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 presents results of field tests in a commercial wall-fired boiler burning pulverized bituminous coal.

In pilot- and full-scale burner testing NOx emissions were reduced by as much as 60%, to below 0.15 lb/MMBtu, when a small portion of low-NOx burner combustion air was replaced with locally injected oxygen. Oxygen injection allowed burner operation at lowered stoichiometric ratio, and raised the temperature of the primary combustion zone to favor NOx reduction kinetics. Oxygen addition also reduced carbon in ash. These promising results led to beta testing in a commercial 44 MW wall-fired boiler beginning fourth quarter of 2002. Testing as part of the demonstration project showed greater than 40% reduction in NOx emissions, reduction in LOI, enhanced flame stability, and unanticipated opacity reductions.

INTRODUCTION

Although oxygen enhanced combustion has been adopted for many high temperature industrial furnaces for productivity improvement, energy reduction 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[3,4] – 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).

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 involving fuel nitrogen species towards 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 using the 5 MMBtu/hr pilot-scale facility at the University of Utah. 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. These tests indicated NOx formation is significantly reduced as the burner zone stoichiometric ratio decreases and that the oxygen enriched combustion provides additional NOx reduction beyond that available from simple air-based staging[3]. 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].

Based on these successful tests a full-scale demonstration of the technology was performed during the last quarter of 2002. This demonstration used the existing burners and overfire air system at the James River Power Station, Unit 3 owned by City Utilities of Springfield, MO to demonstrate the effectiveness of oxygen enhanced combustion for NOx control.

DESCRIPTION OF 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 D B 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 parts 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.

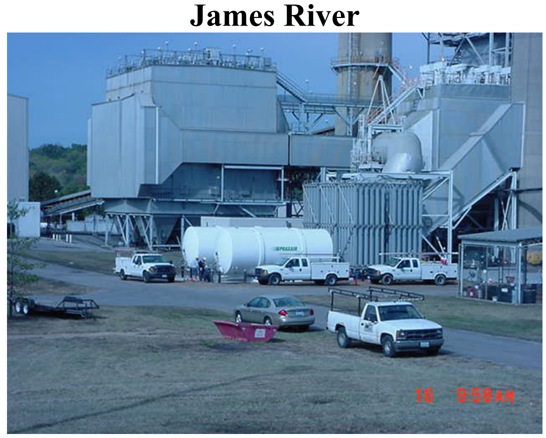
The demonstration program at James River consisted of two phases. In the first phase the plant fired only the bituminous coal it typically uses in its blend. This allowed the test team to determine the effectiveness of the technology with a coal similar to those used for the single burner testing. For 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 1). Atmospheric vaporizers were 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

Figure 1. Oxygen tank installation at James River



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.

Impact of staging and oxygen injection on LOI

Representative data on the effect of both staging and oxygen injection on LOI are shown in Figure 2. These data show 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%. These data suggest that oxygen allows deeper staging with little or no impact on LOI.

Impact of staging and oxygen injection on NOx

The effect of staging with oxygen on NOx emissions is shown in Figure 3. Based on opacity and other limitations the plant is limited to burner zone stochiometric ratios between 0.97 and 1.0 with the air staging system. The NOx reductions shown in Figure 3 were calculated from the staged air baseline case. These data show that even very small oxygen replacements yielded NOx reductions of approximately 40%. This result is particularly encouraging as the burners at this facility are first generation low NOx burners. Even higher reductions are expected from more advanced low NOx burner designs, such as those used in the single-burner pilot and full-scale tests. The data also demonstrates that low oxygen replacement rates help to maintain flame stability and LOI – allowing operation at lower burner stoichiometric ratios than could be achieved otherwise. The staging curve for the bituminous coal, not shown, indicate that even low levels of oxygen addition enhance the staging process, leading to NOx levels lower than could be achieved with air alone at a given SR

