DEVELOPMENT OF AN ENHANCED COMBUSTION LOW NOx PULVERIZED COAL BURNER

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ABSTRACT

For more than two decades, ALSTOM Power Inc. (ALSTOM) has developed a range of low cost, in-furnace technologies for NOx emissions control for the domestic U.S. pulverized coal fired boiler market. This includes the internally developed TFS 2000™ firing system, and various enhancements to it developed in concert with the U.S. Department of Energy (DOE). As of the date of this paper, more than 231 tangentially-fired units representing in excess of 71,500 MWe of domestic pulverized coal fired capacity have been retrofit with ALSTOM low NOx technology. Best of class emissions range from 0.18 lb/MMBtu for bituminous coals to less than 0.10 lb/MMBtu for subbituminous coals, with typical levels at 0.24 lb/MMBtu and 0.13 lb/MMBtu, respectively.

Despite these gains, NOx emissions limits in the U.S. continue to ratchet down for new and existing (retrofit) boiler equipment. Low cost solutions to meet such regulations, and in particular those that can avoid the need for a costly selective catalytic reduction system (SCR), provide a strong incentive to continue to improve low NOx firing system technology. In light of these needs, ALSTOM, in cooperation with the U.S. Department of Energy (DOE), is working on a project to develop an enhanced combustion, low NOx pulverized coal burner which, when integrated with state-of-the-art, globally air staged low NOx firing systems, will provide a means to achieve less than 0.15 lb/MMBtu NOx at less than ¾ the cost of an SCR with little or no impact on balance of plant issues when firing a high volatile bituminous coal.

The burner development program includes CFD modeling and large pilot-scale combustion testing in ALSTOM's Industrial Scale Burner Facility (ISBF) at its U.S. Power Plant Laboratories facility in Windsor, Connecticut. A goal of this work is to optimize the near-field combustion environment to maximize NOx reduction while minimizing the impact on unburned carbon in the fly ash, CO emissions, slagging and fouling, and flame stability / turn-down under globally reducing conditions. The completion of this work will provide sufficient data to design, construct, and demonstrate a commercial version of an enhanced combustion low NOx pulverized coal burner. This paper will describe ALSTOM's low NOx firing system technology and the current low NOx burner development project.

INTRODUCTION

NOx emissions from pulverized coal-fired power plants in the United States have dropped significantly since the Clean Air Act Amendments were passed in 1990. NOx emissions data in 2003 showed a 29% reduction over 1990 levels, even though coal usage increased by almost 30% over the same period (1). Additional reductions in NOx emissions from power plants have been proposed in the EPA's Clean Air Interstate Rule, the Clear Skies Act, other multi-pollutant bills, and state-specific NOx reduction regulations. To address both current and future regulations, the U.S. Department of Energy Office of Fossil Energy's National Energy Technology Laboratory (DOE/NETL) is funding programs for the development of advanced NOx control technologies for the existing fleet of coal-fired utility boilers.

As part of this effort ALSTOM, in cooperation with the DOE, is working on a project to develop an enhanced combustion, low NOx pulverized coal burner which, when integrated with state-of-the-art, globally air staged low NOx firing systems, will provide a means to achieve less than 0.15 lb/MMBtu NOx at less than ¾ the cost of an SCR when firing a high volatile bituminous coal. This NOx reduction should be achieved without significantly impacting CO, unburned carbon in the fly ash, or any other balance of plant issues. This project builds upon a previous DOE co-funded project where ALSTOM developed an Ultra Low NOx Integrated System for NOx emission control from pulverized coal-fired utility boilers (2). That research effort utilized a scaled version of ALSTOM's LNCFS™-P2 low NOx coal nozzle tip and focused on global air staging, windbox air distribution, and fuel air balancing. In contrast, the current project focuses on the near field aerodynamics and aims to develop a new low NOx coal nozzle tip.

ALSTOM LOW NOx FIRING SYSTEM TECHNOLOGY

ALSTOM has developed a broad line of low NOx firing system products to address varying customer needs. With the wide variety of tangentially-fired boiler designs of varying vintage, the broad range of coals being fired, and the local variation in NOx emission regulations, one low NOx firing system technology is not necessarily suitable for all applications. ALSTOM has developed and provides a retrofittable family of low NOx firing system products, which includes Level I, II, and III LNCFS™, LNCFS™-P2, and TFS2000™R technology. These firing system options are shown in Figure 1 with boxes representing the various windbox and overfire air compartments typical of each retrofit option.

Each of these low NOx firing system products utilizes the same basic design features of air-staged combustion, early fuel devolatilization, and local combustion air staging. In general, in applying these low NOx technologies, unburned carbon in the fly ash increases inversely with the extent of NOx reduction, however the ultimate NOx and unburned carbon levels are a function of the furnace design and the coal fired. More highly loaded (hotter) furnaces tend to generate higher NOx emissions and may cause additional waterwall deposits. The high temperatures cause increased thermal NOx levels and the smaller furnace volumes may limit the potential residence time under reducing conditions, which is necessary for NOx reduction under globally staged conditions. The lack of residence time in the furnace may also cause an increase in unburned carbon in the fly ash. Lower rank coals typically have lower NOx emissions and unburned carbon levels under low NOx conditions than high rank coals. The differences among the low NOx firing system options occur in the tradeoffs between the extent of NOx emissions reduction and the complexity and cost of material modification and retrofit requirements.

