DOE/FE-0391

THE BABCOCK & WILCOX COMPANY

# DEMONSTRATION OF COAL REBURNING FOR CYCLONE BOILER $NO_x$ CONTROL

## PROJECT PERFORMANCE SUMMARY
## CLEAN COAL TECHNOLOGY DEMONSTRATION PROGRAM

JUNE 1999

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The Babcock & Wilcox Company

# Demonstration of Coal Reburning for Cyclone Boiler $NO_x$ Control

## Project Performance Summary
## Clean Coal Technology Demonstration Program

Environmental Control Devices

# Demonstration of Coal Reburning for Cyclone Boiler $NO_x$ Control

## Overview

**Coal Reburning offers the following advantages:**

- **Greater than 50% $NO_x$ reduction without supplemental premium fuel**
- **Flexibility to switch fuel for $SO_2$ control and/or fuel savings**

This project is part of the U.S. Department of Energy's Clean Coal Technology Demonstration Program (CCTDP) established to address energy and environmental concerns related to coal use. Cost-shared partnerships with industry were sought through five nationally competed solicitations to accelerate commercialization of the most advanced coal-based power generation and pollution control technologies. The CCTDP, valued at nearly $6 billion, has leveraged federal funding twofold through the resultant partnerships encompassing utilities, technology developers, state governments, and research organizations. This project was one of 16 selected in May 1988 from 55 proposals submitted in response to the Program's second solicitation.

The Babcock and Wilcox Company (B&W), with Wisconsin Power & Light (WP&L) as the host utility, demonstrated the use of coal as an effective reburning fuel for cyclone boiler $NO_x$ control. The demonstration was conducted at the 110-MWe cyclone-fired Nelson Dewey Generating Station, Unit No. 2, in Cassville, Wisconsin. Although cyclone boilers represent only 8.5 percent of pre-New Source Performance Standards (NSPS) coal-fired boiler capacity, they are responsible for over 12 percent of the $NO_x$ generated nationwide due to their inherent turbulent high-temperature combustion. The impetus for the project comes from the Clean Air Act Amendments of 1990 (CAAA), which requires $NO_x$ controls on cyclone boilers by 2000, and subsequent EPA action to further reduce $NO_x$ emissions in ozone nonattainment areas.

B&W's coal reburning technology (Coal Reburning) offers an economic and operationally sound response to the environmental impetus. This technology avoids cyclone combustor modification and associated performance complications, and provides an alternative to cyclone boiler $NO_x$ control options having relatively higher capital and/or operating costs.

The project's focus was to determine maximum $NO_x$ reduction capability without adversely impacting boiler performance, operation, or maintenance. The goal of achieving greater than 50 percent $NO_x$ reduction at full load was met using both bituminous and subbituminous coals. Coal Reburning had minimal impact on overall boiler performance and no electrostatic precipitator (ESP) upgrade was needed to maintain opacity levels. The extra heat input afforded by the added reburn burners offers the flexibility to switch to low-rank coals for fuel savings and control of $SO_2$ without penalty of boiler derating.

Coal Reburning has application to about 89 units representing nearly 27,600 MWe of capacity. Capital costs, in 1990 constant dollars, range from $43/kW (605-MWe) to $66/kW (110-MWe) and levelized costs range from 1.5 mills/kWh (605-MWe) to 2.4 mills/kWh (110-MWe). WP&L accepted the Coal Reburning system and continues to operate it as part of Unit No. 2.

# The Project

WP&L was faced with a particularly challenging $NO_x$ control undertaking with cyclone boilers representing 50 percent of its units and generating 75 percent of the $NO_x$ emissions. Existing options for cyclone boiler $NO_x$ control—selective catalytic and non-catalytic reduction and the emerging gas reburn option—were not viewed as attractive from a capital and operating cost standpoint. Also, WP&L wanted to retain the flexibility to fuel switch for $SO_2$ control. Attempts to reduce $NO_x$ emissions by staging cyclone burner combustion were halted because of concerns about corrosion and only moderate success in $NO_x$ reduction (15–30 percent). Pilot testing supported using pulverized coal as a reburning fuel. Expanding volumetric fuel delivery capacity with reburn burners mitigated concerns over derating associated with switching to low-sulfur, low-rank western coals.

Drawing upon a small boiler simulator (SBS) to evaluate reburn performance and three-dimensional physical and numerical modeling to optimize mixing, the Coal Reburning system was designed and a test program structured. In support of design efforts, baseline testing was used to refine and validate SBS and flow models. Parametric optimization testing, addressing nine variables, was performed on both Lamar and PRB coals. Long-term testing in an automated, load-following dispatch mode was performed only on Lamar coal. As part of a broader DOE/utility partnership, hazardous air pollutant (HAP) testing was conducted at full load on Lamar coal. Only short-term testing was performed on the PRB coal.