Figure 2. Effect of staging on LOI – Full Scale

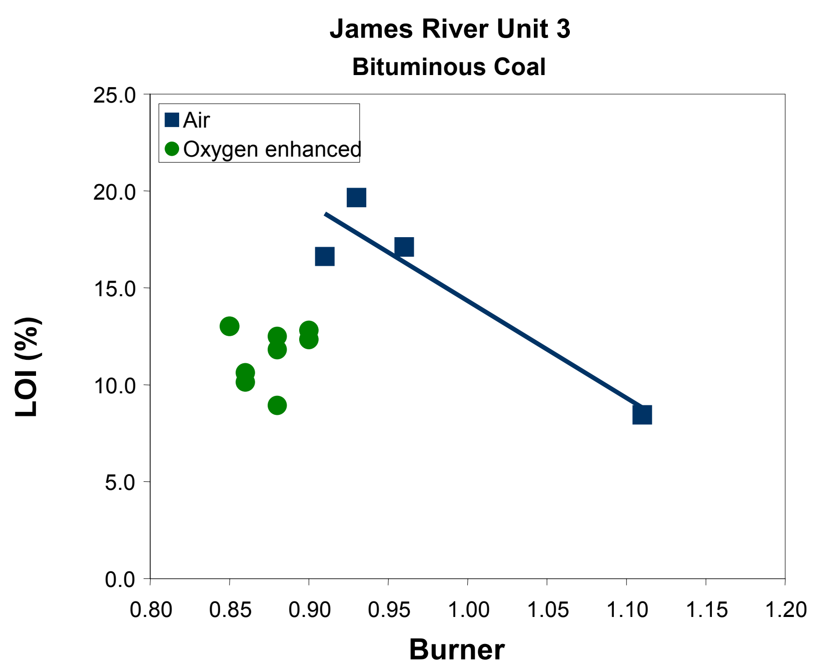
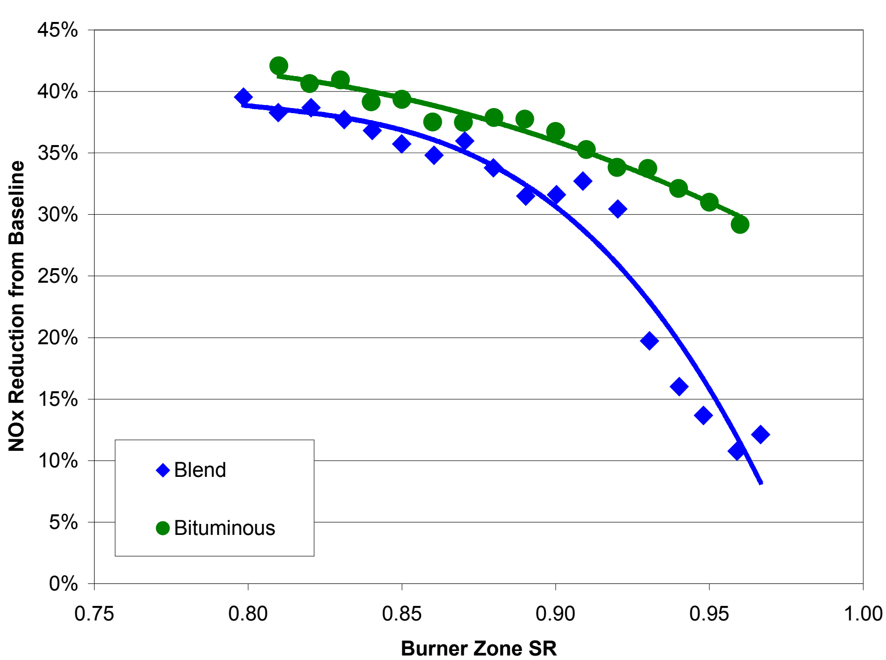
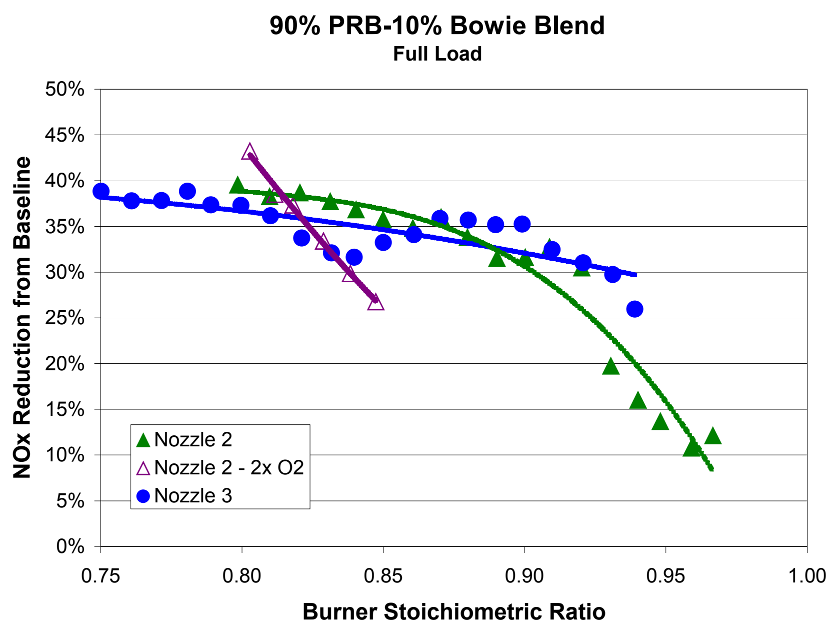


