Advanced In-Furnace NO_X Control for Wall and Cyclone-Fired Boilers

Final Project Report

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DISCLAIMER

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Advanced In-Furnace NO_X Control for Wall and Cyclone-Fired Boilers

ABSTRACT

A NO_x minimization strategy for coal-burning wall-fired and cyclone boilers was developed that included deep air staging, innovative oxygen use, reburning, and advanced combustion control enhancements. Computational fluid dynamics modeling was applied to refine and select the best arrangements. Pilot-scale tests were conducted by firing an eastern high-volatile bituminous Pittsburgh #8 coal at 5 million Btu/hr in a facility that was set up with two-level overfire air (OFA) ports.

In the wall-fired mode, pulverized coal was burned in a geometrically scaled down version of the B&W DRB-4Z® low-NO_x burner. At a fixed overall excess air level of 17%, NO_x emissions with single-level OFA ports were around 0.32 lb/million Btu at 0.80 burner stoichiometry. Two-level OFA operation lowered the NO_x levels to 0.25 lb/million Btu. Oxygen enrichment in the staged burner reduced the NO_x values to 0.21 lb/million Btu. Oxygen enrichment plus reburning and 2-level OFA operation further curbed the NO_x emissions to 0.19 lb/million Btu or by 41% from conventional air-staged operation with single-level OFA ports.

In the cyclone firing arrangement, oxygen enrichment of the cyclone combustor enabled high-temperature and deeply staged operation while maintaining good slag tapping. Firing the Pittsburgh #8 coal in the optimum arrangement generated 112 ppmv NO_x (0.15 lb/million Btu) and 59 ppmv CO. The optimum emissions results represent 88% NO_x reduction from the uncontrolled operation.

Levelized costs for additional NO_x removal by various in-furnace control methods in reference wall-fired or cyclone-fired units already equipped with single-level OFA ports were estimated and compared with figures for SCR systems achieving 0.1 lb $NO_x/10^6$ Btu. Two-level OFA ports could offer the most economical approach for moderate NO_x control, especially for smaller units. O_2 enrichment in combination with 2-level OFA was not cost effective for wall-firing. For cyclone units, NO_x removal by two-level OFA plus O_2 enrichment but without coal reburning was economically attractive.

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ADVANCED IN-FURNACE NO_X CONTROL FOR WALL AND CYCLONE-FIRED BOILERS

EXECUTIVE SUMMARY

Under the joint sponsorship of the U.S. Department of Energy - National Energy Technology Laboratory (DOE-NETL), B&W, and Air Liquide, a NO_x minimization strategy for pulverized coal-burning units was developed that included deep air staging, innovative oxygen use, reburning, and advanced combustion control enhancements. Our goal was to create a large, high-temperature, and oxygen-deficient reaction zone within the furnace prior to the OFA ports. Such conditions have been known to minimize NO_x emissions. Since the oxygen production expense is a major part of the NO_x removal cost, sound scientific and technical methods were applied throughout the development and pilot-scale demonstration of the technology to minimize the O_2 requirement by maximizing its utilization. The objectives of this project were to:

1) Demonstrate a cost-effective and layered NO_x reduction strategy based on deep air staging, innovative use of oxygen, continuous corrosion monitoring, and advanced combustion control enhancements that can achieve a NO_x emissions target of 0.10 lb/million Btu from the combustion of a high-volatile eastern bituminous coal.

2) Evaluate the impact on balance-of-plant issues including steam generation, unburned carbon levels, tube wastage, slagging and fouling, mercury emissions, and others.

3) Demonstrate that this NO_x control technology in achieving NO_x emissions below 0.10 lb/million Btu can reduce the levelized cost of NO_x compliance below ¾ that of a current state-of-the-art SCR system.