**Project Sponsor**
The Babcock & Wilcox Company

**Additional Team Members**
Wisconsin Power & Light Company—cofunder and host
Sargent and Lundy—engineer for coal handler
Electric Power Research Institute—cofunder
Illinois Department of Energy & Natural Resources—cofunder
Utility Companies (14 cyclone boiler operators)—cofunders

**Location**
Cassville, Grant County, WI
(Wisconsin Power & Light Company's Nelson Dewey Station Unit No. 2)

**Technology**
The Babcock & Wilcox Company's Coal Reburning system for $NO_x$ control (Coal Reburning)

**Plant Capacity**
110-MWe

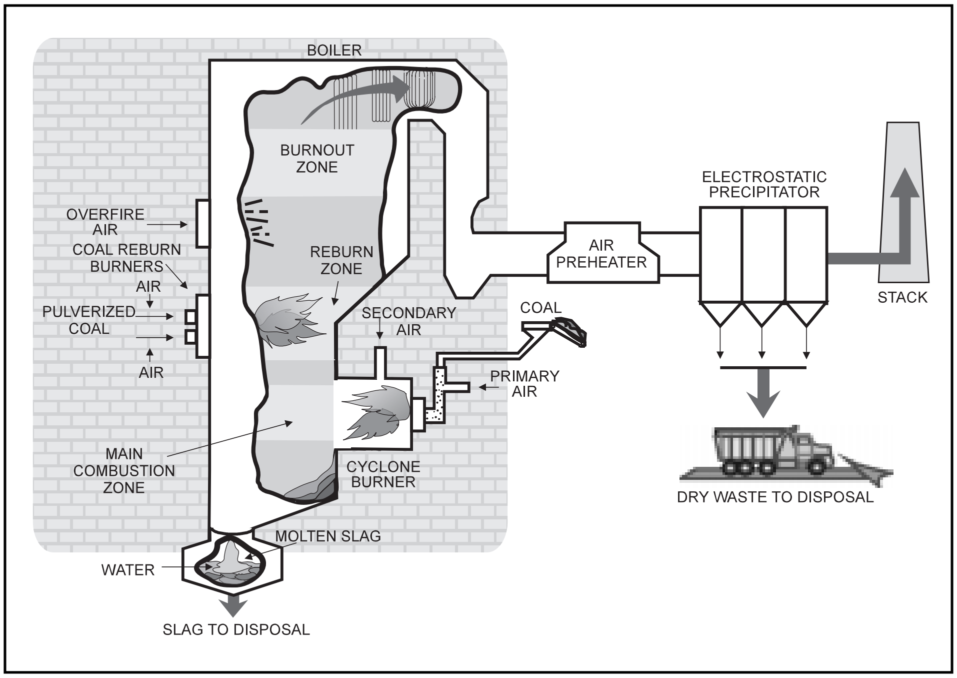
**Coal**
Illinois Basin bituminous (Lamar)—1.15% S/1.24% N
Powder River Basin (PRB) subbituminous—0.27% S/0.55% N

**Demonstration Duration**
November 1991–December 1992

**Project Funding**

| | | |
|---|---|---|
| Total Project Cost | $13,646,609 | 100% |
| DOE | 6,340,788 | 46% |
| Participant | 7,305,821 | 54% |

