September 30, 2004

Ms. Karlene Fine
Executive Director
North Dakota Industrial Commission
600 East Boulevard Avenue
State Capitol, 10th Floor
Bismarck, ND 58505-0310

Dear Ms. Fine:

Subject: EERC Proposal No. 2005-0073

The EERC is pleased to submit the proposal titled "Assessment of Mercury Control Options and Ash Behavior in Fluidized-Bed Combustion Systems" for consideration for funding. We have included an original and seven copies as well as a check for $100.

If you have any questions, please contact me by telephone at (701) 777-5177, by fax at (701) 777-5181, or by e-mail at sbenson@undeerc.org.

Sincerely,

Steven A. Benson
Senior Research Manager

SAB/jlb

Enclosures

ASSESSMENT OF MERCURY CONTROL AND ASH BEHAVIOR IN FLUIDIZED-BED COMBUSTION SYSTEMS

EERC Proposal No. 2005-0073

Submitted to:

Ms. Karlene Fine

Executive Director
North Dakota Industrial Commission
600 East Boulevard Avenue
State Capitol, 10th Floor
Bismarck, ND 58505-0310

Amount of Request: $200,000

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September 2004

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ASSESSMENT OF MERCURY CONTROL AND ASH BEHAVIOR IN FLUIDIZED-BED COMBUSTION SYSTEMS

ABSTRACT

The Energy & Environmental Research Center (EERC) is developing a research consortium project that will focus on mercury control options for fluidized-bed combustion (FBC) systems, including circulating fluidized-bed combustion systems (CFBC). Previous testing with conventional boilers has shown that subbitumonous and lignite coal-fed systems emit 80%-90% elemental mercury, which is difficult to control with existing particulate control devices. The overall goal of this project is to evaluate mercury control options in FBC systems and the potential impacts of these control options on system performance, such as bed agglomeration, corrosion, and ash deposition. Several fuels, including lignite and subbituminous coals, will be tested at the EERC in a pilot-scale CFBC, equipped with a baghouse/spray dryer absorber (SDA) and/or electrostatic precipitator (ESP) for particulate control.

The proposed cost for the project is $1,000,000 and is expected to be completed within 18 months upon initiation. The project will be cofunded by commercial sponsors and the U.S. Department of Energy (DOE) through the EERC–DOE Jointly Sponsored Research Program (JSRP). DOE will provide 35%, or $350,000, of the total project cost and consortium members will provide the balance of $650,000. Based on nine sponsors, the level of funding requested by each industry sponsor will be $25,000 per year for 2 years. Currently, we have four sponsors committed to supporting this project. They are Babcock & Wilcox, ALSTOM, Foster Wheeler, and Montana-Dakota Utilities. Nova Scotia Power, Basin Electric, SEMPRA Energy, and EPRI have expressed strong interest. Funding requested from the North Dakota Industrial Commission (NDIC) is $200,000.

ASSESSMENT OF MERCURY CONTROL AND ASH BEHAVIOR IN FLUIDIZED-BED COMBUSTION SYSTEMS

PROJECT SUMMARY

The overall goal of this project is to evaluate mercury control options and their impact on performance for fluidized-bed combustion power plants. Although FBC is used in a small percentage of current fossil fuel-fired power plants, the technology is being proposed for a number of new power plants. Mercury emission data from these systems are insufficient to make predictions as to the ultimate fate of mercury and the best options for mercury control.

This project aims to provide detailed information on the control of mercury emissions and their effects on ash behavior in the system. The system configurations to be examined include FBC systems equipped with baghouses and/or electrostatic precipitators (ESPs) for particulate control with and without a spray dryer absorber (SDA). The mercury control options include sorbent injection upstream, sorbent enhancements combined with sorbent injection, and mercury oxidation upstream of the SDA/baghouse or ESP. These mercury control strategies will be evaluated at the EERC using a pilot-scale circulating fluidized-bed combustor (CFBC) equipped with a baghouse, ESP, and SDA/baghouse or ESP.

A variety of fuel ranks will be considered for testing in this project, including lignite and subbituminous coals. The final selection of specific fuels to be tested will be based on sponsor input. The specific objectives will be to 1) determine the speciation of mercury in flue gases produced in CFBC systems utilizing a limestone bed, 2) test mercury control options such as sorbent injection to capture mercury and additives to promote mercury oxidation, 3) determine the effect of additives on system performance due to corrosion, ash deposition and agglomeration, and 4) provide a cost estimate for control technologies deemed most promising for FBC systems.

PROJECT DESCRIPTION

Goals and Objectives

The overall goal of this project is to evaluate mercury control options and their impact on performance in power plants using FBC systems. The options will be tested in a pilot-scale CFBC burning a variety of fuel ranks such as bituminous, subbituminous, and lignite coals, and petroleum coke. The selection of specific fuels to be tested will be based on sponsor input. The specific objectives will be to 1) determine the speciation of mercury in flue gases produced in CFBC systems utilizing a limestone bed, 2) test mercury control options such as sorbent injection to capture mercury and additives to promote mercury oxidation, 3) determine the effect of additives on system performance due to ash deposition and agglomeration, and 4) provide a cost estimate for control technologies deemed most promising for CFBC systems.

Work Plan

The work plan for this proposed project consists of five tasks outlined as follows:

- Task 1 – Mercury Speciation in CFBC Flue Gas
- Task 2 – Mercury Control in a System Equipped with Particulate Control
- Task 3 – Mercury Control in a System Equipped with a Dry Scrubber
- Task 4 – Impact of Additives on Ash Deposition and Agglomeration
- Task 5 – Reporting and Management

Task 1 – Mercury Speciation in FBC Flue Gas. The selection of fuels to be tested will be based on input from the sponsors. Mercury speciation measurements will be conducted upstream and downstream of the air pollution control device (APCD). These tests will be conducted for a range of bed temperatures. Dolomite and limestone beds will be tested. This task will include characterization of four fuels selected for pilot-scale CFBC testing for important baseline parameters such as Hg, Cl, S, proximate analysis, ultimate analysis, heating value, and ash composition. The bed material will also be characterized to determine the bulk composition as well as mercury levels. Because the flue gas is expected to contain high levels of particulate, the Ontario Hydro (OH) mercury sampling method will be the primary method used to determine the mercury species in the flue gas of the CFBC. The mercury species determined will be particulate mercury, oxidized mercury, and elemental mercury. The performance of continuous mercury monitors (CMMs), commonly used for continuous monitoring in the flue gas of pulverized coal (pc)-fired systems will be evaluated for providing a secondary, continuous measure of mercury content during control-strategy deployment. Bulk samples of spent bed material and fly ash will be taken during testing and analyzed for mercury to determine partitioning and mass balance of mercury in the system. EPA Method 26A will also be used to determine chlorine–chloride levels in the combustion flue gas.

Chemical additions to the fuel or bed material have the potential to enhance mercury oxidation and mercury capture, especially in low-chlorine coals and high-sulfur petroleum coke. This task will be carried out in parallel with Tasks 2 and 3 to evaluate, and ultimately improve, the ability of chemical agents to enhance mercury control through promotion of mercury oxidation either alone in the furnace or upstream of particulate control devices (PCDs) in conjunction with sorbent injection. Once the removal efficiency of the sorbent injection rate has been established, the rate will then be adjusted back down to a value that provides moderate mercury removal (roughly 50%) and held at that point while gradually introducing a given additive to determine the improvement in removal efficiency. A final full-day test will be performed to obtain and confirm longer-term results of the performance of a selected additive. This final additive will be selected based on performance during screening tests, and considering cost, availability, and any issues associated with its use in a utility system. Based on the test results, initial economic evaluations will be performed to determine the cost savings per pound of mercury removal in comparison to the baseline case of activated carbon injection (ACI) without additives. Several additives and sorbent enhancements such as chloride-containing salts will be tested with fuels that emit a large fraction of elemental mercury to quantify the improvements of mercury removal with each.

Consideration also will be given to solids recycle rates throughout the testing with the EERC circulating fluid bed (CFB) pilot-scale system. Solids inventory will be maintained and controlled by the use of primary and secondary cyclones to maximize the utilization of the limestone bed material used for sulfur capture. The use of the cyclones and the flexibility of the EERC CFB system to selectively drain solids from different locations will help ensure that the system can be operated to simulate various full-scale CFBC boiler systems.

Task 2 – Mercury Control in a System Equipped with Particulate Control. The testing conducted as part of this task will determine the effectiveness of sorbents injected upstream of the baghouse or ESP on the control of mercury in flue gases produced from the four selected fuel types of Task 1. Testing will involve sorbent injection upstream of the PCD such as a fabric filter (FF) baghouse to improve mercury capture. The initial testing will involve shorter-term screening tests for evaluation of the sorbent enhancement additives (roughly two a day).

Initial sorbent injection testing will include ramping up the sorbent injection rate incrementally to generate results of removal efficiency as a function of injection rate for the test coal. Both carbon-based and silicates–amended-silicates sorbent injection will be investigated. Examples include NORIT Americas Inc. DARCO® FGD and lignite-based activated carbon (steam activated at 800°C [1472°F]). Inlet and outlet measurements will be taken using the OH method and CMMs. After each test, ash products will be analyzed for mercury and carbon contents.

Task 3 – Mercury Control in a System Equipped with a Dry Scrubber. The task involves reconfiguring the CFBC with the pilot-scale spray dryer followed by the pilot-scale baghouse. Testing will involve mercury oxidation upstream of the SDA, conducted on NORIT Americas Inc. DARCO® FGD, and lignite-based activated carbon (steam activated at 800°C [1472°F]) will also be injected upstream of the SDA. One of the sorbents will be pretreated with an EERC proprietary material to enhance its sorption capacity; the pretreated sorbent will be injected in the absence and presence of the most effective Hg^0 oxidation additive. In addition, other sorbents, such as amended silicates, sodium tetrasulfide, and enhanced carbons, will be tested based on sponsor input. CMMs will be used to measure Hg^0 and total mercury at the inlet and outlet of the SDA during each test. After each test, slaked-lime slurry feed and the SDA product solids will be analyzed for mercury and carbon contents.

Task 4 – Impact of Ash Deposition and Agglomeration. Ash deposition, bed material agglomeration, and erosion and corrosion of an FBC boiler will be examined in conjunction with mercury control testing. This task will investigate the mechanisms of ash deposition, bed agglomeration, and erosion and corrosion processes, and evaluate the impact of fuel properties and mercury oxidation additives. Work will focus on fuel, deposit and agglomerating material analyses, and erosion and corrosion evaluation. Analyses will include bulk ash analysis and chemical fractionation for coals computer-controlled scanning electron microscope (CCSEM) analysis for coals and fly ash samples, morphology analysis for agglomeration, and scanning electron microscopy point count (SEMPC) for deposits. The purpose of these analyses is to understand the relationship between ash deposition and agglomeration and fuel properties. Cases with and without mercury oxidation additives will be studied to understand the impact of additives. The project team will develop algorithms to predict ash deposition, agglomeration, erosion, and corrosion using fuel analysis data and boiler operating parameters.

Task 5 – Project Reporting and Management. This task will involve coordination of all testing conducted within the various tasks and subtasks of the project. Meetings will be held during the project involving the project manager, project advisor, principal investigators, and other key personnel to ensure communication and joint planning of tests. Reporting will consist of regular meetings with sponsors and project participants, quarterly reports, and a final report.

Deliverables

The project will focus on evaluating mercury control technologies and ash behavior for FBC systems firing a variety of fuels. Key information will be delivered to project sponsors in the consortium throughout the project, with all results and deliverables transferred to project sponsors by the end of the project.

Key deliverables that will be realized by participating companies and agencies include:

1. Information on mercury speciation and oxidation in CFBC systems burning a variety of fuels.
2. Results on mercury emissions and reduction potential for PCDs and a dry scrubber in FBC systems.