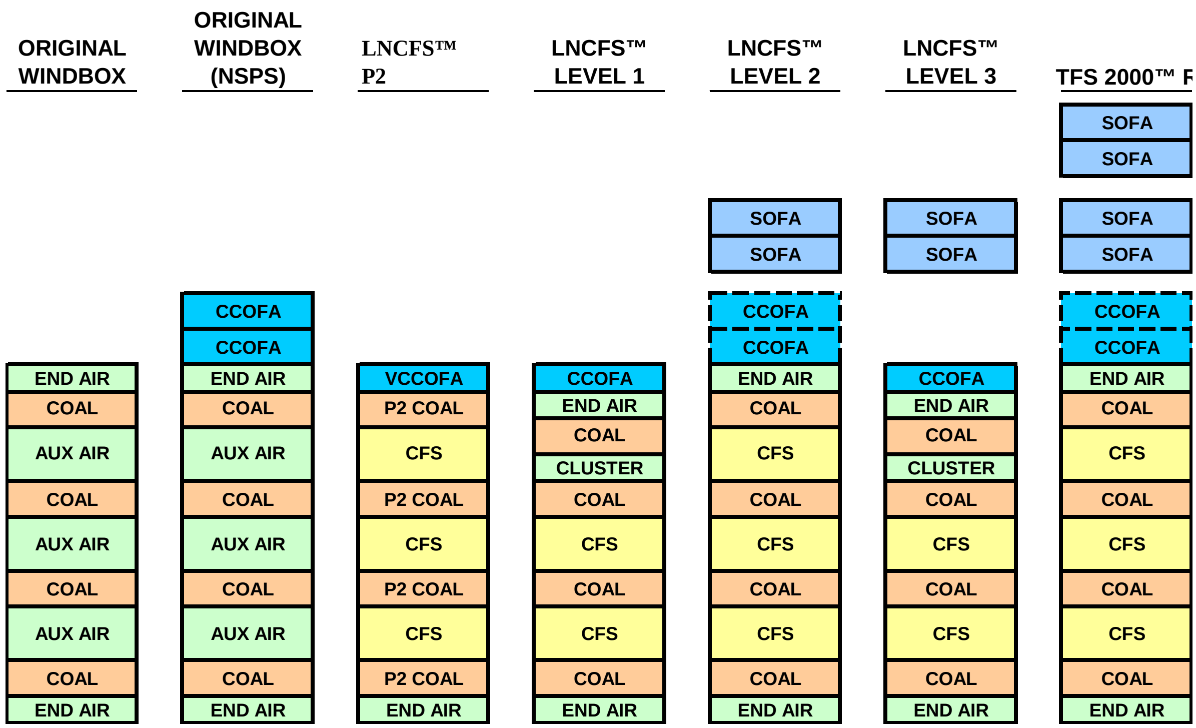

Figure 1. ALSTOM Power Low NOx Firing System Options.

Figure 2 shows the relative costs and reduction efficiencies of ALSTOM Power's low NOx solutions, all based on a typical single furnace 200 MW boiler (3). Baseline uncontrolled NOx emissions from tangentially fired boilers typically range from 0.6 – 0.9 lb/MMBtu, depending upon the unit design and the coal fired. The percent decrease in NOx emissions from baseline is also unit and fuel specific.

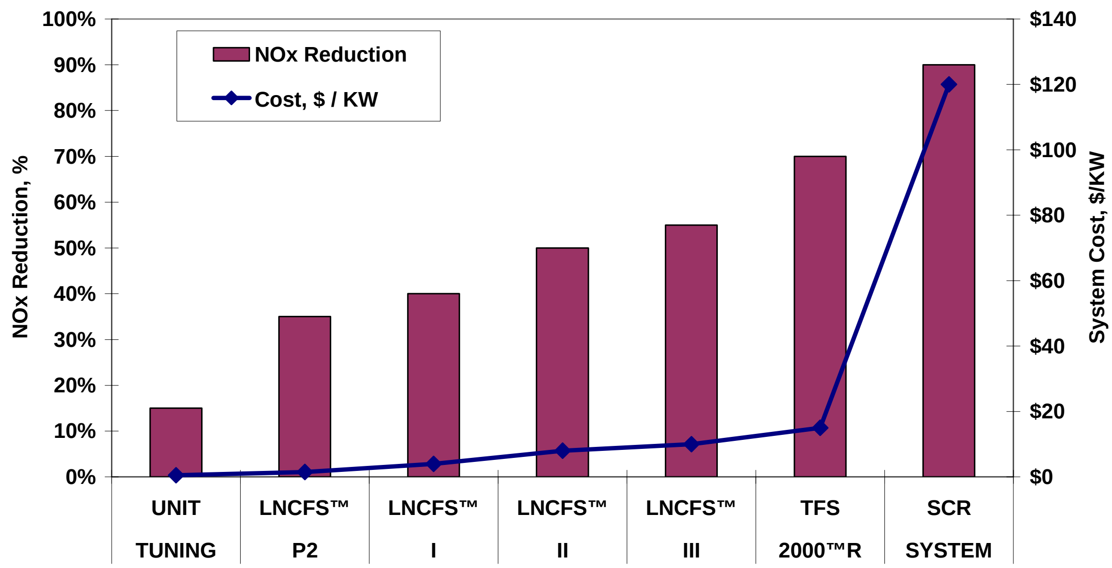

Figure 2. NOx Reduction System Cost versus Performance (3).

