NOx REDUCTION FROM A 44-MW WALL-FIRED BOILER UTILIZING OXYGEN ENHANCED COMBUSTION

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ABSTRACT

Praxair has developed a novel method of using oxygen to bring about additional NOx reduction from low NOx combustion systems burning pulverized coal or other nitrogen-containing fuels. This paper reviews the results of pilot- and full-scale burner tests of this technology, and presents results of field tests in a commercial wall-fired boiler burning pulverized bituminous coal.

In pilot- and full-scale single-burner testing, NOx emissions were reduced by as much as 60%, to significantly below 0.15 lb/MMBtu, when a small portion of low NOx burner combustion air was replaced with oxygen. Oxygen injection allowed burner operation at lowered stoichiometric ratio, and raised the temperature of the primary combustion zone to inhibit the formation of fuel NOx. Oxygen addition also reduced unburned carbon in ash. These promising results led to beta testing in a commercial 44-MW wall-fired boiler beginning fourth quarter of 2002. The NOx, LOI, and opacity results achieved are presented.

BACKGROUND – O_2 ENHANCED COMBUSTION FOR NOx CONTROL

Although oxygen-enhanced combustion has been adopted for many high-temperature industrial furnaces for productivity improvement, energy and NOx reduction, economic considerations have limited the application of oxygen in the utility industry. However, as NOx emissions limits continue to tighten, the ability of oxygen-enhanced combustion to reduce NOx without the need for expensive equipment, such as SCR systems, makes its use more attractive. Praxair has developed oxygen-enhanced NOx reduction technologies for both combustion zone and post-combustion NOx control[1,2]. This paper describes the application of oxygen to prevent the formation of NOx in the combustion zone.

Using oxygen in the combustion zone of the boiler can significantly reduce NOx formation by enhancing the effectiveness of currently available control techniques such as low NOx burners with overfire air (OFA). For example, oxygen can support deep staging of the furnace while avoiding many of the problems inherent with staging. Even small amounts of oxygen can enhance the effectiveness of staging beyond that available with air alone[4] – leading to significant reductions in NOx formation. Finally, since oxygen is fed to the burner zone, it can be preferentially fed to specific burners in order to minimize burner-to-burner variations[3, 4], which can significantly reduce NOx and unburned carbon in ash (UBC).

The basic configuration of an air-fired staged-combustion system for NOx control is illustrated in Figure 1. In a staged-combustion system, a portion of the combustion air is fed to the burners. The remainder of the combustion air is fed through overfire air ports above the burners. The objective is to form a fuel rich region followed by a region where the residual char is burned out. The effect of fuel rich conditions on NOx formation is shown schematically in Figure 2. This figure shows the competition between the formation of NOx and the formation of molecular N_2 from nitrogenous species in the coal[5]. Upon heating, coal pyrolizes and forms volatiles and char, each containing bound nitrogen. Oxygen-rich conditions drive the competition towards NOx formation. Fuel rich conditions, such as those created in staged-combustion, drive the reactions to form N_2. Thus, as shown in Figure 3, by reducing the burner zone stoichiometric ratio, the formation of NOx from volatiles is significantly reduced.

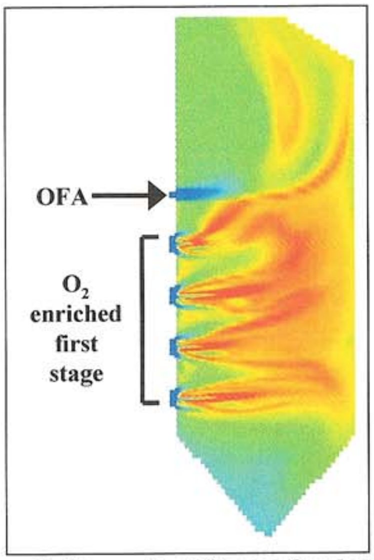

Figure 1. Schematic of Staged Combustion

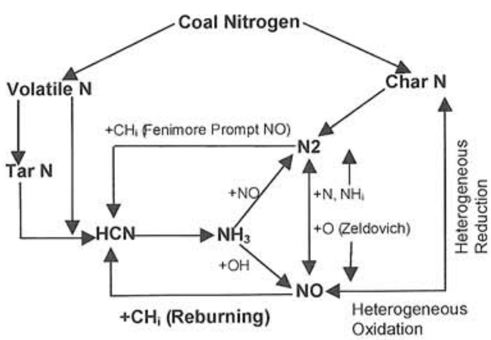

Figure 2. NOx production pathways in coal combustion[5]