3. Performance and cost data for various mercury control options to assist in developing an overall compliance strategy. Data available will be directly applicable to fuels and plants that are part of this project.
4. Evaluation of system performance related to ash deposition and agglomeration in FBC systems as a result of fuel properties and the introduction of oxidizing agents for mercury control.
5. Collaborative research between stakeholders with an interest in developing cost-effective control technologies.
6. Immediate access to comprehensive reports.

STANDARDS OF SUCCESS

The standards of success for this project will be measured through successful pilot-scale testing of the proposed mercury control technologies and through the knowledge and understanding gained about the impacts of control options on the system performance in CFBCs. The control technology needs to demonstrate technical viability and the potential for economic viability based on the design, process, and test conditions, and oxidation-additive feed requirements.

The ability to assess the success of the project is based primarily on the EERC's quality management system (QMS). The EERC is committed to delivering consistent, high-quality research that meets its client's needs and expectations. An organizationwide QMS is in effect that governs all programs. This project is required to be in compliance with the EERC *Quality Manual* and any project-specific quality-assurance (QA) and quality-control (QC) procedures that are identified, thus ensuring that any requirements relating to quality and compliance with applicable regulations, codes, and protocols are adequately fulfilled. Table 1, Project Quality

Table 1. Project Quality Measures

QA/QC Control Measure	Purpose/Clarification
EERC QMS, including *Quality Manual* and quality policy and procedures	Ensure organizationwide compliance with QMS and applicable regulations, codes, and protocols – based on ISO 9000 standards. Authorized and supported by EERC top management.
Project-Independent QA/QC Manager at the EERC (David Brekke)	Assists research managers to plan QA for projects, does reviews and random audits for compliance assurance.
Perform Hg Mass Balance with Values 100% ± 20%	Determine total amount of Hg to be accounted for and determine removal rates: measured at inlet to APCD and stack. Also based on coal Hg and F_d factors.
EERC Expertise in OH Method and CMM Sampling	Understand potential problems that can occur, troubleshoot, ability to get valid data under difficult conditions.
OH Method Blank and Spike Analysis	Determine if contamination exists in sampling conditions and if recovery is complete. Rapid feedback allows immediate action to correct problems.
CMM Calibrations – at least daily. If target not met, may require additional calibration or maintenance and repeat QA/QC check	PS Analytical: sample clean air drawn through carbon trap followed by injecting known Hg standard. This procedure is done 4× to determine scatter (internal QA/QC EERC standard is $R^2 = 0.999$).
OH Samples Compared to CMM Data	After calibration, two concurrent OH method samples taken that should be ±20% of CMM data taken during period.
Chain-of-Custody Procedures	Ensure integrity of samples at all steps, including sample identification, analysis, and storage.
Team Direction by Consortium and DOE	Ensure that communication issues and problems are addressed to ensure objectives of project are attained.
Quarterly Conference Calls (or as needed)	Ensure effective communications among team members, address developing issues, resolve problems.
Information Transfer Via ftp Site	Allows efficient transfer of data between team members.

Measures, outlines project QA/QC measures specific to the measurement and control of mercury emissions.

BACKGROUND

Based on health and emission data, the U.S. Environmental Protection Agency (EPA) has decided to regulate mercury emissions from utility power plants. Given that power plants equipped with FBCs make up a small percentage of fossil fuel-fired power plants, mercury emission data from these systems are limited and insufficient to make predictions as to the ultimate fate of mercury and recommendations for the best options for mercury control. FBCs are also unique among combustion systems because operating conditions and range of fuel types differ greatly from conventional pc- and cyclone-fired boilers. The primary operational differences that have an influence on mercury control include: 1) the average combustion temperature (1500°F [815°C] in FBC units, compared to 2500°F [1371°C] in conventional boilers); 2) the presence of bed materials; and 3) the wide range of fuels fired. These differences have the potential to influence mercury control technologies. For example, the impact of bed material on the ability to control mercury is not known. The bed material has the potential to react with components in the coal that act as mercury oxidants.

The key questions are 1) How effective is the injection of mercury sorbents upstream of various control technologies on mercury control? 2) Are sorbent enhancement agents effective in minimizing the quantity of sorbent needed for mercury control? 3) Does the addition of sorbent enhancement agents have a negative impact on system performance?

Potential Mercury Regulations

Mercury is an immediate concern for the U.S. electric power industry because of EPA's December 2000 decision that regulation of mercury from coal-fired electric utility steam-generating units is appropriate and necessary under Section 112 of the Clean Air Act (1). EPA determined that mercury emissions from power plants pose significant hazards to public health and must be reduced. The EPA *Mercury Study Report to Congress* (2) and the *Utility Hazardous Air Pollutant Report to Congress* (3) both identified coal-fired boilers as the largest single category of atmospheric mercury emissions in the United States, accounting for about one-third of total anthropogenic emissions. On December 15, 2003, EPA proposed a rule to permanently cap and reduce mercury emissions from power plants (4). EPA is proposing two approaches for controlling emissions of mercury from utilities and will take comment on the alternatives before finalizing the proposed rule. The alternatives include: 1) requiring utilities to install controls known as "maximum achievable control technologies" (MACT) under Section 112 of the Clean Air Act; if implemented, this proposal would reduce nationwide emission of mercury by 14 tons (29%) by the end of 2007; and 2) a proposed rule establishing "standards of performance" limiting mercury emissions from new and existing utilities. This proposal, under Section 111 of the Clean Air Act, would create a market-based "cap-and-trade" program that, if implemented, would reduce nationwide utility emissions of mercury in two distinct phases. In the first phase, due by 2010, emissions will be reduced by taking advantage of "cobenefit" controls—that is, mercury reductions achieved by reducing SO_2 and NO_x emissions.

Mercury is a Health Concern

Mercury is a neurological toxin that can cause impairment of mental, sensory, and motor functions in humans, particularly developing fetuses and children. Atmospheric mercury emissions from sources such as power plants contribute to mercury deposition in the environment. Mercury and other contaminants in lakes are bioaccumulated in fish that are consumed by humans, which has prompted governments to issue thousands of fish consumption advisories. Freshwater lake advisories in the United States have more than doubled in the last 5 years, with more than 40 states issuing fish advisories because of mercury.

Mercury Emissions from Fossil Fuel Combustion

The level of mercury emitted from utilities and industry boilers varies with the fuel type, boiler configuration, and control technologies employed in the system. Emissions from U.S utilities burning fossil fuels were determined under EPA's information collection request (ICR), which mandated mercury and chlorine analyses on coal and supplemental fuels shipped to units larger than 25 MW_e during 1999 and required emission testing on 84 units selected to represent different categories of air pollution control equipment and coal rank. Table 2 shows the variation in composition among different coal ranks and petroleum coke as indicated from the Phase II ICR (5). Subbituminous and lignite coals from the western United States contain, on average, significantly lower levels of mercury, chlorine, and sulfur than eastern U.S., Appalachian, or interior bituminous coals. Appalachian and Illinois Basin coals typically have chlorine levels greater than 200 ppm. Conversely, western subbituminous and lignites have chlorine levels <200 ppm, typically <50 ppm. Western subbituminous and lignite coals are also distinguished by their much higher calcium contents. Gulf Coast lignites resemble eastern bituminous coals in their high concentrations of mercury and iron, but are similar to western coals with regard to low chlorine and high calcium contents. Petroleum coke contains, on average, slightly less mercury than subbituminous coal, but slightly more chlorine and considerably more sulfur than all coals (nearly 3 to 20 times as much as bituminous and subbituminous, respectively). These differences in composition have been shown to have important effects on the quantity and form of mercury emitted from a boiler and on the ability of different control technologies to remove mercury from flue gas.

Table 2. Fuel Analysis from ICR Phase II

Fuel Analysis	Bituminous Coal	Subbituminous Coal	Lignite Coal	Petroleum Coke
Hg, ppm	0.113	0.071	0.107	0.050
Cl, ppm*	1033	158	188	211
S, %	1.69	0.50	1.30	4.87
Ash, %	11.1	8.00	19.4	0.80
Btu/lb	13,203	12,005	10,028	15,211

* Methods used for chlorine determination are unreliable below 200 ppm.

The ICR Phase III data also revealed that bituminous coal-fed systems emit about 38% mercury as elemental, with the balance as oxidized and particulate mercury. In contrast, subbitiminous and lignite coal-fed systems emit mercury as 80%–90% elemental. Few ICR data were available for emissions of petroleum coke-fired systems. Only three plants sampled in Phase III blended petroleum coke with the main fuel; of the three plants burning a blend of petroleum coke and coal, one reported all nondetect values for speciated mercury, and the others reported about 90% elemental mercury at the stack.

Mercury Emissions from Fluidized-Bed Combustion (FBC) Systems

Fewer than ten of the 84 plants selected for ICR Phase III emission testing were equipped with FBC systems, resulting in limited mercury emission data for these systems. Because this subcategory represents a range of fuels, fluid-bed types, and particulate control devices, the information is not sufficient to accurately evaluate the mercury emission from these units. Removal efficiencies ranged from 48% to 99% with a variety of fuel types and the majority of the plants tested were equipped with a baghouse (Table 3). In addition, the fuels burned in FBC units during Phase III testing varied significantly in mercury, ash, chlorine, and sulfur levels (Table 4). The low chlorine values associated with some of the fuels are of particular interest because experimental results from pc-fired units indicate that low-chlorine (<50 ppm) coal combustion flue gases (typical of subbituminous and lignite coals) contain predominantly Hg^0, which is substantially more difficult to remove than Hg^{2+} (6). The analysis conducted as part of the ICR for chlorine overestimated the level present in the coals because the analytical techniques used for the coals were not accurate below about 200 ppm Cl. More sensitive techniques have subsequently been developed that have determined chlorine levels in western subbituminous and lignite coals as low as 10 ppm. Additionally, the high calcium contents

Table 3. Removal Efficiencies of FBC Units Sampled in ICR Phase III

Plant Name	Fuel Type	PCD*	Total Hg, Inlet, lb/TBtu	Total Hg, Stack, lb/TBtu	Removal, %
Heskett Station, B2	Fort Union lignite	Multicyclone/ ESP	3.32	1.73	48
TNP-One Station, Unit 2	Lignite	Baghouse	25.9	10.9	58
Scrubgrass Generation Station, Unit 1	Waste bituminous	Baghouse	92.8	0.15	99
AES Hawaii, Unit B	Indonesian bituminous	Baghouse	1.28	0.60	54
Kline Township Generating Plant, Unit 1	Anthracite–bituminous	Baghouse	52.1	0.52	99
Stockton CoGen Plant	Petroleum coke–bituminous	Baghouse	1.96	0.02	99

* Particulate control device.

Table 4. FBC Fuel Properties from ICR Phase III (5)

Fuel type	Heating Value, Btu/lb dry	Hg, µg/g	Ash, % dry	Cl, µg/g dry	S, % dry
Fort Union Lignite	10,438	0.086	11.4	200	1.32
Texas Lignite	9440	0.255	26.6	<167	1.32
Waste Bituminous	8342	0.527	43.8	600	1.47
Indonesian Bituminous	12,625	0.027	8.35	52	0.66
Anthracite–Bituminous	5030	0.33	59.3	233	0.42
Petroleum Coke–Bituminous	14,312	0.028	7.30	415	1.33

typical of a limestone bed as well as characteristic of subbituminous and lignite coals, may reduce the oxidizing effect of the already low chlorine content by reactively scavenging chlorine species (Cl, HCl, and Cl_2) from the combustion flue gas (7).

