JV TASK 117 – IMPACT OF LIGNITE PROPERTIES ON POWERSPAN’S NO_x OXIDATION SYSTEM

Final Report

(For the period May 1, 2007, through December 31, 2007)

Prepared for:

AAD Document Control

U.S. Department of Energy
National Energy Technology Laboratory
626 Cochrans Mill Road
PO Box 10940, MS 921-107
Pittsburgh, PA 15236-0940

Cooperative Agreement No. DE-FC26-98FT40321
Project Manager: Andrew O’Palko

Submitted by:

Scott G. Tolbert
Steven A. Benson

Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

DOE DISCLAIMER

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

This report is available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161; phone orders accepted at (703) 487-4650.

EERC DISCLAIMER

LEGAL NOTICE: This research report was prepared by the Energy & Environmental Research Center (EERC), an agency of the University of North Dakota, as an account of work sponsored by the U.S. Department of Energy. Because of the research nature of the work performed, neither the EERC nor any of its employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement or recommendation by the EERC.

ACKNOWLEDGMENTS

The authors would like to acknowledge the financial support of the following organizations: Minnkota Power Cooperative; Montana–Dakota Utilities Co.; Basin Electric Power Cooperative; Minnesota Power Co.; Powerspan Corporation, the North Dakota Lignite Research Council, Lignite Energy Council, and Industrial Commission; and the U.S. Department of Energy National Energy Technology Laboratory.

TABLE OF CONTENTS

LIST OF FIGURES	ii
LIST OF TABLES	v
EXECUTIVE SUMMARY	VI
INTRODUCTION	1
Goal, Objectives, and Tasks	2
BACKGROUND	3
Lignite Inorganic Composition and Challenges	3
Prior Testing in a High-Sodium Environment	4
Powerspan's Multipollutant Control Technology Overview	7
Powerspan's ECO Commercial Demonstration	9
Integration Opportunity for CO ₂ Separation – ECO2™	10
EQUIPMENT AND PROCEDURES	12
Design, Fabrication, Installation, and Commissioning	12
Test Plan and Schedule	17
Electrode Problems	19
Powerspan Testing Procedures	19
Packaging and Shipping of Sample Electrodes	20
Receipt and Cataloging of Sample Electrodes at Powerspan's Laboratory Facility	20
Preparation of Sample Electrodes for Reactor Testing	21
Laboratory Reactor Testing of Sample Electrodes	21
Packaging and Shipping of Sample Electrodes to the EERC for SEM Analysis....	22
RESULTS AND DISCUSSION	22
DBD Slipstream Operating Conditions	22
Trends in Plant Operating Conditions and Coal Composition	29
DBD Reactor Sampling and Electrode Analysis	29
Fouling Problems Required Cleaning Reactor	34
Performance Test Electrodes for NO _x Conversion at Powerspan	36
September 2007	36
October 2007	38
November 2007	39
SEM and X-Ray Microanalysis of Ash Coatings	40
CONCLUSIONS	48

LIST OF FIGURES

1	Quartz elements prior to mounting and cross-sectioning.....	4
2	Backscattered electron micrograph of spent quartz electrode, showing Analysis Points 1 through 6.....	5
3	Backscattered electron micrograph of spent quartz electrode, showing Analysis Points 7 through 12.....	6
4	Backscattered electron micrograph of blank quartz element, showing Analysis Points 1 through 6.....	6
5	Backscattered electron micrograph of blank quartz element, showing Analysis Points 7 through 12.....	7
6	ECO process flow diagram	8
7	50-MW ECO BCU	10
8	Powerspan DBD reactor.....	13
9	Accessing electrodes in the reactor	13
10	Overall system.....	154
11	Access port and deck location	15
12	DBD reactor stand.....	15
13	Screen shot of control system interface.....	16
14	Reactor location.....	18
15	Sampling schedule.....	18
16	Operational data graph for July 3–19	24
17	Operational data graph for July 19 through August 1	24
18	Operational data graph for August 1 through 16.....	25
19	Operational data graph for August 16 through 30.....	25

Continued . . .

LIST OF FIGURES (continued)

20	Operational data graph for August 30 through September 13.....	26
21	Operational data graph for September 13 through 27	26
22	Power density per electrode	27
23	Operational data graph for September 27 – October 18.....	28
24	Power density per electrode graph for September 27 – October 18.....	28
25	FSEA data for ash constituents during testing	30
26	The FSEA data for sodium.....	30
27	The FSEA data for sulfur	31
28	The FSEA data for calcium.....	31
29	Base-to-acid ratio versus ash content for the coals fired during testing.....	32
30	Example picture taken inside the DBD reactor	32
31	Location diagram.....	33
32	Actual biweekly inspection schedule used for sampling	33
33	Bridging at Location I	34
34	Flake at Location I.....	35
35	Accumulation of ash below the high-voltage entrance into reactor.....	35
36	Lignite pilot reactor electrode: failed upon energization during laboratory testing.....	37
37	Results of performance testing of lignite pilot electrodes.....	38
38	Performance of EERC electrode over time with a “dirty” electrode	40
39	Results of performance testing of lignite pilot electrodes.....	41
40	Example of CCSEM point analysis on Electrode 11	42

Continued . . .

LIST OF FIGURES (continued)

41	Point analysis.....	43
42	Line scan SEM of Electrode 1.....	44
43	Line scan of SEM Electrode 5.....	44
44	Differences in elemental composition of the ash at Section A, 4 inches down	45
45	Differences in elemental composition of the ash at Section B, 8 inches down.....	46
46	Differences in elemental composition of the ash at Section C, 12 inches down.....	46
47	Differences in elemental composition of the ash at Section D, 20 inches down	47
48	Differences in elemental composition of the ash at Section E, 28 inches down.....	47
49	Test results.....	48

LIST OF TABLES

1	Performance Summary of 180-day Reliability Run.....	11
2	Results from Laboratory Testing Conducted During September 2007.....	36
3	History of Electrodes Tested in Powerspan’s Laboratory.....	41

IMPACT OF LIGNITE PROPERTIES ON POWERSPAN'S NO_x OXIDATION SYSTEM

EXECUTIVE SUMMARY

Powerspan's multipollutant control process called electrocatalytic oxidation (ECO) technology is designed to simultaneously remove SO₂, NO_x, PM_{2.5}, acid gases (such as hydrogen fluoride [HF], hydrochloric acid [HCl], and sulfur trioxide [SO₃]), Hg, and other metals from the flue gas of coal-fired power plants. The core of this technology is a dielectric barrier discharge reactor composed of cylindrical quartz electrodes residing in metal tubes. Electrical discharge through the flue gas, passing between the electrode and the tube, produces reactive O and OH radicals. The O and OH radicals react with flue gas components to oxidize NO to NO₂ and HNO₃ and a small portion of the SO₂ to SO₃ and H₂SO₄. The oxidized compounds are subsequently removed in a downstream scrubber and wet electrostatic precipitator.

A challenging characteristic of selected North Dakota lignites is their high sodium content. During high-sodium lignite combustion and gas cooling, the sodium vaporizes and condenses to produce sodium- and sulfur-rich aerosols. Based on past work, it was hypothesized that the sodium aerosols would deposit on and react with the silica electrodes and react with the silica electrodes, resulting in the formation of sodium silicate. The deposit and reacted surface layer would then electrically alter the electrode, thus impacting its dielectric properties and NO_x conversion capability. The purpose of this project was to determine the impact of lignite-derived flue gas containing sodium aerosols on Powerspan's dielectric barrier discharge (DBD) reactor with specific focus on the interaction with the quartz electrodes. Partners in the project were Minnkota Power Cooperative; Basin Electric Power Cooperative; Montana Dakota Utilities Co.; Minnesota Power; the North Dakota Industrial Commission, the Lignite Energy Council, and the Lignite Research Council; the Energy & Environmental Research Center (EERC); and the U.S. Department of Energy.

An electrocatalytic oxidation (ECO) reactor slipstream system was designed by Powerspan and the EERC. The slipstream system was installed by the EERC at Minnkota Power Cooperative's Milton R. Young Station Unit 1 downstream of the electrostatic precipitator where the flue gas temperature ranged from 300° to 350°F. The system was commissioned on July 3, 2007, operated for 107 days, and then winterized upon completion of the testing campaign. Operational performance of the system was monitored, and data were archived for postprocessing. A pair of electrodes were extracted and replaced on a biweekly basis. Each pair of electrodes was shipped to Powerspan to determine NO conversion efficiency in Powerspan's laboratory reactor. Tested electrodes were then shipped to the EERC for scanning electron microscopy (SEM) and x-ray microanalysis. Measurement of NO_x conversion online in operating the slipstream system was not possible because the nitric and sulfuric acid production by the DBD reactor results in conditioning corrosion challenges in the sample extraction system and NO measurement technologies.

The operational observations, performance results, and lab testing showed that the system was adversely affected by accumulation of the aerosol materials on the electrode. NO_x conversion by ash-covered electrodes was significantly reduced; however, with electrodes that

were rinsed with water, the NO_x conversion efficiency recovered to nearly that of a new electrode. In addition, the visual appearance of the electrode after washing did not show evidence of a cloudy reacted surface but appeared similar to an unexposed electrode.

Examination of the electrodes using SEM x-ray microanalysis showed significant elemental sodium, sulfur, calcium, potassium, and silica in the ash coating the electrodes. There was no evidence of the reaction of the sodium with the silica electrodes to produce sodium silicate layers. All SEM images showed a clearly marked boundary between the ash and the silica. Sodium and sulfur are the main culprits in the fouling of the electrodes.

