slightly increases TR-set sparking.
  - No balance-of-plant impacts were observed at either plant due to ACI.

High-Sulfur Coal

Conesville was included in the testing program due to the challenge posed to mercury removal using ACI by the higher SO_3 levels. The challenges identified and characterized at Conesville stemming from the high concentration of SO_3 in the flue gas may represent a larger obstacle to mercury control for the industry than just units that fire high-sulfur coal. The presence of SO_3 in flue gas appears to decrease mercury capture by activated carbon, sometimes dramatically.

- Baseline
  - ESP native mercury capture is very low at Conesville, from 0 to 20%. The mercury is 60–70% oxidized at the ESP outlet, upstream of the WFGD, and 90% elemental at the WFGD outlet.
  - Most of the oxidized mercury is removed in the WFGD.
- Activated Carbon Injection
  - Eighteen sorbents from five vendors were evaluated at full-scale during testing at Conesville. None demonstrated more than 31% mercury removal.
  - The maximum incremental removal by a sorbent was approximately 31% (Norit DARCO® E-12 at 12 lb/MMacf).
  - The next highest removal was 25% (Sorbent Technologies EXP-2 at 16 lb/MMacf).
  - Both of these sorbents caused opacity issues that prevented further evaluation.
  - Several sorbents demonstrated some improvement over standard carbon-based sorbents.
  - Changing the injection lance design did not improve mercury removal.
- Balance-of-Plant Impacts
  - Most of the eighteen sorbents tested at full-scale increased T/R set spark rates, decreased power levels and/or impacted opacity.

At all sites except Conesville, the cost of mercury control was well within the technical and cost goals set by the DOE/NETL. An important part of evaluating different mercury control technologies is determining their impact on plant operation. This is the single most important step in gaining acceptance of these technologies across the industry. No balance-of-plant impacts were observed due to continuous ACI at Holcomb, Meramec, Laramie River, Labadie, and Monroe during long-term tests. High SO_3 flue gas remains a challenge for mercury removal. Continued testing with improved sorbents may be warranted. The cost goals set by the DOE/NETL were achieved for most sites during this program.

PROJECT OBJECTIVES AND TECHNICAL APPROACH

The overall objective of this test program was to evaluate the capabilities of activated carbon injection and other mercury control options at six host sites with configurations that together represent 78% of the existing coal-fired generation plants. The ultimate goals for the program established by DOE/NETL were to reduce the uncontrolled mercury emissions by 50 to 70% at a cost 25 to 50% lower than the benchmark established by DOE of $60,000/lb mercury removed.

The importance of testing at each site, as well as the specific site objectives, are described below.

Low-Sulfur Coal with an SDA and Fabric Filter – Holcomb

New plants that burn PRB coal will often use a configuration of air pollution control equipment that includes a spray dryer absorber (SDA) and FF. However, data available through EPA's Information Collection Request (ICR) database[2] and through other EPRI programs indicate that units burning low-rank fuels and that are configured with SDAs followed by fabric filters demonstrate particularly low native mercury removal.[3] Initial mercury measurements using the ASTM M6784-02 (Ontario Hydro) at Holcomb indicated 13% removal was achieved in the absence of mercury controls. Vapor-phase measurements using a semi-continuous mercury monitor indicated an average of 0% removal. These results are consistent with trends observed at other plants. Therefore, the test team considered mercury control testing at Holcomb critical to provide necessary information as Sunflower Electric and others who establish plans to meet future regulations and/or are considering SDA with FFs for new installations.

The specific site objectives for Holcomb were to determine the effect of the following on mercury removal:

- Blending a PRB coal with a western bituminous coal
- Injecting chemical additives onto the coal
- Injecting sorbents specifically designed to operated in a halogen-deficient flue gas

Low- to Medium-Sulfur Coal with an ESP – Meramec and Laramie River

Meramec Unit 2 was chosen for this evaluation because it fires subbituminous Powder River Basin (PRB) coals and is configured with a cold-side ESP (CESP). This configuration is becoming more common in the industry as many U.S. utilities are fuel-switching to lower-sulfur western coals. Test conducted prior to 2003 at plants with this configuration (PRB/CESP) using sorbents available at the time indicated that the mercury removal was limited to about 70%.

In 2001, a full-scale demonstration of carbon injection for mercury control was conducted by ADA-ES at We Energies Pleasant Prairie Power Plant, another PRB/CESP unit (no SDA), during the DOE Phase I tests. At a sorbent injection concentration of 10 lb/MMacf, mercury capture across the ESP was 60–65% and showed little increase even up to an injection concentration of 30 lb/MMacf. Reducing the injection concentration to

5 lb/MMacf decreased the mercury removal to 50–55%.[4] At 1 lb/MMacf, an average mercury control efficiency of 46% was achieved over a five-day period. However, since the completion of tests at Pleasant Prairie, improved sorbents have been developed, some of which were tested during this Phase II program. The project team determined that evaluation of the new sorbents on a PRB/CESB plant was of key interest.

Laramie River Station also fires PRB coal and is equipped with a cold-side ESP, but also utilizes a SDA for SO_2 control. Previous to the testing discussed in this report, mercury control on a unit configured with an SDA+ESP had not been evaluated at full-scale by either DOE or EPRI. Therefore, the project team determined that inclusion of this particular plant configuration was important.

The specific site objectives for the low to medium sulfur sites with an ESP, Meramec and Laramie River, were to evaluate the effect of the following on mercury removal:

- Blending PRB coal with western bituminous coal
- Coal additives
- Injecting alternative sorbents specifically designed to operate in a halogen-deficient flue gas

Low- to Medium-Sulfur Coal with SO_3 Injection – Labadie and Monroe

Many plants now inject SO_3 for flue gas conditioning to improve the ESP particulate control. AmerenUE's Labadie Station is an example of such a plant, which also fires PRB coal. Labadie presented the opportunity to conduct parametric testing with varying SO_3 concentrations with a given sorbent concentration. The configuration of Labadie also provided the opportunity to evaluate PAC injection both upstream and downstream the APH and SO_3 injection.

DTE Energy's Monroe Power Plant also injects SO_3 for flue gas conditioning, similar to Labadie, but it fires a blend of PRB and eastern bituminous coal. This configuration allowed an evaluation of the effects of sorbent injection and coal blending on mercury control and ESP performance for an ESP that represents the size of many units in the industry. Another key feature of Monroe Unit 4 is that it uses an SCR system during the ozone season. SCR systems are becoming more common in the industry as many U.S. utilities are required to reduce NO_x emissions. Testing at Monroe provided important information concerning mercury speciation and sorbent performance with an SCR system. In addition, SCRs can increase SO_3 concentrations through the oxidation of SO_2. Results with and without the SCR in service are included in this report.

The specific site objectives for the low to medium sulfur sites with SO_3 were to determine the effect of the following on mercury removal:

- Injecting sorbent at a unit equipped with a small- to moderate- sized ESP
- Using a selective catalytic reduction (SCR) system with sorbent injection
- Blending PRB coal with eastern bituminous coals
- Injection of sulfur-tolerant sorbents
- Injecting mercury sorbents upstream of SO_3 injection

- Changing or modifying sorbents to reduce the SO_3 requirements
- Substitute trona for SO_3 for particulate control

High-Sulfur Coal – Conesville

One of the more difficult applications for mercury control with sorbent injection are sites firing high-sulfur bituminous coals. Conesville Unit 6 was chosen for to this evaluation because it has a marginally sized, cold-side ESP (SCA = 301 ft^2/kacfm), and it fires high-sulfur eastern bituminous coal. The configuration at Conesville allowed an evaluation of the effects of sorbent injection on mercury control, ESP performance, and WFGD performance, with an ESP that is representative of many units across the industry.

The specific site objectives for the high-sulfur flue gas stream at Conesville, were to evaluate the effect of the following on mercury removal:

- Inject sorbent at a unit equipped with a cold-side ESP
- Use a coal additive to promote mercury oxidation with and without sorbent injection
- Employ injection of alkali materials to reduce the interference of SO3 with mercury capture

Technical Approach

The technical approach followed during this program allowed the team to evaluate various mercury control technologies at plants with different configurations. Those host sites with promising parametric test results were then used for long-term testing, up to six weeks in duration. The technical approach was outlined in a series of four tasks.

- Task 1. Design and Fabrication of Sorbent Injection System
- Task 2. Site-Specific Activities Including Field-Testing
- Task 3. Technology Transfer
- Task 4. Program Management and Reporting

Tasks 1, 3, and 4 were intended to support the overall direction, implementation, technology transfer, and management of the program. Task 2 was the heart of the program and contained seven subtasks to address each important component of the testing. All Task 2 subtasks were repeated at each host site, except when long-term testing was not conducted (Laramie River Station and Conesville Station). A summary of these subtasks is given in Table 3.

Table 3. Task 2 Subtasks.

Subtask	Description
2.1	Host site kickoff meeting, Test Plan, and QA/QC plan
2.2	Design and install site-specific equipment
2.3 2.3.1 2.3.2 2.3.3 2.3.4 2.3.5	Field-tests Sorbent selection Sample and data coordination Baseline tests Parametric tests Long-term tests *(Thirty-day tests conducted at Holcomb, Monroe, and Meramec. Fifteen-day test conducted at Labadie. No long-term tests conducted at Laramie River or Conesville.)*
2.4	Data analysis
2.5	Sample evaluation
2.6	Economic analysis
2.7	Site (topical) report

Detailed descriptions of the six testing sites can be found in the site final reports.[5–10] The equipment and apparatus used during the project are described in detail in the final site reports and the Appendix. For complete details regarding testing methodology and results, see the individual site reports.

RESULTS AND DISCUSSION

Low-Sulfur Coal with a Fabric Filter

Prior to testing at Holcomb, EPRI conducted full-scale carbon injection tests at Great River Energy's Stanton Station Unit 10 in April 2002.[11] Although Stanton is configured with an SDA-FF and burns a North Dakota lignite coal, the coal has similar chlorine concentrations (< 0.01%) to PRB coal and the results provided insight into potential sorbent performance at Holcomb. Results from the Stanton test program suggested that the mercury removal effectiveness of standard, non-chemically treated, activated carbon injected upstream of an SDA-FF was limited. At an injection concentration of 6.1 lb/MMacf of non-chemically treated activated carbon, 70% mercury removal was achieved. This injection concentration is much higher than would likely be required for a plant without an SDA (90% removal is expected across a fabric filter at an injection concentration of 3 lb/MMacf for a similar unit without an SDA).[11]

SDAs are designed to remove sulfur dioxide, but they are also effective at removing other acidic flue gas components such as HCl. Halogens, including HCl, which is typically present in fairly low concentrations in most low-rank coals (< 10 ppm), are critical to the effective removal of mercury with standard activated carbons. For example, injection of 1 lb/MMacf of a carbon treated with iodine resulted in > 90% removal at Stanton Station.[11] This was significantly better than the performance of the untreated carbon. Because of these results and the expected low flue gas HCl concentrations at Holcomb, ADA-ES contacted several vendors and requested sorbents specifically designed for effective mercury capture in low-halogen environments. Both treated and untreated carbons were tested at Holcomb. In addition, chemical additives for the coal as well as coal blending were also evaluated for mercury control potential.

Holcomb

Site Description

Holcomb Station is located near Garden City, Kansas. The unit is a load-following sub-critical 360-MW pulverized coal opposed-fired Babcock & Wilcox Carolina-type radiant boiler designed to burn PRB coal. The existing unit is equipped with three spray dryer absorber modules followed by very low air/cloth ratio reverse air fabric filters. Key operating parameters are included in Table 1. The plant was originally equipped with "first generation" low-NO_x burners. During a recent upgrade, these burners were optimized, and coal flow controls and in-furnace sensors were installed to balance burners and optimize combustion. These modifications have been done in conjunction with DE-FC26-03NT41418 under DOE's Power Plant Improvement Initiative.

Baseline Mercury Removal

Two weeks of baseline testing were conducted. During week 1, the unit fired 100% PRB coal from the Jacobs Ranch and Cordero mines. The unit was maintained at constant, full-load operation and the air pollution equipment was operated under standard full-load conditions (standard soot blowing, fabric filter cleaning logic, SDA recycle rate, etc.). The

SCEMs show that the mercury at the inlet to the SDA and at the stack was primarily elemental. The concentration of the inlet mercury was 10–12 μg/dNm^3 and native removal was less than 25%.

Coal Blending

The main focus for testing at Sunflower Electric's Holcomb Station was sorbent injection for control of mercury. However, additional options for reducing mercury emissions were also planned because of their potential to enhance baseline mercury removal or mercury removal with injection of untreated activated carbon. One option of interest was the influence of blending small percentages of western bituminous coal with the PRB coal. Many western bituminous coals have slightly higher chlorine content than PRB coals. If the chlorine content of the blended fuel is slightly higher at both the inlet and outlet of the SDA, the ability of the native fly ash and standard activated carbon to remove mercury should improve and approach the level that might be expected in boilers with fabric filters only.

During coal blending, the PRB coal was from the Black Thunder mine and the western bituminous coal was from the West Elk mine. The mercury, halogen, and sulfur content of the coals included in the blending tests are listed in Table 4.

Table 4. Results from Coal Analyses (Dry Basis) Collected during Blend Test Period.

Coal	Hg (μg/g)	Cl (μg/g)	F (μg/g)	Br (μg/g)	S (%)
Jacobs Ranch (PRB)	0.105	7.9	76	1.82	0.56
Black Thunder (PRB)	0.077	8.0	80	0.56	0.32
West Elk (W. Bit)	0.103	106	84	1.38	0.93
Blend 1 (est)	*0.079*	*15*	*80*	*0.62*	*0.36*
Blend 2 (est)	*0.081*	*22*	*81*	*0.68*	*0.41*

Figure 2 shows the percentage of mercury removal as a function of the percentage of western bituminous coal. More detailed results from the coal blending at Holcomb are discussed in detail in the site report.[5]

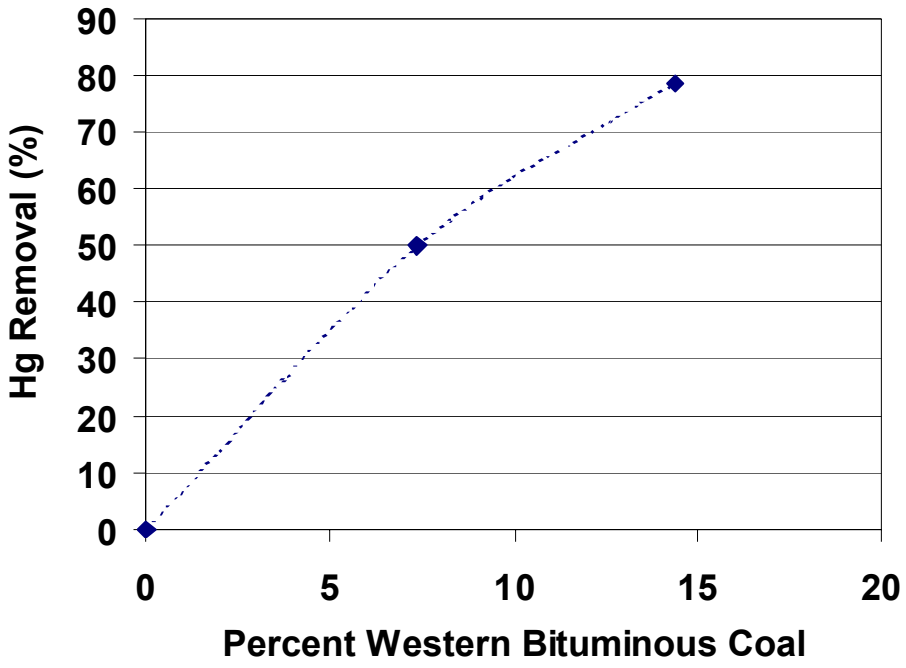


Figure 2. Summary of Coal Blending Tests at Holcomb.

Parametric Testing

Following baseline testing, three weeks of parametric tests were conducted to evaluate sorbent injection for several levels of mercury control. Means of achieving mercury removal levels above those observed with standard activated carbon injection, specifically improved sorbents and halogen-enhancement options, were of key interest. Sorbent screening was completed to narrow the candidates for parametric testing. Details of the sorbent screening are given in the site report.[5] The primary variables of interest during parametric testing included:

- Sorbent
  - DARCO® Hg (benchmark sorbent, no chemical treatment, previously known as DARCO® FGD)
  - Calgon 208CP (highly activated, no chemical treatment)
  - DARCO® Hg-LH (bromine-treated, previously known as DARCO® FGD-E3)
- Sorbent injection concentration
- Sorbent injection location (upstream of the SDA versus between the SDA and FF)
  - Upstream of the SDA
  - Downstream of the SDA
- Enhancement additive with/without sorbent injection
  - Coal additive
  - Flue gas additive

Sorbent Injection

DARCO® Hg and DARCO® Hg-LH were tested at two different injection locations–upstream and downstream of the SDA. Calgon's 208CP was evaluated upstream of the SDA only. For comparison purposes, all sorbent injection concentrations included in this report were calculated based upon the stack flow from the plant CEM and calculated at the SDA inlet temperature (nominally 290 ºF), regardless of injection location (inlet or outlet of SDA), unless otherwise noted.

The alternative sorbent tests were conducted at the SDA inlet injection location. These results are presented in Figure 3. The duration for these tests was between 4 and 7 hours, which was enough time for the outlet mercury to reach a stable concentration. The mercury removal achieved with the 208CP was similar to the benchmark DARCO® Hg. The DARCO® Hg-LH demonstrated the best performance of the three sorbents, resulting in 77% mercury removal at an injection concentration of 0.7 lb/MMacf as compared to 50–54% for the 208CP and DARCO® Hg at an injection concentration of 1.0 lb/MMacf. Two of the injection concentrations shown for DARCO® Hg-LH (1.5 and 4.3 lb/MMacf) represent fairly short tests (< 130 minutes) and the mercury removal had not yet reached steady state. Additional testing during the long-term test period confirmed that with continuous injection of DARCO® Hg-LH, the mercury removal at 1.5 lb/MMacf would be higher than the 77% measured during the short parametric test.

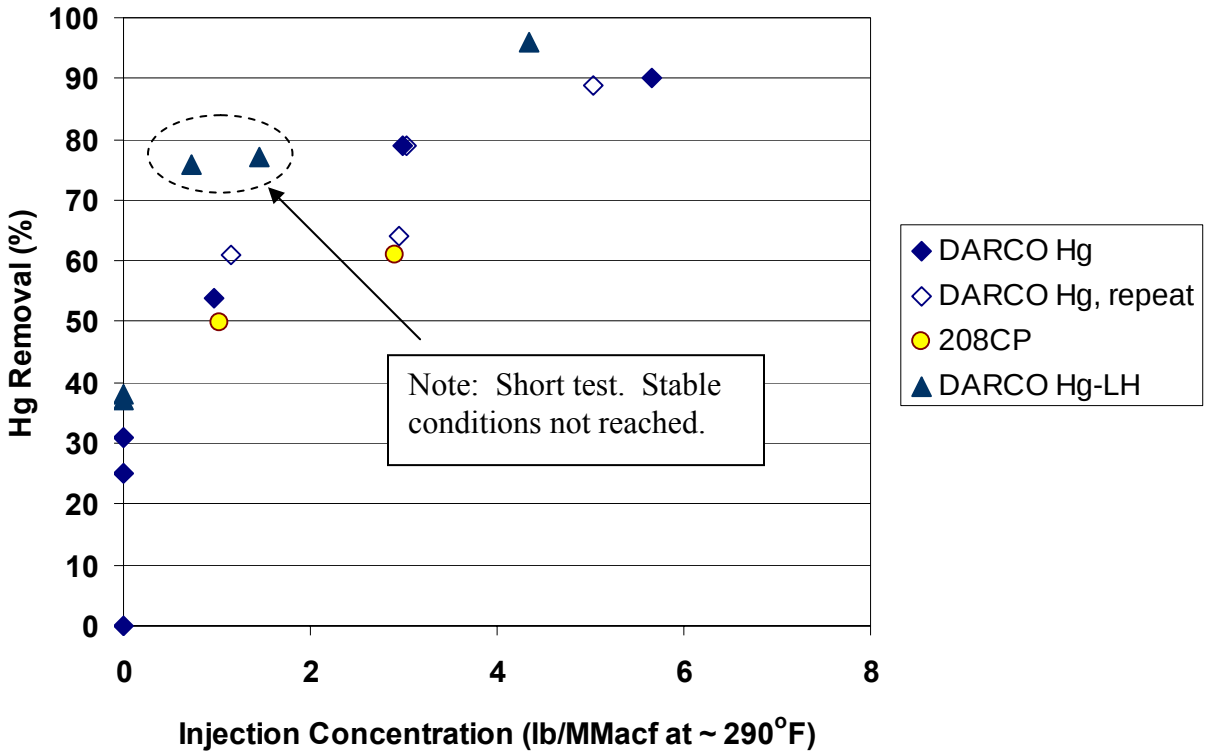
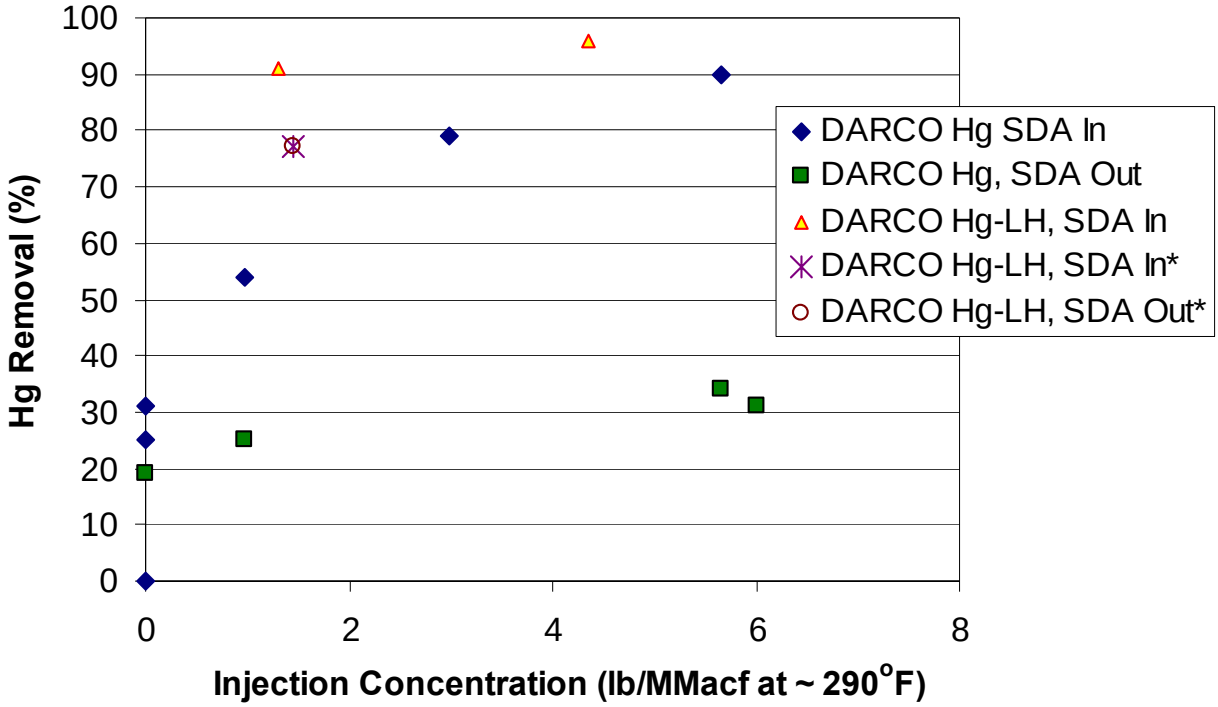


Figure 3. Results of Alternative Sorbent Tests, Holcomb Station, SDA Inlet.