The extensive ALSTOM low NOx retrofit experience for tangentially-fired boilers is show in Table 1. Over 230 pulverized coal-fired tangential boilers have incorporated these systems, representing over 71,500 MWe of generating capacity. These unit retrofits range in size from 44 MWe industrial to a 900 MWe supercritical, divided unit. The retrofit experience covers an extensive range of coal types from lignites to bituminous. It should be noted that the technology developed in the Ultra Low NOx Integrated System program with the DOE in 2001 has been integrated into the entire ALSTOM Power low NOx firing system product line.

Tangentially fired units burning low rank coals consistently produce the lowest NOx emissions levels in the country on a yearly basis. Many units now achieve less than 0.15 lb NOx/MMBtu. Table 2 shows the lowest NOx generating plants (pulverized coal-fired units without an SCR) from the first quarter of 2005 according to data taken from the EPA's website.

Table 1. ALSTOM Power (U.S.) Low NOx Retrofit Experience, T-Fired, P.C. Units.

Firing System	Units	MWe
LNCFS™ – P2	35	4,454
LNCFS™ – Level I	43	11,429
LNCFS™ – Level II	56	15,653
LNCFS™ – Level III	62	27,284
TFS2000™R	24	10,085
Other T-Fired	11	2,844
TOTALS	**231**	**71,749**

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Table 2. EPA Lowest NOx Emitters (pulverized coal-fired, no SCR) 1st Quarter 2005

	Unit No.	NOx, lb/mmBtu	Firing System Supplier	Fuel
Baldwin Energy Complex	3	0.096	ALSTOM	PRB
Sam Seymour	1	0.101	ALSTOM	PRB
Rush Island	1	0.102	ALSTOM	PRB
Sam Seymour	2	0.102	ALSTOM	PRB
Rush Island	2	0.104	ALSTOM	PRB
Meramec	2	0.109	ALSTOM	PRB
Will County	3	0.111	ALSTOM	PRB
Labadie	1	0.112	ALSTOM	PRB
Labadie	2	0.113	ALSTOM	PRB
Joliet	7	0.115	ALSTOM	PRB
Labadie	4	0.118	ALSTOM	PRB
Newton	1	0.122	ALSTOM	PRB
Will County	4	0.122	ALSTOM	PRB
Labadie	3	0.123	ALSTOM	PRB
Joppa	1 & 2	0.125	ALSTOM	PRB
Newton	2	0.126	ALSTOM	PRB
Gibbons Creek Steam	1	0.126	Other	PRB
Joliet	8	0.127	ALSTOM	PRB
Joppa	5 & 6	0.127	ALSTOM	PRB
Hennepin Power Station	1 & 2	0.129	Other	PRB

	Unit No.	NOx, lb/mmBtu	Firing System Supplier	Fuel
Joppa	3 & 4	0.130	ALSTOM	PRB
Scherer	3	0.131	Other	PRB
Meramec	1	0.132	ALSTOM	PRB
Crawford	7	0.134	ALSTOM	PRB
J T Deely	1 & 2	0.134	Mixed*	PRB
Waukegan	8	0.136	ALSTOM	PRB
Wood River Power Station	4	0.136	Other	PRB
Oak Creek	7 & 8	0.137	ALSTOM	PRB
Bridgeport Harbor Station	3	0.139	ALSTOM	Blend
Shiras	3	0.140	ALSTOM	PRB
Big Brown	1	0.140	ALSTOM	Lignite
Waukegan	7	0.141	ALSTOM	PRB
Big Brown	2	0.142	ALSTOM	Lignite
Monticello	2	0.142	ALSTOM	Lignite
Milton L Kapp	2	0.143	ALSTOM	PRB
Scherer	1	0.144	Other	PRB
Columbia	1	0.144	ALSTOM	PRB
Coleto Creek	1	0.148	Other	PRB
Crawford	8	0.154	ALSTOM	PRB
Trenton Channel	9	0.154	Other	PRB

* - Unit 1 by Other, Unit 2 by ALSTOM

Prior to the demonstrated success of ALSTOM's technology to achieve this low level of NOx emissions, it was universally thought that installation of an SCR would be required. The success of low NOx firing technology, used in concert with high reactivity low rank coals, represents an order of magnitude of potential cost savings available by avoiding an SCR installation while maintaining NOx emissions below 0.15 lb/MMBtu. It is the goal of the cooperative research project with the U.S. DOE/NETL, however, to develop in-furnace technologies to achieve NOx emissions below 0.15 lb/MMBtu for high volatile bituminous coals as well.

