Low-Cost Options for Moderate Levels of Mercury Control

Final Report for
DOE Project DE-FC26-05NT42307
MidAmerican's Louisa Generating Station,
MidAmerican's Council Bluffs Energy Center,
and
Entergy's Independence Steam Electric Station
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Principal Author: Sharon Sjostrom

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

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Andrew O'Palko was the project manager for DOE/NETL. David Muggli was the initial ADA-ES project manager until 4Q06. Starting in 4Q06, Sharon Sjostrom was the Project Manager. Tom Campbell was the project engineer responsible for all site activities throughout the test program. The team gratefully acknowledges the efforts and support of Richard Roberts (Entergy Technical Support), Mike Rees (Engineer), Todd Bradberry (Engineer), Steve Coker (Senior Engineer), Kellee Fletcher (Environmental Specialist), Joe Hantz (Fossil Environmental Support), and the staff at Independence Steam Electric Station. The team would also acknowledge Kevin Dodson (MidAmerican Manager, Environmental Engineering), the staff at Walter Scott Energy Center (WSEC) including Brandon Rinehart (Plant Engineer), and the staff at Louisa Generating Station including James Haack (Louisa Senior Engineer), Ron Martel (Louisa Unit Manager, Operations), Steve Harding (Louisa Unit Manager, Maintenance), James Wiegand (Louisa Manager, EHS), and Kevin Williams (Louisa Plant Technical Specialist). Ramsay Chang was a key technical advisor and provided project management for EPRI. Connie Senior at Reaction Engineering International provided technical support and coordinated the CFD modeling efforts conducted by REI. The ADA-ES test team included Brian Donnelly, Cody Wilson, Chad Sapp, Erik Zipp, Brandon Hagen, and Martin Dillon from ADA-ES. Mike Durham, Jean Bustard, Cam Martin, and Travis Starns from ADA-ES provided key technical input into the project. Richard Schlager managed the contracts. Anne Sjostrom and Andrea Adams assisted with the technical writing, and Cindy Larson edited and assembled all technical reports.

ABSTRACT

This is the final technical report for a three-site project that is part of an overall program funded by the U.S. Department of Energy's National Energy Technology Laboratory (DOE/NETL) and industry partners to obtain the necessary information to assess the feasibility and costs of controlling mercury from coal-fired utility plants. This report summarizes results from tests conducted at MidAmerican's Louisa Generating Station and Entergy's Independence Steam Electric Station (ISES) and sorbent screening at MidAmerican's Council Bluffs Energy Center (CBEC) (subsequently renamed Walter Scott Energy Center (WSEC)). Detailed results for Independence and Louisa are presented in the respective Topical Reports. As no full-scale testing was conducted at CBEC, screening updates were provided in the quarterly updates to DOE.

ADA-ES, Inc., with support from DOE/NETL, EPRI, and other industry partners, has conducted evaluations of EPRI's TOXECON II™ process and of high-temperature reagents and sorbents to determine the capabilities of sorbent/reagent injection, including activated carbon, for mercury control on different coals and air emissions control equipment configurations. An overview of each plant configuration is presented below.

- MidAmerican's Louisa Generating Station burns Powder River Basin (PRB) coal in its 700-MW Unit 1 and employs hot-side electrostatic precipitators (ESPs) with flue gas conditioning for particulate control. This part of the testing program evaluated the effect of reagents used in the existing flue gas conditioning on mercury removal.
- MidAmerican's Council Bluffs Energy Center typically burns PRB coal in its 88-MW Unit 2. It employs a hot-side ESP for particulate control. Solid sorbents were screened for hot-side injection.
- Entergy's Independence Steam Electric Station typically burns PRB coal in its 880-MW Unit 2. Various sorbent injection tests were conducted on 1/8 to 1/32 of the flue gas stream either within or in front of one of four ESP boxes (SCA = 542 ft^2/kacfm), specifically ESP B. Initial mercury control evaluations indicated that although significant mercury control could be achieved by using the TOXECON II™ design, the sorbent concentration required was higher than expected, possibly due to poor sorbent distribution. Subsequently, the original injection grid design was modeled and the results revealed that the sorbent distribution pattern was determined by the grid design, fluctuations in flue gas flow rates, and the structure of the ESP box. To improve sorbent distribution, the injection grid and delivery system were redesigned and the effectiveness of the redesigned system was evaluated.

This project was funded through the DOE/NETL Innovations for Existing Plants program. It was a Phase II project with the goal of developing mercury control technologies that can achieve 50–70% mercury capture at costs 25–50% less than baseline estimates of \$50,000–\$70,000/lb of mercury removed. Results from testing at Independence indicate that the DOE goal was successfully achieved. Further improvements in the process are recommended, however. Results from testing at Louisa indicate that the DOE goal was not achievable using the tested high-temperature sorbent. Sorbent screening at Council Bluffs also indicated that traditional solid sorbents may not achieve significant mercury removal in hot-side applications.

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EXECUTIVE SUMMARY

Power plants that burn Powder River Basin (PRB) coal and have only hot-side electrostatic precipitators (ESPs) for air pollution control represent a challenging configuration for controlling mercury emissions. Limited testing on hot-side ESP configurations with injecting conventional powdered activated carbons (PAC) just upstream of the ESP has indicated these sorbents perform very poorly at the elevated temperatures associated with hot-side ESP installations. In order to further the understanding of potential mercury control systems for power plants burning PRB coals and using hot-side ESPs for air pollution control, DOE selected ADA-ES, Inc., to conduct a multi-site test program. These tests were supported with significant cost share from EPRI and industry, including MidAmerican and Entergy. Site descriptions and key results are presented below.

- Hot-Side Mercury Removal
  - Liquid Reagent Evaluations: MidAmerican's Louisa Generating Station

    Louisa Generating Station burns PRB coal in its 700-MW Unit 1 and employs hot-side electrostatic precipitators with flue gas conditioning, ADA-37, for particulate control. Testing was conducted from January 28 to February 13, 2006.

    - Objective: Evaluate the mercury removal effectiveness of ADA-37, and ALSTOM's coal additive, KNX.
    - Results indicate that ADA-37 is not effective at removing mercury across a hot-side ESP. KNX appeared to increase the fraction of oxidized mercury, but no net increase in mercury removal was noted with KNX.
  - Solid Sorbent Evaluation: MidAmerican's Council Bluffs Energy Center

    Council Bluffs Energy Center typically burns PRB coal in its 88-MW Unit 2. It employs a hot-side ESP for particulate control.

    - Objective: Evaluate the mercury removal effectiveness potential of solid sorbents for mercury control in a hot-side ESP.
    - Results from sorbent screening tests indicated there was limited potential for significant mercury removal using the tested sorbents.
- Cold-Side, Mid-ESP Injection (TOXECON II™): Entergy's Independence Steam Electric Station

  Independence typically burns PRB coal in its 880-MW Unit 2. Various sorbent injection tests were conducted on 1/8 to 1/32 of the flue gas stream either within or in front of one of four ESP boxes (SCA = 542 ft^2/kacfm), specifically ESP B.

  - Objective: Determine the cost and effects of sorbent injection using EPRI's TOXECON II™ for mercury control in stack emissions from Unit 2.
    - Three lance designs were evaluated.
    - The following four powdered activated carbon sorbents were tested: Norit DARCO® Hg, DARCO® Hg-LH, DARCO® E-10, and DARCO® E-11.

- Results and Discussion
  - Sorbent Distribution: Ensuring proper sorbent distribution is critical for effective mercury control. Good distribution is more challenging with TOXECON II™ than injection upstream of the ESP for three primary reasons:
    1) The flue gas velocity at full load within the typical medium-sized ESP is usually 3 to 4 ft/sec compared to 40 to 50 ft/sec in the duct upstream of the ESP. The air flow velocity is reduced by increasing the cross sectional area in the direction of flow within the ESP. The increased cross sectional area requires a much larger sorbent injection grid and poses a greater challenge for proper sorbent distribution within the ESP in comparison to the inlet ducting.
    2) The penetration of the sorbent from the lance into the gas is affected by the velocity in the ESP, which can vary from nominally 1.5 to 4 ft/sec. Consequently, varying boiler load can significantly impact the pattern of sorbent distribution. In contrast, the velocity upstream of an ESP is typically 30 to 60 ft/sec and the sorbent penetration across the gas stream is minimal at all boiler loads. Using typical lance conveying air velocities of 10 ft/sec, the change in flue gas velocity in the duct from low to high load will result in a change in sorbent penetration of the flue gas stream by less than 30%. The same load change in the ESP, with its lower flue gas velocities, results in the doubling (or greater) of the plume size of the sorbent distribution pattern.
    3) The distance between the injection lances and the downstream mechanical collection field is limited (nominally 3 feet at Independence Unit 2).
- Mercury Removal
  - Results from lance 1 tests indicated that mercury removal was limited to less than 80% at injection concentrations up to 10 lb/MMacf.
  - Results from lances redesigned to improve the sorbent distribution yielded 89% mercury removal using DARCO® Hg-LH at 5 lb/MMacf.
- Particulate Emissions: Injecting PAC in the TOXECON II™ configuration resulted in particulate spikes during outlet field raps observed in the continuous particulate monitor and in the stack opacity during some testing periods. Increasing the ESP power and increasing the final field rapping cycle timing were effective at minimizing opacity spikes due to PAC injection. Although there was no indication of increased particulate emissions based upon outlet particulate EPA Method 5/17 measurements collected downstream of the ESP with and without PAC injection, additional testing is required to determine with any certainty whether TOXECON II™ implementation would result in a sufficient increase in particulate emissions to trigger a permit review.
- Economics: As a budgetary estimate, a permanent sorbent injection system for TOXECON II™ at Independence Unit 2 would cost $4.7M ± 25%, on an installed basis in 2007 dollars. Assuming the use of DARCO® Hg-LH at a rate of 5 lb/MMacf, which would provide nominally 80% vapor-phase mercury removal, the annual levelized operating costs would be approximately $9.07M ± 15% in 2007 dollars, including the cost of ash disposal and the loss in revenue.

The goals for the program established by the DOE/NETL were to reduce the uncontrolled mercury emissions by 50–70%, at a cost 25–50% lower than the target established by the DOE of \$60,000/lb mercury removed. This goal was exceeded at Independence. Results from testing indicated that 80% mercury removal could be achieved using DARCO® Hg-LH at a sorbent cost of \$14,800 per pound of mercury captured (accounting for the partial loss of ash sales and resultant disposal costs), while preserving the salability of the fly ash. Additional improvements to the injection system design to increase mercury removal by improving the sorbent distribution are anticipated with ongoing development of the technology.

INTRODUCTION

Description of Overall Program

The test program at Entergy's Independence Steam Electric Station (ISES) and MidAmerican's Louisa Generating Station and Council Bluffs Energy Center (CBEC) (subsequently renamed Walter Scott Energy Center (WSEC)) is part of a program funded by the U.S. Department of Energy's National Energy Technology Laboratory (DOE/NETL) and industry partners to obtain the necessary information to assess the feasibility and costs of controlling mercury from coal-fired utility plants using either high-temperature sorbents or EPRI's TOXECON II™ process. High-temperature liquid sorbents were included in the test program at MidAmerican's Louisa Generating Station. High-temperature solid sorbents were screened in the test program at Council Bluffs Energy Center. Sorbent injection into an electrostatic precipitator (ESP), TOXECON II™, was the focus of testing at Entergy's Independence Steam Electric Station. All of the host sites fire Powder River Basin (PRB) coal and currently achieve less than 20% native mercury removal. At the onset of the program, American Electric Power's (AEP) Gavin Plant was also considered as a potential host site. After further consideration of the testing conditions at the AEP Gavin site and budget constraints by the DOE, the test team dropped this site from the testing efforts. A portion of the funding allocated to testing at Gavin was transferred to a follow-on evaluation project at Independence in 4Q06. The Council Bluffs project was cancelled in 1Q07 due to lack of DOE project funding for FY 2008 after only sorbent screening was conducted.

Key descriptive information for the final three host-site plants is included in Table 1. Table 2 shows the field-test schedule for the final program. The technical approach followed during this program allowed the team to 1) evaluate various mercury control technologies at plants with different configurations, and 2) perform long-term testing at the optimum conditions for at least one month. These technical objectives were accomplished by following the series of tasks listed below. These tasks were repeated at Louisa and Independence.

Task 1. Site Coordination, Kickoff Meeting, Test Plan, and QA/QC Plan

Task 2. Design and Install Site-Specific Equipment

Task 3. Sorbent Selection

Tasks 4–6. Field-Tests

Task 7. Data Analysis

Task 8. Sample Evaluation

Task 9. Site Report

Task 10. Technology Transfer

Task 11. Management and Reporting

A detailed description of each task for each project is included in their respective Topical Reports.[1,2]

Table 1. Host Site Key Descriptive Information.