The results from sorbent injection testing upstream of the SDA indicated higher mercury removal for the sorbent treated with bromine than the untreated material. This result indicates that bromine promotes the effectiveness of activated carbon for mercury removal. Another indicator of the importance of halogens can be seen when comparing the performance of DARCO® Hg injected upstream and downstream of the SDA (Figure 4), since the SDA is known to remove HCl. Ninety percent mercury removal was achieved with DARCO® Hg at an injection concentration of 5.7 lb/MMacf upstream of the SDA at Holcomb. The mercury removal was limited to less than 35% when DARCO® Hg was injected downstream of the SDA at injection concentrations up to 5.7 lb/MMacf. The injection concentrations indicated above are both calculated at the SDA inlet temperature for comparison purposes. The injection concentration in pounds per *actual* cubic foot is approximately 17% higher at the SDA outlet location due to the reduced gas volume at the lower temperatures (175 ºF downstream of the SDA as compared to 290 ºF upstream of the SDA).

A short test of DARCO® Hg-LH injection at the outlet of the SDA was also conducted. These results are compared to a short test of DARCO® Hg-LH injection upstream of the SDA. As shown in Figure 4, there was no change in the DARCO® Hg-LH performance when injected either upstream or downstream of the SDA, indicating that flue gas constituents such as HCl or HF are not required for the effective performance of DARCO® Hg-LH.



**** Short (<2 hour) results.***

Figure 4. Results of Injection Location Tests, Holcomb Station.

Enhancement Additive With/Without Sorbent Injection

Results from the DARCO® Hg and DARCO® Hg-LH tests confirm that a bromine-treated carbon outperformed a non-treated carbon on an SDA-FF configuration such as Holcomb. Another option for introducing halogens is to increase the halogen content of the gas stream rather than using treated carbons. To increase the halogen content of the flue gas, the coal was treated with a proprietary ALSTOM Power Inc. additive, called KNX™. The mercury removal with the treated coal was evaluated both with and without the injection of activated carbon.

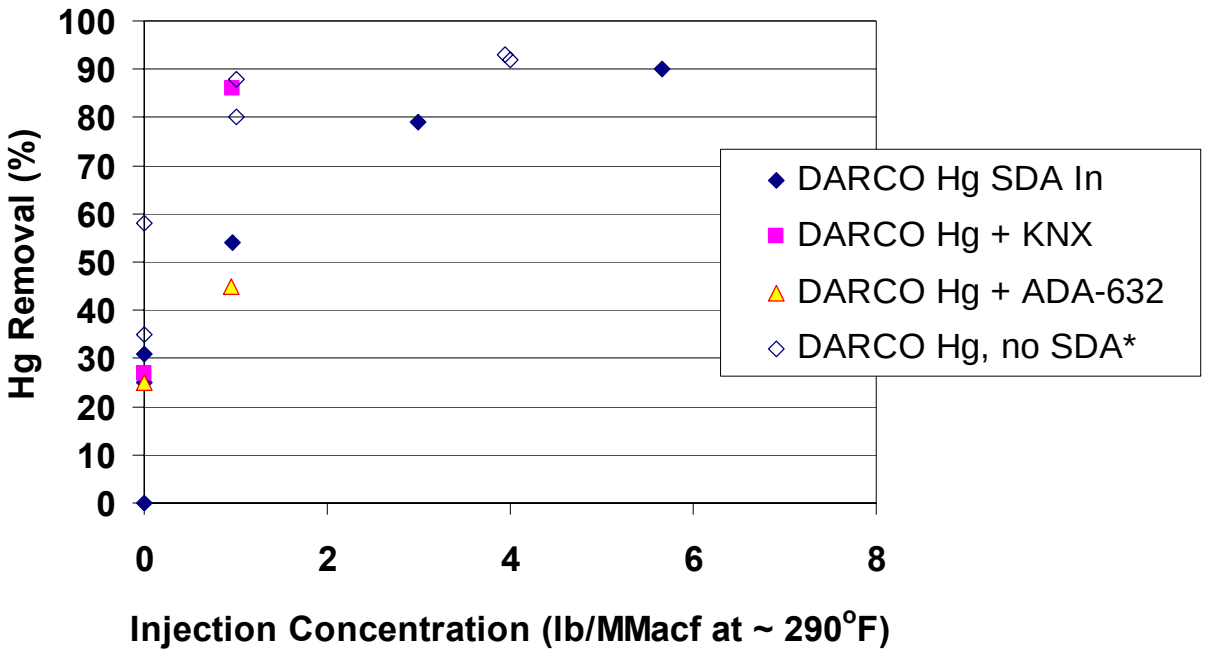
KNX™ was applied to the coal at the crusher house prior to entering the transfer house and coal bunkers. At this chemical injection location, it was estimated that it would take 4–5 hours before the "treated" coal would be fired in the boiler.

During testing with KNX™ injection, the unit was burning coal from the Jacobs Ranch mine. At normal operating conditions, this coal yielded a total vapor-phase mercury concentration of 18–22 $\mu g/Nm^3$ at the outlet of the air preheater with 70–90% in the elemental form. During the chemical additive tests, the fraction of elemental mercury at the air preheater outlet decreased to 20–30%.

Although the fraction of oxidized mercury at the inlet of the SDA increased substantially, no increase in mercury removal across the system was noted. The fraction of oxidized mercury at the outlet of the fabric filter was also lower (nominally 80% elemental compared to typically > 90% elemental mercury when KNX™ was not present with the coal). This suggests that either the KNX™ addition resulted in a sampling artifact that biased the elemental mercury measurement at the air preheater outlet, or the SDA-FF was reducing oxidized mercury back to the elemental form.

The final day of KNX™ testing included the injection of the DARCO® Hg sorbent at the SDA inlet location in conjunction with addition of the KNX™ additive to the coal. The sorbent injection concentration at the inlet to the SDA was 1.1 lb/MMacf, while the chemical additive flowrate was held steady. This parametric testing condition showed the total mercury capture across the system was 86% compared to 54% with DARCO® Hg alone (no KNX™). These data, plotted in Figure 5, clearly indicate the improved performance of DARCO® Hg when halogens are added to the flue gas.

An additional data set included on the graph in Figure 5 compares the performance of DARCO® Hg injected upstream of the SDA during KNX™ coal additive injection with performance of DARCO® Hg on a unit burning PRB coal with a fabric filter and no SDA.[12] The data suggest that the addition of KNX™ allows the DARCO® Hg to perform as well as it would in the absence of an SDA.



** Data collected with DOE pilot plant at Xcel Energy's Comanche Station in 1997.*

Figure 5. Impact of the Addition of Coal Additive (KNX™) on Mercury Removal.

Flue Gas Additive

An additional enhancement additive test was conducted to determine if a halogenated compound could be added directly to the flue gas to improve the performance of untreated activated carbon. The chemical was ADA-623, a proprietary chemical provided by ADA-ES. This material was chosen based upon promising screening tests. ADA-623 was injected at the outlet of the SDA with and without DARCO® Hg. No change in speciation or removal was noted above that expected without the additive. It is possible that the solid ADA-623 material tested was not adequately ground to the appropriate size for in-duct injection. Therefore, the results are inconclusive.

Long-Term Testing

Long-term testing was conducted at the "optimum" settings as determined during the parametric tests and approved by both DOE and Sunflower Electric/Holcomb. It was the intent of DOE that these settings represent the most cost-effective conditions for mercury removal. The goals of this subtask were to obtain sufficient operational data over a 4-week period on removal efficiency, to determine the effects on the particulate control device, to determine the effects on the SDA equipment, to determine the effects on byproducts, and to evaluate impacts to the balance-of-plant equipment to prove viability of the process and determine the economics. During this test, ASTM M6784-02, M29, and M26A measurements were conducted at the inlet and outlet of the SDA-FF.

The standard operation for Holcomb Unit 1 is to recycle approximately 75% of the material collected in the fabric filter back into the SDA. Therefore, during continuous sorbent injection some injected sorbent was also recycled into the SDA. Not all units configured with SDA and FFs use recycle.

The test team decided to evaluate DARCO® Hg-LH during the long-term period due to the following:

- Favorable performance and economics of DARCO® Hg-LH versus DARCO® Hg
- Availability of a similar product from another supplier (not sole-sourced)
- The requirement of only one injection system at the plant (lower projected capital and O&M costs) compared to DARCO® Hg + KNX™.

DARCO® Hg-LH was injected upstream of the SDA for 30 days from July 7 through August 6, 2004. For the first six days of testing, the injection concentration was increased until 90% mercury removal was achieved. From Day 6 through 30, the injection concentration was set for nominally 1.2 lb/MMacf. The logic on the injection skid was set to adjust the sorbent feed rate with boiler load. The average removal for the 30-day test was 91%, with an average removal of 93% for Days 6 through 30. The average outlet concentration for Days 6 through 30 was 1.13 µg/Nm^3 (0.83 lb/TBtu, standard deviation = 0.30 lb/TBtu). Trend graphs of the inlet and outlet mercury concentrations, mercury removal, and injection concentration for the 30-day test are presented in Figure 6.

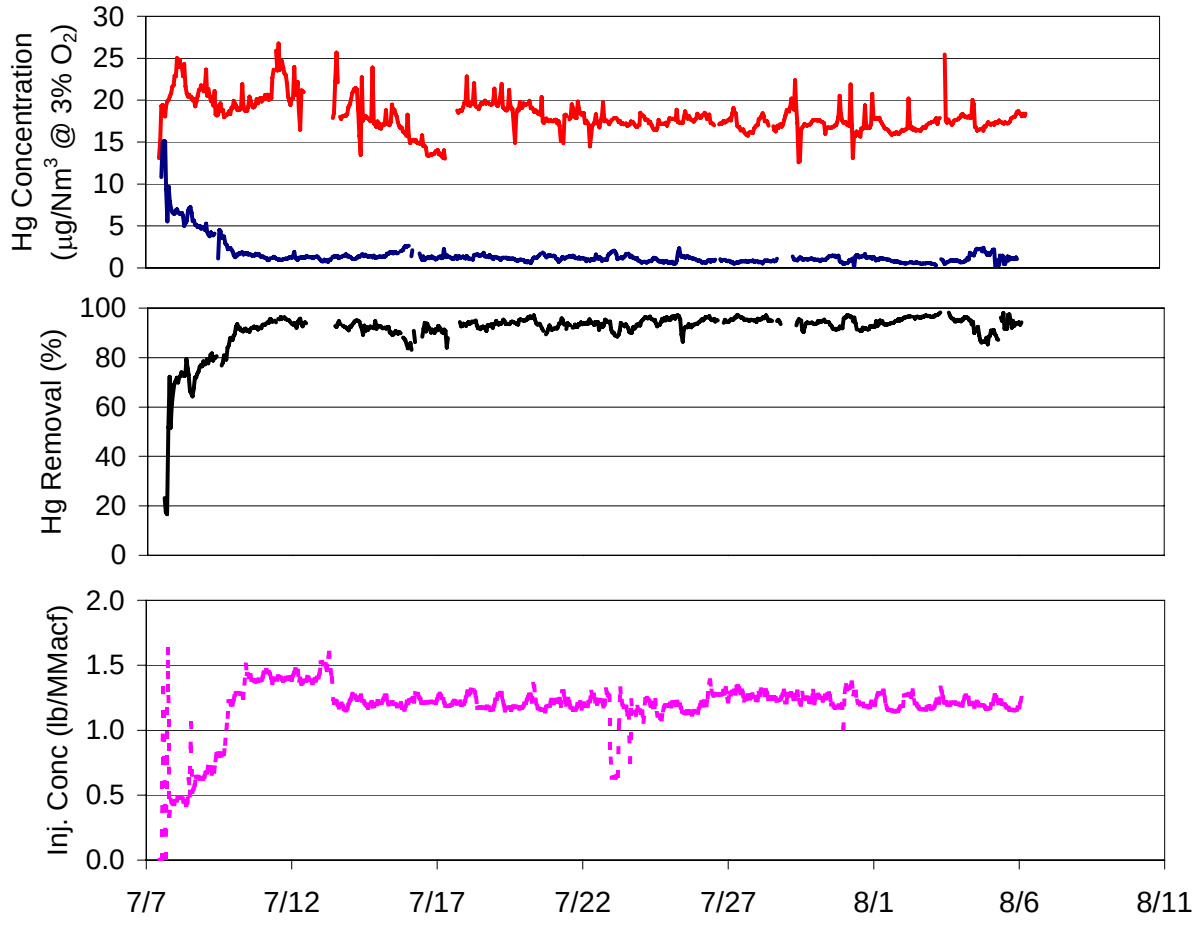
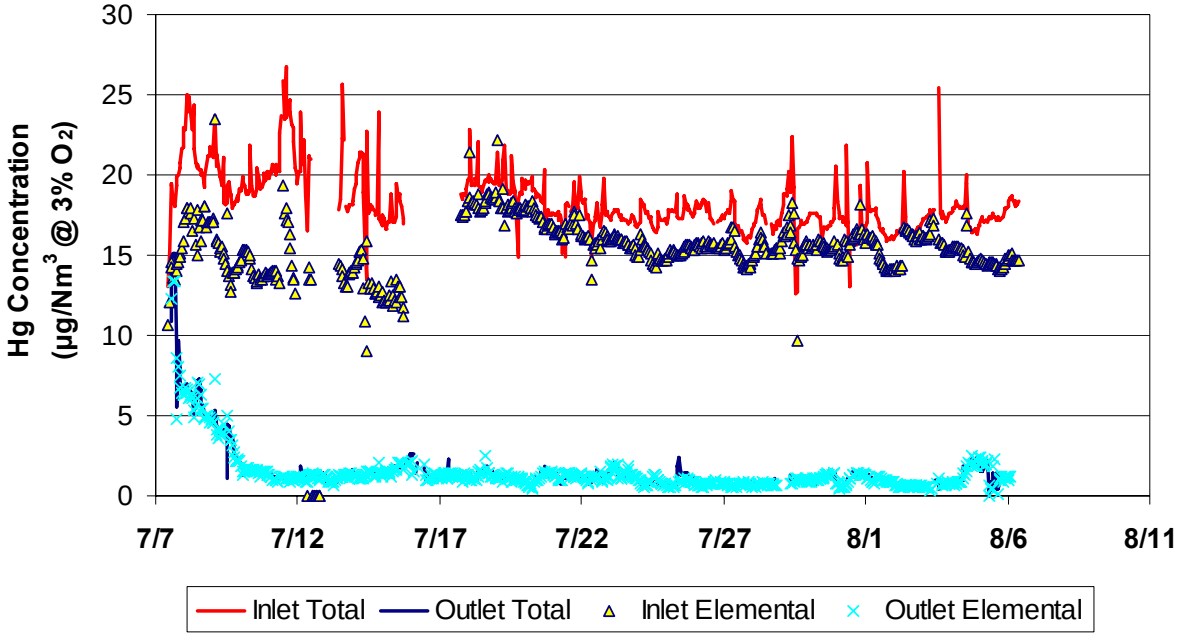


Figure 6. Mercury Removal during 30-Day Continuous Injection of DARCO® Hg-LH, 2004.

Both elemental and total mercury measurements were made during the long-term test period. Trend graphs of these data are shown in Figure 7. The data indicate that the fraction of oxidized mercury at the inlet to the SDA was typically less than 10% of the vapor-phase mercury. At the outlet of the fabric filter, the mercury was primarily in the elemental form.



All data corrected to 3% O_2.

Figure 7. Mercury Speciation during Long-Term Testing at Holcomb, 2004.

Additional analyzers were installed at Holcomb for a portion of the long-term tests under a separate program. The trend graph in Figure 8 shows measurements from five locations: 1) upstream of the SDA and upstream of sorbent injection, 2) upstream of the SDA and approximately 0.5 seconds downstream of sorbent injection, 3) downstream of the SDA, 4) downstream of the baghouse, and 5) at the stack. During these tests, the Thermo analyzers were configured to measure only elemental mercury, which represented over 80% of the vapor-phase mercury at the inlet to the SDA and the bulk of the mercury at the outlet of the fabric filter. Analyzers that were used to collect the data presented in Figure 8 are designated as Thermo and EMC. As shown, the two analyzers matched fairly well at the inlet to the SDA. The extraction probe on the Thermo analyzer was experiencing particulate buildup which resulted in a reduction in the measured mercury over time. This system was designed to automatically blow back the filter, but the cleaning air was not connected during these tests. The filter was manually cleaned on July 12 and 30, 2004, which correspond to periods with higher measured mercury.

Measurements from the analyzer installed downstream of sorbent injection but upstream of the SDA indicate that 30–50% of the mercury is removed prior to the SDA. Reviewing the results from the analyzer installed at the outlet of the SDA indicates that nominally 50% of the incoming, vapor-phase mercury was removed between the injection location and the outlet of the SDA. Measurements from the Thermo analyzer installed at the outlet of the fabric filter matched well with the project analyzer and the Thermo analyzer installed at the stack.

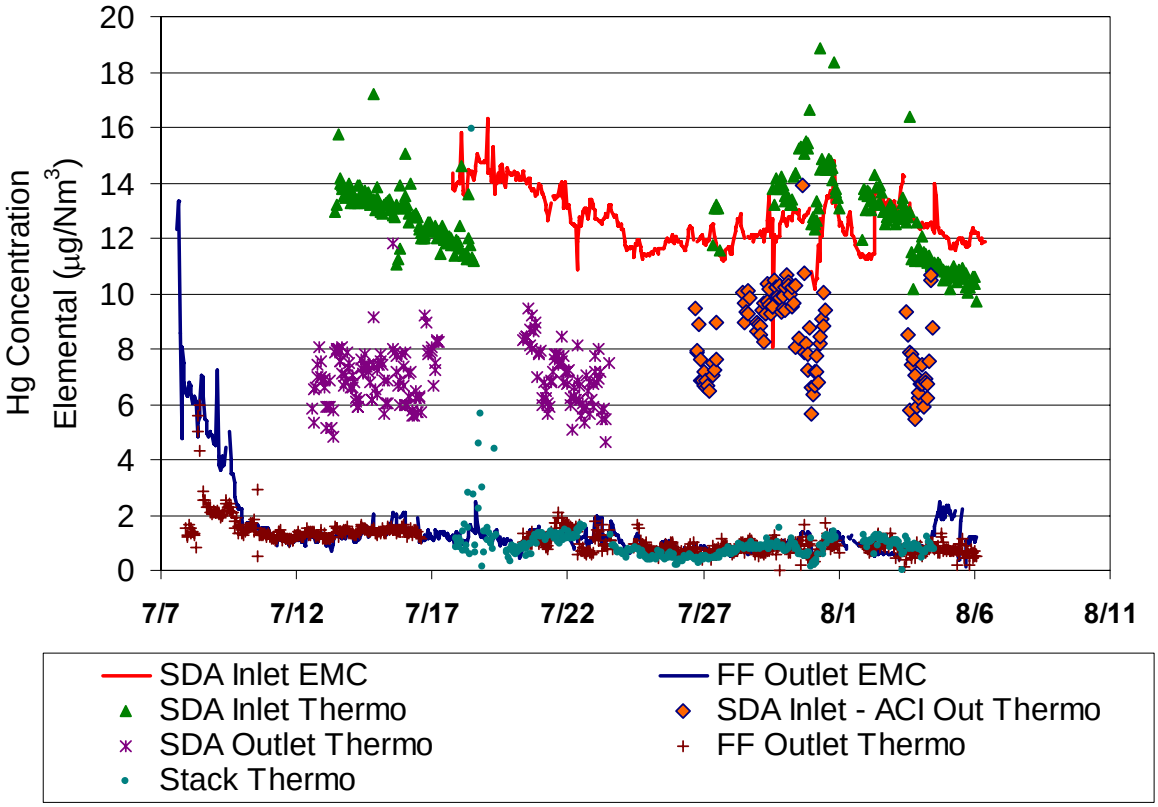


Figure 8. Mercury Measurements from Five Extraction Locations at Holcomb.

