**Development of Fireside Performance Indices, Task 7.33;
Development of Methods to Predict Agglomeration and
Deposition in FBCS, Task 7.36; Enhanced
Air Toxics Control, Task 7.45**

Topical Report

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January 1994

Work Performed Under Contract No.: DE-FC21-86MC10637

**For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia**

**By
University of North Dakota
Energy and Environmental Research Center
Grand Forks, North Dakota**

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January 1994

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Development of Fireside Performance Indices
Task 7.33

DEVELOPMENT OF FIRESIDE PERFORMANCE INDICES

EXECUTIVE SUMMARY

The Energy & Environmental Research Center (EERC) has been developing advanced indices that rank coals according to their fouling and slagging propensity in utility boilers. The indices are based on sophisticated analytical techniques for identifying and quantifying coal inorganics and are useful in predicting the effects of proposed operational changes on ash deposition in coal-fired boilers. These indices are intended to provide an economical way to reduce the amount of full-scale testing needed to determine the best means of minimizing ash-related problems. Developmental work on this project began in October 1992, using \$50,000 in Jointly Sponsored Research Program (JSRP) funds allocated under U.S. Department of Energy (DOE) Cooperative Agreement No. DE-FC21-86MC10637. These funds were matched by an equivalent amount of commercial funds. Work using this initial \$100,000 was completed on June 30, 1993 and additional work will continue on the project under a new DOE Cooperative Agreement (DE-FC21-93MC30097).

The project "Development of Fireside Performance Indices" is sponsored by the DOE, the Electric Power Research Institute (EPRI), Northern States Power Company, Union Electric, Minnesota Power, and Kansas City Power and Light. The goal of this consortium project has been the reliable prediction of coal-related aspects of boiler performance, using a series of advanced performance indices. The indices were calculated based primarily on computer controlled scanning electron microscopy analysis on the coal and limited boiler design and operation specifications. The index calculations were performed by a single simple IBM PC-compatible program, called "PCQUEST," an acronym for Personal Computer Coal Quality Effects Screening Tool. At the completion of this phase of the project PCQUEST was capable of calculating eight parameters: 1) a fouling index to predict fouling propensity for high-temperature zones; 2) a second fouling index for low-temperature zones; 3) an opacity index that uses fly ash resistivity calculated from CCSEM data; 4) a slag formation index based on the results of chemical analyses and bench-scale testing; 5) a slag tapping index based on predicted slag viscosities; 6) a grinding index to evaluate the potential for mill abrasion based on maceral variations; 7) a steam-tube erosion index founded on both bulk and individual particle characteristics of the coals; and 8) a sootblowing index to predict the ease or difficulty of sootblowing for deposits produced when a coal of interest is burned in a particular boiler, based on coal and ash composition and particle size. The fouling and slagging indices will be designed to apply to either conventional or low-NO_x conditions.

The first step in formulating the advanced indices was to obtain complete characterization of discrete minerals and organically associated inorganic components in selected coals. These characteristics were then related to the performance of the coals in full-scale systems. An optical access drop-tube furnace (ODTF) at the EERC was used to generate slagging and fouling deposits and fly ash samples from a variety of coals under conditions similar to those in full-scale systems, but at a fraction of the cost of full- or pilot-scale testing. Diagnostic data collected from the DTF testing were used to assess ash deposit severity in order to properly rank and verify the fouling and slagging indices. The mill performance, opacity, and steam-tube erosion indices were formulated from analysis of the coal and fly ash minerals using optical microscopy and advanced scanning electron

microscopy techniques. Field data were collected at power generating stations belonging to each of the utility participants in order to verify or validate the PCQUEST indices.

During this first phase of the program, several administrative and technical tasks were completed to set the stage for major work on the development of indices. Two meetings were held with the program participants to finalize the work plan, project deliverables, and the format of the PCQUEST index package. On the technical side, substantial modifications to the EERC ODTF were made to better simulate convective pass ash deposition. This included adding a second furnace and a large-particle separator to the ODTF. Other DTF modifications included interfacing the control systems of the furnace assembly and its peripheral components to one main computer system and software platform so that the combustion tests could be set up, controlled, and monitored from one control panel.

A site visit to the Union Electric Labadie Station near St. Louis, Missouri was conducted during this reporting period. Two of the Labadie Station tangentially fired Combustion Engineering boiler units were testing the Rochelle coal, which is a Wyoming Powder River Basin coal. During the visit, EERC personnel observed boiler operating conditions and obtained coal and deposit samples. A report on the site visit was distributed to the sponsors together with a protocol for conducting such visits.

The Rochelle coal that was obtained from the Union Electric Labadie Station site visit was analyzed using both bulk chemical and advanced scanning electron microscope methods. The coal was also used to produce ash and deposits in the EERC ODTF as a beginning to the indices formulation and verification. All of the information obtained for Rochelle coal was entered into the preliminary PCQUEST database. Data for eight coals analyzed during earlier projects, including Thunder Basin Black Thunder, Westmoreland Resources Sarpy Creek, Western Energy Colstrip, Cordero, Antelope, AMAX Belle Ayr, a King Station blend, and Eagle Butte, were updated and added to the PCQUEST database.

Finally, during this first phase of the program, preliminary equations for low-temperature fouling, high-temperature fouling, slagging, and slag tapping indices were formulated using base knowledge of inorganic transformations and ash deposition garnered through previous projects and experience. The indices were calculated for the Rochelle coal and the other coals already in the PCQUEST database from previous work. An initial calibration of the fouling and slagging indices was performed based on limited knowledge of how these coals perform in full-scale applications. The format for the PCQUEST program was converted from a spreadsheet to a C++ computer program format.

**Development of Methods
to Predict Agglomeration and Deposition in FBCS
Task 7.36**

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EXECUTIVE SUMMARY

The successful design and operation of the fluidized-bed combustor requires the ability to control and mitigate ash-related problems. The major ash-related problems in FBC are agglomeration of bed material, ash deposition on heat-transfer surfaces, ash deposition on refractory and uncooled surfaces, corrosion, and erosion. The focus of the Development of Methods to Predict Agglomeration and Deposition in FBCs is on the agglomeration and deposition problems in atmospheric bubbling and circulating beds. This 3-year multiclient program is designed to determine the behavior of inorganic components in FBC units using advanced methods of analyses coupled with bench-scale combustion experience.

The first year of the program yielded many interesting and useful results. An intensive sampling effort was undertaken at the Montana-Dakota Utilities 80-MW_e bubbling-bed facility located at the Heskett Station. Agglomerating tendencies at this unit force a bed turnover approximately every 50 hours. Deposition on the superheat surfaces result in a loss in superheat of over 40°F during the course of 4 months. The analysis of the data from the Heskett Station shows conclusively that certain coal ashes tend to form deposits in the FBC. The mechanisms of adherence and growth appear to be via a molten sulfate matrix, due to fluxing action of sodium with the calcium sulfate matrix. The bed material plays no significant role in the deposition matrix. The agglomeration, on the other hand, shows a definite interaction between the bed material and the ash, with certain minerals in the bed contributing more to agglomeration than others. Details of the proposed mechanisms are provided in this report.

To diagnose and reduce ash-related problems in FBC systems, a detailed understanding of the fuel, ash, and system materials properties must be achieved. This understanding requires that the materials be analyzed in detail to assess their chemical and physical characteristics. Effective materials analysis requires appropriate and effective materials sampling techniques. Because the materials sampling often must be employed by operations personnel, it is important that a standard method of sampling is available. Therefore, a sampling and analysis protocol is being developed to aid the operations engineer in providing effective samples for analysis and testing. This protocol is organized to provide a handy reference for those involved with FBC operations. The sampling and analysis protocols section will specifically address strategies intended to reduce ash-related operational problems.

Construction and shakedown of a bench-scale reactor has been completed. This versatile tool will be used to develop rates and mechanisms of agglomeration and deposition. This reactor has already been used in a related project to verify agglomeration mechanisms in a PFBC mode.

Work on this project will continue for another two years. Funding continues from Ahlstrom Pyropower, Riley Stoker, Electric Power Research Institute (EPRI), Northern States Power Company, and the North Dakota Lignite Research Council. Funding through the new DOE/EERC Jointly Sponsored Research Program is also in place for the remaining two years of the project. It is hoped that, at the end of this 3-year project, an accurate method will have been developed to predict the propensity for fouling and agglomeration, along with methods to reduce or eliminate these ash-related problems.

Deposition in the convective pass has also been noted by bubbling-bed FBC users. This deposition results in the loss in steam temperature. Knowing the propensity of certain coal ashes to deposit in the convective section is important for the design of tube spacing and sootblower coverage and schedule.

Similar problems have been identified in CFBC applications. Again, deposition in the convective pass results in a loss in steam temperature. Knowing deposition rates and deposit strengths will be important for designing tube spacing and sootblower coverage and schedule. Another problem inherent to certain fuels in the CFBC is deposition in the cyclone and other cooled surfaces. Some deposits can fall down, plugging drains and loop seals. The deposits can also serve as sites for alkali corrosion.

Agglomeration in the loop seal and bed of the CFBC is responsible for unscheduled shutdowns. As in the bubbling bed, the CFBC requires high bed turnover rates or limitations on bed material selection for control of agglomeration. These problems limit the range of fuels that can be burned in the CFBC.

Other related problems that will not be addressed in this program include alkali-vapor release in PFBC. This production of alkali vapor results in corrosion and deposition on turbine blades and hot-gas cleanup (alkali removal) requirements.

3.0 GOALS AND OBJECTIVES

3.1 Overall Goals

The overall objective of the program was to advance our knowledge of ash behavior in FBCs so that methods could be generated to predict and, ultimately, mitigate ash-related problems in FBCs. Specific goals are listed below.

- To determine the ash formation mechanisms, including inorganic transformations and vaporization, determining:
 - The size distribution of the ash
 - The stickiness of the ash
 - The partitioning that occurs
- To determine the physical transport mechanisms, focusing on:
 - Elutriation from the bed
 - Attrition of sorbent, bed material, and ash
 - Fluidization characteristics
 - Thermophoresis, van der Waals attraction
 - Other applicable mechanisms to be identified
- To determine the mechanism and rate of deposition and sintering strength development on:
 - In-bed tubes
 - Support surfaces

The goals of Task 3, Bench-Scale Reactor Development, are 1) to simulate the process of agglomeration and deposition and 2) to correlate chemical analysis with run operating variables to effectively predict the occurrence of agglomeration. The information collected will provide an extensive database of fuel, bed, and sorbent properties and operating conditions for model development. Task 3 should result in a procedure/device to use to predict agglomeration and provide a device for studying mitigating measures.

For Task 4, Applied Fundamental Chemistry and Physics, the goals are 1) to determine the physical and chemical processes that result in the partitioning of ash components in FBCs and 2) to better understand the physical and chemical interactions of ash components upon cooling, sintering, and deposition. The information collected during this task will identify specific processes and conditions responsible for operational problems and provide input to the development of predictive techniques and mitigating measures for FBCs.

The goals of Task 5, Development and Verification of Predictive Techniques and Mitigating Measures, are 1) to use the data generated to develop a method of predicting agglomeration and deposition tendencies of any fuel, sorbent, and bed combination and 2) to suggest methods of reducing or eliminating the problem. Some of the alternatives for expressing the predictive techniques are rules-of-thumb, a bench-scale test, advanced indices, a qualitative mechanistic model, and/or computer models.

The ultimate model would be an empirical algorithm to predict the rates of fines generation, sticky particle generation, elutriation, deposition on in-bed tubes and supports, agglomeration and defluidization, deposition on walls, and deposition on convective pass tubes. It is desirable to be able to predict these rates as a function of firing mode, velocity, bed type and size distribution, fuel type and size, sorbent, and oxygen concentration.

The goal of Task 6, Reporting, is to transfer results to sponsors in a timely fashion.

4.0 FULL-SCALE SAMPLING

4.1 Full-Scale Sampling Objectives

One of the primary accomplishments of the project was sampling and analyzing deposits and agglomerates from a full-scale, fluidized-bed combustor and interpreting the results. The specific goals of the full-scale sampling included the following:

- To identify chemical and physical characteristics of ash that influence agglomeration and deposition.
- To obtain data from operational systems to begin mechanistic model development.
- To develop sampling and analytical protocols that a company could use to guide sample collection.
- To provide data to ensure validity and relevance of bench-scale tests.

Figure 1. Location of end-of-test deposit samples collected by EERC personnel on March 24, 1993.

TABLE 1

End-of-Test Deposit Samples Collected by EERC Personnel on March 24, 1993

Sample Number		Location
2	1 ¹	Compartment B tube surface deposit
4	2	Compartment B bed tube support deposit
1	3	Compartment D tube surface deposit
3	4	Compartment D bed tube support deposit
26	5	Large agglomerates removed from hoiling bank division wall by MDU personnel
15	6	Division wall deposit below primary superheater
12	7	Primary superheater deposits on pendants above nose cone
14	8	Primary superheater front side deposit
13	9	Primary superheater deposit on second bank anchors
16	10	Primary superheater bridging material between tubes
9	11	Primary superheater deposit next to mud drum
8	12	Boiling bank next to mud drum
6	13	Boiling bank near steam drum
5	14	Economizer deposit near top
7	15	Economizer deposit near middle
11	16	Agglomerated cinder from dust collector
12	17	Deposit from second section of air heater

¹ Numbers refer to sampling locations shown in Figure 1.