Conclusions gained by this work are:

- 1) Sodium-rich aerosols and small ash particles accumulate and become bonded on the surface of the silica electrodes.
- 2) Ash accumulations adversely affected the NO_x conversion.
- 3) The adverse impact occurs within a 2-week time period.
- 4) The ash accumulations are readily removed with a water wash, and the electrodes are not permanently affected by the ash.
- 5) The Powerspan ECO technology may prove to be viable if the ash accumulation can be kept to a minimum.

Based on the results obtained in the work, it appears that the ECO technology has potential but is significantly impacted by the sodium-rich ash. Sodium reduction upstream of the reactor and aggressive ECO reactor cleaning methods are possible methods that will enable the ECO technology to maintain the expected 90% NO_x removal efficiency.

IMPACT OF LIGNITE PROPERTIES ON POWERSPAN'S NO_x OXIDATION SYSTEM

INTRODUCTION

Minnkota Power Cooperative, Minnesota Power Co., Basin Electric Power Cooperative, Montana Dakota Utilities Co., and the Energy & Environmental Research Center (EERC) are evaluating air pollution control options as part of the planning process for the Milton R. Young (MRY) 3 power plant. One technology being evaluated is Powerspan's multipollutant control process called electrocatalytic oxidation (ECO). The ECO technology is designed to simultaneously remove SO₂, NO_x, PM_{2.5}, acid gases (such as hydrogen fluoride [HF], hydrochloric acid [HCl], and sulfur trioxide [SO₃]), Hg, and other metals from the flue gas of coal-fired power plants. In addition to the ECO technology, Powerspan is developing a cost-effective ammonia-based CO₂ capture process for coal-fired power plants called ECO₂TM. ECO₂ works in conjunction with Powerspan's ECO process to capture and recover CO₂ in flue gas for enhanced oil recovery or other forms of geological sequestration.

ECO treats flue gas in three process steps to achieve multipollutant removal. The first step is a dielectric barrier discharge (DBD) oxidation reactor where an electrical discharge produces reactive O and OH radicals. The O and OH radicals react with flue gas components to oxidize NO to NO₂ and HNO₃ and a small portion of the SO₂ to SO₃ and H₂SO₄. The oxidized species are water-soluble and can be collected in the downstream scrubber. The second process step is an ammonia-based scrubber that is used to remove the SO₂ not converted by the reactor, the acid species (HNO₃ and H₂SO₄), and oxidized forms of mercury. A liquid ammonium sulfate fertilizer product is produced and recovered from the second process step. The third process step is a wet electrostatic precipitator (WESP), which follows the scrubber. It captures acid aerosols produced by the discharge reactor, fine particulate matter, and oxidized mercury. All the material captured in the scrubber and WESP is removed from the process, filtered and treated to remove captured Hg. An ammonia sulfate fertilizer product is then produced for sale.

One of the potential challenges associated with application of the ECO multipollutant technology is the reaction of sodium aerosols produced upon combustion of lignite with the quartz components of the DBD reactor. Sodium vaporizes during combustion, and upon gas cooling, it condenses heterogeneously on surfaces (entrained particle or fireside surfaces) and homogeneously to form an aerosol that is suspended in the flue gas. Small amounts of this aerosol can get through air pollution control devices such as ESPs and baghouses. The ECO DBD reactor, located just downstream of the plant's ESP or fabric filter (FF), would be exposed to these aerosols in commercial installations. An electric current passes between the quartz electrodes and ground tube of the DBD reactor, creating the nonthermal plasma that results in NO oxidation. The temperature of the flue gas at the DBD reactor ranged between 300° and 350°F. The temperature of the quartz electrodes is approximately 100°F higher than the gas temperature. The behavior of sodium in this environment and the impact on the performance of the DBD reactor is unknown. Sodium is known to react with quartz to produce low melting point sodium silicate phases and sulfur oxides to produce low melting point pyrosulfate phases.

Goal, Objectives, and Tasks

The goal of this project was to evaluate the performance of the NO conversion component of Powerspan's multipollutant control technology when flue gases are treated that contain sodium aerosols. In order to meet the goal of the project, the following objectives were identified:

- Expose an operating DBD reactor to sodium-containing flue gases using a slipstream downstream of the ESP at MRY Unit 1.
- Operate the DBD reactor slipstream system for up to 4 months.
- Conduct biweekly examination of the DBD reactor and sampling of electrodes.
- Evaluate the exposed electrodes in both Powerspan and EERC laboratories to characterize potential degradation.

The work plan was developed within the context of the MRY 3 team's schedule and operations at MRY. The identified tasks were as follows:

- Task 1: Design, fabricate, install, and commission a Powerspan DBD reactor slipstream system by June 25, 2007, through modification of the EERC's existing selective catalytic reduction (SCR) slipstream system.
- Task 2: Develop a test plan.
- Task 3: Operate the system up to October 18, 2007, which was the originally scheduled maintenance outage for Unit 1. Monitor the system, continuously acquire operational data, and plot trends on a weekly basis.
- Task 4: Examine the DBD reactor and sample electrodes at 2-week intervals.
- Task 5: Performance test electrodes for NO_x conversion in Powerspan's laboratory-scale reactor.
- Task 6: Perform scanning electron microscopy (SEM) morphology and x-ray analysis on electrodes and ash in the EERC labs.
- Task 7: Communicate progress and report data, interpretations, conclusions, and recommendations.

BACKGROUND

Lignite Inorganic Composition and Challenges

The lignitic coals from the Fort Union region of North America contain ash-forming components that consist of alkali and alkaline-earth elements (sodium, magnesium, calcium, and potassium) associated with oxygen functional groups in the organic matrix and mineral grains (quartz, clays, carbonates, sulfates, and sulfides). Upon combustion, the inorganic components undergo chemical and physical transformations that produce intermediate inorganic species in the form of inorganic gases, liquids, and solids. The organically associated alkali elements such as sodium and potassium will vaporize and condense heterogeneously on the surfaces of entrained ash particles or homogeneously to form aerosols. The organically associated alkaline-earth elements such as calcium and magnesium form small particles in the intermediate size range of 0.5 to 3 μm that form on the surfaces of receding char particles. In addition, the alkali and alkaline-earth elements combine with minerals during combustion, resulting in low melting point phases that cause a wide range of fireside waterwall slagging and convective pass fouling problems. The alkali- and alkaline-earth-rich particles are carried into the backpasses of the combustion system and react with flue gas to form sulfates, phosphates, and carbonates that can cause challenges for downstream air pollution control devices.

Slipstream testing of SCR catalysts in a high-sodium Fort Union lignite cyclone-fired boiler found severe deposition, blinding, and plugging problems in the SCR. In addition, high-sodium-containing fly ash materials have high cohesivities, causing challenges in removal from hoppers that result in ash buildup, cause T/R (transformer/rectifiers) to trip from the formation of electrical grounds in the ESP causing shorting, and result in poor ESP performance.

Because of the severe blinding and fouling of SCR catalysts in tests when North Dakota lignite was fired, alternative technologies are needed that are specifically aimed at reducing NO_x emissions for lignite-fired boilers. The Powerspan technology provides an attractive multipollutant emission control option for lignite-fired systems. This project is specifically aimed at examining the application of Powerspan's ECO reactor system to convert NO species to HNO_3 in a flue gas derived from high-sodium lignite-fired combustion.

The primary concern in the application of the ECO technology to North Dakota lignite is the possibility of sodium aerosols reacting with the quartz materials in the oxidation reactor. Sodium in North Dakota lignite is associated with the organic matrix of the coal. As described earlier, sodium is vaporized during combustion, and upon gas cooling, some of the sodium condenses homogeneously to form a submicron aerosol or fume. These aerosols are very small and can pass through ESPs and baghouses. The form of the sodium in aerosol is likely hydroxide or sulfate. These materials will react with silicate materials. The ECO quartz electrodes operate about 100°F above the flue gas temperature. The ECO quartz electrode temperatures may be as high as 465°F. Another potential problem with the application of the Powerspan ECO technology to North Dakota lignite is the potential to form sodium-rich pyrosulfates. Sodium-rich pyrosulfates, which form at 500° to 750°F, are known to cause corrosion problems. In the presence of halogens, corrosive species can form at temperatures as low as 350°F. This is within the temperature range of the Powerspan ECO system. Typical North Dakota lignite contains low

levels of halogens; however, if the mercury control technology contains halogens in sorbent material or if halogens are added to the furnace to increase oxidation, this could contribute to problems related to the formation of ash deposits and corrosive layers.

Prior Testing in a High-Sodium Environment

Sodium effects testing in the DBD reactor was conducted at Powerspan's laboratory facility. A 25% sodium hydroxide solution was injected into a propane flame to produce up to 200 ppm sodium aerosols. The DBD reactor operated at a gas flow rate of 18 scfm and an energy density of 15.2 W/scfm with a flue gas composition of 6% oxygen, 11.5% carbon dioxide, 12% water vapor, 76 ppm NO_x, and up to 1600 ppm SO₂. The flue gas flow rate and reactor power used in the laboratory testing are consistent with the gas velocities and energy densities expected in the commercial units. Initial testing shows sodium aerosols are not affecting the reactor's ability to oxidize NO to NO₂ and HNO₃.

Two electrodes were examined using SEM. The first sample was an “exposed” quartz electrode from the sodium injection testing. The second sample was a “blank” (unused) quartz electrode used for comparison purposes (see Figure 1).

Backscattered electron imaging was used in the morphological analysis. Backscattered imaging differentiates between elements based on their atomic number. The brightness of the image is a function of the atomic number; higher-atomic-number elements, such as iron, appear

Figure 1. Quartz elements prior to mounting and cross sectioning. The top electrode is the “blank,” and the bottom element is the “exposed.”

brighter than lower-atomic-number elements such as silicon. Silicon and sodium are distinguishable from one another in backscattered electron imaging. X-ray microanalysis was performed along with the backscattered electron imaging. The electron beam was placed on the tube surfaces, and on the thin coating on the electrodes, to determine characteristic x-ray patterns for each analysis point. The x-ray spectra were then quantified.