Several different techniques were used to measure mercury at Holcomb. These included flue gas measurements using EPA Method 29, EPA draft Method 324, Ontario Hydro, and mercury analyzers and analysis of mercury in coal and ash samples. In general, the techniques compared well. The site report discusses in detail the readings obtained from different techniques.[5]

The effectiveness of DARCO® Hg-LH on multi-metals and halides is described in the site report.[5] Analyses were conducted on ash samples collected during the baseline and long-term testing phases to determine the stability of mercury and bromine. The detailed information on these analyses can be found in the site report.[5]

Balance-of-Plant Impacts

An important part of the overall mercury control technology assessment is the impact of the technology on plant operation. At Holcomb, no balance-of-plant impacts were noted as a result of DARCO® Hg-LH injection during the 30-day long-term test. Neither the fabric filter pressure drop nor the stack opacity was affected by the presence of sorbent in the system.

Low- to Medium-Sulfur Coal with an ESP

Power plants that burn Powder River Basin (PRB) coal and have only cold-side electrostatic precipitators (ESPs) for air pollution control represent a challenging

configuration for cost-effectively controlling mercury emissions. Full-scale field tests have confirmed that the average native mercury removal at these PRB units is low, typically < 25%. In addition, the effectiveness of injecting standard, non-chemically treated, activated carbon is greatly diminished by the low halogen concentrations in the flue gas.

Both Meramec and Laramie River sites fire PRB coal and are equipped with a cold-side ESP for particulate control. However, one important difference in the configuration of these two plants is the SDA utilized by Laramie River for SO_2 control. In addition to SO_2, the SDA removes some of the halogens from the flue gas at Laramie River.

Meramec

Site Description

Meramec Unit 2 was chosen for this evaluation because it fires subbituminous Powder River Basin (PRB) coals and is configured with a cold-side ESP (CESP). The specific collection area (SCA) of the ESP is approximately 320 ft^2/kacfm. This configuration is becoming more common in the industry as many U.S. utilities are fuel-switching to lower-sulfur western coals. Previous tests at plants with this configuration (PRB/CESP) using sorbents available at the time indicated that the mercury removal was limited to about 70%. The key operating parameters for Meramec Unit 2 are listed in Table 1.

Baseline Mercury Removal

One week of baseline testing was conducted. During this period, Meramec Unit 2 fired 100% PRB coals, obtained from several different mines. At full-load, the unit operated at sub-stoichiometric oxygen levels in the combustion zone to control NO_x. Pre-baseline mercury measurements showed the average mercury concentrations at the ESP inlet and outlet were 6.0 lb/TBtu and 4.8 lb/TBtu respectively, yielding a native vapor-phase mercury removal efficiency of about 20%. At the beginning of baseline testing, August 24–26, 2004, the full-load mercury concentration at the ESP inlet and outlet was relatively steady. The native, daily average vapor-phase mercury removal across the ESP ranged from 15 to 18%. Both the June and August data agree well with results from other sites firing PRB coals with cold-side ESPs.

Parametric Testing

Following baseline testing, two weeks of parametric testing were conducted. Tests included injection of two activated carbon sorbents and two coal additives. The first coal additive tested was a halogen-based coal additive, KNX™, developed by ALSTOM Power Inc. This material was evaluated during the final week of parametric testing under this DOE program. The second material tested was SEA2, an additive under development at the EERC, which was evaluated during an additional week of testing funded by AmerenUE. The primary variables of interest during parametric testing at Meramec included:

- Sorbent
  - DARCO® Hg
  - DARCO® Hg-LH

- Sorbent Injection Concentration
- Coal Additives
  - KNX™
  - SEA2

Sorbent Injection

There were inconsistencies in unit operation throughout the test program. One of the four coal mills, Mill B, was out of service during the second week of parametric testing. Because of this, Unit 2 was operated at a reduced load of about 115 MW, and higher variations were observed in the vapor-phase mercury concentration at the ESP inlet than during previous tests. These variations were likely caused by rapid changes in unburned carbon as measured by the LOI test method. Changes in the quantity and form of LOI carbon can result in different fractions of particulate and vapor-phase mercury in the flue gas. Oxidized mercury is predicted to be more reactive with LOI carbon than elemental mercury. During coal blending tests, Mill B was returned to service, but the classifiers on the other three mills were not readjusted for optimal, four-mill operation.

During the first week of parametric testing, DARCO® Hg was evaluated at various injection rates. All tests were conducted at standard, full-load conditions. The hour-average mercury removal peaked at 74% at an injection concentration of 5 lb/MMacf. No further increase in mercury removal was observed when injection rates were increased up to the maximum tested sorbent injection concentration of 20 lb/MMacf. When the mercury removal was based on the change in the concentration at the ESP outlet, removal levels peaked at 72% removal at the injection rate of 5 lb/MMacf.

The results obtained at Meramec with DARCO® Hg are similar to those achieved at other cold-side ESP sites burning low-rank coals (PRB and North Dakota lignite), as shown in the Laramie River section, Figure 12. In all cases, the mercury removal was limited to below 80% regardless of carbon injection concentration. It is speculated that the mercury removal is limited because there is insufficient HCl in the flue gas. Halogen species, such as HCl, are needed by activated carbon for effective mercury removal, and halogen concentrations in low rank coals (PRB) are typically relatively low. Activated carbon injection concentrations of 3 to 10 lb/MMacf are sufficient to absorb the available halogens from burning most low-rank coal, so that subsequent increases in carbon injection rates are ineffective at producing additional mercury capture.

The mercury removal limitations observed with DARCO® Hg led to a series of tests with the brominated sorbent, DARCO® Hg-LH. This activated carbon is specifically designed for use in halogen-deficient flue gas; at an injection concentration of 0.6 lb/MMacf, the total mercury removal was 78%. This increased to 97% removal at 3.2 lb/MMacf. The test results clearly demonstrated that enhanced mercury removal performance can be achieved using a bromine-treated activated carbon for sites firing a low-rank coal with an ESP.

Coal Additive KNX™

KNX™ was introduced onto the coal through the foam dust suppression system on the coal belt upstream of the tripper deck and coal bunker during each period of coal loading from September 20 through September 23, 2004. Thus, all coal fired during this period was treated with KNX™. During the final day of KNX™ testing, DARCO® Hg was injected upstream of the ESP to determine if the KNX™ improved the mercury removal effectiveness of the sorbent. Note that the baseline removal in the days leading up to the KNX™ tests was 22 to 34%.

The change in vapor-phase mercury across the ESP can be calculated by comparing the inlet and outlet SCEM concentrations. With KNX™ only, the decrease in the vapor phase mercury content across the ESP ranged from 57 to 64%. KNX™ alone enhanced the effectiveness of the native fly ash at Meramec. When comparing the stack mercury levels to the outlet SCEM, the mercury removal was 88%, indicating that some mercury was already associated with the fly ash at the inlet SCEM location during KNX™ injection.

On the final day of KNX™ testing, DARCO® Hg was injected at the ESP inlet at concentrations from 0.6 to 5 lb/MMacf. The injection concentration of 5 lb/MMacf was held constant for slightly over an hour. The average mercury removal during the testing was 82%. The average vapor-phase mercury removal based upon SCEM measurements during the final 30 minutes of testing at 5 lb/MMacf was 88%. The total mercury content in the coal sample collected was 0.108 µg/g (dry basis), which yields an equivalent total mercury concentration of 12.0 µg/Nm^3 in the flue gas. Thus, the particulate-phase mercury fraction at the ESP inlet was estimated to be around 8.6 µg/g, which represented a total mercury removal of 97%. Also, it should be noted that during KNX™ testing, the fraction of oxidized mercury at the ESP inlet and outlet significantly increased from baseline levels. The average fraction of oxidized mercury at the inlet to the ESP from September 21–23 was 82% versus 20% during baseline testing.

Coal Additive SEA2

The second coal additive tested was SEA2, under development by the EERC. The average total vapor-phase mercury concentrations inlet and outlet of the ESP prior to beginning the SEA2 tests were 4.3 µg/Nm^3 and 3.1 µg/Nm^3 respectively. This represents 27% vapor-phase mercury capture across the ESP. During the first day of testing, SEA2 was introduced at an injection rate of 1.9 lb/hr. The total vapor-phase mercury at the inlet of the ESP decreased from 4.5 µg/Nm^3 to 2.7 µg/Nm^3 and the outlet total vapor-phase mercury decreased from 1.9 to 1.5 µg. On the following test day at an additive injection rate of 5.0 lb/hr, the effectiveness of the SEA2 was more pronounced. The average vapor-phase mercury concentrations at the inlet and outlet prior to SEA2 injection were 8.0 and 3.3 ug/Nm^3 respectively. Following introduction, the vapor-phase mercury concentrations were 2.1 ug/Nm^3 at the ESP inlet and 1.1 ug/Nm^3 (0.86 lb/TBtu) at the outlet. Using 5 lb/hr of SEA2, mercury removal levels reached 52%.

The SEA2 coal additive was tested with DARCO® Hg injection at the ESP inlet. During the activated carbon injection tests, the SEA2 injection rate was maintained at 5 lb/hr and the sorbent injection concentrations ranged from 1.0–2.9 lb/MMacf. Without sorbent injection, SEA2 alone reduced outlet mercury emissions to nominally 1.3 µg/Nm^3

(0.95 lb/TBtu). With the co-injection of DARCO® Hg at the ESP inlet, average outlet mercury emissions dropped slightly to 1.0–1.2 μg/Nm^3. The highest removal rate observed with SEA2 and DARCO® Hg injection was 67%, at 5 lb/hr SEA2 and 1 lb MMacf PAC. The boiler load was not held steady during these tests, so mercury removal level could have been affected significantly by plant operations.

Long-Term Testing

Long-term testing was conducted at the "optimum" settings as determined by the parametric tests and approved by the DOE and AmerenUE/Meramec Station. It was the intent of DOE that these settings represent the most cost-effective conditions for mercury removal. The long-term test period was divided into two phases. For the first phase, the goal was to determine if the sorbent injection concentration could be minimized to maintain ash sales while achieving 60–70% mercury removal. This test was conducted for 5 days. During the second phase, the mercury removal target was 85 to 95%. This phase was conducted for 30 days. The goals of the second phase were to obtain long-term (30-day) data on removal efficiency, determine the effects on the particulate control device, determine the effects on byproducts, evaluate impacts to the balance-of-plant equipment to prove viability of the process, and to determine the process economics. During this test, ASTM M6784-02, M29, and M26A measurements were conducted at the inlet and outlet of the ESP.

After reviewing the parametric testing results, the test team (AmerenUE, ADA-ES, EPRI, and DOE/NETL) agreed to inject DARCO® Hg-LH, a brominated activated carbon, during the long-term testing period based on positive mercury removal performance and cost effectiveness from initial economic analyses.

Continuous sorbent injection began on October 14, 2004, at an injection concentration of 0.5 lb/MMacf. The sorbent injection concentration was adjusted until the total vapor-phase mercury removal was in the desired range (60–70%). Results from this portion of long-term testing indicate a sorbent injection concentration of 1 lb/MMacf yields of 60–70% vapor-phase mercury capture across the ESP.

During the second phase of long-term testing, DARCO® Hg-LH was continuously injected over a 30-day period to achieve an average of > 90% mercury capture across the ESP. The sorbent injection concentration was increased from 2.5 lb/MMacf to 4.5 lb/MMacf over the first four days of testing in order to achieve at least 90% vapor-phase mercury capture. Following four days of Phase II testing, the injection concentration was decreased to approximately 3 lb/MMacf with no significant reduction in the mercury removal across the ESP. A trend graph of the mercury removal and sorbent injection concentration for the Phase I and Phase II test periods is presented in Figure 9.

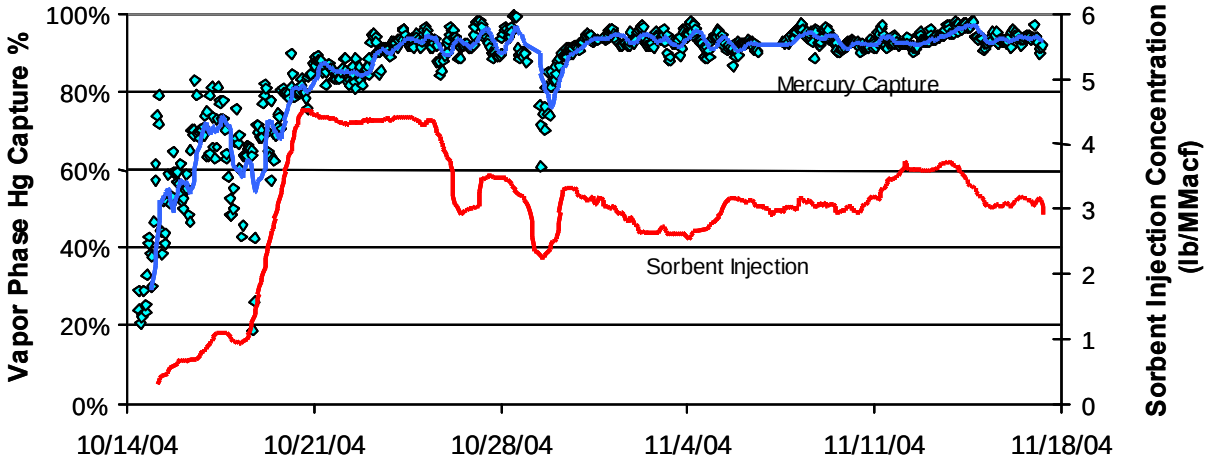


Figure 9. Mercury Removal Trends during Long-Term Testing Series.

The average inlet and outlet mercury concentrations were 8.5 and 0.6 µg/Nm^3 (5.98 and 0.44 lb/TBtu) respectively for the Phase II long-term tests. This yields an average vapor-phase mercury capture of 93% at an average sorbent injection concentration of 3.3 lb/MMacf. This agrees well with the parametric testing results included with the long-term averages shown in Figure 10.

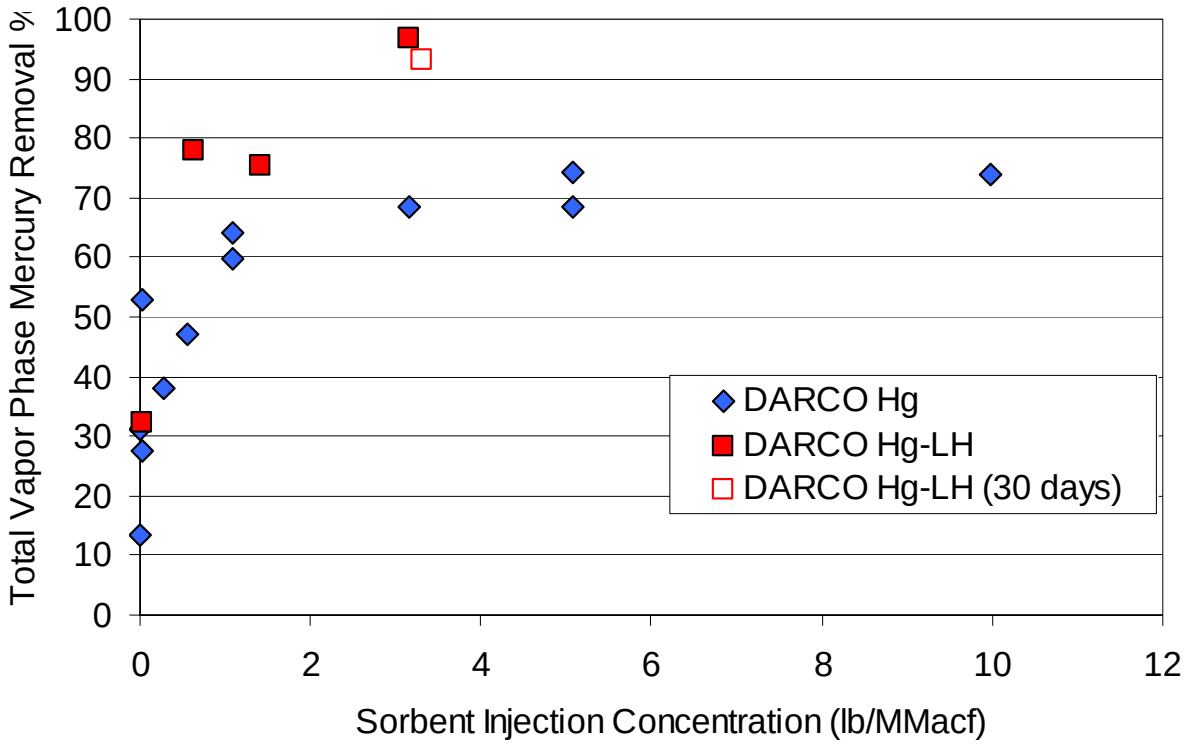


Figure 10. Comparison of DARCO® Hg-LH Results from Parametric and Long-Term Tests.

Balance-of-Plant Impacts

There are two major concerns related to the impact of activated carbon injection on a moderate-sized ESP. The first is the impact on the bulk properties of the ash collected on the plates. A change in the overall resistivity of the material could result in a change in the ESP performance. At all three Phase I test sites with ESPs, there were no changes observed in the fundamental operation of the ESPs.[13] As an example, Figure 11 shows a plot of the ESP power before and during the injection of activated carbon at Dynegy's Brayton Point Station. Even at injection rates up to 20 lb/MMacf, there was no observable change in ESP operation. Similar results were also experienced at Pleasant Prairie and Salem Harbor. These data are available through DOE in the Final Report for the Phase I program.[13]

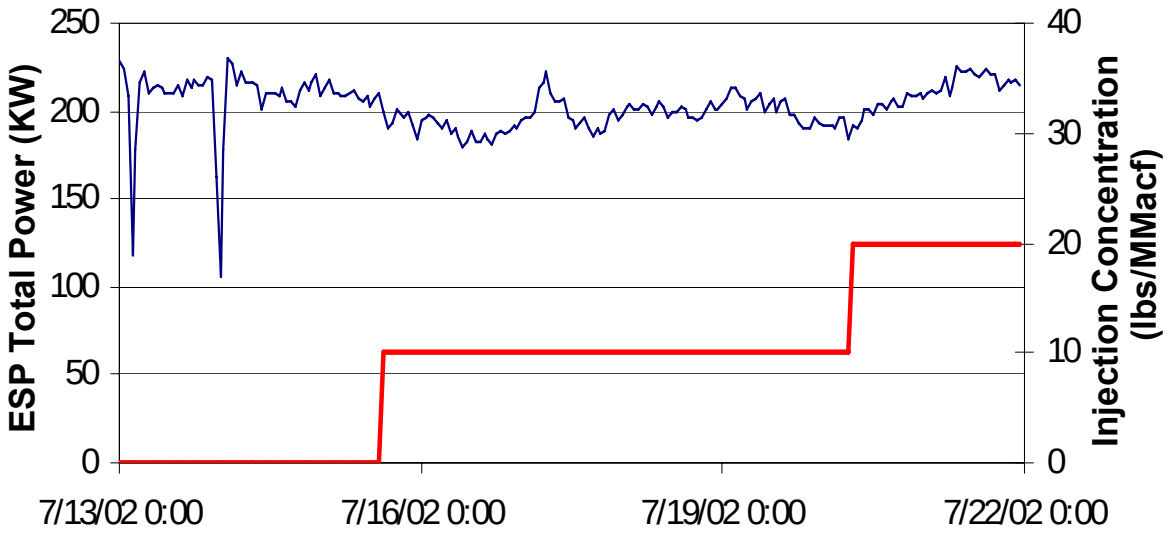


Figure 11. ESP Power during Injection of Activated Carbon at Brayton Point.

The second issue is whether the activated carbon can be effectively captured in the ESP. Plant operating data indicated that there were no increases in opacity during any of the test programs. Typically, the activated carbon represented an increase to the inlet particulate loading of 1–2%. In addition, the activated carbon had a mass median diameter of 17 micrometers, which is not difficult to capture for the medium to large ESPs tested (SCA > 300 ft^2/kacfm). Therefore, no increase in opacity was expected during these tests.

Laramie River

Site Description

Missouri Basin Power Project's Laramie River Station, located near Wheatland, Wyoming, is one of the largest consumer-operated, regional, joint power supply ventures in the U.S. Laramie River Station, which is operated by Basin Electric Power Cooperative, has three units, each with 550 MW of generating capacity, which are fired using PRB coal. The test unit (Unit 3) utilizes an SDA+ESP for air pollution control. The key operating parameters for Laramie River Unit 3 are given in Table 1.

Baseline Mercury Removal

Baseline mercury measurements were made during the first two days of testing. During this period, Unit 3 was held steady at full-load conditions 24 hours a day firing 100% PRB coal. During this period, the total amount of mercury exiting the boiler, assuming no mercury was being removed inside the boiler, was approximately 0.057 lb/hr based on mercury concentrations measured with the SCEMs. Fly ash samples collected from the inlet field of the ESP had an average mercury concentration of 75 ng/g, which is equivalent to a mercury collection rate of 0.0045 lb/hr or an average mercury removal efficiency of 7.9%. This agrees with the removal efficiency measured with the SCEMs of 4.4%. Note that the baseline mercury removal at Laramie River is lower than that of Meramec. Although these stations both fire a low-halogen PRB and use ESPs for particulate control, Laramie River uses a spray dryer while Meramec does not. Tests at Holcomb showed that the lack of halogens from PRB coal and further halogen removal by a SDA can reduce native mercury removal levels as well as those achieved by injection of a standard activated carbon.