	Entergy Independence	MidAmerican Council Bluffs	MidAmerican Louisa
	TOXECON II™	**High-Temperature Sorbents**	**High-Temperature Reagents**
Unit No.	2	2	1
Size (MW)	880	88	700
Test Portion (MW)	110/55	88	700
Coal	PRB	PRB	PRB
Heating Value (as received)	8,870	8,425	8,500
Sulfur (% by weight)	0.32	0.32	0.32
Chlorine (ppm)	50	50–100	50–100
Mercury (µg/g)	0.04	0.08	0.08
Particulate Control	Cold-Side ESP	Hot-Side ESP	Hot-Side ESP
SCA/fields (ft^2/kacfm)	542/4	224/4	459/5
Sulfur Control	Compliance Coal	Compliance Coal	Compliance Coal
Air Preheater	Regenerative	Regenerative	Regenerative
Disposition of Ash	Sold	Some sold	Sold
Typical Inlet Mercury (µg/dncm)	6–7	11.1–13.5	11.1–13.4
Typical Mercury Removal	10–20%	0–10%	0–10%

Table 2. Field-Testing Schedule.

Site	2005		2006				2007	
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
Louisa								
Council Bluffs								
Independence								

There are several organizations participating in this program. The organizations providing co-funding for tests include:

- DOE/NETL
- EPRI
- ADA-ES, Inc.
- Entergy – Independence Steam Electric Station*
- MidAmerican – Louisa Station* and Council Bluffs Energy Center*
- Alliant
- ATCO Power
- DTE Energy
- Oglethorpe Power
- Southern Company
- Xcel Energy
- Norit Americas Inc.
- Arch Coal
- EPCOR

**Indicates host site.*

Key members of the test team include:

- Entergy Independence Station
  - Project Manager: Richard Roberts
  - Independence Project Engineers: Todd Bradberry, Steve Coker
  - Environmental Specialist: Kellee Fletcher
  - Fossil Environmental Support: Joe Hantz
- MidAmerican: Louisa and Council Bluffs
  - Manager, Environmental Projects: Kevin Dodson
  - Louisa Project Engineers: James Haack
  - Louisa Managers: Ron Martel, Steve Harding, James Wiegand
  - Environmental Support: Kevin Williams
- ADA-ES, Inc.
  - Project Managers: David Muggli/Sharon Sjostrom
  - Project Engineer responsible for all site activities: Tom Campbell
- DOE/NETL
  - Project Manager: Andrew O’Palko
- EPRI
  - Project Manager: Ramsay Chang
- Reaction Engineering International
  - Connie Senior

PROJECT OBJECTIVES AND TECHNICAL APPROACH

Three sites were included in this project. The overall project objective for all sites was to assess mercury control using either liquid reagents (Louisa) or solid sorbents (Council Bluffs and Independence). The objectives for each test site are listed below. Additional details are provided for Independence because of the extensive testing conducted there. Site descriptions for Louisa and Council Bluffs are included in the appendix.

Louisa Generating Station (Hot-Side ESP)

- Evaluate potential of the existing flue gas conditioning reagent, ADA-37, to increase mercury removal across the ESP.
- Evaluate potential of ALSTOM's KNX additive, introduced to the coal prior to entering the pulverizers and furnace.

Council Bluffs Energy Center (Hot-Side ESP)

- Evaluate whether available solid sorbents have the potential to achieve at least 50% mercury removal at hot-side conditions.

Independence Steam Electric Station (TOXECON II™)

- Determine the cost and effects of sorbent injection using EPRI's TOXECON II™ for mercury control in stack emissions from Unit 2.
- Determine the impacts of sorbent injection on particulate emissions.

The general approach for the field-testing at each site was similar, and is described below. Some tests were not included at some sites because of poor initial results.

1. Sample and Data Collection (all sites)
2. Baseline Tests (all sites)
3. Parametric Tests (Louisa and Independence)
4. Continuous Injection Tests (long-term, 30 days at Independence)

HOT-SIDE MERCURY CONTROL TESTING: RESULTS AND DISCUSSION

Mercury control evaluations across air pollution control devices upstream of the air preheater, or "hot-side," were conducted at Louisa and Council Bluffs (sorbent screening only). Both units fire Powder River Basin coal and have hot-side ESPs for particulate collection. Louisa uses ADA-37 as a flue gas conditioning agent to improve particulate capture in the ESP. The effectiveness of liquid reagents was evaluated at Louisa and solid sorbents were screened at Council Bluffs. Further descriptions of these units are included in the appendix.

Liquid Reagents – Louisa Station

Mercury Removal

Baseline testing (no ADA-37 or KNX injection) was conducted January 31–February 2 and February 12–13, 2006. ADA-37 testing was conducted February 3–8, 2006, and KNX evaluations were conducted February 9–11, 2006.

ADA-37 Tests

The ADA-37 testing consisted of injecting the flue gas conditioning reagent at rates of 6, 12, and 18 gallons per hour for two days per rate and observing the change in mercury levels across the ESP. The data suggest that there was no change in mercury removal with varying ADA-37 injection rates, including periods with no injection. The flue gas temperature at the inlet to the air preheater was typically between 780 and 800 ºF during full-load conditions.

ALSTOM KNX Tests

The addition of KNX to the coal increased the fraction of oxidized mercury at both the inlet to the ESP and the stack. At an injection rate of 3 gallons per hour, the fraction of oxidized mercury at the inlet to the ESP increased from less than 15% to between 30 and 45%. At 8 gallons per hour KNX, the fraction of oxidized mercury at the inlet to the ESP was nearly 50%. At the stack, the fraction of oxidized mercury was between 30 and 50% without KNX, 68 to 77% at 3 gallons per hour, and over 80% at 8 gallons per hour.

The addition of KNX did not change the mercury removal across the ESP. The increased fraction of oxidized mercury may be beneficial if Louisa were configured with a wet scrubber. In such a case, a portion of the oxidized mercury may be removed in the scrubber.

ESP Performance

The normal flue gas conditioning injection rate is 12 gallons per hour, which the plant injects at a constant rate independent of unit load. During this program, ADA-37 was shut off for periods up to 56 hours and injection rates of 6, 12, and 18 gallons per hour were tested for 48-hour increments. The ESP was offline for a cleaning just prior to the DOE test program and there was sufficient ESP preconditioning so that the plant did not see any change in ESP performance or plant opacity when operating with no reagent injection.

Solid Sorbents – Council Bluffs Energy Center

Several sorbents were screened for their effectiveness to remove mercury in a fixed-bed device during the week of April 17, 2006. Figure 1 shows the results of the Council Bluffs Unit 2 sorbent screening tests. The "sorbent traps" were standard EPA Method 30B traps placed downstream of the test sorbent beds. The test beds were placed in the duct and the "sorbent beds" were maintained at a lower temperature downstream in the test apparatus. The results are indicated in ηg/g mercury captured per gram of sorbent. The higher the capture in the test bed, the lower the capture in the sorbent trap. At CBEC, the two-hour test runs were long enough for full breakthrough into the sorbent bed. The results indicate that there is very little mercury captured in any of the test beds, indicating low likelihood that these materials would result in significant removal if injected hot-side. For comparison, most of the mercury is captured in the test bed during cold-side sorbent screening tests with effective sorbents.

The following manufacturers provided sorbent for the screening tests at CBEC: Calgon, CarboChem, Frontier GeoSciences, General Technologies SPC, Norit Americas, and TDA Research. Ash was also collected from CBEC and tested as a baseline sorbent. All the sorbents screened were carbon based, ranging from baseline PAC to standard brominated PAC and including experimental PAC treatments.

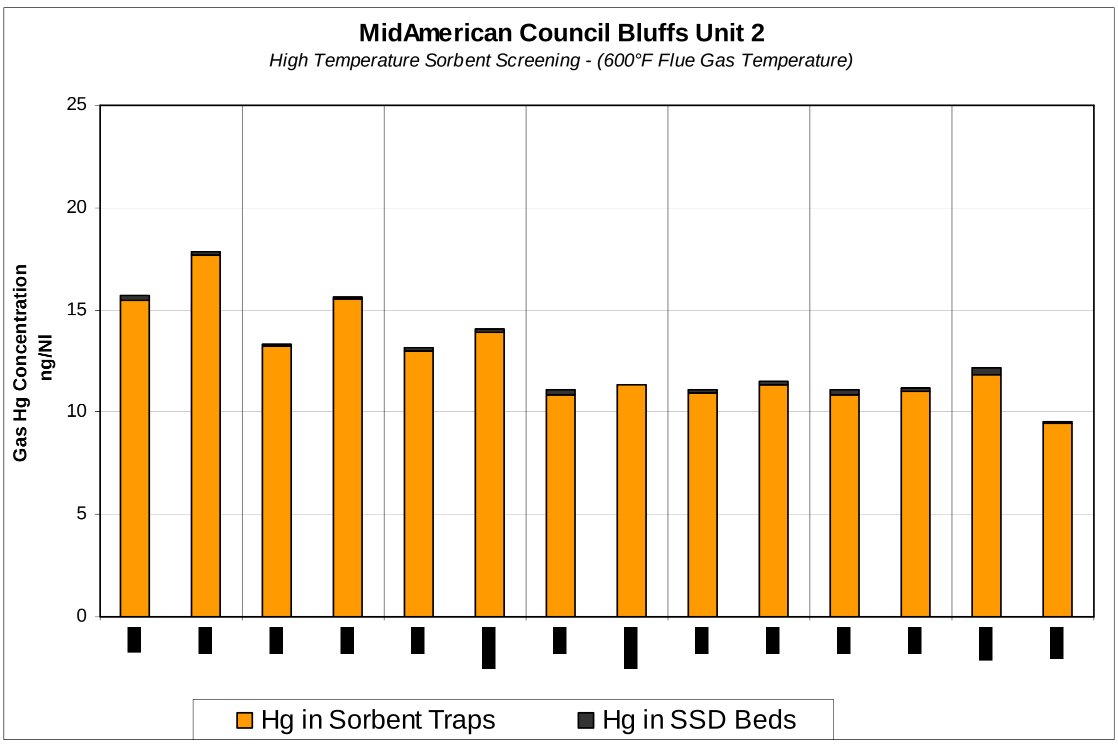

Figure 1. MidAmerican CBEC Unit 2 High-Temperature Sorbent Screening Results.

Based on the results of the sorbent screening tests, none of the reagents/sorbents showed significant levels of mercury capture in the test beds for any of the four sorbents screened. MidAmerican did not support additional testing of any of these sorbents due to the limited potential demonstrated by the test results in 2006. The DOE subsequently removed funding from this program in 2007 as part of the budget readjustments in the mercury control program.

TOXECON II™ MERCURY CONTROL TESTING

TOXECON II™ Technology and Test Description

The bulk of the effort during this project was at Independence Station and was expanded through reallocation of DOE funds and additional funding from EPRI and Industry. The project team selected Independence Unit 2 as the TOXECON II™ test site because it was representative of a significant number of coal-fired plants constructed from 1970 to 1990. Independence is configured with a cold-side, medium-sized ESP (SCA = 542 ft^2/kacfm) and fires pulverized PRB coal. Moreover, the ESP is controlled by a Neundorfer control system, thus enabling several parameters to be monitored.

TOXECON II™ is a retrofit mercury control technology that requires minimal capital investment because it requires only retrofits to the ESP for the sorbent injection system instead of installing a separate, secondary particulate control device. A sketch of the concept is shown in Figure 2. The primary benefit of the TOXECON II™ process is that typically 90+% of the fly ash is collected in the ESP prior to sorbent injection. With TOXECON II™, sorbent is injected between the mechanical collection fields of an ESP, generally after the first two fields, allowing the untreated ash to be segregated from the treated sorbent/ash mixture through the design of the ash handling system. Thus, the advantage for plants, such as Independence, that typically sell fly ash for use in concrete is that TOXECON II™ maintains the salability of most of the ash.

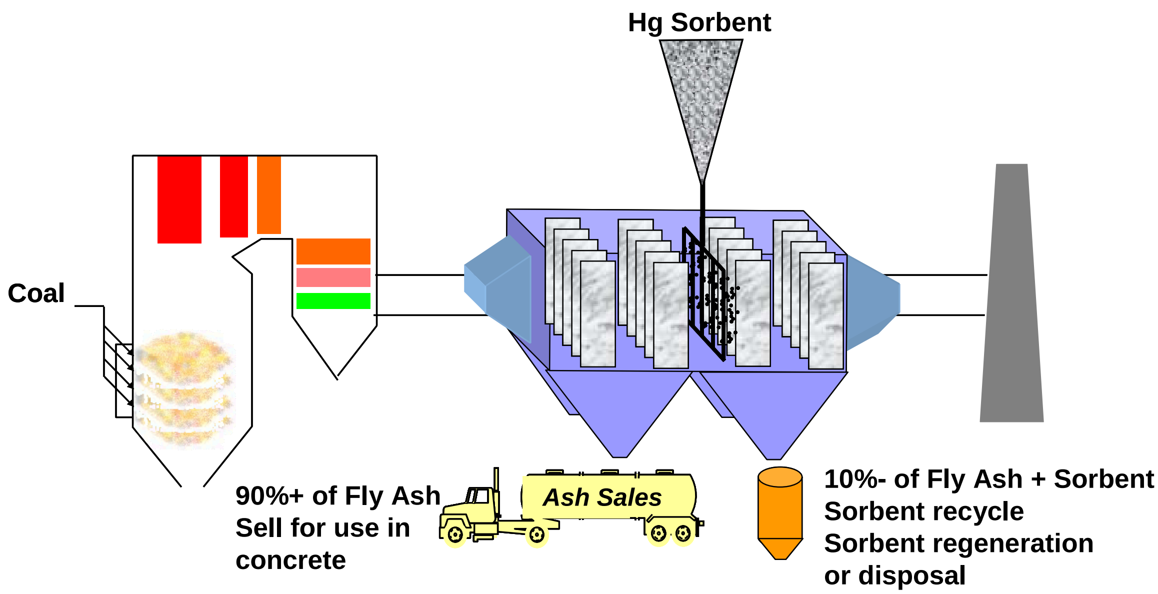

Figure 2. TOXECON II™ General Arrangement.

