A DB RILEY TECHNICAL PUBLICATION

LOW EMISSION BOILER SYSTEM (LEBS) LOW NO_X FIRING SYSTEM

by

T. Ake
R. Lisauskas
DB Riley, Inc.
Worcester, Massachusetts

Presented at the
International Joint Power Generation Conference
San Francisco, California
July 25-28, 1999

RST-157

DEUTSCHE BABCOCK
DB RILEY, INC.

Post Office Box 15040
Worcester, MA 01615-0040
http://www.dbriley.com

Low Emission Boiler System (LEBS)
Low NO_x Firing System

by
T. Ake
R. Lisauskas
DB Riley, Inc., Worcester, MA

ABSTRACT

A new low-NO_x coal firing system is being developed under the U. S. Department of Energy's low emission boiler system (LEBS) program. The goal of the LEBS program is to dramatically improve the environmental performance of pulverized coal-fired power plants by reducing emissions, increasing efficiency, and producing useful byproducts. DB Riley's LEBS supercritical boiler design utilizes a proven U-fired slagging furnace configuration, which converts nearly all of the ash contained in the coal to a vitrified byproduct. Because of the high temperature environment, conventional slagging furnaces typically produce higher NO_x than dry fired systems. The LEBS low-NO_x firing system integrates advanced low-NO_x coal burners with furnace air staging and coal reburning into the U-fired furnace design. Testing of the LEBS combustion system has been performed in DB Riley's 30 MWth U-fired combustion test facility. NOx emissions of less than 0.2 lbs / 10^6Btu (86 g / GJ) were achieved on several U.S. coals. Plans are being made to commercially demonstrate this advanced low-NO_x U-firing system in a new 80 MW_e LEBS proof of concept plant.

INTRODUCTION

The current practice to limit coal fired NO_x emissions is to retrofit low NO_x burners and add pollution controls to existing firing systems. In the U.S. Department of Energy's Low Emission Boiler System (LEBS) program[1], a new supercritical, high efficiency coal-fired boiler design is integrated with a highly advanced emissions control system to achieve much lower emissions levels. The LEBS goal is to achieve emission limits of 0.1 lbs/10^6Btu (43 g/GJ) of nitrogen oxides, 0.1 lbs/10^6Btu (43 g/GJ) of SO_2, and 0.01 lbs/10^6Btu (4.3 g/GJ) of particulate. Additional objectives include reduced waste generation, improved ash disposability, reduced toxic substance emission, and increased efficiency.

DB Riley, Inc. leads an industry team including Sargent & Lundy LLC, Thermo Power Corporation, the University of Utah, and Reaction Engineering International to develop a LEBS meeting all the emission and performance goals. We were one of three industrial teams originally contracted by the U.S. DOE. After five years of design, engineering development, and subscale testing, the DB Riley team was chosen to design and construct a proof-of-concept (POC) facility. The LEBS POC facility will be built at the Turris Mine site in Elkhart Illinois and will produce 80 MW of electric power firing a high sulfur Illinois coal. Since the purpose of the LEBS POC facility is to further develop the low NO_x combustion system, rather than the thermal cycle, the POC boiler will be a subcritical design.

Most of the development of the LEBS concept has been on the firing system. The potential of the firing system to achieve low NO_x emissions was demonstrated in a 10 megawatt electric equivalent combustion test facility located at DB Riley Research in Worcester, Massachusetts. The focus of this paper is the LEBS firing system and the combustion test facility results.

THE LEBS DESIGN CONCEPT

Figure 1 shows the LEBS design concept for a 400 MW_e commercial generating unit (CGU) developed by the DB Riley team. The design includes a supercritical Benson boiler fired with a low-NO_x, slag tap U-firing system, the copper oxide regenerable flue gas desulfurization system with de-NO_x capability[2], advanced low temperature heat recovery, and high efficiency particle removal. The LEBS CGU design is based on a supercritical steam cycle operating at 4500 psi (310 bar) and 1100°F (593 C) with double reheat to 1100°F (593 C). It incorporates the latest steam turbine technology and expanded regenerative feedwater heating (nine stages of feedwater heating with two topping desuperheaters). The net plant efficiency for a LEBS CGU firing high sulfur coal has been calculated at 42.2% based on higher heating value.