Parametric Testing

Following baseline testing, parametric tests was conducted to evaluate various mercury control technologies. The parametric tests were conducted at full-load conditions to document performance of sorbent injection, coal blending and use of a coal additive (with and without ACI), for control of mercury in stack emissions. The primary variables of interest during parametric testing included:

- Sorbent
  - DARCO® Hg
  - DARCO® Hg-LH
- Sorbent Injection Concentration
- Coal Blending
- Coal Additive
  - KNX™

Sorbent Injection

Two sorbents were evaluated at Laramie River Station: non-treated DARCO® Hg, and bromine-treated DARCO® Hg-LH. All tests were conducted at standard full-load conditions.

Vapor-phase mercury removal efficiencies were limited to approximately 50% while injecting the benchmark DARCO® Hg sorbent at injection concentrations up to 6.2 lb/MMacf. Results with DARCO® Hg from other cold-side ESP sites burning low-rank coals (PRB or North Dakota lignite), presented in Figure 12, show similar limitations in mercury capture with this sorbent. Halogen species, such as HCl, are critical for the effective adsorption of elemental mercury by activated carbon. Chlorine concentrations are typically low in low-rank coals (8 μg/g Cl for the PRB used at Laramie River). Activated carbon injection concentrations of 3 to 10 lb/MMacf are sufficient to absorb the available halogens, so subsequent increases in sorbent injection concentrations are ineffective.

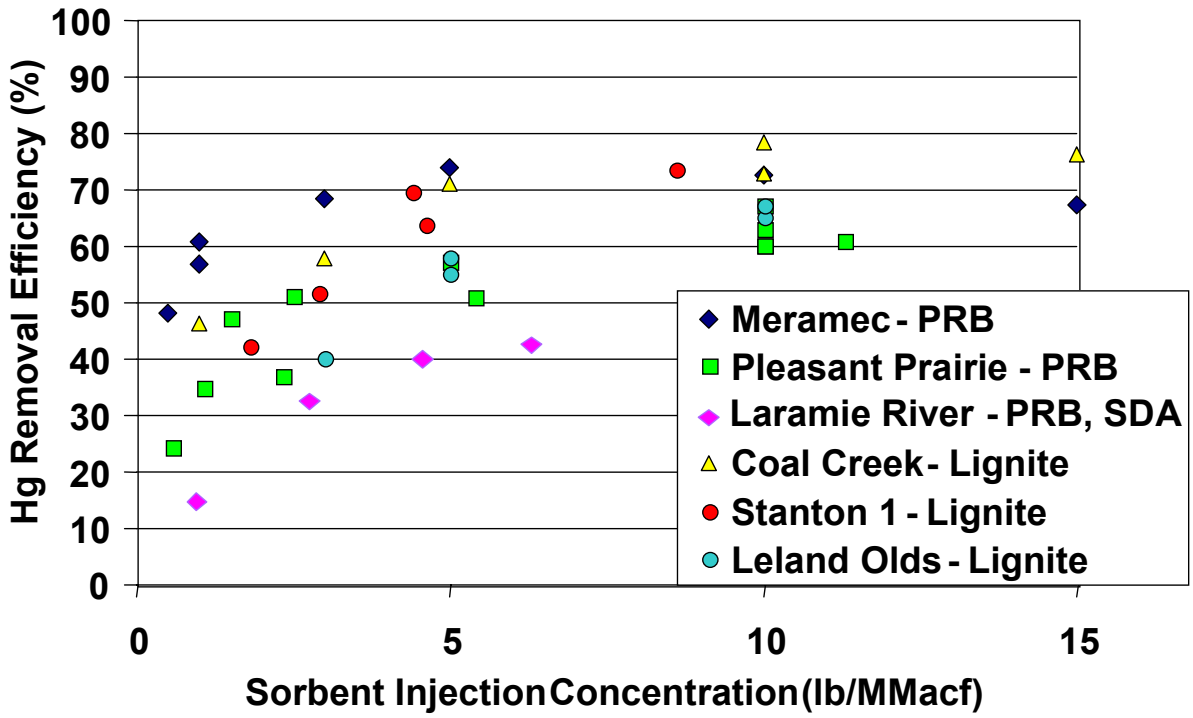


Figure 12. Summary of DARCO® Hg Results on Cold-Side ESPs.

From Figure 12, it is clear that the results at Laramie River showed lower levels of mercury removal than other plants with similar configurations. In part, this may be attributed to the removal of HCl by the spray dryer. Therefore, it was of interest to evaluate the mercury removal level with one untreated carbon, DARCO® Hg, and one brominated carbon, DARCO® Hg-LH. Figure 13 shows the results from the sorbent injection tests with these two carbons. Clearly, there is a significant increase in removal when using the treated carbon. This was also observed at Holcomb, which also has a low-halogen flue gas due to firing with PRB coal and use of a spray dryer.

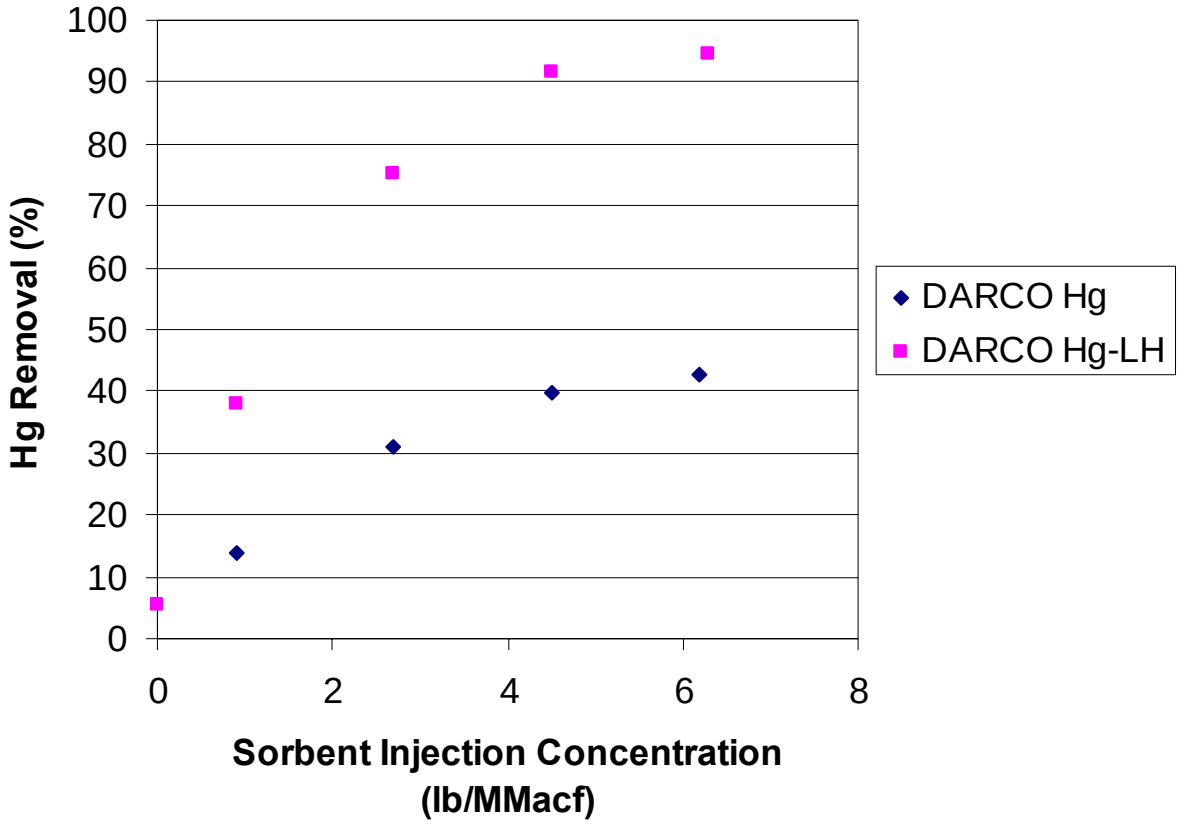


Figure 13. Results from Sorbent Injection Tests at Laramie River.

Coal Blending

During the coal blending tests, two types of western bituminous coals were evaluated at blend ratios of approximately 80% PRB to 20% western bituminous.

While testing at the 80/20 blend ratio with ColoWyo Coal, mercury speciation and mercury removal across the system were similar to baseline measurements. Approximately 2% of the vapor-phase mercury at the SDA inlet was oxidized and 8% was oxidized at the ESP outlet. The total vapor-phase mercury removal was insignificant.

The coal blend ratio for the second blend test was 84% PRB to 16% western bituminous. This coal was from a separate western bituminous mine. Compared to the pure PRB coal, the blend contained 26% more Hg, and 55% less Cl. A few hours prior to the coal #2 blend test, the total vapor-phase mercury removal across the system was approximately 12%. During the coal blend tests, total vapor-phase mercury removal efficiency did not increase above 18%.

Coal Additive With and Without Sorbent Injection

Another option for introducing halogens into the flue gas stream is to treat the coal prior to the boiler. Tests were conducted at Laramie River to determine the effectiveness of KNX™ on native mercury removal and whether the KNX™ additive could enhance the mercury removal of untreated activated carbon.

Unit 3 is a wall-fired unit fed from seven coal feeders. KNX™ was applied at two feeders, 3B and 3C, which supply the lower burner elevations on each side of the boiler. At this location, the treated coal is fired in the boiler within a few seconds after KNX™ was applied. The KNX™ additive was applied at injection rates up to 2.7 gph (0.008 gal/ton coal). Prior to the start of KNX™ testing, the fraction of oxidized mercury at the SDA inlet was 2.4%. While injecting KNX™ onto the coal at a rate of 0.7 gph, the fraction of oxidized mercury at the SDA inlet increased to 4%. At a KNX™ injection rate of 2.7 gph, the fraction of oxidized mercury at the SDA inlet increased to 16%. Although the fraction of oxidized mercury at the inlet of the SDA increased, mercury removal across the system was limited to less than 20%. No mercury removal was noted prior to introducing KNX™. The fraction of oxidized mercury at the outlet of the ESP was also lower than compared to the SDA inlet. This suggests that either KNX™ addition produced a sampling artifact that biased the elemental mercury measurement at the SDA inlet, or the SDA+ESP configuration was reducing oxidized mercury back to the elemental form. This same phenomenon has been observed at Holcomb during KNX™ testing. The final day of KNX™ testing, DARCO® Hg-LH was also injected. There was no increase in mercury removal by combining the KNX™ and the sorbent injection; DARCO® Hg-LH obtained the same level removal with and without KNX™.

The final day of KNX™ testing included the addition of the DARCO® Hg sorbent at the SDA inlet location. The sorbent injection concentration at the SDA inlet was 4.5 lb/MMacf, while the chemical additive flow rate was held steady at 1.6 gph (0.005 gal/ton coal). This combination resulted in a total mercury capture across the system of 94% compared to 50% with DARCO® Hg alone (no KNX™). Notably, there was no difference in performance between pretreating the coal with bromine and pretreating the activated carbon with bromine, since KNX™ with 5 lb/MMacf DARCO® Hg had the same removal rate as injection of 5 lb/MMacf of DARCO® Hg-LH.

Long-Term Testing

No long-term tests were run at the Laramie River site.

Balance-of-Plant Impacts

During parametric testing at Laramie River, no balance-of-plant impacts were noted as a result of sorbent injection or coal additive injection. It should be noted that the tests conducted at Laramie River Station were short, proof-of-concept tests and additional, long-term testing is needed to accurately quantify balance-of-plant impacts.

Low- to Medium-Sulfur Coal with SO_3 Injection

AmerenUE's Labadie Power Plant and DTE Energy's Monroe Station Power Plant were included as host sites in the project because their configuration and operating conditions are similar to many plants throughout the U.S. today. Labadie burns PRB coal, has a series of ESPs and uses SO_3 for flue gas conditioning. Monroe is similar to Labadie in plant configuration, but burns a blend of PRB and eastern bituminous coals. SO_3 can impair the effectiveness of PAC for mercury control. Field testing at these plants lead to important observations concerning mercury removal options in a high SO_3, low halogen flue gas.

Labadie

Site Description

Labadie Unit 2 was chosen for this evaluation because it has a marginally sized, cold-side ESP (SCA = 279 ft^2/kacfm) and it fires a variety of subbituminous coals from the PRB. These coals have chlorine concentrations ranging from 0.01–0.03% and mercury concentrations of 5–12 lb/TBtu. Labadie also injects SO_3 for flue gas conditioning to enhance ESP particulate control. The SO_3 system can also be manually controlled by plant operators 30% (5.2 ppm) to 60% (10.3 ppm). Labadie's configuration allowed for a direct comparison of PAC performance in an SO_3 environment of varying concentration. Key operating parameters for Labadie are given in Table 1.

Baseline Testing

Mercury CEM measurements during the first and second baseline periods indicate that the mercury removal averaged less than 15%. Formal baseline collection data was reinforced by periodic mercury baseline periods collected by the installed CEMs while injection testing was not underway and while test crews were offsite.

Parametric Testing

Following baseline testing, parametric tests were completed at Labadie. The primary variables during parametric testing were:

- Sorbent (and injection location)
  - DARCO® Hg-LH (downstream and downstream of the APH)
  - DARCO® E-25c (downstream of the APH)
  - DARCO® E-26 (downstream of the APH)
  - MS-200 (downstream of the APH)
  - DARCO® Hg (upstream of the APH)
  - FLUEPAC®-MC PLUS (upstream of the APH)
  - Milled DARCO® Hg-LH (upstream of the APH)
  - Milled FLUEPAC®-MC PLUS (upstream of the APH)
- Injection Concentration
- Injection Location
  - Downstream of the APH
  - Upstream of the APH
- Coal Additive
  - KNX™ (tested with injection of DARCO® Hg)
- Trona Injection to decrease SO_3 usage.

Sorbent Injection

When sorbent availability and time allowed, sorbents injection rate and SO_3 concentrations were varied to determine mercury removal effectiveness and to characterize sorbent impact on plant operation. Since Labadie typically injects SO_3 at 30%, when the sorbent supply was limited this SO_3 injection concentration was selected. During the parametric test period, Unit 2 was maintained at standard full-load conditions, about 630 MW_G.

DARCO® E-26™, the bromine-treated carbon with alkali, was the most effective of all the sorbents evaluated during parametric testing at Labadie downstream of the APH. At an injection concentration of approximately 5 lb/MMacf at the APH outlet and nominally 5.2 ppm SO_3, nearly 74% mercury removal was achieved, as presented in Figure 14. Also note that the removal rates of E-26 with 5.2 ppm SO_3 are similar to those of DARCO® Hg-LH with no SO_3 injection (at injection rates of 2 to 5 lb/MMacf).

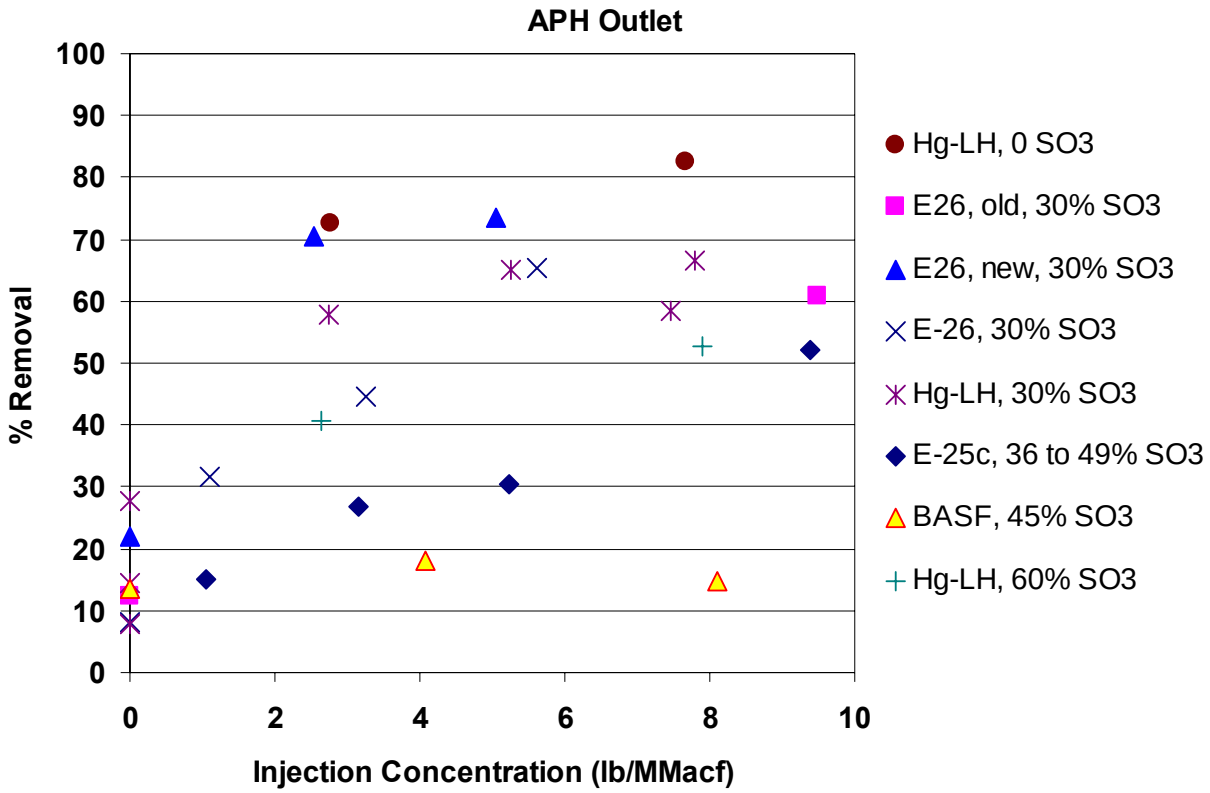


Figure 14. Labadie Fall 2006 Parametric Test Results from Downstream of the Air Preheater and SO_3 Injection.

Evaluations of PAC injection upstream of the air preheater were conducted during both the first stage of parametric testing, between November 2006 and February 2007, and during the second stage of parametric testing, conducted from August to September 2007. FLUEPAC®-MC PLUS, FLUEPAC®-CF PLUS, DARCO® Hg, and DARCO® Hg with the fuel additive KNX™ were evaluated when injected upstream of the APH. A comparison of the performance of Hg-LH™ injected both upstream and downstream of the APH is presented in Figure 15. As shown, the performance of the Hg-LH improved with APH inlet injection for all SO_3 levels tested. This trend may be a result of the additional residence time (roughly 0.5 seconds), increased dispersion as a result of the air preheater, or reactions between the sorbents and mercury prior to SO_3 injection. The impact of SO_3 is also clearly shown in the figure. For example, injecting 5.1 lb/MMacf DARCO® Hg-LH at the APH inlet resulted in mercury removal that ranged from 69% with 10.3 ppm SO_3 to over 90% with the SO_3 injection system off. Injecting at the APH outlet, 53% to 83% with and without SO_3 injection was achieved at 8.1 lb/MMacf. (*Note that all injection concentrations from air preheater inlet injection are calculated using stack temperature.*)

The performance of Hg-LH and the other sorbents are included in Figure 16. During parametric testing, FLUEPAC®-MC PLUS was only evaluated at an SO_3 rate of 30% (5.2 ppm SO_3). At this setting, the performance was similar to Hg-LH. Calgon's ash compatible PAC, FLUEPAC®-CF PLUS was not as effective as Hg-LH. Calgon reported post testing that the batch of FLUEPAC®-CF PLUS sorbent used during Labadie testing may not have been representative of expected production material. The data also indicate that co-injecting DARCO® Hg and the bromine-based coal additive KNX™ at various PAC and SO_3 injection concentrations suggests the addition of bromine to the coal is comparable to injecting chemically enhanced PAC.

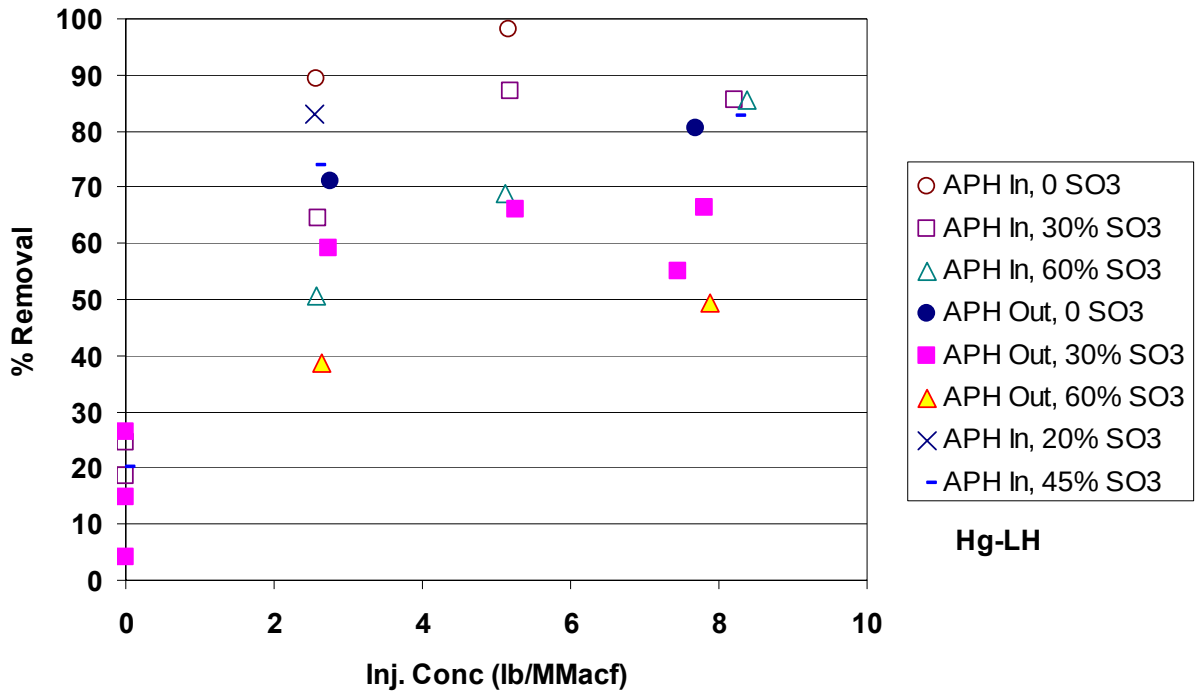


Figure 15. Labadie Parametric Test Results from Hg-LH injected Upstream and Downstream of the Air Preheater.