The fact that FBC systems typically operate at lower temperatures than conventional boilers (1500° vs. 2500°F [815 vs. 1371°C]) could potentially affect the behavior of mercury. The lower combustion temperature will produce fly ash with a higher carbon content, which could enhance the capture efficiency. This would be an added benefit for plants burning low-chlorine fuels that would typically emit a greater percentage of Hg^0 than Hg^{2+}. A recent project conducted by the EERC at the R.M. Heskett Station in Mandan, North Dakota, which burns Fort Union lignite and is equipped with a bubbling-bed FBC, showed 53% reduction in total mercury emissions across the electrostatic precipitator (ESP) (8). Speciated mercury at the inlet was 45% Hg^0, 53% particulate, and 2% Hg^{2+} . This suggests that the reduction in total mercury emissions is partially the result of ESP capture of the unusually high level of particulate-bound mercury in the flue gas. Analysis of ESP hopper ash samples averaged 17.3% (± 3.4) carbon, supporting the assumption that high-carbon ashes facilitate mercury capture. Uncertainty exists about mercury speciation and control efficiency for CFBs with very high carbon conversion efficiency.

Mercury Control Options

The technologies utilized for the control of mercury will ultimately depend upon the EPA-mandated emission limits. Options for controlling mercury emissions in pc- and cyclone-fired systems are being investigated that have the potential to attain more than 90% control of mercury emissions. ICR and test data of mercury control show good control potential for bituminous coals that have high levels of oxidized mercury. However, data from lignite and subbituminous coal-fired systems indicate that low mercury reactivity poses technical and economic challenges. In addition, the impact of limestone in FBCs on mercury speciation is not known and its potential influence on mercury control needs to be further investigated. The current approach to the application of mercury control strategies involves 1) enhancing existing control technologies and 2) investigating and developing new control technologies. The strategies include sorbent injection with and without enhancements upstream of an ESP or FF and mercury oxidation upstream of a wet or dry flue gas desulfurization (FGD) system. The new technologies being investigated include mercury capture using the *Advanced Hybrid*™ filter, gold-coated materials, and carbon beds (7). As with the characterization of mercury emission from utility boilers, evaluation of the efficiency of mercury control options has focused mostly on pc furnace systems.

Mercury Sorption

Sorbent injection for removing mercury involves adsorption of mercury species by a solid sorbent injected upstream of a PCD such as an FF baghouse or ESP. Evaluations of many potential mercury sorbents (9) have demonstrated that the chemical speciation of mercury controls its capture mechanism and ultimate environmental fate. Activated carbon injection (ACI) is the most mature technology available for mercury control. Activated carbons have the potential to effectively sorb Hg^0 and Hg^{2+} but depend upon the carbon characteristics and flue gas composition (9).

Testing conducted at the EERC with lignite coals fired in a pc combustion system illustrates the effectiveness of sorbents injected upstream of the ESP and baghouse. Figures 1 and 2 compare mercury removal efficiencies for EERC pilot-scale and DOE full-scale pc-fired combustion tests using ESP-only, ESP–FF, and TOXECON™(pulse-jet FF) control of bituminous, Powder River Basin (PRB) subbituminous, and Fort Union lignite coal combustion flue gases where activated carbons were injected upstream of the PCDs. Coal type (i.e., composition) is an important parameter that affects the mercury removal efficiency of a control device. During the pilot-scale lignite and utility-scale eastern bituminous coal tests, mercury removal efficiency increased with increasing ACI rates. However, mercury removal efficiency was never greater than 70%, regardless of the ACI rate into the PRB subbituminous coal

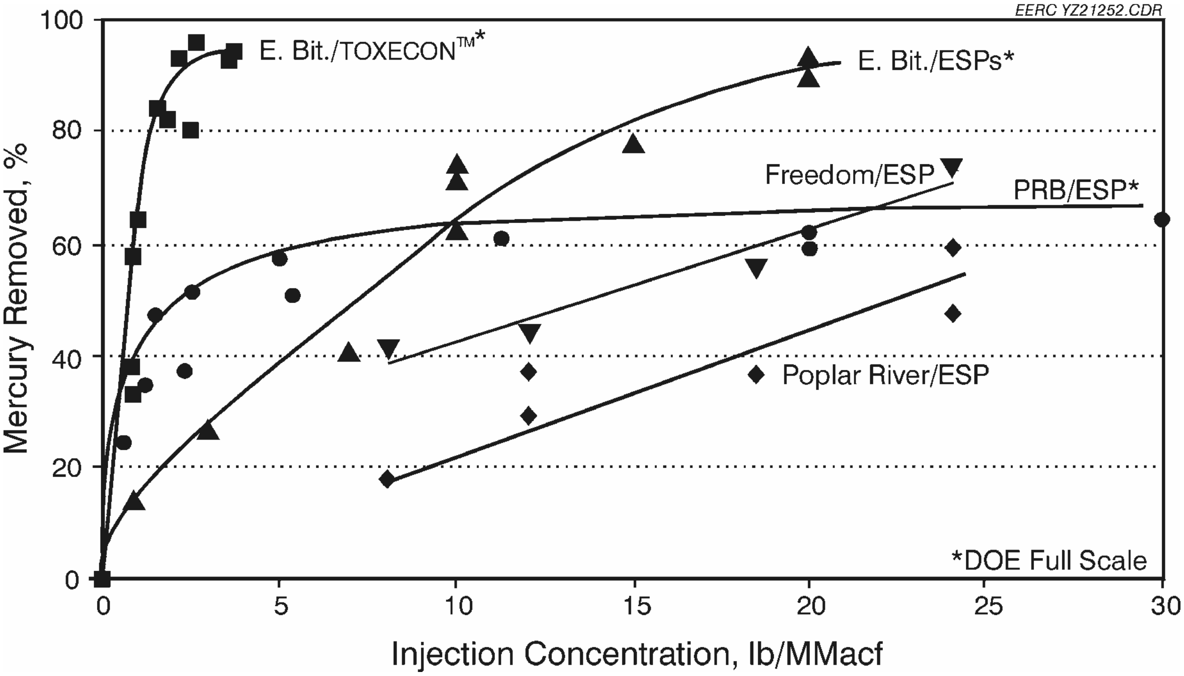

Figure 1. Pilot-scale ESP (10) and full-scale ESP (11) mercury removal efficiencies as a function of ACI rate.

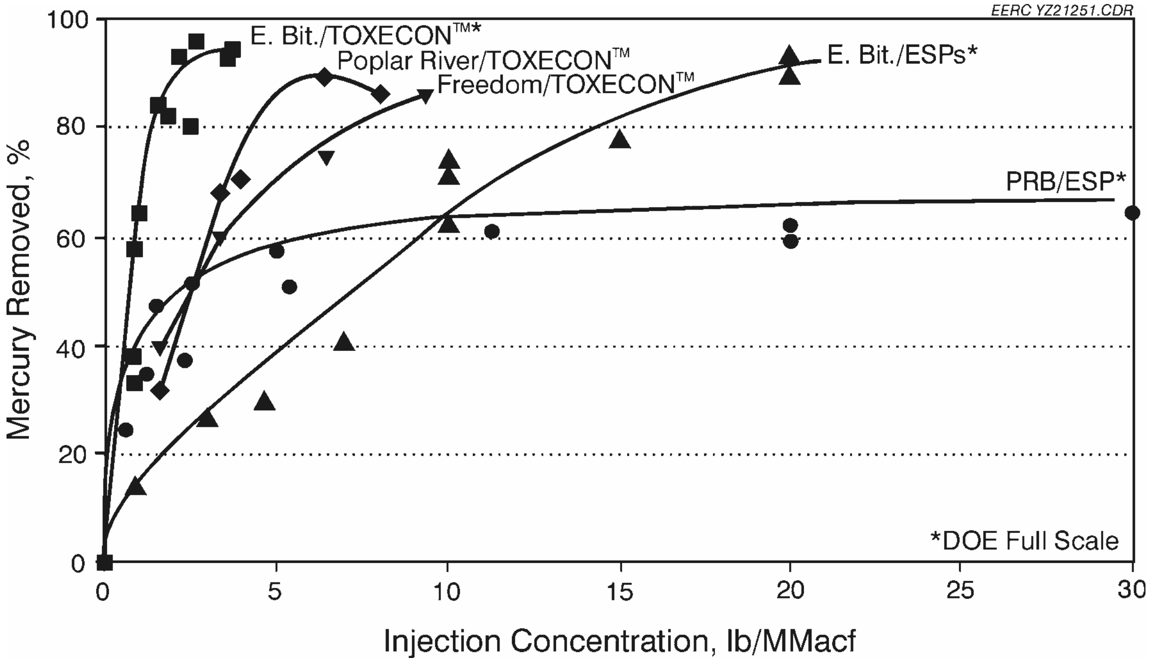

Figure 2. Pilot-scale ESP–FF (10) and full-scale TOXECON™ and ESP (11) mercury removal efficiencies as a function of ACI rate.

combustion flue gas. This limitation was probably caused by the low amount of acidic flue gas constituents, such as HCl, that promote mercury-activated carbon reactivity.

Testing conducted at a lignite-fired power plant firing Fort Union lignite equipped with a spray dryer baghouse indicated poor performance of conventional ACI to control mercury (12). The results indicate control efficiency of less than 35% for NORIT DARCO® FGD and lignite-activated carbon. The poor results are due to the low-acid flue gas and the high proportion of Hg^0 in the flue gas stream. The iodine-impregnated activated carbon showed approximately 90% control.

The projected annual cost for activated carbon adsorption of mercury in a duct injection system is significant. Carbon-to-mercury weight ratios of 3000–18,000 (lb carbon injected/lb mercury in flue gas [1361 kg–8165 kg]) have been estimated to achieve 90% mercury removal from a coal combustion flue gas containing 10 $\mu g/Nm^3$ of mercury (10). More efficient carbon-based sorbents are required to enable lower carbon-to-mercury weight ratios to be used, thus reducing the costs.

Amended silicate injection shows promise in controlling mercury emissions at coal-fired power plants (13). In a pilot-scale test with subbituminous coal, the amended silicates have shown improvement factors of 1.5 to 2 in controlling mercury emissions over activated carbon. In addition, the use of amended silicates will not impact the use of fly ash for cement replacement.

Mercury Oxidation

Mercury oxidation technologies currently being investigated include catalysts, chemical agents, and cofiring materials. The catalysts that have been tested include noble metal- and oxide-impregnated catalysts, and selective catalytic reduction (SCR) catalysts (12).

SCR catalysts will not be investigated in FBCs since there is little need for NO_x reduction in their lower-temperature combustion environment. The chemical agents include chlorine-containing salts, such as NaCl and $CaCl_2$. Fuels used as cofiring materials include tire-derived fuel (TDF) and other coals that contain high chlorine levels.

Mercury oxidation catalysts have shown high potential to oxidize Hg^0 in pc systems. Results from testing a slipstream at a North Dakota power plant indicated more than 80% conversion to oxidized mercury for periods of up to 6 months (12). Tests were also conducted using iron oxides and chromium, with little oxidation. Zygarlicke and others (14) have conducted short-term pilot-scale testing with maghemite (γ-Fe_2O_3) additions and were able to transform about 30% of the Hg^0 in North Dakota lignite combustion flue gases to Hg^{2+} and/or Hg(p) and, with an injection of a small amount of HCl (100 ppmv), nearly all of the Hg^0 to Hg^{2+}. Theoretically, the use of chloride compounds to oxidize Hg^0 to Hg^{2+} makes sense. The evidence including chemical kinetic modeling of bench-scale test results, indicates that the introduction of chloride compounds into the high-temperature furnace region will most likely result in the production of atomic chlorine and/or molecular chlorine. These constituents are generally thought to be the dominant Hg^0 reactants in coal combustion flue gases (7).