Backscattered electron micrographs of the spent electrode are shown in Figures 2 and 3. A thin, <10- μm coating, was present on the surface of the quartz element. On average, the coating consisted of about 56 wt% sodium, 6.2 wt% silicon, and minor amounts of other elements. The electron beam was placed on the electrode-side of the interface with the sodium-rich coating. At this point, the average composition of the element was 77 wt% silicon, with about 3.5 wt% sodium. At Analysis Point 3 (Figure 4), just at the interface, sodium was quantified at 9.37 wt%, and silica was slightly depleted (67.31 wt%).

For comparison purposes, the blank quartz electrode was characterized in the same manner as the exposed quartz electrode. Backscattered electron micrographs of the exposed electrode are shown in Figures 4 and 5. Morphological analysis results show the surface element was comprised over 95 wt% silicon. Within the element (probing toward the center of the tube wall), silicon and oxygen were present. One analysis point was quantified with a small amount of sodium, likely from the background of the x-ray spectrum.

Figure 2. Backscattered electron micrograph of spent quartz electrode, showing Analysis Points 1 through 6.

Figure 3. Backscattered electron micrograph of spent quartz electrode, showing Analysis Points 7 through 12.

Figure 4. Backscattered electron micrograph of blank quartz element, showing Analysis Points 1 through 6.

The results of the test indicate no significant degradation of the electrode in a sodium-rich environment. When exposed to actual flue gas, the surface will accumulate a layer of ash. The interaction of the electrode with the ash and flue gas over time is of critical importance. To gain further understanding of this, a longitudinal, on-site test using a high-sodium coal to fire the plant was necessary.

Powerspan's Multipollutant Control Technology Overview

Powerspan's ECO integrated process has been shown to achieve significant reductions in emissions of SO_2 – 99%, NO_x – 90%, fine particulate matter, and Hg. The ECO technology is designed to simultaneously remove SO_2 , NO_x , $\text{PM}_{2.5}$, acid gases (such as HF, HCl, and SO_3), Hg, and other metals from the exhaust gas of coal-fired power plants. The ECO process converts incoming NO into more soluble NO_x compounds and then absorbs the SO_2 and NO_x compounds. The ECO process also oxidizes a portion of the elemental mercury to mercuric oxide. The converted mercuric oxide as well as oxidized mercury originally in the flue gas is collected along with aerosols and fine particles in a WESP. Additionally, the ECO process produces an ammonium sulfate fertilizer coproduct, eliminating landfill disposal of waste.

In commercial application, the ECO system is installed downstream of a power plant's existing ESP or FF as depicted in the process flow diagram of Figure 6.

Figure 5. Backscattered electron micrograph of blank quartz element, showing Analysis Points 7 through 12.

ECO treats flue gas in three process steps to achieve multipollutant removal. The ECO process consists of a DBD reactor, a scrubber, and a WESP. In the first process step, a barrier discharge reactor oxidizes gaseous pollutants to higher oxides. NO is oxidized to nitrogen dioxide and nitric acid, a small portion of the sulfur dioxide is converted to sulfuric acid, and elemental mercury is oxidized to mercuric oxide. Inside the ECO DBD reactor, quartz electrodes are energized with a high-voltage, high-frequency power. This produces an electrical discharge which, in turn, creates a nonthermal plasma. The plasma produces reactive O and OH radicals that cause oxidation of NO to NO₂ and HNO₃, SO₂ to SO₃ and H₂SO₄ and oxidizes a portion of Hg to HgO. These species are water-soluble and can be collected in the downstream scrubber.

The second process step is an ammonia-based scrubber. The scrubber consists of a lower and upper loop. The lower loop cools the flue gas to saturation temperatures and is used to scrub a portion of the acid species (HNO₃ and H₂SO₄) produced in the plasma, SO₂, and oxidized forms of mercury. The lower loop is where the liquid ammonium sulfate is produced and removed.

The upper loop of the scrubber scrubs SO₂ and NO₂. The SO₂ scrubbing forms sulfite, which reacts with NO₂ to form nitrogen and sulfate. Ammonia is added to maintain pH for the scrubbing process in the upper loop. The scrubber removes the sulfur dioxide not converted by the reactor and, utilizing novel and proprietary chemical controls, removes the oxides of nitrogen produced from the NO in the reactor. Without the conversion of the NO to higher oxides in the reactor, the NO would pass through the scrubber without being captured. Therefore, the reactor and scrubber work in combination to achieve the NO_x reduction.

ECO® Process Flow

EERC ST29348, CDR

Figure 6. ECO process flow diagram.

The third process step is a WESP, which is located above the upper loop of the scrubber. It captures acid aerosols produced by the discharge reactor, fine particulate matter, and oxidized mercury. The WESP also captures aerosols generated in the ammonia scrubber. The ESP is periodically washed with water, and the collected material drains to the lower loop.

All the liquid coming into the absorber tower ultimately ends up in the lower quench loop. This liquid contains all the material removed from the flue gas, which is in the form of dissolved ammonium sulfate salts, dissolved and suspended Hg and other metals, and captured fine particulate matter. The concentration of solid particulate matter in the liquid is very low, and the liquid is basically clear, unlike the slurry used in calcium-based SO₂ scrubbers.

The evaporation of water that occurs in cooling the flue gas is used to concentrate the dissolved salts in the lower loop to just below the concentration at which the ammonium sulfate solution saturates and begins to crystallize. When the lower loop reaches this concentration, a liquid stream is drawn off of the loop and pumped to the coproduct processing system. This concentrated, clear liquid stream presents a very convenient opportunity to remove constituents not desired in the fertilizer coproduct, for example, the fine particulate ash and the mercury. Simple filters and absorbent beds in the flow stream accomplish this function. The processing options available for removing constituents from a clear liquid stream are significantly easier and cheaper than the processing that would be required for solids or slurries. The ammonium sulfate is then crystallized to produce a commercially valuable fertilizer. Some of the NO_x oxidized in the barrier discharge reactor precipitates as nitrate within the ammonium sulfate crystal. This ammonium nitrate is not separable from the ammonium sulfate and adds somewhat to the value of the fertilizer because it increases the nitrogen content above that which is provided by the ammonium. However, since only a fraction of the NO_x is converted to nitric acid (most is oxidized only to NO₂) and since the NO_x is a small fraction of the incoming SO₂, the concentration of ammonium nitrate is usually only a percent or two of the ammonium sulfate.

There is no liquid discharge from an ECO system. The only waste streams are the small quantity of ash that escaped the plant's particulate collection device and was captured in ECO's WESP and the small volume of Hg adsorbent used to remove the Hg from the fertilizer liquid stream.

Powerspan's ECO Commercial Demonstration

Powerspan has been operating a 50-MW ECO unit at FirstEnergy's R.E. Burger Plant near Shadyside, Ohio, since February 2004. The technology has proven effective in reducing NO_x, SO₂, mercury, acid gases, and fine particulate matter. Fertilizer produced by the process has been sold commercially. In September 2005, Powerspan successfully completed a 180-day continuous performance test at the ECO unit.

The 50-MW Burger Commercial Unit (BCU) is a standalone, slipstream unit drawing flue gas from the Burger Plant Unit 4 or 5 ductwork, at a point downstream of the plant's existing ESP. The treated flue gas is returned to the existing plant ductwork just prior to the stack. The ECO unit processes flue gas from high-sulfur, eastern bituminous coals; from mid- and low-

sulfur eastern bituminous coals; and from blends of these coals with PRB (Powder River Basin) coals. Figure 7 depicts the completed ECO unit at the Burger Plant.

The BCU performed steadily, achieved predictable results, and met all performance objectives over the continuous 6-month period. At the end of the 180-day test, performance was essentially unchanged from the start of the run. The operating data indicate the unit could have continued to run indefinitely. Post-operating run internal inspections support this conclusion. A summary of the unit's performance is included in Table 1.

Having demonstrated the performance objectives of the ECO technology at a plant fueled by both bituminous and subbituminous coals, Powerspan recognizes the significant market segment associated with plants fueled by lignite coal.

Integration Opportunity for CO₂ Separation – ECO₂TM

In addition to the ECO technology, Powerspan has been engaged in the development of a cost-effective CO₂ removal process for coal-fired power plants. In 2004, Powerspan and the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL) entered into a cooperative research and development agreement to develop a cost-effective CO₂ removal process for coal-fired power plants. The regenerative process, called "ECO₂TM," works in conjunction with Powerspan's ECO process for multipollutant control and uses an ammonia-based solution to capture CO₂ in flue gas and release it for enhanced oil recovery or another form of geological sequestration. The process can be applied to both existing and new coal-fired power plants and is particularly advantageous for sites where ammonia-based scrubbing of power plant emissions is employed. Powerspan signed an exclusive license to the patent granted DOE on ammonia-based CO₂ scrubbing.

Figure 7. 50-MW ECO BCU.

Table 1. Performance Summary of 180-day Reliability Run

SO ₂	> 98% removal
NO _x	90% removal
Hg	80%–85% removal across the ECO system
PM _{2.5}	< 0.01 lb/MMBtu at outlet
Reliability	Operated continuously for 6 months (03/20/05 – 9/20/05); > 98% online availability even though, as a money saving feature, the BCU was not designed with component redundancy
Operability	Maintained performance through load following, system transients, and plant upsets
Pollutants Removed	3000 tons of SO ₂ 125 tons of NO _x 4.8 lb of mercury
Coproduct Generated and Sold	> 20,000 tons of liquid ammonium sulfate fertilizer (200 railcars)

Powerspan's laboratory testing of the CO₂ absorption process has demonstrated 90% CO₂ removal under conditions comparable to a commercial-scale absorber, confirming test results previously obtained by the DOE under similar conditions.