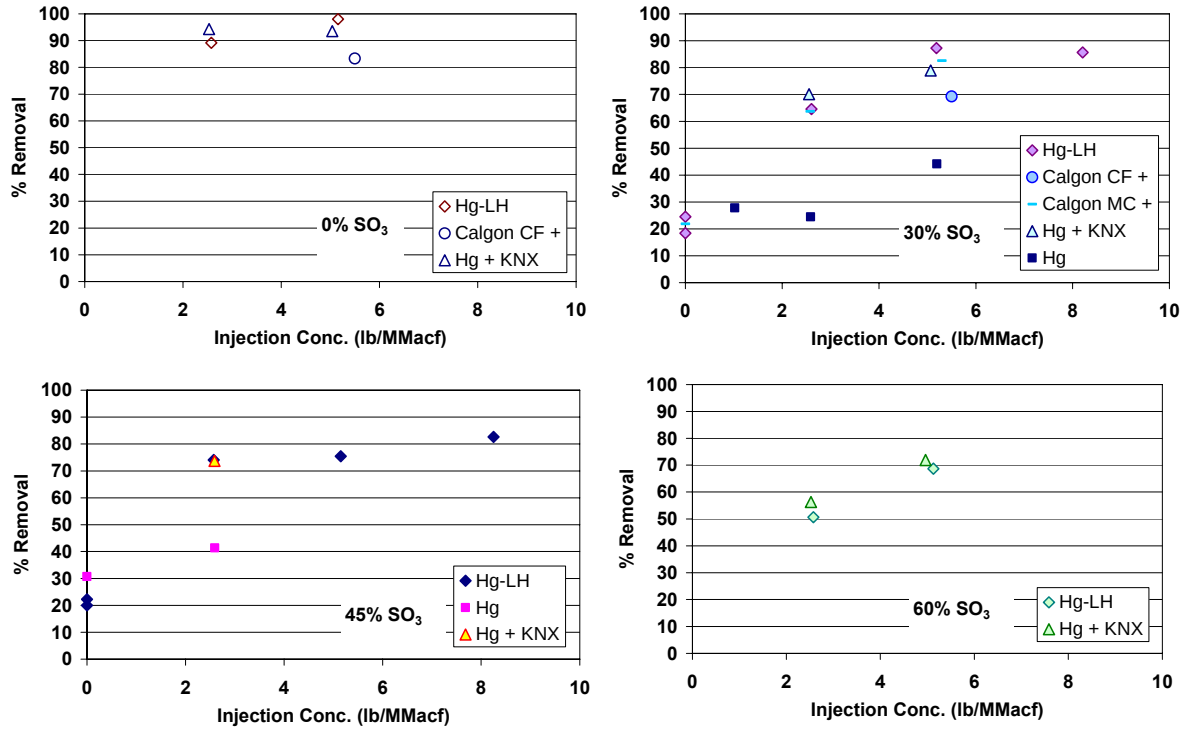


Figure 16. Labadie Parametric Test Results from Upstream of the Air Preheater and the SO_3 Injection Location.

KNX™ Testing

The results with KNX™ testing is included in Figure 16. The coal additive was only used simultaneously with PAC injection. Similar mercury removal levels were observed using both KNX™ and injection of DARCO® Hg to injection of the brominated sorbent DARCO® Hg-LH alone. Clearly the additional halogens are beneficial for mercury control, but both KNX™ and brominated PAC can provide the necessary amounts of bromine. In the 2006 tests, KNX™ with 5 lb/MMacf of DARCO® Hg resulted in over 90% mercury removal with no SO_3 injection. With 30% SO_3 injection (5.2 ppm), but same PAC and KNX™ injection rates, the mercury removal was limited to less than 80%. In 2007, approximately 3 lb/MMacf DARCO® Hg-LH resulted in the same mercury removal levels as KNX™ and DARCO® Hg (also at 3 lb/MMacf).

Trona Injection for Flue Gas Conditioning

Both rounds of parametric testing clearly indicated that mercury removals, during baseline and while injecting PAC, were enhanced without SO_3 injection. Since the particulate control system required the addition to SO_3 to meet permitted particulate levels, Trona was suggested as an alternative conditioning agent. Testing at American Electric Power's Gavin Station suggested that Trona yielded improved ESP performance, as a side reaction, while injecting for SO_3 mitigation.[14] It was anticipated that Trona might be able to provide the necessary conditioning for the ESP through its high sodium content and provide an economical replacement for SO_3 injection at Labadie. However, testing at Labadie revealed that, when used for enhanced particulate control, Trona is unable to increase ESP power levels or decrease opacity as well as SO_3 injection. When the SO_3 flue gas conditioning system is taken to standby mode (off) it was clear that the ESP power levels sharply decreased and opacity began to slowly increase. Since Trona could not increase ESP power levels or decrease opacity as well as SO_3 normally does, no further testing was conducted for this application.

Long-Term Testing

Results from parametric testing indicated that mercury removal efficiencies greater than 85% (combined native and resulting from sorbent injection) could be achieved with standard brominated activated carbons, such as Norit's DARCO® Hg-LH and Calgon's FLUEPAC®-MC PLUS at a target injection concentration of 5 lb/MMacf, with SO_3 injection at 30% (5.2 ppm) and approximately 2 lb/MMacf without SO_3 injection. After reviewing the parametric results, the test team (AmerenUE, EPRI, ADA-ES, and DOE/NETL) agreed to continuously inject MC PLUS during the 15-day extended test period. The mercury emissions goal established by the test team for long-term testing was to maintain an average mercury removal above 85% with the SO_3 system operating at 30%.

Prior to beginning the extended injection period, a short parametric test was conducted with PAC enhanced using the patented ADA-ES on-site milling process. Results indicated that milled PAC may provide increased mercury removal compared to the as-received material. The Labadie test team determined that a greater than 10% reduction in PAC requirements to achieve the same mercury removal would provide an economic incentive to proceed with longer-term tests. To verify the relative difference in performance,

the test team included periods of milled and unenhanced PAC injection during the 15-day period.

The average outlet mercury concentrations, corrected to 3% O_2, were 2.09 lb/TBtu and 1.31 lb/TBtu while injecting as-received and enhanced sorbent, respectively, during the extended injection testing. The average, O_2 corrected to 3%, mercury removal were 73% at 5.5 lb/MMacf for as-received PAC and 83% at 5.0 lb/MMacf for the enhanced sorbent process. The standard PAC injection results differ from previous parametric testing results. During these tests, at an injection rate 5 lb/MMacf a removal of roughly 82% (non-O_2 corrected) was achieved with the MC PLUS sorbent. During extended testing, the as-received material was only able to achieve an average removal of 75% (non-O_2 corrected). The variation in mercury removal could be attributed to quality control issues with the PAC. Specifically, there were large variations in feed rates caused by moisture variations in the sorbent. Variations in moisture content would lead to falsely high feed rates readings while, at the same time, decrease mercury removal because less PAC is actually injected.

The averaged mercury removal data from the 15-day continuous injection tests is presented in Figure 17. To reduce the scatter resulting from the erratic PAC injection rates, only data recorded when the boiler load was greater than 600 MW is included. Data from the extended testing period suggest significant improvement in PAC performance due to on-site sorbent enhancement. The results indicate that 85% mercury removal can be achieved with either 4 lb/MMacf enhanced PAC or 10 lb/MMacf as-received PAC. For Labadie Unit 2, the patented on-site milling process provided a 60% reduction in the amount of PAC required for 83% vapor-phase mercury removal in the presence of 5.2 ppm SO_3. Also, the slope representing the relationship between injection concentration and mercury removal level (in Figure 17) is less steep for the enhanced PAC, indicating that further characterization is warranted at lower injection concentrations to fully assess the benefits of this process.

Throughout the long-term test, mercury measurements were made at the 2A APH inlet and on the stack with CEMs. U.S. EPA Method 5 and 202 measurements were taken at the APH inlet and at the stack during baseline and extended testing periods. An STM relative accuracy check was also conducted on the stack as a backup to the CEM. A discussion of the STM results, including different trap analysis techniques, is included in the site report.[10]

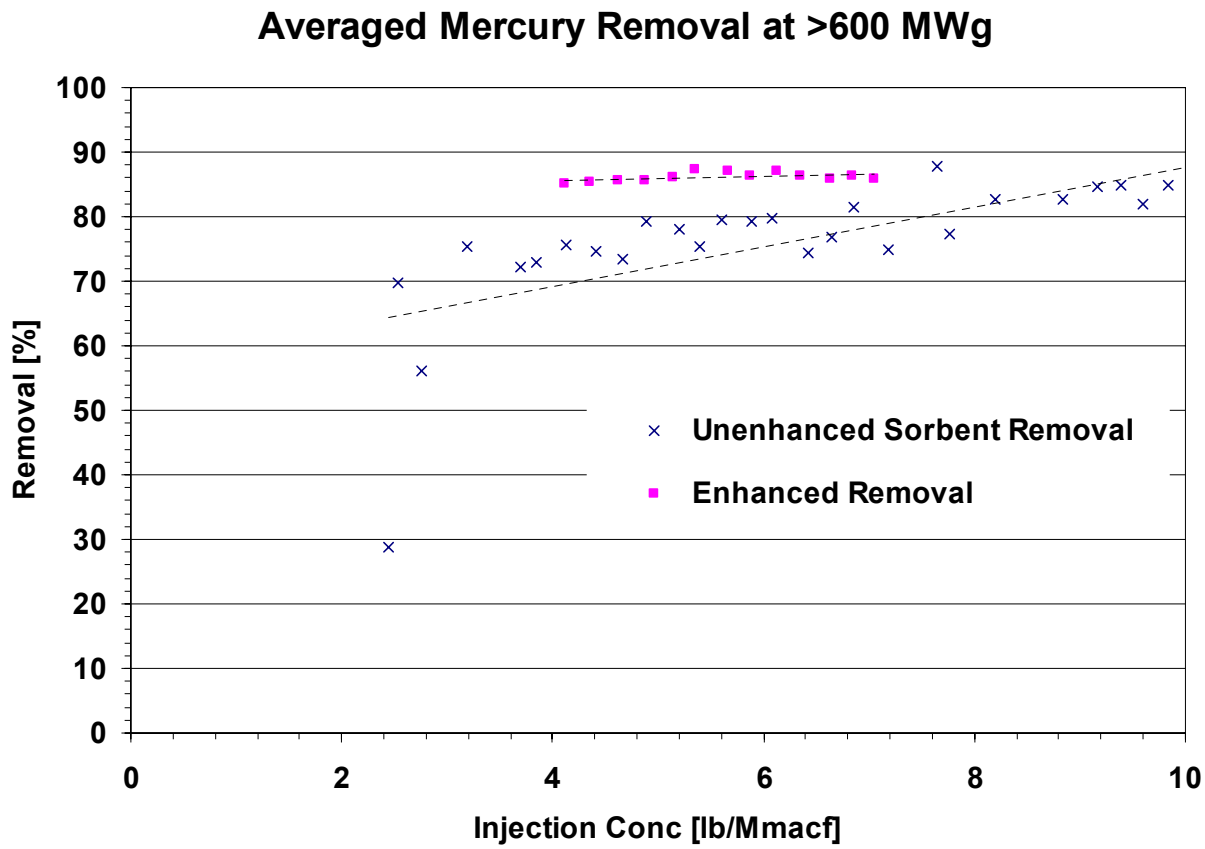


Figure 17. Averaged As-Received vs. Unenhanced PAC Removal at > 600 MW with SO_3 at 5.2 ppm.

Balance-of-Plant Impacts

There was no observable change in the opacity level due to PAC injection during the 15-day test period. In addition, the performance data from the air preheater suggests there was no detectible change in differential pressure during the 15 days of activated carbon injection across it. A longer test is recommended to fully characterize long-term balance-of-plant issues such as air preheater performance issues.

Because of the duration of testing at Labadie Unit 2, only limited conclusions can be made regarding ESP operation. During the 15-day extended test period no degradation of ESP performance was noted. No distinctions in ESP operation between the different sorbents during parametric testing or while injecting for 15-days continuously could be made, as any effects appear to be too subtle. The short-term impacts on the ESP due to carbon injection appear to be minimal.

From the second round of parametric testing, it appears that alkaline materials may absorb some of the SO_3 before it has time to react with the fly ash. The removal of SO_3 increases ash resistivity, which slightly increases TR-set sparking. Due to the increased sparking, overall power to the ESP is lowered. The overall power reduction is too minute to affect opacity in the short-term. Only when the SO_3 system is taken out of service does the opacity increase significantly. However, during testing with reduced SO_3, there were times

when the system could be operated for several hours with the SO_3 system at 0%. At other times it could only be operated for less than an hour before opacity problems arose. Therefore, it can also be concluded that opacity issues are driven by fuel source as well as plant operations.

Monroe

Site Description

Monroe Unit 4 was chosen for this evaluation because it has a marginally sized, cold-side ESP (SCA = 285 ft^2/kacfm) and it fires a blend of PRB and bituminous coals. This combination allowed an evaluation of the effects of sorbent injection and coal blending on mercury control and ESP performance for an ESP that represents the size of many units in the industry. Another key feature of Monroe Unit 4 is that it uses an SCR system during the ozone season. SCR systems are becoming more common in the industry as many U.S. utilities are required to reduce NO_x emissions. Testing at Monroe evaluated the effects of using an SCR system on mercury speciation and sorbent performance. In addition, Monroe uses SO_3 for flue gas conditioning, which presents a challenge for mercury removal technologies. Table 1 gives the key operating parameters for Monroe.

Baseline Testing

Because Monroe uses a SCR part time, and is often blending coal, baseline tests to determine native mercury removal were conducted under the following range of operating conditions:

- SCR in bypass
- SCR in service
- Coal blending

The baseline data were used to characterize native mercury capture across the ESP while no sorbent was injected, and to determine the impact of the SCR on mercury oxidation and removal. During the first two days of each baseline test period, Unit 4 was maintained at standard full-load conditions, about 775 MW_E. During the SCR bypass baseline test period, the coal blend was adjusted to evaluate the effects on native mercury removal at various coal blend ratios without sorbent injection.

Comparison of the three measurement methods with data at the inlet and outlet of the ESP (Ontario Hydro, SCEM, and coal minus ash) suggests that the mercury removal across the ESP was less than 35% during both test periods. In general, the methods suggest that the mercury removal was slightly worse when the SCR was online than while it was bypassed. Potential contributors to a slight difference in baseline mercury removal include temperature, LOI, SO_3, or chlorine. While the SCR was bypassed, the average duct temperature based upon plant operational data was 274 ºF compared to 268 ºF with the SCR online, a difference that does not support the observed difference in mercury removal. The average inlet-field LOI during the March tests was 3.6% compared to 2.9% for the May tests. Lower LOI can result in lower mercury removal. SO_3 measurements were unreliable, but SCRs can increase the SO_3 concentration, which can negatively impact mercury removal effectiveness of ash and sorbents. Finally, the only notable difference in the coal collected during these two test periods was the chlorine, with the earlier sample indicating higher chlorine. The PRB coal

contained nominally 10 ppm, while the bituminous coal typically contained more than 500 ppm chlorine. A higher percentage of bituminous coal in the blend resulted in a higher chlorine content of the flue gas. However, the sulfur of the bituminous was also significantly higher than that of the PRB, 0.72% (by weight) and 0.04%, respectively.

The fraction of elemental mercury as measured using the SCEM was between 20 and 40% of the overall vapor-phase mercury measured in the flue gas at the inlet and outlet of the ESP while the SCR was offline. When the SCR was brought into service, the fraction of elemental mercury in the flue gas dropped below 10%. This indicates that the SCR is effective at oxidizing mercury in Monroe flue gas. The higher fraction of oxidized mercury did not have a significant impact on the native capture of mercury.

The coal blend ratio was varied while the SCR was offline from 60% PRB/40% bituminous to 70% PRB/30% bituminous. No significant changes in mercury speciation or removal were noted.

Parametric Testing

After the completion of baseline tests, parametric tests were conducted to evaluate mercury removal levels using various options. At Labadie, the variables for the parametric tests were:

- Sorbent (SCR status)
  - DARCO® Hg (SCR bypassed and in service)
  - DARCO® Hg-LH (SCR bypassed)
  - DARCO® XTR (SCR in service)
  - NEST (SCR in service)
- Injection concentration
- SCR
  - Bypassed
  - In-service

Parametric testing was conducted during two periods: 1) from March 29–31, 2005, before the SCR was brought online, and 2) from May 23–26, 2005, after the SCR was in-service. Due to reduced demand, the parametric tests during this period were conducted with 65% PRB. While the SCR was in bypass, the balance of the coal was 20% mid-sulfur bituminous, and 15% low-sulfur bituminous coal. After the SCR was brought online, the balance of the coal was all mid-sulfur eastern bituminous. Each injection concentration tested was held steady for a minimum of two hours to allow the system to reach equilibrium. Two sorbents were evaluated at several injection concentrations during the SCR bypass test period (and) and three while the SCR was in-service (DARCO® Hg).

The DARCO® Hg and DARCO® Hg-LH sorbents were evaluated at 1, 3, and 6 lb/MMacf during both test periods. The baseline (no sorbent injection) vapor-phase mercury removal was measured at the beginning of each injection test day. The inlet mercury during both test weeks was fairly steady, with an average concentration of

11.4 lb/TBtu while the SCR was in bypass and 7.6 lb/TBtu while the SCR was in-service. Prior to bringing the SCR in-service, the mercury removal before each parametric test was nominally 40% at the beginning of each test. During the high injection concentration DARCO® Hg test with the SCR in bypass, the outlet mercury concentration began to trend down to 5 lb/TBtu, resulting in 58% native mercury removal. While the SCR was in-service, the native mercury removal ranged from 18 to 32%.

Results from these tests as shown in Figure 18 demonstrate similar performance between the DARCO® Hg and DARCO® Hg-LH with the SCR in bypass. In addition, DARCO® Hg performed essentially the same whether the SCR was in-service or in bypass. Performance of the DARCO® XTR (a cheaper, lower quality grade material than the benchmark DARCO® Hg) was similar to the other Norit products at 3 lb/MMacf, but was measurably less efficient at removing mercury at an injection concentration of 6 lb/MMacf. The non-carbon sorbent, NEST, demonstrated poor removal (10% at 5 lb/MMacf). In order to compare the relative performance of the sorbents, Figure 18 shows only removal associated with sorbent injection and does not include any baseline removal.

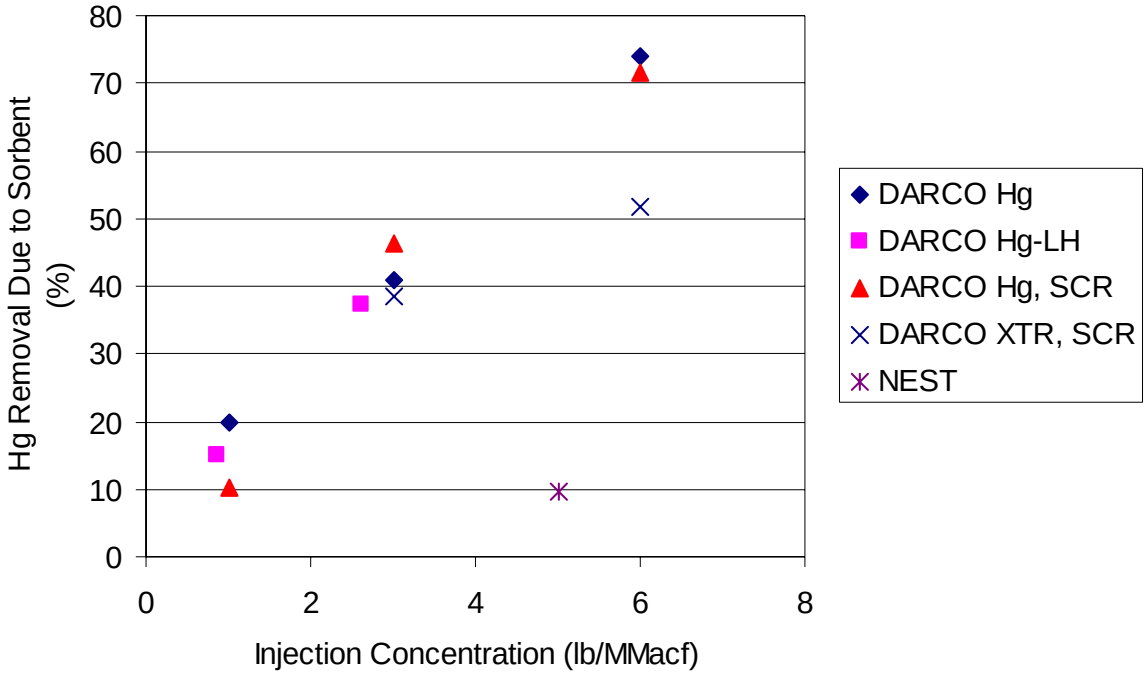


Figure 18. Results of Parametric Testing: Mercury Removal due to Sorbent.

The flue gas at Monroe, due to the addition of eastern bituminous coal to the PRB coal, differs in two key respects from 100% PRB coal that can affect the performance of mercury sorbents: 1) the flue gas HCl is higher, which should improve the performance of untreated activated carbon, and 2) the SO_2 and SO_3 concentrations are higher, which can be detrimental to the mercury removal performance of activated carbon. Monroe also used SO_3 for flue gas conditioning. Specifically, when the SCR was bypassed, the inlet and outlet concentrations of HCl were 83,000 and 64,000 lb/TBtu, respectively. When the SCR was in service, the HCl concentrations at the inlet and the outlet were 49,000 and 39,000,

respectively. For reference, the HCl concentration at the outlet ranged from 41 to 67 ppm. The reported SO_3 concentration varied from 1.7 to 12.7 ppm in the samples collected.