Fuel additives for mercury oxidation and sorbent enhancement have recently been tested at the EERC. The results of the addition of materials with coal at very low levels along with the ACI upstream of an ESP–FF, Advanced Hybrid™ filter, and ESP only are illustrated in Figure 3. The first part of the figure shows the baseline data for mercury emissions ranging from 9 to 12 $\mu g/Nm^3$, with 80%–90% of the mercury in the elemental form. The second case is ACI followed by the addition of proprietary Additive 2 (TOXECON™), showing a 90% removal of mercury emissions. The third case is the *Advanced Hybrid*™ filter, which produced nearly 90% control

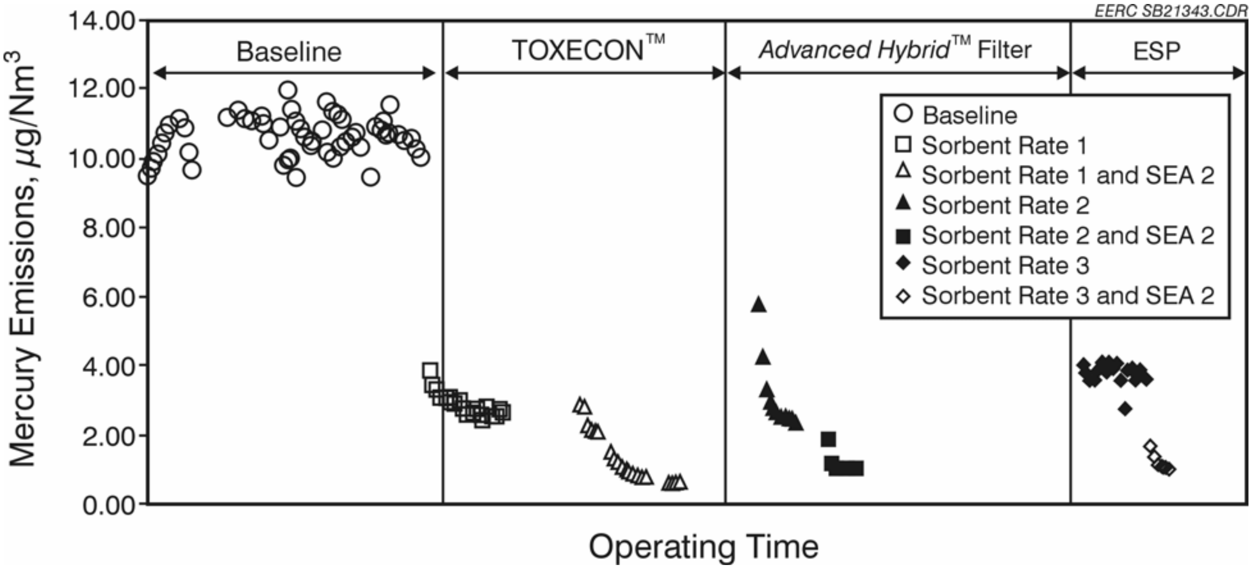

Figure 3. Mercury emissions for ACI combined with additives.

efficiency. The final ESP-only case also indicated up to 90% control. The control efficiency for the ESP-only case showed significant potential improvement compared with the ESP-only case illustrated in Figure 1. This technology also has the potential to improve dry FGD baghouse control efficiency.

In order for chlorine additives to oxidize mercury effectively, temperatures in the combustor must be high enough to dissociate the salt and produce Cl radicals. Figure 4 shows the temperature profile for a conventional coal-fired boiler as a function of residence time in the combustion system. Within the boiler, temperatures shown at 0.5–1.5 seconds on the graph are in excess of 1400 K (2060°F [1127°C]) and are adequate for a high yield of chlorine radical formation. Once the temperature drops below 1400 K (2060°F [1127°C]), the incidence of chlorine radicals drops precipitously. In contrast, the FBC temperatures reach a maximum of 1100 to 1200 K (1520–1700°F [827-927°C]), indicating the reduced potential for radical formation. Therefore, the use of chloride-containing additives at lower combustion

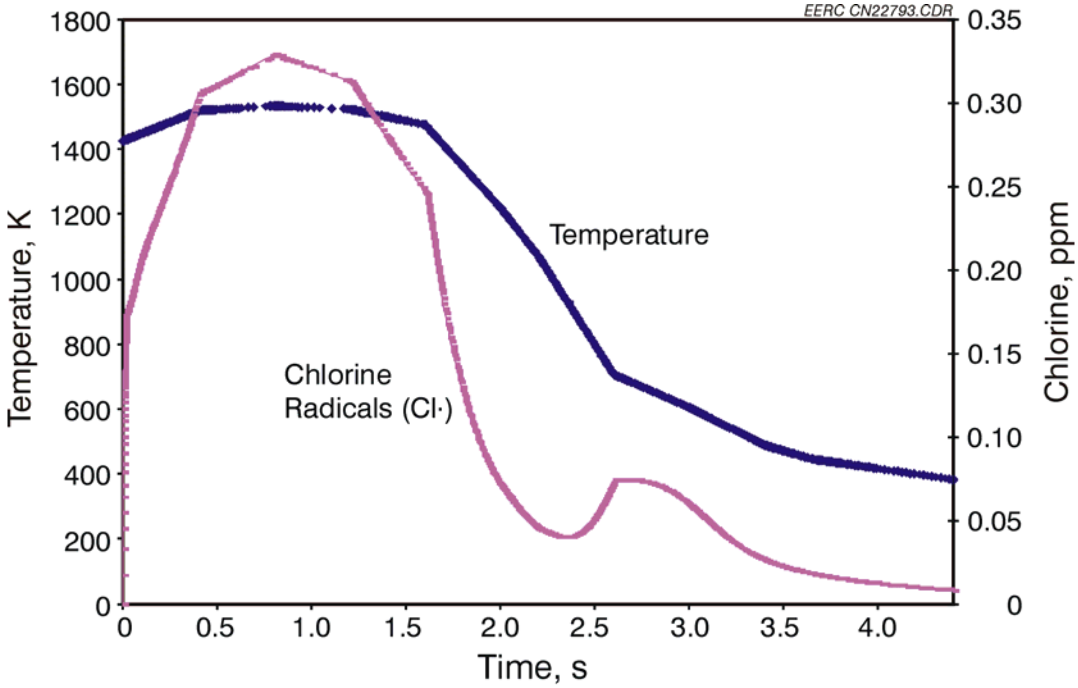

Figure 4. Spatial and temporal depiction of temperature and chlorine radical formation profiles in a conventional pc-fired boiler.

temperatures typical of FBCs may not be as effective in producing reactive Cl species for elemental mercury oxidation.

Recently, testing of activated carbon sorbent and sorbent enhancement agent (SEA) upstream of an ESP was conducted to control mercury emissions from North Dakota lignite. The testing was conducted using the EERC particulate test combustor (PTC) equipped with an ESP only. The results of the testing are illustrated in Figure 5, which shows the inlet total mercury level and baseline initial outlet. NORIT DARCO® FGD activated carbon was injected at 3.75 and 15 lb (1.7 kg and 6.8 kg) C/MMacf, resulting in 50%–60% mercury reduction. The addition of SEA with the coal and injection of 3.75 lb (1.7 kg) C/MMacf resulted in a reduction of over 70% of the mercury emissions.

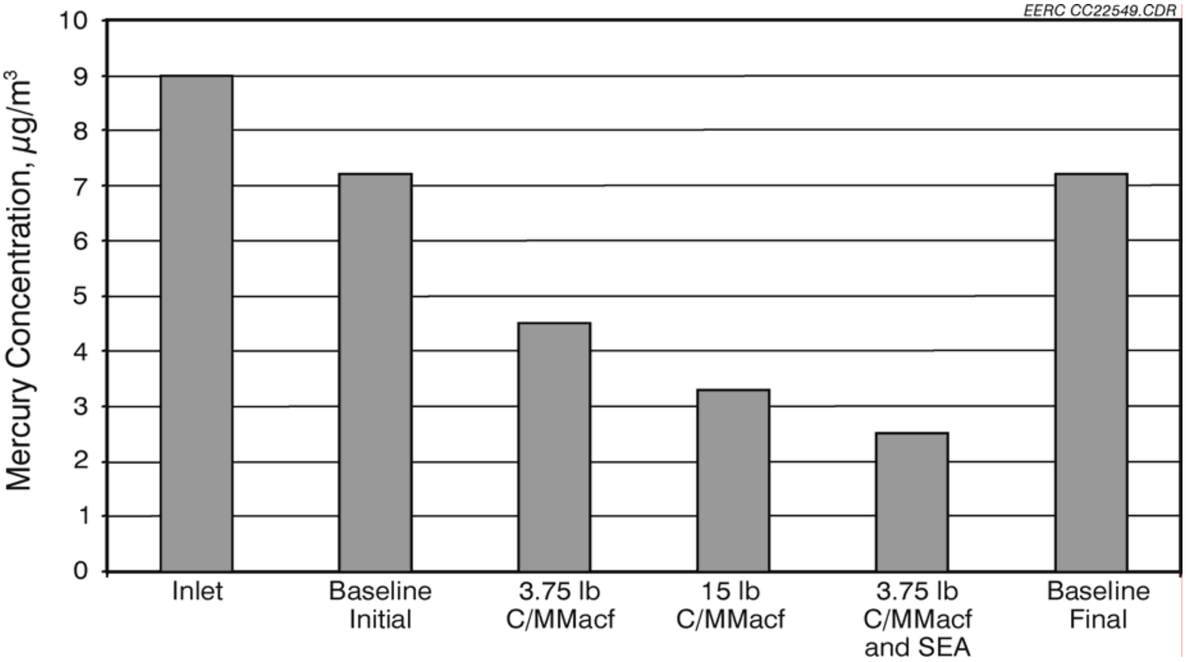

Figure 5. ESP mercury concentrations as a function of sorbent and SEA additive for North Dakota lignite.

The role of calcium in mercury oxidation needs further investigation in FBCs since the majority of these systems use limestone as a bed material. Liu and others (15) found that bituminous coals with very high chlorine content (4000 ppm) were effective at oxidizing mercury in a bench-scale fluidized-bed with limestone addition, which is comparable to the average bituminous coal-fired emissions reported in the ICR Phase III data. In a correlation analysis of the ICR Phase III data with coal analyses linked to specific power plants participating in the ICR, Benson et al. (16) showed that % Hg^0 content of emissions correlated directly with increased calcium oxide and iron oxide content in the coal. These data came mainly from low-rank subbituminous coals, which generally contain lower levels of chlorine and sulfur. Benson et al. suggest that the calcium may be reacting with these components that directly influence mercury speciation.

Researchers at the EERC and elsewhere are striving to attain a better understanding of mercury species reactions on activated carbon surfaces in order to produce more efficient sorbents. Functional groups containing inorganic elements such as chlorine or sulfur appear to have a significant role in bonding mercury (17–19). Recently, detailed analysis of sorbents derived from lignites exposed to flue gas and Hg^0 indicated the key species impacting oxidation and retention of mercury on the surface of the carbon contain chlorine and sulfur (20, 21). The chlorine reacts to form organically associated chlorine on the surface and it appears that the organically associated chlorine on the carbon is the key site responsible for bonding with the Hg^{2+} species.

Ash Deposition and Bed Agglomeration

This project will investigate the impact of mercury control technologies on major ash-related problems, such as bed material agglomeration, erosion, and corrosion with FBC systems. Both ash deposition and bed agglomeration have a strong relationship to the alkali (K, Na) and alkaline (Mg, Ca, Fe) element content in fuels. The major agglomerates are either alkali and alkaline sulfates or alkali and alkaline alumnosilicates (22, 23), depending on temperature. Alkali and alkaline sulfates are also the major factors for low-temperature fouling deposit. Mercury additives (alkali and alkaline chlorides) will change the concentration of alkali and/or alkaline elements of fuels and may alter the deposition and agglomeration behavior, which may result in necessary changes of deposition and agglomeration management strategies and possible changes of operating parameters.