Figure 3. NOx reduction with small amounts of oxygen replacement



One interesting aspect of these results is that, unlike previous single burner data, these low levels of oxygen replacement yielded significant improvements in NOx emissions under relatively lean conditions (SR>0.85). The observed NOx reductions at these burner stoichiometric ratios are probably due in large part to stabilization of the flame and reducing the flame standoff distance. Limited data at higher oxygen replacements (Figure 4) suggest that even greater reductions may be achievable under richer conditions and higher oxygen use (<10% replacement). These conditions more closely match the conditions in the pilot-scale work.

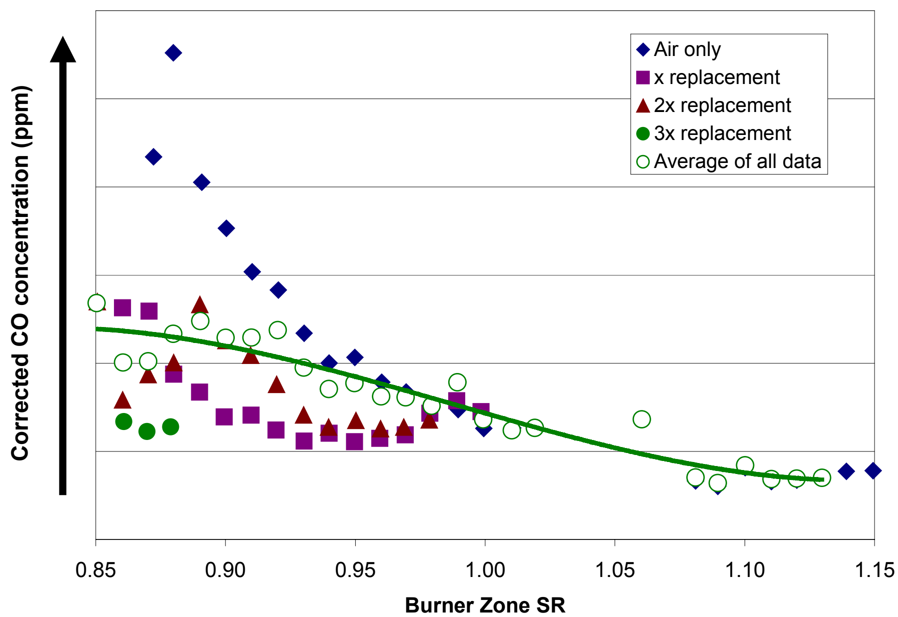
Figure 4. NOx reductions from PRB-bituminous blend



Impact on CO emissions

Another critical factor is the impact of oxygen enhanced combustion on CO emissions. Although reducing the burner zone stoichiometric ratio causes an increase in CO being generated in the burner zone, it is generally understood that CO emissions are typically controlled through the overfire air design and overall boiler operation. Good mixing of the overfire air and adequate excess oxygen are critical to minimize CO emissions. Data from the demonstration program are shown in Figure 5. As can be seen in the figure CO emissions increased to various degrees as the burner zone stoichiometric ratio was reduced. As part of the testing the system was operated on air under staged conditions where burner zone stoichiometric ratio and excess air levels were lower than typical of normal boiler operation. This led to higher CO emissions. The data also suggest that oxygen addition had little or no impact CO emissions and may, in fact, have resulted in lower emissions than air alone. This suggests that oxygen enhanced combustion, when coupled with a well designed staged combustion system operated with adequate excess air, should not significantly impact CO emissions.