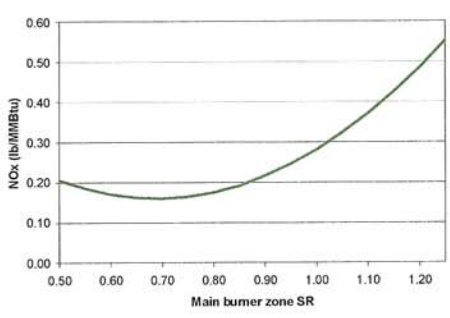

Figure 3. Typical effect of main burner zone SR on NOx – air only

One major factor in the effectiveness of staged combustion is the need to form very fuel rich conditions to drive the N_2 forming reactions. Under very fuel rich conditions, less combustion takes place, and therefore, less heat is released, leading to low-flame temperatures. Since the reaction rates driving NOx and fuel nitrogen species to N_2 are strongly dependent on temperature and residence time, there is a competition between need to create a fuel rich zone and the need to burn enough fuel to maintain the high-flame temperature. This problem is compounded by the fact that the second-stage, or burnout, residence time tends to be relatively short. Char burnout is a slow step and NOx formation from char nitrogen is a significant factor in a low NOx coal-combustion process. Therefore, if the coal is only partially oxidized in the first, fuel rich stage, significant NOx may form from char oxidation and there may not be sufficient residence time to burnout the residual carbon – leading to high unburned carbon in the ash.

Oxygen-enhanced staged combustion can mitigate both of these problems. Since less nitrogen is present in the flame when some of the combustion air in the first stage is replaced with oxygen, the flame temperature is higher for a given stoichiometric ratio. This increase in temperature has two effects. First, increasing the temperature under fuel rich conditions drives the reactions shown in Figure 2 toward the formation of N_2 rather than NOx. Second, the increase in temperature, coupled with higher local oxygen inlet concentrations leads to increased devolatilization rates and yields. The higher volatile yield means that the combustibles in the gas phase increase as compared to the baseline – leading to a more fuel rich gas phase which inhibits NOx formation from the volatile nitrogen species. Therefore, oxygen-enhanced combustion both creates more fuel rich conditions and increases the flame temperature in the fuel rich zone, both of which reduce NOx formation. The enhanced devolatilization also yields less residual carbon that must be burned in the second stage, leading to lower NOx formation from char and lower UBC.

Experimental work performed at two different facilities was used to demonstrate the concept of oxygen-enhanced combustion for NOx control. Detailed experiments were performed at the University of Utah to evaluate the effect of several parameters including burner conditions, coal type, oxygen mixing strategy, and first-stage stoichiometric ratio. Finally, experiments were performed with an "off-the-shelf" commercial RSFC^{TM} burner at ALSTOM Power Inc.'s test facility in Windsor, CT.

Pilot and Full-Scale Single-Burner Testing

Pilot-scale testing was performed using the 5-MMBtu/hr pilot-scale facility at the University of Utah. The pilot-scale facility used a scaled-down dual register DB Riley CCV burner. Full-scale experiments were performed in ALSTOM Power's Industrial Scale Burner Facility (ISBF) in Windsor, CT using a 25-MMBtu/h commercially available Radially Stratified Flame Core (RSFC™) burner. A wide range of burner parameters were evaluated, as were the first-stage stoichiometric ratio and residence time. Several methods were explored to introduce the oxygen into the first stage.

Figure 4 shows a typical NOx vs. staging curve developed during this testing. As indicated, NOx formation is significantly reduced as the burner zone stoichiometric ratio decreases. This reduction in NOx is evident in both the air-based case and the oxygen-enriched cases. This data indicates that the oxygen-enriched combustion provides additional NOx reduction beyond that available from simple air-based staging.

Figure 5 shows the effect of oxygen replacement under deeply-staged conditions. This data further supports that under fuel rich conditions oxygen-enhanced combustion can significantly reduce NOx formation even with very low oxygen replacement rates[4]. Similar data demonstrated that oxygen can enhance staging for NOx control over a wide range of conditions, and that the method for oxygen introduction is critical to the NOx reduction achieved[4].

