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**MATHEMATICAL AND EXPERIMENTAL PILOT-SCALE STUDY OF COAL
REBURNING FOR NO_x CONTROL IN CYCLONE BOILERS**

Topical Report

**By
H. Farzan
R. A. Wessel**

June 1991

Work Performed Under Contract No. FG22-90PC89659

**For
U.S. Department of Energy
Pittsburgh Energy Technology Center
Pittsburgh, Pennsylvania**

**By
The Babcock & Wilcox Company
Alliance, Ohio**

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Principal Investigators

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SUMMARY

The U.S. Department of Energy (DOE) under its Clean Coal II solicitation is sponsoring Babcock & Wilcox (B&W) to perform a 100-MWe demonstration of the coal reburning technology for NO_x control from cyclone boilers. The overall objective of this project is to evaluate the potential of the reburning technology for reducing the NO_x emissions in full-scale cyclone-equipped boilers. The performance goals for the coal reburning retrofit are:

- Greater than 50% reduction in NO_x emissions, as referenced to the uncontrolled (baseline) conditions at full load.
- No serious impact on cyclone furnace operation, boiler efficiency, fireside corrosion and deposition, or boiler ash removal system performance.

There are currently no commercially demonstrated combustion modification techniques for cyclone boilers that reduce NO_x emissions. The emerging reburning technology offers cyclone boiler owners a promising alternative to expensive flue gas cleanup techniques for NO_x emission reduction. Reburning involves the injection of a supplemental fuel (natural gas, oil, or coal) into the main furnace in order to produce locally reducing stoichiometric conditions which convert NO_x produced in the main combustion zone to molecular nitrogen, thereby reducing overall NO_x emissions.

There are presently 105 operating, cyclone-equipped utility boilers representing approximately 14% of pre-NSPS coal-fired generating capacity (over 26,000 MWe). The potential of future acid rain control and the location of the majority of these units (Midwest) eventually will target these boilers for NO_x emission control.

The host site for the demonstration is the Wisconsin Power & Light (WP&L) Company's 100-MWe Nelson Dewey Station. As a part of this project, B&W's 6-million Btu/hr small boiler simulator (SBS) was used to duplicate the operating practices of Nelson Dewey Unit No 2. Baseline and coal reburning tests were performed using the 100-MWe demonstration coal (Lamar - a medium sulfur (1.80%) bituminous coal from Indiana). This report describes the pilot-scale evaluation performed under this contract. The purpose of this pilot-scale study was to examine the effectiveness of reburning for NO_x reduction and to assess the potential side effects. In addition, the potential of a high-sulfur Illinois coal for cyclone reburning application was evaluated.

During reburning tests, the cyclone-fired coal at 10% excess air and at a rate equivalent to 66% to 80% of the total heat input. The remaining 20% to 34% of the heat input was introduced through two reburning burners under substoichiometric conditions to obtain reburn zone stoichiometries of 0.86 to 0.95. Reburn coal fineness was varied from 63% to 90% through 200-mesh. A 49% to

73% NO_x reduction was achieved when varying the reburn zone stoichiometry from 0.95 to 0.86, respectively. The NO_x levels showed good correlation with the reburn zone stoichiometry despite the wide variation in the reburn coal finenesses tested (63%, 78%, and 90% through 200-mesh). These NO_x levels were insensitive to reburn fuel fineness. Similar NO_x reductions were also achieved at 75% boiler load. When flue gas recirculation (FGR) was added into the reburning burner secondary air, the reduction of NO_x increased slightly.

The potential side effects were explored via combustible losses, furnace exit gas temperature (FEGT), physical and chemical properties of the fly ash at the stack (for electrostatic precipitator (ESP) performance), and reburn zone H_2S concentrations (for fireside corrosion). Under the optimum conditions, combustion efficiencies decreased slightly (0.05%) compared to baseline results and CO levels remained low (less than 30 ppm). The FEGT increased by 40°F during non-FGR operation. Addition of FGR resulted in a quenching effect and the FEGT actually decreased by 40°F. Maximum H_2S levels in the reburn zone were 200 ppm for Lamar coal and 300 ppm for high-sulfur Illinois coal. These H_2S levels were observed within the center of the furnace between the two reburning burners while low levels were identified near the boiler sidewalls.

In summary, reburning had a minimal impact on overall combustion efficiencies and a $\pm 40^\circ\text{F}$ variation in FEGT should have a minimal impact to boiler performance. Since H_2S levels measured near the boiler walls were low (12 to 16 ppm), no major boiler corrosion would be predicted for the full-scale retrofit. However, the corrosion rate in the reburn zone is a strong function of coal sulfur content and boiler type. A site-specific analysis is required for future retrofit applications.

Coal reburning could impact ESP performance due to increased particulate loading although no change in ash resistivity was observed between baseline and reburning operation. Potential impact of the technology on the ESP performance is site-specific and is currently under investigation for the Nelson Dewey station.

Supportive numerical modeling was used to assess mixing performance in the SBS. The numerical flow predictions quantify the SBS reburning system mixing performance that achieves over 50% NO_x reduction with minimal effect on combustion efficiency. Based on these results, a methodology was developed for scale-up to the 100-MWe boiler using the pilot-scale data and physical and numerical modeling results.

Section 1

INTRODUCTION

The U.S. Department of Energy (DOE) under its Clean Coal II solicitation is sponsoring Babcock & Wilcox (B&W) and Wisconsin Power & Light (WP&L) to perform a full-scale demonstration of the coal reburning technology for cyclone boiler NO_x emissions control. This full-scale evaluation is justified via a previous Electric Power Research Institute (EPRI) sponsored engineering feasibility study (Project RP-1402-30) and EPRI/GRI (EPRI RP-2154-11; GRI:5087-254-1471) pilot-scale evaluation of reburning for cyclone boilers performed by B&W⁽¹⁾⁽²⁾. The feasibility study revealed that the majority of cyclone-equipped boilers could successfully apply this technology to reduce their NO_x emission levels by approximately 50% to 70%⁽¹⁾. The pilot-scale tests evaluated the potential of natural gas, oil, and coal as the reburning fuel in reducing NO_x emissions. The data obtained from the pilot-scale project substantiated the results predicted by the feasibility study. Though oil/gas reburning could play a role in reducing NO_x emissions from cyclone boilers, B&W coal reburning research has also shown that coal performs nearly as well as gas/oil without deleterious effects on combustion efficiency. This means that boilers using reburning for NO_x control can maintain 100% coal usage instead of switching to 20% gas/oil for reburning. As a result of the coal reburning research performed to date, the technology has advanced to the point where demonstration on a commercial scale is imminent.

There are presently 105 operating, cyclone-equipped utility boilers representing approximately 14% of pre-NSPS coal-fired generating capacity (over 26,000 MW). These units contribute approximately 21% of the NO_x emitted since their inherently turbulent, high-temperature combustion process is conducive to NO_x formation. Although the majority of cyclone units are 20 - 30 years of age, utilities plan to operate many of these units for at least an additional 10 - 20 years. The potential of future acid rain control legislation and the location of the majority of these units (midwest) eventually will target these boilers for NO_x emissions control legislation.

The coal reburning demonstration project for cyclone boiler NO_x control will be carried out at WP&L's Nelson Dewey Station Unit No. 2 in Cassville, Wisconsin. The unit is a B&W RB-type boiler with three cyclone furnaces. Unit No. 2 is small (nominal 100 MWe) to limit project costs, but large enough to assure that the reburning technology can be successfully applied to the cyclone-fired utility boiler population. As part of the project, B&W's 6-million Btu/hr small boiler simulator (SBS) pilot facility was utilized to duplicate the operating practices of WP&L's Nelson Dewey Unit No. 2. The coal that is fired at Nelson Dewey was fired in the SBS cyclone and also was utilized as the reburn fuel. Combining the pilot-scale combustion test results with physical and numerical modeling of the technology as applied to the Nelson Dewey Unit No. 2 provides a comprehensive test program not only for successful application to WP&L's unit, but for the cyclone population as a whole.

This report describes the pilot-scale evaluation performed under this contract. The purpose of the pilot-scale tests was to examine the effectiveness of reburning for NO_x reduction and to assess the potential side effects. This information will aid in identifying the potential commercial application of the technology. The following summarizes the specific objectives of the test program:

- Evaluate major process parameters such as reburning/main combustion zone stoichiometries, reburning coal quantity, and grind size.
- Determine effects of reburning on:
 - Slagging/fouling in the upper furnace and convective pass.
 - Combustion efficiency (based upon unburned combustibles and CO emissions).
 - Waterwall corrosion.
 - Furnace exit gas temperature (FEGT).
 - Electrostatic precipitator (ESP) Performance.
- Maximize NO_x reduction while maintaining combustion conditions compatible with design and operation of cyclone-equipped boilers.

BACKGROUND

The cyclone furnace consists of a cyclone burner connected to a horizontal water-cooled cylinder called the cyclone barrel (Figure 1-1). This auxiliary furnace was an attractive alternative to pulverized coal (PC) by providing the ability to burn low-grade coals, significantly reducing fly ash in the flue gas, requiring less fuel preparation equipment, and allowing for a reduction in total boiler size. Crushed coal and air are introduced through the cyclone burner into the cyclone barrel. The larger coal particles are thrust out to the barrel walls where they are captured and burned in the molten slag layer that has formed, while the finer particles burn in suspension. The mineral matter melts, exits the cyclone furnace from a tap at the cyclone throat, and it is dropped into a water-filled slag tank. The flue gases and remaining ash leave the cyclone and enter the main furnace.

Commercially demonstrated combustion modifications have not significantly reduced NO_x emissions without adversely affecting cyclone operation. Past tests with combustion air staging achieved 15 - 30% reductions. Cyclone tube corrosion concerns due to the resulting reducing conditions were not fully addressed because of the short duration of these tests. Further investigation of staging for cyclone NO_x control was halted due to utility corrosion concern.

The recent emergence of the reburning technology offers a promising alternative to conventional combustion controls and SCR systems. Cyclone-equipped boiler combustion occurs within a water-cooled horizontal cylinder attached to the outside of the furnace and requires intense mixing of fuel and air under high temperatures. This unique configuration and combustion method prevents application of standard low- NO_x burner technology. Furthermore, conventional NO_x reduction techniques such as two-stage combustion cannot be applied to the full extent due to associated cyclone operational concerns such

as corrosion. The use of selected catalytic reduction (SCR) technology offers promise for controlling NO_x from these units, but at high capital and operating costs. Reburning could, therefore, be a promising alternative NO_x reduction approach for these units at more reasonable capital and operating costs. Reburning technology involves injection of a second fuel into the main furnace (above the cyclone region) to produce a zone where a reducing atmosphere exists. This reducing atmosphere converts NO_x to molecular nitrogen, thus destroying a portion of the NO_x produced in the primary cyclone combustion zone.

Figure 1-1 Cyclone Furnace

PILOT-SCALE REBURNING TEST PROGRAM

Technical Objectives

The technical objectives of this project are to demonstrate NO_x reductions of nominally 50% while maintaining acceptable cyclone/boiler operating conditions. Two coals are evaluated while operating under various anticipated full-scale simulated reburning conditions. Table 1-1 summarizes the various ranges of reburning criteria which are evaluated for NO_x reduction capability. Main cyclone/reburning burners fuel splits, reburning fuel type, furnace stoichiometries, and furnace residence times are varied. Additional variables

which are evaluated include mixing, corrosion potential, fireside deposition, and combustion efficiency. The results are utilized to confirm/expand the Phase I engineering feasibility study.

Table 1-1

SUMMARY OF REBURNING CONDITIONS EVALUATED DURING PILOT-SCALE TESTS

	<u>Main Combustion (Primary) Zone</u>	<u>Reburning Zone</u>	<u>Burnout Zone</u>
Fuel	Indiana Lamar Illinois #6 (Peabody)	Indiana Lamar Illinois #6 (Peabody)	----
Fuel Split	65 - 80%	20 - 35%	----
Stoichiometry	1.1	0.85 - 0.95	1.15
Residence Time (Assume Plug Flow)	0.1 sec	0.5 - 0.8 sec	0.6 - 0.9 sec
Coal Grind Size	50%<200 mesh	70 - 90%<200 mesh	----

The major areas of technical uncertainty which were identified in the feasibility case studies and are evaluated during the pilot-scale tests include:

- NO_x reduction potentials of the reburning fuels when operating in a cyclone boiler environment.
- Optimization of process parameters for cyclone application. These parameters include cyclone/reburn zone stoichiometries, reburn/burnout zone residence times, and alternative reburn fuels.
- Effects on increased solids deposition with coal reburning in the upper furnace and convective section. Two-day baseline and coal reburning tests are performed in order to compare the deposition rate and cleanability potential from a simulated secondary superheater tube.
- H₂S measurements throughout the furnace region are obtained to help determine the corrosion potential of the technology with a medium sulfur as well as a high sulfur Illinois coal.
- Unburned combustibles (unburned carbon in the ash and CO emission levels) and furnace exit gas temperature (FEGT) changes are obtained.
- In-situ resistivity, flyash loading, flyash particle size distribution, and flyash density are measured to help determine the impact on ESP performance.

Section 2

REBURNING PROCESS DESCRIPTION

Reburning is a process by which NO_x produced in the primary (main) combustion zone is reduced downstream via supplemental (reburn) fuel injection under reducing conditions. Operating at substoichiometric conditions, the "reburn" fuel produces a secondary combustion zone which is oxygen deficient.

These reducing conditions convert a portion of the NO_x produced in the main combustion zone to molecular nitrogen. In the furnace, the reburning process employs multiple combustion zones as shown in Figure 2-1. These zones are identified as the main (or primary) combustion zone, the reburn zone, and the burnout zone.

Figure 2-1 Reburning Technology

The main combustion zone is operated at a reduced stoichiometry and combusts the majority of the fuel input (70 - 85%). A majority of the investigations have shown that the main combustion zone should be operated at a stoichiometry of less than 1.0. Operating at this stoichiometry minimizes the amount of reburn fuel required in the reburn zone, since optimum NO_x reduction results have been found to occur at a reburn zone stoichiometry of 0.8 - 0.9. Operating the main combustion zone for cyclone units at a stoichiometry of 1.0 is impractical due to the potential for highly corrosive conditions within the cyclones. Most cyclones burn high-sulfur, high-iron bituminous coals which could be highly corrosive under reducing/molten ash conditions. In order to avoid potential problems with its catastrophic consequences, the cyclone main combustion zone is operated at a stoichiometry of no less than 1.1 (10% excess air).