# The Technology

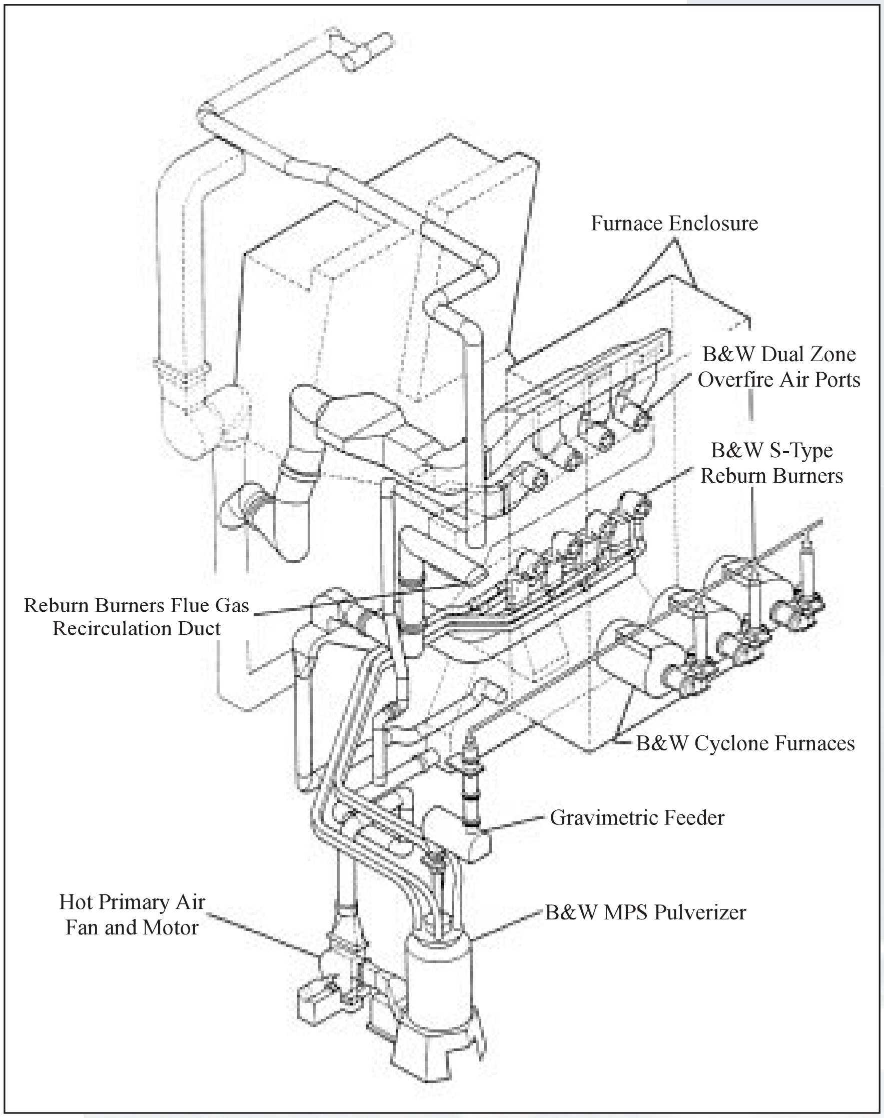



With Coal Reburning technology, pulverized coal is injected above the cyclones to create a fuel-rich zone which strips the oxygen from the $NO_x$ formed in combustion. Introduction of overfire air above the fuel-rich zone provides the oxygen needed to complete combustion. Coal combustion is split between the cyclones and a set of burners similar to those used in wall-fired boilers (S-Type burners). The cyclones receive 70–80 percent of the coal feed and the balance is diverted to the reburn burners after passing through a pulverizer designed for a nominal 90 percent through 200 mesh coal fineness. These additional burners, located above the cyclones, create a fuel-rich, oxygen-deficient zone by operating at stoichiometries well below 1.0 (the theoretical value at which there is just enough oxygen in relation to the fuel to complete combustion). Stoichiometries of less than 1.0 are maintained for as long as possible to allow mixing and chemical reduction of $NO_x$ (removal of oxygen) to occur. Overfire air is added higher in the boiler to provide enough air to complete the combustion process.

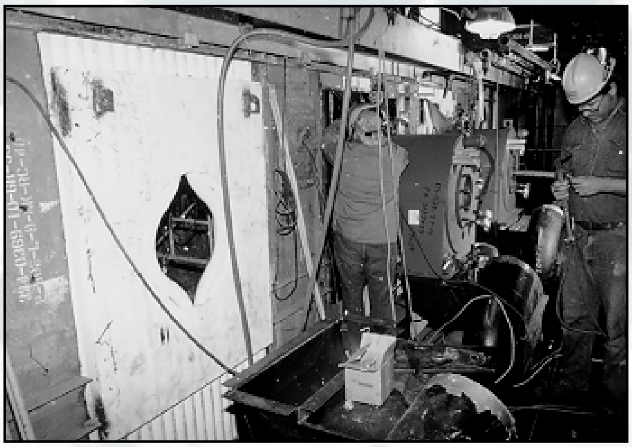
To create the desired 0.85–0.95 stoichiometry in the reburn zone above the cyclones, reburn burners operate at stoichiometries of less than 0.6 (cyclone stoichiometry is about 1.10). Even at these low stoichiometries, effective mixing with the cyclone flue gas is critical and the reason flow modeling is used to optimize burner placement. Flue gas recirculation plays a major role in maintaining the volumetric flow necessary for burner cooling, flame penetration, and flue gas mixing while keeping the stoichiometry low. Large quantities of unburned (unoxidized) hydrocarbon gases are produced in the reburn zone; these gases actively seek oxygen to complete the combustion process. Oxygen is stripped from the $NO_x$ molecules formed in the cyclones, reducing the $NO_x$ to elemental nitrogen. Overfire air ports above the reburn zone provide 15–20 percent excess air to complete combustion, but at significantly lower temperatures (2500 ºF) than found within the cyclone burners (3,300 ºF). This lower temperature limits $NO_x$ formation.