QUALIFICATIONS

The EERC has been a leader in mercury control and ash behavior research for many years and is viewed as an expert in the field. Additionally, the EERC has more than 50 years of experience with western coals and a track record as a leading research and development organization. EERC researchers lead in advancing the understanding of mercury chemistry, measurement, transformations, solid–gas interactions and the development of mercury control technologies. The EERC has more than 13 years of expertise in Hg measurement and control for bench-, pilot-, and full-scale projects. Projects have been conducted specifically on technologies to oxidize and control Hg in flue gases produced from lignitic and subbituminous coals. Research findings from EERC projects have been instrumental to EPA's Maximum Achievable Control Technologies (MACT) Working Group and other agencies involved in regulation of air pollution.

The FBC research team at the EERC has been conducting research on fluidized-bed combustion systems since 1975. Programs have focused specifically on heat transfer, agglomeration, deposition, corrosion, and erosion evaluating a variety of fuels, bed materials, and sorbents.

The team brought together for this research project comprises leaders in the field of emission research and control technologies, especially as they pertain to Hg and lignite coals. Key personnel have participated in government and industry forums to address environmental and regulatory issues related to toxic air pollutants, including Hg.

VALUE TO NORTH DAKOTA

Two of the proposed projects for adding additional capacity using North Dakota lignite as a fuel will employ CFBC technology. The fuels selected for this project will include at least one North

Dakota lignite. A major challenge facing North Dakota lignite-fired power plants is the control of mercury emissions. The mercury species in combustion flue gases produced from North Dakota lignite plants is primarily elemental and much more difficult to control than oxidized mercury forms. This is true for both conventional boilers and FBCs. With increased knowledge and understanding of mercury behavior in fluidized beds, along with the advantages of high combustion efficiency and low NO_x and SO_2 emission performance, this technology is a viable choice for future power plants in North Dakota. Currently, more than 18,000 jobs, $1.3 billion in business volume, and $60 million in tax revenue are generated each year by North Dakota's lignite industry. The proposed additional lignite based power plant production facilities will lead to increased lignite production and use in North Dakota, resulting in more jobs in all lignite-related industries in the state.

MANAGEMENT

Dr. Steven A. Benson will be the overall project manager (PM). Dr. Michael L. Jones will serve as project advisor. Carolyn M. Nyberg will serve as Principal Investigator and Douglas R. Hajicek, Charlene R. Crocker, and Lingbu Kong will serve as co-principal investigators (PIs). Doug Hajicek will coordinate the operation of the CFBC. Charlene Crocker will coordinate the testing of the sorbents and oxidizing agents. Carolyn Nyberg will coordinate the mercury sampling activities. Lingbu Kong will assess the impacts of coal properties, mercury oxidizing agents, and operating conditions on the formation of deposits and agglomerates in the CFBC system. During the course of the project, meetings will be held involving the project manager and advisor, principal investigators, and other key personnel to ensure communication and joint planning of tests. Meetings and conference calls will be held with sponsors and project participants to ensure effective communications among all team members, address developing issues, and resolve problems. The overall organization of the project is illustrated in Figure 6.

TIMETABLE

The project will be completed within 18 months of project initiation. The proposed timeline for the project is expected to be between December 1, 2004 and May 31, 2006. Figure 7 shows the overall project schedule.

BUDGET

The proposed budget for the project is $1,000,000. The project will be cofunded by commercial sponsors and DOE through the EERC–DOE Jointly Sponsored Research Program (JSRP). The

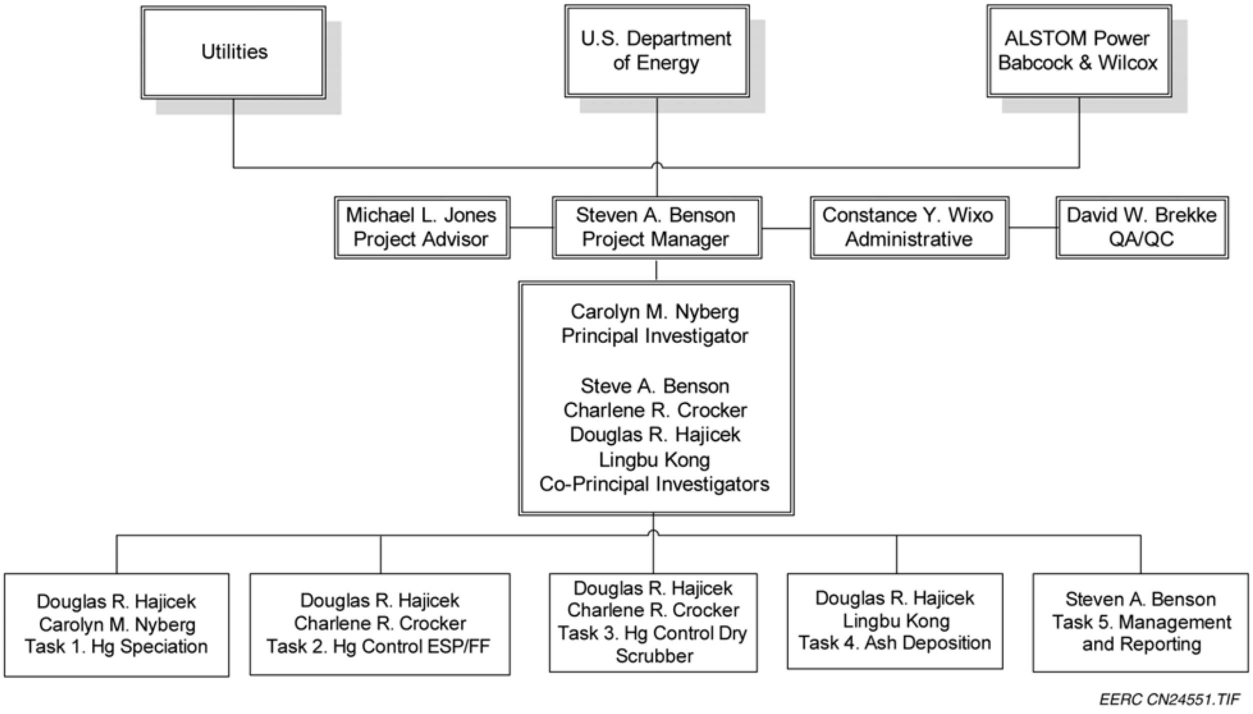

Figure 6. Project organizational chart for Hg control in FBCs.

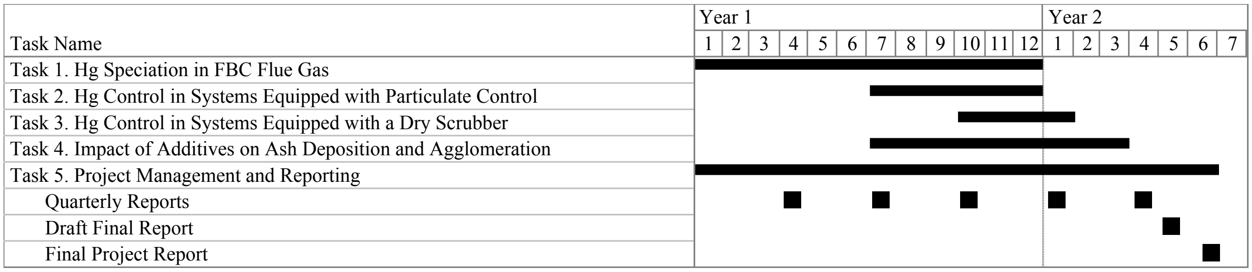

Figure 7. Project schedule.

DOE will provide 35%, or $350,000, of the total project cost, and consortium members will provide the balance of $650,000. A detailed budget is attached.

MATCHING FUNDS

The funding requested from the North Dakota Industrial Commission (NDIC) is $200,000 and the level of funding requested by each industry sponsor will be $25,000 per year for 2 years. This request is based on nine sponsors. Currently we have four sponsors committed to supporting this project. They are: Babcock & Wilcox, ALSTOM, Foster Wheeler, and Montana-Dakota Utilities. Nova Scotia Power, Basin Electric, SEMPRA Energy, and EPRI have expressed strong interest. Letters of support are attached in Appendix A. We anticipate receiving support from the remaining industry sponsors in the near future.

TAX LIABILITY

The EERC—a research organization within the University of North Dakota, which is an institution of higher education within the state of North Dakota—is not a taxable entity.

CONFIDENTIAL INFORMATION

No confidential information is included in this proposal.

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APPENDIX A

RESUMES OF KEY PERSONNEL AND LETTERS OF SUPPORT

DR. STEVEN A. BENSON
Senior Research Manager/Advisor
Energy & Environmental Research Center (EERC)
University of North Dakota (UND)
PO Box 9018, Grand Forks, ND 58202-9018 USA
Phone (701) 777-5000 Fax (701) 777-5181
E-Mail: sbenson@undeerc.org

Principal Areas of Expertise

Development and management of complex multidisciplinary programs focused on solving environmental and energy problems, including 1) technologies to improve the performance of combustion/gasification and associated air pollution control systems; 2) transformations and control of air toxic substances in combustion and gasification systems; 3) advanced analytical techniques to measure the chemical and physical transformations of inorganic species in gases; 4) computer-based models to predict the emissions and fate of pollutants from combustion and gasification systems; 5) advanced materials for power systems; 6) impacts of power system emissions on the environment; 7) national and international conferences and training programs; and 8) state and national environmental policy.

Qualifications

Ph.D., Fuel Science, Materials Science and Engineering, The Pennsylvania State University, 1987.
B.S., Chemistry, Moorhead State University (Minnesota), 1977.

Professional Experience

1999 – Senior Research Manager/Advisor, EERC, UND. Dr. Benson is responsible for leading a group of about 30 highly specialized scientists and engineers whose aim is to develop and conduct projects and programs on power plant performance, environmental control systems, the fate of pollutants, computer modeling, and health issues for clients worldwide. Efforts have focused on the development of multiclient jointly sponsored centers or consortia that are funded by a combination of government and industry sources. Current research activities include computer modeling of combustion and environmental control systems, performance of selective catalytic reduction technologies for NO_x control, carbon-based NO_x reduction technologies, mercury control technologies, particulate matter analysis and source apportionment, the fate of mercury in the environment, toxicology of particulate matter, and in vivo studies of mercury–selenium interactions. The computer-based modeling efforts utilize various kinetic, thermodynamic, artificial neural network, statistical, computation fluid dynamics, and atmospheric dispersion models. These models are used in combination with models developed at the EERC to predict the impacts of fuel properties and system operating conditions on system efficiency and emissions. Dr. Benson is Program Area Manager for Modeling and Database Development for the U.S. Environmental Protection Agency (EPA) Center for Air Toxic Metals^{SM} (CATM$^{®}$) at the EERC. He is responsible for identifying research opportunities and preparing proposals and reports for clients.

1994 – 1999 Associate Director for Research, EERC, UND. Dr. Benson was responsible for the direction and management of programs related to integrated energy and environmental systems development. Dr. Benson led a team of over 45 scientists, engineers, and technicians. In addition, faculty members and graduate students from Chemical Engineering, Chemistry, Geology, and Atmospheric Sciences have been involved in conducting research projects. The research, development, and demonstration programs involve fuel quality effects on power system performance, advanced power systems development/demonstration, computational modeling, advanced materials for power systems, and analytical methods for the characterization of materials. Specific areas of focus included the development and direction of EPA CATM® at the EERC (CATM®, a peer-reviewed, EPA-designated Center of Excellence, is currently in its 12th year of operation and has received funding of over $12,000,000 from government and industry sources), ash behavior in combustion and gasification systems, hot-gas cleanup, and analytical methods of analysis. He was responsible for the identification of research opportunities and the preparation of proposals and reports for clients. Dr. Benson left this position to focus efforts on Microbeam Technologies' Small Business Innovation Research (SBIR).