Results from DARCO® Hg testing at Monroe indicate that the mercury removal at low injection concentrations is lower than at other sites tested that fire 100% PRB coal. This is shown in Figure 19**,** where data from We Energies Pleasant Prairie Power Plant, AmerenUE's Meramec Station, and Dominion's Brayton Point Station are shown for comparison.[13] The slightly lower removal at low injection concentrations at Monroe compared to Meramec and Pleasant Prairie may be a symptom of the higher SO_2 levels in the flue gas at Monroe or a result of SO_3 injection used at Monroe to improve ESP performance. However, the mercury removal continued to improve with increasing activated carbon concentrations, suggesting that sufficient halides, such as HCl, were available for continued effectiveness of the activated carbon beyond what was possible at the PRB-fired sites. The higher mercury removal at Monroe than at Brayton Point may be a result of lower SO_2 or SO_3 levels at Monroe.

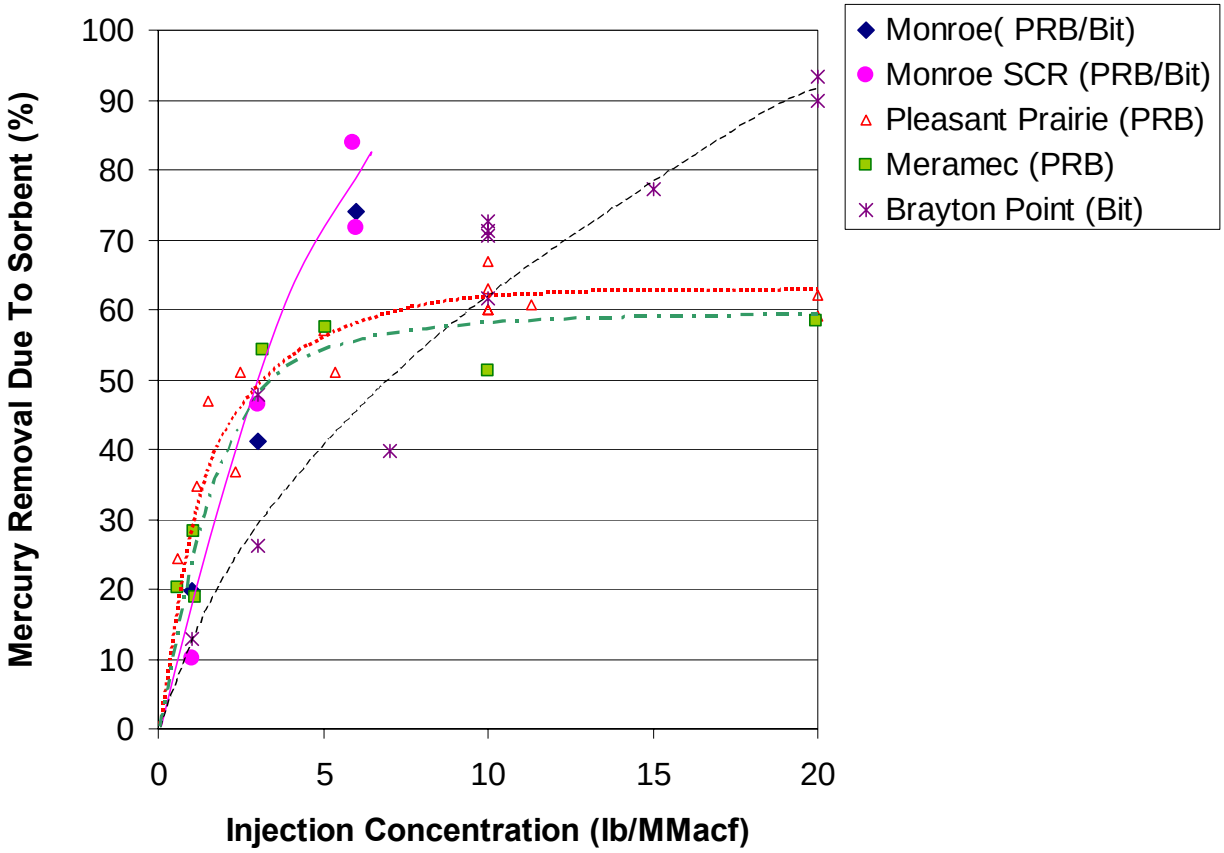


Figure 19. Summary of DARCO® Hg Results at Monroe, Meramec, and Brayton Point.[13]

Additional evidence of the potential impact of SO_3 on mercury removal performance can be observed when comparing data from Monroe with data from DTE's St. Clair Station. These data, presented in Figure 20, show that a brominated carbon was able to achieve more than 80% mercury removal at 2 lb/MMacf. This carbon, BPAC, has shown similar

performance to DARCO® Hg-LH at other test sites, suggesting something in the flue gas at Monroe is impeding performance. It is likely that this is SO_3. It is also possible that sorbent distribution affected sorbent requirements at Monroe.

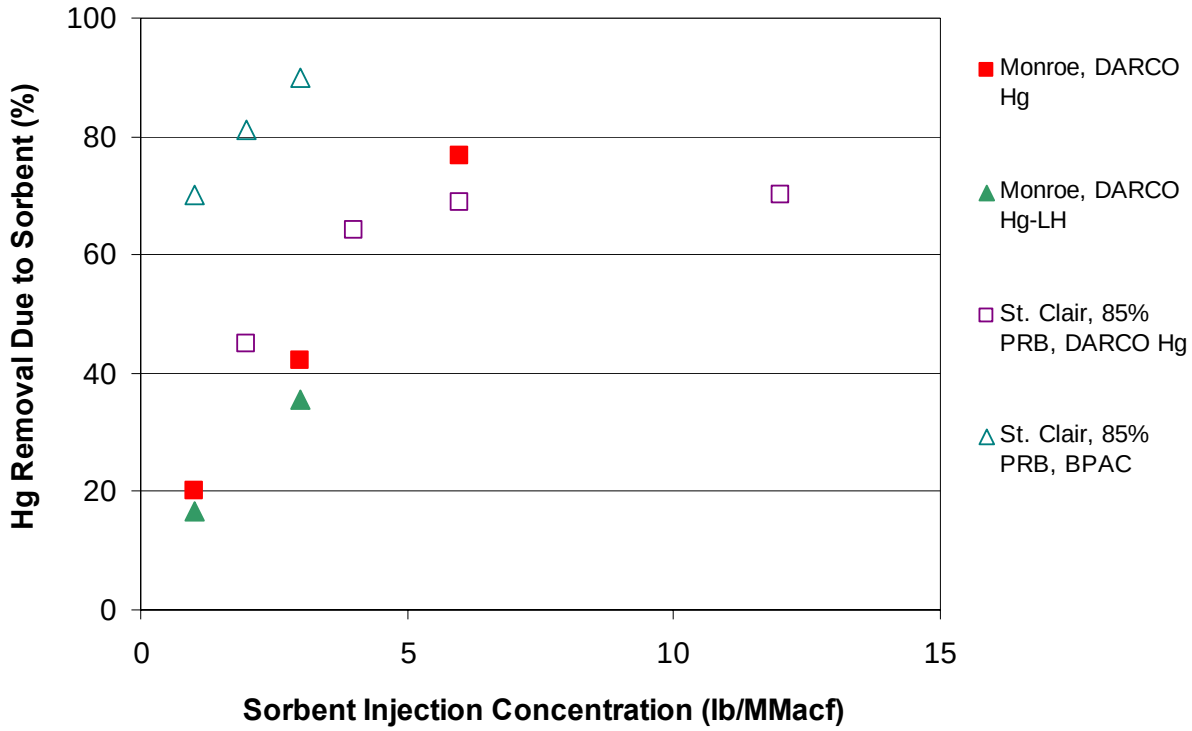


Figure 20. Comparison of Parametric Test Results at St. Clair and Monroe Stations.

Long-Term Testing

Results during the parametric testing series showed that mercury removal efficiencies greater than 80% (combined native and resulting from sorbent injection) could be achieved with DARCO® Hg at an injection concentration of 6 lb/MMacf, and that DARCO® Hg-LH did not demonstrate improved performance. They also showed that the SCR did not significantly impact mercury capture. After reviewing these results, the test team (DTE, ADA-ES, EPRI, and DOE/NETL) agreed to continuously inject DARCO® Hg during the long-term testing period. The mercury emissions goal established by the test team at the onset of long-term testing was to maintain the average outlet mercury emissions for the period below 1 lb/TBtu.

The average outlet mercury concentration was 0.91 lb/TBtu during periods of sorbent injection for the long-term tests. The average mercury emissions were 1.15 lb/TBtu for the entire 30 days. This yields an average vapor-phase mercury capture of 87% while the feeder was operating, or 84% for the entire 30-day period. The average sorbent injection concentration was 5.9 lb/MMacf for the 30-day period. This agrees well with the parametric testing results as shown in Figure 21. It is likely that higher mercury capture could have been achieved if the sorbent distribution was optimized.

The average mercury in the inlet fly ash samples collected with the sampling cyclone was 1.2 lb/TBtu, for an estimated 19.4% baseline mercury removal. Therefore, the additional mercury removal due to the introduction of sorbent was 82% during periods while the feeder was operating (80% for the entire 30-day period).

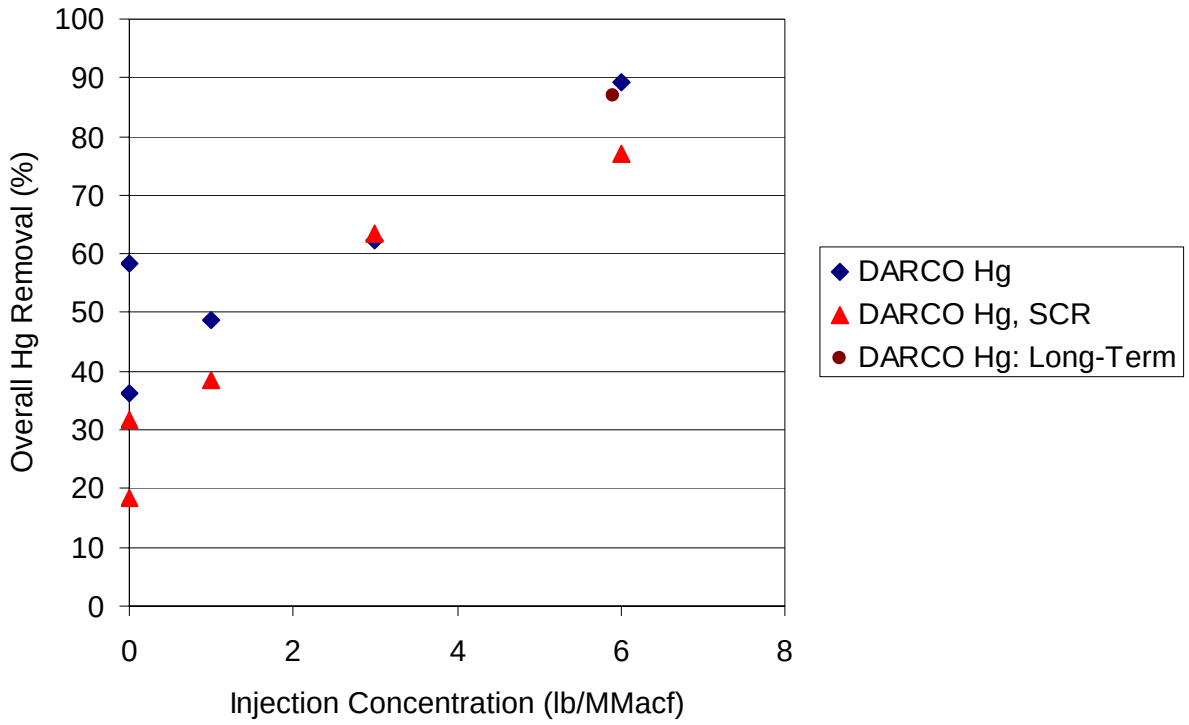


Figure 21. Thirty-Day DARCO® Hg Injection Test Results from Monroe Compared to Parametric Results. Removal shown includes both Native Capture and Sorbent Capture.

Balance-of-Plant Impacts

Two key concerns related to ACI with a moderate-sized ESP are the impact on the bulk properties of the ash and the ability of the ESP to collect the PAC (no increase in opacity). A change in the overall resistivity of the material could result in a change in the ESP performance. The ESP spark rate and power were monitored closely during testing. No change was a noted as result of sorbent injection. Plant operating data indicated that there were no increases in opacity during any phase of the test program. At Monroe, an injection concentration of 6 lb/MMacf represents an increase in the overall particulate loading of nominally 2%. DARCO® Hg activated carbon had a mass median diameter (MMD) of 17 micrometers, which should be readily captured in the ESP. No increase in opacity was expected during these tests, especially because only one-eighth of the gas stream was evaluated.

Assuming the collection efficiency for fly ash was 80% per field, the calculated collection efficiency of unburned carbon during the baseline test period ranged from 59 to 69% (average 64%). During the long-term period, the collection efficiency for PAC + unburned carbon ranged from 69 to 75% (average 72%).

Calculating the relative collection efficiency of carbon is valuable, because it can provide insight into potential increases in particulate emissions resulting from PAC injection. For example, at Monroe during the long-term tests, the injection concentration averaged 5.9 lb/MMacf. If each of three fields captures 72% of the incoming carbon, the estimated increase in outlet emissions is 0.13 lb/MMacf, or 0.00091 gr/acf. Although the projected increase in emissions of 0.00091 gr/acf represents 9.2% of the baseline particulate emissions, it is well within the standard deviation of six measurement runs and may be difficult to measure accurately using a batch method.

High-Sulfur Coal

Mercury control at plants that burn high-sulfur coal is particularly challenging because of the high SO_3 content in the flue gas. AEP's Conesville Station was included in the testing program because it has a flue gas representative of those plants with high-sulfur flue gas that will meet with difficulty trying to use ACI for mercury control.

Conesville

Site Description

Conesville Unit 6 is a 400-MW, Combustion Engineering, tangentially fired, PC unit that normally fires high-sulfur (3.31% by weight) eastern bituminous coal. This unit is equipped with cold-side Research-Cottrell ESPs. Flue gas is drawn through the ESPs via Induced-Draft (ID) fans. Downstream of the ESP and ID fans are two Universal Oil Products wet lime absorber modules (WFGD) for SO_2 removal. The modules have partial bypass capability and have been retrofitted with a Babcock & Wilcox tray design. The system is typically operated with the bypass closed. The bypass valves have a design leak rate of 5% of the flow. Key operating parameters are listed in Table 1.

Baseline Testing

The ESP inlet and outlet CEM values trended well together given the considerable variability in the mercury concentrations over the course of the week (14 to 40 $\mu g/m^3$). The CEM and Ontario Hydro measurements indicate little mercury removal across the ESP. Analyses of ash collected during the baseline test also show low mercury removed across the ESP. The Ontario Hydro data indicated 37% removal across the WFGD, while the CEMs data showed 60%. This suggests that most of the oxidized mercury is removed in the wet scrubber. The CEM elemental mercury at the ESP outlet was low compared to the Ontario Hydros.

Parametric Testing

The baseline tests revealed that the wet scrubber at Conesville is able to remove most of the oxidized mercury. The goal of the parametric testing was to increase the mercury removal levels, including both elemental and oxidized mercury, upstream of the wet scrubber. The variables during parametric testing were:

- Sorbent (17 tested, see Figure 22)
- Sorbent Injection Concentration

Figure 22 is a compilation of all parametric full-scale test results. Mercury removal efficiency across the ESP ranged from 5 to 31% at injection concentrations of 9 to 18 lb/MMacf for all sorbents tested at full-scale. Injection tests at 9.5 lb/MMacf with DARCO® Hg resulted in only 8% removal. The highest removal attained was 31% using DARCO® E-12 at 12 lb/MMacf. The next-highest removal was 25% using Sorbent Technologies EXP-2 at 10 lb/MMacf. Although the injection concentrations varied widely, the results indicate that none of the sorbents were able to achieve the minimum mercury removal goal of 50% at an injection concentration below 10 lb/MMacf. During several later tests, the open-ended, dual-injection lance configuration was used on the B-Side of the duct. No significant difference in performance was noted between the half-duct, open-ended nozzle tests and tests across the entire duct with the multi-nozzle lance configuration.

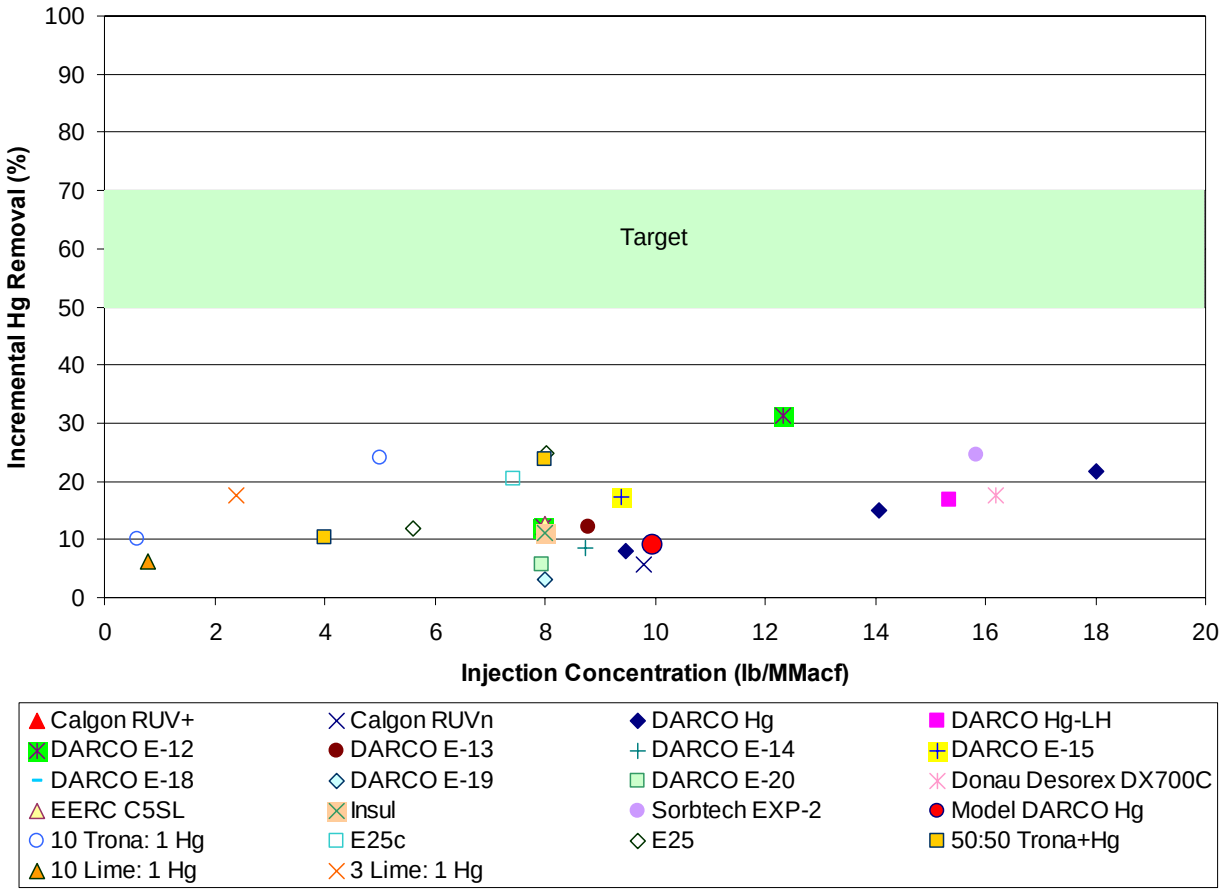


Figure 22. Parametric Results for Full Scale Testing at Conesville Unit 6.

Long-Term Testing

No long-term tests were conducted at Conesville.

Balance-of-Plant Impacts

The two key concerns related to sorbent injection for mercury control is the impact on the ESP sparking and potential increases in capacity. For most sites tested during this program, there were little to no notable balance-of-plant impacts. However, Conesville was a

unique case; the higher rates of injection and different types of sorbents led to more significant impacts when compared to the other plants included in the program.

During sorbent injection at Conesville, most of the sorbents tested resulted in increased sparking in the ESP. Moreover, spark rate generally increased as sorbent concentration increased. One theory that may explain the impact of sorbent in ESP performance is the interaction of the sorbent with SO_3. SO_3 concentration affects the resistivity of the fly ash and the resulting behavior of the ESP as ash is collected. The instantaneous duct opacity was monitored closely during injection tests.

The average duct opacity on the A-Side (west) and B-Side (east) ducts was recorded for one hour before each injection period, as well as during the injection periods. DARCO® E-12, the sorbent with the highest mercury removal efficiency, also caused the largest increase in duct opacity (A-Side increased from 4.0% to 6.6% and the B-Side increased from 5.9% to 10.2%). The average opacity was unchanged or decreased when most of the other sorbents were injected. Although the opacity was relatively unchanged, the maximum opacity spikes increased significantly for several sorbents, especially when these materials were injected at concentrations greater than 10 lb/MMacf.