By providing approximately 30 percent greater heat input capacity with the addition of the reburn burners, an estimated 10–25 percent derating of the boiler is avoided when using low-rank coals. Coal Reburning expands the total volumetric fuel delivery capacity to the boiler, enabling a higher quantity of lower Btu fuel to be burned.

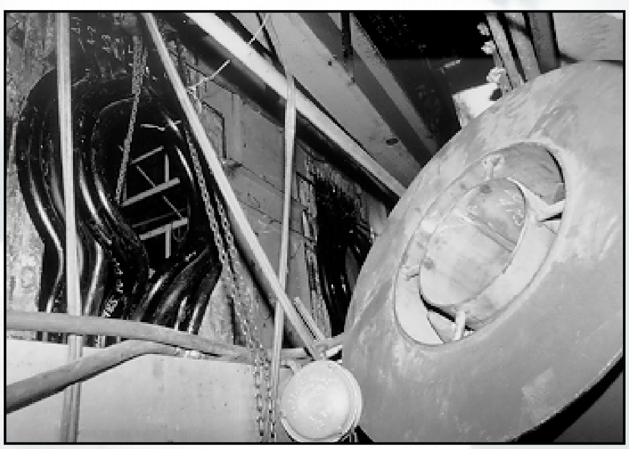
# The Coal Reburning System Installed at WP&L's Nelson Dewey Unit No. 2



# Demonstration Results



**Reburn burners being installed, showing the new boiler penetration**



**Overfire air unit being positioned for installation**

- Coal Reburning achieved greater than 50 percent $NO_x$ reduction at full load with Lamar and PRB coals.
- No major boiler performance problems were experienced with Coal Reburning operations.
- Reburn zone stoichiometry had the greatest effect on $NO_x$ control.
- Flue Gas recirculation was vital to maintaining reburn zone stoichiometry while providing necessary burner cooling, flame penetration, and mixing.
- Optimum Coal Reburning heat input was 29–30 percent at full load and 33–35 percent at half to moderate loads.
- Boiler turndown capability was 66 percent, exceeding the 50 percent goal.
- Opacity levels and ESP performance were not affected by Coal Reburning with either coal tested.
- ESP efficiency improved slightly during Lamar coal testing and did not change with PRB coal.
- Coal fineness levels above the nominal 90 percent through 200 mesh were maintained (typically 94–96 percent) mitigating unburned carbon loss (UBCL).
- UBCL was the only major contributor to boiler efficiency loss, which was 0.1, 0.25, and 1.5 percent at loads of 110-, 82-, and 60-MWe respectively.
- Superior flame stability was realized with PRB coal, contributing to better $NO_x$ control than with Lamar coal.
- Expanded volumetric fuel delivery capacity with reburn burners enabled switching to PRB low-rank coal without boiler derating.
- Capital costs for 110- and 605-MWe plants were $66 and $43/kW respectively. Levelized 10- and 30-year busbar power cost for a 110-MWe plant were 2.4 and 2.3 mills/kWh respectively. Levelized 10- and 30- year busbar power costs for a 605-MWe plant were 1.6 and 1.5 mills/kWh respectively. (Costs are in 1990 constant dollars.)

## Approach

*Table 1* lists the variables included in the test matrix along with the approximate ranges tested. *Table 2* lists the information collected throughout the parametric evaluations.

An initial tune-up test was performed by B&W to establish optimum Coal Reburning system control curves and validate modeling. This was followed by an independent third party test (by Acurex Corp.) to confirm findings. Initial performance testing ensued to provide a Coal Reburning baseline from which subsequent performance tests could be compared to assess degradation. After performance testing, a 4-month continuous evaluation under automated load following dispatch mode was conducted. Questions raised during the long-term testing were addressed in a final series of tests to fill in data gaps and provide a direct comparison with initial performance tests. HAP testing at full load was conducted at the conclusion of the final test series. All these test series were performed with Lamar coal. The last test series was run on PRB coal and duplicated the Lamar coal tests with the exception of HAP and long-term testing.

## Environmental Performance

The most critical factor affecting $NO_x$ emissions was reburn zone stoichiometry. This can be changed by varying the air flow, the percent of reburn heat input, the gas recirculation flow rate, or the cyclone stoichiometry. *Table 3* shows $NO_x$ reductions measured as a function of reburn zone stoichiometry over the load range at an economizer $O_2$ level of 3.0 percent with Lamar coal. Using PRB coal, 50 percent $NO_x$ reduction at full load could be achieved at a reburn zone stoichiometry of 0.91. At the lowest stoichiometry tested with PRB coal, 0.85, $NO_x$ emissions were reduced by 62.9 percent at full load.