1986 – 1994 Senior Research Manager, Fuels and Materials Science, EERC, UND. Dr. Benson was responsible for management and supervision of research on the behavior of inorganic constituents, including air toxic metals during combustion and gasification, hot-gas cleanup (particulate gas-phase species control), fundamental combustion, and analytical methods of inorganic analysis, including SEM and microprobe analysis, Auger, XPS, SIMS, XRD, and XRF. Responsible for identification of research opportunities, preparation of proposals and reports for clients, and publication.

1989 – 1991 Assistant Professor (part-time), Department of Geology and Geological Engineering, UND. Dr. Benson was responsible for teaching courses on coal geochemistry, coal ash behavior in combustion and gasification systems, and analytical methods of materials analysis. Taught courses on SEM/microprobe analysis and mineral transformations during coal combustion.

1984 – 1986 Graduate Research Assistant, Fuel Science Program, Department of Materials Science and Engineering, The Pennsylvania State University.

1983 – 1984 Research Supervisor, Distribution of Inorganics and Geochemistry, Coal Science Division, UND Energy Research Center. Dr. Benson was responsible for management and supervision of research on the distribution of major, minor, and trace inorganic constituents and geochemistry of coals and ash chemistry related to inorganic constituents and mineral interactions and transformations during coal combustion and environmental control systems.

1980 – 1983 Research Chemist, U.S. Department of Energy (DOE) Grand Forks Energy Technology Center. Dr. Benson performed research on surface and/or chemical analysis and characterization of coal-derived materials by SEM, XRF, and thermal analysis in support of projects involving SO_x, NO_x, and particulate control; ash deposition; heavy metals in combustion systems; coal gasification; and fluidized-bed combustion.

1979 – 1980 Research Chemist, DOE Grand Forks Energy Technology Center. Dr. Benson performed research on the application of such techniques as differential thermal analysis, differential scanning calorimetry, thermogravimetric analysis, and energy-dispersive XRF analysis with application to low-rank coals and coal process-related material. In addition, research was performed on the use of x-ray analysis to measure trace elements in fuels and conversion products.

1977 – 1979 Chemist, DOE Grand Forks Energy Technology Center. Dr. Benson performed analysis on coal and coal derivatives by techniques such as wavelength-dispersive x-ray analysis, argon plasma spectrometry, atomic absorption spectrometry, thermal analysis, and elemental analysis (CHN).

1976 – 1977 Teaching Assistant, Department of Chemistry, Moorhead State University.

Professional Memberships and Activities

United States Senate Committee on the Environment and Public Works

- One of three technical panelists invited to provide testimony on mercury control for the coal-fired power industry.
- American Chemical Society (ACS)
  - Chair – Fuel Division 2004 – Duties comprise coordinating all aspects of the division, including publications and national conferences.
  - Fuel Division – Participates on the Executive Committee involved in the coordination and direction of division activities, including outreach, programming, finances, and publications.
  - Councilor, Fuel Division – Represents the Fuel Division at the National ACS Council meeting.
  - Chair Elect, Fuel Division – August 2002 – Elected to be Chair of the Fuel Division.
  - Member, Committee on Environmental Improvement (CEI) – The committee provides advice and direction to the ACS governance on policies and programs related to the environment. Since becoming a member of the committee, we have developed policy statements on Global Climate Change, Reformulated Gasoline and MtBE, and Energy Policy. These policy statements are used to assist legislators in developing national environmental policy. Members of CEI also provide testimony on a variety of environmental issues.
- American Society for Mechanical Engineers (ASME)
  - Advisory Member, ASME Committee on Corrosion and Deposition Resulting from Impurities in Gas Streams. Developed several conferences through the International Engineering Foundation.
- Mercury Reduction Initiative – Minnesota Pollution Control Agency (MPCA)
  - Participated in meetings for the mercury reduction initiative and provided advice regarding mercury control technologies for electric utilities and MPCA for voluntary mercury reduction strategies.
- Elsevier Science, *Fuel Processing Technology*

- Editorial board member whose role is to provide advice and direction for the journal.

Publications and Presentations

- Has authored/coauthored over 210 publications and is the editor of eight books and *Fuel Processing Technology* special issues.

CAROLYN M. NYBERG

Laboratory Manager/Research Chemist
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Energy & Environmental Research Center (EERC)
PO Box 9018, Grand Forks, North Dakota 58202-9018 USA
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Principal Areas of Expertise

Ms. Nyberg's principal areas of interest and expertise include atomic absorption spectroscopy (flame, graphite furnace, and hydride generation), cold vapor atomic absorption spectroscopy, inductively coupled argon plasma spectroscopy, Ontario-Hydro sample analysis, inductively coupled argon plasma spectroscopy, microwave digestion methods, trace element analysis of coal and coal by-products, and leaching characterization of coal fly ash for environmental impact.

Qualifications

B.S.Ed., Education and Science, University of North Dakota, 1986.
B.S., Biology with Chemistry minor, University of North Dakota, 1984.

Professional Experience

1990 –	Laboratory Manager/Research Chemist, Analytical Research Laboratory (ARL), EERC, UND. Ms. Nyberg's responsibilities include general laboratory management, including scheduling of samples and workloads of laboratory staff and preparation of research proposals, reports, and scientific publications. Additional duties include coordinating the financial aspects and contractual obligations of the ARL.
1988 – 1990	Laboratory Technician IV, Biology Department, UND. Ms. Nyberg's responsibilities included assisting professors by conducting radioimmunoassays to understand the reproductive cycles of sandpipers and salmon.
1987 – 1988	Soil Technician, Minnesota Valley Testing Laboratories, Grand Forks, North Dakota. Ms. Nyberg's responsibilities included testing for a variety of soil parameters such as pH, texture, organic matter, and numerous soil nutrients.

Research Experience

- Nickel speciation of residual oil fly ash (ROFA)
- Verification and implementation of Ontario-Hydro Method for Hg speciation for various emissions testing programs
- Leaching characterization of coal conversion solid residues for environmental impact
- Inductively coupled argon plasma atomic emission spectroscopy methods development for fly ash and related coal conversion solid residues
- Selenium mobility as it relates to overburden in post-coal mining environments

Publications and Presentations

Has co-authored numerous publications

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Principal Areas of Expertise

Dr. Jones' principal areas of interest and expertise include management of and technical direction for multidisciplinary science and engineering research teams focused on a wide range of integrated energy and environmental technologies. Specific program areas of interest include clean and efficient combustion of low-rank fuels, matching of fuel characteristics to system design and operating parameters, development of advanced power systems based on low-rank fuels, fundamentals of combustion, ash deposition in combustion systems, and analysis of inorganic materials. Projects emphasize a cradle-to-grave approach from resource assessment, to optimum utilization systems, to minimization of emissions and waste management featuring by-product utilization.

Qualifications

Ph.D., Physics, University of North Dakota, 1978.
M.S., Physics, University of North Dakota, 1973.
B.S., Physics, Bemidji State University (Minnesota), 1971.

Professional Experience

1994 –	Adjunct Professor, Physics, UND.
1983 –	Senior Research Advisor, EERC, UND. Dr. Jones’ responsibilities include planning and technical direction of combustion research, including projects in combustion chemistry, ash fouling and slagging, fluidized-bed combustion, coal–water fuels combustion, SO_x/NO_x removal, and particulate removal and characterization. Special emphasis is given to low-rank coal systems; activities range from field-testing of full-scale power plants to pilot-scale studies and laboratory investigations that examine both fuel and system characteristics and their impact on overall performance.
1990 –	Adjunct Professor, Department of Chemical Engineering, The University of Utah, Salt Lake City, Utah.
1979 – 1983	Grand Forks Energy Technology Center, U.S. Department of Energy. Dr. Jones’ responsibilities included technical direction of research and development projects related to combustion technology for low-rank coals, with specific responsibility for fundamental research on pulverized coal combustion. Directed research on new, specialized analytical procedures for determination of inorganics and trace elements in coal and materials derived from coal combustion and conversion processes. Instrumentation included methods Auger/ESCA spectrometer,

scanning electron microscope, x-ray diffraction, x-ray fluorescence, argon plasma spectrometer, and atomic absorption spectrometer.

Professional Memberships

- Adjunct Membership, Graduate Faculty, University of North Dakota, 1994
- Chair, ASME Research Committee on Corrosion and Deposits from Combustion Gases
- Utility Advisory Task Force for DOE-FE Study on RCRA Impact on Coal-Fired Utilities
- Sigma Xi – The Scientific Research Society
- Society for Applied Spectroscopy
- The Combustion Institute
- North Dakota Academy of Science

Publications and Presentations

- Has authored or coauthored over 80 publications

DOUGLAS R. HAJICEK

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Principal Areas of Expertise

Mr. Hajicek's principal areas of interest and expertise include atmospheric fluidized-bed combustion; the design, construction, and/or procurement of bench- and pilot-scale research equipment; and coal gasification.

Qualifications

B.S., Mechanical Engineering, University of North Dakota, 1976.
Registered Professional Engineer, State of North Dakota.

Professional Experience

2000 – Research Manager, Advanced Power Systems Group/Design Engineer, EERC, UND. Mr. Hajicek's responsibilities include the successful contractual operation, procurement of funding, and reporting activities associated with several pilot- and laboratory-scale gasification and combustion facilities at the EERC. Since 1999, he has served as a Design Engineer, where he has overall responsibility to ensure that code requirements are met for all construction, modifications, and operations of high-pressure systems at the EERC.

1989 – 2000 Senior Research Engineer, Systems Development, EERC, UND. Mr. Hajicek's responsibilities included the design and construction of a MW_{th} pulverized coal-fired slagging combustor for advanced heat-transfer materials testing; design of a state-of-the art bench-scale pressurized fluidized-bed reactor and high-temperature combustor simulator for trace metal studies; operation of existing pilot plant facilities associated with fluidized-bed combustion; and design, construction, and operation of 1-MW_{th} circulating fluidized-bed combustion test facility. He also assists with planning, project supervision, execution, and reporting of funded projects and the procurement of funding for new projects.

1984 – 1989 Research Engineer, Combustion and Environmental Systems Research Institute, EERC, UND. Mr. Hajicek's responsibilities included design, construction, and operation of a pilot plant facility used in research programs associated with fluidized-bed combustion. He also assisted with the design, construction, and modification of new and existing research equipment and in planning, supervision, execution, and reporting of funded projects for the fluidized-bed combustion of low-rank coals and other fuels.

1983 – 1984 Research Supervisor, Fluidized-Bed Combustion, Energy Research Center. Mr. Hajicek's responsibilities included planning, supervision, execution, and reporting of funded projects on the fluidized-bed combustion of low-rank coals and other fuels. Pilot-scale facilities are used to address such problems as sulfur capture, NO_x production, and bed agglomeration.

1977 – 1983 Mechanical Engineer, Grand Forks Energy Technology Center, U.S. Department of Energy. Mr. Hajicek's responsibilities included coordination between in-house management and contractor to accomplish a test program on a 200-lb/hr coal-fired fluidized-bed combustor; modifications and maintenance to keep the fluidized-bed combustor operational; design and construction of a continuous gas flow, high-temperature furnace and related systems used in conjunction with an optical system for the observation and analysis of burning coal particles in a simulated flue gas atmosphere; design, construction, and evaluation of a 300-lb/hr ion-exchange system for the removal of sodium from coal; and design, construction, and operation of a gaseous and liquid effluent sampling system used to obtain material balances and samples for chemical analysis from a 1-ton/hr slagging fixed-bed gasifier. He also assisted with data reduction for the slagging fixed-bed gasifier.

Professional Memberships

- American Society of Mechanical Engineers

Publications and Presentations

- Has authored or coauthored over 40 publications

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Principal Areas of Expertise

Ms. Crocker’s principal areas of interest and expertise include mercury and halogens in coal combustion, developing carbon-based mercury control sorbents, airborne particulate matter instrumentation, water quality monitoring and analytical methods, development and implementation of fish consumption surveys, general public and K–12 education, laser-induced breakdown spectroscopy (LIBS), atomic absorption spectroscopy (AAS) (flame, graphite furnace, and hydride generation), inductively coupled plasma spectroscopy (ICP), trace element analysis of water, coal and coal by-products, and atomic fluorescence spectroscopy (AFS).