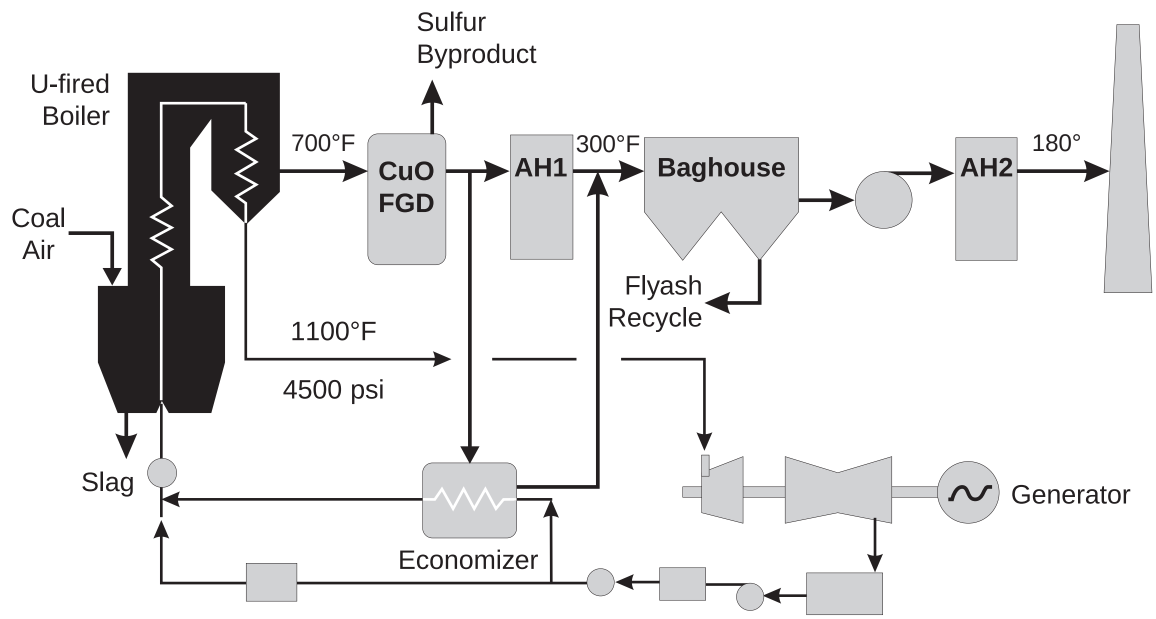

Figure 1 The Low Emission Boiler Commercial Generating Unit Concept

The CGU design, in addition to meeting the performance and emission goals, eliminates flyash and scrubber solids waste streams. It has significant benefits to the environment because:

- The ash in the coal is converted into non-leachable, inert slag by the firing system instead of flyash;
- The sulfur in the coal is converted into either elemental sulfur, sulfuric acid, or ammonia sulfate by the flue gas desulfurization system as a byproduct of coal combustion;

- Nitrogen oxides are controlled primarily by the firing system, requiring only moderate post combustion treatment;
- Less carbon dioxide is emitted per megawatt of electricity due to a high steam cycle efficiency.

THE U-FIRING SYSTEM

The CGU firing system is based on the well established U-fired slagging boiler design[3]. As shown in Figure 2, the fuel is fired down into a refractory chamber. Slag forms on the chamber walls and bottom, and on the slag screen at the chamber exit. The slag is continuously tapped from the combustion chamber, quenched, and dewatered. The hot gases then flow up and out through the slag screen, and final air is added to complete combustion.

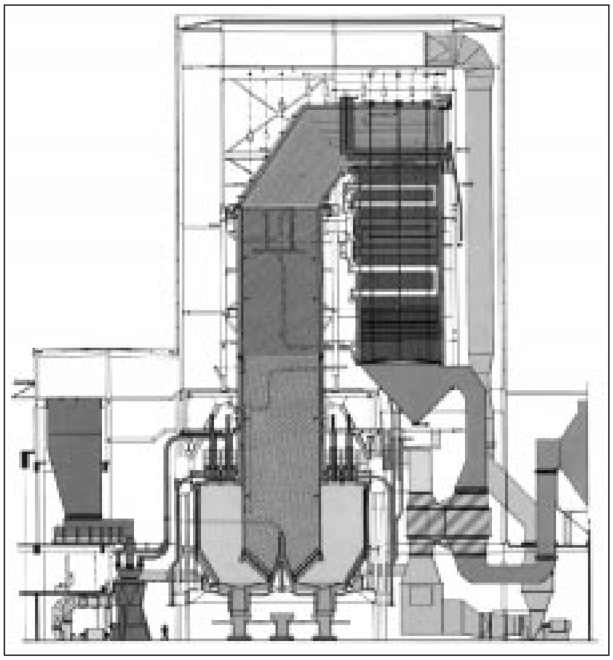

Figure 2 Commercial 320 MW, U-fired Benson Boiler Using Two Chamber Design

Over fifty utility scale U-fired slagging boilers have operated in this century. The U-firing system can fire a wide range of coals under varying utility operating conditions. When not recycling the flyash, the firing system converts over one half of the coal ash into slag. As it is quenched, the slag converts into a low volume, inert, vitreous granulate. Almost all of the coal ash can be converted to slag by recycling the flyash back to the boiler, as is the standard practice in many operating units.