ENHANCED COMBUSTION LOW NOx PULVERIZED COAL BURNER PROJECT

ALSTOM, in cooperation with the DOE, is working on a project to develop an enhanced combustion, low NOx pulverized coal burner to help to achieve the goal of achieving NOx emissions below 0.15 lb/MMBtu for high volatile bituminous coals. The burner development program includes CFD modeling and large pilot-scale combustion testing in ALSTOM's Industrial Scale Burner Facility (ISBF) at its U.S. Power Plant Laboratories facility in Windsor, Connecticut. A goal of this work is to optimize the near-field combustion environment to maximize NOx reduction while minimizing the impact on unburned carbon in ash, slagging and fouling, and flame stability / turn-down under globally reducing conditions. The performance of this work at large pilot scale (approximately 50 MMBtu/hr) will provide sufficient data to allow ALSTOM to design, construct and demonstrate a first of a kind commercial version of the final system upon completion of the project.

ALSTOM is utilizing computational fluid dynamics (CFD) to evaluate different coal nozzle tip geometries and/or near field stoichiometry controls in order to screen promising design concepts for large pilot scale testing. Following this CFD screening work, several coal nozzle tip prototypes were constructed for testing in the ISBF. The first of three series of ISBF test campaigns was completed in November of 2005, while the second was completed in March of 2006. The final ISBF test program will be executed in late summer of 2006 and will continue to optimize the most promising nozzle tip design and then test fire a subbituminous coal and possibly a bituminous coal from the Western U.S.

The following sections will describe in more detail the CFD modeling, fuels characterization, and ISBF testing tasks that are part of this coal nozzle tip development project.

CFD Modeling

CFD modeling was used to evaluate the proposed coal nozzle tip concepts before the ISBF testing was performed. The CFD modeling was performed with Fluent version 6.2 and focused on predicting the near field mixing and particle dispersion rates. The simulations were run as steady state, turbulent, non-reacting flow with heat transfer. The typical grid sizes for the different coal nozzle tip simulations ranged from 2.5-3 million cells.

The ISBF geometry used in the simulations is illustrated in Figure 3. As shown in the figure, the model includes the coal pipe, the windbox, two levels of overfire air, and a simulated convective section. The convective section was simulated using a porous media region.

The CFD simulations assumed a secondary air temperature of 450 °F and a primary air temperature of 150 °F. A Rosin-Rammler coal particle size distribution was used with a top size of 200 microns, consistent with a DYNAMIC™ classifier grind. A primary air to fuel ratio of 2.0 was assumed for the CFD modeling. A separate air species was used for the primary air, fuel air, auxiliary air, and overfire air compartments to facilitate looking at the mixing of the various air streams.

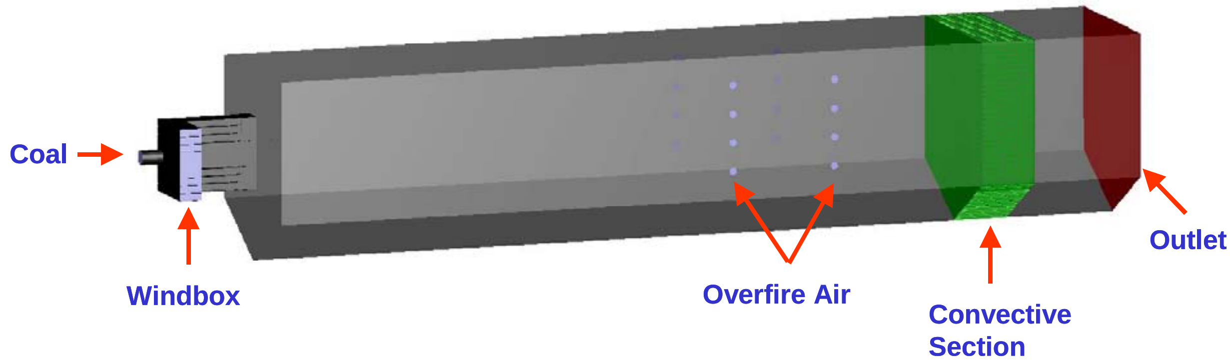

Figure 3.   ISBF Geometry for CFD Simulations.

The geometry of the ISBF windbox is shown in more detail in Figure 4. As illustrated in the figure, there were three auxiliary air compartments above and below the coal nozzle compartment. The secondary air that enters the compartment with the coal nozzle is referred to as fuel air. The geometry of the Shearbar/Air Deflector and LNCFS™ P2 coal nozzle tips, as modeled with CFD, are also shown on the right in Figure 4. Note that the CFD model included sufficient grid resolution to resolve the fine features of the coal nozzle tips. These two coal nozzle tips are commercially available and were selected as the baseline tips for this project.