Qualifications

B.S., Chemistry, University of North Dakota, 1994
B.A., French, Colby College, Waterville, ME, 1986

Professional Experience

1994 –	Research Chemist, Responsibilities include managing projects relating to environmental management and air quality; collaborating with other scientists on development of carbon-based flue gas sorbents, particulate matter (PM) sampling, fish consumption survey development, corrosion of ceramic and alloy materials, coal ash, water purification, and surface decontamination research; proposal and report writing, data analysis, presentation of results, and budget tracking; developing PM sampling protocols; participating in development of a water-based geoscience education program and outreach activities for school children; directing activities of student assistants; developing and implementing analytical methods employing LIBS. Previous duties performed in the Analytical Research Laboratory focused on water quality and energy-related analyses. Responsibilities included preparing and analyzing ultratrace element samples in aqueous and inorganic media using AAS, ICP, and IC; recording and disseminating analytical results and quality control checks; performing research on ultratrace elemental analysis of mercury using AFS; and preparing reagents and solutions.
1993 – 1994	Research Assistant, EERC, UND. Ms. Crocker’s responsibilities included preparing and analyzing ultratrace element samples in inorganic media; performing research on ultratrace element analysis of mercury in air using AFS; and preparing reagents and solutions.
1990	Naturalist, Deep Portage Conservation Reserve, Hackensack, Minnesota. Ms. Crocker’s responsibilities included planning and conducting environmental education programs for children and adults; evaluating curriculum; and organizing lending of educational learning stations.

1988 – 1990 Sanctuary Manager, Wetlands, Pines & Prairie Audubon Sanctuary, Warren, Minnesota. Ms. Crocker's responsibilities included planning and conducting environmental education programs; organizing chapter meetings; publishing the Sanctuary newsletter; and performing administrative tasks.

1988 Park Ranger/Interpreter, Boston Harbor Islands State Park, Boston, Massachusetts. Ms. Crocker's responsibilities included interpreting natural and human history; developing special programs and leading walking tours of the islands; and conducting school programs.

Presentations and Publications

Has co-authored several publications

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Principal Areas of Expertise

Mr. Kong's principal areas of interest and expertise include fuel analysis, coal ash behavior modeling, and software development.

Qualifications

M.S., Computer Science, University of North Dakota, Grand Forks, ND, 1997.
M.S., Geology, University of North Dakota, 1993.
B.S., Geological Engineering, Hebei Institute of Technology, Shijiazhuang, China, 1982.

Professional Experience

2001 – Research Scientist, EERC, UND. Mr. Kong's responsibilities include computer modeling of coal combustion systems. Major projects completed include:

- Developed software modeling ash transformation and deposition in coal combustion systems. The software uses fuel analysis data to predict ash transformation and slagging and fouling properties of boilers.
- Developed software modeling SO_x transformation and control with sorbent injection. The software uses fuel analysis data to predict the level of SO_x emission with or without sorbent injection.
- Developed software visualizing various types of data from ash transformation and deposition modeling. The software divides a cyclone barrel or furnace walls into millions of cells and graphically displays ash impaction rate, temperature, deposit viscosity, deposit growth rate, and deposit thickness of each cell.

1999 – 2001 Senior Software Engineer, Teradyne Inc. Mr. Kong's responsibilities included developing software for semiconductor testing equipment using Sun's Visual Workshop C++ on Salaris and completing an X-windows software project setting, reading and displaying memories of hardware, and an X-windows software creating licenses for Teradyne customers.

1999 Senior Software Engineer, Digital River Inc. Mr. Kong's responsibilities included developing software using Microsoft Visual C++ - MFC, Win32 APIs, and ATL. Projects completed include istream and ebot, two versions of the Digital River software helping customers shopping and downloading digital products on-line. Information about this software can be found at the Web site at www.ebot.com.

1998 –1999 Software Development Consultant. Projects completed included the following:

- Participated the development of the speech recognition software, IBM ViaVoice, with IBM in West Palm Beach, Florida. The software converts human voice to text in thirteen languages. Development tools used for this project included Microsoft Visual C++, MFC, Win32 API, and Microsoft SourceSafe.
- Independently designed and implemented the Mailroom Sorter software for Deluxe Corporation. The software was designed using OOA and OOD technology and implemented on Windows NT using Microsoft Visual C++, MFC, and MS-Excel. ODBC architecture was used to connect the software to an Excel database.

1993 – 1997 Senior Scientist, Microbeam Technologies Inc., Grand Forks, ND. Mr. Kong's responsibilities included the following:

- Principal investigator for CQMS (Coal Quality Management System). This project investigated the characteristics of inorganic components of different ranks of coals and developed new algorithms for power plants to better understand, predict, and solve power engineering and environmental problems related to coal combustion.
- Completed a software project managing fuel quality, power engineering, and environmental problems related to coal combustion. The software integrates CCSEM analysis, chemical fractionation, and ultimate analysis to model the chemical and physical characteristics of inorganic materials associated with fuel and ash-related materials and predict the impacts of fuel characteristics on system performance in power systems.
- Completed numerous commercial research projects for various customers such as power plants, chemical plants, coal mines, and power engineering and environmental research laboratories.
- Developed numerous computer programs for data processing and modeling of CCSEM analysis.

1990 – 1994 Graduate Research Assistant, EERC, UND. Major projects completed/participated included the following:

- Developed a procedure to analyze organically associated inorganic components using SEM. This project was awarded the Antoinette Lierman Medlin Scholarship and the Best Student Research in 1992 by GSA Coal Division.
- Analysis of toxic trace elements in coals using SEM.

Publications and Presentations

- Has authored or coauthored numerous publications

APPENDIX B

EERC PILOT-SCALE AND LABORATORY FACILITIES

FACILITIES

The EERC has the trained personnel, analytical facilities, and all of the laboratory and testing equipment needed to support this project, including semicontinuous emission monitors (SCEMs) and a full range of bench- and pilot-scale systems, as described below.

Mercury Sampling and Analysis Capabilities

The EERC has performed sampling and measurement for mercury in flue gases for 13 years. This work involves the sampling and comprehensive testing for mercury and other trace metals in bench-, pilot-, and full-scale systems. The EERC operates two mobile laboratories that are used for pilot- and full-scale sampling and analysis. These laboratories utilize OH mercury speciation sampling trains and SCEMs to sample and measure speciated mercury levels in the flue gases.

The EERC utilizes mercury SCEMs, along with wet-chemistry pretreatment units, and has gained considerable expertise in their operation over the last 8 years. EERC researchers are world-class experts in the operation of these instruments. The EERC has sampled some of the most demanding sites, including those with wet scrubbers and high particulate matter content in the emissions. The EERC owns 12 mercury SCEMs—nine atomic fluorescence-based monitors (Tekran and Sir Galahad) and three using cold-vapor atomic absorption (Semtech and Ohio Lumex). These instruments have been used at more than 40 coal-fired units in the United States and Canada.

Computer-Controlled Scanning Electron Microscopy (CCSEM) Analysis

Size and composition of mineral grains in pulverized coal can be determined by CCSEM, a program used in conjunction with an SEM and microprobe system and a mineral characterization program. The CCSEM analyzed 3000 mineral particles, providing information on size, shape, chemistry, and relation to coal of each particle. CCSEM also is used to characterize fly ash.

Scanning Electron Microscopy Point Count (SEMPC) Analysis

SEMPC is used to quantify the phases present in the deposit. The analysis provides different phases and information on the degree of interaction and melting of the deposited ash components and the abundance of crystalline, amorphous, and unreacted ash particles. These data are critical in identifying the components in ash deposits that are responsible for deposit growth and strength development.

Scanning Electron Microscope (SEM) Morphology

Scanning electron microscope–microprobe (SEM–EMPA) techniques are an effective means to examine coals, fly ashes, deposits, slags, soils, cements, and other complex heterogeneous materials. Morphology of materials refers to the spatial and chemical arrangements of the different components of a material. The SEM–EMPA system facilitates the observation and chemical analysis of very fined-grained phases while simultaneously preserving both the original chemistry of the minerals and their relationships to the organic constituents. Especially important is the liquid-phase composition, reactivity, and crystallinity which can be discerned using SEM morphology.

X-ray Diffraction (XRD) Analysis

Qualitative XRD is used to identify the crystalline phases present in coal combustion products.

Circulating Fluidized-Bed Combustor (CFBC)

The CFBC is a 20-in. (51-cm) -diameter 1-MW_{th} pilot-scale unit designed and constructed at the EERC. It has been used to perform evaluations on the effects of operating conditions, fuel characteristics, and sorbent characteristics on combustion and emissions performance (Figure 7).

Testing has been performed on this unit that provides emission data and ash stream samples to facilitate permitting of a full-scale CFB boiler. A wide variety of fuels have been tested in the CFBC, including high- and low-rank coals, petroleum cokes, and dried municipal sewage sludge. The pilot plant is capable of operating over the range of conditions currently offered by most boiler vendors.

Fuel is delivered to the combustor via two hoppers. The storage hopper has a capacity of about 3000 lb (1361 kg) of fuel, which is transferred to a permanent feed hopper in 600-lb (272 kg) increments. Limestone is fed with a variable-speed screw that can be calibrated to a desired sorbent feed rate. The fuel and sorbent feed into a common pipe, which drops into a 3-in. (7.6 cm) horizontal auger that conveys the mixture adjacent to the combustor. At this point, the mixture drops downward through a 3-in. (7.6 cm) pipe and feeds by gravity with air assist into the combustor.

Orifice plates are used for measuring primary and secondary air (PA and SA) to the combustor, fluidizing air, and flue gas flow rates. Instrumentation is interfaced with the data acquisition and control system to record and display the flow rates. Orifice differential and static pressures, along with other critical pressures, are monitored with magnehelic pressure gages.

The components of the solids recirculating system include the primary cyclone, the downcomer sections, and the external heat exchanger (EHX). Solids that are captured by the primary cyclone drop into the downcomer and travel downward into the EHX. Thermocouples monitor the temperature at the entrance and exit of the primary cyclone. Additional solids that drop out in the ash-fouling section hopper and that are collected by the secondary cyclone can either be added back into the downcomer or collected separately.

Flue gas exits the top of the combustor (Figure 1), then flows progressively through the refractory-lined primary cyclone with an inside diameter of 25 in. (63.5 cm), the ash-fouling section, an air-cooled flue gas cooler, the combustion air heater, an 18-in. (45.7 cm) stainless steel secondary cyclone, eight water-jacketed flue gas heat exchangers, either through the pulse-jet fabric filter baghouse or the flue gas bypass, then the induced-draft blower and, finally, out the stack. Temperatures and pressures are monitored throughout the flue gas system.

There exists the potential for a slipstream to other possible control devices including a spray dryer and then to either an ESP or another pulse-jet baghouse combination. The slipstream would be tied in midway through the set of eight flue gas water-jacketed heat exchangers before the CFBC baghouse. The ESP (Figure 2) is designed to provide a specific collection area of 125 ft^2 (11.65m^2)/1000 acfm (28.3 m^3.min) at 300°F (149°C). A slipstream of flue gas from the CFB will be diverted to the ESP with a flow rate of 130 scfm; the gas velocity through the ESP is 5 ft (1.5 m)/min. The plate spacing for the unit is 11 in. (28 cm). The ESP has an electrically isolated plate that is grounded through an ammeter, allowing continual monitoring of the actual plate current to ensure consistent operation of the ESP from test to test. The tubular plate is suspended by a load cell that helps to monitor rapping efficiency. In addition, sight ports are located at the top of the ESP to allow for real-time inspection of electrode alignment, sparking, rapping, and dust buildup on the plate. The ESP was designed to facilitate thorough cleaning between tests so that all tests can begin on the same basis.