High temperatures are needed to maintain slag flow in U-fired boilers resulting in high NO_X emissions. In early U-fired slagging boilers, highly turbulent burners produced NO_X emissions as high as 1.6 lbs/10^6Btu (688 g/GJ). Applying air staging and burner design improvements reduced the emission level to 0.8 lbs/10^6Btu (340 g/GJ) for currently operating units. A major challenge for the DB Riley team was to satisfy the LEBS emission goals while operating at high temperature slagging conditions to satisfy the reduced waste generation goal. A NO_X emission target of 0.2 lbs/10^6Btu (86 g/GJ) was established for the firing system alone to minimize the amount of NO_X reduction for the post combustion emissions control system.

Our approach for achieving the combustion system NO_x emission target was to apply the Controlled Combustion Venturi (CCV®) Dual Air Zone coal burner in combination with advanced air staging and coal reburning techniques in the U-fired slagging system. DB Riley originally developed the CCV® Dual Air Zone burner, shown in Figure 3, for low-NO_x dry-fired applications[4].

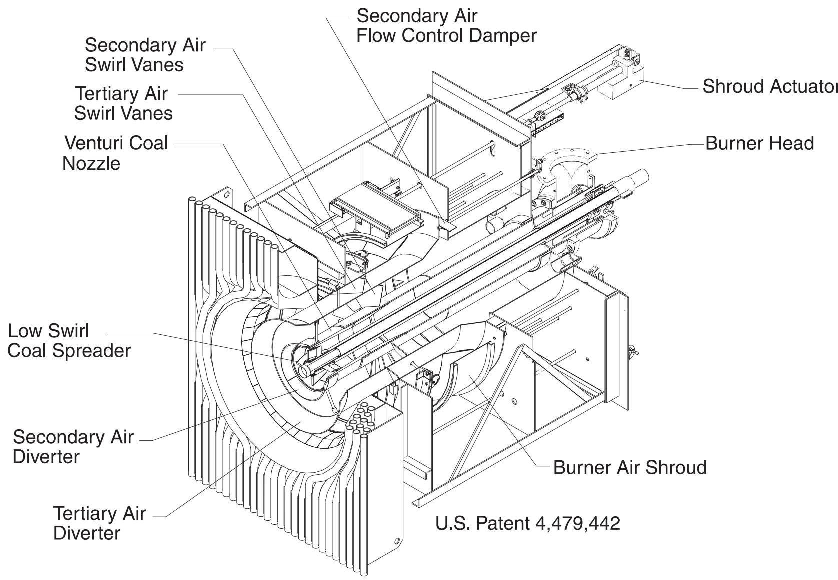

*Figure 3 DB Riley Controlled Combustion Venturi (CCV®)
Dual Air Zone Burner*

DB Riley built a 100 million Btu/hr U-fired combustion test facility to test our low NO_x firing approach in a U-fired slagging system for the U.S. DOE LEBS program. An existing CCV® dual air zone test burner was modified for down-firing and installed in the U-fired test facility. The University of Utah performed parametric tests of the effects of air staging and coal reburning in a 15 million Btu/hr (4 MW) thermal input L1500 test furnace to support the test facility design[5]. Reaction Engineering International carried out computational fluid dynamic simulations to examine coal reburning jet design parameters[6].

THE U-FIRED TEST FACILITY

The U-fired Test Facility (UFTF) is located at DB Riley Research in Worcester, Massachusetts. Figure 4 provides an aerial view of the DB Riley Research combustion test facilities.

Figure 5 shows the U-fired test facility constructed in 1997 to test the LEBS firing system at 100 million Btu/hr thermal input. It matches residence time, or volumetric heat release, of a commercially operating U-fired slagging boiler. It includes a single refractory-lined chamber fired by one burner mounted on the roof, a slag tap system, slag screen, and an upflow section corresponding to the lower part of the radiant furnace in the commercial boiler.

Figure 6 shows the various air staging and coal reburning locations in the test facility. These locations provided zones of various combustion stoichiometric ratios (SR) in the furnace. Various reburn residence times were tested depending upon the reburn injection and final air locations.

Figure 4 The DB Riley Research Combustion Test Facilities in Worcester, Massachusetts.