Cost Analysis

Sorbent Injection

A detailed cost analysis was for the implementation of ACI for mercury control was performed for each site except Conesville and Laramie River Station based on plant conditions and results. Fewer test results were available at Laramie River, thus a less detailed cost analysis was performed for this site. No cost analysis was performed for the Conesville site. Although the exact costs for mercury removal will be site specific, the results of this program provide important information about costs related to implementing commercial scale mercury control for configurations that represent most coal-fired plants in the U.S. The plant configuration, coal type, mercury control implemented (coal blending, additive, ACI), and PAC used all had a significant effect on mercury removal levels. For all cost analysis details, please see the specific site reports.[5–10]

Costs for the PAC storage and injection equipment are provided by ADA-ES based on the design requirements. ADA-ES has built and installed systems at several coal-fired power plants for mercury control. Estimated costs for the distribution manifold, piping and injection lances, installation man-hours and crane-hour estimates, and an estimate for foundations including pilings are also included.

EPRI TAG methodology was used to determine the indirect costs. A project contingency of 15% was used. Because the technology is relatively simple and well proven on similar scale, the process contingency was set at 5%. PAC equipment can be installed in a few months; therefore, no adjustment was made for interest during construction, a significant cost factor for large construction projects lasting several years.

Operating costs include sorbent costs, electric power, operating labor, maintenance (labor and materials), and spare parts. An average requirement of one hour per day was

estimated to cover the incremental labor to operate and monitor the PAC system. The annual maintenance costs were based on 5% of the uninstalled equipment cost. Levelized costs were developed based on a twenty-year book life and are presented in constant dollars.

Data collected from the Phase I DOE tests at Gaston indicate mercury removal levels of up to 90% were obtained with COHPAC® (a baghouse installed downstream of an ESP) and DARCO® Hg sorbent injection. At Pleasant Prairie, 50–70% removal while injecting DARCO® Hg was the maximum achievable mercury control, with the configuration of an ESP collecting PRB ash. At Brayton Point, mercury removal levels of up to 90% were obtained with an ESP collecting bituminous ash with DARCO® Hg sorbent injection.[13]

DOE Phase II testing at Holcomb showed mercury removal levels of 90% were obtained with an SDA and FF while injecting DARCO® Hg-LH. Data from Meramec also showed mercury removal levels of 90% with DARCO® Hg-LH and an ESP. The results from Meramec indicate that using DARCO® Hg-LH would result in higher mercury removal (90%) at less than the cost of the maximum achievable removal at Pleasant Prairie (67% mercury removal). Both units fire PRB coal and have ESPs installed for particulate control. The critical difference in the sorbent costs is the improved effectiveness of DARCO® Hg-LH over DARCO® Hg. Testing at Labadie showed mercury removal levels of 80% with DARCO® Hg injection at 6.0 lb/MMacf. Table 5 and Figure 23 summarize the results, in terms of the relationship between mercury removal sorbent costs. The sorbent costs presented in Table 5 were carried over from those presented in the respective Topical Reports and have not been updated into present day dollars.

Table 5. Summary of Mercury Removal Efficiencies and Costs for Different Air Pollution Control Configurations, Coals, and Sorbents.

Plant	APC Equipment	Coal	Sorbent	Removal %	Sorbent Cost (mills/kWh)
Gaston	COHPAC®	Bituminous	DARCO® Hg	90	0.43
Pleasant Prairie	ESP	PRB	DARCO® Hg	67	1.2
Brayton Point	ESP	Bituminous	DARCO® Hg	90	2.4
Holcomb	SDA+FF	PRB	DARCO® Hg-LH	90	0.44
Meramec	ESP	PRB	DARCO® Hg-LH	90	0.74
Laramie River	ESP	PRB	DARCO® Hg	90	
Monroe	ESP	PRB/Bit. Blend	DARCO® Hg	80	0.85
Conesville	ESP	Bituminous	DARCO® Hg	35	N/A
Labadie (as-received PAC)	ESP with 5.2 ppm SO_3 FGC	PRB	DARCO® Hg-LH	75	1.21
Labadie (enhanced PAC)	ESP with 5.2 ppm SO_3FGC	PRB	Calgon MC-PLUS	85	1.02

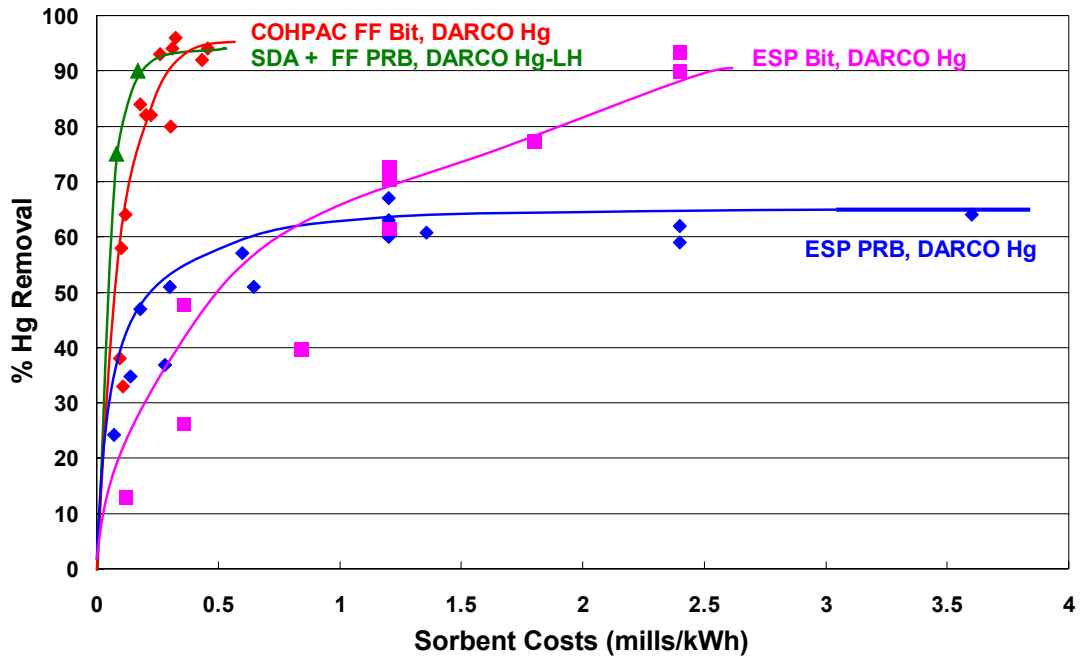


Figure 23. Comparison of Projected Annual Sorbent Costs for ESP, COHPAC® Fabric Filter, and SDA+FF Configurations based on Results from NETL Full-Scale Tests.

The cost of process equipment sized and designed based on the long-term test results for approximately 90% mercury control, and on the plant-specific requirements (sorbent storage capacity, plant arrangement, retrofit issues, winterization, controls interface, etc.) have been estimated. The system design was based on the criteria listed in Table 6.

Over 90% mercury removal can be achieved at several different plant configurations at a low annual sorbent cost. For example, results have shown that plants firing bituminous coal, with a COHPAC® fabric filter, can achieve over 90% mercury removal with an annual sorbent cost of approximately 0.5 mills/kWh. Similar results were achieved for plants firing PRB coal, with and SDA, fabric filter, and injecting DARCO®.

The capital and operating costs for installation and use of commercial ACI systems for the test sites are given in Table 6. The capital and operating costs presented in Table 6 were carried over from those presented in the respective Topical Reports and have not been updated into present day dollars.

Table 6. Cost Analysis for Commercial Mercury Removal Systems and Operation.

Parameter	Holcomb	Meramec	Laramie	Labadie	Labadie	Monroe
Hg Removal Level	>90%	90%	90%	75%	85%	80%
Number of silos	1	1	1	1	1	2
Number of injection trains	2 operating, 1 spare	2 operating, 1 spare	2 operating, 1 spare	2 operating, 1 spare	2 operating, 1	4 operating, 2 spare
Design feed capacity/train (lb/hr)	600	600	1060	700	700	520
Operating feed capacity/train (lb/hr)	43	55	600	660	528	325
Estimated Feed (lb/MMacf)	1.2	3.3	3.3	5	4	6
Sorbent storage capacity (lbs)	70,000	70,000	*	35,000	35000	456,000
Conveying distance (ft)	200	150	*	200	200	200
Sorbent	DARCO® Hg	DARCO® Hg-LH	DARCO® Hg	Milled MC-Plus	MC-Plus	DARCO® Hg
Costs						
Uninstalled Equipment Costs	$710,000	$964,000	$750,000	$1,100,000	$1,700,000	$1,769,000
Installed Equipment Costs	$1,309,000	$1,285,000	*	*	*	$3,006,000
Capital Cost	$3.64/kW	$9.17/kWh	*	$1.68/kWh	$2.69/kWh	$3.87/kW
Annual Sorbent Costs	$467,000 (85% capacity factor)	$778,200	$4,800,000	$5,161,000	$4,128,000	$5,308,000
Sorbent Cost (mills/kWh)	0.44	0.74	*	1.21	1.02	0.85
O&M	$1.54/kW	$6.17/kW	*	$8.2/kW	$6.55/kW	$7.06/kW
Increase in annual landfill/waste costs	Low	$1,070,000	*	$500,000	$500,000	Low
Sorbent cost reduction for DARCO® Hg-LH instead of DARCO® Hg	67%	N/A	N/A	N/A	N/A	N/A
Total Cost ($/lb Hg)			3,980	10,900	9,100	18,000
20-yr Levelized Costs						
	Holcomb	**Meramec (including lost ash sales)**	**Laramie**	**Labadie (As Received PAC)**	**Labadie (Milled PAC)**	**Monroe**
Fixed Costs	$153,000	$150,000	*	$125,000	193,000	$352,000
Variable O&M	$704,000	$2,231,000	*	$5,707,000	$4,794,000	$6,965,000
Total	**$857,000**	**$2,610,000**	*	**$5,832,000**	**$4,987,000**	**$7,317,000**
Total Levelized Costs ($/kW)	**2.38**	**18.65**	*	**11.72**	**9.99**	**8.71**
Operating Levelized Costs ($/kW)	1.96	17.57	*	11.52	9.68	8.29
hr	0.26	2.36	*	1.22	1.02	1.11
Total Levelized Costs mills/kW-hr	**0.32**	**2.50**	*	**1.57**	**1.3**	**1.17**

* Not Calculated

CONCLUSIONS

The power industry in the U.S. is faced with meeting state imposed regulations, as well as expected federal legislation, to reduce the emissions of mercury compounds from coal-fired plants. Regulations are directed at the existing fleet of nearly 1,100 boilers. These plants are relatively old with an average age of over 40 years. Although most of these units are capable of operating for many additional years, there is a desire to minimize large capital expenditures because of the reduced (and unknown) remaining life of the plant to amortize the project. Injecting a sorbent such as powdered activated carbon into the flue gas represents one of the simplest and most mature approaches to controlling mercury emissions from coal-fired boilers.

Activated carbon injection was successfully evaluated in NETL's Phase I tests at scales up to 150 MW on plants burning subbituminous, bituminous and blends of coals and with fabric filters and electrostatic precipitators (ESP). The tests also identified issues that still needed to be addressed, such as evaluating performance on other configurations, optimizing sorbent usage (costs), and gathering longer-term operating data to address concerns about the impact of activated carbon on plant equipment and operations.

The overall objective of this Phase II test program was to evaluate the capabilities of activated carbon injection and other mercury control options at six host sites with configurations that together represent 78% of the existing plants. The ultimate goals for the Phase II program were to reduce the uncontrolled mercury emissions by 50 to 70% at a cost 25 to 50% lower than the benchmark established by DOE of $60,000/lb mercury removed.

Holcomb, Meramec, Laramie River, Labadie, Monroe, and Conesville were the six testing host sites that together represent configurations for most coal-fired plants in the U.S. A summary of the key descriptive parameters for the Phase II host sites can be found in Table 1.

During the program, the project team identified the significant impact of SO_3 and halogens on mercury removal. For native removal or sorbent injection, low SO_3 and high halogen levels are optimal. High SO_3 levels can be caused by burning high-sulfur coal, oxidation of SO_2 in a SDA, or by SO_3 injection for flue gas conditioning. Halogens can be used to promote mercury removal by increasing levels through high-halogen coals, coal additives or by treating sorbents with a halogen-based material. Based on the SO_3 level and the particulate control, the six host sites can be categorized as follows:

1. Low sulfur with a SDA and fabric filter (Holcomb)
2. Low to medium sulfur with an electrostatic precipitator (Meramec and Laramie River)
3. Low to medium sulfur flue gas with SO_3 injection (Labadie and Monroe)
4. High sulfur (Conesville)

Results from the field tests revealed that different levels of mercury removal can be achieved depending on the air pollution control equipment and flue gas conditions. Data collected from the Phase I DOE tests at Gaston indicate mercury removal levels of up to 90% were obtained with COHPAC® (a baghouse) and DARCO® Hg sorbent injection. At Pleasant Prairie, 50–70% removal while injecting DARCO® Hg was the maximum

achievable mercury control, with the configuration of an ESP collecting PRB ash. At Brayton Point, with an ESP and SO_3 injection for flue gas conditioning, 90% removal was achieved with injection of DARCO® Hg.

Several options for removing mercury from flue gas were evaluated. Coal blending was the most costly of all the options if used for mercury control alone, although it was effective for the site with an SDA and FF. Coal additives can be used to increase halogen content. However, it was concluded that the coal additive, KNX, must be paired with sorbent injection to increase mercury removals, and for plants with higher halogen flue gas, such as those that burn coal with > 0.03% chlorine (by weight) no benefit is expected. Activated carbon injection will be the most simple, cost effective mercury control option for coal-fired power plants firing western fuels or low sulfur eastern fuels. ACI was evaluated during both parametric testing and long-term testing during this DOE Phase II project. The results were highly specific to the plant configuration and operating conditions. The following figure summarizes the results of the Phase I and Phase II test programs.

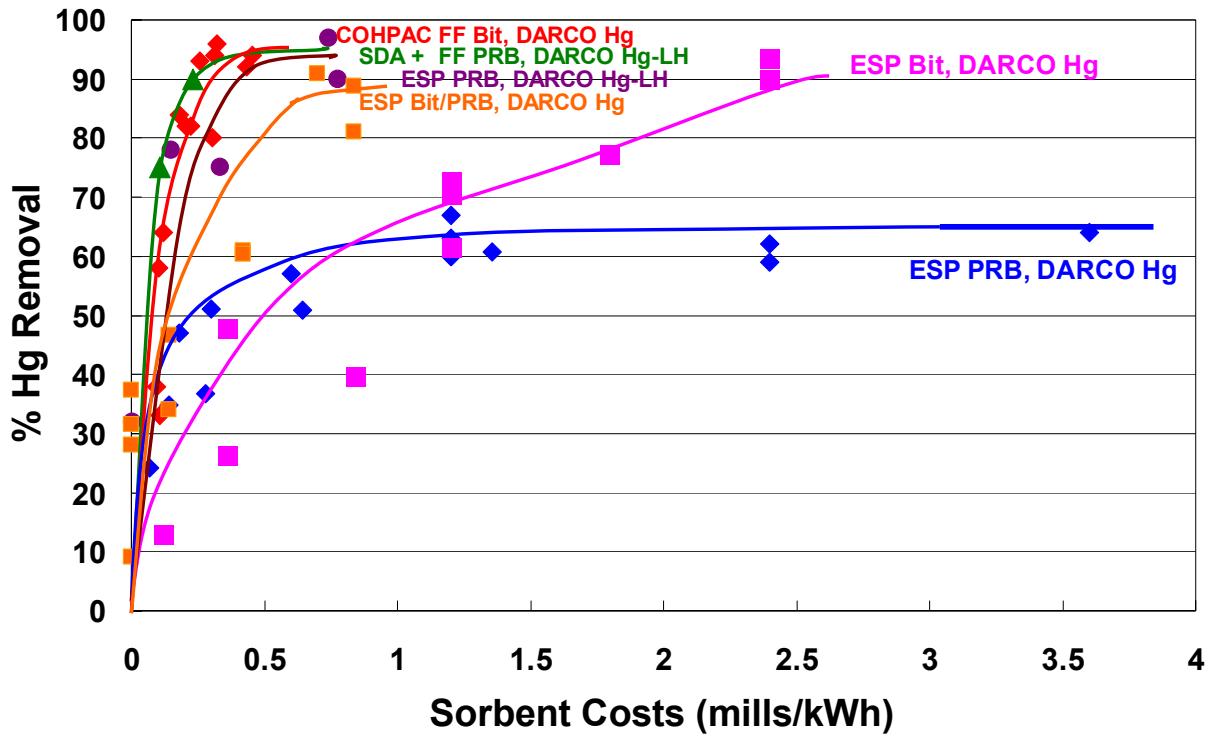


Figure 24. Compilation of Results from DOE Phase I and Phase II Mercury Control Programs.

Table 7. Summary of Mercury Removal Efficiencies and Costs for Different Air Pollution Control Configurations, Coals, and Sorbents[f].

Plant	Coal	APC Equipment	FGC	Sorbent	Removal %	Sorbent Cost (mills/kWh)	Removal Cost ($/lb/Hg)[ec]
Gaston	Bituminous	COHPAC®	None	DARCO® Hg	90	0.43	N/A[d]
Pleasant Prairie	PRB	ESP	SO_3	DARCO® Hg	67	1.2	N/A[d]
Brayton Point	Bituminous	ESP	SO_3[a]	DARCO® Hg	90	2.4	N/A[d]
Holcomb	PRB	SDA+FF	None	DARCO® Hg-LH	90	0.44	1,500
Meramec	PRB	ESP	None	DARCO® Hg-LH	90	0.91	6,500
Monroe	PRB/ Bituminous Blend	ESP	SO_3	DARCO® Hg	80	0.85	18,000
Laramie River	PRB	ESP	None	DARCO® Hg-LH	90	N/A	4,000
Conesville	Bituminous	ESP	None	DARCO® Hg	31	N/A[b]	13,600
Labadie (as-received PAC)	PRB	ESP	SO_3	DARCO® Hg-LH	75	1.21	7,900
Labadie (enhanced PAC)	PRB	ESP	SO_3	DARCO® Hg-LH	85	1.02	5,600

[a] SO_3 injected as needed.
[b] No cost estimate since sorbents were not able to meet mercury removal targets.
[c] DOE goal was 25–50% lower than $60,000/lb Hg (i.e., target = $30,000–$45,000/lb Hg).
[d] Total removal cost not calculated during Phase I testing.
[e] Only includes cost of sorbent. Does not include costs related to equipment installation or maintenance, lost ash sales, or related ash disposal. Costs are dependant on inlet Hg concentration, which was highly variable at most plants.
[f] All costs presented in this table have been carried over from the respective Topical Reports and have not been updated into present day dollars.

Low-Sulfur Coal with a Fabric Filter

New units burning PRB coal are likely to consider installing a spray dryer absorber (SDA) and fabric filters (FF) for combined SO_2 and particulate control. However, past results indicated that power plants that burn Powder River Basin (PRB) coal and have SDA-FFs for air pollution control systems represent a challenging application for controlling mercury emissions. ICR measurements and subsequent full-scale field tests have confirmed that the spray dryer removes halogens that are critical for the adsorption of vapor-phase mercury onto solid surfaces such as native fly ash or activated carbon-based mercury sorbents. This results in very low levels of native mercury removal, typically < 20%, at plants with this configuration and greatly diminished effectiveness of standard activated carbon for mercury control.

The test program at Holcomb was designed to provide a full-scale evaluation of different technologies that can overcome the limited mercury removal achievable with native fly ash or standard activated carbon. Several tests were based on supplementing halogens that were not available in sufficient quantities in the PRB coal. The most significant conclusions from testing at Holcomb were:

- Baseline
  - Native removal was less than 15%.
- Coal Blending
  - Blending the PRB with western bituminous coal led to an increase in mercury removal. At 15% bituminous coal, native mercury removal was nearly 80%.
  - Coal blending was the most expensive mercury control option.
- Coal Additive
  - The combination of coal additive, KNX™ and DARCO® Hg achieved the same mercury removal levels as injection of DARCO® Hg-LH alone.
- Activated Carbon Injection
  - At the same injection concentration, the brominated DARCO® Hg-LH performed better than DARCO® Hg.
  - Mercury removal levels of over 90% were obtained while injecting DARCO® Hg-LH at 1.2 lb/MMacf.
  - The projected cost for mercury removal by ACI at Holcomb was $1,500/lb of mercury removed.
- Balance-of-Plant Impacts
  - No balance-of-plant impacts were observed at Holcomb.

Low- to Medium-Sulfur Coal with an ESP

Both Meramec and Laramie River sites fire PRB coal and are equipped with a cold-side ESP for particulate control. This configuration is becoming more common in the industry as many U.S. utilities are fuel-switching to lower-sulfur western coals. Previous tests at plants with this configuration (PRB/CESP) using sorbents available at the time

indicated that the mercury removal was limited to about 70%. One important difference in the configuration of these two plants is the SDA utilized by Laramie River for SO_2 control, which was expected to further complicate mercury control, since the SDA is known to remove halogens. The most significant conclusions from the tests at Meramec and Laramie River were:

- Baseline
  - Native removal was < 30% at Meramec and < 20% at Laramie River.
- Coal Blending
  - No benefit was observed due to coal blending.
- Coal Additive
  - KNX™ increased the amount of mercury captured by the flue gas up to 64%.
  - Combining KNX™ and DARCO® Hg injection led to 84% Hg removal at Meramec and 94% at Laramie River.
- Activated Carbon Injection
  - Removal was limited to 74% using DARCO® Hg at 5 lb/MMacf at Meramec and < 45% at 6 lb/MMacf at Laramie River.
  - DARCO® Hg-LH could remove up to 97% at 3.2 lb/MMacf at Meramec and 95% at Laramie River using 6 lb/MMacf.
  - During long-term tests at Meramec with DARCO® Hg-LH, 60–70% of mercury was removed at an injection concentration of 1 lb//MMacf and 90% remove was achieved with 3 lb/MMacf.
  - The cost of mercury removal was $6,500/lb Hg at Meramec and $4,000/lb Hg at Laramie River.
- Balance-of-Plant Impacts
  - No balance-of-plant impacts were observed during testing.