**Table 1. Test Matrix Variables**

| Variable | Range |
|---|---|
| ***Major*** | |
| Boiler Load | 37–118 MWe |
| Reburn Heat Input | 25–40% |
| Reburn Zone Stoichiometry | 0.83–0.96 |
| Reburn Burner Stoichiometry | 0.35–0.70 |
| Reburn Gas Recirculation Rate | 0.0–5.0% total boiler flow |
| Reburn Coal Fineness | 80–98% thru 200 mesh |
| Economizer Outlet $O_2$ | 2.0–4.0% |
| ***Burner Adjustments*** | |
| Reburn Burner Spin Vane and Impeller/Swirler | |
| Overfire Air Spin Vane and sliding Disk | |

**Table 2. Information Collected Through Parametric Evaluations**

| | |
|---|---|
| Emission monitoring grid (economizer outlet) | $NO_x/O_2/CO/CO_2$ |
| CEMS at ESP Outlet | $NO_x/O_2/CO/CO_2/SO_2$ |
| On-Line Boiler Performance Monitor | All boiler functions |
| Physical Measurements | ESP inlet & outlet loadings<br>ESP inlet size distribution<br>Particulate resistivity<br>VOCs<br>Trace metals<br>UBCL |

**Table 3. $NO_x$ Reduction as a Function of Reburn Zone Stoichiometry (Lamar Coal)**

| Load (MWe) | Reburn Zone Stoichiometry | $NO_x$ (ppm @ 3% $O_2$) | % $NO_x$ Reduction |
|---|---|---|---|
| 110 | 0.95 | 365 | 40.0 |
| 110 | 0.89 | 305 | 50.0 |
| 110 | 0.81 | 233 | 61.8 |
| 82 | 0.93 | 310 | 41.6 |
| 82 | 0.87 | 266 | 50.0 |
| 82 | 0.85 | 250 | 52.9 |
| 60 | 1.00 | 375 | 25.9 |
| 60 | 0.90 | 290 | 42.7 |

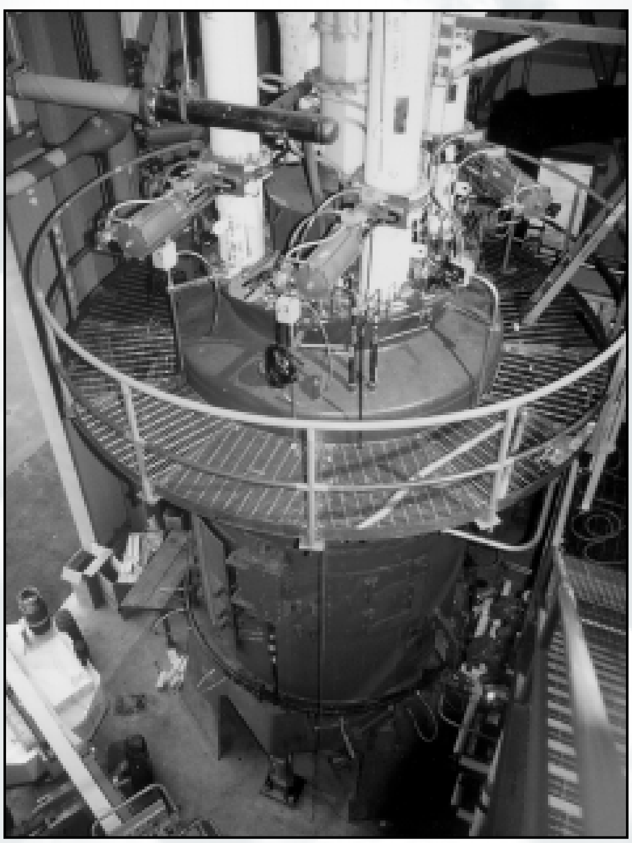
*Table 4* shows the average $NO_x$ emissions measured over the load range with the boiler in automatic control mode using control curves established in optimization tests (baseline provided for reference).

**TABLE 4. $NO_x$ EMISSIONS IN LB/$10^6$ BTU @ 3% $O_2$ AND (% REDUCTION)**

| Load (MWe) | Baseline Lamar | Reburn Lamar | Baseline PRB | Reburn PRB |
|---|---|---|---|---|
| 110 | 0.83 | 0.39 (52.4%) | 0.75 | 0.34(55.4%) |
| 82 | 0.72 | 0.36 (50.1%) | 0.64 | 0.31 (52.1%) |
| 60 | 0.69 | 0.44 (35.8%) | 0.62 | 0.30 (52.6%) |

Following the performance testing from which the Lamar coal data was developed, a long-term (4-month) Coal Reburning test ensued using Lamar coal in a load-following dispatch mode. Over the course of testing, the following $NO_x$ reductions were achieved:

| Load | | $NO_x$ Reduction |
|---|---|---|
| >100-MWe | (Avg 108-MWe) | 51.2% |
| >80-MWe | (Avg 98-MWe) | 49.0% |
| All Loads | (Avg 74-MWe) | 40.0% |



**New coal pulverizer dedicated to supplying reburning fuel**

Only short-term Coal Reburning tests were run on PRB coals, but projections indicate that the average $NO_x$ reduction in the long-term using PRB coal under load following would be 50 percent or greater, as compared to the 40 percent realized with Lamar coal.