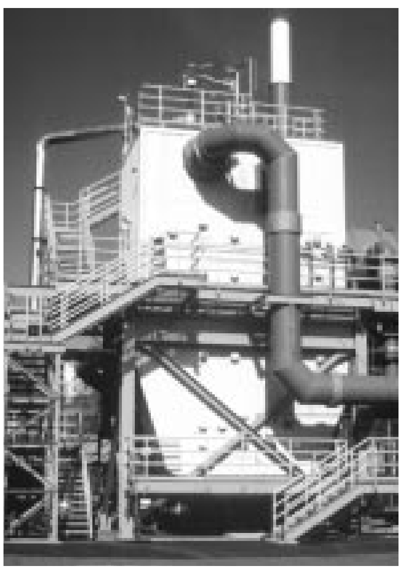

Figure 5 The 100 million Btu/hr ($30\ MW_t$) U-fired Test Facility

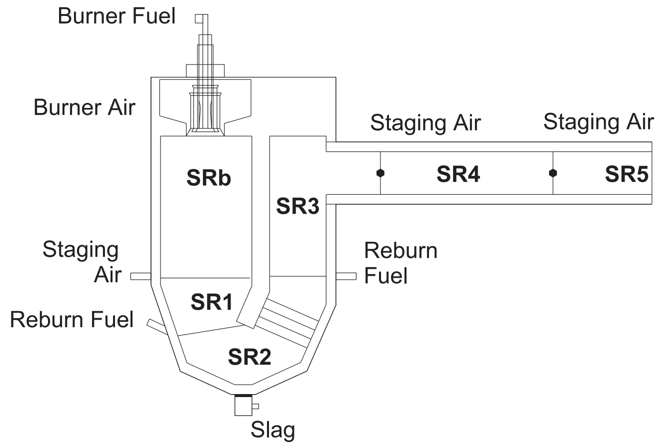

Figure 6 U-fired Test Facility Air Staging and Coal Reburning

TEST PROGRAM OVERVIEW

Most of the tests conducted to date in the U-fired test facility were completed with the Illinois No. 5 coal from the Turris Mine site. Illinois No. 5 is a high sulfur, high volatile Bituminous C coal. Selected conditions were also tested with a medium sulfur, high volatile Bituminous A coal.

Several burner coal nozzle variations were tested to provide the lowest NO_X emissions while maintaining slag production and carbon burnout. The test burner was also modified to simulate burners installed in a commercially operating U-fired slagging boiler. This burner modification is identified in this paper as the baseline burner, because it was intended to provide a comparison between the test facility and an existing U-fired boiler.

NO_X EMISSION RESULTS

Figure 7 shows the NO_X results for the baseline highly turbulent burner compared to the CCV® Dual Air Zone Burner in the U-fired test facility when staging the burner with air. NO_X emissions are plotted against burner stoichiometry. The total excess air was maintained at 15%. The CCV® Dual Air Zone Burner performance was significantly different than the baseline burner. The CCV® Dual Air Zone Burner NO_X emissions were remarkably low for slag tap operation. We believe the low NO_X results achieved by the CCV® Dual Air Zone Burner is primarily due to a fuel rich and well-attached coal flame. The baseline burner produced a wide, detached flame with rapid mixing of the burner air and coal. This difference in flame shape could be seen in the flame videos, as shown in Figure 8, and the slag deposition patterns in the furnace.