Limited data are available for mercury removal using the TOXECON II™ injection configuration. In an earlier short-term test at Great River Energy’s Coal Creek Station (a lignite-coal-burning plant), TOXECON II™ showed a 50% reduction in mercury emissions at sorbent injection rates of 1.25 lb/MMacf. With these results, the overall mercury removal costs are only 10–15% of what was estimated in the DOE and Environmental Protection Agency (EPA) cost projections. The project at Independence provided the opportunity to evaluate sorbent injection using the TOXECON II™ injection system through both short-term parametric testing and over a 30-day continuous injection testing periods. The long-term testing periods were aimed at identifying balance-of-plant impacts that may not be apparent during the shorter parametric tests.

The evaluation at Independence Unit 2 focused on activated carbon injection (ACI) using treated and untreated sorbents and the potential of increasing particulate pass-through of the ESP using the TOXECON II™ system. Reinjection of collected sorbent/ash mixture was also evaluated for mercury control.

Preliminary analyses indicated that the TOXECON II™ process required higher-than-expected sorbent concentrations to achieve significant mercury removal at Independence. Consequently, the test team established an additional objective: evaluate the possibility that the sorbent injection grid failed to distribute sorbent uniformly or its injection nozzles became plugged.

To determine further whether the sorbent usage requirements were a result of poor sorbent distribution, EPRI funded three independent modeling efforts:

1. Computational Fluid Dynamics (CFD) modeling by Reaction Engineering International
2. Physical modeling of the ESP and injection grid by NELS Consulting Services
3. Physical modeling of the lance design by ADA-ES

An outcome of the modeling efforts included redesigning the sorbent injection grid and delivery system and its subsequent evaluation. The results of this follow-on test program are also presented here. Most of the early evaluations were conducted on 1/8 of the 880-MW Unit 2 flue gas stream; later evaluations were generally on 1/16 or 1/32 of the unit (see Appendix A, Independence Test Plans, of the Independence Topical Report).[2]

Independence Steam Electric Station Site Description

The ESP for Unit 2 has four boxes arranged in a piggyback configuration, two on top and two on the bottom, operating in parallel. Approximately one-fourth of the total flue gas stream passes through each box. At the inlet and outlet of each box, the ducts are split into two separate ducts. Due to the duct arrangement and box construction, the crossover of the flue gas between the two halves of a box is minimized. Thus, one box can serve as both test and control. Injection grids were installed in one-half of the Unit 2 B ESP (a bottom box) to treat one-eighth of the total flue gas flow. In early 2007, a smaller portion of the test box was used to treat 1/32 to 1/16 of the Unit 2 flue gas. During most of the testing at Independence, activated carbon was injected after the first two of four ESP collection fields, as shown in Figure 3. Mercury removal was also characterized at two other injection locations: upstream of the ESP and between the third and fourth collection fields.

A key feature of Independence Unit 2 that supported mercury control testing is that it has the ability to modify its fly ash collection procedure. A percentage of the fly ash becomes mixed with sorbent downstream of the injection grid during the TOXECON II™ process. Because the sorbent/fly ash mixture from each row of collection hoppers could be separately collected, Entergy maintained the option to sell most of their fly ash and the effectiveness of recycling the sorbent/fly ash mixture could be tested.

The physical layout of the ESP and combination of control features allowed the TOXECON II™ process to be evaluated in two following configurations: the first with PAC injection upstream of two collection fields and an effective SCA = 270 ft^2/kacfm and the second with injection upstream of a single collection field and an effective SCA = 135 ft^2/kacfm. Independence is operated as a swing load unit, therefore responding to rapid, large swings in load conditions, allowing further evaluation of the performance of the mercury removal system.

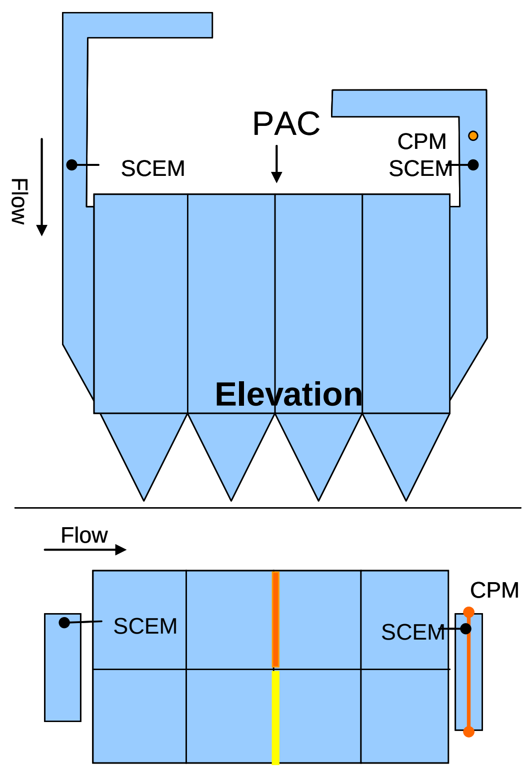

Figure 3. West Half of the Unit 2 B ESP (1/8 of the Unit 2 Flue Gas) with Mid-ESP Injection and Inlet/Outlet Monitor Locations Indicated.

Results and Discussion

The initial field-testing program of the TOXECON II™ system at Independence was divided into three periods: baseline, parametric, and long-term. Details on specific tests are included in the Independence Topical Report.[2] During baseline testing, no sorbent was injected into the ESP. During parametric testing, the mercury removal performance of four sorbents was evaluated. During long-term testing, the performance of one sorbent was evaluated during a 30-day continuous injection period. Summary results from each test series are included in this section. The program was extended to include modeling of the sorbent injection grid and subsequent redesign of the grid and delivery system. Ash/carbon recycling tests were also conducted as part of the initial field-test program and the results are presented below.

Baseline Mercury Removal

Four rounds of baseline tests (no sorbent injection) were conducted: (1) August 15–21, 2005; (2) September 28–30, 2005; (3) January 15, 2007; and (4) January 29–February 4, 2007. Prior to the first round of tests, some data were also gathered from August 6–14, 2005. As expected, a PRB plant using a cold-side ESP for particulate control had low native removal capability. The Ontario Hydro results (taken during the first round of testing) showed an average removal efficiency of 12.2%.

Parametric and Long-Term Mercury Removal Results

Parametric testing to evaluate the performance of four different sorbents was undertaken in three stages. The first stage was conducted in late August 2005 with the ESP outlet field, T/R Field B-7, out of service and one of the middle fields, T/R Field B-3, in a reduced capacity. This stage was followed by a two-day set of limited tests in early September 2005 to confirm particulate/opacity readings from the first stage of testing. A complete series of parametric testing following the original test plan scheme was completed in early October 2005 when Field B-7 was again in service. During testing, the varying power levels for field B-3 had no correlation with varying vapor-phase mercury removal trends.

When it became apparent that the original PAC injection and delivery system did not provide sufficient PAC distribution, the system was redesigned. After the redesigned injection grid was constructed, a final stage of parametric tests was completed in January 2007. The results from these various stages of testing follow. For each stage, a description of the injection grid design is included for reference.

Stages I and II – Initial Grid Design

Based on the positive mercury removal results during a test performed by ADA-ES at Great River Energy's Coal Creek Station, the initial decision was made to install a similar grid at Independence Unit 2.[3] The dimensional changes from plant to plant were minimal, on the magnitude of 2–3 feet per each injector grid section, both lengthwise as well as in depth. There was no modeling performed prior to the Independence grid installation, again based on the Coal Creek results and previous modeling in support of that project.

The initial grid design was simple. As with injection systems located upstream of the ESP, the goal was to provide adequate sorbent distribution to allow contact and residence time between the sorbent and the flue-gas-entrained vapor-phase mercury. With a TOXECON II™ delivery system, the problem is more complex in comparison to a high-velocity duct distribution grid—the larger cross-sectional area of coverage, the lower flue gas velocities, the potential for significantly higher relative biases from top-to-bottom and side-to-side in flue gas velocity through the ESP, the potential for hopper carry-over with less collection area available for recapture of the sorbent, the relatively higher nozzle exit velocities in comparison to the flue gas flow, the lower conveying air flows resultant from large distribution grids and therefore less carrying capacity for sorbent, and the inherent biases in multi-port distribution along the path of the lance.

The initial grid design was installed at two locations at Independence: in between the second and third mechanical collection fields and then between the third and fourth mechanical collection fields. For Independence, this design layout resulted in a mid-ESP injection grid and an outlet field injection grid location. To cover the cross-sectional area of the ESP box, a multi-nozzle lance was installed, consisting of a single lance per penetration running from top to bottom of the ESP with equidistant holes alternating from side to side with sorbent penetration configured perpendicular to the flue gas flow (see Figure 4). Several nozzles were slightly offset to prevent interference with structural support members. Each lance was designed to operate with equal nozzle exit flows from top to bottom of the lance. Therefore, the lance was configured with three different pipe diameters from top to bottom and three different nozzle sizes. The larger diameter pipe was matched with the smaller size holes to achieve the equal exit nozzle flow design concept.

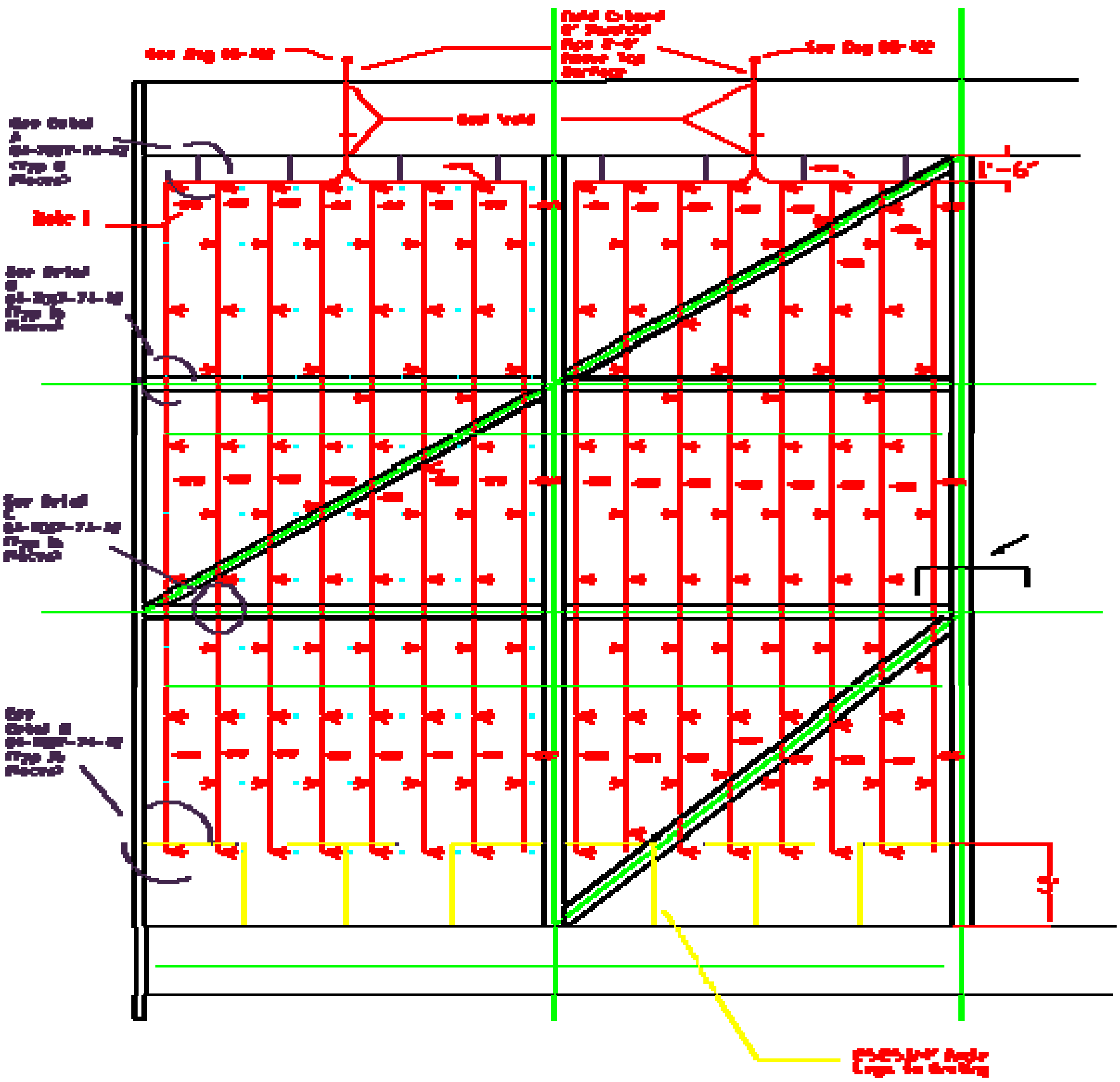

Figure 4. Initial Grid Design Plan.