TABLE 2

Run-Time Samples Collected by MDU Personnel on March 3, 1993

Sample Number		Location
25	A ¹	Composite coal ash sample
24	B	Bed material (sand) sample
17	C	Bed drain material, Compartments B & C
18	D	Bed drain material, Compartment A
19	E	Bed agglomerates, Compartment A
20	F	Cyclone dust from hopper
21	G	ESP dust - 1st row precipitator
22	H	ESP dust - 2nd row precipitator
23	I	ESP dust - 3rd row precipitator

¹ Letters refer to sampling locations shown in Figure 2.

TABLE 5

Summary of CCSEM Results for Heskett Station Beulah
Lignite Coal, wt% on a Mineral Basis

Particle-Size Distribution, μm	1.0- 2.2	2.2- 4.6	4.6- 10.0	10.0- 22.0	22.0- 46.0	46.0- 100.0	Total
Quartz	2.9	3.6	3.7	5.4	1.4	0.6	17.6
Iron Oxide	0.5	0.3	0.1	0.0	0.0	0.0	0.9
Rutile	0.1	0.0	0.0	0.0	0.0	0.0	0.1
Calcite	0.1	0.4	0.1	0.4	0.4	0.0	1.4
Kaolinite	2.0	4.6	2.2	1.3	0.2	0.7	11.0
Montmorillonite	0.5	0.7	0.4	0.6	0.0	0.0	2.2
K Al-Silicate	0.2	0.3	0.2	0.0	0.1	0.0	0.8
Ca Al-Silicate	0.1	0.1	0.0	0.0	0.0	0.0	0.2
Na Al-Silicate	0.1	0.0	0.0	0.2	0.0	0.0	0.3
Aluminosilicate	0.2	0.2	0.1	0.2	0.0	0.0	0.7
Mixed Al-Silicate	0.1	0.0	0.0	0.0	0.0	0.0	0.1
Ca Silicate	0.0	0.1	0.0	0.0	0.0	0.0	0.1
Pyrite	2.5	2.9	6.1	9.0	18.6	15.5	54.6
Oxidized Pyrrho.	0.1	0.0	0.0	0.0	0.0	0.0	0.1
Gypsum	0.1	0.0	0.0	0.0	0.0	0.0	0.1
Barite	0.4	0.5	0.6	0.9	0.3	0.0	2.7
Ca Al-P	0.4	1.1	0.0	0.0	0.0	0.0	1.5
Gypsum-Barite	0.1	0.1	0.0	0.0	0.0	0.0	0.2
Gyp-Al-Silicate	0.2	0.0	0.0	0.0	0.0	0.0	0.2
Si-Rich	0.2	1.1	0.7	0.0	0.0	0.0	2.0
Unknown	1.6	0.9	0.0	0.5	0.2	0.0	3.2
Total	12.4	16.9	14.2	18.5	21.2	16.8	100.0

TABLE 6

Chemical Fractionation Results of the Beulah Lignite Coal Used at the Heskett Station
Beulah Lignite Coal, wt%*

	Initial, ppm	Water- Associated	Organic Acid Groups	Carbonate and Coordination Complexes	Insoluble Minerals
Silicon	8,927	0	0	0	100
Aluminum	4,681	0	0	1	99
Iron	12,072	13	0	0	87
Titanium	0	0	0	0	100
Phosphorus	94	0	0	0	100
Calcium	14,493	8	47	42	3
Magnesium	4,945	41	28	27	4
Sodium	4,883	0	98	0	2
Potassium	269	69	0	3	28

* Results are expressed with silicon loss normalized to zero.

TABLE 7

XRF/Elemental Analysis of Heskett Station Samples

Run-time samples collected by MDU personnel on 8-08-98 including coal ash and sand analysis																	
	Fresh Sand	Coal	Bed Drain	Bed Drain	Aggl. ¹	Cyclone Ash	ESP-1 Ash	ESP-2 Ash	ESP-3 Ash								
Location	A	B	C	D	E	F	G	H	I								
Sample Number	1	2	3	4	5	6	7	8	9								
Sample Number	25	24	17	18	19	20	21	22	23								
Oxide, wt%																	
SiO ₂	66.7	18.6	59.2	59.2	54.7	35.6	21.9	24.2	17.8								
Al ₂ O ₃	7.7	8.6	7.6	8.7	10.4	14.4	11.0	11.7	9.4								
Fe ₂ O ₃	5.3	16.8	7.0	7.5	10.6	13.4	6.6	6.6	6.4								
P ₂ O ₅	0.1	0.2	0.0	0.2	0.1	0.2	0.6	0.6	0.5								
CaO	14.8	19.6	12.6	10.4	13.4	17.3	26.1	25.6	27.3								
MgO	3.2	8.0	3.8	2.2	2.9	4.3	6.6	6.5	7.1								
Na ₂ O	1.4	6.4	3.6	4.5	2.9	2.3	6.4	5.6	7.9								
K ₂ O	0.6	0.4	0.5	0.5	1.5	1.2	0.6	0.6	0.6								
SO ₃	0.2	21.3	5.6	6.6	3.6	11.3	20.3	18.7	23.0								
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0								
Element ratios																	
Ca:S	91.99	1.32	3.19	2.25	5.33	2.18	1.84	1.95	1.69								
Alkali:S	101.69	1.72	4.08	3.20	6.71	2.54	2.27	2.37	2.16								
Ca:Na	12.05	3.40	3.89	2.54	5.18	8.25	4.52	5.06	3.80								
Base:Acid	0.34	1.86	0.41	0.37	0.48	0.77	1.39	1.23	1.78								
Ca:Mg	3.35	1.78	2.39	3.34	3.30	2.93	2.83	2.83	2.79								
Ca:Si	0.24	1.13	0.23	0.19	0.26	0.52	1.28	1.13	1.65								
End-of-test deposit samples arranged from bed to exit of FBC																	
	Bed Tube Deposits				Division Wall		Superheater				Boiler Bank		Economizer		Clinker	Air Heater	
Point Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Sample Number	2	4	1	3	26	15	12	14	13	16	9	8	6	5	7	11	10
Oxide, wt%																	
SiO ₂	8.8	8.0	8.9	10.0	4.9	6.3	10.2	10.1	9.5	12.9	9.6	11.3	8.2	7.0	8.3	61.6	17.0
Al ₂ O ₃	5.6	4.7	5.6	4.4	3.8	4.9	5.5	6.2	5.9	6.3	5.8	5.8	5.7	6.1	6.6	10.1	8.7
Fe ₂ O ₃	7.1	14.0	7.3	11.2	38.8	27.6	8.2	5.6	11.9	3.8	4.6	5.8	4.6	3.9	4.4	7.3	7.3
P ₂ O ₅	0.2	0.2	0.2	0.1	0.0	0.1	0.3	0.3	0.2	0.4	0.3	0.3	0.4	0.5	0.6	0.2	0.6
CaO	27.0	21.8	26.3	20.8	17.1	18.6	20.8	20.0	18.8	17.8	19.1	21.8	23.3	23.3	26.4	19.1	28.4
MgO	5.3	2.9	5.2	3.5	4.2	3.1	3.5	3.2	2.7	4.5	5.0	5.6	5.1	5.6	6.2	3.5	8.9
Na ₂ O	5.9	7.3	6.1	9.2	3.3	3.6	5.6	8.9	9.7	5.6	7.2	7.9	7.6	9.4	5.8	3.2	4.0
K ₂ O	0.8	0.7	0.8	0.9	0.3	0.5	0.8	0.9	0.8	0.8	1.1	1.1	0.6	0.6	0.4	0.3	0.4
SO ₃	39.5	40.5	39.5	39.8	27.6	35.4	45.0	44.9	40.5	48.0	47.4	40.4	44.6	43.7	41.4	4.8	24.7
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Element Ratios																	
Ca:S	0.97	0.77	0.95	0.75	0.88	0.75	0.66	0.64	0.66	0.53	0.58	0.77	0.75	0.76	0.91	5.72	1.64
Alkali:S	1.18	1.02	1.17	1.06	1.05	0.89	0.84	0.91	0.99	0.69	0.79	1.05	0.98	1.05	1.10	6.65	1.86
Ca:Na	5.07	3.30	4.76	2.50	5.67	5.76	4.11	2.49	2.14	3.53	2.95	3.07	3.37	2.76	5.00	6.59	7.93
Base:Acid	3.14	3.63	3.11	3.13	7.38	4.74	2.44	2.32	2.81	1.66	2.35	2.42	2.90	3.15	2.80	0.54	1.87
Ca:Mg	3.68	5.43	3.63	4.23	2.94	4.27	4.23	4.53	5.00	2.84	2.78	2.81	3.28	3.01	3.07	3.89	2.29
Ca:Si	3.28	2.92	3.16	2.23	3.74	3.19	2.18	2.13	2.11	1.48	2.14	2.07	3.05	3.58	3.41	0.40	1.79

¹ Agglomerates.

Figure 5. Comparison of deposit and coal-ash chemistry for various locations in the Heskett Station.

Figure 6. Comparison of deposit and fly ash chemistry from the Heskett Station.

4.4 Summary of Bulk Chemistry

The coal used at the Heskett Station contains a large percentage of organically bound cations. Approximately 60% of the calcium, magnesium, and potassium are organically associated, as is virtually all of the sodium. These elements will produce either very fine particles or vapor during the combustion of the coal. The nonorganically associated calcium and magnesium in the coal are present as dolomite.

Mineral content of the coal consists of approximately 55% pyrite, 18% quartz, and 11% kaolinite. Over 40% of the minerals are less than 10 microns in size, making them available for chemical reactions.

Iron was concentrated in the coarse particles of the bed and cyclone ash streams. Calcium, sulfur, and sodium were enriched in the fine particles of the ESP ash. The fly ash streams were depleted in quartz and pyrite while some iron oxides were present in the ash. Although kaolinite was present in the coal, the clay-derived phases in the fly ash had silicon-to-aluminum ratios similar to montmorillonite or other complex aluminosilicates (such as sodium aluminosilicates). The silicon:aluminum is 1:1 for kaolinite vs. 1:3 for fly ash. This reduced silicon content indicates that reactions were occurring which would lower the melting point of the silicates.

XRD analyses of the bed material and agglomerates showed that the virgin bed material is a mixture of minerals and not a pure silica sand. Relatively high quantities of dolomite, calcite, and plagioclase were identified in addition to that of quartz. The coal ash did influence the final composition of the bed and was present primarily as ash coatings. Sodium, sulfur, and iron were at higher levels in the bulk bed material as compared to the virgin bed material, and was later identified as the main constituent of the ash coatings. As compared to the virgin bed, the agglomerates had higher concentrations of iron and calcium and lower levels of sodium and sulfur. Overall, the agglomerates showed similar chemistry to that of the bulk bed material.

The sodium content of the in-bed deposits ranged from 6%–9%, while deposits in the superheat, reheat, and economizer sections had 7%–10% sodium. The coal ash, by comparison, contained 6.4% sodium. The calcium concentration of the ESP and reheat deposits were 20% to 25%, while the superheater deposits had 20% calcium as compared to 20% calcium in the coal ash. All deposits were high in sulfur, ranging from 40% to 45%. Deposits from uncooled surfaces were high in iron.

Several important trends were also noted from the determinations of the bulk chemistry. Going from the front (superheater) to the back (ESP) of the boiler, the concentration of sodium increases while calcium content decreases slightly. The silicon, iron, and aluminum concentrations decreased going from front to back. The trend indicated that larger ash particles were falling out in the front part of the boiler, while those elements organically bound that formed fine particles or were vaporized were carried farther back in the system.

The deposits tended to be higher in sodium and sulfur than was the corresponding fly ash. The increase in sulfur indicated that the deposits were sulfating after they were deposited, leading to increased strength. The increase in sodium indicated that the sodium was probably present as very fine-grained ash and/or aerosol particles. The

The morphological examination has been supplemented with scanning electron microscopy point count (SEMP) analyses. During a morphological examination, the chemical composition of a few areas selected by the instrument operator is determined, and the SEMPC routine determines the chemical composition of 250 randomly selected points in these areas. To assist in the interpretation of the SEMPC data, a number of element ratios were calculated and compared. Some of the trends from this ratio analysis are presented here.

A change in the calcium-to-sulfur ratio from greater than 1 for the coal and fly ash to less than 1 for the deposits indicated that the ash deposited was only partially sulfated and that sulfation of the ash occurred once the material was deposited. This was seen in the cooler sections of a pc-fired boiler and contributed to strength development. Calcium:silicon and base:acid were higher for the deposits than for the coal and fly ash, indicating a sulfate-based rather than silicate-based deposition. Calcium:sodium, meanwhile, was significantly lower for the deposits than for the coal and fly ash, indicating that the sodium was concentrating in the deposits. Sodium may be acting as a fluxing agent, lowering the melting point of the deposited material.

4.6 Preliminary Mechanism

Based on the analyses of the samples from the Heskett FBC and the testing of similar fuels at the EERC, a mechanism of agglomerate formation is proposed. This mechanism is shown pictorially in Figure 9 and is described below.

EERC MM09864 CDR

Figure 9. Pictorial reproduction of the mechanisms of sinter formation.

to form an egg. This minimum size will be a function of ash quantity in the coal and its mineral composition.

4.6.5 Stage 5 - Coal Burnout Leaving Sintered Egg

Once a sufficient quantity of ash is present on the coal surface to form a continuous layer, the coal will continue to burn out, leaving this layer as a hollow sphere. Evidence of the coal particle burning out and leaving a hollow egg was found in samples of agglomerates from the Heskett Station. Figure 10 shows a portion of an unburned coal particle that was found inside one of the Heskett eggs.