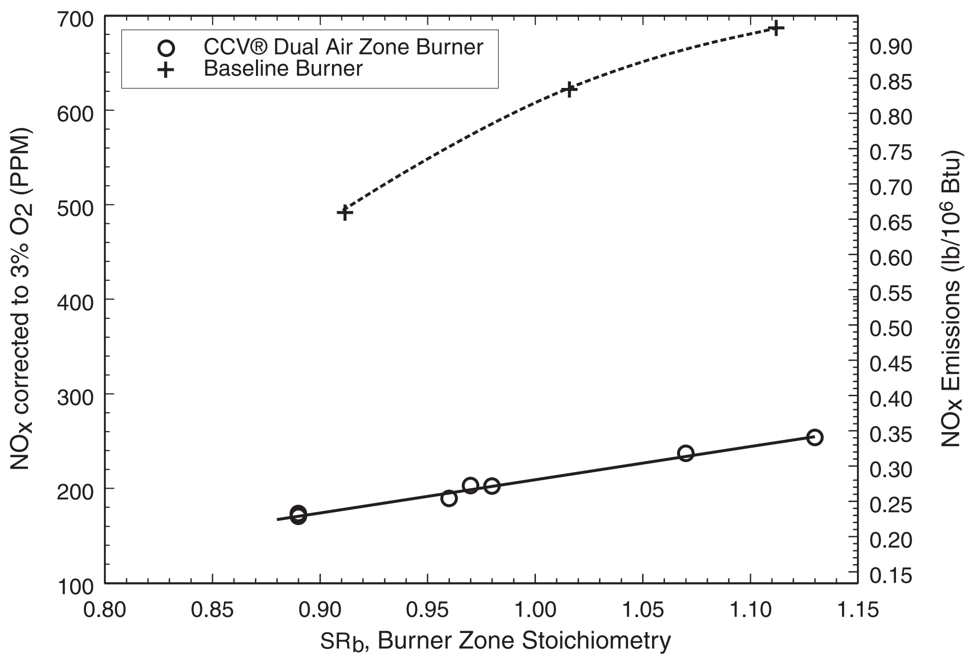

Figure 7 NO_X versus Burner Stoichiometry, Baseline Burner and CCVC® Dual Air Zone Low NO_X Burner

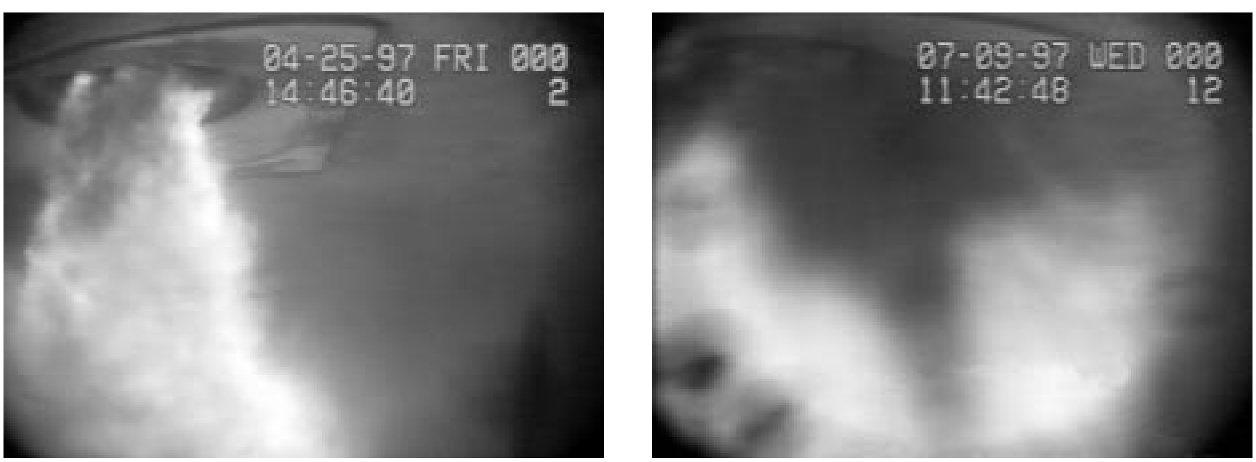

Figure 8 CCV® Dual Air Zone (left) and Baseline Burner (right) Flames

The NO_X levels in the U-fired test facility were further reduced to below 0.2 lbs/10^6 Btu (86 g/GJ) by operating the low-NO_X burner in combination with extended air staging or by introducing coal reburning. As shown in Figure 9, the residence time in the fuel rich zone was extended by introducing air staging farther downstream achieving the firing system target. The target was also achieved by coal reburning at about 10% of the total firing rate to lower the stoichiometry in the upflow section to 0.9.