Typically, for Lamar coal, carbon monoxide (CO) emissions under baseload conditions ranged from 50–60 ppm and increased slightly during Coal Reburning operations to 90–100 ppm. For PRB coal, CO emissions under baseline conditions were somewhat lower, ranging from 28–48 ppm, increasing slightly to 45–84 ppm during Coal Reburning. These increases in CO emissions were considered minimal and presented no significant impact on operation.

No change in opacity levels and only slight increases in ESP outlet particulate emissions were observed with Coal Reburning operating on either Lamar or PRB coal. This was attributed to no change in particulate resistivity, slightly larger flyash mean particle size, improved ESP efficiency with Lamar coal, and ESP inlet loadings well within design specifications.

HAP testing addressed the trace elements arsenic, beryllium, cadmium, chromium, lead, nickel, manganese, selenium, and mercury. Also measured were levels of volatile and semi-volatile organic compounds (benzene and toluene), aldehydes, and acid gases (hydrogen fluoride and hydrogen chloride). In general, HAP emissions were well within expected levels at baseline conditions and emission levels were comparable to baseline with Coal Reburning. Reburning had no major effect on trace metal partitioning. None of the 16 polynuclear aromatic semi-volatile organics targeted by the CAAA were present in detectable concentrations (at detection limit of 1.2 ppb). Of the 28 volatile organic compounds (VOCs) targeted by the CAAA, the only compounds at detectable levels were benzene and toluene. Toluene increased from 0.38 to 0.44 ppb and benzene decreased from 0.84 to 0.25 with Coal Reburning in service. Aldehydes were not detectable at the 2.8-ppb level for formaldehyde and 1.9-ppb level for acetaldehyde.

## Operational Performance

***Boiler Performance***—Unburned carbon loss (UBCL) was the only significant reburn-driven factor impacting boiler efficiency. UBCL is directly affected by the amount of flyash leaving the boiler. Flyash increased as did UBCL with Coal Reburning because the reburn coal does not pass through the high-temperature cyclone, where most coal ash is slagged. The percent of ash as flyash increases with Coal Reburning in service. For Lamar coals, the baseline and Coal Reburning values (baseline–Coal Reburning) were 23–37 percent at 110-MWe, 26–36 percent at 82-MWe, and 47–57 percent at 55-MWe. For PRB coals, there was a large scatter in the ash split data (bottom verses flyash) but splits are assumed to be the same as with Lamar coal. Because the unburned carbon in the PRB ash was very low, flyash split had little impact on UBCL. Boiler efficiency losses due to UBCL with Coal Reburning are shown for both Lamar and PRB coal in *Table 5*.

The percentage of unburned carbon was reduced from about 20 percent to 6–12 percent while varying reburn burner coal fineness from 81–82 percent to 94–96 percent through 200 mesh. No major changes in $NO_x$ emissions were observed as a result of these coal fineness changes.

At full load, furnace exit gas temperature (FEGT) decreased by approximately 100–150 ºF with Coal Reburning in service using Lamar coal (25 ºF attributable to flue gas recirculation). No change was measured at 82-MWe and an increase of 50–75 ºF was noted at 55-MWe. Using