Multi-Hole Lance Grid Performance

The initial parametric test was conducted in August 2005 and consisted of four days of testing, one for each type of PAC. As mentioned previously, ESP TR field set B-3 was operating at reduced or shutoff power levels and field B-7 was non-operational during the first stage of parametric testing (August 21–25, 2005). Consequently, sorbent was injected mid-box (i.e., between Fields B-3 and B-5). Figure 5 shows box-whisker plots of the average total vapor-phase mercury removal efficiency of the four different test sorbents at various injection concentrations during August 2005.

Initial parametric results at Independence were promising. Mercury removals above 75% with both a standard and a brominated sorbent, Norit's DARCO® Hg and Hg-LH, were achieved. Since Independence fires PRB coal, brominated carbon was expected to provide better mercury removal than standard PAC. Oxidation of mercury across the ESP could have contributed to the enhanced mercury removal with standard PAC. Mercury measurements at the inlet and outlet of the ESP without PAC injection indicated less than 10% oxidation at the ESP inlet to 50–60% oxidation at the ESP outlet. The large ESP with potential back-corona effects could have contributed to the increase in oxidized mercury. Since PAC was injected mid-ESP at Independence, and since standard PAC is effective at removing oxidized mercury in low-halogen environments, the resulting difference in mercury removal performance between PAC and brominated PAC may have been minimized during these initial tests.

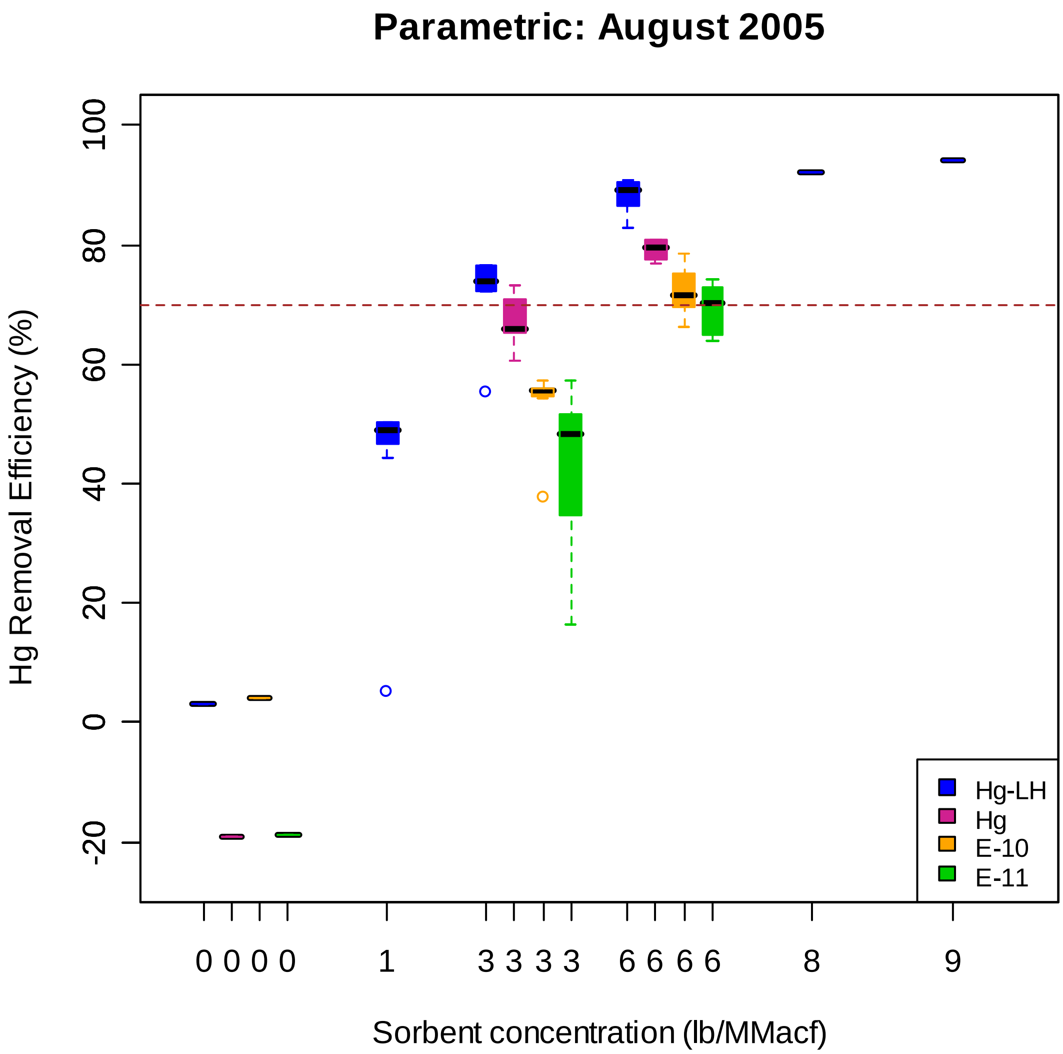

Figure 5. Comparison of Sorbent Performance During the First Set of Parametric Tests (mid-box injection, field B-7 down, field B-3 low/no power, dashed line at 70%).

An unscheduled outage in late September 2005 allowed the plant to repair field B-7. During this outage, ADA-ES was on site to perform a visual inspection of the injection grid. Access to the grids included the upper and lower sections of the field B-7 grid and the lower sections of the field B-5 grid. Internally, the vertical lances appeared to be clean, with the lower injection ports being clean and free of any material. There was some buildup of ash on the leading and trailing edges of the injection lances, but the lance sides perpendicular to the flue gas flow, where the injection ports are located, were clean.

Based on the visual inspection, the performance during the first parametric testing, and using the previous TOXECON II™ system results as a guide, there was little evidence to suggest any issues with PAC distribution at this time in testing.

Another issue immediately apparent was the relative impacts on opacity that each sorbent had. The brominated sorbent demonstrated a significantly lower opacity impact than the standard PAC.

Stage II

Parametric tests were continued after ESP field B-7 was repaired. The test sorbents were injected in the rear of the ESP B-Box, between fields B-5 and B-7, and their performance evaluated at different concentration levels. From this stage onwards, readings of mercury levels across both the test and control side of ESP B-Box were taken (total vapor-phase mercury only). All inlet S-CEM mercury measurements were taken on the vertical duct on the ESP B test side. Outlet mercury measurements were taken on the vertical outlet ducts on both the control side and test side of ESP B. Monitoring the control side outlet gave a continuing verification of the native removal without PAC injection.

It is worth noting that the results from the first two stages of parametric testing indicate that a particular sorbent, its concentration, and the injection location impact mercury removal efficiency across the ESP. Several comments on the comparative performance of the sorbents follow.

Norit's DARCO® Hg-LH compared favorably to the benchmark test sorbent, DARCO® Hg, and its derivatives, Hg E-10 and E-11. The two derivatives of DARCO® Hg are test products designed to study the impacts of particle sizing on particulate pass-through and opacity. The two products were not designed to enhance the mercury removal capability of DARCO® Hg. Specifically, Norit predicted prior to testing that the two derivative PAC materials would not perform as well as the baseline DARCO® Hg.

Although DARCO® Hg-LH exhibited higher mercury removal efficiency than DARCO® Hg, its relative performance was not as favorable as expected for a site firing a PRB coal and configured with an ESP. Performance limitations resulting from poor sorbent distribution may have limited the relative difference between the sorbents.

In general, sorbents performed better when injected at the ESP mid-box location and in higher concentrations. An exception was the injection of DARCO® Hg-LH at low concentrations (0.5 to 1 lb/MMacf), where injection in the rear-box grid outperformed injection in the mid-box (65.5% vs. 43.4%). Similarly, injection of DARCO® E-11 at a concentration of 3 lb/MMacf in the rear-box grid showed a slight improvement in performance over the mid-box location (48.9% vs. 43.7%). When DARCO® Hg-LH was injected simultaneously in both the mid-box and rear-box locations at 3 lb/MMacf, it performed slightly better than either the mid-box- or rear-box-only injections at the same concentration (73.1% vs. 71.3% and 68.8%, respectively), but this performance was still lower than when it was injected at higher concentrations in either the mid-box or rear-box locations.

During the second stage of parametric tests, relatively high levels of native mercury removal were observed directly prior to injecting DARCO® Hg and also DARCO® Hg-LH. As with all parametric testing, one potential pitfall of the test results was a failure to allow proper time for the system to reestablish baseline conditions prior to attempting to establish a new sorbent trend data point. Residual effects from the previous day's parametric run may partially account for the unusually high levels of mercury removal in the absence of sorbent injection and may also have influenced the relatively high performance observed at low injection concentrations.

Long-term testing started after the completion of the second parametric test runs. After several days of continuous injection, the mercury removal performance was no longer matching the performance established during parametric testing. The highest mercury removal achieved was now in the 60% range during full-load operations (parametric load equivalent), and there was a significant change in mercury removal as a result of load changes, with low-load conditions demonstrating 10–20% higher mercury removal than high-load conditions.

Internal inspections of the Independence ESP and internally mounted lances after the initial 30-day long-term test during subsequent outages revealed that the lower one-third of each lance was plugged and several lances had significantly higher pluggage percentages. Because of the pluggage and mercury removal/opacity performance issues, EPRI sponsored an additional program to model the ESP and lances to correlate with the full-scale results and determine potential remedies. These visual results were confirmed through physical modeling at NELS and ADA-ES.[2] CFD modeling by Reaction Engineering International modeled similar results with additional details about side-to-side distribution issues.[2]

Long-Term Mercury Removal

Based on the slightly better removal rates for the DARCO® Hg-LH, minimal opacity spiking during ESP plate rapping, and discussions with other project participants, DARCO® Hg-LH was chosen for all the long-term tests. The initial 30-day long-term test was carried out October 10–November 9, 2005. A follow-on long-term operational demonstration commenced mid-November through mid-December 2005, resumed at the end of January, and continued through early March 2006.

In general, mercury removal during the initial long-term testing during 2005 and 2006 was not as high as expected, based on previous results with the injection of brominated PAC injected upstream of the ESP at other PRB power plants and with parametric testing at Independence and Coal Creek. The average mercury removal during this period was 69.6 ± 13.8%.

A comparison of the average performance of DARCO® Hg and DARCO® Hg-LH at various injection concentrations during the 2005 parametric and long-term test sequences is shown in Figure 6. The higher removal rates during the long-term testing occurred during lower unit load, and the lower removal rates occurred during higher unit load. The points generally show that removal rate increases with injection concentration. This trend agrees with the general trends from other testing programs on PRB plants without SO_3 flue gas conditioning, although for the TOXECON II™ process, the required injection concentration for a given removal rate is higher.

A second comparison point evident in Figure 6 is the difference in removal between mid-ESP (F5) and rear-ESP (F7) injection locations. Injection in the mid-ESP grid typically demonstrated an improvement of 10% over rear-ESP injection through identical TOXECON II™ injection grids. The improvement appears to be due to the increased potential for contact time between the PAC and vapor-phase mercury as it passes through the collection fields of the ESP. A separate, but related, point of interest is the matching of the rap cycle downstream of the injection grids with sharply reduced mercury emissions. As the rap frees the entrained ash-PAC from the collection plate to fall to the hoppers, the PAC that is temporarily reentrained in the flue gas will add to the capture potential of the PAC that is being injected.