Figure 5. CO emissions



Impact of staging and oxygen injection on flame stability

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 and burner standoff distances were significantly improved when oxygen was used. Figures 6 and 7 show the typical trend observed during the testing. As the burner zone was staged deeper with air alone the flame became less stable and typically had a fairly significant standoff distance. Flame impingement on the rear wall was noticed when the overfire was used with air alone. However, when even small amounts of oxygen were used the flame stability and flame attachment were significantly improved. These small amounts of oxygen replacements also shortened the flames enough to eliminate this problem under almost all stoichiometric ratio conditions.

Figure 6. Typical staged air flame, note standoff distance and lack of definition

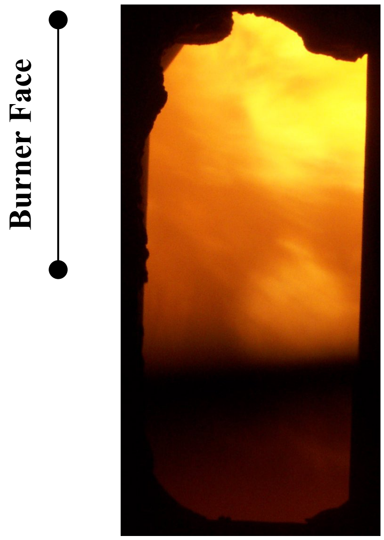
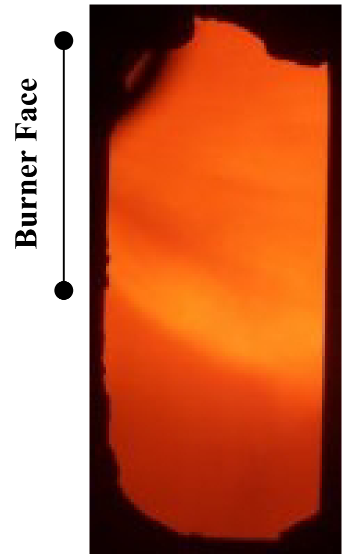


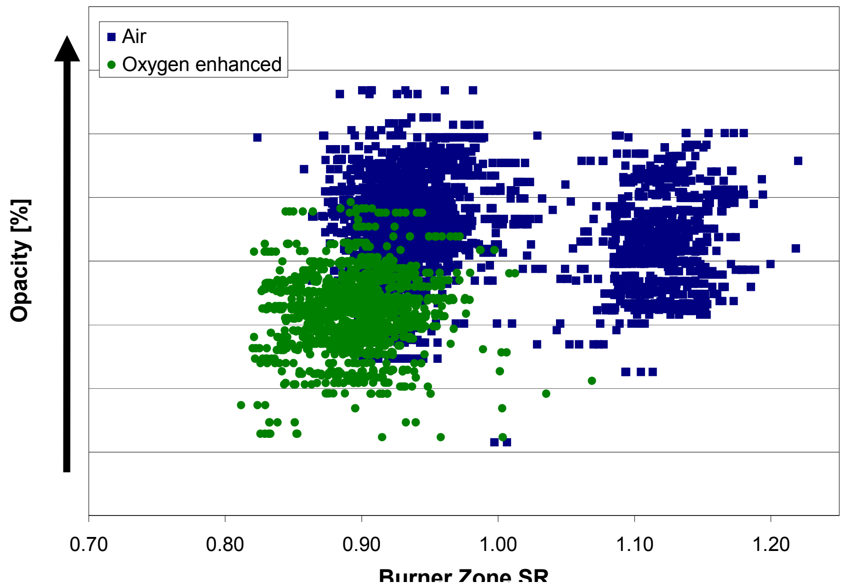
Figure 7. Typical staged flame with small O_2 addition, note clear and well attached