4.6.6 Factors Enhancing Agglomerate Formation

Egg-type agglomerates will form if conditions within the bed promote melting of the fuel ash. Therefore, agglomeration is enhanced by the mineral content of the fuel. The size and composition of the minerals in the fuel must be known to determine if agglomerates may be a problem with a particular fuel.

Agglomeration is enhanced by local reducing zones, since the liquidus temperature of the mixture is lower for reducing than for oxidizing zones. The viscosity is also lower in the reducing zones, making sinter formation easier.

Figure 10. "Egg" from Heskett Station showing remains of unburned coal.

**FBC Sampling and Analysis: Protocols to Aid in the Prediction
and Control of Ash-Related Operational Problems**

1.0 INTRODUCTION

- 1.1 Program Overview
- 1.2 Need for Protocols/Sampling and Analysis Philosophy
- 1.3 Organization of this Report

2.0 BACKGROUND

- 2.1 Agglomeration in FBCs
- 2.2 Deposition in FBCs
- 2.3 Sampling and Analysis of FBC Fuels and Ashes

**3.0 SAMPLING AND ANALYSIS PROTOCOLS INTENDED TO REDUCE ASH-RELATED
OPERATIONAL PROBLEMS IN FBC SYSTEMS**

- 3.1 Sampling Protocols
 - 3.1.1 Operational Data
 - 3.1.2 Fuel Sampling Procedures
 - 3.1.3 Bed-Material Sampling Procedures
 - On-line
 - Off-line
 - 3.1.4 Agglomeration Sampling Procedures
 - 3.1.5 Fly Ash Sampling Procedures
 - On-line
 - Off-line
 - 3.1.6 Ash-Deposit Sampling Procedures
- 3.2 Analytical Protocols
 - 3.2.1 Analysis Strategy
 - 3.2.2 Fuel Analysis Procedures
 - 3.2.3 Bed Analysis Procedures
 - 3.2.4 Agglomeration Analysis Procedures
 - 3.2.5 Fly Ash Analysis Procedures
 - 3.2.6 Deposit Analysis Procedures

4.0 CASE STUDIES

5.0 REFERENCES

6.0 APPENDICES

- 6.1 Standard Sampling Procedures
- 6.2 Standard Analytical Procedures
- 6.3 Advanced Analytical Procedures

Figure 11. Organization of sampling and analysis protocol.

The rate of deposit growth will be determined from visual observation and by weighing deposit forms. The mechanisms of deposit formation will be studied using XRD and XRFA for bulk mineral and elemental composition, SEMPC for mineral composition, SEM morphology of elemental mapping, sintering (dilatometer), and TGA/DTA.

7.0 SUMMARY

The successful design and operation of the fluidized-bed combustor requires the ability to control and mitigate ash-related problems. The major ash-related problems in FBC are agglomeration of bed material, ash deposition on heat-transfer surfaces, ash deposition on refractory and uncooled surfaces, corrosion, and erosion. The focus of the Development of Methods to Predict Agglomeration and Deposition Program is on the agglomeration and deposition problems in atmospheric bubbling and circulating beds. This 3-year multiclient program is designed to determine the behavior of inorganic components in FBC units using advanced methods of analyses coupled with bench-scale combustion experience.

The first year of the program yielded many interesting and useful results. An intensive sampling effort was undertaken at the Montana-Dakota Utilities 80-MW_e bubbling-bed facility located at the Heskett Station. Agglomerating tendencies at this unit force a bed turnover approximately every 50 hours. Deposition on the superheat surfaces result in a loss in superheat of over 40°F during the course of 4 months. The analysis of the data from the Heskett Station shows conclusively that certain coal ashes tend to form deposits in the FBC. The mechanisms of adherence and growth appear to be via a molten sulfate matrix, due to fluxing action of sodium with the calcium sulfate matrix. The bed material plays no significant role in the deposition matrix. The agglomeration, on the other hand, shows a definite interaction between the bed material and the ash, with certain minerals in the bed contributing more to agglomeration than others. Details of the proposed mechanisms are provided in this report.

To diagnose and reduce ash-related problems in FBC systems, a detailed understanding of the fuel, ash, and system materials properties must be achieved. This understanding requires that the materials be analyzed in detail to assess their chemical and physical characteristics. Effective materials analysis requires appropriate and effective materials sampling techniques. Because the materials sampling often must be employed by operations personnel, it is important that a standard method of sampling is available. Therefore, a sampling and analysis protocol is being developed to aid the operations engineer in providing effective samples for analysis and testing. This protocol is organized to provide a handy reference for those involved with FBC operations. The sampling and analysis protocols section will specifically address strategies intended to reduce ash-related operational problems.

Construction and shakedown of a bench-scale reactor has been completed. This versatile tool will be used to develop rates and mechanisms of agglomeration and deposition. This reactor has already been used in a related project to verify agglomeration mechanisms in a PFBC mode.

Work on this project will continue for another 2 years. Funding continues from Ahlstrom Pyropower, Riley Stoker, EPRI, Northern States Power Company, and the North

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Environmental
Research
Center*

APPENDIX A
MORPHOLOGY OF HESKETT SAMPLES

SEM micrographs of spent bed material - MDU Heskett Station

Elemental Analysis of Selected Points from Sample 17, Bed Drain Material

Point	1	2	3	4
Na	7.36	9.57	2.85	0.78
Mg	0.08	5.42	0.40	6.14
Al	11.33	5.85	0.16	0.00
Si	30.62	2.48	0.22	0.43
S	0.10	12.41	2.18	15.86
K	0.09	0.83	0.00	0.18
Ca	1.77	11.16	1.02	28.90
Fe	0.00	7.46	59.08	0.00
O	48.47	43.58	33.99	46.80
Total	100.00	100.00	100.00	100.00

$\text{Na}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2$
5404
 EERC No. MS00410.Cdr

5404
 EERC No. MS00410.Cdr

Eutectics of selected points from spent bed material – MDU Heskett Station

SEM micrograph of bed agglomerate - MDU Heskett Station

Elemental Analysis of Selected Points from Sample 19 - Bed Agglomerate

Point	3	4	5	6
Na	3.41	0.39	0.34	0.23
Mg	1.10	3.28	8.48	0.23
Al	5.51	4.63	2.21	0.36
Si	18.84	16.31	0.17	0.00
S	0.64	0.00	0.00	0.00
K	0.95	0.00	0.00	0.00
Ca	20.31	16.20	0.59	0.44
Fe	8.66	18.41	56.19	68.00
O	40.26	40.28	32.02	30.74
Total	100.00	100.00	100.00	100.00

-Al₂O₃-SiO₂

5406
EERC No. MS09408.Cdr

CaSO₄
(~1450°)

5406
EERC No. MS09414.Cdr

Eutectics of selected points from bed agglomerate - MDU Heskett Station

SEM micrograph of deposit from the in-bed superheater - MDU Heskett Station

Elemental Analysis of Selected Points from Sample 2 - Bed Tube Deposit

Point	5	6
Na	0.53	9.37
Mg	18.20	30.81
Al	0.00	0.00
Si	0.23	0.16
S	0.33	7.90
K	0.30	0.60
Ca	31.11	2.85
Fe	0.33	0.00
O	48.27	48.31
Total	100.00	100.00

SEM micrographs of deposit from the division wall – MDU Heskett Station

Elemental Analysis of Selected Points from Sample 15 – Division Wall

Point	1	2	3
Na	0.27	4.51	1.33
Mg	0.18	6.39	7.44
Al	0.14	4.33	7.64
Si	0.11	0.20	0.20
S	0.28	20.55	9.43
K	0.00	0.11	0.21
Ca	0.28	10.53	19.31
Fe	66.73	1.42	4.55
O	32.00	50.99	48.77
Total	100.00	100.00	100.00

Eutectics of selected points from division wall deposit - MDU Heskett Station

Micrograph of deposit from primary superheater - MDU Heskett Station

SEM micrographs of deposit from the boiling bank - MDU Heskett Station

Elemental Analysis of Selected Points from Sample 6 - Boiling Bank

Point	1	4	5
Na	8.20	3.37	3.80
Mg	3.82	4.16	2.41
Al	3.73	5.20	14.07
Si	1.84	1.20	13.61
S	14.71	17.04	9.62
K	0.36	0.07	0.63
Ca	12.62	3.88	2.99
Fe	12.17	1.38	0.97
O	41.58	63.36	51.61
Total	100.00	100.00	100.00

Na₂O-Al₂O₃-SiO₂
5393
 EERC No. MS00408.Cdr

5393
 EERC No. MS00415.Cdr

Eutectics of selected points from boiling bank deposits - MDU Heskett Station

**Enhanced Air Toxics Control
Task 7.45**

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EXECUTIVE SUMMARY

The 1990 Clean Air Act Amendments require study of air toxic emissions from coal combustion systems. Since most of the toxic metals present in coal will be in particulate form, a high level of fine-particle control appears to be the best approach to achieving a high level of air toxics control. However, over 50% of mercury and a portion of selenium emissions are in vapor form and are not typically collected in particulate control devices. If these vapor-phase metals could be retained in a particulate control device by the use of a conditioning agent or sorbent, an effective method of controlling all metal air toxic emissions would be available at a minimum impact on existing boiler systems. Therefore, the goal of this project is to develop methods that capture the vapor-phase metals while simultaneously achieving ultrahigh collection efficiency of particulate air toxics.

The project is scheduled for a duration of two years and is currently about 60% complete. The work is divided into three tasks. Task 1 entails planning, facility preparation, and project management. Task 2 consists of performing initial trace element balances around the particulate control device and screening up to seven potential additives for their ability to capture vapor-phase metals. Task 3 involves more in-depth testing of the most promising methods of air toxic control. Task 2 was completed and results were presented in a Task 2 Summary Report that was submitted to the U.S. Department of Energy (DOE) and the Electric Power Research Institute (EPRI) in September 1993. The Task 2 Summary Report constitutes the Cooperative Agreement Task 7.45 Topical Report for the year 1993. At the end of the project a comprehensive report will be completed.

Preliminary conclusions from the project are as follows:

- The particulate collection efficiency of the pulse-jet baghouse after 20 hr of filtration, while firing Absaloka coal, was very high, ranging from a minimum of 99.9% for submicron particles to 99.99% for total mass.
- The addition of activated carbon sorbents did not appear to have any significant impact on fabric filter performance.
- A good mercury balance around the pulse-jet fabric filter was achieved in the EERC pilot-scale baghouse.
- Although the overall mercury concentration at the inlet to the fabric filter was constant, the speciation data varied significantly.
- In the baseline tests, the concentration of mercury in the hopper ash decreased with increasing temperature.
- Lignite-based activated carbon appeared to collect oxidated mercury; however, it was not very effective in collecting elemental mercury.
- Iodated activated carbon was very effective in collecting elemental mercury and appears to be a promising mercury sorbent. However, it was less effective at collecting oxidated mercury.

- Although the sulfur-impregnated activated carbon and the zeolite gave better total mercury removal than the baseline tests, they were not as effective as the iodide-impregnated activated carbon.
- If arsenic, cadmium, nickel, lead, and chromium are exclusively in particulate matter form at the inlet to the baghouse, then a fabric filter is an effective method of removing these trace metals.
- Based on the separate tests with elemental mercury and mercury(II) chloride permeation tubes, Method 29 appears to provide highly accurate mercury speciation information.

ENHANCED AIR TOXICS CONTROL TASK 2 SUMMARY REPORT

1.0 INTRODUCTION

The 1990 Clean Air Act Amendments address the issue of air toxic emissions by requiring study of air toxic emissions from coal combustion systems. Since most of the toxic metals present in coal will be in particulate form, a high level of fine-particle control appears to be the best approach to achieving a high level of air toxics control. However, over 50% of mercury and a portion of selenium emissions are in vapor form and are not typically collected in particulate control devices. If these vapor-phase metals could be retained in a particulate control device by the use of a conditioning agent or sorbent, an effective method of controlling all metal air toxic emissions would be available at a minimum impact on existing boiler systems. Therefore, the goal of this project is to develop methods that provide ultrahigh collection efficiency of particulate air toxic emissions and to improve capture of the vapor-phase metals.

The work is being conducted at the Energy & Environmental Research Center (EERC) with a pilot-scale pulverized coal-fired combustion system and is divided into three tasks. Task 1 is for the purpose of planning, facility preparation, and project management. Task 2 is to perform initial trace element balances around the particulate control device and to screen up to seven potential additives for their ability to capture vapor-phase metals. Task 3 involves more in-depth testing of the most promising methods of air toxic control. This report is a summary of the results from Task 2 testing.

2.0 OBJECTIVES

The overall objective of the work is to evaluate the potential of additives to remove trace metal air toxic emissions from coal combustion in conventional particulate control devices. Specific goals of the work include the following:

- Determine trace element balances for arsenic, cadmium, chromium, lead, mercury, nickel, and selenium in a pilot pc (pulverized coal)-fired combustion system for a minimum of two coals.
- Evaluate the effect of particulate collector type, i.e., fabric filter or electrostatic precipitator (ESP), on trace element removal.

- Determine the potential to enhance collection of mercury and selenium by injecting conditioning agents or sorbents upstream of the particulate collector.
- Evaluate the collection enhancement performance of vapor-phase metals for up to seven potential conditioning agents or sorbents.
- Evaluate the effect of conditioning agent concentrations on collection performance of vapor-phase metals for the most promising additives.
- Determine the impact of the conditioning agents on particulate collector performance.
- Evaluate the effect of particulate collector temperature on trace element collection efficiency.
- Evaluate the basis for enhanced performance by relating the characteristics of fly ash and conditioning agents to the collection of particulate and vapor-phase metals.