Our approach for achieving the ultra low-NO_x levels of 0.10 lb/million Btu for high-volatile eastern bituminous coal combustion relied on a layered strategy that included deep air staging, innovative oxygen use, continuous corrosion monitoring, and advanced combustion control enhancements. Strategic use of oxygen in various boiler zones has great potential for achieving significantly lower NO_x emissions relative to conventional staged combustion or other in-furnace NO_x control methods.

Prior to pilot-scale testing, the effects of major operating parameters (e.g., combustion stoichiometry, extent of reburning, pure O_2 distribution and dispersion, flue gas recycle flow, etc.) were simulated with the aid of the B&W combustion model COMO^{SM}. COMO^{SM} is a multi-dimensional computational fluid dynamics code with advanced capabilities for simulating turbulent flow, particle trajectories, heat transfer, radiation, and heterogeneous and gas-phase reactions. It uses an unstructured mesh with a mixture of element shapes, and adaptive mesh refinement for higher resolution in regions of high temperature, velocity, or concentration gradients. COMO^{SM} simulated the furnace, main burner, cyclone combustor, reburn burners, overfire air ports, and oxygen injectors with sufficient control volumes. Computer simulations included sub-stoichiometric combustion of a high-volatile Pittsburgh #8 coal at part load operation (70% firing rate in the main combustion zone and 30% in reburn burners) with and without oxygen enrichment, and the baseline full load (100% firing rate in the main combustion zone) air-blown operation without oxygen addition.

Over thirty cases were modeled by COMO^{SM} spanning different boiler geometries, hardware settings, swirl direction, and oxygen and flue gas recycling (FGR) use in the main burner and reburn burners. Since hot and oxygen-deficient combustion zones are conducive to nitric oxide destruction, oxygen injectors and reburn burner design selections for testing were based on these attributes, and thus NO_x was not predicted. Pilot-scale evaluations were carried out at 5 million Btu/hr and the performance highlights are summarized below.

Wall-Fired DRB-4Z® Burner Operation

- At a fixed overall excess air level of 17%, NO_X emissions with single-level OFA ports were around 0.32 lb/million Btu at 0.80 burner stoichiometry.
- Two-level OFA operation lowered the NO_x levels to 0.25 lb/million Btu.
- Oxygen enrichment at 8.9% level in the staged burner (SR=0.7) reduced the NO_x values to 0.21 lb/million Btu.
- Coal reburning in the 9-19% range in conjunction with oxygen enrichment further trimmed the NO_x emissions from 0.21 to 0.19 lb/million Btu.
- Oxygen enrichment plus reburning and 2-level OFA operation curbed the NO_x emissions by 41% relative to conventional air-staged operation with single-level OFA ports.
- Measured corrosion rates were up to three times faster relative to conventional staged operation.
- Oxy-reburn had no adverse effect on heat transfer characteristics.
- Transformation of elemental to oxidized mercury and the potential for removing the water soluble Hg^{2+} in a wet scrubber was increased with oxy-reburn.

Cyclone-Fired Operation

- Unstaged combustion of the high-volatile bituminous Pittsburgh #8 coal with air in the 1.16 to 1.18 stoichiometry range produced 1.13 to 1.39 lb NO_x/million Btu.
- Switching from the Pittsburgh #8 coal to the Powder River Basin Black Thunder coal generated 1.04 lb NO_x/million Btu at 1.17 combustion stoichiometry.
- Staged combustion at 0.7 stoichiometry while using 2-level OFA ports to maintain an overall stoichiometry of 1.17 resulted in 0.23 lb NO_x/million Btu for the Pittsburgh #8 coal and 0.15 lb NO_x/million Btu for the Black Thunder coal.
- With 5% oxygen enrichment of the cyclone furnace under otherwise similar conditions as stated above, the NO_x emissions were reduced to 0.18 lb/million Btu for the Pittsburgh #8 coal and 0.13 lb/million Btu for the Black Thunder coal while maintaining good slag tapping.
- By combining oxygen enrichment of the staged cyclone, 2-level OFA operation, and 10% coal reburning, NO_x levels for the Pittsburgh #8 coal dropped to 0.15 lb/million Btu.
- Optimum results for the Pittsburgh #8 and Black Thunder coals represent 88% NO_x reduction from the uncontrolled operation.
- Measured corrosion rates were up to three times faster relative to conventional un-staged operation.