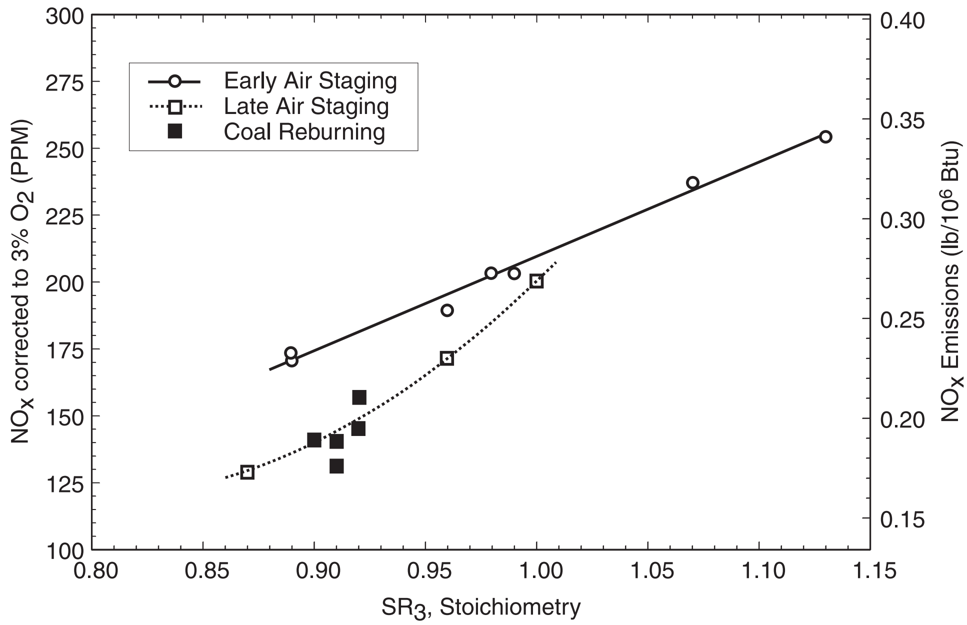

Figure 9 NO_X versus Stoichiometry, Comparison of Air Staging to Coal Reburning

Although coal reburning and extended air staging operate at similar stoichiometries, coal reburning provides a smaller fuel rich zone in the furnace. A shorter reducing zone minimizes the need for corrosion resistant materials in the furnace. Coal reburning also separates the substoichiometric zone from the slagging chamber of the furnace. Under U-fired reburn conditions, the firing chamber slag tap can be operated at a stoichiometry of 1.

The effect of reburning zone residence time on NO_X emissions is illustrated in Figure 10. As shown in the illustration, coal reburning required sufficient residence time to be effective. In the test facility, the maximum residence time for injecting reburn fuel after the slag screen was one second. A higher residence time was tested by injecting the reburn fuel before the slag screen. While NO_X was reduced further at the higher reburn residence time, injecting the reburn before the slag screen caused poor slag flow. The best conditions for the low NO_X emissions and good slag flow was to set the slagging chamber at a stoichiometry of 1 and introduce the reburn fuel after the slag screen with at least one second residence time.

SLAG AND FLYASH RESULTS

The carbon in the slag averaged less than 0.5% over a large range of firing conditions never exceeding 2%. Since over half of the coal ash was converted into slag, the overall heat loss due to unburned carbon was small, averaging less than 1%. Coal reburning generally

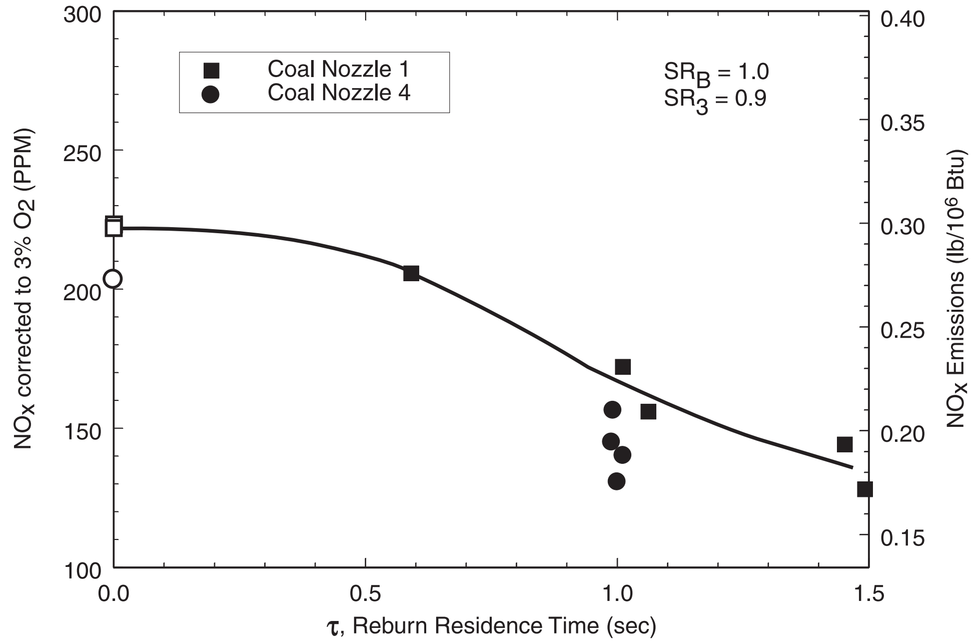

Figure 10 NO_X versus Reburn Residence Time

gave lower values of carbon loss than air staging for equivalent NO_X levels. Nearly all the carbon loss was associated with carbon in the flyash. In a commercial system, the carbon loss would be reduced even further by recycling the flyash into the firing chamber.

A very important characterization was the Toxicity Characteristic Leaching Procedure (TCLP) results shown in Table 1. The leachable metals in the slag were well below 1990 RCRA toxicity limits. Slag produced in the LEBS U-fired system is suitable for roadfill or other uses.