3.0 SCOPE OF WORK

The work is intended to be sufficient to determine the potential to control vapor-phase metals with conventional particulate control devices. The primary variables in the test program are discussed below.

Coal Type. Coal type is important because it determines initial particle collectibility, and it may influence the ability of the ash to retain vapor-phase metals. The absolute concentrations of vapor-phase metals in the raw coal may also vary by at least an order of magnitude. Two test coals were selected based on current and potential usage and on the concentrations of trace metals in the raw coal.

Additive Type. Carbon-based sorbents such as activated carbon have shown promise to be effective capture agents of mercury. Other high surface area materials such as diatomaceous earth, vermiculite, and zeolites may provide some level of mercury retention. Approximately seven conditioning agents will be initially screened and the most promising ones selected for more in-depth testing.

Additive Concentration. The best starting add rate for the carbon-based sorbents is not clear, but the starting add rate used for Task 2 screening was a mass ratio of sorbent to mercury of approximately 1000:1. The add rates may be adjusted in subsequent tests, depending on initial results.

Control Device. Baghouses and ESPs are the only widely used particulate control methods that offer a reasonably high level of control. ESPs are more widely used than baghouses, but have somewhat lower fine-particle collection efficiencies. Because of better gas-solid contact, baghouses would appear to have better potential for vapor-phase metal capture by the use of additives. However, because of the large numbers of ESPs in use on utility boilers, air toxics control with ESPs should be addressed. Therefore, air toxics control with both fabric filters and ESPs will be investigated.

Temperature. Most particulate control devices operate at a typical air heater exit temperature of approximately 300°F. However, retention of vapor-phase metals is known to be temperature-dependent. Therefore, three temperatures were selected for testing, ranging from 240° to 400°F.

3.1 Task 1

Task 1 is intended to include all initial planning and preparation as well as general project management and reporting for the life of the project. Also included in Task 1 is the design and construction of a tubular ESP.

3.2 Task 2

Task 2, which has been completed, was originally to consist of 15 initial baseline and additive screening tests, with about 8 hours of test time planned for each. Several changes were made to the original Task 2 test plan. These included the following:

- Repeating several tests due to difficulties in sampling and analyzing mercury.
- Conducting baseline tests over several days to help establish steady-state mercury concentrations.
- Testing only the Absaloka coal. Tests with the second coal are to be conducted in Task 3.
- Using only the pulse-jet baghouse for the tests. Tests with the ESP are to be completed in Task 3.

- Testing only five of the seven additives. Additional additives will be screened with the bench-scale system.
- Performing initial tests to evaluate the effects of temperature and additive concentration. These tests were originally scheduled under Task 3.
- Design, construction, and initial operation of a bench-scale test system. No bench-scale tests were originally planned.

A total of 16 tests were completed in Task 2, which included 21 days of operation. Additives tested were lignite- and wood-based activated carbons, sulfur-impregnated activated carbon, iodine-impregnated activated carbon, and a zeolite. Three temperature ranges were tested, nominally 250°, 300°, and 400°F. The completed test matrix for Task 2 is shown in Table 1.

Design and setup of a bench-scale system to be used to quickly evaluate the effectiveness of other possible sorbents in removing mercury from a gas stream were completed under Task 2. This system will also allow the EERC to verify analytical procedures for mercury speciation. A complete description of the bench-scale system is found in Section 4.4.

3.3 Task 3

For Task 3, additional tests will be completed to evaluate the effects of additive concentration, coal type, control device type, and control device temperature on metal vapor removal efficiency. The type and total number of tests to be completed in Task 3 will depend on the initial results and the overall project budget. Further discussion of the planned Task 3 tests is given in Section 7.0.

4.0 FACILITY DESCRIPTION AND PROCEDURES

4.1 Particulate Test Combustor, Pulse-Jet Baghouse, and ESP

The pilot furnace, known as the particulate test combustor (PTC), is a 550,000-Btu/hr pc-fired unit designed to generate fly ash representative of that produced in a full-scale utility boiler. The combustor is oriented vertically to minimize wall deposits. A refractory lining helps to ensure adequate flame temperature for complete

TABLE 1
Revised Task 2 Test Matrix

Test No.	Sorbent	Hg/Sorbent Mass Ratio	Baghouse Temperatures, °F
1	Baseline	NA ¹	300
2	Lignite-Activated Carbon	1000	300
3	Wood-Activated Carbon	1000	300
4	Baseline	NA	300
5	Baseline	NA	400
6	Baseline	NA	300
7	Iodine-Activated Carbon	1000	300
8	Sulfur-Activated Carbon	1000	300
9	Lignite-Activated Carbon	3000	300
10	Lignite-Activated Carbon (repeat)	3000	300
11	Iodine-Activated Carbon	1000	300
12	Iodine-Activated Carbon	1000	400
13	Baseline	NA	250
14	Lignite-Activated Carbon	3000	250
15	Zeolite	3000	300
16	Iodine-Activated Carbon	500	300

¹ Not applicable.

combustion and prevents rapid quenching of the coalescing or condensing fly ash. Based on the superficial gas velocity, the mean residence time of a particle in the combustor is approximately 3 seconds. The coal nozzle of the PTC fires axially upward from the bottom of the combustor, and secondary air is introduced concentrically to the primary air with turbulent mixing. Coal is introduced to the primary air stream via a screw feeder and ejector. An electric air preheater is used for precise control of the combustion air temperature. Originally, the PTC used cold-water annular heat exchangers to provide flue gas temperature control to the baghouse or ESP. However, analysis of ash deposits collected from the heat exchangers indicated that some mercury was collected on the duct

walls. To minimize this effect, the heat exchangers were modified to provide for higher duct wall temperatures.

The PTC instrumentation permits system temperatures, pressures, flow rates, flue gas constituent concentrations, and baghouse operating data to be monitored continuously and recorded on a data logger. Figure 1 illustrates the PTC schematically.

Flue gas samples can be taken at three system sample points: the furnace exit, the baghouse inlet, and the baghouse outlet. After passing through sample conditioners to remove the moisture, the flue gas is typically analyzed for O_2 , CO_2 , SO_2 , and NO_x . Except for the CO_2 , each constituent is normally analyzed at both the furnace exit and outlet of the baghouse simultaneously, using two analyzers. The concentration values from all of the instruments are recorded continuously, using circle charts. In addition, data are manually recorded at set time intervals. NO_x is determined using two Thermo Electron chemiluminescent NO_x analyzers. The O_2 and CO_2 analyzers are made by Beckman, and the SO_2 analyzers are manufactured by DuPont. Each of these analyzers is regularly calibrated and maintained to provide accurate flue gas concentration measurements.

Figure 1. Schematic of PTC.

The baghouse vessel is a 20-in.-internal diameter chamber that is heat-traced and insulated, with the flue gas introduced near the bottom. Since the combustor produces about 200 acfm of flue gas at 300°F, three 13-ft by 5-in. bags provide an air-to-cloth ratio of 4 ft/min. Each bag is cleaned separately with its own diaphragm pulse valve. In order to quantify differences in pressure drop for different test conditions, the bags are cleaned on a time basis, rather than with the cleaning cycle initiated by pressure drop. Once bag cleaning is initiated, all three bags are pulsed in rapid succession on-line. Ryton felted bags are being used for each of the tests. Baghouse specifications are given in Table 2.

According to the planned test matrix, some tests will be conducted with an ESP rather than a baghouse. For the ESP tests, a new single-wire, tubular ESP has been fabricated. Specifications for the ESP are given in Table 3, and a schematic of the ESP is shown in Figure 2.

The ESP has an electrically isolated plate that is grounded through an ammeter, allowing continual monitoring of the actual plate current. This will help to ensure consistent operation of the ESP from test to test. The tubular plate is suspended by a load cell which will help to monitor rapping efficiency. In addition, sight ports are located at the top of the ESP to allow for on-line inspection of electrode alignment, sparking,

TABLE 2
Pulse-Jet Fabric Filter Specifications

Baghouse Temperature	250°, 300°, and 400°F
Air-to-Cloth Ratio	4 ft/min @ 300°F
Fabrics	Ryton needled felt with Ryton scrim, singed face of fabric in and plain side out, weight – 17.56 oz/yd ² , permeability – 39.4 cfm/ft ² @ 0.5 in. W.C., Mullen burst – 496 psi
Bag Size	5 in. by 13 ft
Cages	Royal Wire Products Inc., 20 vertical wires, 6-in. ring spacing, 11-gauge pregalvanized wire
Bag-Cleaning Mode	On-line
Venturi	None
Pulse-Reservoir Pressure	40 psig
Pulse-Nozzle Diameter	0.5 in.
Pulse Volume Per Bag	0.3 scf

TABLE 3
ESP Specifications

Design Type	Single wire, tubular
Field(s)	One
Velocity	5 ft/s
SCA	125 @ 300°F
Plate Spacing diameter	11 in.
Plate Length, height	8.6 ft
Electrode	1/8-in.-diameter smooth wire,
Applied voltage	50,000 V at start of tests

Figure 2. Schematic of ESP.

rapping, and dust buildup on the plate. The ESP was fabricated to facilitate thorough cleaning between tests. Removal of both the top of the ESP and the bottom hopper will allow access to the ESP interior for complete cleaning of the wire and plate so that all tests can begin on the same basis.

4.2 Particulate Sampling and Measurement

Near real-time measurements are made for particles ranging in size from 0.5 to 30 μm using an aerodynamic particle sizer (APS 33) manufactured by TSI, Inc. The primary advantages of this system are the high resolution and the short sampling time. For most applications, the particle-size distribution (either as number or mass concentrations) can be obtained within 20 seconds, giving near real-time measurements. A more convenient and effective method of plotting fine-particle emissions as a function of time is to use the computer-generated respirable mass feature of the APS program. Rather than look at emissions of several particle-sizes, this feature combines fine-particle emissions by using a calculated value of respirable mass. The respirable mass from all of the channels is added to obtain the total respirable mass.

To determine the concentration of submicron particles (0.01 to 1.0 μm), a differential mobility particle sizer (DMPS), also manufactured by TSI, Inc., is used. The DMPS system consists of two primary sections: an electrostatic classifier and a condensation particle counter (CPC). The purpose of the electrostatic classifier is to remove a predictable fraction of the particles within a narrow size range and pass these on to the CPC where the particles are counted. The CPC measures particle number concentration by using the light-scattering technique. This instrument can be used independently of the electrostatic classifier as a continuous real-time monitor of the number of fine particles that are present in the flue gas. An impactor, prior to the gas stream entering the CPC, removes the larger particles, giving the number concentration of submicron particles.

In addition to the DMPS and APS, EPA Method 29 provides dust loadings at the inlet and outlet of the particulate control device for determining the overall particulate collection efficiency.

4.3 Mercury Sampling and Measurement

4.3.1 Mercury Sampling

Tentative EPA Method 29, known as a multimetals train, is the primary sampling procedure determining the trace element concentrations in the flue gas. Figure 3 illustrates the multimetals sampling train complete with particulate probe, impinger train, pump, and

train, pump, and dry gas meter. As shown in Figure 3, the impinger train consists of a series of glass impingers filled with trapping solutions, ending with a final moisture trap, vacuum pump, and dry gas meter. The filter assembly and impinger train are prepared by cleaning with brushes and hot, soapy tap water. Next, the train is rinsed three times in tap water and then three times in deionized (DI) water. All glassware, including quartz and teflon parts, are soaked a minimum of 4 hours in a 10% nitric acid (HNO_3) bath. After 4 hours, the glassware and teflon parts are removed from the acid bath and again rinsed in DI water three times. The sampling train is dried in as contaminant-free an environment as possible. The DI water is checked periodically for trace metal contamination.

A total of six impingers are included in the train. Impingers 1 and 2 are filled with 200 mL of 10% hydrogen peroxide (H_2O_2) in a 5% HNO_3 solution. Impinger 3 is empty to prevent any mixing of the two types of trapping solutions. Impingers 4 and 5 are filled with a 4 wt% potassium permanganate (KMnO_4) solution in a 10% sulfuric acid (H_2SO_4) solution. Impinger 6 contains silica gel to ensure the flue gas is thoroughly dried before it leaves the impinger train. The actual sampling procedure is similar to EPA Method 5

Figure 3. Illustration of the multimetals sampling train.

in that particulate matter is collected on a quartz fiber filter; however, in Method 29, vapor-phase metals that penetrate the filter are collected in the impinger solutions downstream from the filter.

4.3.2 Sample Preparation for Mercury Analyses

To prepare a coal sample for mercury analyses, approximately 0.5 g of coal, 2 mL of H_2SO_4 , and 2 mL of HNO_3 are added to a microwave digestion vessel. The vessel is sealed, placed in the microwave, and heated to attain a pressure of 40 psi for 140 minutes. After the sample has been cooled to room temperature in an ice bath, an additional 2 mL of HNO_3 is added. The vessel is then heated to attain a pressure of 80 psi for 70 minutes. The sample is again cooled, followed by reheating to 80 psi for 70 minutes. An additional three cycles of heating to a pressure of 100 psi for 40 minutes and subsequent cooling are performed. The final step in the procedure is heating to attain a pressure of 120 psi for 40 minutes. After the sample has been cooled, it is then transferred to a 50-mL volumetric flask, brought to volume, and filtered.