Low- to Medium-Sulfur Coal with SO_3 Injection

Similar to Meramec and Laramie River, Labadie also burns PRB coal and is configured with a cold-side ESP. However, Labadie must inject SO_3 to maintain permitted particulate emissions, which increases ESP performance, but dramatically decreases mercury removal from PAC. Parametric tests were completed at Labadie with different rates levels of SO_3 injection. Monroe also injects SO_3, but fires a blend of PRB and bituminous coals, which is an even greater challenge for mercury removal. Select results from the testing completed under this program at the Labadie and Monroe sites include:

- Baseline
  - Baseline removal was limited to <15% at Labadie and <35% at Monroe.
  - Baseline removal was slightly worse when the Monroe SCR was online, rather than bypassed.

- Coal Blending
  - No changes in mercury speciation or removal were observed at Monroe due to coal blending.
  - Due to the higher halogen levels in the bituminous coal at Monroe, brominated PAC did not increase mercury removal levels over those observed from standard PAC.
- Coal Additive
  - At Labadie, similar mercury removal levels were observed using both KNX™ and injection of DARCO® Hg compared to injection of the brominated sorbent DARCO® Hg-LH alone.
- Activated Carbon Injection
  - SCR Effects (Monroe)
    - The inlet mercury during both test weeks was fairly steady, with an average concentration of 11.4 lb/TBtu while the SCR was in bypass and 7.6 lb/TBtu while the SCR was in-service.
    - DARCO® Hg performed essentially the same whether the SCR was in-service or in bypass.
  - Downstream of the APH
    - At Labadie, DARCO® E-26™, the bromine-treated carbon with alkali, was the most effective of all the sorbents evaluated during parametric testing at Labadie downstream of the APH. At an injection concentration of approximately 5 lb/MMacf at the APH outlet and nominally 5.2 ppm SO_3, nearly 74% mercury removal was achieved.
  - Upstream of the APH
    - Sorbents were more effective when injected upstream of the APH, possibly due to more residence time or increased dispersion.
    - In the presence of 5.2 ppm (30%) SO_3 Envergex and the commercially available FLUEPAC®-MC PLUS and DARCO® Hg-LH performed very comparably. At an injection rate of 5.2 lb/MMacf, all three sorbents were able to achieve roughly 85% (± 2.5%) vapor phase mercury removal.
    - At Monroe, mercury capture during long-term testing was over 87%, using DARCO® Hg.
  - SO_3 Levels
    - For all the mercury sorbents tested, an increase in SO_3 concentration led to a reduction in the mercury removal.
    - Trona was unable to increase ESP power levels or decrease opacity as well as SO_3 injection.

- ADA-ES Patented On-Site Milling Process
  - Data from the extended testing period suggests significant improvement in PAC performance due to on-site sorbent milling. The results indicate that 85% mercury removal can be achieved with either 4 lb/MMacf milled PAC or 10 lb/MMacf as-received PAC.
- Cost
  - The cost of mercury removal by injecting DARCO® Hg-LH at Labadie was calculated to be $7,900/lb Hg with as received PAC for 75% control and $5,600/lb Hg with enhanced PAC for 85% control with SO_3 at 5.2 ppm.
  - Mercury removal using ACI at Monroe was projected to cost $18,000/lb Hg for 90% removal.
- Balance-of-Plant Impacts
  - At Labadie, when injecting Trona, it was concluded that alkaline materials may absorb some of the SO_3 before it has time to react with the fly ash. The removal of SO_3 increases ash resistivity, which slightly increases TR-set sparking.
  - No balance-of-plant impacts were observed at either plant due to ACI.

High-Sulfur Coal

Conesville was included in the testing program due to the challenge posed to mercury removal using ACI by the higher SO_3 levels. The challenges identified and characterized at Conesville stemming from the high concentration of SO_3 in the flue gas may represent a larger obstacle to mercury control for the industry than just units that fire high-sulfur coal. The presence of SO_3 in flue gas appears to decrease mercury capture by activated carbon, sometimes dramatically.

- Baseline
  - ESP native mercury capture is very low at Conesville, from 0 to 20%. The mercury is 60 to 70% oxidized at the ESP outlet, upstream of the WFGD, and 90% elemental at the WFGD outlet.
  - Most of the oxidized mercury is removed in the WFGD.
- Activated Carbon Injection
  - The maximum incremental removal by a sorbent was approximately 31% (DARCO® E-12 at 12 lb/MMacf).
  - The next highest removal was 25% (Sorbent Technologies EXP-2 at 16 lb/MMacf).
  - Several sorbents demonstrated some improvement over standard carbon-based sorbents.
  - Changing the injection lance design did not improve mercury removal.
  - Both DARCO® E-12 and Sorbent Technologies EXP-2 had an opacity impact that would require further evaluation.

- Balance-of-Plant Impacts
  - Most of the eighteen sorbents tested at full-scale increased T/R set spark rates, decreased power levels and/or impacted opacity.

At most sites, the cost of mercury control was well within the goals set by the DOE/NETL. An important part of evaluating different mercury control technologies is determining their impact on plant operation. This is the single most important step in gaining acceptance of these technologies across the industry. No balance-of-plant impacts were observed due to continuous ACI at Holcomb, Meramec, Laramie River, Labadie, and Monroe during long-term tests. High SO_3 flue gas remains a challenge for mercury removal. Continued testing with improved sorbents may be warranted. The cost goals set by the DOE/NETL were achieved for most sites during this program.

REFERENCES

1. Carey, T.C., O.W. Hargrove, C.F.Richardson, R.Chang, and F.B.Meserole (1998), "Factors Affecting Mercury Control in Utility Flue Gas Using Activated Carbon," J. Air & Waste Manage. Assoc., 48, 1166–1174.
2. United States Environmental Protection Agency. Technology Transfer Network, Air Toxics Website. Information Collection Request database. http://www.epa.gov/ttn/atw/combust/utiltox/utoxpg.html
3. Sjostrom, S., T. Ebner, R. Slye, R. Chang, M. Strohfus, J. Pelerine and S. Smokey (2002). "Full-Scale Evaluation of Mercury Control at Great River Energy's Stanton Generating Station using Injected Sorbents and a Spray Dryer/Baghouse," Air Quality III Conference, Arlington, VA, September 9–12.
4. Bustard, J., M. Durham, T. Starns, C. Martin, R. Schlager, C. Lindsey, K. Baldrey, L. Monroe, T. Coughlin, D. Johnson, S. Renninger and R. Chang (2002). "Full-Scale Evaluation of Sorbent Injection for Mercury Control on Coal-Fired Power Plants," Air Quality III Conference, Arlington, VA, September 9–12.
5. U. S. DOE Cooperative Agreement No. DE-FC26-03NT41986. Topical Report for Sunflower Electric's Holcomb Station, Report No. 41986R07.
6. U. S. DOE Cooperative Agreement No. DE-FC26-03NT41986. Topical Report for AmerenUE's Meramec Station Unit 2, Report No. 41986R09.
7. U. S. DOE Cooperative Agreement No. DE-FC26-03NT41986. Topical Report for Basin Electric Power Cooperative's Laramie River Station, Report No. 41986R11.
8. U. S. DOE Cooperative Agreement No. DE-FC26-03NT41986. Topical Report for DTE Energy's Monroe Station, Report No. 41986R16.
9. U. S. DOE Cooperative Agreement No. DE-FC26-03NT41986. Topical Report for AEP's Conesville Station Unit 6, Report No. 41986R24.
10. U. S. DOE Cooperative Agreement No. DE-FC26-03NT41986. Topical Report for AmerenUE's Labadie Power Plant, Report No. 41986R26.
11. Sjostrom, S., T. Ebner, R. Slye, R. Chang, M. Strohfus, J. Pelerine and S. Smokey (2002). "Full-Scale Evaluation of Mercury Control at Great River Energy's Stanton Generating Station using Injected Sorbents and a Spray Dryer/Baghouse," Air Quality III Conference, Arlington, VA, September 9–12.
12. Sjostrom, S., J. Smith, T. Hunt, R. Chang, and T. Brown (1997) "Demonstration of Dry Carbon-Based Sorbent Injection for Mercury Control in Utility ESPs and Baghouses," Air and Waste Management Association 90th Annual Meeting, paper 97-WA72A.07, Toronto, Ontario, Canada, June 8–13.
13. U. S. DOE Cooperative Agreement No. DE-FC26-00NT41005. Final Technical Report "Field Test Program to Develop Comprehensive Design, Operating, and Cost Data for Mercury Control Systems," Report No. 41005R22.
14. Successful SO_3 Mitigation While Enhancing the ESP Performance at AEP's Gavin Plant by Dry Injection of Trona Upstream of the ESP, PowerGen 2004.

APPENDIX: EQUIPMENT DESCRIPTION

Carbon Injection and Delivery System

Figure 1 is a photograph of the sorbent silo and feeder trains designed to treat a 150-MW boiler on a unit with an ESP. The unit is approximately 50 feet high and 10 feet in diameter with an empty weight of 10 tons. The silo will hold 20 tons of sorbent.

Powdered activated carbon (PAC) was delivered in bulk pneumatic trucks and loaded into the silo, which was equipped with a bin vent bag filter. From the discharge section of the silo, the sorbent was metered by variable speed screw feeders into eductors that provide the motive force to carry the sorbent through flexible hose to distribution manifolds located on the flue gas ducts, feeding the injection lances. Regenerative blowers provided the conveying air. A Programmable Logic Controller (PLC) system was used to control system operation and adjust injection rates.

Figure 1. Carbon Injection Storage Silo and Feeder Trains for 150 MWe (Phase I System).

Mercury Analyzers

Two mercury semi-continuous emissions monitors (SCEM) were used during testing at Holcomb to provide real-time feedback during baseline and sorbent injection testing. The monitor, shown in Figure 2, consisted of a cold-vapor atomic absorption spectrometer (CVAAS) coupled with a gold amalgamation system (Au-CVAAS). The analyzers are capable of measuring both total vapor-phase mercury and elemental vapor-phase mercury. The analyzer determines total vapor-phase mercury concentrations by reducing all of the oxidized mercury to the elemental form near the extraction location. To measure elemental mercury, the oxidized mercury is removed while allowing elemental mercury to pass through without being altered. The system was calibrated using vapor-phase elemental mercury.

The extraction probe was an inertial separation design that separates the particulate matter from the sample with minimal sampling artifacts from fly ash or injected sorbent.

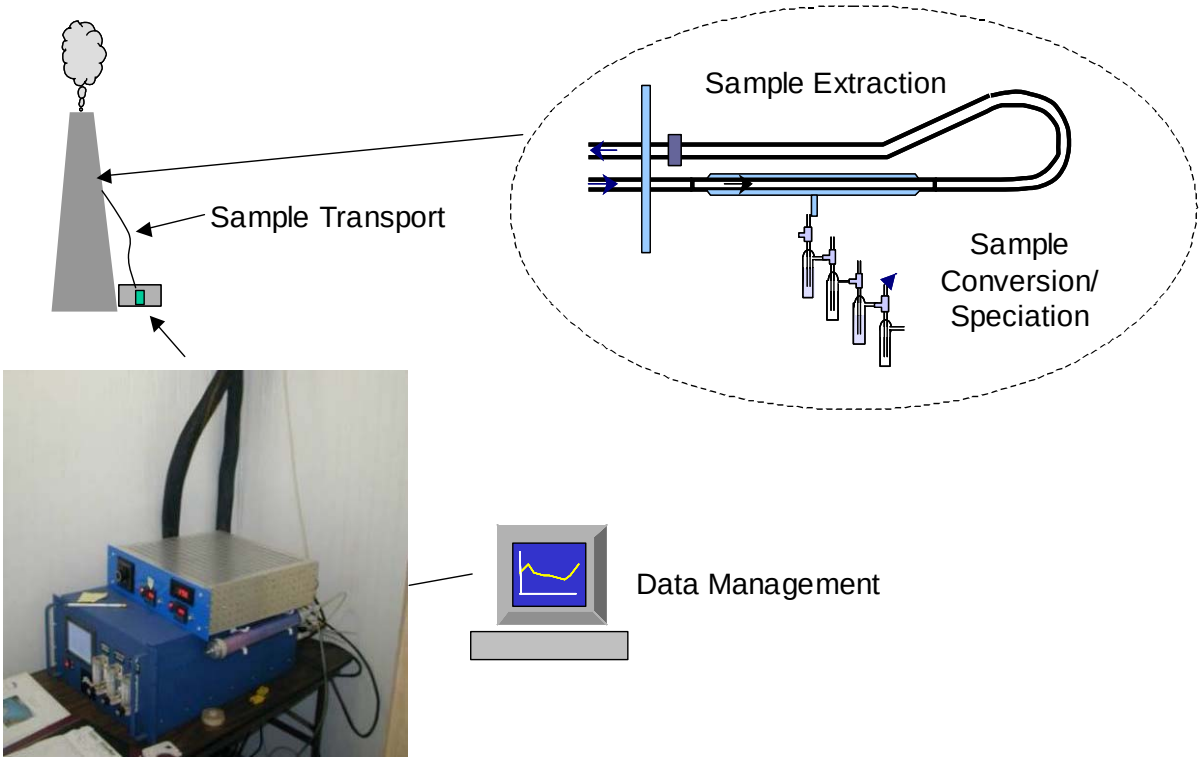


Figure 2. Sketch of Mercury Measurement System.

Prototype Mercury Analyzers – Thermo Electron

A prototype mercury analyzer developed by Thermo Electron Corporation was also installed on site and operated by ADA-ES under a different test program. These data were made available to this program. The measurement technique of the Thermo analyzer is cold-vapor atomic fluorescence spectroscopy (CVAFS). It is a real-time analyzer that does not employ gold amalgamation. This system uses an extraction probe similar to the Au-CVAAS analyzers described above, with the addition of a dilution module. Diluting the gas sample reduces the moisture content for measurement and the potential interference that may be

caused by other flue gas species. Because most of the vapor-phase mercury at Holcomb was in the elemental phase, no converter was used and only elemental mercury was measured. The Thermo extraction probe can be configured with a converter to measure total vapor-phase mercury.

Ash Sampling Cyclone

The mercury analyzers used at Holcomb measure only vapor-phase mercury. Fly ash samples were collected at the inlet of the spray dryer for subsequent mercury analyses using sampling cyclones. Cyclones are more effective at collecting ash samples without changing the vapor/particulate speciation than sampling through a filter because the interaction of the vapor with the particulate is minimized. The cyclones used at Holcomb were Cegrit samplers. The Cegrit is a sampling cyclone designed for continuous sample collection at a permanent installation. One unit was installed at the inlet to each of the three spray dryer modules. A photo of one of the Cegrit samplers at Holcomb is shown in Figure 3.

Figure 3. Cegrit Fly Ash Sampler.

Sorbent Screening Apparatus

Several groups have conducted mercury sorbent screening tests over the past few years and the performance of the sorbents has been reported as the maximum mercury that can be collected by the sorbent, or the capacity of the sorbent. Although these data provide valuable information to compare the relative performances of several sorbents, they do not provide a direct indication of the injection concentration required to achieve a given level of mercury removal. To overcome these shortcomings, ADA-ES developed a sorbent screening device (SSD) that allows simultaneous comparison of several sorbents, provides an indication of the maximum mercury removal achievable with a particular sorbent, and provides an estimate of the amount of sorbent required to achieve various mercury removal levels in a full-scale application.

The SSD is shown in Figures 4 and 5. It consists of a heated enclosure that houses three sample filters, and is designed to simulate the range of gas velocities, temperature, sorbent loading, and ash loading typical of full-scale fabric filters. Tests can be conducted on site with extracted flue gas or with simulated flue gas in the laboratory. Sorbent loading can be varied to provide data over a range of injection concentrations, nominally 1 to 10 lb/MMacf. A typical test lasts up to 12 hours or can be terminated when the outlet mercury concentration equals the inlet mercury concentration (100% breakthrough).

The important parameters that are measured and controlled consist of the SSD temperature, the inlet and outlet elemental mercury concentration in the flue gas, the gas flow rate through each of the filters, and the weight of the sorbent sample applied to the filter media. The addition rate of any flue gas conditioning agents is also controlled. The mercury SCEMs are calibrated at the beginning and end of each run for quality assurance.

At Holcomb, flue gas was extracted from between the dry scrubber and baghouse using an inertial separation probe to remove particulate. The gas was then transported through a heated line to the SSD. Test samples consisted of a mixture of sorbent and Holcomb baghouse ash, and were evenly deposited onto glass filter paper in appropriate concentrations. Treated gas exited the heated box through chemical impingers to convert all mercury to elemental mercury, and a chiller to remove moisture. The total vapor-phase mercury concentration was measured at the inlet and outlets of the samples using CVAAS Hg SCEMs. Flue gas conditioning agents could also be added ahead of the sample filters to evaluate the effect of conditioning agents on sorbent performance.

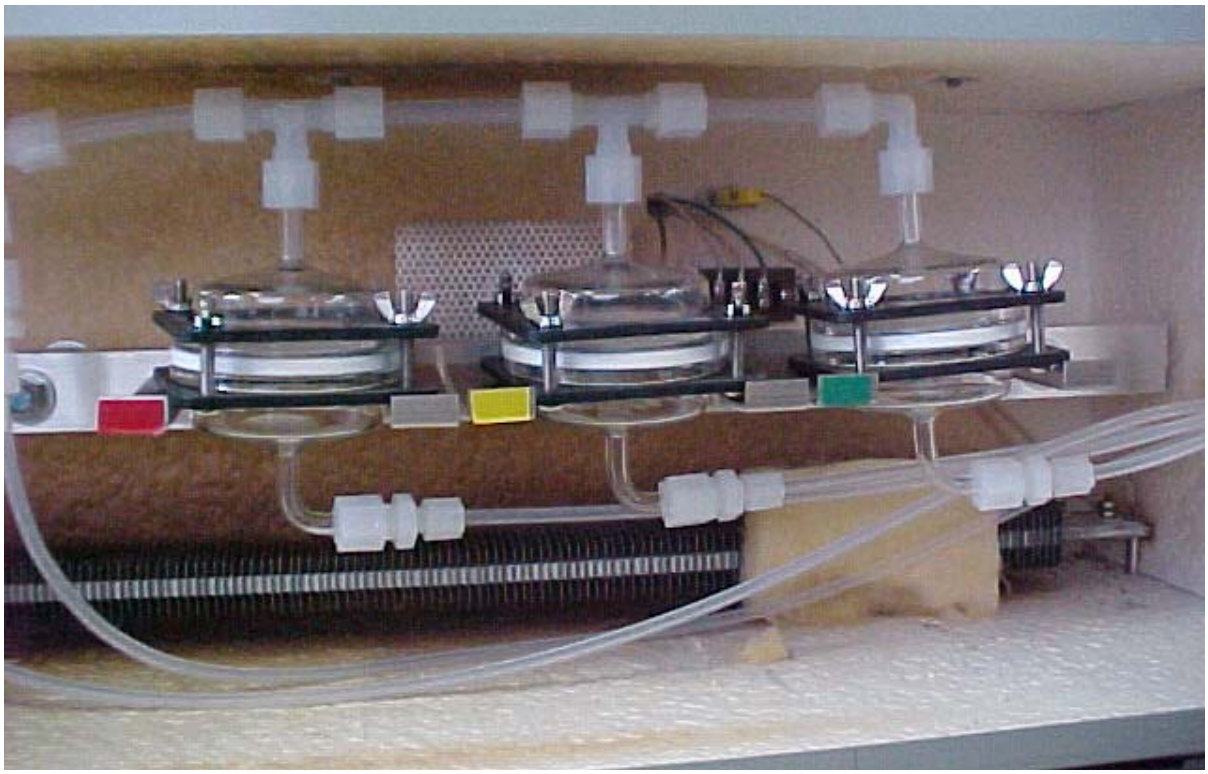


Figure 4. Sorbent Screening Device—Sample Filters.

Figure 5. Sorbent Screening Device—Heated Box and Impingers.

The SSD was designed to simulate the conditions present across the filter in a full-scale fabric filter and the results can be used to estimate the sorbent injection concentrations required for various levels of mercury removal. This type of information cannot be calculated directly from the usual information provided by vendors or from laboratory tests using a bed of sorbent. Fixed-bed testing can provide both capacity and reactivity (slope of the breakthrough curve) data and this can be incorporated into a model for predictions. However, the applicability of the data is limited because sorbents are typically removed from the gas stream before the equilibrium capacity has been reached.

The equivalent sorbent injection concentration (EC), in lb/MMacf, is calculated as shown in equation 1.

Equivalent Concentration=(Sorbent Loading)/(Cumulative Gas Volume)/2 (1)

Therefore, if 0.01 g sorbent is preloaded onto a filter and the average flow for the first hour is 1 actual liter per minute, the equivalent loading is 5.2 lb/MMacf.

EC=0.01 g*(1 lb/454 g)/[1 lpm*(1 cf/28.32 l)*(60 min/hr)*1 hr]/2*1E6 cf/MMacf

EC=5.2 lb/MMacf

The sorbent loading represents the amount of sorbent that would have collected on a section of a full-scale bag over the entire filtering cycle. To calculate the equivalent concentration, the loading is divided by two because the ***average*** amount of sorbent present on a full-scale bag between cleaning cycles is half the amount present on the bag at the end of the filtering cycle. For the sorbent screening tests, since the test sorbent is pre-loaded onto the filter before being introduced to flue gas, the *equivalent sorbent injection concentration* is much higher at the beginning of the test and decreases as the test progresses. In this example, if 90% mercury removal is achieved over the first hour, this indicates that 90% removal would be achieved in a full-scale application at an injection rate of 5.2 lb/MMacf. If the cumulative average mercury removal of this sorbent was 40% after 4 hours, this suggests that 40% removal would be achieved by this sorbent at an injection rate of 1.3 lb/MMacf (5.2/4).