The EERC recently added an SDA for testing the application of spray dryer–baghouse combinations for mercury control. A schematic diagram of the spray dryer is shown in Figure 3. The SDA is a Niro product minor spray dryer designed to operate in conjunction with flue gas

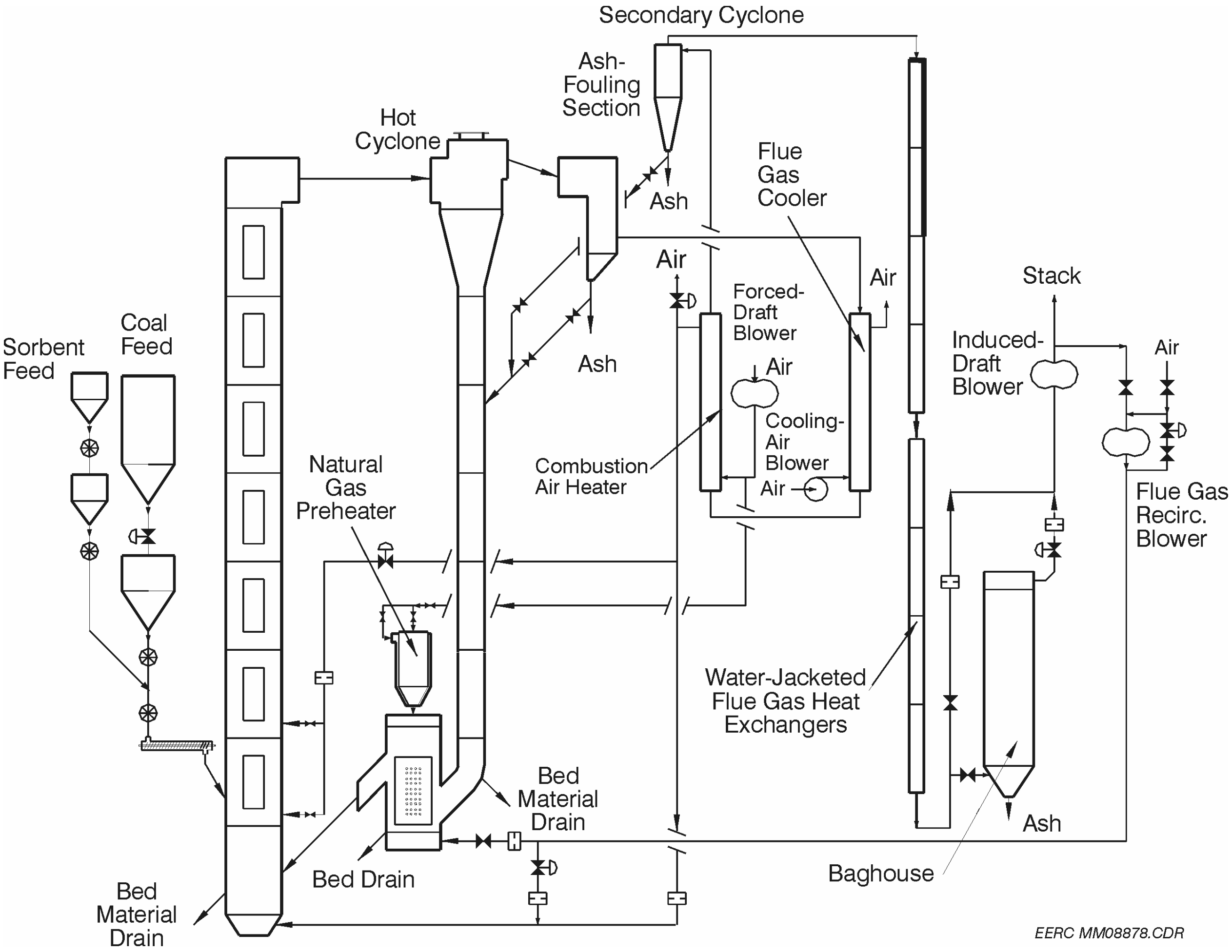

Figure B-1. Schematic of CFBC pilot plant.

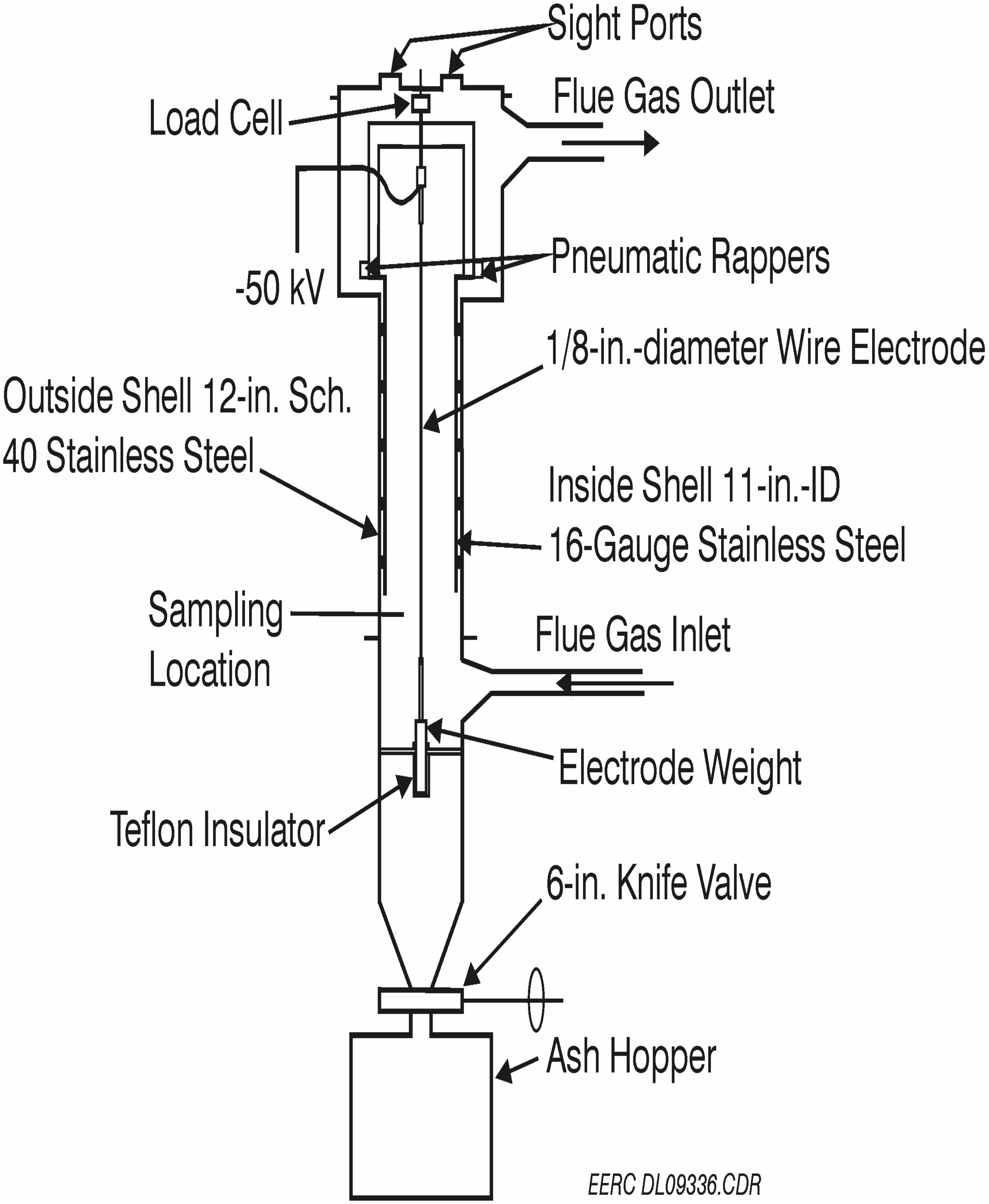

Figure B-2. Schematic diagram of ESP.

slipstreams or pilot-scale combustors. For example, a slipstream between the fourth and fifth heat exchangers of the CFBC can be diverted to the SDA with an inlet gas flow rate of 218 acfm at 300°F (149°C). The lime slurry flow rate is 0.17 lb (77 g)/min, with 20% solid content. The SDA vessel has an inside diameter of 2.5 ft (0.76 m), height of 7.2 ft (2.2 m), and a residence time of about 10 sec. The spray dryer operation can be varied, but typically the flue gas is cooled to around 165°F (174°C) at the outlet.

To quantify the effect of CFBC design and operating parameters and the effects of fuel and sorbent properties, the EERC measures a number of important performance variables and relates them to design and operating conditions, fuel, and sorbent properties. Environmental performance is evaluated by measuring sorbent addition and utilization to achieve the desired SO_2 control; NO_x, N_2O, CO, and hydrocarbon emissions; particulate collectibility; and waste

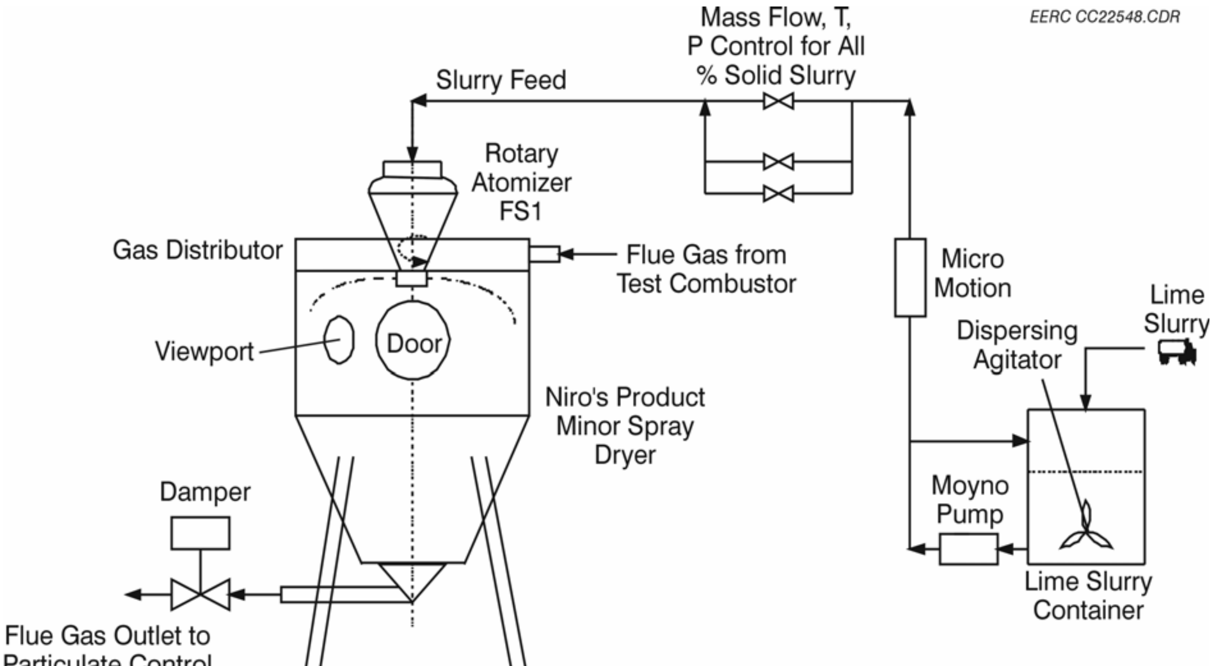

Figure B-3. Schematic diagram of SDA.

characterization and disposal. Evaluation of thermal performance is accomplished through measurement of combustion efficiency (carbon burnout), heat transfer, sorbent thermal losses, and fouling in the convective pass. Operational performance can be qualitatively assessed by examining for fouling and deposition on heat-transfer surfaces, agglomeration or sintering of the ash or bed materials, changes in coal or ash particle size, and evidence of erosion or corrosion.