In February 2005, DOE published *An Economic Scoping Study for CO₂ Capture Using Aqueous Ammonia*, which compared the cost of CO₂ capture and sequestration for a new supercritical pulverized coal (PC) power plant using conventional air pollution control equipment and monoethanol amine (MEA)-based CO₂ absorption, versus a multipollutant control system such as ECO and CO₂ removal using ammonia (i.e., ECO₂). The economic results project that 90% CO₂ capture and sequestration with the conventional pollution control systems and MEA would cost \$47/ton of CO₂ removed, and the cost of electricity would be 7.6 cents/kWh. By comparison, the estimated costs for the ECO system with ammonia-based CO₂ capture and sequestration were \$14/ton of CO₂ removed and 5.5 cents/kWh for electricity. Thus the projected incremental costs of CO₂ removal with ECO are less than one-third of the costs for conventional technology on pulverized coal (pc) plants. On November 2, 2007, Phillip Boyle, President of Powerspan, stated to the MRY 3 team that Powerspan's carbon capture target cost was \$20/ton of CO₂ with approximately \$10/ton in capital expenses and \$10/ton in operating expenses.

In September 2005, Powerspan and FirstEnergy announced plans to pilot-test the ECO₂ technology at FirstEnergy's R.E. Burger Plant in Shadyside, Ohio. The ECO₂ pilot unit will process a 1-MW slipstream (20 tons CO₂/day) from the 50-MW ECO BCU. The pilot program will demonstrate the ability of the CO₂ capture process to be integrated with the ECO process and will confirm process design and cost estimates.

On November 2, 2007, Powerspan and NRG Energy announced their memorandum of understanding to demonstrate Powerspan's ECO₂ technology on a commercial scale. This demonstration will be conducted at the WA Parish Plant near Sugarland, Texas, on flue gas equal

to that of a 125-MW unit. It is expected to capture about 1 million tons of CO₂ annually—ranking it among the world’s largest carbon capture and sequestration projects and potentially the first to achieve commercial-scale capture and sequestration from an existing coal-fueled power plant. The CO₂ is expected to be used in enhanced oil field recovery operations in the Houston area. Powerspan’s ECO₂ facility will be designed to capture 90% of incoming CO₂ and is expected to be operational in 2012.

EQUIPMENT AND PROCEDURES

Design, Fabrication, Installation, and Commissioning

The slipstream system used in past SCR catalyst testing equipment was modified for use with the Powerspan technology. The EERC’s slipstream equipment redesign and new components were constructed to incorporate Powerspan’s ECO DBD reactor, power supply, and control system. A simplified diagram of the ECO DBD system is illustrated in Figure 8.

The Powerspan DBD reactor is composed of several sections. The plenum was designed to slow the gas flow to prevent nonuniform, high-velocity flow into the reactor body. A large plenum was also required to provide electrical isolation of the electrodes. Access to the electrodes is through the top of the plenum (Figure 9). Appropriate fittings were used to enable quick uncoupling of the inlet Tee from the plenum and a jack screw was used to raise the Tee. Once the Tee is elevated, it is swung aside to allow access. Electrodes may be inserted and extracted vertically through this opening. Figure 10 shows the overall system design.

The DBD reactor was equipped with a pneumatically driven acoustic horn for cleaning ash accumulations from the electrodes. The controls for timing and duration were incorporated into the slipstream control system. Compressed air was supplied by the project’s air compressor, located in the Powerspan equipment shed, at a pressure of 120 psi.

An investigation early in the project was conducted to determine if a continuous gas measurement system for NO was available that could withstand the harsh, high-temperature, acidic environment. The review included an examination of the U.S. Environmental Protection Agency’s NO_x Measurement Methods (Methods 7A-7E), Powerspan’s work in developing laboratory instrumentation, and literature and instrumentation vendors. The results of the investigation indicated that a complex impinger train was necessary to deal with the acids produced by the DBD reactor and protect the instrumentation. The reliability of the measurements obtained are of concern as well as the requirement of constant oversight. Based on these findings, no NO_x measurements were made while the system was in operation.

The system was installed downstream of the induced-draft (ID) fan on MRY Unit 1. The requirement of the location was to allow for flue gas to be extracted and passed through the slipstream system and reinjected back into the flue gas duct. A site was surveyed, and the location of access ports was determined as shown in Figure 11. This was identified as the best location since it was downstream of the ID fan, eliminating the concern that nitric acid produced

Figure 8. Powerspan DBD reactor.

Figure 9. Accessing electrodes in the reactor.

Figure 10. Overall system.

by the ECO DBD reactor could cause corrosion problems with the ID fan. The flue gas is flowing upward at this location. It was also decided that it would be cost-prohibitive and more complex to locate the system components on the ground and run the slipstream piping down to the ground and back up. Therefore, a platform was constructed by Minnkota Power on top of the existing structural steel. EAPC Architects Engineers performed the structural design work for the additional steel required to support the 8 tons of equipment.

Steel enclosures were required to house controls and electrical equipment as well as Powerspan's transformer and power supply. A crane from BNI's Center Mine was used to lift all heavy materials and equipment. The EERC's existing control enclosure from the SCR slipstream system was installed on the platform. A stand for the DBD reactor and blower were constructed on-site. This was an open frame design to permit easy access to the piping and valves. Because of space limitations on the platform, the DBD reactor stand shown in Figure 12 had a deck about 8 ft above the main platform with ladder access.

The DBD reactor was installed on the stand, and piping was fabricated on-site. There is potential for corrosion. Because of the high nitric acid concentrations produced by the DBD reactor 4-in.-diameter, Schedule 40, 316 stainless steel pipe with 150# flanges was installed from the DBD outlet back to the duct. Pneumatically actuated, stainless steel knife gate valves were

Figure 11. Access port and deck location.

Figure 12. DBD reactor stand.

used for automated shutoff of the flue gases. Two sections of PTFE-lined hose were used to facilitate flexibility and vibration isolation from the main duct work. These were also used to enable easy disassembly for periodic corrosion inspections. Insulation of the piping was performed by Minnkota Power.

Minnkota Power installed the electrical service. Two circuits were required for the system. One 480-volt circuit was for the power supply, which fed the DBD reactor, and the other 208-volt circuit was for all other equipment. Minnkota Power also wired the Powerspan power supply to the Powerspan step-up transformer. Minnkota Power personnel were instrumental in diagnosing problems with the electrical system during initial start-up.

The control of flue gas flow rates was through the use of a positive displacement fan. The control system monitored and logged flow rate, temperatures, pressures, and DBD reactor power at 1-minute intervals. Minnkota Power provided network wiring. This allowed access to the controller via the Internet for remote monitoring, control, and access of data. Control software was written by the EERC using National Instruments' LabVIEW. Controller hardware used was National Instruments' Field Point. The National Instruments software and hardware are widely used in short duration laboratory and pilot-scale applications. An example of a control screen is shown in Figure 13.

Figure 13. Screen shot of control system interface.

Two Powerspan representatives were on-site during the final stages of installation. Their main tasks were to inspect, calibrate, and commission the DBD reactor portion of the system. These activities were carried out over a 3-day period. The Powerspan power supply and DBD reactor are capable of running independently of other control systems. This mode of operation would pose a safety threat so the power supply was linked, via a hardwired emergency shutdown relay, to the controller and through a DeviceNet connection for monitoring the power supply. By monitoring the power supply via the DeviceNet connection, data could be read from it directly. The EERC was unsuccessful in developing a means of controlling the power supply's output power using the DeviceNet communications link. This would have enabled the system to automatically respond to the slowly changing performance characteristics in the DBD reactor, in a closed-loop manner, as the electrodes became ash-laden. Because of this limitation, power output was set manually at the power supply and changed periodically, as needed.

Operating procedures were written and left in the control enclosure. Minnkota Personnel were briefed on the operation of the system. An on-site log book was available to document operation information for Minnkota personnel.

Test Plan and Schedule

A detailed test plan and schedule were developed for the project to ensure all objectives of the project are met while maintaining integrity of operations, data, samples, and results. The test plan was developed through collaborative efforts of the EERC, Powerspan, and Minnkota Power. Since the technology being evaluated is unique, NO_x conversion performance of sampled electrodes would be done in Powerspan's laboratory-scale reactor, SEM morphology and x-ray analysis would be done at the EERC, and MRY Station was the host site. Channels and modes of communication were identified in the process of developing the test plan to avoid loss of information and other communication errors.

Day-to-day monitoring and control of the system, sampling, and maintenance were exclusively the responsibility of the EERC via remote Internet access and site visits. The only exception to control of the system was that if Minnkota Power needed to shut the system down for any reason, it could do so at its discretion. Minnkota Power provided on-site checking of the system and also provided manual adjustments and restarts, if it was not possible to do it remotely by the EERC. Powerspan served in an "advisory" capacity for the operation of the system. Performance data were communicated to Minnkota Power frequently at the start of the campaign to allow for feedback and recommendations. After the initial shakedown, biweekly operational performance graphs were used.

Electrodes were loaded into the DBD reactor by Powerspan just prior to commissioning the system. Each of the 14 spaces in the reactor was assigned a letter, A through N, to identify its location. Each electrode that was loaded into the reactor was assigned a number, 1 through 14 shown in Figure 14. Electrodes were replaced as they were sampled. In all, 26 electrodes were tested. No cleaning of the reactor or electrodes was to be done during the testing campaign; however, this changed following the shutdown of MRY Unit 1.