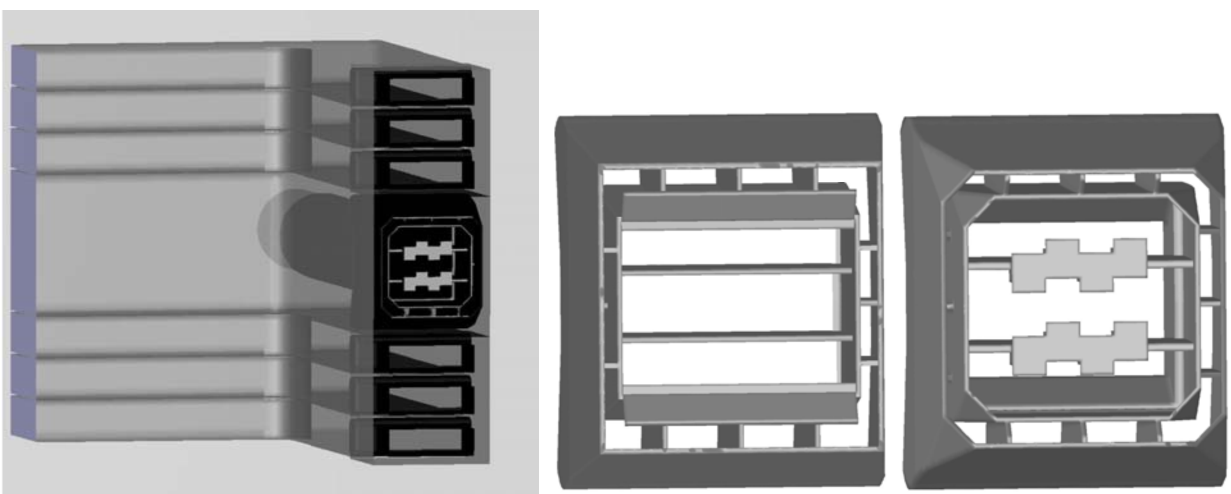

Figure 4. ISBF Windbox Geometry, Shearbar/Air Deflector and LNCFS™-P2 Nozzle Tips.

The predicted velocity magnitude on the center plane of the burner tips is shown in Figures 5. The air deflectors on the top and bottom of the tip cause recirculation zones to form, which can help the flame ignition point to attach to the top and bottom of the coal nozzle tip. Recirculation zones form behind the pumpkin teeth on the LNCFS™ P2 tip, which increase the turbulence levels and mixing in the primary air stream.

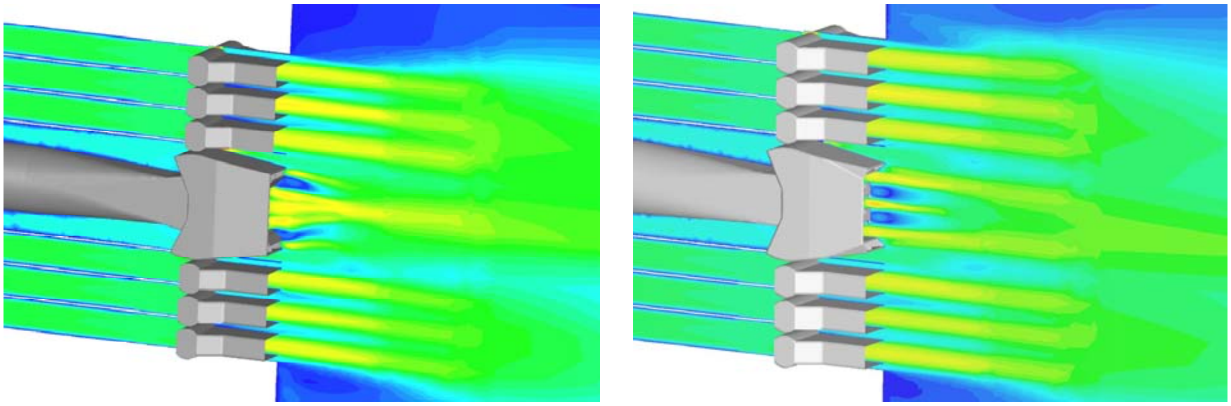

Figure 5. Predicted Velocity Magnitude for LNCFS™ P2 Tip.

The predicted particle phase concentration for the baseline tip is shown in Figure 6. As seen in the figure, the LNCFS™ P2 tip tends to segregate the particles into several distinct rich/lean zones. Similar CFD models were constructed for the new coal nozzle tip concepts as well in order to compare the predicted flow fields, gas phase mixing rates, and particle dispersion rates.

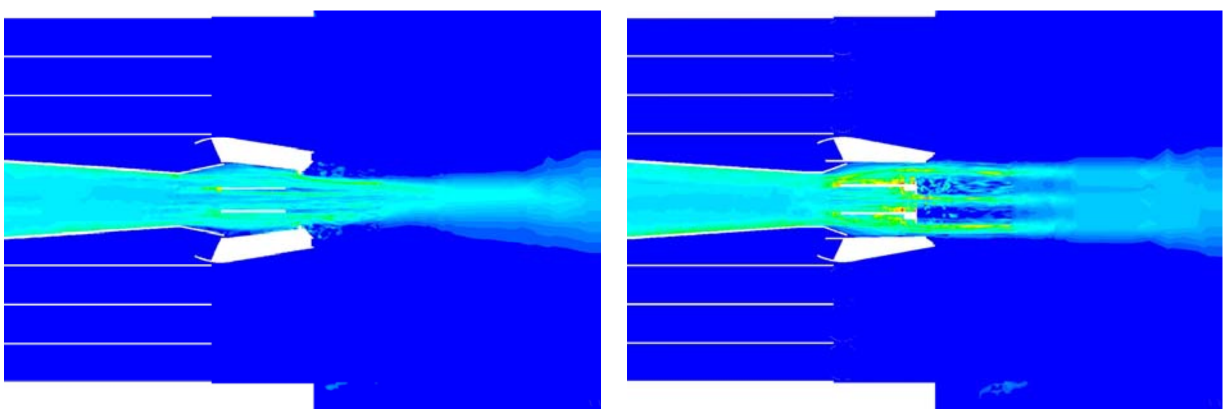

Figure 6. Predicted Particle Concentration for LNCFS™ P2 Tip.