Impact of staging and oxygen injection on opacity

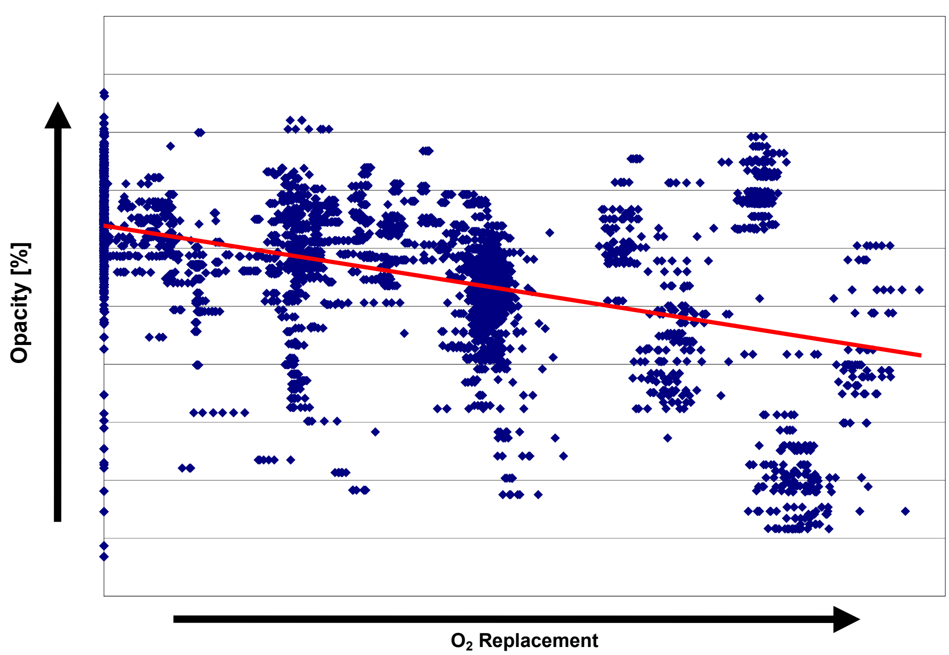
One factor that often limits the use of staged combustion systems is the stack opacity, which can increase to unacceptable levels when overfire air systems are used. Although the mechanisms leading to changes in opacity are complex, one potential explanation is that the increased carbon in the ash and residual soot can lead to degradation in ESP performance. Figure 8 illustrates how staging impacted stack opacity during testing with the bituminous coal. As noted on the plot these data do not include the opacity spikes typical during the sootblowing cycle. These data were removed in order to better focus on the effect of burner stoichiometric ratio and oxygen use on the stack opacity. As can be seen from the data going from an unstaged condition to a staged condition with air alone resulted in a slight increase in stack opacity. However, when small amounts of oxygen were used the stack opacity values were actually lower than the unstaged air case. Figure 9, where all the stoichiometric ratio data for a given oxygen replacement are combined, confirms that on average adding even small amounts of oxygen can significantly reduce stack opacity.

Figure 8. Effect of staging on opacity – bituminous coal



CONCLUSIONS

Figure 9. Effect of oxygen replacement on opacity



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 being comparable or only slightly higher than the unstaged air-only condition. The measured opacity was actually lower in many cases with oxygen-enhanced staging than the original unstaged condition for the bituminous coal. Observations of the plant operation and the available data suggest that deep staging with oxygen didn't lead to significant operational problems, such as slagging. Efficiency estimates suggest that staging without oxygen addition can lead to lower boiler efficiencies, while staging with oxygen results in little or no degradation in boiler efficiency as compared to the unstaged case. Finally, CFD models coupled with correlations based on the current understanding of waterwall wastage suggests that deep staging with air alone can result in significant increases in waterwall wastage. However, using even small amounts of oxygen under deeply staged conditions leads to corrosion rates comparable to those associated with mildly staged systems. Based on these conclusions, this project successfully 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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4. Patents pending

KEY WORDS

NOx, oxygen, staging, low NOx burner