The balance of the fuel (approximately 15 - 30% heat input) is introduced above the main combustion zone through the reburning burners. These burners are similar in design and operation to standard wall-fired burners. The furnace reburn zone is operated at stoichiometries in the range of 0.85 - 0.95 in order to achieve maximum NO_x reduction based upon numerous investigations. (3,4,5) To obtain these furnace stoichiometries while maintaining a 1.1 cyclone stoichiometry, reburn fuel is injected at a stoichiometry of 0.2 to 0.4. The reburn zone temperature must be sufficiently high -- above 1800°F -- to provide an environment for decomposition of the reburn fuel.

The balance of the required combustion air -- totaling 15 - 20% of the excess air -- is introduced in the burnout zone through overfire air (OFA) ports in order to complete the combustion of all of the fuel introduced in the boiler.

The kinetics involved in the NO_x reduction process within the reburn zone are complex. Although the chemistry is not fully understood at this time, the main reactions are described by Okiura, et al. (3) The major chemical reactions are:

1. The reaction process is initiated by the formation of hydrocarbon radicals at the reburn zone. The release of radicals is caused by the pyrolysis of the fuel in an oxygen-deficient, high-temperature environment. The presence of high oxygen concentrations in the reburn zone would inhibit the NO_x reduction process by converting (combusting the hydrocarbons) carbon dioxide (CO₂) and carbon monoxide (CO).

2. The hydrocarbon radicals mix with the combustion gases entering the reburn zone from the main combustion zone. The radicals, which are actively searching for oxygen in order to stabilize, will react with NO to eventually form CN radicals and other products.

3. The CN radicals and other products then react with NO to form N₂ and, thus, the major NO_x reduction step is completed.

As stated earlier, an important parameter in the above series of kinetic steps is the deficiency of oxygen in the reburn zone. The following reactions are in competition with the NO_x reduction process and, if oxygen levels are high, the NO_x reduction mechanisms will be halted and these reactions will predominate:

Available residence time in the reburn zone is a controlling parameter for the NO_x reduction reactions. Efficient mixing between the reburn fuel and combustion flue gases from the main zone can minimize the residence time requirement in this zone.

In order to complete the combustion process, air is introduced above the reburn zone (burnout zone) through the OFA ports. Within the burnout zone, conversion of HCN and ammonia compounds may regenerate some of the decomposed NO_x through the following reactions:

Additionally, HCN and ammonia compounds may continue to improve the overall NO_x reduction via the following reactions:

The temperature and oxygen concentrations in the burnout zone are the driving forces for regeneration or destruction of NO_x within this region. Lower temperature and oxygen concentrations will promote greater conversion of the nitrogen compounds to elemental nitrogen. However, these lower concentrations and temperatures will promote higher carbon losses.

This zone also requires adequate residence time for oxygen to thoroughly mix and react with the furnace combustibles prior to entering the convection pass. This is necessary to reduce the potential of unburned carbon.

Section 3

EXPERIMENTAL APPARATUS

SMALL BOILER SIMULATOR (SBS)

Based on the industry need for a pilot-scale cyclone boiler simulator, Babcock & Wilcox (B&W) designed, fabricated, and installed such a facility at its Alliance Research Center (ARC) in 1985. The project involved conversion of an existing pulverized coal-fired facility to be cyclone-firing capable. Additionally, convective section tube banks were installed in the upper furnace in order to simulate a typical boiler convection pass. The small boiler simulator (SBS) is designed to simulate most fireside aspects of full-size utility boilers such as combustion and flue gas emissions characteristics, fireside deposition, etc.

Simulation Criteria

Prior to the design of the pilot-scale cyclone boiler simulator, the various cyclone boiler types were reviewed in order to identify the inherent cyclone boiler design characteristics which are applicable to the majority of these boilers. The cyclone boiler characteristics that were reviewed include NO_x emissions, furnace exit gas temperature (FEGT), carbon loss, and total furnace residence time. Previous pilot-scale cyclone-fired furnace experience identified the following concerns:

- Operability of a small cyclone furnace (e.g., continuous slag tapping capability).
- The optimum cyclone(s) configuration for the pilot-scale unit was debated. Commercial cyclone boiler systems can include front-wall fired, opposed-wall fired, and single or multiple cyclone elevations. In addition, there are different cyclone burner and cyclone furnace designs presently in operation.
- Compatibility of NO_x levels, carbon burnout, cyclone ash carryover to the convection pass, cyclone temperature, furnace residence time, and FEGT. Due to the various sizes/types/fuels burned, commercial cyclone units operate within a large range of combustion and pollutant conditions.

Originally, an opposed-wall fired, cyclone design was proposed, based on the large number of cyclone utility boilers falling into this design category. Using this as the design basis for the pilot-scale unit would involve having two 3-million Btu/hr cyclones. A review of past experience revealed that the smallest cyclone ever designed/operated was 10-million Btu/hr. Based on this and coupled with concerns about fabrication and slag tap operation (due to size), it was decided to proceed with designing a single 6-million Btu/hr cyclone to accommodate the SBS facility.

Pilot-Scale Furnace Design Criteria

The design of the pilot-scale cyclone-fired furnace offers many challenges to the designer. A design criteria is required in order to obtain experimental results that can be directly scaled-up to commercial cyclone boilers. Pertinent parameters were identified and incorporated in the pilot furnace design. These parameters are as follows:

- Cyclone exit conditions: coal burn-out, gaseous species concentrations, and flue gas temperatures.
- Flue gas time/temperature history within the furnace/convective surface regions.

Cyclone Exit Conditions. One concern of designing a 6-million Btu/hr size cyclone is that a high amount of combustion heat is transferred through the cyclone barrel water-cooled walls. Thus, the cyclone exit temperature and slag tapping capability of the cyclone could be affected. To ensure slag tapping capabilities, one approach is to overheat the combustion air to compensate for the extra heat loss. In addition, coal particle size can be reduced from the typical utility cyclone size coal (crushed) in order to intensify the combustion process. An additional concern is to simulate the cyclone collection efficiency, or percent of the fuel burned in the molten slag layer versus in-suspension. This is a function of cyclone design parameters such as cyclone barrel diameter, air velocities, and coal particle size. Therefore, the following design parameters had to be considered simultaneously to satisfy the above-stated potential operational problems:

- Cyclone design parameters
 - Combustion air velocities
 - Surface-to-volume ratio
- Average cyclone gas residence time
- Available cyclone heat per unit cooling area
- Combustion air temperature
- Coal particle size

The cyclone furnace was then designed by geometrically scaling down a single-wall-fired utility cyclone unit to 6-million Btu/hr. Air velocities to the cyclone were considered the major parameter and, thus, they were scaled one-to-one with the commercial cyclone unit. Average coal particle size was reduced to approximately duplicate the commercial unit's centrifugal force and, consequently, the cyclone collection efficiencies. The reduced particle size also increased the combustion intensity. Finally, to simulate the available heat per unit surface area, the design temperature of the combustion air for the 6-million Btu/hr cyclone was higher than for normal utility cyclone operation.

Flue Gas Time/Temperature History. The various cyclone boiler design types were reviewed in order to predict furnace gas residence times. Based upon

this review, a range of residence times was generated in order to bracket the general cyclone boiler population (refer to Section 5). Generally, the study showed that single-wall-fired cyclone units contain furnace residence times on the lower side of the general population range. Although this is true, the majority of single-wall fired units do have sufficient residence time available for the reburning technology. Thus, the SBS cyclone design criteria was to simulate the geometry of B&W's commercially operated, single-wall-fired cyclone boiler type. In addition, the SBS furnace was insulated in order to achieve a comparable flue gas time/temperature relationship to actual field operating experience.

Pilot-Scale Furnace Facility Description

B&W's 6-million Btu/hr small boiler simulator (Figure 3-1) was utilized to perform the pilot-scale cyclone reburning tests. The SBS is fired by a single, scaled-down version of B&W's cyclone furnace. Coarse pulverized coal (44% through 200 mesh), carried by primary air, enters tangentially into the burner. (Pulverized coal had to be utilized in the SBS instead of crushed coal in order to obtain complete combustion in this small cyclone.) Preheated combustion air at 700°F enters tangentially into the cyclone furnace. The larger coal particles are captured and burn in the molten slag layer formed within the cyclone furnace, while the finer particles burn in suspension. The mineral matter melts, exits the cyclone furnace from the tap at the cyclone throat, and is dropped into a water-filled slag tank. Only 15 - 20% of the ash leaves the cyclone with the flue gases and enters the main furnace.

Figure 3-1 Small Boiler Simulator (SBS) Facility

The furnace is water-cooled and simulates the geometry of B&W's single-cyclone, front-wall fired cyclone boilers. It consists of four separate water-cooled sections. The SBS facility has been operating for a total of 8 years, with the last 6 years being operated in the cyclone configuration. This cyclone facility has been proven to simulate typical full-scale cyclone units via furnace/convective pass gas temperature profiles and residence times, NO_x levels, cyclone slagging potential, ash retention within the resulting slag, unburned carbon, and fly ash particle size. A summary of these comparisons is shown in Table 3-1.

Table 3-1

COMPARISON OF BASELINE CONDITIONS FOR SBS FACILITY AND COMMERCIAL UNITS

	<u>SBS</u>	<u>Typical Cyclone-Fired Boilers</u>
Cyclone Temperature	>3000°F	>3000°F
Residence Time	1.4 sec at full load	0.7 - 2 sec
Furnace Exit Gas Temperature	2265°F	2200° - 2350°F
NO _x Level	900 - 1200 ppm	600 - 1400 ppm
Ash Retention	80 - 85%	60 - 90%
Unburned Carbon	<1% in ash	1 - 20%
Ash Particle Size (MMD; Bahco)	6 - 8 microns	6 - 11 microns

The inside surface of the furnace is insulated to yield an FEGT of 2265°F at the design heat input rate of 6-million Btu/hr. A water-cooled tube bank simulates the flue gas time/temperature history inherent in full-scale cyclone convective passes. The tube bank consists of four separate sections for simulating a secondary superheater, reheater, primary superheater, and economizer. Each section consists of a water-cooled jacket and tubes to quench the flue gases. All four sections are connected to a common atmospheric drum. This use of convective tubes to cool the gas, in conjunction with the cyclone furnace, makes this a unique facility among pilot-scale combustors.

Two reburning burners were installed on the SBS furnace rear wall, above the cyclone burner/barrel. The facility is capable of firing natural gas, oil, or coal at the reburning burner region. The multi-fuel reburning burners were designed to accommodate the required velocities for furnace penetration and also to allow for enough flexibility for varying mixing characteristics. Each burner consists of essentially two zones: an outer zone housing a set of spin vanes and an inner zone contains the reburn fuel injector. Air and flue gas recirculation (FGR) flow can be introduced through the outer zone. Figure 3-2 is a photograph of the actual reburn burners location and associated air/gas recirculation/fuel piping.

OFA ports are available on both the front and rear walls of the SBS at three elevations, with each elevation containing two ports. Locating the OFA ports at different elevations assists in assessing the effects of residence time on fuel burnout and NO_x reduction. Rear OFA ports were used in this project to simulate the WP&L reburning system.

Figure 3-2 SBS Reburning Burners and Associated Piping Location

The SBS furnace and convective pass sections are equipped with numerous observation ports at different elevations to allow for complete evaluation of the process under investigation. Utilizing the viewports for in-furnace probing assists in determining temperatures and gas/solids composition.

Two air-cooled ash deposition probes are available in the convective section (simulating secondary superheater and reheater tubes) in order to allow for fouling (deposition) studies to be performed. These probes are equipped with thermocouples for measuring metal wall and inlet/outlet air temperatures. The probe metal temperature is maintained at a typical boiler tube temperature in order to assure meaningful ash deposition results. The effect of ash deposition on heat transfer is determined by energy balance calculations for each probe. In addition, a simulated commercial sootblower is available to determine the required sootblower pressure necessary to remove the deposits and restore maximum heat flux potential. In this project, only the superheater probe was used.

SELECTION OF TEST FUELS

Two coals were tested -- a medium-sulfur content (1.74%) bituminous coal from Indiana (Lamar) that will be fired at Nelson Dewey Unit No. 2 during the demonstration; a second bituminous coal from Illinois (Peabody) was evaluated to study the reburning technology with a high-sulfur coal. The same coals, pulverized to 63%, 78%, and 90% through 200 mesh, were utilized as the reburn fuels during the coal reburning tests. The coal analyses are shown in Table 3-2. The coal ash analysis and grind size are shown in Table 3-3 and Figures 3-3, and 3-4, respectively.

Table 3-2

COAL ANALYSIS

	<u>Indiana Lamar</u>		<u>Peabody</u>	
	<u>As-Received</u>	<u>Dry</u>	<u>As-Received</u>	<u>Dry</u>
<u>Proximate Analysis, %</u>				
Moisture	14.65*	---	16.39*	---
Volatile Matter	37.89	44.39	36.98	44.23
Fixed Carbon	43.70	51.20	36.78	43.99
Ash	3.76	4.40	9.85	11.78
Gross Heating Value, Btu/lb	11,811	13,838	10,212	12,214
Btu per lb (M&A Free)	---	14,476	---	13,845
<u>Ultimate Analysis, %</u>				
Moisture	14.65	---	16.39	--
Carbon	66.05	77.39	58.13	69.53
Hydrogen	4.59	5.38	4.26	5.10
Nitrogen	1.28	1.50	1.13	1.35
Sulfur	1.74	2.04	3.54	4.24
Ash	3.76	4.41	9.85	11.78
Oxygen (Difference)	7.93	9.28	6.70	8.00
Total	100.00	100.00	100.00	100.00

* Both coals were dried before firing in SBS. The as-fired coals contain 4-5% moisture.

Table 3-3

INDIANA LAMAR COAL ASH ANALYSIS

Ash Analysis (I.C.P.)*, %

Silicon as SiO_2	29.23
Aluminum as Al_2O_3	16.29
Iron as Fe_2O_3	36.00
Titanium as TiO_2	0.93
Calcium as CaO	10.76
Magnesium as MgO	0.78
Sodium as Na_2O^{**}	0.46
Potassium as K_2O^{**}	1.20
Sulfur as SO_3	3.34
Phosphorus as P_2O_5	0.43

* The results of I.C.P. analysis are reported by the Alliance Research Center as the oxides. This does not necessarily mean that the elements occur as such in the sample.

** By Flame Photometer

Figure 3-3 Indiana Lamar Coal Grind Size Distribution

Figure 3-4 Illinois Peabody Coal Grind Size Distribution

INSTRUMENTATION

Gas Analyzers

The gas analysis system uses on-line analyzers to continuously monitor and record stack concentrations of O_2 , SO_2 , NO_x , CO , and CO_2 (see Table 3-4 and Figure 3-5).