FULL-SCALE DEMONSTRATION

The main driver for the development of oxygen-enhanced combustion for NOx control is to not only allow utility operators to control NOx emissions, but to also avoid or minimize many of the detrimental side effects common to alternative control strategies. The successful demonstration of the concept at the pilot- and full-scale single-burner levels led to an agreement between Praxair and City Utilities of Springfield, Missouri, to test oxygen-enhanced combustion at full scale. The demonstration project utilized Unit 3 at the James River Power Station to evaluate the effect of the O_2 addition during staged combustion on NOx emissions, residual carbon in ash, opacity and plant operation.

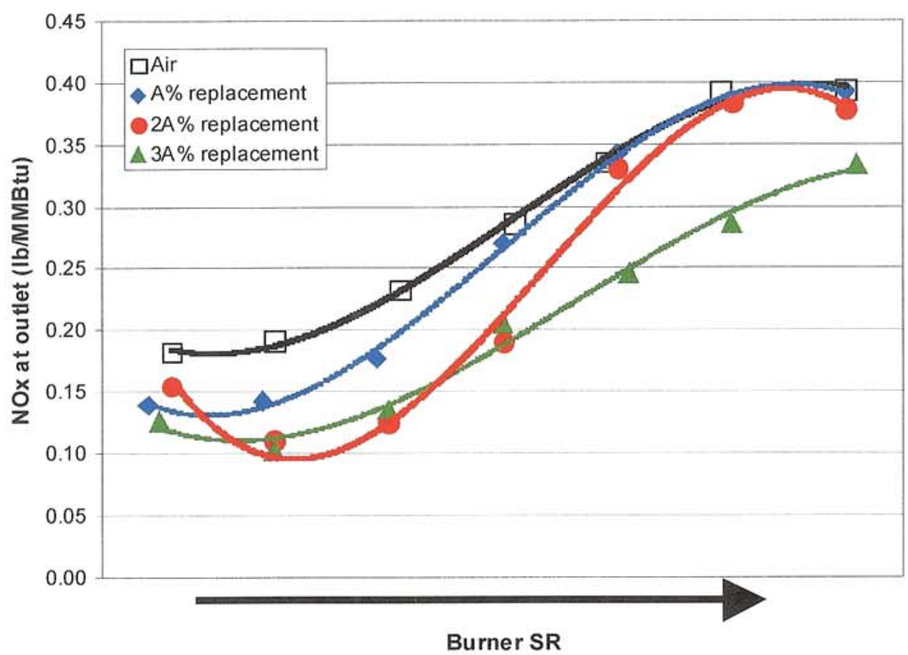

Figure 4. Pilot-scale results – University of Utah

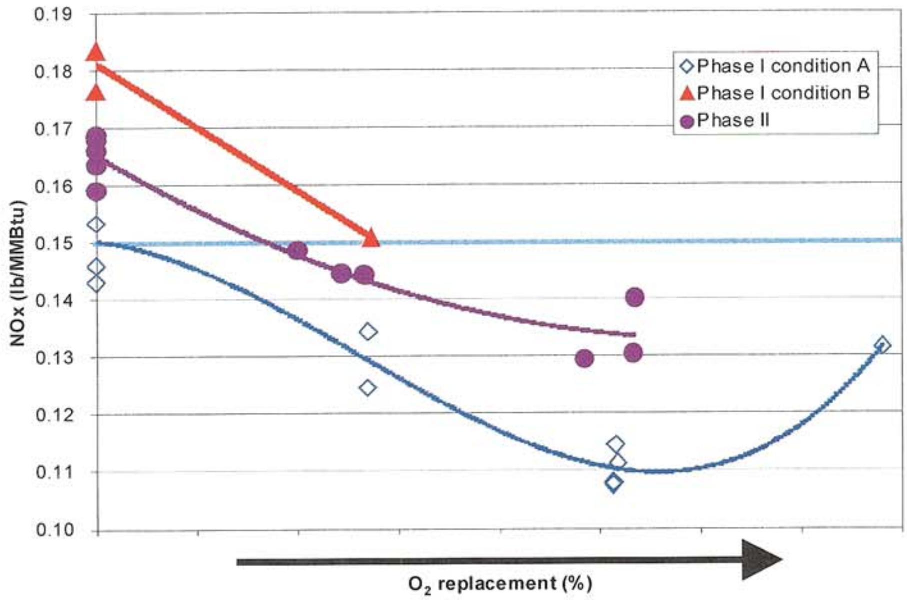

Figure 5. Full-scale single-burner results – ALSTOM Power

James River Unit 3

The James River Power Station, Unit 3, is a Riley Stoker, pulverized coal, sub-critical steam generator with a capacity of 44 MW. The unit is equipped with 3 Attrita Pulverizers. Six DB Riley CCV Low NOx Burners are arranged in two elevations on the front wall of the boiler. An overfire air system consisting of 5 ports had previously been installed on a single elevation above the top row of burners. The OFA ducts were designed such that each duct is divided into two ducts in a 1/3-2/3 arrangement.