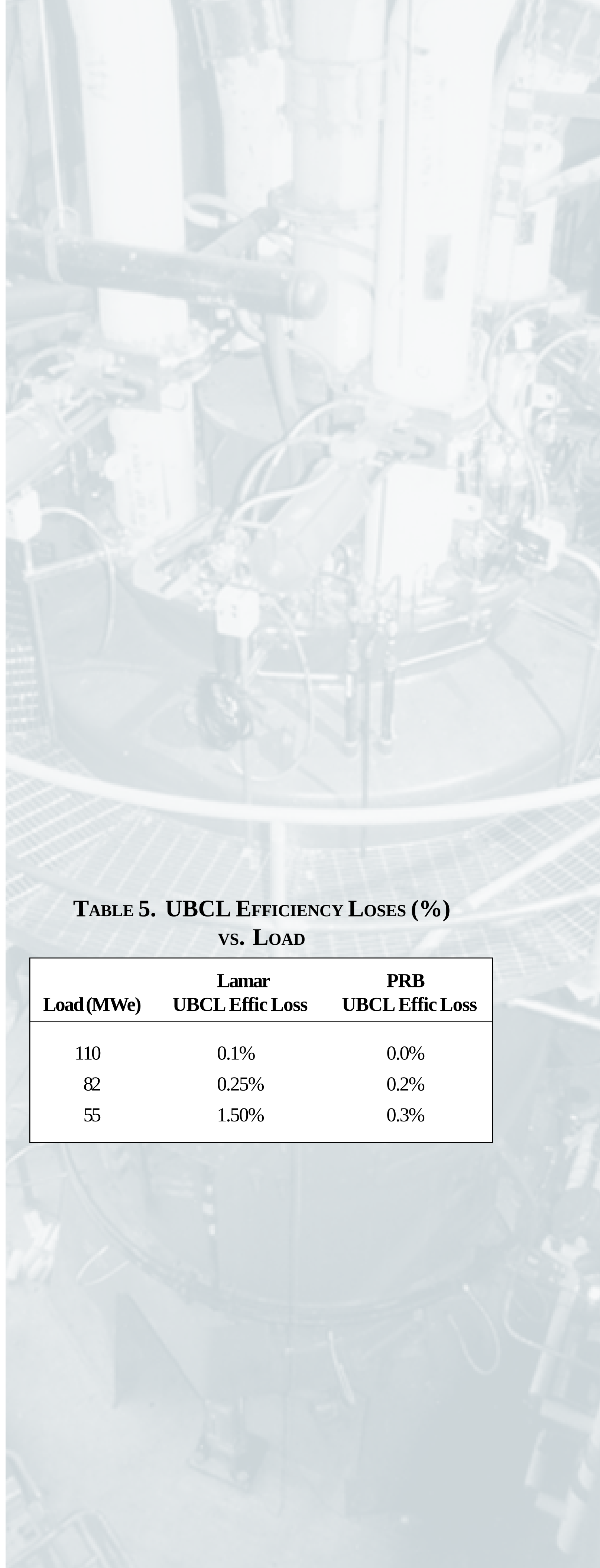


**Table 5. UBCL Efficiency Loses (%) vs. Load**

| Load (MWe) | Lamar UBCL Effic Loss | PRB UBCL Effic Loss |
|---|---|---|
| 110 | 0.1% | 0.0% |
| 82 | 0.25% | 0.2% |
| 55 | 1.50% | 0.3% |

PRB coal, FEGT decreased by 50 ºF at full load (25 ºF attributable to flue gas recirculation), remained the same at 82-MWe, and increased by 75 ºF at 55-MWe. This unexpected phenomenon was attributed to changes in absorption profiles in the furnace. It is possible that changes in the emissivities (heat transfer characteristics) in the substoichiometric region (reburn zone) resulted in more heat being absorbed in the furnace itself. If observed in all reburning applications, this could be beneficial when FEGT is at an upper limit or when slagging or fouling could be alleviated by reducing FEGT. Superheat and reheat final steam temperatures were not negatively affected with Coal Reburning in service.

Overall, slagging and fouling were more fuel dependent than reburn dependent. With a given fuel, reburn operation did not result in significant changes to slagging and fouling characteristics compared to baseline conditions.

No corrosion was apparent from ultrasonic thickness measurements, and no hydrogen sulfide was detected near the boiler tube walls to indicate corrosion potential. Ultrasonic thickness testing will continue over the next few years.

***Boiler Operation***—Flame stability considerations and the need for cyclones to maintain a minimum firing rate required the low-load limit to be adjusted from 30 to 37-MWe. This still afforded a 66 percent turndown, exceeding the project goal of 50 percent.

To improve reburn burner flame stability at low loads, two burner modifications were made. Fixed spin vanes at the outer air zone displaced adjustable vanes to minimize leakage around them. An adjustable conical impeller was replaced with a swirler to increase the swirl component of the primary air/coal flow.

Use of Coal Reburning affords the opportunity to switch to lower rank coals for fuel savings and to control $SO_2$ emissions without derating the boiler. The nominal 30 percent increase in heat input capacity by adding the reburn burners avoids an estimated 10–25 percent derate when using PRB coal.

Flue gas recirculation is essential for controling reburn zone stoichiometries; is critical to $NO_x$ reduction; and provides burner cooling, flame penetration, and mixing critical to boiler operation. Air could not be used because the quantities needed to cool the reburn burners and effect the desired flame penetration and mixing would preclude meeting the required stoichiometries.

Also, Coal Reburning technology is control intensive, requiring a distributed control system to integrate reburn parameters with those of the existing boiler system.