Table 3-4

SMALL BOILER SIMULATOR (SBS) GAS ANALYZERS

<u>Analyzer</u>	<u>Range(s)</u>	<u>Manufacturer/ Model</u>	<u>Serial No.</u>
SO_2	0-500 ppm, 0-2500 ppm, 0-5000 ppm	Anarad AR-30	0890325
NO_x	0-10 ppm, 0-25 ppm, 0-100 ppm, 0-1000 ppm, 0-2500 ppm, 0-5000 ppm	Beckman 951A	0900020
O_2	0-10%, 0-25%, 0-50%	Beckman 755	0870142
CO_2	0-5%, 0-20%	Beckman 864	0890661
CO	0-1000 ppm, 0-5000 ppm	Beckman 864	0890660

Figure 3-5. Schematic of Gas Analysis System

In this program, the analyzers were calibrated daily (before and after the tests) with standard gases. The calibrated gases were injected at two locations: 1) at the stack into the gas sampling line, and 2) at the inlet of the gas analyzers. First, the analyzer was calibrated with the calibration gases introduced into the analyzer inlet. To ensure that sorbent injection does not interfere with the NO_x/SO_2 reading, the calibration gases were introduced at the stack into the gas sampling line both before and after sorbent injection. When the gas analyzer readings were compared to the known concentration of the calibration gases, they showed less than 2% deviation. The flue gas cleanup system utilizes a water trap system to dehumidify the flue gases. A Perma-Pure dryer is used for additional dehumidifying before the gases enter the analyzers.

Suction Pyrometer

Gas temperature measurements were obtained with a single-shield suction pyrometer. In the uninsulated convection pass, the temperature measurements could be in error by as much as 80°F (at 2200°F) due to radiation heat loss to the cold walls. The measured gas temperatures in the insulated furnace are fairly accurate and were not corrected for the radiation loss (since it is small).

H₂S Measurements

In-furnace sulfur species (H₂S and SO₂) sampling were performed by a water-cooled probe, SO₂ analyzer, and drager tubes. A water-cooled probe was utilized to cool the flue gas, but not below 300°F to avoid condensation of water vapor. The gas temperature was adjusted by inlet water temperature as well as flow rate. H₂S drager tubes were used to measure the H₂S concentration. These drager tubes are hydrogen sulfide #29801 and #67-19001 (purchased from Safety First Supply Co., Pittsburgh, Pennsylvania). The detection ranges are 1 to 200 ppm, and 5 to 600 ppm. The drager tubes were randomly calibrated against H₂S standard calibration gas. A minimum of one tube from each package was calibrated and good agreement (within ± 5%) was observed. Duplicate measurements were performed in majority of the tests to ensure the reliability of the data. In addition, SO₂ concentrations were measured (with on-line analyzer) to ensure that the H₂S measurements were reasonably accurate. An accuracy of ± 10% was achieved with this technique and is acceptable for corrosion rate calculations.

Section 4

RESULTS

INTRODUCTION

An existing pulverized-coal-fired pilot-scale facility at the Babcock & Wilcox (B&W) Alliance Research Center (ARC) was utilized for pilot-scale evaluation. This cyclone-equipped small boiler simulator (SBS) was initially tested in 1985 with Ohio No. 6 coal in order to verify its ability in simulating typical cyclone firing characteristics and operability. The cyclone characteristics and operability evaluated during that investigation included the following: continuous slag tapping capability, percentage of ash retention in the slag, NO_x emission levels, unburned carbon, furnace temperature profile, and the flue gas time/temperature relationship within the convective pass region. After the successful completion of the verification tests, the facility was first utilized to examine the potential of upper furnace sorbent injection technology for SO₂ reduction in cyclone units⁽⁶⁾. Following the sorbent injection project, a cyclone reburning engineering feasibility study and the subsequent pilot-scale cyclone reburning test program was performed^{(1) (2)}. Table 4-1 summarizes the comparison of baseline condition of the SBS and commercial boilers prior to this project. The present evaluation was then initiated using the existing retrofitted pilot-scale cyclone.

Table 4-1

COMPARISON OF SBS AND COMMERCIAL UNITS

	<u>SBS Data</u>			<u>Commercial Units</u>
	<u>Ohio No. 6</u>	<u>West Virginia</u>	<u>Kittanning Seam No. 2</u>	
NO _x , ppm @ 3% O ₂	1050	1000	925	600 - 1400
Residence Time, Sec	---	---	1.4	0.7 - 2.0
FEGT, °F	2248	2209 - 2285	2250 - 2300	2200 - 2350
Unburned Carbons	---	---	(% in Fly Ash)	
Cyclone Temperature, °F	---	---	2900 - 3020	>3000
Coal Feed Size	44.0	50.0	51.8	1/4" x 0
Distribution of Ash, %				
- Slag	83.2	---	---	60 - 90
- Fly Ash @ Stack	12.6	12.3 - 13.5	12.6	10 - 40
- Fly Ash @ FE	18.2	---	18.2	-----
CO, ppm	---	---	20 - 30	<100

During the current pilot-scale evaluation, the majority of the tests were performed while firing a medium-sulfur content (1.74%) bituminous coal from Indiana (Lamar) that will also be fired at Nelson Dewey Station Unit No. 2 during the demonstration phase. A second bituminous coal from Illinois (Peabody) was also tested to address the technology's capabilities when firing a high-sulfur content coal. The pertinent boiler parameters which were simulated as closely as possible between the SBS and Nelson Dewey Unit No. 2 were furnace residence time and thermal conditions. The key parameters which were investigated throughout the pilot testing include: NO_x reduction capability, unburned carbon, fireside corrosion, and deposition.

In addition, impact of reburning on precipitator performance was studied by measuring fly ash resistivity, particulate loading, particulate size distribution, elemental analysis, and SO₃ concentrations.

DEMONSTRATION HOST SITE'S COAL COMBUSTION EVALUATION

NO_x Emission Levels

Baseline NO_x emission levels adjusted to 3% O₂ ranged from approximately 950 to 1070 ppm while varying stack O₂% from 2 to 3.75%, respectively, at the SBS full-load rated capacity of 6-million Btu/hr. Since 3% stack O₂ is considered typical, all subsequent reburning conditions are shown while maintaining an overall stack O₂ of 3%. Thus, the referenced baseline NO_x level when operating at 3% O₂ is 1025 ppm. Reducing SBS load to 75% of rated capacity (4.5-million Btu/hr) resulted in NO_x emissions of 915 to 1000 ppm corrected to 3% O₂ when varying excess O₂ from 2.4 to 4.3%, respectively. The NO_x emission level at 3% O₂ and 75% load is 950 ppm corrected to 3% O₂. Figure 4-1 shows these results of NO_x versus stack O₂ (%) for the full and partial load conditions.

Incorporating coal reburning operation at the SBS revealed NO_x reductions on the order of 49 to 73% from baseline depending on reburn zone stoichiometry (0.95 to 0.85). Maintaining the cyclone furnace stoichiometry at 1.1 throughout the test sequence is critical due to the potential corrosion/operating concerns (slag tapping) of the cyclone. Thus, while maintaining the cyclone stoichiometry at 1.1, the reburn zone stoichiometry is varied by increasing the amount of heat input diverted to the reburning burners (while also maintaining a constant reburning burner stoichiometry). Figures 4-2 and 4-3 show NO_x emissions (@ 3% O₂) versus reburn zone stoichiometry (or reburning burner coal flow) for the 6-million and 4.5-million Btu/hr cases, respectively. Full-load testing including varying the reburn coal size fraction, e.g., nominal standard (63% thru 200 mesh), medium (78% thru 200 mesh), and fine (90% thru 200 mesh) grind. Figure 4-2 shows no major deviations with respect to reburn coal grind size versus NO_x except for a direct comparison at about 0.94 reburn zone stoichiometry between medium grind and fine grind. The medium grind resulted in approximately 110 ppm higher NO_x level, presumably due to experimental error. All remaining data showing grind size versus NO_x is in good agreement.

At full-load conditions, Figure 4-2 reveals that varying reburn zone stoichiometries from 0.95 to 0.85 while maintaining 3% stack O₂, provided NO_x reductions from baseline results of 49 to 73%, respectively. To obtain these NO_x reductions, the corresponding cyclone/reburning burner coal splits are approximately 80/20 (0.95 stoichiometry) and 66/34 (0.85 stoichiometry).

Figure 4-1 Baseline NO_x Emissions With Lamar Coal

Figure 4-2 Reburning NO_x Emissions at Full Load With Lamar Coal

Figure 4-3 Reburning NO_x Emissions at Partial Load With Lamar Coal

Figure 4-3 shows the effects of reburning on NO_x reduction at 75% of rated boiler capability while utilizing the fine grind reburn coal size (90% through 200 mesh). NO_x reductions on the order of 43 to 63% are shown when varying stoichiometry from 0.95 to 0.86.

All of the above data corresponds to 0% flue gas recirculation (FGR) addition. Adding FGR to the reburning burners increases the mass flow through the burner and thus results in higher burner velocities/turbulence. Figure 4-4 shows the NO_x reduction results during 10% FGR addition and at full-load (6-million Btu/hr) conditions. Comparing the NO_x reduction capability during FGR addition with the baseline 0% FGR case shows that NO_x reductions of 53 to 75% are achieved while varying reburn zone stoichiometry from 0.95 to 0.85. Thus, a slight improvement in NO_x reduction potential was observed when FGR was utilized.

Furnace Exit Gas Temperature (FEGT)

Furnace exit gas temperature (FEGT) did not change significantly between baseline and reburning operation. Figure 4-5 compares these operating conditions for the 6-million and 4.5-million Btu/hr cases. Baseline FEGTs at full load and 75% loads were 2175°F and 1975°F, respectively, at a stack O₂ of 3%. Incorporating reburning at full load revealed minimal FEGT effects within a range of about ± 40°F. The +40°F and -40°F conditions were observed during 0% and 10% FGR addition cases, respectively. Although these values can be considered low, convection pass metal temperatures are recommended to be monitored throughout full-scale testing to assure that no problems are encountered.

Figure 4-4 Effect of FGR on NO_x Reduction

Figure 4-5 Effect of Reburning on FEGT With Lamar Coal

Lower load operation showed a potential FEGT increase up to about 100°F. This increase at lower loads should not be a problem, but convective pass metal temperatures should be monitored to confirm this statement. Thus, based upon this data (in conjuncture with past pilot test/engineering studies), no significant reburning impacts on FEGT would be predicted.

Combustion Efficiency

Reviewing unburned carbon data shows that the pilot-scale testing would predict an increase in unburned carbon when operating under reburning conditions. Increasing the reburn coal grind size does reduce the magnitude of this increase. Thus, the full-scale reburning retrofit design will incorporate the capability to change the coal particle size distribution. Figure 4-6 shows fly ash carbon content versus % reburn fuel for various reburn coal grind sizes. Baseline unburned combustible content of the fly ash from the SBS facility are low (less than 1%) during short-term testing. Operating in the reburning mode at about a 0.9 (approximately 27% reburn fuel) reburn zone stoichiometry shows a fly ash carbon content of approximately 5 - 6% when utilizing the fine grind or 90% thru 200 mesh coal size.

Figure 4-6 Effect of Percent Reburn Fuel and Coal Fineness on Combustible Losses

Since the total ash content to the furnace is typically low in cyclone boilers during normal operation (due to the slag tapping capability), but increases in total boiler ash will be observed with reburning, changes in unburned carbon levels in the fly ash should also be evaluated based upon combustion efficiency. Fly ash samples were collected throughout the long-term deposition test

phase (48-hour continuous runs) for both baseline and reburning cases. The unburned carbon (UBC) / combustion efficiency results are as follows:

- Baseline - 3.5% UBC / 99.99% Combustion Efficiency
- Reburning - 5.1% UBC / 99.94% Combustion Efficiency

Thus, two items of interest are revealed. The first is that over a longer period of time, the baseline UBC increased to about 3.5% versus the less than 1% reported in Figure 4-6. This is due to the normal boiler upsets which are observed in the SBS during long-term operation. The second item pertains to the small change in combustion efficiency observed (0.05% decrease during reburning). Thus, although the pilot-scale tests have highlighted unburned carbon as a potential issue, minimal impact on combustion efficiency should result.

HIGH-SULFUR ILLINOIS COAL COMBUSTION EVALUATION

NO_x Emission Levels

Baseline NO_x emission levels during high-sulfur Illinois (Peabody) coal firing tests are illustrated in Figure 4-7. At full-load (6-million Btu/hr), NO_x levels (adjusted to 3% O₂) increased from 884 to 989 ppm when varying stack excess oxygen from 2.25 to 4.1%. Since operating at 3% excess oxygen is considered typical, all subsequent reburning conditions are shown while maintaining an overall stack oxygen of 3%. The full-load baseline NO_x level at 3% excess O₂ was 935 ppm and all subsequent reburning NO_x levels will be compared to this condition. At 4.5-million Btu/hr, NO_x emissions were lower and ranged from 851 to 970 ppm, adjusted to 3% O₂ when varying excess oxygen from 2.1 to 4.4%, respectively. The formation of N₂O during coal reburning was also investigated; the levels were 7 to 11 ppm at a reburn zone stoichiometry of 0.9.

The NO_x levels with the reburning system in operation are illustrated in Figure 4-8. Overall NO_x reductions of 30 to 54% from the baseline condition were achieved for the reburn zone stoichiometries of 0.96 to 0.87, respectively. In all tests, the cyclone stoichiometry was maintained at 1.1 due to potential corrosion/slag tapping concerns. A fine (90% through 200 mesh) grind pulverized coal was used for all reburning tests performed with Peabody coal. The reburn zone stoichiometry was varied by changing the amount of the heat input introduced at the reburning burners. The heat input to the reburning burners ranged from 20.8 to 34.9% of the total for reburn zone stoichiometries of 0.96 to 0.87, respectively.

The % NO_x reduction observed was lower for the Peabody coal than Lamar coal. Both coals have similar fuel nitrogen contents on a per unit heat input. Peabody coal has a higher volatile matter to fixed carbon (VM/FC) ratio than Lamar. Although coals with a higher VM/FC ratio content are expected to produce higher NO_x levels in cyclone boilers, baseline NO_x levels were lower for the Peabody coal as compared to the Lamar coal. At the present time, this result is unexplainable and requires further review.

Figure 4-7 Baseline NO_x Emissions With Peabody Coal

Figure 4-8 Reburning NO_x Emissions With Peabody Coal

Furnace Exit Gas Temperature (FEGT)

Furnace exit gas temperature (FEGT) did not change significantly between baseline and reburning conditions (+11°F). Figure 4-9 compares the FEGT for reburning and baseline operating conditions. Baseline FEGT was 2157°F at full load with 3% excess oxygen. The FEGT under reburning conditions ranged from 2156° to 2168°F for 20.8 to 34.9% reburn fuel, respectively. The FEGT changes shown during these tests are less sensitive than that observed during the Lamar coal testing (+11°F versus +40°F).