City Utilities normally fires a blend of PRB and bituminous coal in Unit 3 and typically does not utilize the existing OFA system. Excess oxygen is measured with in-situ probes before the air heater. NOx, SOx, and opacity are measured in the stack. Plant operating data are automatically recorded in a data acquisition system.

For this test, an independent testing contractor, GE Mostardi Platt, installed a 12-point gas sampling grid immediately below the in-situ oxygen probes. This grid was used to measure gas composition in various locations in the duct and to derive an average over the entire duct. Ash samples were collected under specific conditions for loss on ignition (LOI) analysis.

The demonstration program at James River consisted of two phases. In the first phase, the plant fired only the bituminous coal it typically uses in its blend. This allowed the test team to determine the effectiveness of the technology with a coal similar to those used for the single-burner testing. For the second phase of testing, the plant switched back to its normal PRB-bituminous blend for this Unit.

In each phase, plant operating data and gas composition data was taken at full load under a wide range of burner stoichiometric ratios and oxygen-replacement rates, including baseline data with no oxygen added. The overall and burner stoichiometric ratios were calculated using measured plant data and these flue gas compositions.

O_2 Implementation at James River Unit 3

For the demonstration at James River, an oxygen delivery system was designed and constructed to allow a wide range of oxygen replacement rates to be tested. Liquid oxygen was delivered to the plant using tanker trucks and then stored in two cryogenic storage tanks (Figure 6). Atmospheric vaporizers were

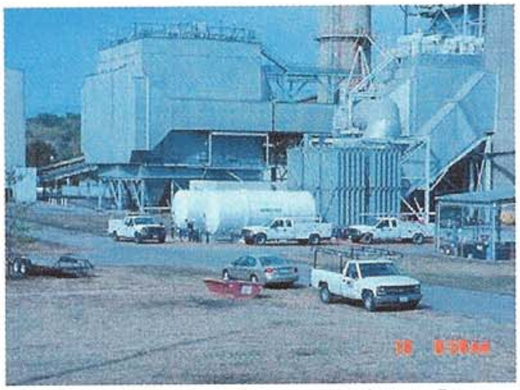

Figure 6. Oxygen tank installation at James River

used to convert the oxygen from liquid to gas. The gaseous oxygen was then piped to a flow skid located near the burner front. This flow skid consisted of a total flow controller followed by metered flow to each burner. A remote switch was installed to allow the operator to shut the oxygen flow off at any time. This remote switch was also tied into the plant control system such that any condition leading to loss of fuel flow would shut the system down.

The design of the oxygen storage and delivery system was such that it could be constructed and installed with little or no impact on the plant operation. In fact, the minor burner modifications required for oxygen-enhanced combustion were performed while the unit was operating at full load. For a commercial operation, the only major modification to this system would be use of an on-site oxygen generator in place of the liquid oxygen delivery and storage.

Full-Load Results

During the first phase of the test program, the unit was held at full load to explore the effect of air-alone staging on NOx emissions. Plant operating data, as well as emission information and ash samples, were collected over a wide range of operating conditions. Various oxygen injection methods and replacement rates were evaluated to confirm the effectiveness of oxygen for NOx reduction and the importance of the injection strategy on the technology performance. Periodically the burner would be returned to the "as found" condition and data collected without oxygen to evaluate the repeatability of the air-only conditions. These air-only results provided insight on the minimum NOx the plant could consistently achieve while keeping other operational and emissions parameters, such as LOI and opacity, within acceptable ranges.