Figure 14. Reactor location.

Two electrodes were replaced with fresh electrodes every 2 weeks throughout the testing campaign. This was done to detect operational problems early in the testing campaign and to provide an early indication of how the system was performing to the MRY 3 partners. If problems were found, changes to the test plan or protocols could be implemented. A sampling schedule was developed based on randomization of the electrodes being sampled. The sampling schedule is shown below in Figure 15.

EERC ST31407.CDR

SAMPLING SCHEDULE					
SAMPLING DATE	LOCATION	REMOVE ROD #	DAYS IN REACTOR	REPLACE WITH ROD	DAYS IN REACTOR
3-Jul	START TESTING				
19-Jul	F K	6 11	16	15 16	91
1-Aug	M B	13 2	29	17 18	78
16-Aug	H D	8 4	44	19 20	63
30-Aug	C J	3 10	58	B1 B2	49
13-Sep	I G	9 7	86	B3 B4	35
27-Sep	E L	5 12	100	B5 B6	21
11-Oct	NO SAMPLES EXTRACTED DUE TO THE PROXIMITY TO THE FINAL SAMPLING.				
18-Oct	A N	1 14	107	All of the electrodes listed above will be removed for lab testing and analysis.	

Figure 15. Sampling schedule.

Electrodes were removed from the reactor, numbered with a paint pen on the cap, photographed, and then sent to Powerspan for NO_x conversion performance testing, as received, in its laboratory-scale reactor. After completion of the testing, Powerspan would number the electrode at the bottom end prior to removal of the cap-and-cathode assembly from the top of the electrode. This also vented the proprietary gas in the electrode. The cap and cathode are reused by Powerspan. Electrodes were then sent to the EERC for SEM morphology and x-ray analysis. Upon receipt, the EERC would again photograph the electrodes prior to cutting, mounting, and polishing cross sections.

Electrode Problems

Initially, removed electrodes were replaced by virgin electrodes. However, there were several catastrophic failures of electrodes upon start-up during the first Powerspan laboratory reactor tests. Powerspan felt there may be a chance that the original electrodes supplied may have some flaws originating from their manufacturer. Some of these new electrodes were also being used at FirstEnergy's R.E. Burger Plant, and they were exhibiting a marginally high failure rate there. Powerspan and the EERC discussed the matter, and both felt it would be prudent to use "low time" electrodes that had been in service at FirstEnergy's R.E. Burger Plant. These electrodes were from an earlier production lot known to not have quality control issues. The electrodes were cleaned and then baseline-tested in Powerspan's laboratory reactor prior to being sent. These electrodes are numbered as B1, B2, B3, B4, B5, and B6 in the sampling schedule.

Results were communicated between the EERC and Powerspan via PDF file format. This file format was used to ensure that accidental loss or change of the data would not occur. Phone conversations were used to discuss results.

Operational data were logged automatically by the control computer to a data file at 1-minute intervals throughout the campaign. Separate data files were manually saved on a 1- to 2-day basis. These files were transferred to the EERC's computers for archiving, postprocessing, and trend analysis. The critical performance trends that were monitored were reactor power, differential pressure across the reactor, flue gas flow rate, and the inlet temperatures. Other subsystems were also monitored, such as shed temperatures, compressed air pressures, and power supply cooling system temperature.

Trend analysis results were communicated in the form of graphs to Powerspan by EERC personnel on a daily and then weekly basis, initially. As the performance trends stabilized, it was decided to address these trends on a biweekly basis. Phone conversations were used to discuss these results and decide if and what responsive actions were necessary. Responsive actions taken were to adjust power, adjust flue gas flow rate, and adjust air horn parameters.

Powerspan Testing Procedures

A critical goal of the lignite slipstream reactor project is to accurately characterize the potential for NO_x removal from flue gas streams containing sodium aerosols produced upon combustion of lignite fuels. Early in the project planning phase, it was determined that accurately

measuring NO conversion in the field could not be done within the constraints of the budget and time line. Given the complexities of measuring NO_x removal in situ, the project test plan was developed such that the slipstream reactor electrodes would be exposed to the flue gas produced by the Unit 1 boiler for a predetermined period after which sets of two sample electrodes would be pulled from the reactor at 2-week intervals, according to the sampling schedule. The sample electrodes would be packaged for shipment to Powerspan's laboratory facilities in New Hampshire where the electrodes would be tested for NO conversion in a controlled laboratory setting. In an effort to maintain sample integrity, best efforts were made to package the exposed sample electrodes such that the deposited fly ash layer would remain intact during shipment.

Powerspan has previously used its single electrode, laboratory-scale DBD reactor for NO conversion testing of ash-coated electrodes removed from both operating pilot and commercial-scale installations with a high degree of statistical confidence. Powerspan's DBD reactor converts incoming nitrogen oxide into more soluble NO_x compounds that are then absorbed in the ECO scrubber vessel. By accurately measuring the NO conversion efficiency within the DBD reactor system, NO_x removal efficiency across the complete ECO system can be predicted and verified.

Packaging and Shipping of Sample Electrodes

As mentioned previously, both EERC and Powerspan recognized the value of employing packaging and shipping methods that would minimize the potential for sample electrodes to be damaged or broken during shipment as the electrodes were shipped from the site to Powerspan for performance testing and then to the EERC for SEM analysis. Several shipping containers were designed and tested to protect the sample quartz electrodes and to keep the ash layer on the electrodes intact. However, the combination of two methods was found to provide the best opportunity to minimize breakage and to maintain the integrity of the ash layer.

After several failed attempts to make use of a heavy-duty PVC shipping container designed specifically to protect and support sample electrodes, both parties agreed to make use of the oversize boxes that quartz tubing manufacturers use to ship the raw stock material. These boxes, while large, allowed for ample packing material to protect the electrodes.

The preferred shipping method was UPS Red overnight delivery. This decision proved to be justified based on the minimal handling and transit time.

Receipt and Cataloging of Sample Electrodes at Powerspan's Laboratory Facility

Upon receipt of the sample electrodes at Powerspan's facility, the electrodes were carefully unpacked and cataloged by the numbers on the end cap. Each electrode was inspected for obvious damage and observations recorded into the receiving log. Pieces of damaged or broken electrodes were then labeled to indicate which sample they were from and put aside for shipment back to EERC for SEM analysis.

Preparation of Sample Electrodes for Reactor Testing

The sample electrodes were prepared for NO conversion testing as specified by the test plan. Early in the sample testing campaign, Powerspan experienced a few dielectric failures during laboratory testing of sample electrodes with intact ash layers. This phenomenon was unusual in Powerspan's experience because of the relatively low power level at which the electrodes failed. Comparable ash-covered electrodes from other commercial ECO installations rarely fail at the power levels applied to the slipstream lignite reactor electrodes. In an effort to preserve the sample electrodes and to understand the observed phenomena, the test plan was modified to water-rinse one of the two electrodes from each sample set. Following is a description of how the sample electrodes were prepared for laboratory reactor testing:

- a. Under the original test plan, sample electrodes were tested with the deposited ash layer intact.
- b. After the test plan was modified, one sample electrode from each sample set was gently water-rinsed to remove the ash layer. Care was taken to remove the deposited ash without employing high-pressure washing or any other scrubbing or scouring of the quartz surface. After rinsing, the tubes were left to dry naturally.

Laboratory Reactor Testing of Sample Electrodes

Powerspan's laboratory reactor is designed to simulate design flue gas, temperature, and power conditions experienced in the field. Simulated flue gas was produced from the exhaust of a gas-fired furnace with appropriate concentrations of CO₂, H₂O, O₂, NO_x, and SO₂ added from cylinders to mimic flue gas conditions at a power plant. Reactor power is measured in terms of watts per scfm (W/scfm) of flue gas. All sample and control electrodes were tested for NO conversion at power levels ranging from 10 to 18 W/scfm in 2-W/scfm increments. The results were plotted, and the trends were identified.

Prior to slipstream reactor commissioning, the reactor was populated with newly fabricated electrodes with an end cap design that had not undergone performance and reliability testing. Upon initial start-up of the slipstream reactor, it was noted that a few of the electrodes failed to light off properly. This was characterized by a narrow helical plasma inside the electrode instead of a wide, straight plasma. Given the small number of sample electrodes for this test, Powerspan and the EERC concluded that any infancy failure rate was unacceptable. As a result, the decision was made to replace electrodes, using a modified sampling schedule, with electrodes that had been in service for a short time previously at Powerspan's BCU. This set of electrodes was known to have good performance and reliability characteristics. The BCU electrodes were removed from the Burger reactors, cleaned of any surface ash, shipped to the MRY Plant and installed in the slipstream reactor according to the modified sampling schedule. The control electrode was taken from the same batch of electrodes used to populate the EERC slipstream ECO reactor.

Each of the sample electrodes was tested in incremental steps from 10 to 18 W/scfm. The results were recorded and plotted for both ash-covered and water-rinsed sample electrodes. All data points were plotted in graphical format and provided to the EERC for interpretation.

Packaging and Shipping of Sample Electrodes to the EERC for SEM Analysis

The final phase of Powerspan laboratory testing was to repackage and ship the tested sample electrodes back to EERC's facility for SEM analysis.

RESULTS AND DISCUSSION

DBD Slipstream Operating Conditions

The DBD reactor slipstream system was commissioned on July 3 and operated until the planned termination date of October 18. The system operated a total of 107 days. Shakedown of the system was conducted over the first 2 weeks of operation.