Combustion Efficiency

Figures 4-10 and 4-11 illustrate carbon content of the fly ash under the baseline and reburning conditions. In the majority of the baseline tests, low (less than 1.0%) combustibles were found in the fly ash with the Peabody coal. Operating at 70% load and 2% excess oxygen produced the highest level of combustibles (approximately 1.4%). During the reburning conditions while utilizing fine (90% through 200 mesh) pulverized coal, combustible losses ranged from 0.72 to 2.26% for 20.8 to 34.9% reburn fuel input. Combustible losses are very small (less than 0.1% combustion efficiency) and are in agreement with the Lamar coal tests. But the percent carbon in the fly ash differs considerably from the Lamar coal mainly due to the variation in ash content of the flue gas which is a dilutant for unburned combustibles. Peabody coal contains more ash than Lamar coal, 11.78 and 4.4%, respectively on a dry basis.

Figure 4-9 Effect of Reburning on FEGT With Peabody Coal

Figure 4-10 Baseline Combustible Losses With Peabody Coal

Figure 4-11 Reburning Combustible Losses With Peabody Coal

ELECTROSTATIC PRECIPITATOR PERFORMANCE

Electrostatic precipitator (ESP) performance is a potential concern during operation of a coal reburning system. The fly ash loading to the ESP increases since the ash from the coal reburning system is not removed as slag. If the fly ash particle size increases due to the larger ash particles being emitted from the reburn coal, a potential improvement in ESP efficiency may result. Chemical composition and resistivity of the fly ash may change due to the different history of ash particles. Due to the aforementioned differences, the ESP performance may alter. Therefore, the following measurements were performed during baseline and reburning tests to assist in the determination of the potential impact of reburning on ESP performance:

- In-situ resistivity of the fly ash
- Particle size distribution, density, and concentration of the fly ash in the flue gas
- SO₃ concentration

Fly Ash Loading

The ash loading at the full-load conditions of the SBS increased from 0.51 - 0.53 lb/million Btu for the baseline tests to 0.65 - 0.83 lb/million Btu at the reburning conditions. This represents a 42% average increase in fly ash loading from baseline conditions when 28% reburn fuel (ground to 90% through 200 mesh) was utilized.

SO₃ Measurements

The SO₃ levels slightly decreased from an average of 1.9 ppm at the baseline tests to 1.7 ppm for the reburning conditions. The SO₃ concentrations ranged between 1.8 - 2.1 ppm and 1.2 - 2.6 ppm for baseline and reburning conditions, respectively. Standard EPA Method 8 was used in these measurements.

Fly Ash Chemical Analysis

Table 4-2 shows the chemical analysis of the fly ash. The sodium and potassium concentrations decrease slightly from the baseline to the reburning conditions. This is expected since the low melting compounds like sodium and potassium vaporize to a greater extent within the cyclone as compared to the reburn zone.

Fly Ash Particle Size Distribution and Density

The fly ash from the reburning test was coarser than the fly ash from the baseline test. Figure 4-12 shows particle size distribution. The reburn fly ash contains lower fine fly ash, e.g. 38% less than 2.3 microns (baseline) versus 30.6% less than 2.3 microns (reburning) for the baseline and reburning conditions, respectively. This trend would help increase the ESP collection efficiency. The density was almost unchanged. The results are obtained with the fine pulverized coal as the worst-case scenario.

Table 4-2

CHEMICAL ANALYSIS OF ASH

Sample No. Description	Baseline <u>K-29327</u>	Reburning <u>K-29327</u>
<u>Ash Analysis (I.C.P.)*, %</u>		
Silicon as SiO_2	30.79	29.87
Aluminum as Al_2O_3	18.20	17.76
Iron as Fe_2O_3	23.74	24.08
Titanium as TiO_2	1.18	1.03
Calcium as CaO	7.48	9.96
Magnesium as MgO	1.05	0.85
Sodium as Na_2O^{**}	0.86	0.80
Potassium as K_2O^{**}	2.41	1.99
Sulfur as SO_3	3.35	3.87
Phosphorus as P_2O_5	0.47	0.49

* The results of I.C.P. analysis are reported by the Alliance Research Center as the oxides. This does not necessarily mean that the elements occur as such in the sample.

** By Flame Photometer.

Figure 4-12 Effect of Reburning on Fly Ash Size Distribution

In-Situ Resistivity

APCO Services performed resistivity measurements for the baseline and reburning SBS tests. A point-plane probe was used for in-situ resistivity measurements. The probe is inserted directly into the dust-laden gas stream and allowed to come to thermal equilibrium. The particulate sample is deposited electrically onto the measurement cell by corona discharge between the point and plane. Thus, the particles are charged and collected in a manner analogous to that occurring in a precipitator.

In the point-plane technique, two methods of making measurements on the same sample may be used. The first is called the "V-I method". In this method, a current-voltage curve is obtained before the electrostatic deposition of the dust while the collecting surface is clean. A second current-voltage curve is obtained after the dust layer has been collected. The voltage drop across the dust layer is determined by the shift in the current-voltage characteristic along the voltage axis. After the layer has been collected and the clean and dirty current-voltage curves have been obtained, the layer thickness is determined by lowering a second electrode the same size as the collecting electrode onto the deposited layer until electrical contact is made. The layer thickness is then read from a dial micrometer.

The second method, called the "spark method", may be used after the above data are obtained. In this method, the electrode which was lowered onto the collected sample has increasing voltages applied to the dust layer and the current obtained for each voltage is recorded until the dust layer breaks down electrically and sparkover occurs. Dust resistivity is determined from the voltage measured just prior to sparkover. The resistivity is calculated in both methods as the ratio of the average electric field across the layer to the average current density.

The in-situ resistivity results obtained for both the reburning and baseline cases are listed in Table 4-3. Four successful runs were made for the "reburning" case. In general, there was good agreement between individual measurements and between values obtained by the V-I method and the spark method. The average ash resistivity was on the order of 5×10^{10} ohm-cm and did not noticeably change from baseline to the reburn conditions.

Resistivity as a function of temperature was predicted using a predictor developed by Dr. Roy Bicklehaupt for the U.S. Environmental Protection Agency. Chemical analyses of coal and ash samples for both operating conditions were used in the predictor. The predicted resistivity for the "baseline" case is plotted in Figure 4-13, while that for the "reburning" case is plotted in Figure 4-14. Also displayed in each of these figures are the results from the in-situ measurements. One can see that the in-situ data are approximately a half-order of magnitude higher than the predicted resistivity at the temperature of the measurements. This is a typical deviation between the predicted and the measured data. The temperature of the various runs varied. For both cases, the experimental data follow curves having the same general shape as that of the predicted curve, but the data are shifted approximately 100°F to the right of the predicted curve. The accuracy of predicted curve is approximately half-order to one order of magnitude.

Table 4-3

IN-SITU RESISTIVITY MEASURED AT THE OUTLET OF THE SBS

	Gas Temperature (°F)	Resistivity	
		V-I (ohm-cm)	Spark (ohm-cm)
Reburning	496	7.5×10^{10}	
	532		2.1×10^{10}
	514	4.2×10^{10}	
	536	4.6×10^{10}	4.5×10^{10}
	538	6.9×10^{10}	5.8×10^{10}
Baseline	534	2.4×10^{10}	4.6×10^{10}
	496	5.9×10^{10}	5.9×10^{10}
	511	4.3×10^{10}	3.7×10^{10}

Figure 4-13 Baseline In-Situ Resistivity

SYM	NO.	NAME	C/F	PR	H ₂ O	O ₂	CO ₂	SO ₂	SO ₃	FE	E _{kV/cm}
■		Reburn			6.7	4.6	13	.12	.0		10
●									1.7

Figure 4-14 Reburning In-Situ Resistivity

Chemical analyses of coal and ash from coal for a sample taken from the weigh feeder belt were also provided. The resistivity versus temperature was also predicted for these samples. These predictions are given in Figure 4-15. Little difference in predicted or measured resistivity was seen for the three samples studied.

SYN	NO.	NAME	C/P	PR	H ₂ O	O ₂	CO ₂	SO ₂	SO ₃	P%	E, kV/cm
■		Weigh Belt			7.9	4.6	13	12	2		10
●									1.2

Figure 4-15 Predicted Fly Ash Resistivity From Coal Ash Analysis

Flue gas SO₃ measurements were made for the "reburning" and the "baseline" cases with values of 1.7 ppm and 1.9 ppm, respectively, being obtained. These values were also used to determine the influence of SO₃ on the predicted resistivity. The modification in resistivity occurs for temperatures below 440°F -- well below the stack temperature of the measurements. Thus, one would not expect any modification of the in-situ values due to the concentration of SO₃ in the gas at the WP&L electrostatic precipitator (ESP). When a cold-side ESP is used, then the effect of SO₃ on ESP performance should be considered.

It can be seen that the ESP performance changes as the result of the combined effect of the increased mass loading, and the fly ash particle size distribution.

These data along with the Nelson Dewey Station baseline operating conditions are currently being used in a study to evaluate the ESP performance under the reburning conditions and will be reported in the detailed final design report.

FIRESIDE ASH DEPOSITION

Convective surface ash deposition is a potential concern during operation of a reburning system. Since reburning involves delaying the combustion process, slightly higher furnace exit gas temperatures could result and thus change the boiler deposition characteristics during coal reburning. Coal reburning presents deposition concerns due to the added dust loading to the convection pass which results during this mode of reburning operation. Not only could the increased mass loading magnify an ash build-up problem, but a change in particle size distribution and increases in average gas velocity through the convection surface could promote deposition and erosion. Two 48-hour convective surface deposition tests were performed during baseline and coal reburning conditions to investigate simulated superheater surface deposition, heat flux variations, and sootblower cycle frequency and jet energy requirements.

Furnace waterwall deposition is also a potential area which needs to be addressed. Unfortunately, no provisions to investigate this parameter at the pilot-scale was included in this test project. Since the SBS furnace walls are refractory-board covered to maintain proper gas temperature at this scale, full-scale utility conditions are not simulated such that general deposition observations in this region would not be directly applicable. However, no change in SBS furnace deposition was observed between the baseline and reburning conditions.

Several key parameters are considered important for experimental simulation of full-scale convective pass fouling parameters in the SBS tests:

- Particle size distribution
- Particle composition
- Gas temperature
- Sootblowing parameters
- Gas velocity
- Tube metal temperature and material

Simulation of all of these key parameters cannot be achieved during SBS testing because of practical limitations (e.g. boiler and convective pass size) of pilot-scale furnaces. Trade-offs exist between the direct simulation of several of these parameters. The primary area of concern exists between the simulation of ash particle size/density distribution versus gas velocity. Convective pass design must either consist of smaller areas (large length of heat transfer sections) to increase flue gas velocities to typical commercial utility velocities (60 to 100 ft/sec) or maintain more reasonably sized heat transfer surface which results in lower gas velocities (approximately 10 ft/sec) in the SBS. Reducing the cross-sectional area in the pilot-scale unit to permit more realistic velocities will produce significant changes in the quality and quantity of fly ash. To accomplish this, a constriction section would be required to reduce the flow cross-section area, and selective deposition would occur on the walls of this constriction. B&W's mathematical modeling techniques are capable of accounting for velocity differences. Therefore, the SBS facility was designed to simulate particle size/density distribution at the expense of gas velocity.

The experimental data collected in the SBS are quite valuable, even without mathematical modeling. This is due to the pilot-scale and commercial-scale observations that heat flux degradation can occur rapidly from the initial layer of fly ash deposit on the tube surface. The SBS deposition probes simulate this critical, initial deposit layer. In order to recover the heat flux loss, this strong, initial deposit layer bond has to be broken with sufficient sootblower pressure.

The results from the SBS can be utilized on a relative basis to determine if a retrofit technology increases the fouling potential. This determination is accomplished by performing baseline tests, followed by a set of tests utilizing the technology in question. Not only can heat flux data be gathered to determine potential deposition questions, but various sootblower pressures can be utilized to evaluate deposit strength. The correlating parameter for the sootblower pressure requirement is called the peak impact pressure (PIP). The PIP can then be utilized to directly scale-up the results to full-scale operation. PIP is a measurement of the sootblower potential jet energy actually impacting the ash deposit. This parameter is considered the most important factor in determining the cleaning potential of a sootblower. It is an empirical correlation which is based upon actual operating data and is specified in units of inches of Hg. B&W's modeling techniques could then predict potential scale-up concerns with respect to deposit thickness and heat flux variations. In this project, the main concern was evaluating the resulting sootblower pressure requirement and sootblowing cycle frequency. Thus, no mathematical modeling was performed during this program.

Heat Flux

Two 48-hour, full-load (6-million Btu/hr) baseline and coal reburning tests were performed with the Lamar coal to evaluate the heat flux variations versus time and sootblower pressure. Fine pulverized coal was used in the reburn zone as the worst-case scenario. Figures 4-16 and 4-17 illustrate the simulated superheater probe heat flux data during the 48-hour baseline and coal reburning tests, respectively. The clean superheater probe initial heat flux was approximately 14,500 Btu/hr-ft². During the first sootblowing cycle for each of the two operating conditions (baseline and reburning), three

sootblowing pressures (30, 60, and 100 psi) were tested to determine the required cleaning pressure to fully restore the probe heat flux capabilities.

Figure 4-16 Heat Flux of Superheater Probe During Baseline Conditions

Figure 4-17 Heat Flux of Superheater Probe During Reburning Conditions

Prior SBS deposition investigations revealed that sootblower pressure requirements ranged from 30 to 100 psi. Utilizing this pressure range corresponds to PIPs of 9 to 20 inches Hg, which is well below the capabilities of commercial (approximately 60 inches Hg) sootblowing systems.

During the baseline tests, five sootblowing cycles were performed. The results show that the heat flux degradation leveled out to about 75% of the initial clean probe values in about a 7- to 10-hour time span. Utilizing sootblower pressure of 60 psi provided the necessary jet energy to restore initial clean heat flux levels. Thus, 60 psi was utilized throughout the remaining sootblowing cycles. The coal reburning deposition test sequence involved seven sootblowing cycles of approximately 7 hours in duration. The data reveal that the heat flux decreased and leveled out to approximately 75% of the initial clean probe values at approximately the 7-hour time span.

Chemical Analysis of Superheater Deposit

Chemical analysis of the fly ash, coal, and superheater deposits under coal reburning conditions showed that concentrations of sodium and potassium were less than baseline conditions on the superheater probe (Tables 4-4 and 4-5). Typical cyclone-equipped boiler superheater deposits contain more sodium and potassium than normal PC superheater deposits since these compounds evaporate in the cyclone barrel and then condense out on the superheater tube surface. Under coal reburning conditions, the superheater deposit consists of ash from two sources: cyclone coal and reburning burner pulverized coal. The ash loading during coal reburning conditions increased by approximately 40%. The lower sodium and potassium concentrations in the fly ash and superheater probe suggest that, as expected, the ash from the pulverized coal reburning burner does not evaporate to the degree that is observed during cyclone-only firing. Thus, the chemical analysis of the deposits and the required sootblowing pressure to recover the heat flux indicates that the fouling potential on the superheater tube will not be adversely affected with coal reburning.