Although the program target of 0.10 lb $NO_X/10^6$ Btu was not met, significant progress was made toward developing a NO_x minimization approach for coal-burning power plants. Levelized costs for additional NO_x removal by various in-furnace control methods in reference wall-fired or cyclone-fired units already equipped with single-level OFA ports were estimated and compared with figures for SCR systems achieving 0.1 lb $NO_x/10^6$ Btu. Two-level OFA ports could offer the most economical approach for moderate NO_x control, especially for smaller units. O_2 enrichment in combination with 2-level OFA was not cost effective for wall-firing. For cyclone units, NO_x removal by two-level OFA plus O_2 enrichment but without coal reburning was economically attractive.

PATENTS AND PRESENTATIONS

Research performed in this program has culminated into one patent application and three technical papers as listed below.

1. System and Method for Minimizing Nitrogen Oxide (NO_x) Emissions in Cyclone Combustors, Patent Application WO/2008/151271 (B&W Case 7224).

2. Sarv, H., Sayre, A.N., Maringo, G.J., Varagani, R., and Levesque, S., "Selective Use of Oxygen and In-Furnace Combustion Techniques For NO_x Reduction In Coal Burning Cyclone Furnaces," Presented at the 33rd International Technical Conference on Coal Utilization & Fuel Systems, Clearwater, FL, June 2008.

3. Sarv, H., Chen, Z., Sayre, A.N., Maringo, G.J., Varagani, R., and Levesque, S., "Oxygen-Enriched Combustion of a Powder River Basin Black Thunder Coal For NO_x Reduction in a Cyclone Furnace," Presented at the 34th International Technical Conference on Clean Coal & Fuel Systems, Clearwater, FL, May 31-June 4, 2009.

4. Sarv, H., Sayre, A.N., Maringo, G.J., Varagani, R., and Levesque, S., "Selective Use of Oxygen and In-Furnace Combustion Techniques for NO_x Reduction in a Wall-Fired Pulverized Coal Burning Pilot Boiler" Presented at the 34th International Technical Conference on Clean Coal & Fuel Systems, Clearwater, FL, May 31-June 4, 2009.

INTRODUCTION

Wall-fired pulverized coal-burning units in the U.S. generate around 150,000 MW of electricity. Over the years, most of these units have been retrofitted with low-NO_x burners and/or staged combustion technologies. In the future, the majority of these units will require additional NO_x emissions reductions to comply with environmental regulations.

According to the Coal Power Plant database released in 2007 by the Energy Information Administration of the U.S. Department of Energy [1], coal-fired cyclone boilers in the U.S. have a generation capacity of 25,226 MW_e. Over 60% of the power generated by cyclone boilers comes from units that burn low-sulfur, sub-bituminous, Powder River Basin (PRB) coals. Cyclone-equipped furnaces were originally developed to burn a wide range of crushed coals with low fly ash handling expenses and fuel preparation costs. Due to the intense turbulent mixing of coal and air, and the high-temperature combustion, NO_x ($NO+NO_2$) emissions from cyclone furnaces typically exceed 1.0 lb/10^6 Btu, requiring staging, fuel reburning, and/or backend pollutant control technologies for compliance with environmental regulations. Current commercial performance in air-staged cyclone units has been around 0.5 to 0.6 lb $NO_x/10^6$ Btu for eastern bituminous coals and 0.30 to 0.40 lb $NO_x/10^6$ Btu for PRB coals. Lower NO_x levels are achievable in exchange for higher fly ash loading and unburned carbon content, and lower furnace slag tapping efficiency. Fuel reburning is another proven technology for NO_x reduction in cyclone boilers. In conventional coal reburning, baseline NO_x levels drop by 40 to 60% when 20 to 30% of the heat is released by the supplementary fuel downstream of the main combustion zone [2].