Similarly to the coal samples, ash samples are also digested using a microwave digestion system. Approximately 0.5 g of ash, 3 mL of HNO_3 , 3 mL of hydrochloric acid (HCl), and 3 mL of hydrofluoric acid (HF) are added to a microwave digestion vessel. The vessel is placed in the microwave, heated to a pressure of 100 psi for 40 minutes, and then cooled to room temperature in an ice bath. Fifteen mL of 4% boric acid (H_3BO_3) is then added to the vessel, which is heated to attain a pressure of 50 psi for 20 minutes, cooled, and reheated. The sample is transferred to a 50-mL volumetric flask, brought to volume, and filtered.

To analyze the Method 29 H_2O_2 solutions, 5 mL of sample is transferred to a 50-mL test tube. A sufficiently large tube is necessary to prevent the sample from overflowing during the effervescent neutralization step. The samples are placed in an ice bath and allowed to cool for 15 minutes. To decompose the H_2O_2 , 0.25 mL of KMnO_4 solution is added. After 15 minutes of cooling, the procedure is repeated four times. As a final step, an additional 2 mL of KMnO_4 solution is added in 0.5-mL additions to provide an excess of reagent. After each addition, the samples are cooled and agitated. As a final step, 2 mL of hydroxylamine sulfate solution is added in 1-mL additions (cooled and agitated after each addition) to reduce the KMnO_4 . The reduction is complete when a clear solution is obtained.

For the KMnO_4 solutions, solid hydroxylamine sulfate is added to the sample to reduce the KMnO_4 until no color persists and the KMnO_4 residue is dissolved. The sample, which is usually in a 250- or 500-mL volumetric flask, is brought to volume.

4.3.3 Mercury Analyses and Quality Control

All mercury analyses at the EERC are done using a commercial cold-vapor atomic adsorption (CVAA) analyzer (Leeman PS200). With this instrument, a prepared sample enters the system and is mixed with a reducing agent (10% stannous chloride) to form elemental mercury vapor. The mixture flows into a liquid-gas separator where nitrogen is introduced to carry the mercury vapor through a drying tube for water vapor removal. The dry vapor then enters one path of a double optical cell that has been optimized for fast response time and sensitivity. A mercury source, powered by a constant-current power supply, delivers a stable source of emissions at 254 nm. Absorbance by the mercury vapor is measured using a solid-state detector with a wide dynamic range. The resulting signal is referenced to the simultaneous absorbance of the pure carrier gas flowing through the second optical path under identical conditions. These signals are then sent to a computer system, where the mercury concentration of the solution is calculated and reported. A diagram of the instrument is shown in Figure 4. Although 0.1 ppb is reported as the detection limit of the instrument, EERC personnel have determined that the instrument has a credible detection limit below 0.1 ppb.

To ensure the precision and accuracy of the instrument, it is calibrated on a regular basis using quality control standards. The calibration check standards are analyzed every five samples to check for instrument drift, and every ten samples, a reslope is performed. All samples are run in duplicate, and one in every ten samples is spiked to verify analyte recovery.

4.4 Bench-Scale Test Unit

A bench-scale test unit (shown in Figure 5) was designed and built to simulate flue gas conditions. Specific objectives for the bench-scale system are to evaluate the mercury speciation capability of EPA Method 29 and to screen selected sorbents for mercury removal.

Known quantities of elemental mercury vapor and mercury(II) chloride vapor are introduced into the system by flushing nitrogen around calibrated permeation tubes (purchased from VICI Metronics, Inc.). The quantity of mercury vapor released into the gas stream is determined by its vapor pressure at a specific temperature. Therefore, it is critical that the temperature of the permeation tube, the chamber surrounding the tube, and the carrier nitrogen stream are held constant throughout the test period. Other gases that can be injected into the system to simulate flue gas include O₂, CO₂, SO₂, NO, and water vapor.

Figure 4. Schematic of Leeman PS200 CVAA.

Figure 5. Schematic of bench-scale test unit.

Particulate matter can be added to the system using a disperser purchased from TSI, Inc. (the same unit that is being used to inject mercury sorbents into the pulse-jet baghouse). Nitrogen gas carries the redispersed fly ash into the flue gas stream. Sorbents to be screened in the bench-scale system will be mixed with the fly ash and then injected into the system.

4.5 Coal Selection

Approximately 25–50 tons of two coals are to be used for the test program. The selection criteria were as follows:

- The coals should contain as high of a level of mercury as is obtainable.
- At least two domestic coals, representing different geographic (and geologic) regions, should be used.
- The coals must come from operating mines, preferably significant producers.

Although the U.S. Geological Survey, the Illinois State Geological Survey, and Pennsylvania State University trace element databases indicated that a number of mines produced coals with mercury concentrations from 0.5 to 1 ppm, we were unsuccessful in locating a coal from an established seam with a mercury content in this range. The coal that was selected for Task 2 testing was a Powder River Basin subbituminous coal from the Absaloka mine. Data from a trace element emissions study at a power plant indicated that this coal had a mercury concentration of about 150 ppb; however, the measured mercury concentration of the shipment received at EERC was only 65 ppb. Even though the Absaloka coal mercury was lower than anticipated, the flue gas mercury concentration at the baghouse inlet was considered high enough to quantify the effectiveness of added mercury sorbents.

For the second test coal, which will be used in Task 3, an eastern Pittsburgh No. 8 bituminous coal from the Blacksville mine was chosen. Initial analysis indicates that the mercury concentration of the Blacksville bituminous coal is 97 ppb (dry). Combustion of the Blacksville coal is expected to result in fly ash LOI values in the range of 3% to 5%, based on previous combustion tests at EERC. The Blacksville coal is also expected to have a higher chlorine content. A difference in fly ash LOI and coal chlorine content should provide a basis for evaluating the effect of these variables on mercury speciation and retention.

4.6 Additive Selection

The purpose of using an additive injected just upstream of an ESP or fabric filter is to enhance the collection of vapor-phase metals such as mercury and selenium. The additive retains the vapor-phase metals either by physical adsorption or by chemical bonding and is then collected in the fabric filter or ESP along with the fly ash. An ideal additive should:

- Be a good mercury and selenium sorbent both in terms of the level of control achieved and the amount of additive needed.
- Be effective over a broad temperature range.
- Not be considered a hazardous waste.
- Not readily release the collected metals upon exposure to water and/or air.
- Not adversely affect the performance of the ESP or fabric filter.
- Be reasonable in cost.

A short description of sorbents that are being tested in either the pilot- or bench-scale unit is given below.

Activated Carbon. Carbon-based sorbents have been shown to be effective for controlling vapor-phase trace elements, especially mercury, in a number of applications, including waste incineration and natural gas production. However, until recently, little research examined activated carbon sorbents in coal combustion systems. Activated carbon can be made from a number of different sources, including wood, coal, bone, and coconut shells. The two primary types tested for control of mercury in waste incinerators are made from either lignite or wood. Lignite char is thermally activated using steam, while wood char is chemically activated. Activated carbon can be used in either a virgin state where adsorption of the vapor-phase mercury is the dominant mechanism, or the carbon can be impregnated with either sulfur or iodine. The mercury then reacts with the sulfur or iodine to enhance mercury retention in the particulate control device. One concern with activated carbon is that the effectiveness of activated carbon to adsorb mercury is highly temperature-dependent. Literature indicates that activated carbon can efficiently control mercury, but little data exists as to its effectiveness in removing vapor-phase selenium.

Zeolites. Zeolite is a generic term describing a number of hydrated aluminum silicates containing alkali or alkaline earth metals. Although they occur naturally, they can also be synthetically made. Due to their high surface area, zeolites have been used as catalysts for a number of processes, including selective catalytic reduction. The zeolite chosen for this test program was a y-faujasite manufactured by Englehard. This is a commercial, naturally occurring zeolite that has undergone an ion-exchange reaction with either lanthanum or yttrium to increase its stability and surface area.

Vermiculite. Vermiculite is a micaceous mineral (magnesium-iron-alumina silicate), which, when thermally treated, expands to form a good insulating material with excellent absorption properties. Whether it will be able to remove vapor-phase trace elements from a flue gas stream is unknown.

Diatomaceous Earth. Diatomaceous earth, the siliceous remains of diatoms, is used in many industrial fields as a filtering agent. In addition, it has very good insulating properties. Diatomaceous earth is a porous, low density material, with a surface area of about 20 m²/g. Although it can adsorb up to four times its weight in water, it is unknown whether diatomaceous earth will adsorb mercury and selenium in a flue gas stream.

Other Additives. Fly ashes that have a high carbon content and flue gas conditioning with ammonia and sulfur trioxide (SO₃) may also be tested. The carbon carried over from the combustor into the fly ash may have many of the same properties as activated carbon, including a relatively high surface area. It is possible that these fly ashes may be effective sorbents for mercury. Ammonia and SO₃ conditioning of the flue gas has been shown to be an effective method of improving fine particulate capture in both fabric filters and ESPs. Although recent tests at EERC have shown that ammonia and SO₃ conditioning can reduce fine particulate matter and, therefore, most trace elements, by up to four orders of magnitude in a fabric filter, it may not enhance removal of vapor-phase trace elements. The level of mercury and/or selenium capture due to flue gas conditioning with ammonia and SO₃ needs to be evaluated.

5.0 TASK 2 RESULTS

5.1 Coal and Additive Analyses

Two different coals and up to seven different additives will be evaluated in the test program. A summary of the coal analyses is given in Table 4. Absaloka coal, used during Task 2, has been extensively analyzed. For the Blacksville coal, which will be

TABLE 4
Results of Coal and Coal Ash Analysis

	Absaloka Subbituminous Coal (avg. of 5 composite samples)	Blacksville Bituminous Coal (one composite sample)
Proximate Analysis, wt%		
Moisture	19.70	1.70
Volatile Matter	33.54	41.24
Fixed Carbon	37.98	49.02
Ash	8.76	8.03
Ultimate Analysis, wt%		
Hydrogen	6.00	5.05
Carbon	54.87	74.84
Nitrogen	0.72	1.27
Sulfur	0.54	2.27
Oxygen	29.09	8.52
Ash	8.76	8.03
Heating Value, Btu/lb	9,208	13,401
Major Elements as Oxides, wt% on a dry basis		
SiO ₂	34.27	40.19
Al ₂ O ₃	20.28	18.82
Fe ₂ O ₃	3.54	23.63
TiO ₂	1.00	0.78
P ₂ O ₅	2.56	0.73
CaO	14.15	7.28
MgO	6.16	0.68
Na ₂ O	1.93	1.13
K ₂ O	0.55	1.11
SO ₃	15.56	5.44
Trace Elements, ppm on a dry basis		
Hg	59 ± 10 ppb ¹	97 ± 3 ppb ²
As	1.6	NA ⁴
Cd	ND ³	NA ⁴
Cr	3.7	NA ⁴
Pb	1.2	NA ⁴
Ni	7.1	NA ⁴
Se	0.5	NA ⁴
Cl	45	NA ⁴
Sieve Analysis, % <200 mesh	75.50	76.01

¹ Average of eleven analyses.

² Average of two analyses.

³ Not detected.

⁴ Not yet analyzed.

used during Task 3, trace element analyses have not yet been completed. The coals were sampled from the coal feeder about once every 2 hours and then combined into a single composite sample for each run. In addition, a composite truck sample was taken for the Absaloka coal.

To validate the mercury content of the Absaloka coal, a triplicate sample was sent to an independent laboratory (MVTL, Bismarck, North Dakota). The MVTL data showed no statistical difference from those obtained at the EERC. The average mercury concentration for the Absaloka coal, shown in Table 5, was 59 ppb $\pm$ 17%, on a dry basis for eleven samples. In addition, the EERC is participating in a round-robin coal mercury analysis program. The results of this program were not available for this report, but will be included in the final report. A duplicate sample of the Blacksville bituminous coal was also sent to MVTL for mercury content determination. These results were 99 and 95 ppb, respectively.

During Task 2, five different additives were tested. These were wood- and lignite-based activated carbons, sulfur-impregnated activated carbon, iodine-impregnated activated carbon, and zeolite. Table 6 presents the physical properties of these additives and the cost per pound for each. The surface areas were measured using BET analyses, and the particle-size distribution was measured using a Coulter counter. The wood- and lignite-based activated carbons were obtained in a powder form, while the other three were pulverized at the EERC. The zeolite was difficult to grind and resulted in a volumetric median diameter of 50 μ m, which is larger than would be desired. On the other hand, the median diameter of the sulfur- and iodine-impregnated activated carbon was quite small, at 3 and 4 μ m, respectively.

5.2 Combustion Test Results

The results from the 16 tests completed in Task 2 are summarized in Tables 7-11. Parameters evaluated included five additives and three temperatures. During the first few tests (AB-442 through 444), the mercury results were not as consistent as would be desired. To help reduce the inconsistencies, modifications were made to the heat exchangers to increase the duct wall temperatures, thereby minimizing mercury deposition on the heat exchanger walls. In addition, baseline tests were extended to 2 days to help stabilize the inlet mercury concentrations.

The summary of system temperatures, major flue gas constituents, and baghouse pressure drop is presented in Table 7. These results show that the operation of the combustor was quite stable and repeatable from test to test.

5.3 Fabric Filter Performance

5.3.1 Particulate Emission Results

Dust-loading data from the individual tests are presented in Table 8. Also, total mass particulate emissions from both the baseline and additive tests are presented in Figure 6 as a function of filtration time. With new bags, results show that emissions were highest (0.003 lb/MM Btu) when outlet dust-loading measurements were taken during the first 5 hours of testing. This is not surprising, because higher emissions are expected when the bags are new and a residual dust cake has not yet been established.