FIRESIDE CORROSION

Inherent operating characteristics of cyclone-equipped boilers dictate that accurate air/fuel ratios must be maintained to minimize cyclone barrel corrosion potential. Low air flow to the cyclone creates localized reducing zones within the cyclone barrel and thus, provides an environment conducive for corrosion to occur. Incorporating the reburning technology to reduce NO_x emissions involves operating the reburn zone within the furnace region under substoichiometric conditions. There is concern about the substoichiometric effects on the life of boiler tubes within this furnace region. By operating the cyclone in the excess air mode, the majority (if not all) of the sulfur from the coal in the main combustion zone is converted to SO_2 . Due to the reducing environment in the reburn zone, H_2S formation is from two potential sources:

- The reburn fuel is producing H_2S since this zone is under substoichiometric condition
- The SO_2 from cyclone is reduced to H_2S

Table 4-4

CHEMICAL ANALYSIS OF THE ASH DURING THE BASELINE TEST

Sample No. Description	<u>C-20507</u> Indiana Lamar Coal Ash	<u>K-29329</u> Deposition Probe Sample	<u>K-29327</u> Fly Ash
<u>Ash Analysis (I.C.P.)*, %</u>			
Silicon as SiO ₂	29.23	26.70	30.79
Aluminum as Al ₂ O ₃	16.29	15.65	18.20
Iron as Fe ₂ O ₃	36.00	29.50	23.74
Titanium as TiO ₂	0.93	1.15	1.18
Calcium as CaO	10.76	6.27	7.48
Magnesium as MgO	0.78	1.06	1.05
Sodium as Na ₂ O**	0.46	1.11	0.86
Potassium as K ₂ O**	1.20	3.85	2.41
Sulfur as SO ₃	3.34	9.76	3.35
Phosphorus as P ₂ O ₅	0.46	0.74	0.47

* The results of I.C.P. analysis are reported by the Alliance Research Center as the oxides. This does not necessarily mean that the elements occur as such in the sample.

** By Flame Photometer.

Table 4-5

CHEMICAL ANALYSIS OF THE ASH DURING THE COAL REBURNING TEST

Sample No. Description	<u>C-20507</u> Indiana Lamar Coal Ash	<u>K-29330</u> Deposition Probe Sample	<u>K-29327</u> Fly Ash
<u>Ash Analysis (I.C.P.)*, %</u>			
Silicon as SiO ₂	29.23	26.70	29.87
Aluminum as Al ₂ O ₃	16.29	16.56	17.76
Iron as Fe ₂ O ₃	36.00	31.67	24.08
Titanium as TiO ₂	0.93	0.98	1.03
Calcium as CaO	10.76	8.31	9.96
Magnesium as MgO	0.78	0.82	0.85
Sodium as Na ₂ O**	0.46	0.84	0.80
Potassium as K ₂ O**	1.20	2.00	1.99
Sulfur as SO ₃	3.34	7.30	3.87
Phosphorus as P ₂ O ₅	0.43	0.59	0.49

* The results of I.C.P. analysis are reported by the Alliance Research Center as the oxides. This does not necessarily mean that the elements occur as such in the sample.

** By Flame Photometer.

High concentrations of H_2S can be conducive to increased rates of corrosion. Flue gas chemistry analyses were obtained throughout the SBS baseline and reburning test program to help quantify this potential concern. The main objective is to evaluate the effect of the coal sulfur content on H_2S formation within the reburn zone of the coal reburning system.

Corrosion Evaluation

Table 4-6 shows the H_2S levels during firing of the medium- and high-sulfur coals tested under baseline and reburning conditions. In the baseline conditions, 0 ppm H_2S was found with the Lamar coal and only a trace amount could be seen with the Peabody coal. The reburning system produced up to 200 and 300 ppm H_2S in the reburn zone with Lamar and Peabody coals, respectively. The maximum H_2S concentrations were found between the flames of the reburning burners, and H_2S levels near the boiler side walls were low. Figures 4-18 and 4-19 show furnace mapping of the H_2S concentrations measured during the Lamar and Peabody coal testing, respectively. The highest sidewall measured level was 20 ppm during the higher sulfur Peabody coal test. Thus, minimum H_2S contact with the boiler walls was observed. In-furnace H_2S and SO_2 levels are shown in Appendix D. If these low H_2S levels can be reproduced in the full-scale large boilers, tube wastage will be negligible for the WP&L Nelson Dewey Station Unit No. 2 boiler type.

Table 4-6

H_2S CONCENTRATIONS IN REBURN ZONE

	<u>Baseline</u>	<u>Reburning</u>
Lamar Coal (1.87% sulfur, dry)	0 ppm	0 to 200 ppm*
Peabody Coal (4.24% sulfur, dry)	0 to 2 ppm	0 to 300 ppm*

- * 1) H_2S levels vary within the reburn zone.
 2) Maximum H_2S levels were observed between the two reburning burner flames
 3) H_2S levels were low near the side walls.

REBURNING BURNER FLAME DETECTOR EVALUATION

One aspect of the reburning system retrofit is the burner management system. Since 20 to 30% of the total heat input is introduced through the reburning burners, by law it is required to install flame safety equipment to monitor the reburning burner flames. Commercial equipment are available for utility and industrial burner management for various fuels (coal, gas, and oil). However, reburning burner throat stoichiometry is different from typical utility burners. Therefore, the performance of a commercial flame detector for detecting a reburning burner flame was evaluated in the pilot-scale facility.

Figure 4-18 In-Furnace H₂S Levels -- Lamar Coal During Reburning Conditions

Figure 4-19 In-Furnace H₂S Levels -- Peabody Coal During Reburning Conditions

A commercial flame scanner (Model C9502N from Detector Electronics Corporation, Minneapolis, Minnesota) was used in this study. The flame scanner is an infrared (IR) flicker-type scanner. The scanner sends an output signal to the controller only when the IR radiation being detected is accompanied by a flame flicker in the range of 100 to 500 Hz. The combination of flame flicker (resulting from turbulent mixing of fuel and air and combustion) and IR radiation are characteristics of flame only. Therefore, the scanner is insensitive to the background such as hot walls. The scanner was installed in the furnace next to the reburning burner on the left side of the SBS (see Figure 3-2).

The detector was checked periodically during the reburning tests. Regardless of the fuel split between the reburning burners and cyclone, the flame detector read 5 volts DC. When the reburn fuel was turned off and the only flame (background) was in the cyclone, the reading was 0 volts indicating no output signal. The reburning burners' primary air, secondary air, and FGR were nearly shut off (in the order listed) one after another, but no change in the voltage reading was observed and no output signal was seen. It was concluded that the flame detector worked satisfactorily with the coal reburning flame.

REBURNING TECHNOLOGY LITERATURE SEARCH

The published literature was searched for articles containing data on the coal reburning process. The purpose of the literature search was to expand the data from the pilot-scale study and to define the feasibility of the process at the commercial-scale.

Four data bases were searched: DOE Energy, Compendex Plus (Engineering Information Inc.), National Technical Information services (NTIS), and Electric Power Database. The last three sources were searched for the articles published between 1980 to 1989. DOE Energy was searched between 1983 to 1989. The key words utilized were as follows:

- Reburn/Reburning
- Fuel/Fuel Staging
- Nitrogen Oxide(s)/NO_x

A total of 82 articles were finally selected that contained reburn and/or fuel staging in their title or descriptor and had their abstract available in English.

The abstracts were reviewed to identify recent coal reburning studies at large pilot or commercial scales. No pertinent information was found. The majority of the literature had already been reviewed in B&W's internal study and/or was related to the gas reburning process. It was decided to terminate the literature review and concentrate on the pilot-scale evaluation of the technology performed in the SBS facility. This direction was confidently pursued since the B&W cyclone reburning pilot studies are considered the most comprehensive testing which has been performed in this area.

Section 5

NUMERICAL EVALUATION

INTRODUCTION

Effective mixing between the reburn fuel and cyclone gases is needed to obtain acceptable NO_x reduction. In addition, good mixing between overfire air (OFA) and reburn zone gases is necessary to avoid unacceptable unburned combustible losses. Furnace flow patterns and mixing performance were evaluated by in-furnace probing as well as three-dimensional mathematical simulation of the baseline and reburning flow conditions in the small boiler simulator (SBS).

The Babcock & Wilcox (B&W) FORCE numerical flow model solves the governing equations for conservation of mass and momentum, to predict the three-dimensional turbulent flow within the furnace region. Velocity predictions for the SBS were compared with velocity measurements at four elevations in the furnace. Predicted distributions of stoichiometric ratio (SR) were also used to evaluate mixing in the SBS.

A detailed study of the flow patterns, furnace mixing, and residence time using B&W's FORCE is presented in this section for the SBS operating at baseline and coal reburning conditions. The objectives of this work are:

- Benchmark FORCE with physical flow data available for the SBS and with actual velocity data measured in the SBS while firing natural gas
- Evaluate the effect of reduced load, flue gas recirculation (FGR), and fuel split on coal reburning
- Provide information necessary for scale-up of the reburning system performance from the SBS to Wisconsin Power & Light (WP&L) Nelson Dewey Station Unit No. 2.

OVERVIEW OF NUMERICAL RESULTS

Three-dimensional simulations of flow in the SBS were completed. Flow patterns were predicted for baseline operating conditions at full load, and the results are summarized as follows:

- Predicted velocities for baseline operation were compared with hot velocity traverses of the SBS. Predictions were in partial agreement with the data. Some of the hot flow measurements for baseline conditions were repeated, and inconsistencies exist between old and new data. The new data, while incomplete, are considered to be more reliable and are in better agreement with numerical predictions.

- Parametric evaluations of grid size and cyclone swirl were conducted to determine the sensitivity of the model to input parameters. However, discrepancies between data and predictions were not fully resolved with reduced grid size or changes in swirl number.
- General features of the flow which could be validated for baseline operating conditions include:
 - High vertical velocities near the right and left sidewalls with a bias to the left side of the furnace
 - Low velocity and the existence of a small recirculation zone near the center front wall of the furnace

Flow patterns and stoichiometry distributions were predicted for reburning conditions at full load with 0% and 10% FGR added to the reburning burner secondary air flow. The reburning results are summarized as follows:

- Predicted velocities for reburning conditions were compared with hot velocity traverses of the SBS, and predictions were in general agreement with the data. Direct comparisons with data were unwarranted due to differences in flow rates and reburning burner swirl direction between gas reburning conditions for which the data were taken and coal reburning conditions for which the model predictions were made.
- General features of the flow which could be validated for reburning conditions include:
 - Flow bias to the left side of the furnace causes the left reburning burner and overfire air jets to deflect upward more than the right.
 - Large increase in coal reburning burner jet penetration with flue gas recirculation

Predicted distributions of furnace stoichiometry, defined later as a measure of mixing effectiveness, were used to evaluate coal reburning in the SBS.

- Approximately 81% of the mass flow achieves substoichiometric conditions in the reburn zone with no FGR. The average gas residence time for the substoichiometric region of the reburn zone is 0.81 second. Mixing in the burnout zone is complete, with 100% of the flow achieving stoichiometry greater than 1 before reaching the furnace exit.
- The effect of FGR on coal reburning is shorter residence time (0.75 second), better early mixing (more flow in reducing conditions at the reburning burner elevation), and worse late mixing (less flow in reducing conditions inside the reburn zone) in the reburn zone.

- Regions of the flow field with substoichiometric conditions correspond to the regions of low carbon utilization measured in the SBS.

The effect of reburning fuel split and reduced load on coal reburning was not numerically investigated.

NUMERICAL RESULTS

The SBS furnace is equipped with numerous observation ports at different elevations to allow for complete evaluation of the reburning process. Velocity traverses were conducted at the observation port locations for two test conditions while firing natural gas. The first test was conducted with the SBS operating near full-load at baseline conditions (no reburning or overfire air) ⁽⁷⁾. The second test was conducted with the SBS operating at 5.3-million Btu/hr with gas-fired reburning burners and overfire air ⁽⁷⁾. The direction and magnitude of velocity were measured with a water-cooled Fechheimer probe. These measurements are shown in Figures 5-1 and 5-2 for baseline and reburning conditions, respectively. Velocities under 5 ft/sec were considered too small to measure and velocities below 10 ft/sec had a large amount of uncertainty. Measurements at port locations 7 and 8 were repeated for the baseline configuration, and magnitude and direction of the velocity changed significantly, as shown in Figure 5-1. Based on these results, the accuracy and repeatability of measurements at lower velocities are questionable.

Baseline Flow Predictions

The operating parameters used in the CYCLONE and FORCE computer models for the baseline configuration of the SBS are summarized in Table 5-1. These conditions were chosen to represent the conditions tested while firing at full-load (6-million Btu/hr) with the Southern Indiana "Lamar" coal with 15% excess air (3% O₂ measured on a dry basis at the stack). Inlet boundary conditions at the cyclone reentrant throat were calculated with the CYCLONE model. The CYCLONE model solves equations for conservation of the mass, momentum, and energy for a single control volume representing the cyclone furnace.

The furnace geometry and computational grid that are used for the baseline configuration of the SBS are shown in Figure 5-3. The flow is modeled from the reentrant throat of the cyclone to the furnace exit. A finer mesh of control volumes is used in the lower furnace (where the magnitude and gradients in velocity are large) than in the upper furnace.

Predicted flow patterns were compared with hot velocity traverse data as shown in Figure 5-4 for several planes through the furnace. Planes 1, 2 and 4 had to be displaced in the Z direction, as shown in Figure 5-5, to pass as closely as possible to all of the Fechheimer probe measurement locations. Measured velocities are indicated by the bold arrows with magnitudes (ft/sec) depicted below each arrow. Predicted velocities are shown by the small arrows pointing in the direction of the flow with the length of the arrow proportional to the magnitude in velocity.