Fuels Characterization

The analyses of the "as received" and "as fired" coals are shown in Table 3. As shown in the table, the moisture dropped from 16.4 to 9 % due to the grinding process. As the ISBF is not direct fired, the moisture that is removed from the coal during the grinding process is lost. A grind of approximately 83% -200 mesh was used for all of the tests. The coal ash properties, shown in Table 3, are indicative of a highly slagging coal.

Pulverized coal samples were obtained throughout the week to determine the variation in the size and composition of the coal that was being fired. As shown in Table 4, there was a variation of approximately ± 1% on the amount of coal passing through a 200 mesh sieve during the testing. As shown in Table 5, the composition of the pulverized coal was reasonably consistent over the course of the test week.

Table 3. ASTM Analysis of Illinois 6 Coal Used in ISBF Testing.

Fuel Properties	As Received	As Fired
% Total Moisture	16.4	9.0
% Volatile Matter	30.0	32.7
% Fixed Carbon	46.1	50.1
% Ash	7.5	8.2
HHV Btu/lb	11,110	12,084
% Moisture	16.4	9.0
% Hydrogen	4.3	4.7
% Carbon	61.7	67.1
% Sulfur	1.6	1.7
% Nitrogen	1.3	1.4
% Oxygen (diff)	7.2	7.9
% Ash	7.5	8.2
% Total	100.0	100.0
Grind		83% -200 mesh

Coal Ash Properties	
Ash Fusibility (reducing)	
I.T. (deg F)	2158
S.T. (deg F)	2199
H.T. (deg F)	2215
F.T. (deg F)	2248
% SiO2	44.4
% Al2O3	21.2
% Fe2O3	15.5
% CaO	5.8
% MgO	0.7
% Na2O	2.0
% K2O	1.8
% TiO2	1.1
% P2O5	0.1
% SO3	5.0
% MnO	0.1

Table 4. Variation in the pulverized coal size distributions.

	11/15/05	11/16/05	11/17/05	11/18/05
Sieve Sizing				
+ 50 mesh	0.07	0.11	0.06	0.04
+ 100 mesh	1.49	1.24	1.46	1.66
+ 200 mesh	14.93	13.93	15.56	15.91
Pan	83.46	84.65	82.86	82.40
% Recovery	99.95	99.93	99.94	100.01

Table 5. Variation in the pulverized coal analyses.

	11/15/05	11/16/05	11/17/05	11/18/05
Fuel Properties - As Rec'd				
% Total Moisture	9.12	9.49	8.53	9.09
% Volatile Matter	32.52	32.43	32.80	32.75
% Fixed Carbon	50.34	50.06	50.45	49.87
% Ash	8.02	8.02	8.22	8.29
HHV Btu/lb	12056	11947	12075	11966
% Sulfur	1.80	1.79	1.85	1.88
lbs Ash/MM Btu	6.65	6.71	6.81	6.93
lbs SO2/MM Btu	2.98	2.99	3.06	3.14
FC/VM Ratio	1.55	1.54	1.54	1.52
HHV (MAF basis)	14550	14483	14505	14483

ISBF Combustion Testing

Combustion testing in the ISBF (shown in Figure 7) commonly proceeds as follows: after a cold facility start-up, several hours are allowed for the ISBF to reach desired load and the refractory lining to reach operating temperatures/thermal equilibrium. Then, test conditions (firing system configuration, furnace stoichiometry history, firing rate, excess air level, etc.) are set to the desired level based on the test matrix specification. Testing then occurs 24 hours per day to avoid significant changes in the thermal environment in the furnace. A gas ignitor is used to help maintain furnace temperature when changing out a coal nozzle tip, a task which typically requires approximately one hour to complete.

Figure 7. Photo of ALSTOM's Industrial Scale Burner Facility (ISBF).

The ISBF DCS is continually monitoring system variables and the desired data (over 200 system variables) are logged at 1-minute intervals with a Labview data acquisition system. The data for a particular matrix test point is then extracted from the continuous data log from the actual start and stop times of the test point. Some of the variables logged for each data point include the global air and fuel input mass flow information, associated temperature data, main burner region windbox air flow rates and total separated overfire air (SOFA) flow rates, which allows for on-line calculation and control of bulk furnace stoichiometry history. Additional, pertinent operational data such as individual windbox compartment pressures and main windbox and SOFA windbox damper positions are manually recorded as test board data.