*Table 1 Average TCLP Analysis**

	Firing Coal	**Detection Limit**	**1990 RCRA Toxicity Limit**
Total Arsenic as As (mg/L)	BDL	0.20	5
Total Barium as Ba (mg/L)	1.07	0.05	100
Total Cadmium as Cd (mg/L)	BDL	0.05	1
Total Chromium as Cr (mg/L)	BDL	0.05	5
Total Lead as Pb (mg/L)	0.29	0.10	5
Total Mercury as Hg (mg/L)	BDL	0.001	0.2
Total Selenium as Se (mg/L)	BDL	0.20	1
Total Silver as Ag (mg/L)	BDL	0.05	5

* UFTF slag samples: Average of three firing Illinois No. 5 Coal

SCALE-UP OF TEST FACILITY RESULTS

Very low levels of NO_X were achieved in the U-fired test facility compared to current operating slagging boilers. To understand the influence of furnace scale and surface area heat release, we compared the baseline burner test facility results to field data from a commercially operating U-fired slagging furnace[3]. Figure 11 compares the NO_X emissions of the test facility and the field boiler as a function of surface area heat release. This figure shows that the U-fired test facility firing a single baseline burner simulated the NO_X emissions of the field boiler with multiple burners operating at 50% load. When staging the baseline burner in the test facility, a similar NO_X reduction was observed as found when the field boiler controlled NO_X with flue gas recirculation. These data suggest that the NO_X emissions observed in the test facility would increase about 20% for a factor of two increase in the surface area heat release.

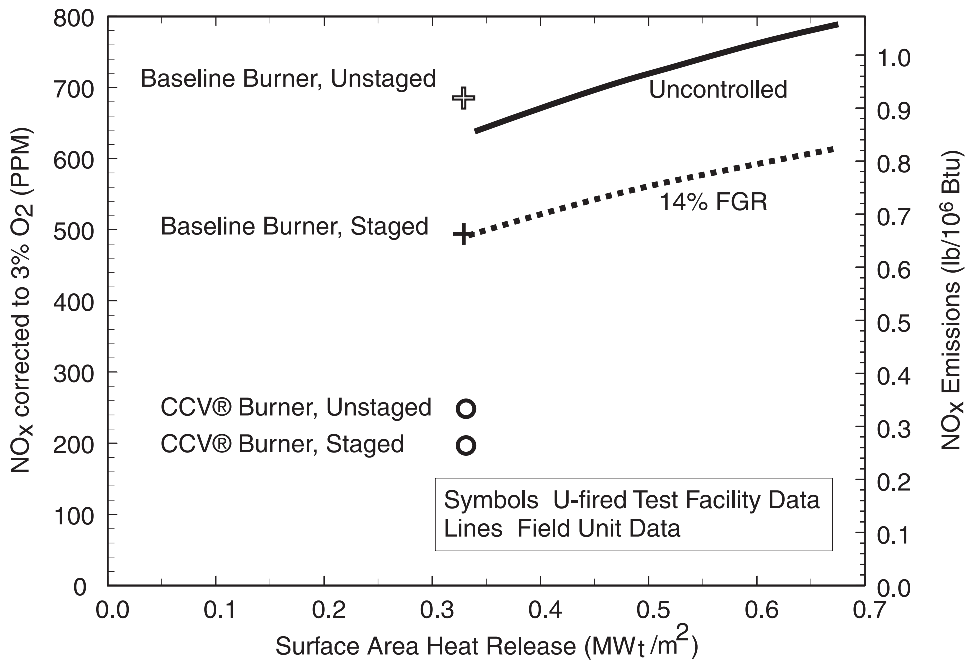

Figure 11 NO_X versus Heat Release, Scale-up of U-fired Test Facility Results

THE PROOF OF CONCEPT FACILITY

Information gained from the U-fired test facility is being used in the design of the LEBS proof of concept facility that will demonstrate the low-NO_X firing system at a commercial scale. Figure 12 shows the POC U-fired boiler that will be built adjacent to the Turris Coal Company mine at Elkhart IL. It will fire Illinois No. 5 high sulfur coal supplied by the mine. The POC will generate 80 MW of electric power with a conventional steam cycle. Four 200 million Btu/hr CCV® Dual Air Zone burners will be used to fire the coal. Coal reburning and overfire air will take place in the upflow section of the furnace after the slag screen.

The POC facility will demonstrate a full-scale, U-fired low NO_X slag tap fired boiler designed for continuous operation and capable of meeting the service life and availability demands for commercial operation. It will provide a commercial scale reference plant for this technology.