Figure 5-1 Velocity Flow Traverse Results -- Baseline Conditions

Figure 5-2 Velocity Flow Traverse Results -- Gas Reburning Conditions

Table 5-1

BASELINE OPERATING PARAMETERS FOR FORCE MODEL PREDICTIONS OF THE SBS

Fuel Specifications:

Type:	Indiana "Lamar" Coal
Higher Heating Value (Btu/lb)	13,269
Theoretical Air* (lb/lb fuel)	9.9498
Ultimate Analysis:	
Moisture	3.00
Carbon	74.35
Hydrogen	4.94
Nitrogen	1.46
Sulfur	1.86
Ash	6.39
Oxygen	8.00

Cyclone Operating Conditions:

Coal Flow Rate (lb/hr)	452.2
Temperature (°F)	150
Primary Air Flow Rate (lb/hr)	160.4
Temperature (°F)	150
Secondary Air Flow Rate (lb/hr)	4217.0
Temperature (°F)	710
Tertiary Air Flow Rate (lb/hr)	796.8
Temperature (°F)	150
Slag Tap Flow Rate (lb/hr)	20.1
Reentrant Throat Flow Rate (lb/hr)	5606.2
Temperature (°F)	3012
Swirl Number	0.6500

Furnace Operating Conditions:

Furnace Load (10^6 Btu/hr)	6.000
Stoichiometric Ratio	1.15

*Based on an air moisture level of 0.003 lb/lb dry air.

Figure 5-3 Mathematical Flow Model for the Baseline Configuration of the SBS

Figure 5-4 Comparison Between the Predicted Flow Patterns and the Hot Flow Measurements in the SBS for Baseline Conditions (6-million Btu/hr, 15% excess air, 0.65 swirl, and 42,174 grid points)

Figure 5-5 Measurement Locations for Hot Velocity Traverses and Planes Which Have Numerical Flow Predictions Plotted for Comparison to Measurements

Predictions are in general agreement with trends in the data. Vertical velocities are high near the right and left sidewalls and low in the center of the furnace. A small recirculation zone exists near the sloping front wall in the region of low velocity. In the upper furnace, the flow bends around the furnace arch without forming a recirculation zone above the arch.

Several disparities exist between data and predictions, however. The most notable disparity is that the predicted flow is biased to the left side of the furnace, while measured velocities are highest on the right side. Grid refinement was used to check that spatial discretization errors were not affecting the predicted velocity distribution (refer to Appendix A). The amount of swirl at the cyclone reentrant throat was also varied to demonstrate that the flow was not sensitive to modeling assumptions (also discussed in Appendix A). Finally, measured velocities were repeated at locations 7 and 8 (see Figure 5-1) and shown to be in better agreement with predictions.

Several features can be discerned from the numerical flow results that are not apparent in the data. Figure 5-6 shows the flow patterns at several planes as viewed from the front of the furnace. The regions of high velocity near the side walls are clearly shown. Vertical velocity is skewed significantly to the left and a recirculation zone is present under the furnace arch.

Figure 5-7 shows the flow patterns at the reburning burner and OFA port elevations. Vertical velocity is shown as a contour plot, while horizontal velocity is shown as a vector diagram. At the reburning burner elevation, downward flow is present near the front and back walls and large, upward velocities exist near the side walls. At the OFA port elevation, the flow is upward everywhere, and the flow is once again biased to the left side. These features are shown to persist with coal reburning and have an effect on mixing performance.

Reburning Flow Predictions

The operating parameters used in the CYCLONE and FORCE computer models for the reburning configuration of the SBS are summarized in Table 5-2. These conditions were chosen to represent the reburning conditions tested while firing at full-load (6-million Btu/hr) with the Indiana Lamar coal. Inlet boundary conditions at the cyclone reentrant throat were calculated with the CYCLONE model for the cyclone firing coal at a rate of 4.3-million Btu/hr with 10% excess air. A reburn zone stoichiometry of 0.9 and burnout zone stoichiometry of 1.15 were used for all cases. The amount of flue gas recirculation (FGR) was varied from 0 to 10% to evaluate the effect of reburning burner jet penetration on mixing performance.

The furnace geometry and computational grid that were used for the reburning configuration of the SBS are shown in Figure 5-8. Additional grid lines were added to include the reburning burner and OFA inlets.

Predicted flow patterns for the two reburning cases are shown in Figures 5-9 and 5-10 for several planes through the furnace. Additional figures of predicted flow patterns are included in Appendix B. Coal and air enter the furnace through the reburning burners with counterclockwise swirl. The horizontal reburning burner flow bends upward and mixes with the stream of cyclone combustion gases which emanate from the bottom of the furnace. A recirculation zone is formed above the burners, which circulates air down from the OFA ports and mixes it with the reburning burner flow. The effect of FGR is an increase in burner jet penetration and an increase in flow recirculation between reburning burners and OFA ports.

The overfire air enters the furnace through large (6-inch diameter) ports on the rear wall without any swirl. These jets bend upward and mix with the reburning burner and cyclone combustion gases. In both cases, the reburning burner and OFA jets penetrate less and deflect upward more on the left side than on the right due to the leftward bias of flow from the cyclone.

A qualitative comparison was made between the coal reburning flow patterns in Figure 5-9 (and Appendix B) and the gas reburning hot velocity data shown in Figure 5-2. The flow patterns are in general agreement with the data for the following trends:

- The effect of the OFA jet penetration to the middle or near front wall of the furnace
- The flow is biased to the left side of the furnace as indicated by the magnitude of vertical velocity in the upper furnace

Reburner Elevation
(6 ft, 0.5 in)

Overfire Air Elevation
(10 ft, 1 in)

Figure 5-7 Predicted Flow Patterns in the SBS for Baseline Conditions
(6-million Btu/hr, 15% excess air, 0.65 swirl, and 42,174 grid points)

Table 5-2

REBURNING OPERATING PARAMETERS FOR FORCE MODEL PREDICTIONS OF THE SBS

<u>Fuel Specifications:</u>		
Type		Indiana "Lamar" coal
Higher Heating Value (Btu/lb)		13,423
Theoretical Air* (lb/lb fuel)		10.089
Ultimate Analysis:	Moisture	3.00
	Carbon	75.06
	Hydrogen	5.22
	Nitrogen	1.46
	Sulfur	1.98
	Ash	4.28
	Oxygen	9.00
<u>Cyclone Operating Conditions:</u>		
Coal Flow Rate (lb/hr)		319.3
Temperature (°F)		150
Primary Air Flow Rate (lb/hr)		109.9
Temperature (°F)		150
Secondary Air Flow Rate (lb/hr)		2888.0
Temperature (°F)		710
Tertiary Air Flow Rate (lb/hr)		545.7
Temperature (°F)		150
Slag Tap Flow Rate (lb/hr)		8.7
Reentrant Throat Flow Rate (lb/hr)		3854.2
Temperature (°F)		2929
Swirl Number		0.676
<hr/>		
*Based on an air moisture level of 0.003 lb/lb dry air.		

<u>Reburner Operating Conditions</u>	<u>With FGR</u>	<u>Without FGR</u>
Total Coal Flow Rate (lb/hr)	127.7	127.7
Temperature (°F)	140	140
Total FGR Flow Rate (lb/hr)	563.3	0
Temperature (°F)	355	
Burner Swirl Direction	CCW	CCW
Swirl Number	0.739	0.412
<u>Overfire Air Port Operating Conditions</u>		
Total Air Flow Rate (lb/hr)	1197.8	1127.4
Temperature (°F)	682	682
<u>Furnace Operating Conditions</u>		
Furnace Load (10^6 Btu/hr)	6.000	6.000
Mean Stoichiometric Ratio at Cyclone Exit	1.100	1.100
Reburn Zone	0.909	0.900
Burnout Zone	1.150	1.150

Furnace Geometry

Computational Grid

Figure 5-8 Mathematical Flow Model for the Reburning Configuration of the SBS

Figure 5-9 Predicted Flow Patterns in the SBS for Reburning Conditions
 (6-million Btu/hr, 10% FGR, cyclone SR = 1.10, reburning
 burner SR = 0.9, and OFA SR = 1.15)

Figure 5-10 Predicted Flow Patterns in the SBS for Reburning Conditions
(6-million Btu/hr, no FGR, cyclone SR = 1.10, reburning
burner SR = 0.9, and OFA SR = 1.15)

Direct comparisons with data were unwarranted due to large differences (in flow rates, reburning burner swirl direction, etc.) between the gas reburning conditions for which the data were taken and the coal reburning conditions for which model predictions were made.

Additional validation of numerical results was obtained by visual observations made during coal reburning tests. The reburning burner flames were observed from the roof of the furnace during the test without FGR. The reburning burner flame on the right side of the furnace was visible beyond the furnace arch, while the flame on the left was completely blocked from view. These trends were predicted numerically as shown by the penetration of the reburning burner jets in Figures 5-10 (10% FGR) and 5-11 (0% FGR).

Reburning Mixing And Residence Time Results

Mixing effectiveness and gas residence time were evaluated for coal reburning in the SBS using the FORCE code. The distribution of stoichiometric ratio (SR) is shown in Figures 5-11 and 5-12 for the two cases of coal reburning in the SBS (refer to Appendix E). Each figure depicts the flow at four elevations in the furnace. The contours represent lines of constant stoichiometry.

At the reburning burner elevation, the flow enters the furnace through the burners with $SR = 0.40$ ($SR = 0.51$ with FGR) and mixes with cyclone combustion gases with $SR = 1.10$. The flow is predominantly unmixed at this elevation. At a higher elevation in the reburn zone, the mixing has improved. Approximately 90% of the flow has $SR < 1$ at the reburn zone measurement elevation. A region of $SR > 1$ exists along the left side wall due to the high vertical velocity of cyclone gases. The effect of FGR is increased burner jet penetration and increased recirculation between the reburning burners and OFA ports. A region of $SR > 1$ exists near the rear wall, for the case with FGR, due to the large recirculation zone which brings air down from the OFA ports. Consequently, the case with FGR has better early mixing (more flow with $SR < 1$ at the reburning burner elevation) and worse late mixing (less flow with $SR < 1$ at the reburning burner measurement location).

The effect of overfire air mixing is shown in the contour plots of SR at elevations 10 feet - 4.5 inches and 14 feet - 4.75 inches. The air enters the furnace with $SR = \infty$ and mixes with the reburn zone gases at a mean stoichiometry of 0.90. The jet of overfire air on the left side of the furnace does not penetrate as deeply as the jet on the right. Higher up in the burnout zone, the mixing has improved. Only a small fraction of the flow near the right-front corner has $SR < 1$. These gases become fully mixed as the flow turns at the roof and all of the flow has $SR > 1$ before exiting the furnace.

The mean residence times for gases in the reburning zone are:

With FGR	--	0.742 sec
Without FGR	--	0.812 sec

The shorter residence time with FGR is caused by the increased mass flow through the furnace.

Reburner Elevation (6 ft., 0.5 in.)

Reburn Zone Measurement Elevation (7 ft., 10.5 in.)

Burnout Zone Measurement Elevation (10 ft., 4.5 in.)

Burnout Zone Measurement Elevation (14 ft., 4.75 in.)

Figure 5-11 Predicted Stoichiometric Ratio in the SBS for Reburning Conditions (6-million Btu/hr, 10% FGR, cyclone SR = 1.1, reburning burner SR = 0.9, and OFA SR = 1.15)

Figure 1 is a contour map of a rectangular area. The map is oriented with 'Front Wall' at the bottom and 'Rear Wall' at the top. The left side of the map is shaded and labeled 'Left Side', while the right side is unshaded and labeled 'Right Side'. The map shows contour lines with values 0.95, 1.00, 1.50, 2.00, 2.50, 3.00, and 3.50. The shaded region contains a large area with a value of 0.95 and a smaller area with a value of 1.00. The unshaded region contains several contour lines with values 1.50, 2.00, 2.50, 3.00, and 3.50. The contour lines are labeled with their respective values.

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Regions of high CO concentration generally correspond to regions of low stoichiometry and vice-versa. Figures 5-13 and 5-14 show a comparison between measured CO and the predicted region of $SR < 1$ for coal reburning without and with FGR. CO measurements are shown in units of mole concentration. Agreement between CO measurements and SR is particularly good in the upper furnace. However, some disparities exist in the lower furnace at elevations of 5 feet - 4.5 inches and 7 feet - 10.5 inches. These may be caused by delay of CO oxidation due to turbulent mixing or finite rate chemical kinetics.

The results of the mixing analysis are shown in Figure 5-15 for the two cases of coal reburning in the SBS. The figure shows the mean stoichiometric ratio ($\overline{SR}$), fractional standard deviation (FSD) and percent mass flow with $SR < 1$ (%M) versus furnace elevation (refer to Appendix E). The mean stoichiometry is 1.1 in the lower furnace and decreases to 0.9 in the reburn zone and increases to 1.15 in the burnout zone as expected. The standard deviation in SR is a maximum at the reburning burner and OFA inlets and decreases with elevation. The percent mass flow with $SR < 1$ is zero in the lower furnace, increases to a maximum just below the OFA ports, then decreases with furnace elevation. These results are tabulated in Appendix B.

The effect of FGR on mixing performance is evident from Figure 5-15. Coal reburning without FGR has better mixing (lower fractional standard deviation and greater % mass flow with $SR < 1$) everywhere except near the reburning burner elevation. The case with FGR has better early mixing due to increased burner jet penetration and poorer late mixing due to the downward recirculation of air from the OFA ports. These results make it difficult to assess whether the effect of FGR is beneficial to the performance of the coal reburning system. During SBS combustion tests, lower NO_x emissions were achieved with FGR addition. Therefore, lower NO_x levels can be attributed to good early mixing or to other effects (e.g., temperature) not quantifiable at this time.

Reburner Elevation (6 ft., 0.5 in.)

Burnout Zone Measurement Elevation (10 ft., 4.5 in.)

Reburn Zone Measurement Elevation (7 ft., 10.5 in.)

Burnout Zone Measurement Elevation (14 ft., 4.75 in.)

Figure 5-13 Comparison of Measured CO and Predicted SR in the SBS for Reburning Conditions (6-million Btu/hr, 10% FGR, cyclone SR = 1.1, reburning burner SR = 0.9, and OFA SR = 1.15)

Reburner Elevation (6 ft., 0.5 in.)

Burnout Zone Measurement Elevation (10 ft., 4.5 in.)

Reburn Zone Measurement Elevation (7 ft., 10.5 in.)

Burnout Zone Measurement Elevation (14 ft., 4.75 in.)