TABLE 5

Mercury Concentration in Absaloka Subbituminous Coal
(on a dry basis)

Analyzed at EERC, ng/g		Analyzed at MTVL, ng/g
71	47	60
57	60	44
69	49	61
74	57	
Mean = 60 ± 10^1		Mean = 55 ± 10^1
Total Population Mean = 59 ± 10		

¹ Plus or minus one standard deviation.

TABLE 6

Physical Properties of Sorbents Used in Task 2

Sorbent	Bulk Density, g/cm ³	Mass Median Diameter, ¹ μm	Surface Area, ² m ² /g	Cost, ³ \$/lb
Lignite-Activated Carbon	0.26-0.32	5.5	447	0.53
Wood-Activated Carbon	0.45 ⁴	11.5	1462	0.78
Iodine-Activated Carbon	0.54-0.59	3	823	4.00
Sulfur-Activated Carbon	0.58	4.2	438	3.50
Zeolite	1.06 ⁴	50	77	2.00

¹ Measured by Coulter counter.

² Measured by BET method.

³ Costs as quoted by vendors.

⁴ Packed density (all density information was obtained from vendors).

TABLE 7

Summary of Task 2 Combustor Data (Absaloka subbituminous coal)

Run	Sorbent	Total Run Time, hr	Additive Injection Time, hr	Combustor Outlet Temp., °F	HX No.1	HX No. 2	HX No. 2	Pulse-Jet Baghouse		Air-to- Cloth Ratio, ft/min	Average Flue Gas Concentrations (on a dry basis)				
					Inlet Temp., °F	Outlet Temp., °F	Inlet Temp., °F	Inlet Temp., °F	Outlet Temp., °F		SO ₂ , ppm	O ₂ , %	NO _x , ppm	CO ₂ , %	H ₂ O, %
442	None	8.03	NA ¹	1694	1380	942	609	309	287	3.8	471	4.8	426	15.8	10.9
443	LAC	9.03	9.03	1698	1343	971	601	301	287	3.8	462	5.0	438	15.9	9.5
444	WAC	8.00	8.00	1686	1303	943	584	305	287	3.8	432	5.1	402	15.6	9.3
445	None	52.50	NA	1711	1404	984	601	307	294	3.8	454	4.8	432	15.8	9.8
446 A-B	None	40.25	NA	1699	1378	1045	847	409	378	4.3	476	4.5	388	16.2	10.0
446 C-D	None	41.02	NA	1763	1444	941	712	315	291	3.9	456	4.7	381	15.8	10.0
447	IAC	12.17	12.17	1657	— ¹	843	689	310	285	3.8	482	4.5	451	16.8	10.0
448	SAC	23.42	12.17	1722	—	940	704	307	284	3.8	483	4.4	439	16.1	9.7
449	LAC	22.95	11.37	1735	—	961	710	309	285	3.8	466	4.6	443	16.0	9.9
450	LAC	11.77	11.77	1689	1255	920	723	309	287	3.8	458	4.6	399	16.5	10.2
451	IAC	23.43	11.43	1734	1472	981	676	301	283	3.8	479	4.8	421	15.8	10.0
452	IAC	23.83	11.50	1761	1480	1088	857	407	376	4.3	496	4.6	350	15.9	10.3
453	None	35.93	NA	1690	1349	—	605	256	230	3.6	487	4.8	495	15.7	10.7
454	LAC	12.17	12.17	1627	1317	904	604	267	239	3.6	458	5.1	451	15.1	11.1
455	Zeolite	23.63	11.38	1698	1408	954	639	310	286	3.8	477	4.8	426	15.9	10.9
456	IAC	23.42	11.08	1722	1424	998	663	311	285	3.9	456	5.0	385	15.5	10.4

¹ Thermocouple failure.

NA = Not applicable.

LAC = Lignite-based activated carbon.

WAC = Wood-based activated carbon.

IAC = Iodine-impregnated activated carbon.

SAC = Sulfur-impregnated activated carbon.

TABLE 8

Summary of Task 2 Pulse-Jet Baghouse Results

Run No.	Pulse-Jet Baghouse Temp., °F	Sorbent	Hg/Sorbent Mass Ratio	Air-to- Cloth Ratio, ft/min	End of Run ΔP in. H ₂ O	Hopper Ash Inlet, gr/scf	Dust Loading		Outlet Emissions, lb/10 ⁶ Btu	Particulate Collection Efficiency, ¹ %	Hopper Ash LOI, % wt	Residual Dust Cake, g/m ²	Initial K ₂ , in. H ₂ O- ft-min/lb	Effective K ₂ , in. H ₂ O- ft-min/lb
							EPA Method 5							
							Inlet, gr/scf	Outlet, gr/scf						
442	300	None	NA	3.8	9.2	32.13	1.96	0.0015	0.0027	99.930	1.05	204.9	4.1	23.2
443	300	LAC	900	3.8	3.0	3.19	3.19	0.0016	0.0028	99.950	0.84	123.9	4.1	5.2
444	300	WAC	1000	3.8	4.5	2.89	2.51	0.0006	0.0010	99.981	0.66	124.8	4.6	8.0
445	300	None	NA	3.8	3.3	3.53	2.74	0.0005	0.0008	99.988	NA	146.4	3.5	4.8
446 A-B	400	None	NA	4.3	3.8	3.48	2.90	0.0002	0.0004	99.994	0.67	— ²	2.4	5.7
446 C-D	300	None	NA	3.9	3.0	3.51	2.88	0.0003	0.0005	99.992	0.39	151.8	— ²	4.0
447	300	IAC	1100	3.8	3.0	2.90	2.40	0.0008	0.0014	99.974	0.34	— ²	3.5	4.9
448	300	SAC	1400	3.8	3.8	3.62	2.67	0.0003	0.0006	99.992	0.44	— ²	— ²	4.5
449	300	LAC	3000	3.8	4.3	3.61	2.84	0.0002	0.0004	99.995	0.42	16.5	— ²	5.4
450	300	LAC	3400	3.8	3.2	3.46	2.85	0.0003	0.0008	99.987	0.87	— ²	3.1	4.1
451	300	IAC	1100	3.8	3.6	3.64	2.89	0.0001	0.0002	99.997	0.98	— ²	— ²	4.2
452	400	IAC	1200	4.3	5.4	3.65	3.00	0.0001	0.0001	99.998	1.06	137.1	— ²	4.1
453	250	None	NA	3.6	3.3	3.19	2.58	0.0004	0.0008	99.987	0.43	131.4	2.4	6.8
454	260	LAC	3400	3.6	3.2	3.24	2.97	0.0003	0.0005	99.991	1.61	— ²	2.9	4.8
455	300	Zeolite	3200	3.8	3.5	3.49	2.56	0.0002	0.0003	99.996	0.82	— ²	— ²	4.3
456	300	IAC	650	3.9	4.5	3.62	2.69	0.0003	0.0005	99.993	0.76	129.9	— ²	5.3

¹ Based on hopper ash dust loading and average outlet dust loading.² Continuation of a multiple-day run and, therefore, not applicable.

LAC = Lignite-based activated carbon.

WAC = Wood-based activated carbon.

IAC = Iodine-impregnated activated carbon.

SAC = Sulfur-impregnated activated carbon.

TABLE 9

Mass Emissions and Baghouse Collection Efficiency Based on Particle Size

Run No.	Total Mass Emissions, ¹ mg/m ³	Respirable Mass Emissions (0.7–7 µm), ² mg/m ³	Submicron Mass Emissions (0.01–1µm), ³ mg/m ³	Total Mass Collection Efficiency, ⁴ %	Respirable Mass Collection Efficiency, ⁵ %	Submicron Mass Collection Efficiency, ⁶ %
AB-442	3.435	0.797	0.0197	99.930	99.906	99.975
AB-443	3.664	1.610	0.0071	99.950	99.810	99.991
AB-444	1.374	0.492	0.0520	99.981	99.942	99.935
AB-445-B	0.916	0.212	0.0057	99.989	99.975	99.993
AB-445-C	0.687	0.152	0.0065	99.992	99.982	99.992

¹ Measured using EPA Method 29.² Measured using APS.³ Measured using DMPS.⁴ Collection efficiency is based on hopper ash inlet dust loading.⁵ Collection efficiency is based on a particle density of 2.5 g/cm³ and an estimated inlet measurement of 850 mg/m³, which is based on previous results.⁶ Collection efficiency is based on a particle density of 2.5 g/cm³ and an estimated inlet measurement of 80 mg/m³, which is based on previous results.

TABLE 10

Mercury Removal Results from Task 2

Run	Sorbent	Sorbent/Hg Mass Ratio	Baghouse Temp., °F	Total Hg, $\mu\text{g}/\text{m}^3$			Hg Balance ³ , %	% Hg Removal		
				Inlet ¹	Outlet ²	Hopper Ash		Total	H ₂ O ₂ Only ⁴	KMnO ₄ Only ⁵
442	None	NA	300	4.87	1.05	1.03	42.7	78	ND ⁶	67
443	Lignite carbon	900	300	5.04	1.07	2.45	69.8	78	ND ⁶	0
444	Wood carbon	1000	300	4.82	1.42	1.95	69.9	71	ND ⁶	16
445	None	NA	300	4.97	1.86	2.81	94.0	63	57	0
446 A-B	None	NA	400	5.91	4.19	3.65	132.7	29	31	8
446 C-D	None	NA	300	5.80	1.96	3.83	99.8	66	52	39
447	Iodated carbon	1100	300	5.93	0.89	3.80	79.1	85	68	91
448	Sulfated carbon	1400	300	4.16	1.22	4.26	131.7	71	62	53
449	Lignite carbon	3000	300	4.86	0.75	4.29	103.7	85	60	38
450	Lignite carbon	3400	300	5.11	0.79	3.78	89.4	85	100	31
451	Iodated carbon	1100	300	5.89	0.16	5.79	101.0	97	21	94
452	Iodated carbon	1200	400	6.27	0.45	6.91	117.4	93	5	98
453	None	NA	250	5.72	1.12	3.55	81.6	81	53	0
454	Lignite carbon	3400	260	4.50	0.42	4.50	109.3	91	ND ⁶	32
455	Zeolite	3200	300	5.20	1.22	5.44	128.1	74	91	-34
456	Iodated carbon	650	300	5.75	0.10	5.35	94.8	98	43	98

¹ Total inlet mercury includes mercury on filter, mercury captured in KMnO₄ impingers, and mercury captured in H₂O₂ impingers.

² Total outlet mercury includes only KMnO₄ and H₂O₂ impinger catches, because all outlet filter values were below the detection limits.

³ Mercury concentration in the outlet + mercury concentration in the hopper ash $\div$ inlet mercury concentration $\times$ 100%.

⁴ Based only on the inlet and outlet mercury captured in the H₂O₂ impingers.

⁵ Based only on the inlet and outlet mercury captured in the KMnO₄ impingers.

⁶ No mercury was detected in the H₂O₂ solutions for either inlet or outlet samples.

TABLE 11

Trace Metal Emissions at the Outlet of the Pulse-Jet Baghouse
Based on Baghouse Particulate Collection Efficiency

Trace Metal	Coal Concentration, ppm	Inlet Concentration in the Flue Gas, ¹ $\mu\text{g}/\text{m}^3$	Outlet Concentration (assuming 99.9% collection efficiency), $\mu\text{g}/\text{m}^3$	Outlet Concentration (assuming 99.99% collection efficiency), $\mu\text{g}/\text{m}^3$
As	1.6	213.8	0.21	0.02
Cd	ND ²	ND ²	ND ²	ND ²
Cr	3.7	494.42	0.49	0.05
Pb	1.2	160.35	0.16	0.02
Ni	7.1	948.8	0.95	0.10

¹ Inlet concentration based on a coal feed rate of 65 lb/hr and a flue gas flow rate of 130 scfm.

² Not detected in the coal.

The highest emissions, however, were still a factor of 10 lower than the 0.03 lb/MM Btu emission standard. For all dust loadings taken after more than 20 hours of filtration time, emissions were below 0.001 lb/MM Btu, corresponding to a collection efficiency of at least 99.99%. Each of the dust loadings was taken continuously over a 4-hour period as part of the Method 29 procedure and included the emission spikes that occur immediately after each bag cleaning. From the data in Figure 6, the additive had no apparent effect on total mass particulate emissions for a pulse-jet baghouse with Ryton fabric.

For Runs 442–445, particulate emission measurements were also taken with the APS and DMPS/CPC, as shown in Table 9. An example of the APS data, presented as respirable mass emissions, is shown in Figure 7 for Run 444. Note that just after bag cleaning, there is a brief spike in emissions that is about three orders of magnitude higher than emissions before bag cleaning. Using the APS, which has the capability to sample over an entire cleaning cycle, two integrated average emission samples were taken for Run 444, as shown in Figure 7. Integrated average APS respirable mass emissions for Runs 442–445 are shown in Figure 8 as a function of time, along with total mass emissions as determined by Method 29. The respirable mass emissions follow the same trend as the Method 29 data: both indicate a reduction in emissions with time for the first 10 hours of operation and fairly constant emissions for filtration times greater than 20 hours. Inlet respirable mass measurements were not conducted with the APS, but would likely be in the range of 300–900 mg/m^3 , based on previous inlet APS data collected during other research projects. An outlet respirable mass of 0.2 mg/m^3 , which

Figure 6. Results showing the effect of sorbent addition on particulate mass emissions.