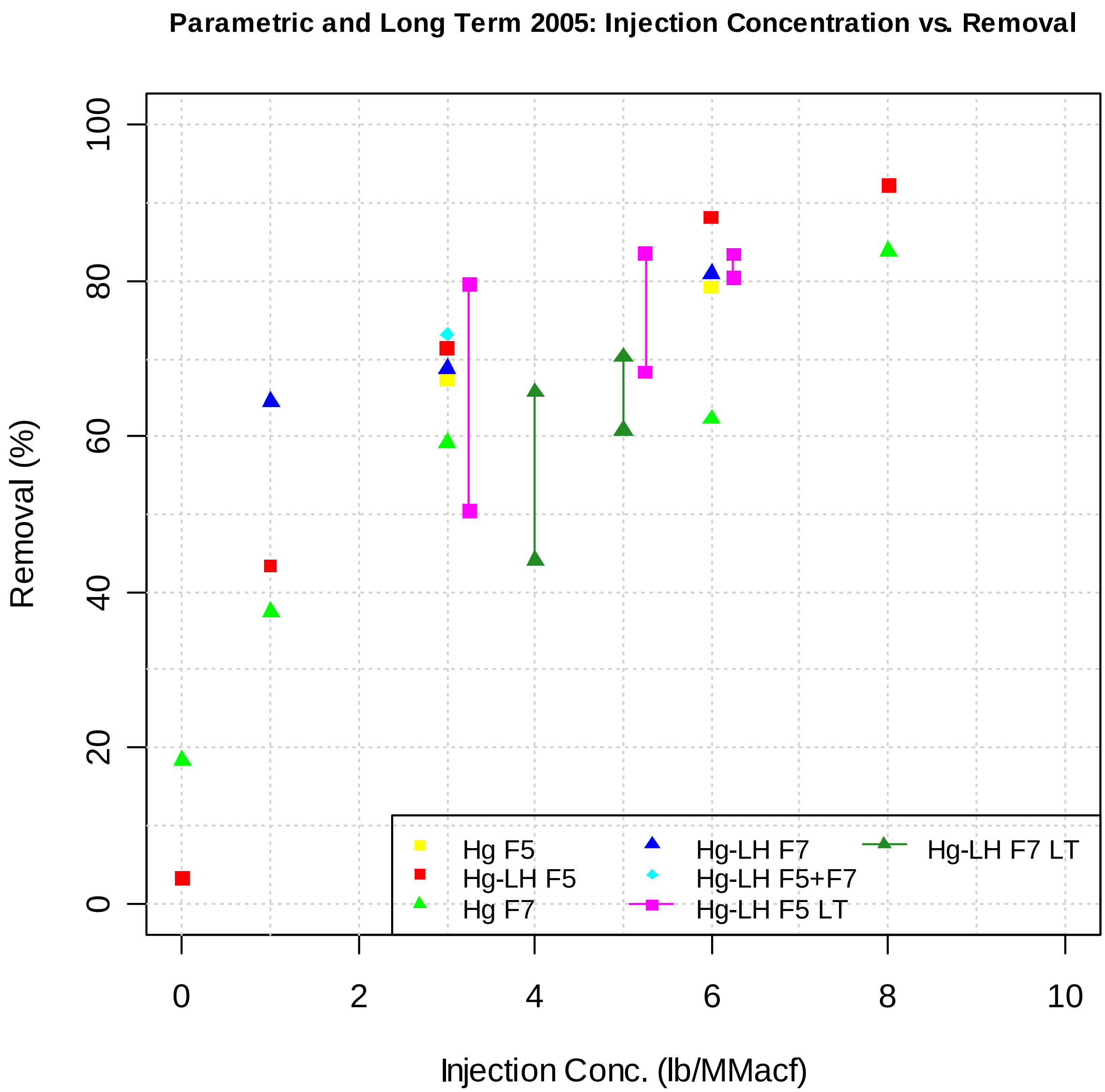

Figure 6. Comparison of DARCO® Hg and Hg-LH Performance from Parametric and Long-Term (LT) Tests at the Mid-ESP (F5) and Rear-ESP (F7) Injection Locations.

Another statistical anomaly is the difference in removal rates at the same injection concentrations between parametric testing and long-term testing. During the several parametric test sequences, removal rates approached those expected for a brominated PAC being injected upstream of an ESP on a plant firing PRB coal. The mercury removal measured during long-term testing was much lower. It is believed that the difference in performance is mainly a result of pluggage in the TOXECON II™ injection grid. There is extensive discussion concerning injection system design in the Independence Topical Report.[2]

The performance of DARCO® Hg compared to DARCO® Hg-LH during parametric testing is also interesting. Typically, injection of a bromine-treated PAC results in significantly better performance in a halogen-deficient gas stream, such as PRB-derived flue gas. At Independence, the mercury removal with DARCO® Hg was not significantly worse than the mercury removal achieved with DARCO® Hg-LH. It is likely that limitations resulting from poor sorbent distribution affected the performance. It is also possible that DARCO® Hg benefited from the high baseline mercury oxidation across the ESP, often as high as 60%. The traditional injection location is upstream of the ESP, where no corona-induced oxidized mercury is present. Thus, the TOXECON II™ configuration and the specific electrical characteristics of Independence may have contributed to the performance of DARCO® Hg. In Figure 7, the Coal Creek results are also included as reference for the removals at Independence.

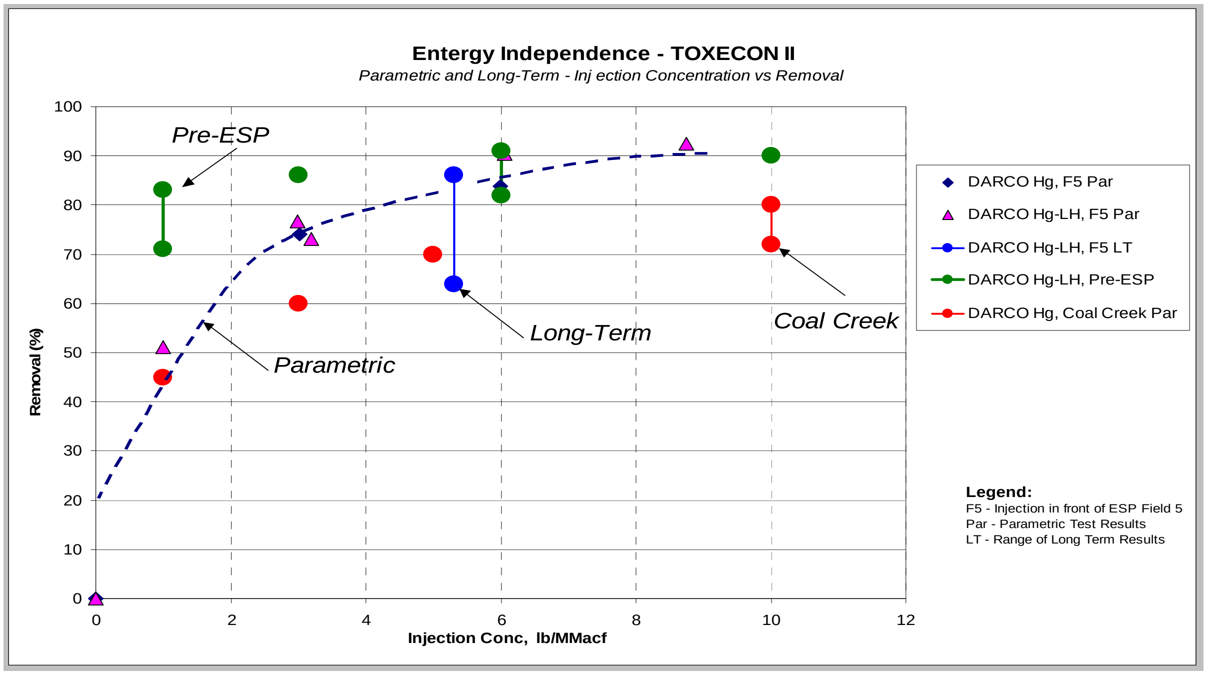

Figure 7. Varying Mercury Removal Performances.

Stage III – Redesigned Injection Grid

The third stage of parametric testing was conducted January 16–18, 2007, with repeat tests conducted on January 26 using DARCO® Hg-LH and a redesigned injection grid. The results indicate that the new lance design and conveying system was an improvement from the original lance design (see Figure 9).

Significant effort was expended during the TOXECON II™ program at Independence to optimize sorbent distribution, including redesign of the sorbent injection grid and delivery system. Lance improvements resulted from extensive modeling efforts by ADA-ES (physical), NELS (physical), and Reaction Engineering (CFD). Three lance designs were evaluated, including the original multi-nozzle lance. Based on the modeling results, design changes were implemented to improve the overall distribution of the PAC as well as to determine the effectiveness of changing conveying air parameters to match varying plant conditions.

The condensed summary of the modeling identified and confirmed that ensuring proper sorbent distribution is critical for effective mercury control. Good distribution is more challenging with TOXECON II™ than injection upstream of the ESP for three primary reasons:

1. The flue gas velocity within the ESP is typically 4–5 ft/sec compared to 40–50 ft/sec upstream of the ESP. The velocity in the ESP is reduced by increasing the cross sectional area in the direction of flow within the ESP. The increased cross sectional area requires a much larger sorbent injection grid and poses a greater challenge for proper sorbent distribution.

2. The penetration of the sorbent from the lance into the gas is affected by the velocity in the ESP. Consequently, varying boiler load can significantly impact the sorbent distribution.

3. The distance between the injection lances and the downstream collection field is limited to nominally 3 feet.

There were several significant stages in the modified designs to improve overall performance.

The first significant design modification was to shift from an internal grid to an exterior grid horizontal distribution manifold, with the horizontal grid placed outside the ESP box. This allowed several improved capabilities, the most significant of which was the ability to change out the TOXECON II™ vertical distribution grid without taking the unit offline. Precautions had to be taken to ensure worker safety, but the new design allowed several successful lance changes and inspections without waiting for an outage or requiring the unit to come offline for the testing program.

The most significant improvement was a change from one vertical lance per vertical distribution section to a three-section lance, with each lance section covering a smaller portion of the vertical section of the ESP (Figure 8). This greatly reduced the vertical biases in sorbent distribution.

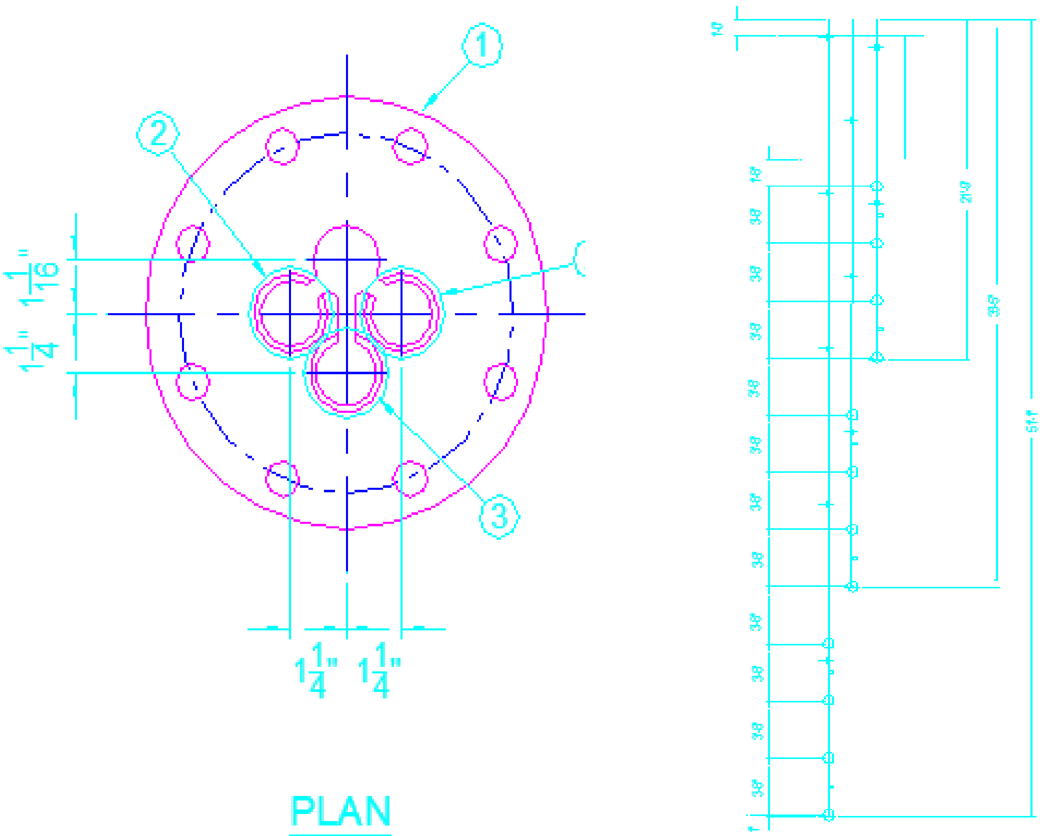

Figure 8. Three-Section Lance Top and Plan View.

In addition to the shift to three lances per port for vertical coverage, the nozzle holes were no longer orientated perpendicular to the flue gas flow. Based on testing done by ADA-ES, the nozzles were now orientated in a horizontal plane, usually symmetrical around the 0 theta angle (orientated to point directly upstream counter-flow to flue gas flow) to provide better cross-sectional coverage. Design consideration was given to nozzle style to improve coverage, with testing of various style nozzle heads, replaceable nozzles, and venture nozzles being considered. Design tests were performed to deviate from the horizontal plane to improve coverage as well.

Multi-Lance Grid Performance

In February and March 2007, tests with lances redesigned to improve the sorbent distribution yielded 89% mercury removal using DARCO® Hg-LH. In May 2007, the third lance design was evaluated. The mercury removal varied with boiler load from 78% (high boiler load) to 92% (low boiler load). Performance was significantly improved from the original lance design (Figure 9).