The targeted operational parameters for the DBD slipstream reactor were specified by Powerspan. Changes to operating parameters were made as the system was monitored and trends plotted by Powerspan and the EERC. The target operating parameters were as follows:

Flue gas flow rate:	277 scfm
Power density per electrode:	5 W/scfm
Differential pressure:	<6 inches WC
Acoustic horn:	60 sec every 60 min
Flue gas temperature:	300° to 350°F

The temperature of the flue gas remained within the 300° to 350°F range throughout the testing campaign. This was within the system's original design parameters. The exception to this was during the biweekly samplings. The reactor was opened and cooled to allow access to the electrodes. Upon start-up, the humid flue gas condensed in the reactor so the DBD reactor was not energized until 15 minutes after it had reached 300°F. This allowed most of the condensed water to evaporate. Failure to do this resulted in highly conductive wet ash that promoted arcing across the electrical isolation parts in the reactor. The power supply's protection circuits would sense these transients and temporarily trip the unit before initiating an automatic restart. In instances where more than three consecutive transients are detected and after three unsuccessful attempts at automatically restarting, the power supply is designed to go into standby mode to alert the operator of a possible short circuit condition.

Foaming of the gear oil in the system's blower was observed immediately after commissioning. The blower speed was reduced until a suitable high-temperature lubricant could be obtained. Mobil SHC 634 was tried but was subject to rapid oxidative degradation. This oil lacked the high-temperature rating of synthetic gear oil but would support high-speed operation without foaming. On June 30, about 550 hours into the testing campaign, the flue gas flue rate was increased to 400 acfm after switching to the Mobil gear oil. Amsoil SGN synthetic, high-

pressure gear oil was later used. This oil was changed on a biweekly basis because of degradation under the harsh operating conditions.

The Powerspan power supply is a high-frequency current source. The current is set, and the voltage floats in response to the load impedance. A decreasing voltage is indicative of decreasing load impedance. Flue gas and ash electrical properties influence the load impedance seen by the power supply.

The operational data graph for July 3–19 shows a steady downward trend in the power output of the system as the electrodes became fouled with ash, as shown in Figure 16. The actual cubic feet per minute flue gas flow rate was plotted to look for any “scubbing” effects on the electrodes as the flow rate changed. The system used a positive displacement blower so issues of a fouled orifice plate and loss of flow calibration were avoided.

During the first 475 hours of operation, the air horn was unable to remove the ash accumulated on the surface of the electrodes. The fouling rate was higher than expected. In order to possibly increase the removal of ash from the electrodes, the amplitude of the horn was increased by increasing the air supply to the horn. The rapid downward trend in power output was reversed slightly following the increase in the horn’s amplitude, as shown in the operation data graph for July 19 through August 1 in Figure 17.

During the 850- to 1000-hour period, an increasing and then decreasing trend in the power output was experienced, as shown in Figure 18. This was compared against the full-stream elemental analyzer (FSEA) data provided by MRY.

On August 16 and 17, the system was down for sampling, small repairs, and maintenance. This was a period significantly longer than that of the 4-hour interruption for normal biweekly sampling. As a result, the system got relatively cold. Upon restart, it was noted that the power output dropped dramatically over a 2-day period and gradually leveled out. It was thought that the ash was affected more than by the extended period of exposure to air and excessive water condensation during start-up. The ash may have become more conductive with hydration, changing the impedance, and resulting in higher power output. As the ash gradually returned to its normal state in the DBD reactor, the power output trend stabilized, as shown in Figure 19.

The operational data trends for August 30 through September 13 as illustrated in Figure 20. The 1400- to 1500-hour period showed significant changes in the power output of the system. Spikes in the power output were due to start-up surges of the power supply.

Figure 21 shows the operational trends for September 13–27; the interruption in the reactor power at the 1675-hour mark occurred late, on the evening of Friday, September 14, and was not detected until the following Monday. The cause of this could not be determined. Sampling had been conducted the day prior to this event on September 13. Because of gradually falling power output, the power supply current was increased based upon the recommendation of Powerspan. The change in the power output and the loss of power appear to be unrelated; however, the increased power output can be seen in Figure 21.

Figure 16. Operational data graph for July 3–19.

Figure 17. Operational data graph for July 19 through August 1.

Figure 18. Operational data graph for August 1 through 16.

Figure 19. Operational data graph for August 16 through 30.

Figure 20. Operational data graph for August 30 through September 13.

Figure 21. Operational data graph for September 13 through 27.

Aside from the initial 2-week shakedown period, the September 13–27 period had the greatest variability in power output. The target power density per electrode for the DBD reactor during the testing campaign was 5 W/scfm, as established by Powerspan. A graph of the power density per electrode can be seen in Figure 21. The average power density per electrode for this period was 5.05 W/ scfm, with a standard deviation of 0.32 W/scfm. This was also well within Powerspan’s allowable range of 4 to 7 W/ scfm. Lower power densities result in lower NO_x conversion.

MRY Unit 1 was originally scheduled to go down for cleaning and maintenance on October 18. Because of a boiler tube leak and the need for repair, it was down September 29 through October 2. Upon start-up of Unit 1, ash filled to the piping of the DBD slipstream reactor inlet pipe. Upon start-up of the DBD system, the ash was blown into the reactor area. That combined with the condensing water fouled the system to the extent that cleaning of the reactor with compressed air was required. A heater in the high voltage duct (conduit) failed during this period, resulting in condensation and arcing in the duct. Repair parts were ordered but took several days to be delivered and replaced. These events can be seen in the operational data graph for the period of September 27 to October 18 in Figure 23.

Following the repairs and restarting of the systems, the power output of the reactor jumped significantly, as shown by operational data trends and the power density per electrode graph for September 27 – October 18 in Figures 23 and 24, respectively. The cleaning of the reactor at the 2200-hour mark resulted in a change from approximately 5 W/scfm to approximately 6 W/scfm. Additionally, shown in Figures 23 and 24, power output would gradually drop after restarting

Figure 22. Power density per electrode.

Figure 23. Operational data graph for September 27 – October 18.

Figure 24. Power density per electrode graph for September 27 – October 18.

the system, but in this case, the power output was increasing at a fairly rapid rate. The average power density per electrode increased by approximately 10%, from 6 to 6.6 W/scfm, during this period of 54 hours that started at 2155. It was theorized that after the aggressive cleaning of the reactor with compressed air, the “scrubbing” of the electrodes by the flue gas removed additional ash deposits. The rapid decline in power output during the final hours was done intentionally with the power supply and was not a function of ash accumulation.

It should be mentioned that “typically” the power supply output is automatically controlled by tying the power supply input and output into the plant’s distributed control systems thus providing the ability to set a desired power density (i.e., W/scfh) and allowing the automation to adjust the unit’s output irrespective of changes in load impedance. Prior to commencing this testing campaign, it was mutually agreed that this level of automation would not be implemented.

Trends in Plant Operating Conditions and Coal Composition

Minnkota Power supplied plant and mine data to the EERC. These were in the form of spreadsheets containing core data from BNI’s Center Mine, FSEA data of the coal being fed from the pile, and stack emission data.

The overall variation of the ash constituents is shown in Figure 25. The variability in the constituents is generally consistent with past results. The sodium levels are slightly higher than paste testing. There is a wide variability in the level of silicon dioxide. The elements that are vaporized during combustion in the cyclone include sodium, potassium, and sulfur. The propensity of the sodium and potassium to form aerosols is related to the ash content of the coal. Coals having higher ash contents typically have higher levels of silicon and aluminum that provide surfaces for heterogeneous condensation of vaporized constituents, inhibiting the formation of homogeneously condensed components or aerosols.

Postprocessing of these data and the DBD reactor’s operational data were done to look for correlations and draw inferences about the characterization and behavior of the flue gas and ash deposits. The FSEA data are shown in Figures 26–28 for sodium, sulfur, and calcium. Figure 29 shows the base-to-acid ratio versus the ash content, indicating an inverse relationship between base-to-acid ratio and ash content.

DBD Reactor Sampling and Electrode Analysis

The DBD reactor was opened and inspected on a bi-weekly basis by the EERC. Observations and documentation of fouling were made. An example of the ash accumulations is shown in Figure 30. Biweekly inspections were conducted as shown in Figure 31–32. The entire system was also inspected and maintenance conducted during these periods. Maintenance consisted of draining condensation from the compressed air system, changing oil on the blower’s gear cases, and removing any significant ash accumulations in the DBD reactor, with the exception of accumulations on the electrodes proper.

Figure 25. FSEA data for ash constituents during testing.

Figure 26. The FSEA data for sodium.

Figure 27. The FSEA data for sulfur.

Figure 28. The FSEA data for calcium.

Figure 29. Base-to-acid ratio versus ash content for the coals fired during testing.

Figure 30. Example picture taken inside the DBD reactor.

Figure 31. Location diagram. The initial loading of electrodes into the reactor was as follows: 1 = A, 2 = B, 3 = C.

EERC ST31407.CDR

SAMPLING SCHEDULE					
SAMPLING DATE	LOCATION	REMOVE ROD #	DAYS IN REACTOR	REPLACE WITH ROD	DAYS IN REACTOR
3-Jul	START TESTING				
19-Jul	F K	6 11	16	15 16	91
1-Aug	M B	13 2	29	17 18	78
16-Aug	H D	8 4	44	19 20	63
30-Aug	C J	3 10	58	B1 B2	49
13-Sep	I G	9 7	86	B3 B4	35
27-Sep	E L	5 12	100	B5 B6	21
11-Oct	NO SAMPLES EXTRACTED DUE TO THE PROXIMITY TO THE FINAL SAMPLING.				
18-Oct	A N	1 14	107	All of the electrodes listed above will be removed for lab testing and analysis.	