## Economic Performance

An economic analysis of total capital and levelized revenue requirements was conducted using the *Electric Power Research Institute Economic Premises* for retrofit of a 110- and 605-MWe plant. In addition, annualized costs per ton of $NO_x$ removed were developed for 110- and 605-MWe plants over both 10 and 30 years. The results of these analyses are shown in *Table 6*. These values assume typical retrofit conditions and do not take into account any fuel savings from using low-rank coal. The pulverizers and associated coal handling modifications are taken into account. Site-specific parameters that could significantly impact these retrofit costs include the state of the existing control system, availability of flue gas recirculation, space for coal pulverizers, space for reburn burners and overfire air ports within the boiler, scope of coal-handling modification, sootblowing capacity, ESP capacity, steam temperature control capacity, and boiler circulation considerations.

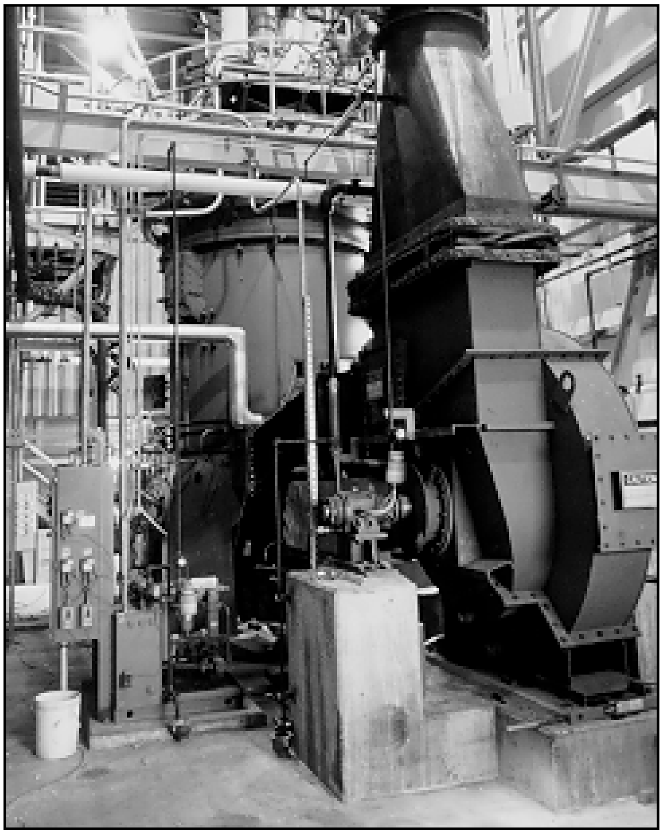
**Table 6. Coal Reburning Economics (1990 constant dollars)**

| | **Plant Size** | |
|---|---|---|
| **Costs** | **110-MWe** | **605-MWe** |
| Total Capital Cost ($/kW) | 66 | 43 |
| Levelized Busbar Power Cost (mills/kWh) | | |
| —10 Years | 2.4 | 1.6 |
| —30 Years | 2.3 | 1.5 |
| Annualized Cost ($/ton removed) | | |
| —10 Years | 1075 | 408 |
| —30 Years | 692 | 263 |

# Commercial Applications

***Market Potential***—Coal Reburning is potentially applicable to 89 existing units representing nearly 27,600- MWe of capacity. These units range from 100- to 1,150- MWe, with most in the 100–300 MWe range. In addition to $NO_x$ control, Coal Reburning offers the flexibility to switch to low-rank coals for fuel savings and control of $SO_2$ emissions without penalty of boiler derating.

***Site-Specific Considerations***—Because Coal Reburning technology requires accurate and responsive control of air and fuel throughout the boiler, a digital control system is needed. Flue gas recirculation to the reburn burners is required to maintain consistently high $NO_x$ reduction levels. The need for accurate individual cyclone air/fuel measurement and controllability is a concern for large, open windbox cyclone boilers. However, the $NO_x$ control and mixing models developed in parallel and in conjunction with the demonstration and B&W's small boiler simulation capability significantly reduce the risk of translating Coal Reburning to commercial applications.



**Hot primary air fan and motor for Coal Reburning system with new pulverizer in background**

**New coal feeder for Coal Reburning system**

## Contacts

Dot K. Johnson
(330) 829-7395
(330) 821-7801 (Fax)
McDermott Technology, Inc.
1562 Beeson Street
Alliance, OH 44601
dot.k.johnson@mcdermott.com

David J. Beecy, DOE/HQ, (301) 903-2787

John C. McDowell, FETC, (412) 892-6237

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U.S. DEPARTMENT OF ENERGY

ASSISTANT SECRETARY FOR FOSSIL ENERGY

WASHINGTON, DC 20585