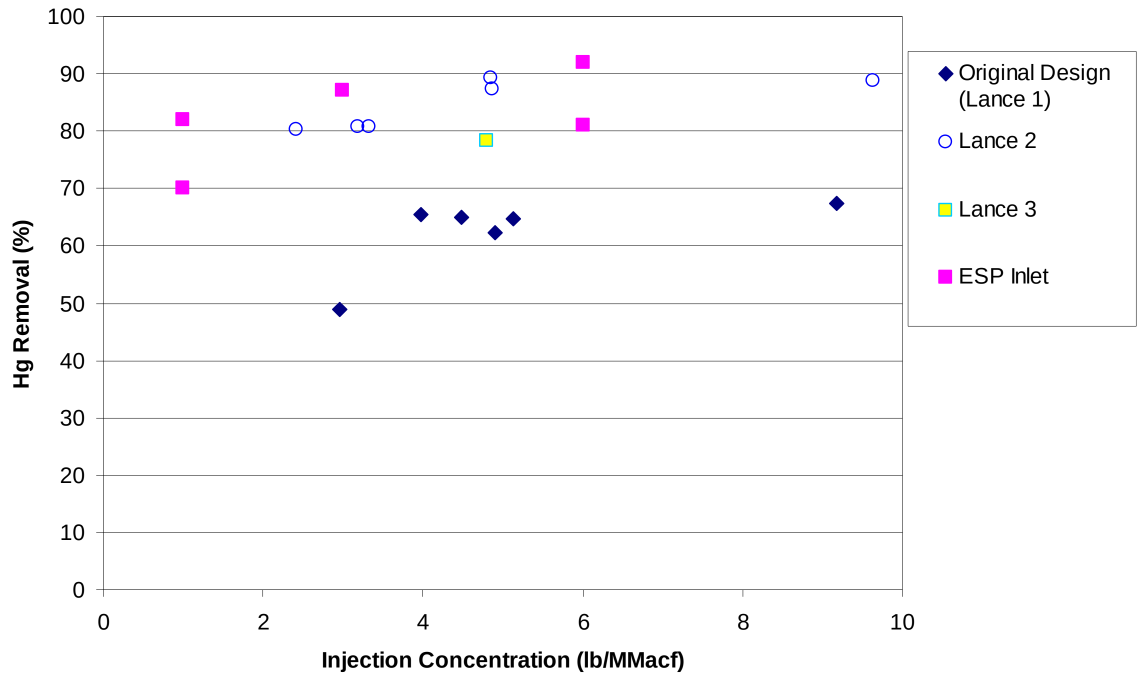

Figure 9. Lance Design Improvements.

The long-term reliability of the system was also improved, although there still were indications that settling in the lances (with the potential for pluggage) was slowly occurring. The shift to a nozzle head design seemed to have mitigated this settling issue, but long-term testing with the design is required to ensure reliable commercial viability.

The mercury removal achieved with the new lance designs was within the range expected based upon results achieved with injection upstream of the ESP (see Figure 9). Operational issues, such as sorbent settling and plugging the conveying system, were encountered with the later lance designs. It is expected that these issues would be overcome if the conveying system were redesigned for the operating requirements of the upgraded lances. It is possible that improved mercury removal performance could also be achieved if the conveying system were modified to overcome operational issues.

Extended Test with Redesigned Grid

Based upon the positive results achieved during 2007 parametric testing, the decision was made to continue testing for a 30-day trial to evaluate long-term removal trends and operational constraints on the new lance design.

A summary of the mercury removal achieved during the 30-day test is shown in Figure 10. Data from previous test periods are included for reference. As shown, the mercury removal with the TOXECON II™ arrangement and the modified lances was similar to the removal achieved with injection upstream of the ESP. Little difference in mercury removal performance was observed across a wide range of PAC injection system operating parameters.

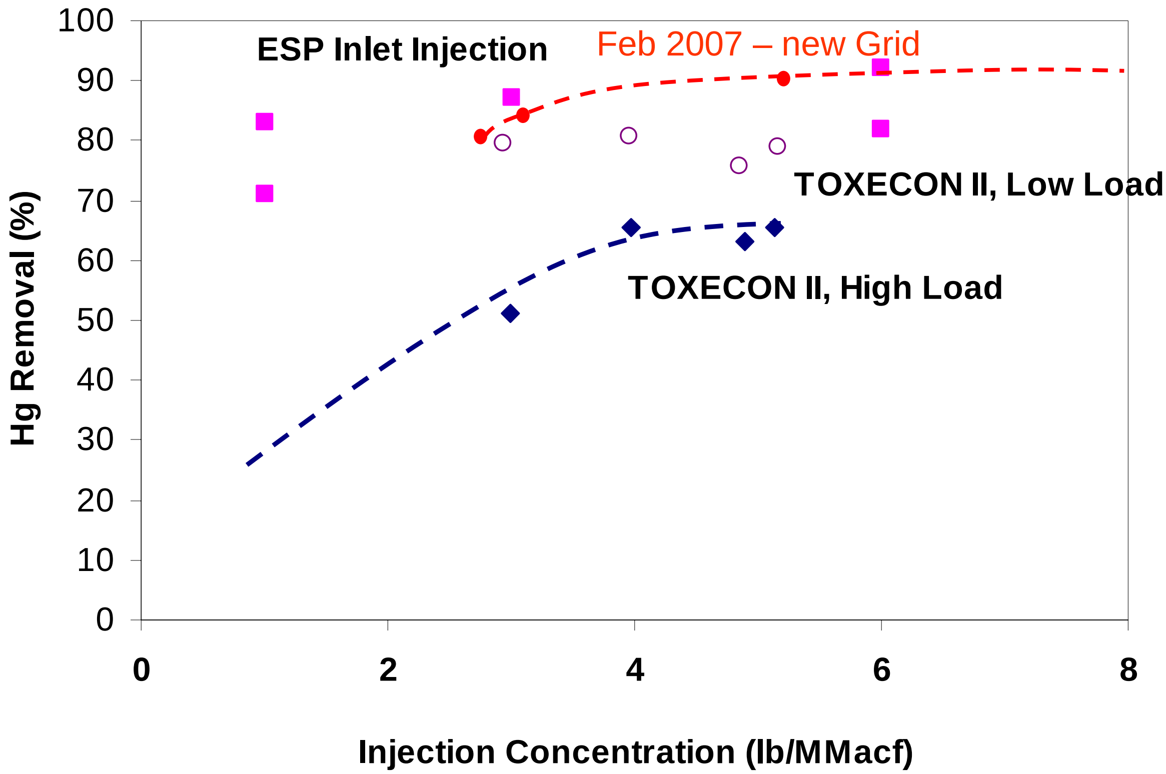

Figure 10. Mercury Removal Comparison of Injection Location and Grid Design.

Ash-Carbon Recycle Test Results

During one series of tests from November 9–13, 2005, a mixture of collected ash containing PAC was reinjected into the ESP. The recycled mixture was initially estimated to contain approximately 20–30% carbon, based on the average percent loss on ignition (LOI) results of ash samples that were taken from the rear hoppers during parametric and long-term testing. Based on later ash analysis from the actual injection material, the PAC percentage could have been as low as 12%.

Some challenges operating the injection system were encountered during the recycle test. Differences in material handling characteristics and density of the mixture compared to either ash or carbon alone were noted during the ash-carbon recycle test at Independence. The recycle test sequence was curtailed when it was evident that the recycle material was not entering the ESP test fields. A subsequent inspection of the injection grid revealed that the ash-carbon mixture had plugged the injection lances, particularly in the lower section of the injection grid. While the injection grid had experienced some pluggage during the long-term test using standard PAC materials for injection, the change in the composition of the injection material led to significantly increased plugging.

Consistent with the results from the long-term tests, the recycle mixture performance improved at low boiler loads. Overall, mercury removal during the ash-carbon recycle testing was considerably less than that observed when using DARCO® Hg-LH alone.[2] However, the concentration of carbon injected during the ash recycle sequence was much less than that during either the parametric or long-term tests.

Balance-of-Plant-Impacts

In conjunction with the mercury removal testing at Independence, the second parameter of concern was the potential of the TOXECON II™ configuration to affect other balance-of-plant issues. The primary concern was whether injecting PAC within the ESP would effect the operation of the ESP and the subsequent particulate emissions. Since the ESP collects the majority of the ash in the first fields, the ash loading in the rear ESP fields is significantly less than in the first fields. In the case of Independence, the first two fields remove 96% of the incoming fly ash based on data collected from the Neundorfer ash collection data system. Thus, the collection efficiency of the rear ESP fields is more dependent on the properties of the sorbent-ash mixture rather than just the ash because the sorbent comprises a significant fraction of the total mixture. The carbon content of the third collection field increased by 20–30% when injecting using the mid-ESP injection grid, indicating that the particulate loading to the third collection field increased by approximately 30–40%, since DARCO® PAC contains nominally 30% ash. The particulate loading percentage was higher when injecting in the rear grid due to the lower levels of ash in the flue gas downstream of three collection fields. This mixture could have a significantly different resistivity than ash alone, which could affect collection efficiency. Carbon may also migrate from hopper to hopper because of the density difference between the carbon and the ash. Additionally, sorbent injection in the mid-ESP will increase the particulate loading in the rear fields, which can further affect total particulate exiting the fields.

Particulate emissions were monitored during testing at Independence using three techniques: periodic EPA Method 5 and 17 measurements (see Appendix D, Source Testing, of the Independence Topical Report), TEOM 7000 continuous particulate monitor measurements, and CPM 5000 measurements.[2] Stack opacity was also monitored, but was not as useful because only 1/32 to 1/8 of the Unit 2 flow was treated with PAC. The TEOM 7000 was used periodically through the second round of parametric testing until weather-related equipment problems were encountered. When compared to a Method 5 on the outlet duct during the baseline test period, the TEOM 7000 was reading within 10% of the Method 17 results. These measurements were not collected concurrently because the TEOM 7000 was removed during Method 5 measurements to allow a traverse of the duct.

Baseline ESP Performance

Stack opacity and ESP parameters such as particulate emissions, power levels, and spark rates during the baseline test series were of interest in establishing benchmarks against which the performance of the parametric and long-term tests could be measured. Recall that the ESP B-box electrical field B-7 was non-operational during the August 2005 test period and well into September 2005.

Parametric ESP Performance

The data indicate that during the August and September tests, injection of any sorbent resulted in both opacity and CPM spikes. Although PAC was injected into only 1/8 of Unit 2, each time the ESP-B test side outlet field was rapped during August and September while PAC was injected into either Field 5 or 7, the spikes were clearly visible on the stack opacity.

Based on the August 2005 trend charts, DARCO® Hg-LH appeared to have slightly less impact on ESP operation than DARCO® Hg or the two derivative DARCO® Hg materials, E-10 and E-11. To verify the observed trends at Independence, a two-day supplemental test sequence was carried out in early September 2005. During the supplemental testing, the order of testing was reversed from the August test order, with DARCO® Hg-LH being injected in the middle of ESP B-box on September 8, and DARCO® Hg on September 9, 2005. No changes were made in the ESP power optimization system (POS). Later data suggest that the POS was not optimized for PAC injection. During injection, the power levels in the T/R sets would often spike up, followed by a period when the power levels returned to a fairly low level. If a rap occurred during the period with low power, there was often a spike in the CPM and opacity measurements.

Higher concentrations of DARCO® Hg were associated with increased opacity values when the POS system was operating, especially when the sorbent was injected in the rear injection location (i.e., between F5 and F7). During the October 2005 test sequence, unusually high particulate and opacity spiking was observed during the injection of DARCO® Hg and its derivatives, E-10 and E-11, on October 1–4 while the POS was in operation. The POS was disabled for the remaining PAC injection tests (October 5–8) and the power levels on Fields 5 and 7 were increased. This change in ESP operation minimized but did not completely eliminate the spikes in the CPM and Unit 2 opacity measurements during PAC injection (DARCO® Hg-LH).

Long-Term ESP Performance

Based on the 2005 parametric test results, it was expected that DARCO® Hg-LH would have a lesser impact on ESP performance during long-term testing. As mentioned previously, the initial long-term test sequence was divided into two main phases. During the first phase, sorbent was injected between the last two fields on the test side of ESP B-Box. During the second phase, injection was shifted to mid-box (i.e., between the second and third fields).

During the second day of Phase I long-term testing, Independence plant personnel expressed concern over the increase in the 6-minute average as well as the peak opacity being reached when using the 10-second instantaneous opacity results. Opacity levels were exceeding 20% at high boiler loads. The high opacity values were spikes that coincided with rapping which occurred every hour and lasted for 140 seconds. After shifting to the mid-ESP injection grid, opacity spiking was significantly decreased. During the last few days of October 2005 testing when the CPM and opacity monitor recorded few spikes resulting from DARCO® Hg-LH injection, B-F5 power was typically between 60 and 80 kW.[2] B-F7 power was typically near 100 kW. During the initial long-term testing period, the B-F7 power was less than 80 kW. This was a direct result of the plant removing the rear fields downstream of the injection point from POS control and placing them in manual control at the highest power appropriate with minimizing back corona effects.