Figure 32. Actual biweekly inspection schedule used for sampling.

Locations in the reactor were prone to ash accumulation and eventual bridging. The bridging appeared to happen at the top end of the stainless steel tube that the electrode resided in. Locations I, J, and K were the most prone to this; whereas, the four center locations never exhibited significant ash accumulations. In Figure 33, the beginning stages of the bridging can be seen after 6 weeks of operation. After 8 weeks, the same deposit has continued to grow. Powerspan has indicated that growths like this are not uncommon and that they break off prior to completely bridging.

Figure 33. Bridging at Location I.

On one occasion, bridging was noted in the same location as shown above; however, it appeared to be a flake that may have fallen off the inside wall of the reactor. Refer to Figure 34. The EERC conferred with Powerspan, and it concluded the same thing. This highlighted the fact that every time the reactor was opened and cooled for sampling, the environment was being contaminated with air. Upon restart, the reactor was heated prior to energizing the electrodes. During this time, a large amount of water condensation in the reactor may have hydrated the ash, forming cement deposits in the reactor.

The degree of these accumulations in the plenum of the reactor can be seen in Figure 35. The location of the accumulation was directly below the horizontal high voltage feed coming into the reactor. Flakes were falling off the vertical end cap and the horizontal cylindrical section. This buildup was at the 86-day mark.

During sample extraction, the electrode was extracted vertically from the DBD reactor. A side force was applied so that ash scraped off the electrode by the power distribution lattice would be on one side, leaving a thicker layer on the opposite side.

Fouling Problems Required Cleaning Reactor

On September 29, MRY Unit 1 was shut down for tube repair and cleaning. This was earlier than the scheduled date of October 18. For this reason, the DBD reactor slipstream system was also shut down during the duration of the outage. MRY Unit 1 was brought back online on October 2, and the slipstream system was started up the next day. When Unit 1 was brought back up, excessive ash was deposited in the inlet pipe of the slipstream system and was drawn in

Figure 34. Flake at Location I.

Figure 35. Accumulation of ash below the high-voltage entrance into reactor, 86 days.

during its start-up. This ash, coupled with water condensation in the reactor, caused excessive fouling and highly conductive loading of the power supply. The power supply went into a fault mode each time that it was restarted. Powerspan and the EERC agreed that the reactor needed to be cleaned. Compressed air was used to blow out the reactor.

Performance Test Electrodes for NO_x Conversion at Powerspan

September 2007

Laboratory testing of the first set of ash-covered sample electrodes received from the MRY pilot reactor showed poor performance and an unanticipated high rate of electrode failures, as shown in Table 2.

Typical NO conversion rates of 90% and above are measured for electrodes that have been exposed to flue gas from coal-fired boilers. However, the first round of laboratory testing of the electrodes from the lignite slipstream pilot showed poor NO conversion as compared to the baseline electrode that demonstrated the expected 90+ % conversion rate. It should also be noted that the baseline electrode used for control purposes had been in service in Powerspan's BCU for an extended period of time. This electrode demonstrated 99% NO conversion after being water-rinsed to remove fly ash. Similar tests have demonstrated that the presence of fly ash on the Burger electrodes does not significantly reduce the NO conversion rate.

During testing of the first set of electrodes received from the site, two electrode failures were noted. Electrode failures are caused either by dielectric failure or by mechanical failure. Dielectric failures typically occur at a point along the quartz tube within the discharge zone (inside the reactor bundle) at a point that cannot withstand the dielectric stress being applied. The result is a pinhole burn through the quartz, which causes a short circuit. Both failures observed in the lab were dielectric failures.

Table 2. Results from Laboratory Testing Conducted During September 2007

Electrode No.	Notes	Reactor Power, w/scfm	Inlet NO, ppm	NO Conversion, %
Baseline Electrode	Previously operated electrode from Powerspan's operating commercial unit	12	86	99
11		12.5	81	16
6	Failed immediately after energizing in lab reactor	—	—	—
13	Failed immediately after energizing in lab reactor	—	—	—
2	Broken during shipment	—	—	—
4		12	85	38
8		12	85	27

A picture of one of the failed electrodes is shown in Figure 36. The discolored line seen in the ash layer is the result of electrical tracking along the surface of the quartz.

Laboratory Testing Problem. Power levels used for the laboratory testing were 18, 16, 14, 12, and 10 W/scfm. NO_x conversion performance results were compared with new electrodes and graphed. Test results were communicated to the EERC and discussed. Initially, Powerspan's standard test procedure was to energize the electrode at a power level of 18 W/scfm. Under this regimen, there were immediate failures of electrodes due to pinholes being burned through the silica tube of the electrode. The gas inside the tube was contaminated, and the dielectric properties of the electrode were lost. In some cases, the electrode was also broken. Powerspan and the EERC discussed the testing regimen and decided to make two changes. The first change was to energize the electrode being tested at the lower power first, 10 W/scfm. The other change was to lightly rinse one of the two electrodes to be tested. The other electrode was tested "as-received." By rinsing the electrode, it was felt that failure of the electrode could be avoided and it would also test the electrode's ability to recover from excessive fouling after being cleaned.

At the time the failures occurred, it was unclear if the observed electrode failures were due to the ash and its impact on the electrodes or a result of a new electrode cap design. Therefore, the lab testing protocol was changed such that one of each sample electrode pair was rinsed with water prior to testing in the laboratory reactor while the remaining electrodes were tested with the ash coating intact. Water rinsing was done to increase the probability of testing electrodes without failure, as experienced in previous tests and to provide the opportunity to determine if the ash coating irreversibly alters the quartz in a manner that impacts its performance in the DBD reactor. After testing in Powerspan's laboratory, all electrodes were shipped to EERC's facility for SEM analysis.

Powerspan's laboratory reactor is configured to measure the performance of sample electrodes across a range of power levels. For consistency, Powerspan measures power input to the reactor in terms of W/scfm of flue gas. Laboratory testing of the sample electrodes was conducted at power levels ranging between 10 and 18 W/scfm. This range represents typical power levels for commercial DBD reactor applications.

Figure 36. Lignite pilot reactor electrode: failed upon energization during laboratory testing.

The lignite pilot reactor was designed to operate at a power input of 5 W/scfm based on the relatively low NO_x inlet condition of 0.15 lb/MMBtu and outlet requirement of 0.07 lb/MMBtu. This translates into ~55% NO_x removal requirement for the planned MRY 3 project. NO conversion efficiency at the 5-W/scfm power level can be predicted with a high degree of confidence based on extrapolation of the laboratory data.

October 2007

Testing conducted during October followed the modified test plan. Figure 37 shows the results from lab testing of sample electrodes conducted during October. Electrodes 3, 5, 7, 9, 10, and 12 were removed from the pilot reactor according to the schedule in Figure 32 and shipped to Powerspan's laboratory facility. It was intended that one of the two electrodes removed on each sampling date be rinsed with water prior to testing in the lab reactor. However, Electrodes 3, 7, and 9 were rinsed prior to testing, and Electrodes 5, 10, and 12 were tested as-received (ash layer intact). The cleaned electrodes are identified in Figure 37 with the label "CL." In addition to the MRY pilot electrodes, an electrode removed from the BCU reactor was cleaned and tested. It is labeled "Burger – CL" in Figure 37.

Figure 37 shows that the NO conversion of the ash-coated electrodes is well below that measured with the cleaned electrodes. Visual observation of the discharge with Electrode 10 (ash-coated) showed the presence of numerous streamers in the gas, as opposed to the uniform glow discharge typically observed. Streamers are observed as concentrated discharges that resemble narrow visible bolts of electrical energy that travel from electrode surface to ground source. Streamers are typical at flue gas temperatures below 210°F and/or under conductive

Figure 37. Results of performance testing of lignite pilot electrodes.

conditions in the reactor. Conductive conditions can be the result of high moisture conditions in the reactor or conductive compounds being deposited onto the surface of the electrodes. The presence of streamers can inhibit NO conversion by concentrating the discharges, thereby preventing optimum treatment of the flue gas stream.

Electrode 10 was operated continuously for 4 hours at 10 W/scfm to determine if the NO conversion would change over time. Improved performance over time has been observed historically with ash-coated electrodes where the ash was thought to contain carbon and the carbon was oxidized over time. However, Figure 38 shows that NO conversion did not improve over time and that the measured NO conversion remained well below what was measured for the cleaned electrodes. The key parameters of power and NO_x concentration in the flue gas were verified to be stable over the course of the test.

The electrodes removed from the pilot reactor for laboratory testing were replaced with electrodes that had been in service in the BCU reactor. After removal from the BCU, the electrodes were cleaned and tested, then shipped to the EERC for use in the pilot. The BCU electrodes used in the pilot are labeled B1–B6 in the sampling schedule shown in Figure 32.

November 2007

Results of laboratory testing of the sample electrodes during November are shown in Figure 38. The water-rinsed electrodes are labeled as “CL.” The electrodes tested as-received are reported just by number. Electrodes labeled B# are electrodes previously used at the BCU and tested by Powerspan prior to being used in the slipstream system. The results show consistent performance for the rinsed electrodes but show a high variability of performance for electrodes coated with ash from the lignite pilot. The best-performing electrodes were electrodes highlighted in yellow in Table 3, which can potentially be the product of a manual cleaning operation conducted as a troubleshooting measure described below. Table 3 is sorted by the best performer to the worst performers for the unwashed electrodes only.

As stated above, sample electrodes highlighted in the Table 3 were manually cleaned on October 5, 2007, with an air lance while installed in the lignite pilot reactor. This cleaning was completed 13 days prior to completion of the testing campaign as part of a troubleshooting effort to rule out the potential that the electrodes were the source of an observed short circuit, which at the time was preventing testing operations. It was later determined that the short circuit was the result of a failed heater element in the high-voltage insulator compartment. Once the new heater element was installed, the system remained operational for the duration of the testing program.