Selective use of oxygen in the combustion zone can extend the sub-stoichiometric operating range and offer the potential for lowering the NO_x emissions relative to other in-furnace NO_x control methods. Under the joint sponsorship of DOE-NETL, Babcock & Wilcox (B&W) Power Generation Group, and Air Liquide, a program was undertaken for minimizing the NO_x emissions in wall-fired and cyclone-fired units that burn coal. Our NO_x reduction approach was based on sub-stoichiometric operation of the main combustion zone, deeply staged reburning zone, and managed use of oxygen and recycled flue gas in selective combustion zones. This report discusses the computer modeling simulations of promising concepts, pilot-scale proof-of-concept testing, and economic analysis of NO_x emissions control for reference coal-fired utility boilers.

COMPUTER MODEL APPLICATION FOR CONCEPT SELECTION

A task team consisting of B&W and Air Liquide engineers with complementary expertise in NO_x control and oxygen-enriched combustion was assembled to generate innovative oxygen injection concepts capable of achieving the performance targets. Both the wall-fired and cyclone-fired modes of operation were considered. Promising ideas that could meet our project goal included staged main combustion zone, deeply staged reburn zone, and managed use of oxygen and recycled flue gas in selective combustion zones. Those concepts were further refined for subsequent modeling based on commercial practicality, safe operation, mechanical simplicity, and maximum utilization of O_2 (minimum O_2 flow rate) for highest NO_x reduction and combustion enhancement. Practical ranges of key operating parameters (e.g., main combustion zone stoichiometry, reburning burner design and stoichiometry, extent of reburning, oxygen flow and velocity, flue gas recirculation flow, etc.) were also established by the team.

Combustion Model Description - B&W has leading edge capabilities for computational fluid dynamics (CFD) and combustion modeling. These capabilities were developed over the past 20 years and have culminated in the proprietary combustion model, $COMO^{SM}$. This model has been used routinely at B&W for more than a decade for improving the design and operation of boilers and boiler components (burners, NO_x ports, windboxes, convection passes, etc.). The CFD model uses an unstructured mesh with a mixture of element shapes for greater geometric flexibility, and adaptive mesh refinement to control resolution in regions of high gradients (e.g. turbulent jets, diffusion flames, etc.). $COMO^{SM}$ includes advanced capabilities for simulating turbulent flow, energy and radiation, heterogeneous reactions, particles, surface reactions, gas phase reactions, and tube banks. Coal combustion and emissions (CO and NO_X) models are maintained and improved on a continuous basis. $COMO^{SM}$ includes advanced sub-models for coal devolatilization and char burning, and utilizes especial algorithms for fuel-nitrogen release and char nitrogen conversion. Gas phase chemical kinetics are simulated with any number of species and reactions, using established mechanisms for hydrocarbons and nitrogen species, and including the effect of turbulent interactions on kinetic rates.

Modeled Cases – Over thirty cases were modeled by $COMO^{SM}$ spanning different boiler geometries, hardware settings, swirl direction, and oxygen and flue gas recycling (FGR) use in the main burner and reburn burners. COMO simulated the furnace, main burner, cyclone combustor, reburn burners, overfire air ports, and oxygen injectors. All components were modeled with sufficient control volumes. Local grid refinement was added to resolve the large gradients in flow, temperature, and species concentration in the burner near-field regions. Figure 1 shows the computer model of the wall-fired burner arrangement including two reburn burners and two OFA ports. Figure 2 shows the computer model of the cyclone combustor and the pilot-scale boiler. In the cyclone firing arrangement, the OFA ports were situated on the rear wall and the reburn burners were positioned about 3.25 ft below them. Table 1 lists the chemical composition of the reference eastern bituminous Pittsburgh #8 coal for modeling simulations. Table 2 lists the assumed coal size distributions.