Manual Particulate Measurements

One of the difficulties involved with the test program at Independence was determining a means to accurately measure particulate emissions. The two triggers for New Source Review (NSR) for particulate emissions at Independence are 25 tons/year PM increase and 15 tons/yr

PM10 increase. The corresponding contribution of the ESP-B outlet duct particulate loading that would result in a NSR is approximately 0.839 lb/hr at full load. This level is within the typical run-to-run variation of standard 1-hour EPA Method 5 or Method 17 tests. In an effort to reduce run-to-run "noise," 6-hour Method 5 tests were run both at the stack and at the ESP B outlet duct during the 2007 tests. One run was conducted per day for 5 consecutive days. Results from testing at the stack and at the outlet of the ESP control and test-side B ESP boxes are presented in Table 3. This data indicate that PAC injection was increasing particulate loading enough to trigger an NSR. Conversely, comparison of the continuous particulate monitor data between periods with and without injection does not support that PAC injection results in an increase in particulate emissions unless the ESP power is not optimized and rapping the final collection field is causing particulate spikes. Further testing needs to be conducted to provide performance parameters for the TOXECON II™ injection system with regard to particulate pass through.

Table 3. 2007 Method of 5 PM Measurements.

2007 Method 5 PM Measurements — Baseline and Injection Periods (lb/hr)							
Location	**Condition**	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Average**
Stack	Baseline	13.78	16.84	14.80	13.24	15.13	14.76
Stack	PAC Injection	15.45	17.58				16.51
ESP B Outlet Duct	PAC Injection	25.58	23.23	19.73	20.25	32.46	24.25
ESP B Outlet Duct	Control Side (No Injection)	31.91	22.56	15.84	14.48	19.24	20.81

Ash Sales

One of the primary advantages of TOXECON II™ for mercury control is to preserve the bulk of the fly ash at a saleable quality. During TOXECON II™ testing at Independence, all ash captured in the first two collection fields was sold for use in concrete. This represented the bulk of the ash collected from Unit 2. The balance of the ash, which contained PAC, was landfilled after a leaching analysis was performed (refer to the Independence Topical Report for detailed analysis) and the ash met criteria established by the State of Arkansas.[2]

A question that has been discussed within the project team, based upon concerns from an ash contractor, is whether the size distribution and resulting concrete properties will be adversely affected if the rear field ash is not included in the ash delivered for concrete use. The size distribution of ash collected in the first two fields, the material available for ash sale, was analyzed. Although there was a shift from the inlet hopper (B12) to the second hopper (B22), the distribution was fairly uniform. The ash from the inlet field represented the bulk of the fly ash captured in the ESP. Ash collected in the third and fourth fields represented at most four percent of the overall ash captured and it was unlikely that not including this in the ash provided for concrete use would impact the overall properties of the ash for this use.

Plant Suitability Considerations

There are several key criteria that must be assessed when considering implementing a TOXECON II™ system. First, offsetting ash disposal costs through ash sales must be an important component of the plant's operating budget. A TOXECON II™ installation will be more complicated and expensive to install and operate than a standard ESP inlet installation due to the size of the injection grid, the lance design details required for proper distribution, additional conveying air requirements, and potential increased maintenance requirements resulting from the larger and more complex design. If the ash sales specification is based upon concrete suitability parameters such as foam index tests or hardness and do not include a color specification, some specialty carbons or on-site enhancement technologies may also be an option.

If TOXECON™ is identified as the most promising alternative, there are several components of plant design that will ensure a greater chance of success than others.

ESP Size

At ISES, the ESPs were medium-large with an SCA of 542 ft2/kacfm. The velocity in the ESP was low at 3.3 fps per design. The spacing between the mechanical collection plates was close to three feet. Although there was structural steel located between the ESP collection plates, there was still enough room to situate the lances to allow for a straight vertical run from top to bottom, or bottom to top, of the ESP that allowed for regular lance maintenance.

Ash Separation

ISES also had the ability to collect the PAC-ash mixtures in a separate silo, allowing unhindered sale of the ash collected upstream of the injection grid.

T/R Set and Other ESP Controls

ISES also had the ability to discretely control individual collection field power levels to improving the collection efficiency. The rapping sequence could also be controlled to limit rap induced particulate emissions spikes.

ESP Baffles

Physical modeling of the ISES ESP at NELS identified the need for baffles mounted at the bottom of the ESP to prevent hopper carry-over and indicated that baffling at the outlet of the ESP might have allowed a more even flow of flue gas.

The best potential sites for TOXECON II™ are those with larger ESPs and clear access to the open areas within the ESP between the mechanical collection plates. Low flue gas velocities are generally be preferable to higher velocity ESPs. Properly installed hopper baffles should assist in minimizing the carry-over of PAC from hopper to hopper. The ability to isolate individual hoppers and individually control ESP power levels for separate fields would also be beneficial design features.

ECONOMIC ANALYSIS

Louisa Cost Analysis

No cost analysis performed at Louisa due to failure to attain project goals.

Council Bluffs Cost Analysis

No cost analysis performed at Council Bluffs Energy Center due to failure to attain project goals with the solid sorbent screening tests and the lack of DOE/NETL funding for FY 2008.

Independence Cost Analysis

The cost of process equipment sized and designed based on the long-term test results for approximately 80% mercury control, and on the plant-specific requirements (sorbent storage capacity, plant arrangement, retrofit issues, winterization, controls interface, etc.) has been estimated for full-scale, permanent commercial implementation of the necessary equipment for mercury control using sorbent injection technology at the 880-MW Independence Station Unit 2. The system design was based on the criteria listed in Table 4.

Table 4. System Design Criteria for Mercury Control at Independence Unit 2 (5 lb/MMacf injection, >80% mercury control).

Parameter	
Number of Silos	2
Number of injection trains	6 (2 spare)
Design feed capacity/train (lb/hr)	1920
Operating feed capacity/train (lb/hr)	960
Sorbent storage capacity/silo (lbs)	460,800
Conveying distance (ft)	200/400
Sorbent	DARCO® Hg-LH
Aerated Density (lb/ft^3)	18
Settled Density (lb/ft^3)	28
Particle MMD (microns)	18

The estimated uninstalled cost for a sorbent injection system and storage silo for the 880-MW Unit 2 is $2,730,000. Costs were estimated based on a long-term activated carbon injection concentration of 5 lb/MMacf. For Independence Unit 2, this would require an injection rate of nominally 960 lbs/hr at full load. Assuming a unit capacity factor of 85% and a delivered cost for DARCO® Hg-LH sorbent of $0.95/lb, the annual sorbent cost for injecting sorbent into the existing ESP would be about $6,791,000. This corresponds to a nominal sorbent cost of $14,800 per pound of mercury removed.

Results from the field-tests conducted to date indicate different levels of mercury removal can be achieved depending on the air pollution control equipment and different flue gas conditions. Data collected from the Phase I DOE tests at Gaston indicate mercury removal levels of up to 90% were obtained with a COHPAC® (a baghouse) and DARCO® Hg sorbent injection.[4] 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.[4] At Brayton Point, mercury removal levels of up to 90% were obtained with an ESP collecting bituminous ash with DARCO® Hg sorbent.[4] DOE Phase II testing at Holcomb showed mercury removal levels of 90% were obtained with a SDA and FF while injecting DARCO® Hg-LH.[5] Data from Independence and five other sites are summarized in Table 5.

Table 5. Summary of Mercury Removal Efficiencies and Costs for Different APC 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[6]	ESP	PRB	DARCO® Hg-LH	90	0.74
Independence	ESP	PRB	DARCO® Hg-LH	80	1.14

The results from Independence indicate that using DARCO® Hg-LH would result in higher mercury removal (80%) 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. These results are presented as mills/kWh in Table 5 (Equipment O&M not included).

Cost and Economic Methodology

Costs for the sorbent storage and injection equipment were provided by ADA-ES based on the design requirements in Table 4. ADA-ES has built and installed many similar systems at coal-fired power plants for mercury control. Estimated costs for the distribution manifold, piping and injection lances, an installation man-hour estimate and crane-hour estimate and an estimate for foundations including pilings are also included. As construction costs are rising rapidly, these costs are tentative and very dependent upon local labor conditions as well as current national demand for related equipment.

EPRI TAG methodology was used to determine the indirect costs. A project contingency of 15% was used. Since the technology is relatively simple, the process contingency was set at 5%. Based upon requested guarantee language, that contingency may increase to cover anticipated risks for a newer technology. ACI 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 incremental operating labor requirement of 1 hour per day was estimated to cover the incremental labor to operate and monitor the ACI system. The annual maintenance costs were based on 5% of the uninstalled equipment cost.

Levelized costs were developed based on a 20-year book life and are presented in constant dollars.

Capital Costs

The uninstalled ACI storage and feed equipment costs are estimated at $2,730,000. The estimated cost for a sorbent injection system and storage silo installed on the 880-MW Unit 2 is $4,743,000 and includes all process equipment, foundations, support steel, plant modifications utility interfaces, engineering, taxes, overhead, and contingencies. The capital and O&M costs are summarized in Table 6.

Table 6. Capital and Operating and Maintenance Cost Estimate Summary for ACI System on Independence Unit 2 (Annual Basis 2007).

Capital Costs Summary	
Equipment, FOB Independence	2,225,000
Site Integration (materials and labor)	159,000
Installation (ACI silo and process equipment, foundations)	1,600,000
Taxes	185,000
Indirects/Contingencies	574,000
Total Capital Required	4,743,000
$/kW	5.39
Operating and Maintenance Costs Summary	
Sorbent @ $.95/lb	6,791,000
Power, labor, maintenance	172,000
Variable O&M for 2007 ($/kW)	7.91
Variable Mills/kW-hr	1.20

Operating and Levelized Costs

With the exception of the waste disposal costs, which are discussed below, the most significant operational cost of sorbent injection for mercury control is the DARCO® Hg-LH sorbent. Sorbent costs were estimated for an average of > 80% mercury control based on the long-term sorbent injection concentration of 5 lb/MMacf. For Independence Unit 2, this would require an injection rate of nominally 960 lbs/hr at full load. Assuming a unit capacity factor of 85% and a delivered sorbent cost of $0.95/lb, the 20-year levelized annual cost of injecting sorbent via a TOXECON II™ system would be $9,414,000 ($9,628,000 assuming lost ash sales an disposal). Included in this is other annual operating levelized costs including electric power, operating labor, and maintenance.

Based on the test program results and assuming that sorbent injection at the ESP inlet for mercury control is sustainable, an average of > 80% mercury control can be attained at Independence Unit 2 for an initial capital investment of $4,743,000 with first year operating costs of $8.76/kW ($8.95/kW), or annual 20 year constant-dollar levelized costs of $10.70/kW ($10.94/kW). This information is summarized in Table 7.

The levelized costs reported in Table 7 are specific to Independence Unit 2. The levelized cost summary uses the following factors:

1. Ash Sales—$3/ton (conservative estimate—higher prices will increase costs for the TOXECON II™ system but will also improve the cost advantage of the TOXECON II™ system over traditional pre-ESP injection systems)
2. Ash Disposal—$20/ton
3. TOXECON II™ System—preserves 96% of ash sales

In the case of ISES, ash sales are dependent upon color, so any pre-ESP injection of a standard or concrete compatible PAC has proven to be detrimental to the ash sales. In the case below for pre-ESP injection, the assumption is all ash is disposed.

Table 7. Levelized Costs Summary.

20-Year Levelized Costs Summary—$ Constant			
	Lost Ash Sales Revenue and Disposal Costs Not Included TOXECON II™	All Ash Sales Revenue and Disposal Costs Are Lost Pre-ESP Injection	Lost Ash Sales Revenue and Disposal Costs Included TOXECON II™
Fixed Costs	555,000	328,000	555,000
Variable O&M	8,859,000	13,396,000	9,073,000
Total	9,414,000	13,723,000	9,628,000
Fixed Levelized Costs $/kW	0.63	0.37	0.63
First-Year Operating Levelized Costs $/kW	10.07	15.22	10.31
Total 20-Year Levelized Costs $/kW	10.70	12.46	10.94
First-Year Operating Levelized Costs mills/kW-hr	1.35	1.67	1.20
Total 20-Year Levelized Costs mills/kW-hr	1.44	2.04	1.47
Total 20-Year Levelized Cost $/lb Hg removed	14,500	20,500	14,800

CONCLUSIONS

Hot-Side ESP Mercury Control

Liquid Reagents

Results from testing at MidAmerican's Louisa Station while the plant fired a typical PRB coal indicated that:

- ADA-37 is not effective at removing mercury across the hot-side ESP at Louisa at injection rates up to 18 gallons per hour.
- KNX increased the fraction of oxidized mercury, but no net increase in mercury removal was noted with KNX with the current particulate control equipment.

Solid Sorbents

Results from sorbent screening at MidAmerican's Council Bluffs Energy Center while the plant fired a typical PRB coal indicated that the solid sorbents were ineffective for mercury capture at hot-side temperatures of 600 to 800 ºF.