Acquisition of data for each matrix test point typically consists of 30 minutes of steady state furnace operation, for which configuration and operational variables are monitored and held constant. For tests where collection of fly ash samples were not required, approximately 15 minute tests were performed. At the end of a test point, furnace operation and/or configuration are modified and, after the necessary time for conditions to equilibrate has elapsed, the process is started again.

The ISBF utilizes a continuous sampling gas analysis system to measure the gaseous species concentrations in the furnace effluent gas stream, prior to the post-combustion, flue gas conditioning equipment. The GAS system utilizes gas species analyzers meeting the requirements of 40 CFR methods 7E, 6C, 3A, 10, and 3A for NO/NOx, SO_2, CO_2, CO, and O_2, respectively. This system is calibrated against certified bottled gas standards at least every twelve hours when taking test matrix data.

Carbon loss data is obtained through a pseudo-isokinetic sampling of fly ash with a water-cooled sampling probe, which is inserted in the furnace gas duct downstream of the simulated convective pass. The fly ash was sampled at six locations across the approximately 5ft diameter outlet duct. The flow-rate through the sampling system was measured/controlled during the entire sample time to ensure that the ash system was operated at approximately isokinetic conditions. A water-cooled, suction pyrometer with a single Type B thermocouple can be utilized to measure in-furnace gas temperatures (furnace outlet plane temperature, etc.).

RESULTS AND DISCUSSION

The first week of ISBF testing was completed in November 2005 where six coal nozzle tips were fired on an Illinois #6 coal. The firing rate was nominally 45 MMBtu/hr for each of the tests, with 20% excess air. All furnace and operating conditions were repeated as closely as possible for the testing on each coal nozzle tip.

NO emissions as a function main burner zone stoichiometry are presented in Figure 7. A reduction in NO emissions of approximately 15% was achieved with Tip 5 as compared to the baseline coal nozzle tips. Test week 2 evaluated refinements to some of the promising coal nozzle tips from week 1 and included some new nozzle tip designs incorporating knowledge gained from test week 1. As seen in Figure 8, a reduction of approximately 35% as compared to the baseline tips was achieved.

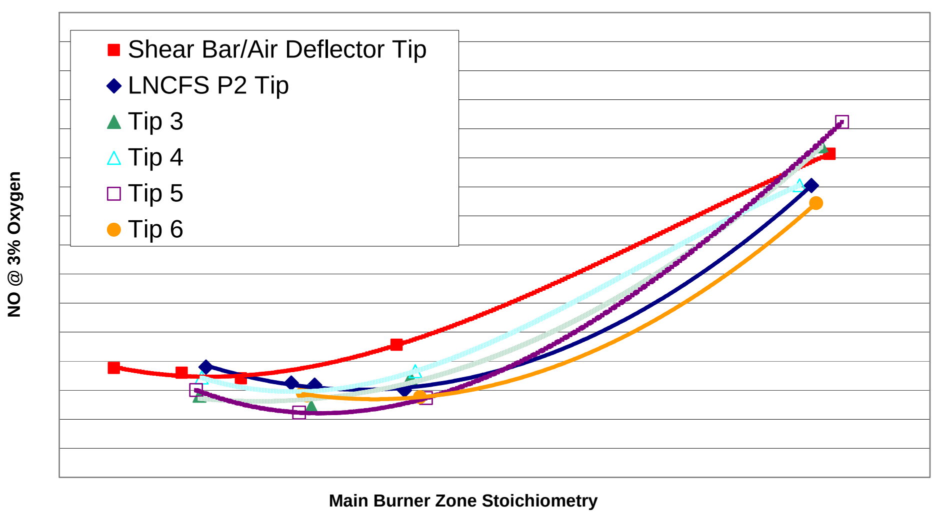

Figure 7. NO Emissions vs Main Burner Zone Stoichiometry, Test Week 1.

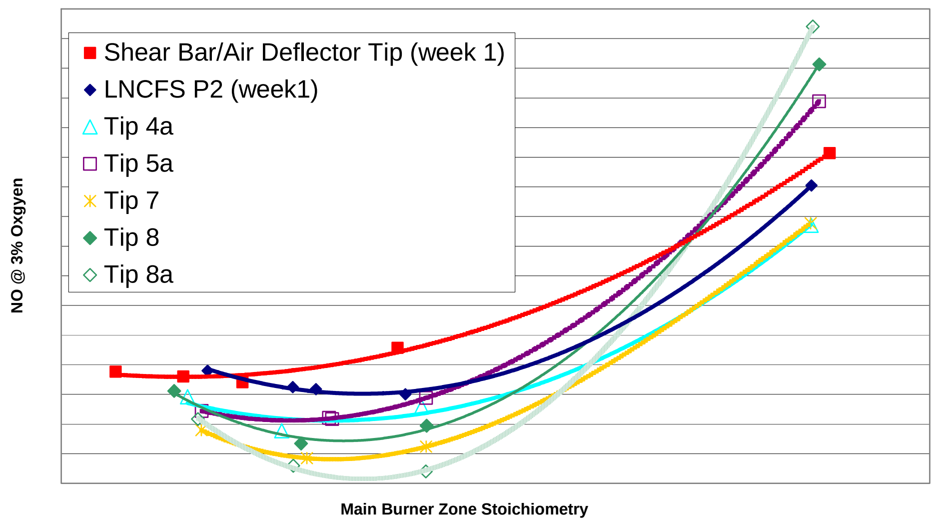

Figure 8. NO Emissions vs Main Burner Zone Stoichiometry, Test Week 2.