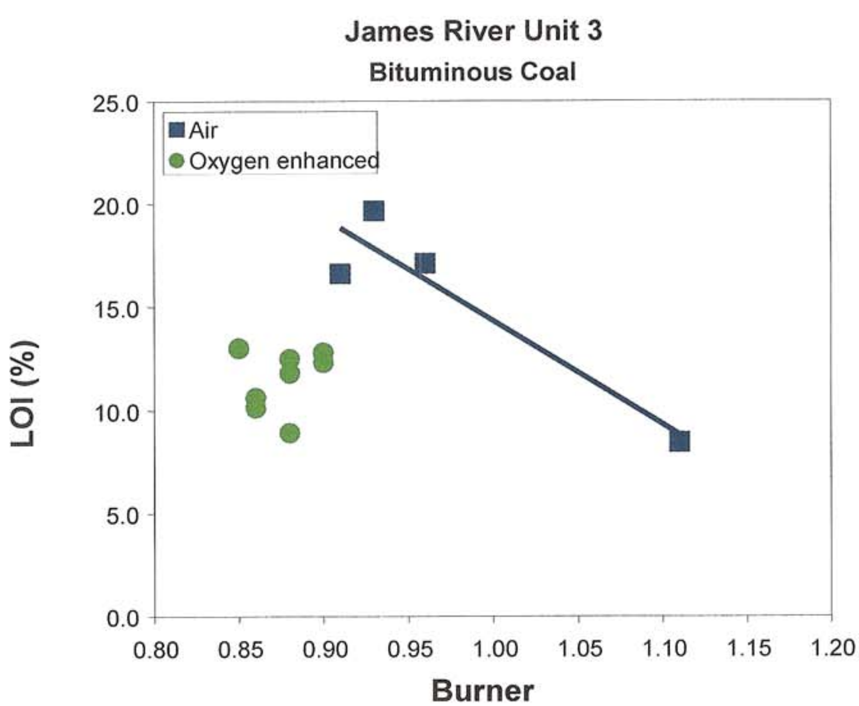

Figure 7. Effect of staging on LOI – Full Scale

Representative data on the effect of both staging and oxygen injection on LOI are shown in Figure 7. This data shows that as the burner stoichiometric ratio is reduced from the unstaged condition to approximately 0.92, the LOI increased significantly. However, even when the burner stoichiometric ratio was further reduced to approximately 0.85, and a small amount of oxygen was added, the LOI was comparable to, or only slightly higher than, the unstaged air case. This is true even for oxygen replacements less than 5%. This data suggests that oxygen allows deeper staging, with little or no impact on LOI.

The effect of small amounts of oxygen addition on NOx performance can be seen in Figure 8 for both coals. This figure shows the percent reduction achieved against the baseline air emissions. For this data, the baseline was defined as the NOx the plant could achieve with the overfire air without being limited by LOI, opacity, or burner stability. As can be seen from the figure, even very small oxygen replacements (less than 5%) yielded NOx reductions of approximately 40%. Limited data, at higher oxygen replacements, suggested that even greater reductions may be achievable under richer conditions and higher oxygen use (<10% replacement).

Comparing the NOx reductions and the LOI, demonstrate that deeper staging and oxygen addition yields significant reductions in NOx emissions *with little or no impact on LOI*. Observations of the flames, with and without oxygen addition, indicated that flame stability was significantly improved when oxygen was used. Flame impingement on the rear wall was noticed when the overfire was used with air alone; however, even small amounts of oxygen shortened the flames enough to eliminate this problem under almost all stoichiometric ratio conditions. Finally, the opacity measurements (not shown) indicate that the opacity was reduced when oxygen was used, thus allowing the unit to better use the technology for NOx control without exceeding their opacity limits.

Part-Load Results

The next key factor for demonstrating the viability of oxygen-enhanced combustion for NOx control was to determine the effectiveness of the technology at part load. For this unit, flame stability concerns typically limit the amount of OFA that can be used when the unit is operated under part load conditions. Since one of the advantages of oxygen-enhanced combustion is significant improvements in flame stability, the plant was able to use the full OFA system with oxygen at part load. As shown in Figure 9, this enhanced staging, coupled with longer residence times in the staged zone and cooler second-stage temperatures yielded better NOx reductions as compared with the full load test.