TOXECON II™ Mercury Control

The primary objective of testing at Entergy's Independence Steam Electric Station was to determine the cost and effects of sorbent injection using EPRI's TOXECON II™ for mercury control in stack emissions from Unit 2. Unit 2 was chosen for this evaluation because it fires PRB coal and is equipped with a medium-sized, cold-side ESP (SCA = 542 ft^2/kacfm) for particulate control. General observations and conclusions include:

- Native mercury removal and speciation
  - Less than 20% mercury removal during four rounds of baseline testing. While firing PRB coal, the ESP B inlet mercury averaged 7.9 lb/TBtu during baseline tests while the ESP B outlet averaged 6.6 lb/TBtu.
  - The inlet mercury during most of the baseline tests was primarily elemental mercury, 65–70% (SCEM) and 65% (Ontario Hydro). During most of the tests, the fraction of elemental mercury at the outlet of the ESP was 37–55% (SCEM) and 55% (Ontario Hydro), indicating some oxidation in the ESP.
- Parametric Testing
  - DARCO® Hg-LH was the most effective sorbent evaluated at Independence during the DOE program. Short-term results indicate that 80% mercury removal was achieved at 2.4 lb/MMacf and nearly 90% at 4.8 lb/MMacf (injection between fields B-3 and B-5). Injecting downstream of field B-5 reduced mercury capture by nominally 10%.
  - Pre-ESP DARCO® Hg-LH injection resulted in 85% mercury removal at 5 lb/MMacf with a non-optimized injection grid.
  - During the 2005 tests, injection of any sorbent resulted in both opacity and CPM spikes. Turning off the Power Optimization System and increasing ESP power in

the rear fields minimized but did not completely eliminate the spikes in the CPM and Unit 2 opacity measurements during long term PAC injection (DARCO® Hg-LH).

- Long-Term Testing
  - Average mercury removal during the initial 30-day long-term test (October 2005) was 69% and the average outlet mercury concentration was 1.91 lb/TBtu. The average DARCO® Hg-LH injection concentration during this period was 5.5 lb/MMacf.
  - During subsequent continuous injection periods (typically 5-day or 30-day) using the TOXECON II™ injection system with modified lances, the average vapor-phase mercury capture ranged from 70–85% based on the lance design with an average sorbent injection concentration of 5–5.5 lb/MMacf.
- Balance-of-Plant
  - Increasing the ESP power and increasing the final field rapping cycle were effective at minimizing opacity spikes due to PAC injection.
  - Additional testing is required with improved injection technology to determine whether TOXECON II™ implementation would result in a sufficient increase in particulate emissions to trigger a permit review.

The goals for the program established by DOE/NETL were to reduce the uncontrolled mercury emissions by 50–70% at a cost 25–50% lower than the target established by the DOE of $60,000/lb mercury removed. This goal was not achieved at Louisa or Council Bluffs. The goal was exceeded at Independence. Results from testing at Independence indicated that 80% mercury removal could be achieved using DARCO® Hg-LH at a sorbent cost 75% lower than the benchmark. The estimated 20-year levelized costs for control at Independence are 1.47 mills/kWh or 14,800 $/lb mercury removed (accounting for the partial loss of ash sales) while preserving the salability of the fly ash. Additional improvements to the injection system design to increase mercury removal by improving the sorbent distribution are anticipated with ongoing development of the technology.

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APPENDIX: SITE DESCRIPTIONS

Louisa Site Description

The test unit (Unit 2) is a single 700-MW PRB coal-fired electric generating unit. The unit typically fires PRB coal in a balanced draft Babcock & Wilcox opposed wall fired boiler. The Research-Cottrell hot-side ESP is followed by two Ljungström regenerative air heaters. Key operating parameters for Louisa Unit 2 are shown in Table A-1. A general sketch of the flue gas flow is shown in Figure A-1.

The ESP configuration for Louisa Unit 2 has four boxes in a split wedge arrangement, with each box consisting of 27 transformer/rectifier (TR) sets, 3 chambers, 51 gas passages, 5 electrical fields and 8 bus sections. A sketch of the ESP showing the TR sets and electrical fields is shown in Figure A-2.

Table A-1. Louisa Key Operating Parameters.

Unit	1
Size (MWnet)	700
Test Portion (MWe)	700
Coal	PRB
Heating Value (as received)	8500
Sulfur (% by weight)	0.32
Chlorine (%)	~0.01
Mercury (µg/g)	0.08
Particulate Control	Hot-Side ESP; SCA = 459 ft^2/kacfm
Sulfur Control	Compliance Coal (Dry Scrubber – FF installed in December 2007)
Air Preheater	Regenerative
Ash Reuse	Sold

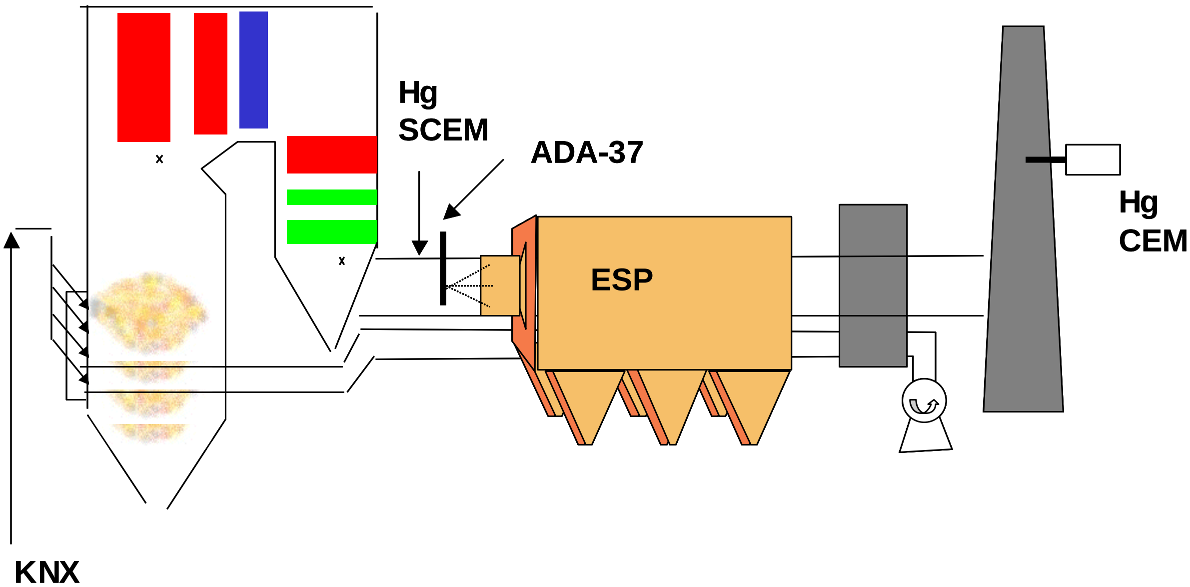

Figure A-1. Sketch of Louisa Unit 2 General Configuration.

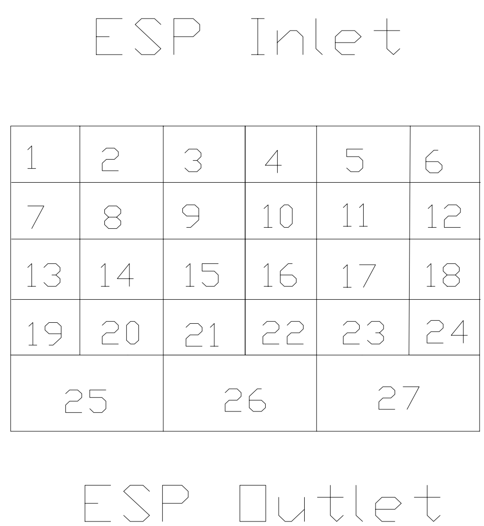

Figure A-2. Single ESP Box Electrical Field Configuration.

Because Louisa sells its fly ash, it was important that the reagents used during testing would not impact the marketability of the fly ash. The reagents tested at Louisa should have no impact on ash sales.

For collection of plant operating data, the plant installed a workstation in the ADA-ES testing office trailer that was connected to the plant control and information system.

Council Bluffs Site Description

Council Bluffs Unit 2 is located at the Council Bluffs Energy Center (CBEC) (subsequently renamed Walter Scott Energy Center (WSEC)), near Council Bluffs, Iowa. Unit 2 is a Combustion Engineering, tangentially fired, dry-bottom boiler. This plant is rated at 88 MWe (gross) and was commissioned in 1959. There were no NO_x or SO_2 control devices installed at the time of screening. Particulate control is accomplished with two parallel ESPs, rebuilt in 1994. A small percentage (10–20%) of fly ash from Unit 2 precipitators is sold to ash marketers for asphalt mixes. Loss on ignition levels are typically around 1%.

The flue gas from Unit 2 exits the economizer at a temperature of approximately 600–650 ºF, flows through the ESP, and then through the air heater before being exhausted to the atmosphere 250 feet above grade. A continuous emissions monitoring system (CEMS) monitors NO_x, SO_2, CO_2, opacity, and gas flow rate. The CEMS ports and monitors are located on a platform 150 feet above plant grade.

The Unit 2 general configuration is shown in Figure A-3 and a summary of operating parameters is included in Table A-2.

Table A-2. Council Bluffs Unit 2 Operating Parameters.

Parameter Identification	Units	Council Bluffs Unit-2
Boiler Manufacturer		Combustion Engineering
Type		Tangentially fired
Turbine Rating	MWe	88
Burner Type		Vertically Adjustable Tangential (Pinned at 0°)
NO_x Control		None (at time of testing)
Air Preheater (Type)		Regenerative
Particulate Matter Control Device		Hot-Side ESP
ESP Manufacturer		Universal Oil Products (UOP)
Specific Collection Area	ft^2/kacfm	224
Typical ESP Operating Temperature	°F	600–650

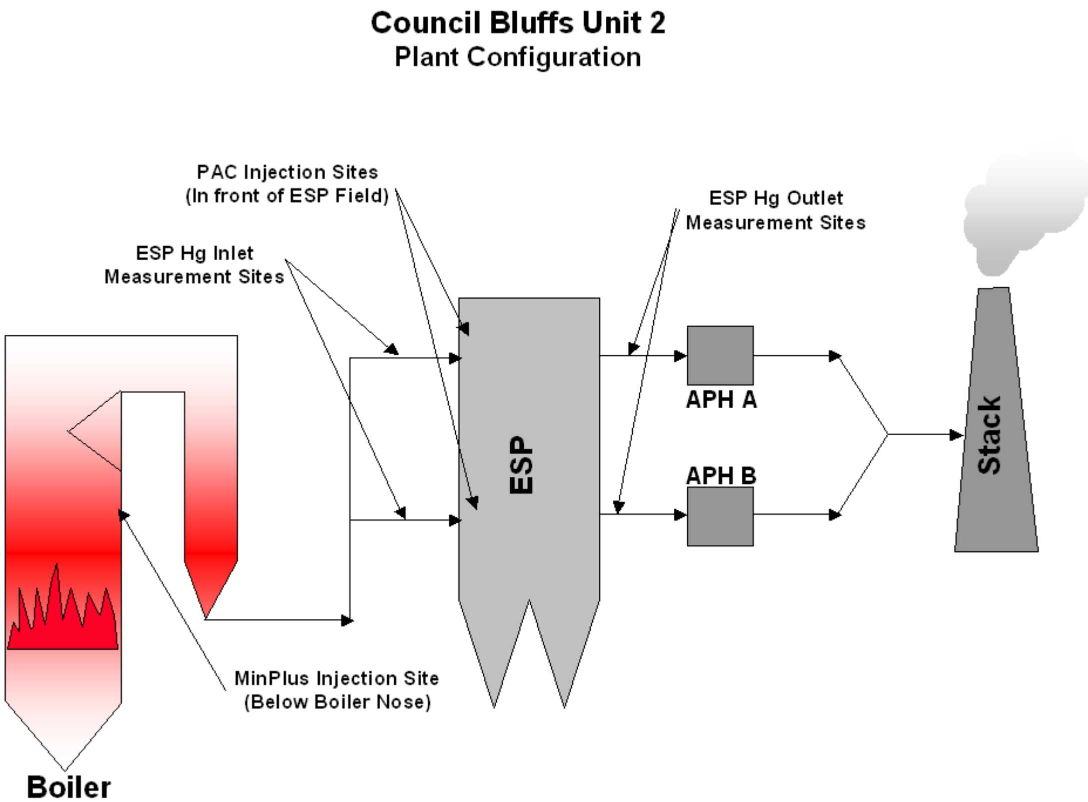

Figure A-3. Council Bluffs Unit 2 Plant Configuration and Potential Injection Sites.

Council Bluffs Unit 2 combusts PRB coal from various mines. Unit 2 primarily receives its coal from the Caballo Rojo and Belle Ayr mines. Although this unit primarily combusts coal from these two mines, the coal pile at Council Bluffs Energy Center contains coal from other mines in the PRB region.