Figure 5-14 Comparison of Measured CO and Predicted SR in the SBS for Reburning Conditions (6-million Btu/hr, 0% FGR, cyclone SR = 1.1, reburning burner SR = 0.9, and OFA SR = 1.15)

Figure 5-15 Predicted Mixing Performance for SBS With Coal Reburning

Section 6

CONCLUSIONS

Based upon the small boiler simulator (SBS) facility pilot-scale results, the following conclusions can be derived:

- Reburning is a technically feasible and economically sound approach for NO_x reduction from cyclone units.
- A 43 - 75% overall NO_x emission reduction is achievable in cyclone-equipped units via the reburning technology. This overall NO_x reduction is attributed to two different mechanisms:
 - NO_x destruction in the reducing environment of the reburn zone via the reburning process
 - NO_x reduction via lower heat input at the cyclone
- The lower in-furnace reburn zone stoichiometry of 0.85 provided the best overall NO_x reduction.
- Flue gas recirculation (FGR) to the reburning burners slightly improved the mixing (turbulence) characteristics between the combustion gases/reburn fuel and consequently improved the NO_x reduction capabilities. This tool could be beneficial in future application of reburning to large boilers.
- CO emission levels were low (less than 30 ppm) throughout the various optimal test conditions and, thus, should not be a problem when using reburning.
- Combustible losses were only slightly higher than baseline while operating the reburning system under optimum conditions. Combustible losses were sensitive to reburn coal fineness. The carbon content of the fly ash increased, but the combustion efficiencies did not decrease drastically. Reburning with fine ground coal (90% <200 mesh) provided the best overall results.
- Furnace exit gas temperature (FEGT) changed by less than 40°F during reburning operation. A ±40°F change should not adversely impact boiler performance.
- Fireside deposition was affected during reburning. Fly ash loading increased by approximately 40%; however, sootblowing pressure requirements did not change.

- Maximum in-furnace H_2S concentrations in the reburn zone were 200 ppm and 300 ppm for Lamar and Peabody coals, respectively. These levels were identified within the center region of the furnace between the two reburning burners. Concentrations of less than 20 ppm were observed near the boiler sidewalls. Thus, only a small portion of sulfur in the coal was converted to H_2S .
- Based on the Babcock & Wilcox (B&W) SBS facility tests, significant amounts of SO_2 from the cyclones are not expected to be reduced to H_2S in the reburn zone. This important finding implies that the reburn zone will be less corrosive than the primary (substoichiometric) combustion zone in a staged-combustion boiler.
- Comparisons to hot velocity data and physical flow model results provided validation of the numerical flow predictions. General agreement between computed stoichiometries and in-furnace CO measurements was observed.
- Mixing effectiveness is an indirect measure of reburning system performance. Full-scale performance will be similar to the performance of the SBS provided that the mixing effectiveness in the reburn zone, residence time, and similarity among other variables (e.g., temperature, chemistry, etc.) exists.
- The benefits of FGR cannot be assessed on the basis of mixing effectiveness alone. During experimental tests, however, lower NO_x emissions were achieved with FGR than without. Based on these results, the early mixing caused by the addition of FGR is desirable.
- During reburning, fly ash loading increased, average particle size diameter decreased, and in-situ resistivity was not affected. The impact of these variables will be reported in the design of the reburning system.
- A commercial infrared (IR) flicker-type flame scanner detected the reburning burner flames. The flame detector worked satisfactorily with 20 - 35% reburn fuel and was insensitive to the background radiation.

Section 7

RECOMMENDATIONS

- Utilize the pilot-scale stoichiometries and average residence times in the design of full-scale retrofit as a starting point for the physical and numerical modeling.
- The reburn coal pulverizer should be able to grind the reburn coal to 90% <200 mesh at a total heat input of 30% of boiler load.
- Further investigation is required concerning boiler back-end clean-up equipment operability when applying reburning technology. The electrostatic precipitator (ESP) performance is currently being studied.
- Improved combustion controls, including air and fuel input to the cyclones, reburning burners, and overfire air (OFA) ports, is essential to the successful demonstration of the reburning technology.
- The cyclone itself must be operated under excess air conditions in order to minimize corrosion potential within the cyclone barrel. Accurate air/fuel control is also essential to alleviate this potential concern.
- Use the mixing performance of the small boiler simulator (SBS) as a minimum criteria for reburning system design for Wisconsin Power & Light (WP&L) Nelson Dewey Station Unit No. 2.

Section 8

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Appendix A

PARAMETRIC EVALUATION OF RESULTS FOR THE BASELINE CONFIGURATION OF THE SBS

Appendix A

PARAMETRIC EVALUATION OF RESULTS FOR THE BASELINE CONFIGURATION OF THE SBS

A.1 EFFECT OF GRID RESOLUTION

The baseline configuration of the SBS was first modeled with 20,000 grid points. The grid was subsequently refined to 42,174 grid points to check that spatial discretization errors were not affecting the predicted velocity distribution. A comparison of the two grids is shown in Figure A-1. Most of the grid refinement was made in the lower furnace.

A comparison of the predicted velocities and hot velocity data is shown in Figure A-2. The predicted flow patterns are approximately the same, with small differences occurring in the size of the recirculation zones. Further refinement in the grid is not expected to significantly change the results or improve agreement with experimental data.

A.2 EFFECT OF CYCLONE SWIRL

The velocity and momentum boundary conditions at the cyclone reentrant throat are calculated from mass and momentum balances on the cyclone combustor. These boundary conditions are provided as input to the numerical flow model of the SBS.

The amount of swirl at the cyclone reentrant throat is characterized by the swirl number, which is the ratio of angular to axial momentum: $S_N = G_t / RG_x$ where:

G_t = angular momentum (lb ft²/s²)

G_x = axial momentum (lb ft/s²)

R = cyclone reentrant throat radius (ft)

The swirl is responsible for the skewed flow patterns in the SBS, without which the predicted flow patterns are symmetric about the furnace centerline plane.

The effect of cyclone swirl was investigated for the baseline configuration of the SBS. The swirl number was increased from 0.65 (calculated by the CYCLONE model) to 0.728 and the effect on the predicted flow patterns is shown in Figure A-3. The vertical velocity on the left side of the furnace increases and the size of the recirculation zone near the sloping front wall increases with swirl number. These results do not improve agreement with the hot velocity measurements. Furthermore, a reduction in the swirl number does not improve agreement, since the flow patterns just become more symmetrical about the centerline plane. Therefore, a change in swirl number used in the flow predictions is not justified.

FINE GRID (42,174 POINTS)

COARSE GRID (20,000 POINTS)

Figure A-1. Computational grids for the baseline configuration of the SBS.

Figure A-2. Effect of grid resolution on numerical flow predictions for the baseline configuration of the SBS.

Figure A-3. Effect of cyclone swirl on numerical flow predictions for the baseline configuration of the SBS.

Appendix B

SUPPLEMENTAL RESULTS FOR THE REBURNING CONFIGURATION OF THE SBS

Appendix B

SUPPLEMENTAL RESULTS FOR THE REBURNING CONFIGURATION OF THE SBS

Numerical flow model results for the reburning configuration of the SBS are included here to supplement those given in Section 5 in the main body of this report. Velocity plots are presented in Figures B-1 through B-4 for coal reburning with FGR (see Table 5-2, Section 5 of the main body of this report) and in Figures B-5 through B-8 for coal reburning without FGR.

Figure B-1. Predicted flow patterns in the SBS for reburning conditions (6 MKB/hr, 10% FGR, cyclone SR = 1.10, reburning SR = 0.9, OFA SR = 1.15).

Figure B-2. Predicted flow patterns in the SBS for reburning conditions (6 MKB/hr, 10% FGR, cyclone SR = 1.10, reburning SR = 0.9, OFA SR = 1.15).

Reburner Elevation
(6 ft, 0.5 in)

Vertical Velocity (ft/sec)

Horizontal Velocity
Scale: 50 ft/sec →

Reburn Zone Measurement Elevation
(7 ft, 10.5 in)

Vertical Velocity (ft/sec)

Horizontal Velocity
Scale: 50 ft/sec →

Figure B-3. Predicted flow patterns in the SBS for reburning conditions
(6 MKB/hr, 10% FGR, cyclone SR = 1.10, reburning SR = 0.9,
OFA SR = 1.15).

Burnout Zone Measurement Elevation (10 ft, 4.5 in)

Vertical Velocity (ft/sec)

Burnout Zone Measurement Elevation (14 ft, 4.75 in)

Vertical Velocity (ft/sec)

Horizontal Velocity
Scale: 50 ft/sec →

Horizontal Velocity
Scale: 50 ft/sec →

Figure B-4. Predicted flow patterns in the SBS for reburning conditions
(6 MKB/hr, 10% FGR, cyclone SR = 1.10, reburning SR = 0.9,
OPA SR = 1.15).

Figure B-5. Predicted flow patterns in the SBS for reburning conditions (6 MKB/hr, no FGR, cyclone SR = 1.10, reburning SR = 0.9, OFA SR = 1.15).

Figure B-6. Predicted flow patterns in the SBS for reburning conditions (6 MKB/hr, no FGR, cyclone SR = 1.10, reburning SR = 0.9, OFA SR = 1.15).

Reburner Elevation
(6 ft, 0.5 in)

Reburn Zone Measurement Elevation
(7 ft, 10.5 in)

Horizontal Velocity
Scale: 50 ft/sec →

Figure B-7. Predicted flow patterns in the SBS for reburning conditions (6 MKB/hr, no FGR, cyclone SR = 1.10, reburning SR = 0.9, OFA SR = 1.15).

**Burnout Zone Measurement Elevation
(10 ft, 4.5 in)**

Vertical Velocity (ft/sec)

**Burnout Zone Measurement Elevation
(14 ft, 4.75 in)**

Vertical Velocity (ft/sec)

**Horizontal Velocity
Scale: 50 ft/sec →**

**Horizontal Velocity
Scale: 50 ft/sec →**

**Figure B-8. Predicted flow patterns in the SBS for reburning conditions
(6 MKB/hr, no FGR, cyclone SR = 1.10, reburning SR = 0.9,
OFA SR = 1.15).**

Appendix C

PILOT-SCALE DATA

SUMMARY OF UP&L/DOE PILOT-SCALE TEST RESULTS FOR INDIANA LAMAR COAL

Test ID	Load MBTU/hr	Cyclone SR	Reburner SR	Reburning Zone SR	Overall SR	O2 %	CO ppm	NOx ppm	SO2 ppm	FGR %	W/Ox (PPH) %	Load at FGR Reburner	F	EXIT, F	CYCLONE F	FLY ASH % IN	% TOTAL FLY ASH COAL	REBURNING FLY ASH MEAS H2O CALC.	H2O (% VOL)	
BASEIND-1	6	1.16	N/A	N/A	1.16	3.04	29	1064	N/A	0	1066	0	2213	3030	9.72	0.60	N/A	0.41	N/A	6.75
BASEIND-2	6	1.16	N/A	N/A	1.16	3.01	32	1043	1760	0	1044	0	2187	3030	8.42	0.46	N/A	0.35	N/A	6.75
BASEIND-3	6	1.21	N/A	N/A	1.21	3.71	40	1030	N/A	0	1072	0	2162	2980	LOST	0.77	N/A	N/A	6.49	
BASEIND-4	6	1.10	N/A	N/A	1.10	2.04	37	942	N/A	0	894	0	2171	2960	21.49	1.01	N/A	0.90	N/A	7.11
BASEIND-4d	6	1.09	N/A	N/A	1.09	1.80	31	1035	1960	0	970	0	N/A	N/A	N/A	N/A	N/A	N/A	7.17	
BASEIND-8	6	1.22	N/A	N/A	1.22	3.82	30	991	1660	0	1038	0	2168	2940	12.49	0.69	N/A	0.52	N/A	6.44
BASEIND-9	6	1.15	N/A	N/A	1.15	2.74	84	1028	N/A	0	1013	0	N/A	N/A	N/A	N/A	N/A	N/A	6.81	
BASEIND-10	6	1.18	N/A	N/A	1.18	3.28	24	1045	1700	0	1062	0	2155	N/A	N/A	N/A	N/A	N/A	6.64	
BASEIND-5	4.5	1.25	N/A	N/A	1.25	4.33	21	953	N/A	0	1029	0	1962	2970	13.64	0.82	N/A	0.57	N/A	6.29
BASEIND-5d	4.5	1.24	N/A	N/A	1.24	4.09	31	915	1720	0	974	0	N/A	N/A	N/A	N/A	N/A	N/A	6.34	
BASEIND-6	4.5	1.18	N/A	N/A	1.18	3.24	23	937	1720	0	950	0	1974	2940	16.96	1.26	N/A	0.71	N/A	6.64
BASEIND-6d	4.5	1.13	N/A	N/A	1.13	2.44	31	980	1920	0	950	0	N/A	N/A	N/A	N/A	N/A	N/A	6.93	
BASEIND-7	4.5	1.12	N/A	N/A	1.12	2.32	138	934	2000	0	900	0	2013	2970	13.73	2.58	N/A	0.58	N/A	6.98
FGRIND-1	6	1.13	N/A	N/A	1.15	2.88	41	984	1975	10	977	0	2125	3120	10.99	1.52	N/A	0.46	N/A	6.81
FGRIND-2	6	1.15	N/A	N/A	1.17	3.09	39	984	2100	18	989	0	2083	3030	7.51	3.96	N/A	0.32	N/A	6.70
RBIND-1	6	1.08	0.41	0.94	1.15	2.87	36	629	2150	0	624	21.0	2195	3015	17.02	1.37	80%	0.70	N/A	6.81
RBIND-2	6	1.12	0.44	0.88	1.17	3.13	121	341	1950	0	343	35.6	2174	N/A	17.75	7.75	80%	0.71	N/A	6.70
RBIND-3	6	1.13	0.43	0.92	1.17	3.19	33	498	2150	0	503	29.6	2147	N/A	17.30	9.39	80%	0.70	N/A	6.70
RBIND-3R	6	1.13	0.43	0.92	1.17	3.19	33	498	N/A	0	N/A	29.6	N/A	N/A	17.71	3.54	80%	0.72	N/A	6.70
RBIND-4	6	1.09	0.42	0.86	1.19	3.42	21	315	N/A	0	323	34.5	2186	2990	18.07	9.57	60%	0.73	N/A	6.59
RBIND-5	6	1.08	0.41	0.90	1.16	2.89	36	400	N/A	0	398	27.3	2168	3040	17.17	8.56	60%	0.70	N/A	6.75
RBIND-6	6	1.09	0.42	0.96	1.16	2.94	26	581	N/A	0	579	20.0	2124	3010	15.34	5.54	60%	0.63	N/A	6.75
RBIND-9	6	1.08	0.41	0.94	1.15	2.79	31	517	N/A	0	511	20.1	2175	3010	25.44	4.40	90%	1.09	N/A	6.81
RBIND-10	6	1.07	0.42	0.85	1.17	3.11	37	283	N/A	0	285	34.1	2169	3020	27.86	5.92	90%	1.21	N/A	6.70
RBIND-11	6	1.09	0.41	0.90	1.16	3.01	28	413	N/A	0	413	27.8	2143	3020	23.79	6.21	90%	1.03	N/A	6.75
RBIND-12	6	1.09	0.41	0.90	1.18	3.22	38	451	N/A	0	457	28.0	N/A	N/A	N/A	N/A	90%	N/A	N/A	6.64
RBIND-14	6	1.14	0.39	0.92	1.17	3.15	35	516	2050	0	520	29.6	2198	N/A	N/A	N/A	90%	N/A	N/A	6.70
RBIND-14R	6	1.10	0.39	0.90	1.15	2.83	43	422	1900	0	418	29.3	N/A	N/A	N/A	N/A	90%	N/A	N/A	6.81
RBIND-14RR	6	1.12	0.39	0.91	1.16	3.00	52	460	1790	0	460	29.5	N/A	N/A	N/A	N/A	90%	N/A	N/A	6.75