Figure 7. Respirable mass as a function of time for Run AB-444.

Figure 8. Comparison of respirable mass emissions from the APS to EPA Method 29 data.

was achieved for filtration times greater than 20 hours, corresponds to a respirable mass collection efficiency range of 99.93% to 99.98%.

The DMPS/CPC measures submicron particulate emissions either continuously as particle number concentration or, over a 30-minute period, as a differential distribution in the range of 0.01 to 1 μm . Submicron mass emissions can be obtained over a 30-minute period in the DMPS mode, but samples are valid only if emissions are steady. Therefore, DMPS sampling cannot include the spike in emissions after bag cleaning. The data from Runs 445-B and 445-C show that submicron emissions after 20 hours of filtration were about 0.006 mg/m^3 . Inlet DMPS samples were not taken for these tests; however, the inlet submicron mass emissions can be approximated from inlet multicyclone sampling. Typically, about 1% of the inlet particulate mass is smaller than 1 μm , which corresponds to a concentration of approximately 80 mg/m^3 . Comparing this value with the measured DMPS submicron mass emissions value of 0.006 mg/m^3 shows that the submicron collection efficiency was 99.99%. This value is higher than the respirable mass collection efficiency, because the DMPS emissions do not include the emissions spike immediately after bag cleaning. Inspection of real-time APS data indicates that the integrated average (which includes bag-cleaning spike) emissions are typically about one order of magnitude

higher than the emissions between bag cleaning (for example, see Figure 7). Applying this relationship to the DMPS data shows that the submicron collection efficiency would be approximately 99.9% if the emission spikes were included.

After 20 hours of filtration, the Method 29 data indicate the total mass collection efficiency was 99.99%; the APS data indicate that respirable mass (particles between 0.7 and 7 μm) collection efficiency was between 99.93% and 99.98%; the DMPS data indicate that submicron collection efficiency was about 99.9%. Some deterioration in collection efficiency is expected with decreasing particle size, so the data appear to be consistent. Fine-particle collection efficiency is important because of the enrichment in concentration with decreasing particle size for some hazardous trace elements. The particulate emissions data indicate that all trace metals in particulate form will be collected with a minimum efficiency of at least 99.9% and a maximum efficiency approaching 99.99%. Actual trace metal collection efficiencies are more likely to approach 99.99% because most of the trace element mass will be in particles larger than 1 μm , even though the trace metal concentration is greater in submicron particles.

5.3.2 Fabric Filter Pressure Drop

The pressure drop across the fabric filter was easily controlled, usually between 3 and 4-in. W.C. For all tests, the cleaning cycle was set at either 45 min or 1 hr, depending on the length of test. The initial and effective K_2 values for each of the runs are shown in Table 8. The initial K_2 value is based on the linear part of the ΔP versus time curve from the first filtration cycle, with new bags. An effective K_2 value is based on a ΔP that is an average of the difference between the before- and after-cleaning ΔP s. Effective K_2 is higher than the initial K_2 , because the bags do not generally clean uniformly. With the exception of Run PTC-AB-442, both the initial and effective K_2 's were reasonably low for all the tests. For Run PTC-AB-442, there is no explanation for the high effective K_2 (23.17 in. H_2O ft-min/lb). The pressure drop for Run 442 increased rapidly to over 9-in. W.C. after about 16 hours of run time at a cleaning cycle of 1 hr. This type of rapid increase in pressure drop was not apparent in any other test. Combustor and fabric filter operational data for all the runs are presented in Appendix A.

5.4 Mercury Sampling Results

A summary of the mercury removal results for tests performed in Task 2 is shown in Table 10. The actual mercury data collected for each of the runs is in Tables A-1 and A-2 in Appendix A.

The total inlet mercury concentrations were fairly constant, with a mean value of $5.45 \mu\text{g}/\text{m}^3$, with a standard deviation of $0.69 \mu\text{g}/\text{m}^3$ for 35 samples. The expected flue gas mercury concentration is $5.8 \mu\text{g}/\text{m}^3$ based on a mercury level in the coal of 59 ppb. When the total inlet mercury concentration is compared with the combination of mercury in the baghouse hopper ash and outlet mercury, closures average $105\% \pm 18\%$ and range from 79% to 133% (not including Runs 442–444 which were conducted prior to modification of the heat exchangers). While the total inlet mercury concentrations were steady, the split between the mercury collected on the filter, H_2O_2 impingers, or KMnO_4 impingers was more variable. Although variable, the mercury collected on the filter appeared to be dependent on the flue gas temperature. For the tests at 300°F , an average of 59% of the mercury was collected on the filter compared to 26% at 400°F and 80% at 250°F . For the baseline tests, it would also be expected that the concentration of mercury in the ash collected on the filter would be the same as the mercury collected in the baghouse hopper ash, since both are excellent gas–solid contactors and were at the same temperature. Figure 9 shows that the mercury retained by the filter was comparable to the baghouse ash mercury, with the exception of several outlier points. The concentration of mercury collected in the impingers at the inlet showed a split of about 25% collected in the H_2O_2 solutions (ionic mercury) and 75% collected in the KMnO_4 solution (elemental mercury). This split did not appear to be temperature-dependent.

Figure 10 is a graph of total mercury removal as a function of temperature for the the baseline, lignite-based activated carbon and iodine-impregnated activated carbon tests. Figure 11 shows the percentage of mercury vapor removal for each of the three sorbents. For the baseline tests, there appears to be a strong inverse dependence of mercury retention on temperature. At 300°F for the baseline tests, an average of 65% of the mercury was removed in the fabric filter, compared to 80% at 240°F and 30% at 400°F . Although the temperature dependence was anticipated, the amount of mercury removed in the baghouse was higher than expected. The fact that the same approximate concentrations show up in the inlet filter and baghouse hopper ash is an indication that it is not simply a sampling artifact. To address the issue of the possibility of high bias during ash sample analysis, two baghouse hopper ash samples were heated to 750°F for 4 hours to drive off the mercury. These samples, along with the original sample, were submitted for analysis. The mercury concentration in the two original samples was within 10% of the previous results, and the mercury concentrations of the heated ash samples were 92% and 93% lower than the unheated sample. This provides strong evidence that the mercury measured on the fly ash is real.

The first tests completed while injecting sorbents (PTC-AB-443 and 444) were with a lignite-based and a wood-based activated carbon. These sorbents were both injected at a

Figure 9. Comparison of mercury concentration in the hopper ash and on the sampling filter.

Figure 10. Total mercury removal as a function of temperature and sorbent.

Figure 11. Vapor mercury removal as a function of temperature and sorbent.

sorbent-to-mercury mass ratio of 1000:1. Although the wood-based activated carbon has a much higher surface area (447 to 1462 m²/g), there was no significant difference in the total mercury removal; however, only one test was completed with the wood-based activated carbon (PTC-AB-444). In addition, the data from these two runs are somewhat suspect, especially the oxidated mercury data.

Two tests using lignite-based activated carbon were conducted with a sorbent-to-mercury mass ratio of 3400:1 and a baghouse temperature of 300°F. Results gave total mercury removals of 83% and 85%, but the impinger results alone do not indicate an improvement over the baseline test. An explanation is that a greater fraction of the inlet mercury was on the filters for the lignite-activated carbon compared to the baseline tests. The total inlet and outlet mercury concentrations appear to be the most consistent and, therefore, should be the most valid indication of the sorbent effectiveness. From the total mercury values, the lignite-based activated carbon is somewhat effective at this temperature and add rate. However, to achieve higher levels of control with the lignite-based activated carbon, either a lower temperature or higher add rate may be required.

Iodated activated carbon was much more effective than the lignite-based activated carbon in removing elemental mercury from the gas stream. However, it appears that the removal of the oxidated mercury is less. At a sorbent-to-mercury mass ratio of 1000:1, the removal of the elemental mercury averaged 93% compared to an average of 45% for the oxidated mercury. Even when the sorbent-to-mercury mass ratio was reduced to 650:1, the percentage removal was 98% of the elemental mercury and 43% of the oxidated mercury. This suggests that mixing sorbents may have a beneficial effect on overall mercury removal. When the baghouse temperature was increased to 400°F, there was no significant decrease in mercury removal when the iodated activated carbon was injected.

For the sulfur-activated carbon and the zeolite, only one test was performed with each sorbent. From Figure 12, it can be seen that these two sorbents collected more mercury than the baseline tests, but they were not nearly as effective as the iodated activated carbon. At the same sorbent-to-mercury mass ratio, the zeolite was not as effective as the lignite-based activated carbon. However, the speciation data using the zeolite sorbent were interesting, because they indicate a 91% capture of the oxidated mercury and a negative 34% capture efficiency for the elemental mercury. This was the only test in which the outlet elemental mercury increased over the inlet level and raises the possibility that the zeolite surface acts as a catalytic agent to reduce some of the oxidated mercury to elemental mercury. Shager reported an increase in elemental mercury across test system components and suggested that a possible explanation was the reduction of mercury chloride by stainless steel surfaces.¹ The zeolite does not appear to be the most promising mercury capture agent because of its relatively high cost and marginal effectiveness.

5.5 Other Trace Metals

At this point in the test program, the concentration of the other trace elements, arsenic, chromium, lead, selenium, nickel, and cadmium, at the outlet of the pulse-jet baghouse has not been addressed. However, with the possible exception of selenium, it is expected that these trace metals will be primarily in the form of particulate matter. The collection efficiency of the pulse-jet baghouse, even for submicron particles, was greater than 99.9% and had a maximum collection efficiency approaching 99.99%. As shown in

¹ Peter Schager. *The Behavior of Mercury in Flue Gases*; Department of Inorganic Chemistry, Chalmers University of Technology and University of Göteborg, 1990.

Figure 12. Comparison of the total mercury removal resulting from the injection of a zeolite and sulfur-impregnated activated carbon to the other sorbents tested.

Table 11, the outlet emissions for each of these trace elements is at least an order of magnitude lower than the mercury emissions.

5.6 Bench-Scale Results

Although the bench-scale work has just begun, several mercury speciation tests have been completed. One sampling and analysis necessity is to determine the adequacy of tentative EPA Method 29 to speciate between oxidated and elemental mercury. The method makes no claim as to its ability to speciate the two forms of mercury. The first two bench-scale tests were made using an elemental mercury permeation tube to generate a known concentration of mercury to the Method 29 impingers. In the first test, the calculated mercury concentration, based on the permeation tube emission rate, was 10 $\mu\text{g/L}$. Analysis of the H_2O_2 solution indicated a mercury concentration of $<0.1 \mu\text{g/L}$ in the H_2O_2 solution. Analysis of the KMnO_4 solution indicated a mercury concentration of 10 $\mu\text{g/L}$. For the second test, the calculated concentration was 20 $\mu\text{g/L}$, and the measured concentrations in the H_2O_2 and KMnO_4 solutions were 0.2 and 20.0 $\mu\text{g/L}$, respectively.

The next tests involved injecting the oxidated species (using the mercury(II) chloride permeation tube) and then measuring the concentration of mercury in the H_2O_2 and KMnO_4 solutions. Initial results indicated that over 99% of the mercury(II) chloride was captured in the H_2O_2 solution when the mercury concentration was high (in the range of 25 to 350 $\mu\text{g}/\text{m}^3$). However, when the mercury concentration was in the range of 1 to 2 $\mu\text{g}/\text{m}^3$, about 94% was retained in the H_2O_2 solution. At the lower concentrations, the measured oxidated mercury was lower than expected from the permeation tube mass emission rate and also appeared to be somewhat variable. Future tests are planned to help resolve these issues.

Based on the separate tests with elemental mercury and mercury(II) chloride permeation tubes, results indicate that Method 29 can provide highly accurate mercury speciation information.

6.0 PRELIMINARY CONCLUSIONS

- The particulate collection efficiency of the pulse-jet baghouse after 20 hr of filtration, while firing Absaloka coal, was very high, ranging from a minimum of 99.9% for submicron particles to 99.99% for total mass.
- The addition of activated carbon sorbents did not appear to have any significant impact on fabric filter performance.
- A good mercury balance around the pulse-jet fabric filter was achieved in the EERC pilot-scale baghouse.
- Although the overall mercury concentration at the inlet to the fabric filter was constant, the speciation data varied significantly.
- In the baseline tests, the concentration of mercury in the hopper ash decreased with increasing temperature.
- Lignite-based activated carbon appeared to collect oxidated mercury; however, it was not very effective in collecting elemental mercury.
- Iodated activated carbon was very effective in collecting elemental mercury and appears to be a promising mercury sorbent. However, it was less effective at collecting oxidated mercury.

- Although the sulfur-impregnated activated carbon and the zeolite gave better total mercury removal than the baseline tests, they were not as effective as the iodine-impregnated activated carbon.
- If arsenic, cadmium, nickel, lead, and chromium are exclusively in particulate matter form at the inlet to the baghouse, then a fabric filter is an effective method of removing these trace metals.
- Based on the separate tests with elemental mercury and mercury(II) chloride permeation tubes, Method 29 appears to provide highly accurate mercury speciation information.