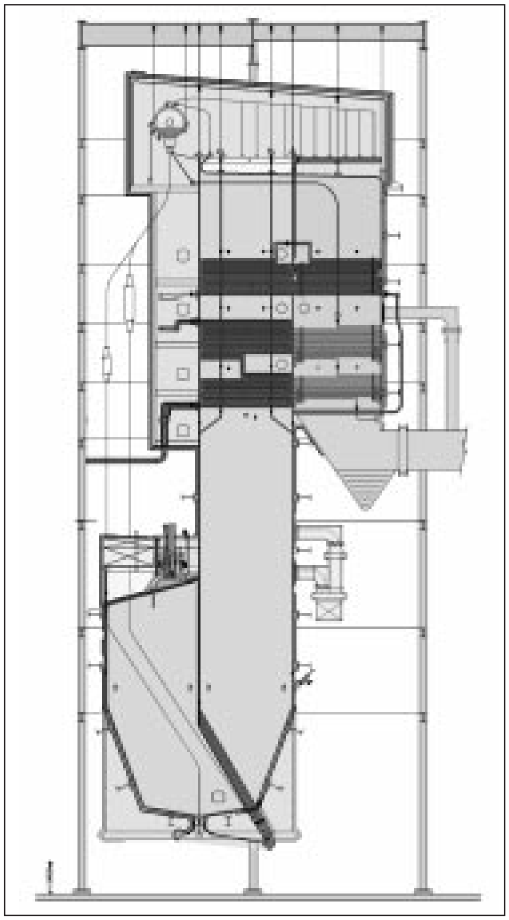

Figure 12 U-fired Proof of Concept Boiler

CONCLUSIONS

DB Riley demonstrated the LEBS NO_X emission combustion system goal of 0.2 lbs/10^6 Btu (86 g/GJ) in a U-fired test furnace using the CCV® Dual Air Zone Burner with either advanced air staging or coal reburning. When firing the burner without these staging techniques, the NO_X levels were very low for slag tap conditions. These results were achieved while converting the coal ash into an inert, low volume, non-leachable solid. Coal reburning provided independent control of the slag tap stoichiometry and reducing zone stoichiometry. Independent control was needed to maintain conditions for good slag production as found in commercially operating slag tap firing systems.

Since over half of the coal ash was converted to low carbon slag, the overall carbon loss was small (1% on a heat loss basis), even under very low NO_X firing conditions. In a commercial system, the carbon loss would be reduced even further by reinjecting the flyash back into the firing chamber.

The U-fired test facility provided a valid simulation of the effectiveness of NO_X control measures applied to a high temperature U-fired slagging boiler. The U-fired test facility data matched absolute values from a field unit operating at half load. The data from the field unit indicated the NO_X values would increase at most 20% for a factor of two increase in surface area heat release. The information gained from the U-fired Test Facility is being used to design a commercially operating proof of concept facility in Elkhart, Illinois.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy Federal Energy Technology Center (FETC). The authors gratefully acknowledge the contributions of the project team, as well as the support of U.S. DOE Contracting Officer Representative Dr. Soung S. Kim.

REFERENCES

1. Beittel, R.; Darguzas, J. N.; Ruth, L. A. LEBS Plant Leaves the Drawing Board, Power Engineering, April 1998.
2. Breault, R. W.; Litka, A. F. "Update on Performance Tests from the COBRA Process, A Combined SO_2 and NO_x Removal System" Presented at the 24th International Technical Conference on Coal Utilization & Fuel Systems, Clearwater, FL, March 1999
3. Schuster, H., "Advanced Coal Firing Systems for Low Emission Steam Generators" Presented at the 11th Annual Pittsburgh Coal Conference, Pittsburgh, PA, September 1994.
4. Penterson, C.; Ake, T., "Latest Developments and Application of DB Riley's Low NO_x CCV® Burner Technology" Presented at the 23rd Coal Utilization and Fuel Systems Conference, Clearwater FL, March 1998
5. Bockelie, M. J.; Brouwer, J.; Eddings, E. G.; Harding, N. S.; Heap, M. P. Engineering Development of Advanced Coal-Fired Low Emission Boiler Systems (LEBS). Phase II Report, Volume II-B – Reburning Applied to U-fired System: Computational Model Development and Subscale Tests. Prepared for the Federal Energy Technology Center, August 15, 1997.
6. Brouwer, J.; Bockelie, M. J.; Davis, K.; Heap, M. P.; Pershing, D.; Beittel, R. Analysis of Low Emission Firing Systems for a Slag Tap LEBS International Joint Power Generation Conference, Houston, TX October, 1996.