SUMMARY OF WP&L/DOE PILOT-SCALE TEST RESULTS FOR INDIANA LAMAR COAL

Test ID	Load MBTU/hr	Cyclone SR	Reburner SR	Reburning Zone SR	Overall SR	O2 %	CO ppm	NOx ppm	SO2 ppm	FOR NOx %	3% O2 Reburner	FEGT F	CYCLONE EXIT, F	FLY ASH %C IN % TOTAL FLY ASH COAL	REBURNING FLY ASH MEAS N2O CALC. N2O SIZE LB/MBTU (% VOL) (% VOL)				
RBIND-15	4.6	1.1	0.43	0.95	1.16	3	30	400	1850	0	400	20.8	2826	23.88	N/A	90%	0.89	N/A	6.75
RBIND-15R	4.6	1.1	0.44	0.96	1.18	3.25	33	580	1700	0	588	20.9	1989	20.45	3.88	90%	0.76	N/A	6.64
RBIND-16	4.7	1.11	0.43	0.92	1.16	3	31	480	1700	0	480	27.3	2010	24.98	7.98	90%	0.93	N/A	6.75
RBIND-17	4.8	1.09	0.41	0.86	1.17	3.05	38	350	1725	0	351	33.8	2040	27.68	9.69	90%	1.04	N/A	6.70
FGRIND-3	6	1.09	0.45	0.91	1.14	2.66	25	487	N/A	10	478	27.9	2187	20.40	3.38	80%	0.83	N/A	6.87
FGRIND-4	6	1.09	0.47	0.96	1.17	3.19	26	540	N/A	10	546	21.3	2092	16.38	5.12	80%	0.67	N/A	6.70
FGRIND-5	6	1.10	0.48	0.88	1.16	2.92	29	478	N/A	10	476	34.8	2154	18.01	3.50	80%	0.72	N/A	6.75
FGRIND-6	6	1.08	0.44	0.95	1.17	3.17	35	478	N/A	10	483	20.5	2068	15.75	9.18	60%	0.64	N/A	6.70
FGRIND-7	6	1.13	0.43	0.93	1.19	3.43	33	433	N/A	9	444	28.2	2043	17.00	12.33	60%	0.69	N/A	6.59
FGRIND-8	6	1.13	0.40	0.88	1.18	3.28	36	351	N/A	9	357	34.9	N/A	21.70	15.25	60%	0.87	N/A	6.64
FGRIND-8D	6	1.08	0.40	0.84	1.17	3.10	42	281	N/A	9	283	34.6	2106	N/A	N/A	60%	N/A	N/A	6.70
FGRIND-9	6	1.09	0.43	0.91	1.16	3.04	32	360	N/A	10	361	27.7	2086	22.41	8.85	90%	0.97	N/A	6.75
FGRIND-10	6	1.12	0.45	0.98	1.18	3.29	32	554	N/A	10	563	20.8	2044	18.95	9.78	90%	0.81	N/A	6.64
FGRIND-11	6	1.04	0.39	0.82	1.15	2.74	35	215	N/A	9	212	33.1	2162	23.01	12.82	90%	1.00	N/A	6.81
FGRIND-12	6	1.04	0.39	0.83	1.15	2.75	36	217	N/A	10	214	33.0	N/A	N/A	N/A	90%	N/A	N/A	6.81
FGRIND-14	6	1.08	0.45	0.91	1.16	3.00	38	400	1750	10	400	27.1	N/A	N/A	N/A	90%	N/A	N/A	6.75

LONG TERM PERFORMANCE TEST RESULTS FOR INDIANA LAMAR COAL

Test ID	Load MBTU/hr	Cyclone SR	Reburner SR	Reburning Overall SR	O2 %	CO ppm	NOx ppm	SO2 ppm	FCR NOx (PPM) %	% Load at FEGT Reburner	F %	CYCLONE EXIT, F	FLY ASH XC IN % TOTAL FLY ASH	REBURNING FLY ASH COAL SIZE LB/MBTU	(ClO4)2 ml	M2504 MEAS H2O CALC. PPMV (% VOL.)	H2O (% VOL.)				
RBIND-13A	5.35	1.11	0.41	0.92	1.18	3.20	26	596	1700	0	603	26.9	N/A	N/A	90%	N/A	N/A	6.64			
RBIND-13B	5.50	1.07	0.40	0.89	1.16	2.60	66	532	1640	0	520	26.2	2124	3000	90%	N/A	N/A	6.87			
RBIND-13C	5.38	1.10	0.42	0.92	1.17	3.16	183	527	1650	0	532	26.8	N/A	22.22 FILTER1	90%	0.83	2.6E-06	3.70			
RBIND-13D	5.41	1.11	0.42	0.93	1.18	3.35	30	553	1610	0	564	27.0	N/A	18.42 FILTER2	90%	0.69	1.8E-06	1.95			
RBIND-13E	5.45	1.08	0.42	0.91	1.16	3.01	23	436	1800	0	436	26.4	2125	3010	90%	N/A	N/A	6.75			
RBIND-13F	5.38	1.08	0.43	0.91	1.17	3.10	158	434	M/A	0	436	26.8	2061	N/A	90%	N/A	N/A	6.70			
RBIND-13G	5.31	1.09	0.43	0.91	1.17	3.17	47	453	M/A	0	457	27.1	N/A	N/A	90%	N/A	N/A	6.70			
RBIND-13H	5.32	1.11	0.42	0.92	1.18	3.27	26	581	1775	0	590	27.1	N/A	20.56 FILTER3	90%	0.77	1.2E-06	4.42			
RBIND-13I	5.32	1.09	0.41	0.91	1.16	2.99	56	507	M/A	0	507	27.1	2069	N/A	90%	0.65	1.2E-06	1.98			
RBIND-13J	5.19	1.11	0.40	0.91	1.17	3.11	23	563	M/A	0	566	28.2	N/A	N/A	90%	N/A	N/A	6.70			
RBIND-13AVG	5.36	1.10	0.42	0.91	1.17	3.10	64	518	1696	0	521	27.0	2095	3005	19.67	4.99	90%	0.74	1.7E-06	3.01	6.71
BASIND-11A	5.52	1.15	N/A	N/A	1.15	2.84	27	994	1670	0	985	0	2147	3160	13.90 FILTER1	N/A	0.51	2.1E-06	4.30	6.81	
BASIND-11B	5.47	1.16	N/A	N/A	1.17	3.05	27	985	1620	0	988	0	2178	3090	N/A	N/A	N/A	N/A	6.70		
BASIND-11C	5.46	1.17	N/A	N/A	1.18	3.23	25	917	1475	0	929	0	N/A	N/A	N/A	N/A	N/A	6.64			
BASIND-11D	5.55	1.14	N/A	N/A	1.15	2.75	24	997	1500	0	983	0	N/A	14.54 FILTER2	N/A	0.53	1.9E-06	4.51	6.81		
BASIND-11E	5.55	1.14	N/A	N/A	1.15	2.75	24	997	1550	0	983	0	N/A	13.88 FILTER3	N/A	0.51	1.8E-06	2.46	6.81		
BASIND-11F	5.49	1.17	N/A	N/A	1.17	3.10	25	926	M/A	0	931	0	2081	N/A	N/A	N/A	N/A	6.70			
BASIND-11F	5.46	1.16	N/A	N/A	1.16	2.98	29	893	M/A	0	892	0	N/A	13.56 FILTER4	N/A	0.50	1.8E-06	3.91	6.75		
BASIND-11AVG	5.50	1.16	N/A	N/A	1.16	2.96	26	958	1563	0	956	0	2135	3125	13.97	3.52	N/A	0.51	1.9E-06	3.80	6.75

SUMMARY OF WP&DOE PILOT-SCALE TEST RESULTS FOR ILLINOIS COAL

Test ID	Load MBTU/hr	Cyclone SR	Reburner SR	Zone SR	Reburning Overall	O2 %	CO ppm	NOx ppm	SO2 ppm	FGK %	MOx %	Reburner %	Load at Reburner	FEET F	EXIT, F	FLY ASH %	FLY ASH %	IN %	REBURNING FLY ASH MEAS LB/MBTU (% VOL.)	H2O CALC. H2O (% VOL.)	
BASEIL-1	4.5	1.23	N/A	N/A	N/A	1.26	4.61	23	894	N/A	0	970	0	1959	3080	12.45	0.73	N/A	1.15	N/A	6.68
BASEIL-2	4.5	1.15	N/A	N/A	N/A	1.17	3.17	31	855	N/A	0	863	0	1986	3032	11.72	0.74	N/A	1.08	N/A	7.17
BASEIL-3	4.5	1.08	N/A	N/A	N/A	1.11	2.13	34	892	N/A	0	851	0	2010	3061	13.84	1.38	N/A	1.28	N/A	7.54
BASEIL-7	5.8	1.23	N/A	N/A	N/A	1.24	4.10	37	929	N/A	0	989	0	2171	3012	12.51	0.28	N/A	1.15	N/A	6.78
BASEIL-8	5.8	1.12	N/A	N/A	N/A	1.12	2.25	32	921	N/A	0	884	0	2190	3044	12.84	0.58	N/A	1.18	N/A	7.47
BASEIL-9	5.7	1.16	N/A	N/A	N/A	1.17	3.07	24	903	3650	0	907	0	2157	N/A	12.98	0.41	N/A	1.20	N/A	7.17
BASEIL-9R	5.7	1.17	N/A	N/A	N/A	1.18	3.29	26	977	3700	0	993	0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	7.11
RBIL-1	5.7	1.11	0.41	0.96	1.19	3.46	32	662	N/A	0	679	20.8	2163	3080	19.52	0.72	90%	1.85	8.93	7.05	
RBIL-2	5.8	1.12	0.39	0.87	1.19	3.47	54	415	N/A	0	426	34.9	2168	3160	25.03	1.52	90%	2.41	N/A	7.05	
RBIL-3	5.7	1.11	0.40	0.91	1.19	3.43	36	531	N/A	0	544	28.1	2156	N/A	24.98	2.26	90%	2.38	N/A	7.05	
RBIL-3R	5.8	1.09	0.41	0.90	1.17	3.12	28	472	N/A	0	475	27.9	N/A	N/A	N/A	N/A	90%	N/A	N/A	7.17	

Appendix D

IN-FURNACE PROBING DATA

Figure D-1. In-Furnace CO₂ Levels -- Baseline Conditions

Figure D-2. In-Furnace Oxygen Levels -- Baseline Conditions

Figure D-3. In-Furnace NO_x Levels -- Baseline Conditions

Figure D-4. In-Furnace CO Levels -- Baseline Conditions

Figure D-5. In-Furnace SO₂ Levels -- Baseline Conditions

Figure D-6. In-Furnace H₂S Levels -- Baseline Conditions

Figure D-7. In-Furnace Temperatures -- Baseline Conditions

Figure D-8. In-Furnace CO₂ Levels -- Coal Reburning Conditions

Figure D-9. In-Furnace Oxygen Levels -- Coal Reburning Conditions

Figure D-10. In-Furnace NO_x Levels -- Coal Reburning Conditions

Figure D-11. In-Furnace CO Levels -- Coal Reburning Conditions

Figure D-12. In-Furnace SO₂ Levels -- Coal Reburning Conditions

Figure D-13. In-Furnace Temperatures -- Coal Reburning Conditions

Figure D-14. In-Furnace CO₂ Levels -- Baseline Conditions (Illinois #6)

Figure D-15. In-Furnace Oxygen Levels -- Baseline Conditions (Illinois #6)

Figure D-16. In-Furnace NO_x Levels -- Baseline Conditions (Illinois #6)

Figure D-17. In-Furnace CO Levels -- Baseline Conditions (Illinois #6)

Figure D-18. In-Furnace SO₂ Levels -- Baseline Conditions (Illinois #6)

Figure D-19. In-Furnace H₂S Levels -- Baseline Conditions (Illinois #6)

Figure D-20. In-Furnace Temperatures -- Baseline Conditions (Illinois #6)

Figure D-21. In-Furnace Temperatures -- Coal Reburning Conditions (Illinois #6)

Appendix E

MIXING PERFORMANCE STATISTICAL EQUATIONS

Appendix E

MIXING PERFORMANCE STATISTICAL EQUATIONS

FORCE predicts the distribution of fuel mixture fraction in the furnace. The fuel mixture fraction is a conserved quantity defined as

$$f_{\text{mix}} = \frac{\text{initial mass of fuel}}{\text{total mass of mixture}}$$

The distribution of stoichiometric ratio* is then calculated to provide a more convenient interpretation of the results.

$$SR = (1/f_{\text{mix}} - 1)/\phi_{\text{th}} \quad (1)$$

where ϕ_{th} is the theoretical air required for complete combustion.

Three statistical quantities were defined to evaluate the mixing and provide a means of quantitative comparison of mixing effectiveness. The first quantity is the mean stoichiometric ratio, $\bar{SR}$, calculated from Eq. 1 from the mean mixture fraction $\bar{f}_{\text{mix}}$:

$$\bar{f}_{\text{mix}} = \left(\sum m_i f_{\text{mix},i} \right) / \sum m_i \quad (2)$$

The summation extends over all control volumes at a particular elevation in the furnace. This represents the perfectly mixed condition. The second quantity is the fractional standard deviation, FSD, defined as

$$FSD = \frac{\sigma_{SR}}{\bar{SR}} = \frac{1}{\bar{SR}} \left[\frac{\sum |\dot{m}_i| (SR_i - \bar{SR})^2}{\sum |\dot{m}_i|} \right]^{1/2} \quad (3)$$

This represents the nonuniformity of mixing. The third quantity (%M) is defined as the percentage of flow, passing through a plane that has stoichiometric ratio less than 1.

* This definition of stoichiometric ratio is based on the total carbon and may differ from values of SR calculated based on un-utilized carbon only.

$$\%M = \left[\sum_{SR < 1} |\dot{m}_i| / \sum |\dot{m}_i| \right] \times 100\% \quad (4)$$

This quantity represents the size of the region where reburning occurs.

The mean residence time τ of the gas in the reburning zone is the sum of the contributions from each increment in furnace elevation:

$$\tau = \sum \Delta\tau_k$$

The contribution from one elevation is the mass of gas with $SR < 1$ divided by the total mass flow rate through the furnace at that elevation.

$$\Delta\tau_k = \left(\sum_{SR < 1} \rho_i V_i \right) / \left(\sum \dot{m} \right)$$

END

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