7.0 FUTURE WORK AND RECOMMENDATIONS

7.1 Task 3 Test Program

7.1.1 Pilot-Scale Tests

A suggested test matrix of 21 pilot-scale tests to be completed under Task 3 is presented in Table 12. The test matrix is based on the project changes that were implemented in Task 2. The initial baseline tests with the Blacksville bituminous coal for both the pulse-jet baghouse and the ESP will be 2-day runs, while the others will be single-day tests. The first tests in Task 3 are to evaluate the impact of firing a Blacksville bituminous coal on metal vapor emissions. A lignite-based activated carbon and iodine-impregnated activated carbon will be injected and tested at two different feed rates and baghouse temperatures. The next tests are essentially a repeat of two tests completed in Task 2 (Absaloka subbituminous coal, lignite-based activated carbon, and pulse-jet baghouse) and are intended to verify previous results. The remainder of the short-term tests are to evaluate trace metal control in an ESP. Tests will be completed with each of the two coals, comparing two different sorbents, ESP temperatures, and sorbent add rates.

7.1.2 Bench-Scale Test Program

The bench-scale test program has two primary goals. The first is to validate Method 29 as to its ability to speciate mercury forms. The second is to screen sorbents for mercury control potential and evaluate the effect of temperature on mercury removal for the most promising sorbents. A total of 34 bench-scale tests are planned under Task 3, as shown in Table 13. The tests include 12 additional Method 29 verification tests,

10 sorbent screening tests, nine tests to evaluate the effects of temperature on sorbent performance, and three tests to determine the effectiveness of a sorbent mixture (iodine-impregnated activated carbon and lignite-based activated carbon). With the exception of the Method 29 verification tests, Absaloka fly ash will be injected into the system and, if needed, the sorbent will be mixed with the fly ash. Ryton fabric, housed in a heated filter holder, will be used to collect the fly ash and sorbent.

7.2 Proposed Tests Not Within the Current Enhanced Air Toxic Control Program

In discussion with EPRI and DOE, a number of additional research needs were identified that are beyond the scope of work for this project. A separate proposal addressing these needs will be submitted to EPRI and DOE. A short discussion of each is given below:

- **100-hr Pilot-Scale Tests.** In the original test plan, two 100-hr tests were scheduled for Task 3. However, because of the addition of the bench-scale work and additional tests completed in Task 2, these two tests cannot be completed within the current budget. However, these tests are still essential to determine the longer-term performance of selected sorbents.
- **Stability of Mercury on Fly Ash or Sorbents.** A major question exists as to the long-term stability of mercury adsorbed on activated carbon that is collected in a baghouse along with the fly ash. After cooling, it is imperative that the mercury remain on the carbon and not offgas into the air with long-term storage. Therefore, fly ash samples containing adsorbed mercury should be evaluated with respect to the stability of the mercury when it is exposed to the air or water.
- **Particle Size of Sorbents.** It is unknown if mercury capture depends significantly on particle size. A small particle size is needed to facilitate good mixing with the flue gas and to ensure that particles do not drop out before they reach the bags or ESP plates. However, whether better sorbent utilization can be attained by using smaller particle size is unknown.
- **Tests with the Comanche Station Coal.** Mercury control tests with carbon sorbents have been conducted by EPRI with a pilot pulse-jet baghouse at the Comanche Station. It would be of interest to see if the data generated at the EERC could duplicate that produced at Comanche with the same coal.

TABLE 12
Revised Task 3 Test Matrix

Test No.	Additive	Coal Type	Control Device	Sorbent/Hg Mass Ratio	Control Device Temperature, °F
1	Baseline	Blacksville	Baghouse	NA	350
2	Baseline	Blacksville	Baghouse	NA	250
3	Lignite Carbon	Blacksville	Baghouse	3000	250
4	Lignite Carbon	Blacksville	Baghouse	3000	350
5	Iodated Carbon	Blacksville	Baghouse	1000	250
6	Iodated Carbon	Blacksville	Baghouse	1000	350
7	Iodated Carbon	Blacksville	Baghouse	300	300
8	Lignite Carbon	Absaloka	Baghouse	3000	350
9	Lignite Carbon	Absaloka	Baghouse	3000	250
10	Baseline	Absaloka	ESP	NA	350
11	Baseline	Absaloka	ESP	NA	250
12	Lignite Carbon	Absaloka	ESP	3000	250
13	Lignite Carbon	Absaloka	ESP	3000	350
14	Iodated Carbon	Absaloka	ESP	1000	250
15	Iodated Carbon	Absaloka	ESP	1000	350
16	Baseline	Blacksville	ESP	NA	350
17	Baseline	Blacksville	ESP	NA	350
18	Lignite Carbon	Blacksville	ESP	3000	250
19	Lignite Carbon	Blacksville	ESP	3000	350
20	Iodated Carbon	Blacksville	ESP	1000	250
21	Iodated Carbon	Blacksville	ESP	1000	350

TABLE 13
Proposed Bench-Scale Test Program

Test No.	Sorbent	Temperature, °F
1-12	--- Method 29 Verification Testing ---	
13	Absaloka Fly Ash	250
14	Wood-Activated Carbon	250
15	Lignite-Activated Carbon	250
16	Iodine-Activated Carbon	250
17	Sulfur-Activated Carbon	250
18	Zeolite	250
19	Diatomaceous Earth	250
20	Vermiculite	250
21	High-LOI Fly Ash	250
22	Sorbalit	250
23	Absaloka Fly Ash	200
24	Absaloka Fly Ash	300
25	Absaloka Fly Ash	350
26	Lignite-Activated Carbon	200
27	Lignite-Activated Carbon	300
28	Lignite-Activated Carbon	350
29	Iodine-Activated Carbon	200
30	Iodine-Activated Carbon	300
31	Iodine-Activated Carbon	350
32	25% Iodine-Activated Carbon/ 75% Lignite-Activated Carbon	250
33	50% Iodine-Activated Carbon/ 50% Lignite-Activated Carbon	250
34	75% Iodine-Activated Carbon/ 25% Lignite-Activated Carbon	250

There appear to be some differences between the results obtained at EERC with the Absaloka coal and those obtained at the Comanche Station with a different Powder River Basin coal.

- **Sampling Method Comparison.** In addition to Method 29, several other mercury sampling procedures have been developed. The two primary methods are the Hazardous Element Sampling Train (HEST), developed by Chester Environmental, and the KCl-soda lime mercury speciation method, developed by Nick Bloom. Using both the bench- and pilot-scale testing facilities at the EERC, the three methods can be evaluated and compared. In addition, if other mercury-sampling methods are developed, these can also be evaluated.

APPENDIX A

COMBUSTOR AND PULSE-JET FABRIC FILTER PERFORMANCE DATA

Figure A-1. Baghouse temperature as a function of time for Run AB-442.

Figure A-2. Baghouse temperature as a function of time for Run AB-443.

Figure A-3. Baghouse temperature as a function of time for Run AB-444.

Figure A-4. Baghouse temperature as a function of time for Run AB-445.

Figure A-5. Baghouse temperature as a function of time for Run AB-446.

Figure A-6. Baghouse temperature as a function of time for Runs AB-447, 448, and 449.

Figure A-7. Baghouse temperature as a function of time for Runs AB-450, 451, and 452.

Figure A-8. Baghouse temperature as a function of time for Run AB-453.

Figure A-9. Baghouse temperature as a function of time for Runs AB-454, 455, and 456.

Figure A-10. Baghouse pressure drop as a function of time for Run AB-442.

Figure A-11. Baghouse pressure drop as a function of time for Run AB-443.

Figure A-12. Baghouse pressure drop as a function of time for Run AB-444.

Figure A-13. Baghouse pressure drop as a function of time for Run AB-445.

Figure A-14. Baghouse pressure drop as a function of time for Run AB-446.

Figure A-15. Baghouse pressure drop as a function of time for Runs AB-447, 448, and 449.

Figure A-16. Baghouse pressure drop as a function of time for Runs AB-450, 451, and 452.

Figure A-17. Baghouse pressure drop as a function of time for Run AB-453.

Figure A-18. Baghouse pressure drop as a function of time for Runs AB-454, 455, and 456.

Figure A-19. Respirable mass emissions as a function of time for Run AB-442.

Figure A-20. Respirable mass emissions as a function of time for Run AB-443.

Figure A-21. Respirable mass emissions as a function of time for Run AB-444.

Figure A-22. Respirable mass emissions as a function of time for Run AB-445.

TABLE A-1

Mercury Concentrations from PTC-Enhanced Air Toxics Test Program

Run No.	Temp., °F	Sorbent	Sorbent Add Ratio	Inlet No. 1, $\mu\text{g}/\text{m}^3$				Inlet No. 2, $\mu\text{g}/\text{m}^3$				Outlet No. 1, $\mu\text{g}/\text{m}^3$			Outlet No. 2, $\mu\text{g}/\text{m}^3$		
				Filter	H ₂ O ₂	KMnO ₄	Total	Filter	H ₂ O ₂	KMnO ₄	Total	H ₂ O ₂	KMnO ₄	Total	H ₂ O ₂	KMnO ₄	Total
442	300	None	NA	0.85	0.88	3.14	4.87	-	-	-	-	ND	0.99	0.99	ND	1.11	1.11
443	300	LAC	900	4.01	ND	1.03	5.04	-	-	-	-	ND	1.07	1.07	ND	1.06	1.06
444	300	WAC	1000	2.97	0.17	1.68	4.82	-	-	-	-	ND	1.41	1.41	ND	1.43	1.43
445-A	300	None	NA	3.36	ND	1.18	4.54	-	-	-	-	ND	1.91	1.91	-	-	-
445-B	300	None	NA	1.61	1.05	1.86	4.52	-	-	-	-	0.45	1.74	2.19	0.27	1.88	2.15
445-C	300	None	NA	4.78	ND	1.06	5.846	-	-	-	-	ND	1.20	1.20	-	-	-
446-A	400	None	NA	1.12	ND	5.69	6.81	0.70	0.91	4.43	6.04	ND	4.66	4.66	0.54	5.12	5.66
446-B	400	None	NA	0.67	1.99	2.71	5.37	2.15	0.43	2.85	5.43	1.61	2.41	4.02	0.16	2.28	2.44
446-C	300	None	NA	2.21	1.97	1.71	5.89	3.76	0.46	1.89	6.11	0.74	1.22	1.96	0.19	1.31	1.50
446-D	300	None	NA	2.84	1.52	1.72	6.08	0.44	1.84	2.83	5.11	0.63	1.21	1.84	1.20	1.35	2.55
447	300	IAC	1100	1.49	2.24	2.01	5.74	1.60	-	4.52 ¹	6.12	0.82	0.23	1.05	0.61	0.12	0.73
448	300	SAC	1400	2.95	0.71	2.03	5.69	0.82	-	1.80 ¹	2.62	0.31	0.89	1.20	0.23	1.01	1.24
449	300	LAC	3000	3.51	0.63	0.98	5.12	3.55	ND	1.04	4.59	0.25	0.58	0.83	ND	0.68	0.68
450	300	LAC	3400	3.78	0.34	1.10	5.22	2.81	0.99	1.19	4.99	ND	0.73	0.73	ND	0.85	0.85
451	300	IAC	1100	5.08	0.17	0.60	5.85	5.06	0.12	0.75	5.93	ND	0.05	0.05	0.23	0.03	0.26
452	400	IAC	1200	3.16	ND	3.11	6.27	0.59 ²	0.81 ²	3.64 ²	5.04 ²	0.22	0.02	0.24	0.55	0.10	0.65
453-A	250	None	NA	4.48	0.16	0.63	5.27	3.07	0.81	1.57	5.45	0.22	1.04	1.26	0.36	1.10	1.46
453-B	245	None	NA	3.98	0.11	0.48	4.57	5.92	0.71	0.86	7.49	0.05	0.50	0.55	0.21	0.89	1.10
454	260	LAC	3400	3.91	ND	0.57	4.48	3.86	ND	0.67	4.53	ND	0.34	0.34	ND	0.50	0.50
455	300	Zeolite	3200	4.25	0.36	0.98	5.59	3.16	0.74	0.91	4.81	ND	1.22	1.22	0.10	1.33	1.43
456	300	LAC	650	4.12	0.22	1.40	5.74	4.58	0.06	1.12	5.76	0.11	0.02	0.13	0.05	0.02	0.07

¹ Hydrogen peroxide impinger not used.² Sample nozzle was pointed downstream.

NA = Not applicable.

ND = Below detection limits.

LAC = Lignite-based activated carbon.

WAC = Wood-based activated carbon.

IAC = Iodine-impregnated activated carbon.

SAC = Sulfur-impregnated activated carbon.

TABLE A-2

Mercury Concentration and Loss-On-Ignition of Hopper Fly Ash Samples

Run No.	Temp., °F	Sorbent	Mercury Concentration		Loss-On-Ignition	
			Fly Ash Sample No. 1	Fly Ash Sample No. 2	Fly Ash Sample No. 1	Fly Ash Sample No. 2
442	300	None	0.4	1.6	0.86	1.24
443	300	LAC	1.6	3.3	0.97	0.71
444	300	WAC	1.0	3.0	-	-
445-A	300	None	1.8	-	-	-
445-B	300	None	1.7	-	-	-
445-C	300	None	5.0	-	-	-
446-A	400	None	4.9	-	0.79	-
446-B	400	None	2.4	-	0.54	-
446-C	300	None	4.0	-	0.40	-
446-D	300	None	3.7	-	0.44	-
447	300	IAC	3.8	-	0.34	-
448	300	SAC	4.3	-	0.44	-
449	300	LAC	4.3	-	0.42	-
450	300	LAC	3.8	-	0.87	-
451	300	IAC	5.8	-	0.98	-
452	400	IAC	6.9	-	1.06	-

LAC = Lignite-based activated carbon.
 WAC = Wood-based activated carbon.
 IAC = Iodine-impregnated activated carbon.
 SAC = Sulfur-impregnated activated carbon.

END DATE
 5/20/94