Additional tests were performed for each coal nozzle tip in an attempt to optimize the performance of each tip. Parameters that were adjusted for each tip included the quantity of fuel air, the distribution of auxiliary air between the various compartments, and the overfire air configuration. The minimum NO for each tip was recorded and the results are presented in Figure 9 as a percent reduction in NO emissions from the LNCFS™ P2 tip which, for reference, duplicated NOx emissions typical of a current field installed low NOx firing system equipped boiler firing Midwest bituminous coal. These results suggest that the coal nozzle tip design has a significant impact on the NO emissions, even at deeply staged conditions. Unfortunately the carbon in ash values from test week 2 were not available at the time this paper was written.

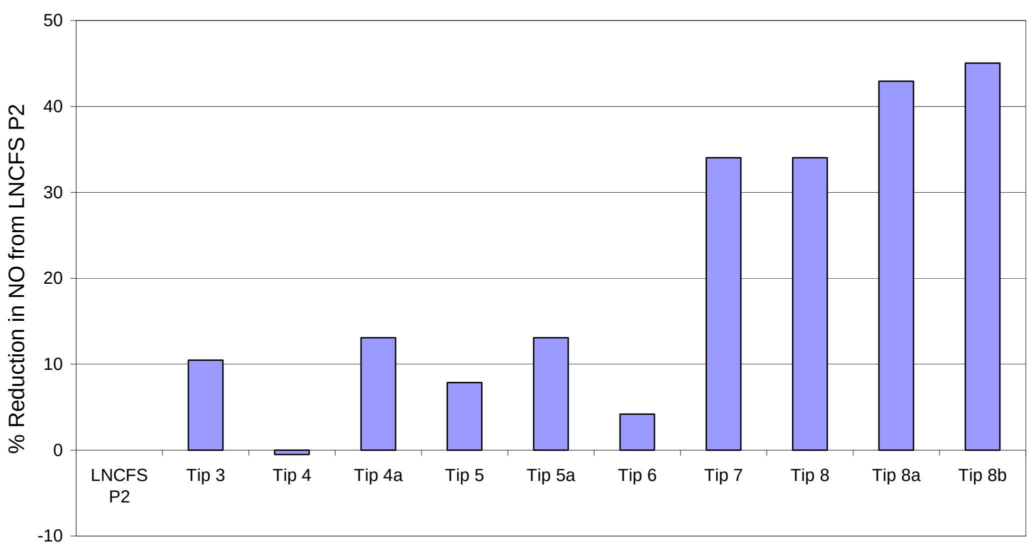

Figure 9. Percent Reduction in Minimum NO Emissions vs LNCFS™ P2 Tip.

Work is currently underway to evaluate the potential benefit of the new coal nozzle tip designs in a tangential fired boiler where burner-to-burner interactions and the swirled flow field may be important as well.

SUMMARY

ALSTOM's low NOx retrofit technology has achieved NOx emissions less than 0.15 lb/MMBtu in many pulverized coal-fired utility boilers burning high reactivity low rank coals. Consistent NOx emissions as low as 0.10 lb/MMBtu has been achieved in several units firing Powder River Basin coals. A cooperative research project with the U.S. DOE/NETL is in progress to develop in-furnace technologies to achieve NOx emissions of 0.15 lb/MMBtu for high volatile bituminous coals as well without significantly impacting CO emissions or unburned carbon in the fly ash.

Large pilot-scale testing in ALSTOM's Industrial Scale Burner Facility has demonstrated that the coal nozzle tip design has a significant impact on the NO emissions, even at deeply staged conditions. NOx reductions of approximately 40%, as compared to the LNCFS™ P2 tip, were seen with some of the new coal nozzle tip designs. As these large reductions in NOx emissions were achieved with a single burner in a test facility, work is currently underway to help evaluate the potential benefit of the new coal nozzle tip designs in a tangential fired boiler where burner-to-burner interactions and the swirled flow field may be important as well. Additional pilot-scale testing will help optimize the new coal nozzle tip designs and then test them on low rank coals as well.

ACKNOWLEDGEMENT

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REFERENCES

1. Lani, B. W., Feeley, T.,J. III, Murphy, J., and Green, L., "A Review of DOE/NETL's Advanced NOx Control Technology R&D Program for Coal-Fired Power Plants," DOE/NETL NOx R&D Program Review, March 2005.

2. Richards, G.H., Maney, C.Q., Borio, R.W., and Lewis, R.D., "Ultra Low NOx Integrated System for NOx Emission Control from Coal-Fired Boilers," Final Report to U.S. DOE under Cooperative Agreement No. DE-FC26-00NT40754.

3. Lewis, R., Camody, G., and Jennings, P., "Summary of Recent NOx Achievements with Low NOx Firing Systems and Highly Reactive PRB and Lignite Coal: as low as 0.11 lb NOx/MMBtu," 27th International Technical Conference on Coal Utilization & Fuel Systems, March 2002.