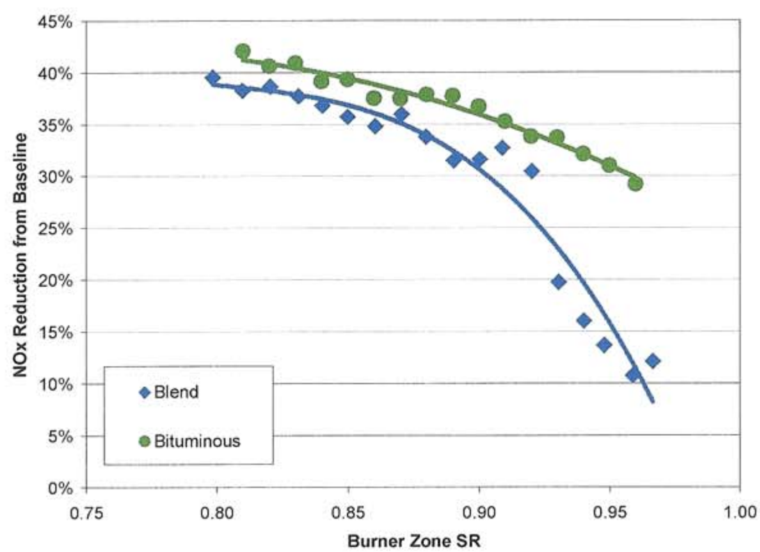

Figure 8. NOx reduction with <5% oxygen replacement – full scale

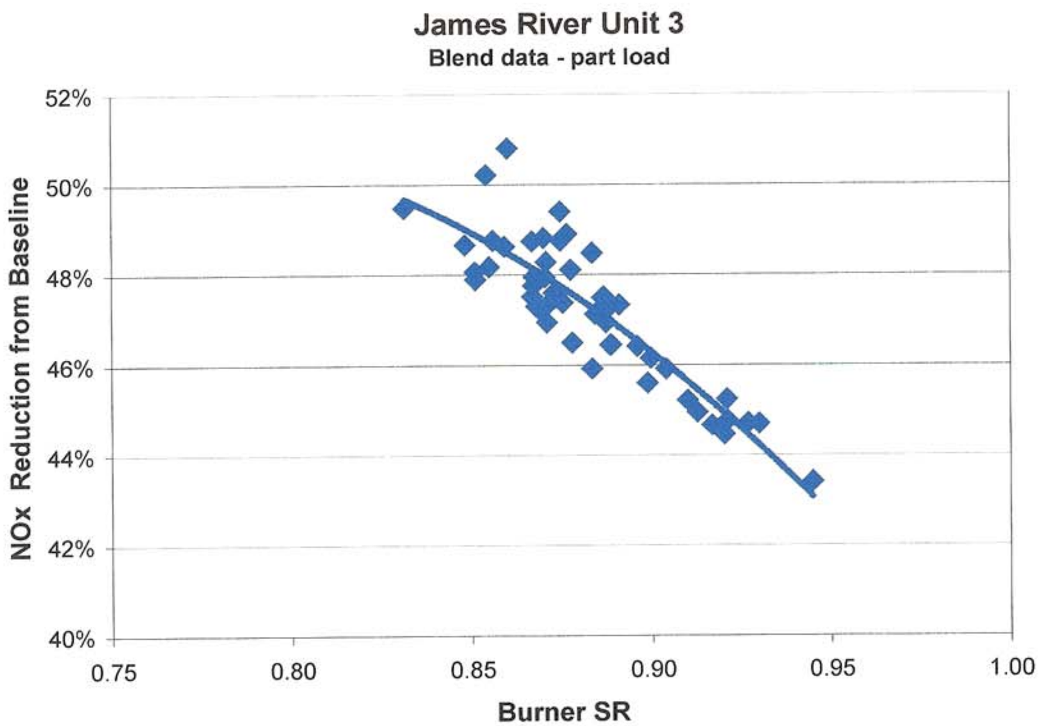

Figure 9. NOx reduction with oxygen enhanced combustion at part load – full scale.

CONCLUSIONS

The results of the demonstration project at James River Unit 3, and the single burner work that preceded it, demonstrated that oxygen enhanced combustion can substantially reduce NOx emissions from coal-fired power plants. The burner observations indicate that flame stability was dramatically improved with oxygen addition. The use of oxygen also *reduced* LOI and opacity as compared to the air-alone staging, with measured LOI and opacity being comparable or only slightly higher than the unstaged air-only condition. Therefore, this project demonstrated that oxygen enhanced combustion leads to significant reductions in NOx emissions *without* many of the problems typically associated with staged combustion systems.

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