It should be noted that full commercial ECO systems are designed with a heated purge air system that feeds heated air to the high-voltage feed through insulator compartments. Redundant blowers and heaters are incorporated into the design to prevent condensation and to keep the surrounding insulator compartment environment above the acid dew point. Given the time and budget constraints for the lignite pilot reactor project, a small electrical heating element was used to heat the feed through insulator compartment of the lignite pilot reactor.

Figure 38. Performance of EERC electrode over time with a “dirty” electrode.

Figure 39 shows that the NO conversion of the ash-coated electrodes remains well below that measured with the cleaned electrodes, but there is a large variation in performance. The performance has been split into three separate zones: good, below normal, and poor performance. Visual observation of the discharge of the below normal and poor performers showed the presence of numerous streamers in the gas, as opposed to the uniform glow discharge typically observed.

Electrode 14 failed to light off in the reactor. This electrode was rinsed with water prior to being put into the reactor for testing. When it was pulled out, a pinhole was found at 25 inches from the top cap. Since the electrode never lit off, it is possible this electrode came to us with the pinhole. Subsequent electrodes were tested with a tesla coil to verify the electrode was operational prior to testing in the lab reactor.

SEM and X-Ray Microanalysis of Ash Coatings

Cross sections of each ash-covered electrode were cut and prepared. Each sample was examined in detail with specific focus on the ash–quartz interface and characterization of the ash constituents. Results were communicated to Powerspan and discussed in an attempt at gaining a better understanding of what was happening to the electrodes. X-ray fluorescence (XRF) on a bulk ash sample, scraped from three electrodes, was also used to confirm the elemental composition of the ash.

Table 3. History of Electrodes Tested in Powerspan's Laboratory

EERC Electrode No.	Time in Rx, days	NO Conv at 14 W/scfm, %	Position	Original/Replaced
B3	34	75	I	Replaced
B5	20	69	E	Replaced
19	62	65	H	Replaced
1	106	62	A	Original
17	77	45	M	Replaced
B1	48	42	C	Replaced
12	100	28	L	Original
10	58	24	J	Original
5	100	24	E	Original
8	44	24	H	Original
15	90	24	F	Replaced

Each electrode that was submitted to the EERC's Natural Materials Analytical Research Lab (NMARL) was assigned a catalog number by the lab and photographed prior to having cross sections cut and mounted. Initially, point morphologies were conducted to gain an understanding of what was happening at the ash-electrode interface since the concern was that sodium would be penetrating into the silica electrode and permanently degrading the performance. An example is shown in Figure 40 of Electrode 11's Cross-Section E, which was 28 inches down from the top

Figure 39. Results of performance testing of lignite pilot electrodes.

Figure 40. Example of CCSEM point analysis on Electrode 11 (16 days of service).

of the electrode. This electrode was in service for 16 days. Each point was analyzed for elemental composition for select elements. Concentrations were tabulated based on weight %. Using this method, an examination of sodium penetration into the silica electrode could be made. It should be noted that when the SEM is used, one needs to consider the “excitation volume” since the system is not looking a specific point but rather a small area with some depth.

No sodium penetration into the silica electrode was found in any of the sampled electrodes throughout the testing campaign. A clearly defined ash–electrode interface was always present. Over time, ash was building up on the electrodes, causing degradation in performance. For this reason, additional methods were employed to examine the ash layer and gain a better understanding of its composition to determine the root causes of the loss in conversion.

In the point analysis shown in Figure 41, the outer surface of Electrode 1 was examined instead of the cross section. This electrode was in service for 107 days. Elements with

Figure 41. Point analysis.

measurements under 1 wt% were not displayed in the table. Points 3, 4, 5, and 6 were targeting ash deposits. Points 1 and 2 were targeting the electrode surface. The measurement of sodium, sulfur, calcium, and iron at Points 1 and 2, which appear to be in a clear area, indicate there is a thin film of ash covering the electrode surface. This was most likely formed by the deposition of submicron particles that fused forming sulfate deposits. The energized volume of the SEM is most likely detecting the underlying silicon of the electrode. Other samples with highly ash-laden surfaces were comparable to Points 3, 4, 5, and 6. The materials forming on the surface were rich in sulfur, calcium, sodium and, sometimes, potassium. The silicon may be derived from the ash or the electrode.

To avoid SEM operator biasing because of point selection, a line scan method was employed. Using this method, a straight line with the number of points along the line were specified. The wt% values were tabulated for each point along the path of the line. This method automated the process, thereby increasing the number of points analyzed. An example is shown in Figures 41 and 42. Because of the large number of points, a graph of the elements with higher wt% values is presented. Those elements with low concentrations were not graphed to enhance

Figure 42. Line scan SEM of Electrode 1/(107 days).

Figure 43. Line scan of SEM Electrode 5/(100 days).

the readability and interpretation of the graph. Graphs of wt% for Electrodes 1 and 5 are shown below. Section A was located 4 inches down from the top of the electrode, and Section B was 8 inches down from the top of the electrode. The two examples showed very similar traits. Again, the excitation volume will create the impression that the transition from the ash layer to the electrode is not abrupt on the graphs. However, visual examination of the picture confirms a clear demarcation line between the ash and electrode.

Analysis of three electrodes sampled at 20, 48, and 107 days was performed using averaged elemental data from the SEM line scan process. Each electrode was cross-sectioned at the 4-, 8-, 12-, 20-, and 28-in. locations. The 4-in. location is above the reaction zone of the reactor; as such, the ash accumulation was not subjected to the discharges of the electrode. The data were plotted to reveal differences in elemental composition of the ash at each cross section, based on time in service as shown in Figures 44–48.

Additionally, by looking down through each graph and referring to just one bar (one element for one electrode), it can be seen how the wt% values change. The 20-day electrode can be used as an example. Sodium dropped along the length of the electrode, whereas the sulfur appeared to remain at about the same level and the calcium appeared to increase in the reaction zone (below the 4-in. location).

XRF was also used to examine the bulk ash composition of ash scraped from three electrodes that were sampled at 20, 48, and 107 days. Results of this test are shown in Figure 49. This was done as another means of confirming what was being found using SEM techniques. Since a relatively large sample of ash is required to conduct this test, it was not possible to perform XRF testing on the ash from each electrode.

Figure 44. Differences in elemental composition of the ash at Section A, 4 inches down.

Figure 45. Differences in elemental composition of the ash at Section B, 8 inches down.

Figure 46. Differences in elemental composition of the ash at Section C, 12 inches down.

Figure 47. Differences in elemental composition of the ash at Section D, 20 inches down.

Figure 48. Differences in elemental composition of the ash at Section E, 28 inches down.

Energy & Environmental Research Center Natural Materials Analytical Research Laboratory WD-XRF Chemical Analysis Report						
Sample Description: Ash from Quartz rods (107 day, 48 day, and 20 day rods)						
Oxides (wt.%)	(a)	(b)	(c)	Elemental (wt.%)	(d)	(e)
SiO ₂	10.3	10.8	22.0	Si	9.6	15.8
Al ₂ O ₃	4.1	4.3	8.8	Al	4.4	7.2
Fe ₂ O ₃	4.3	4.5	9.2	Fe	6.0	9.8
TiO ₂	0.2	0.2	0.4	Ti	0.2	0.4
P ₂ O ₅	0.1	0.1	0.2	P	0.1	0.2
CaO	10.5	11.0	22.5	Ca	15.1	24.7
MgO	2.1	2.2	4.4	Mg	2.5	4.1
Na ₂ O	11.7	12.3	25.1	Na	17.4	28.5
K ₂ O	3.4	3.6	7.3	K	5.7	9.3
SO ₃	48.5	51.0	-----	S	39.0	-----
Total	95.0					
(a) Oxide concentrations (wt.%) on an ash basis. (b) Oxide concentrations normalized to a closure of 100%. (c) Oxide concentrations renormalized to a SO ₃ -free basis. (d) Elemental concentrations (wt.%) on an ash basis. (e) Elemental concentrations renormalized to a S-free basis.						
Comments: BaO = 0.87% Unknowns = 3.54% SrO = 0.34%						

Figure 49. Test results.

CONCLUSIONS

Conclusions gained by this work are the following:

- Sodium-rich aerosols and small ash particles accumulate and become bonded on the surface of the silica electrodes.
- Ash accumulations from sodium-rich lignite flue gas adversely affected the NO_x conversion.
- The adverse impact occurs within a 2-week time period.

- The ash accumulations are readily removed with a water wash, and the electrodes are not permanently affected by the ash.
- The lignite ash produces a coating on the electrode that interferes with the discharge, causing streamers that negatively impact NO conversion.
- Rinsing the electrodes with water returns the performance to levels seen prior to exposure to lignite flue gas.
- There is a high variation in the performance of the ash-coated electrodes. It is unclear what is causing this variation.
- The performance of the ash-covered electrode does not recover with continued operation of the electrode, as has been seen with bituminous ash at the BCU.
- There is no indication of degradation in electrode performance over time for cleaned electrodes that have been exposed to lignite flue gas.
- The Powerspan ECO technology may prove to be viable if the ash accumulation can be kept to a minimum.

Based on the results obtained in the work, it appears that the ECO technology has potential but is significantly impacted by the sodium-rich ash. Sodium reduction upstream of the reactor and aggressive ECO reactor cleaning methods are possible methods that will enable the ECO technology to be feasible. Future testing of the technology must be aimed at measures to reduce the sodium aerosol content of the flue gas in order to prevent the formation of sodium-rich deposits.