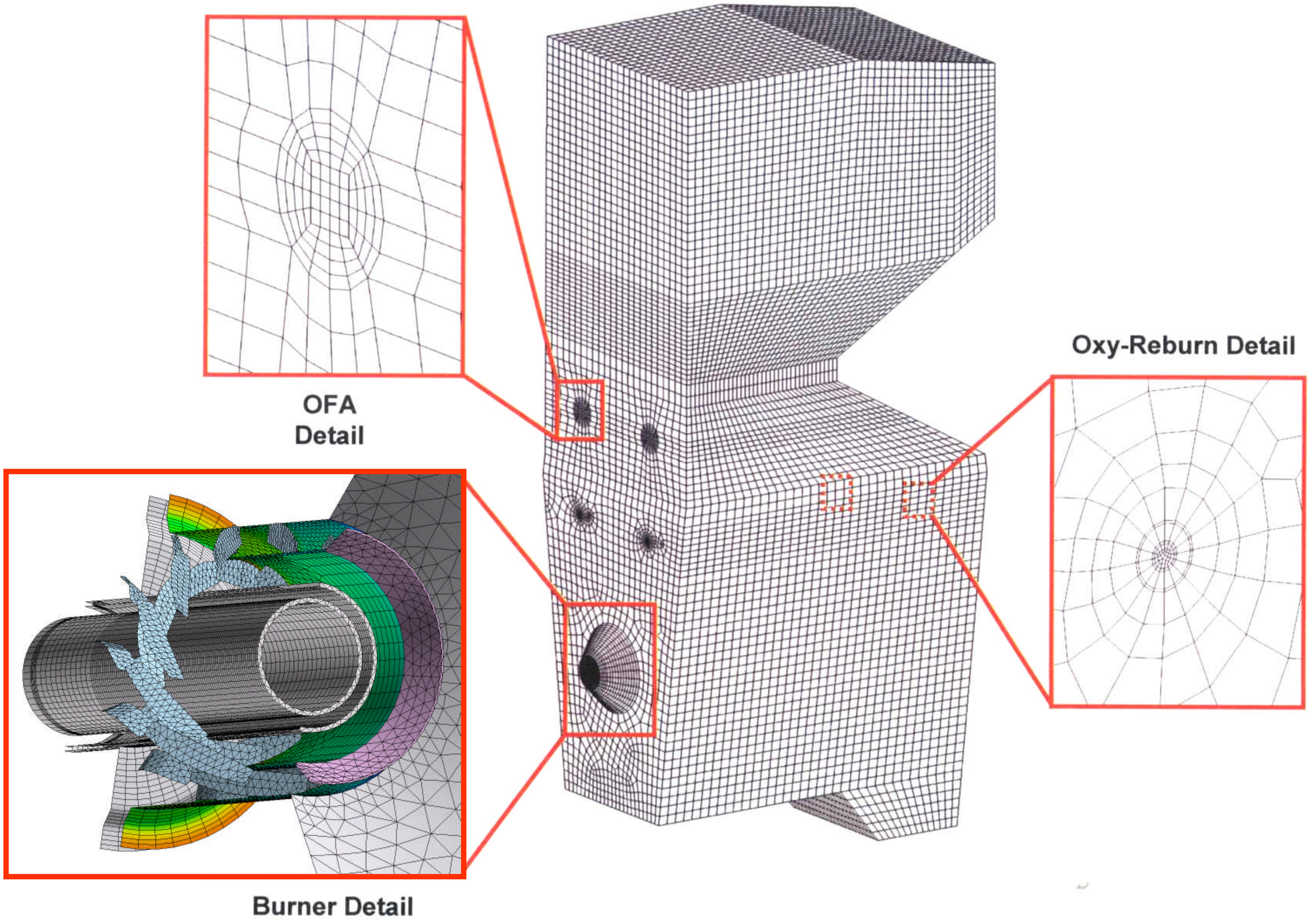

Figure 1. Computer model of the wall-fired burner and furnace

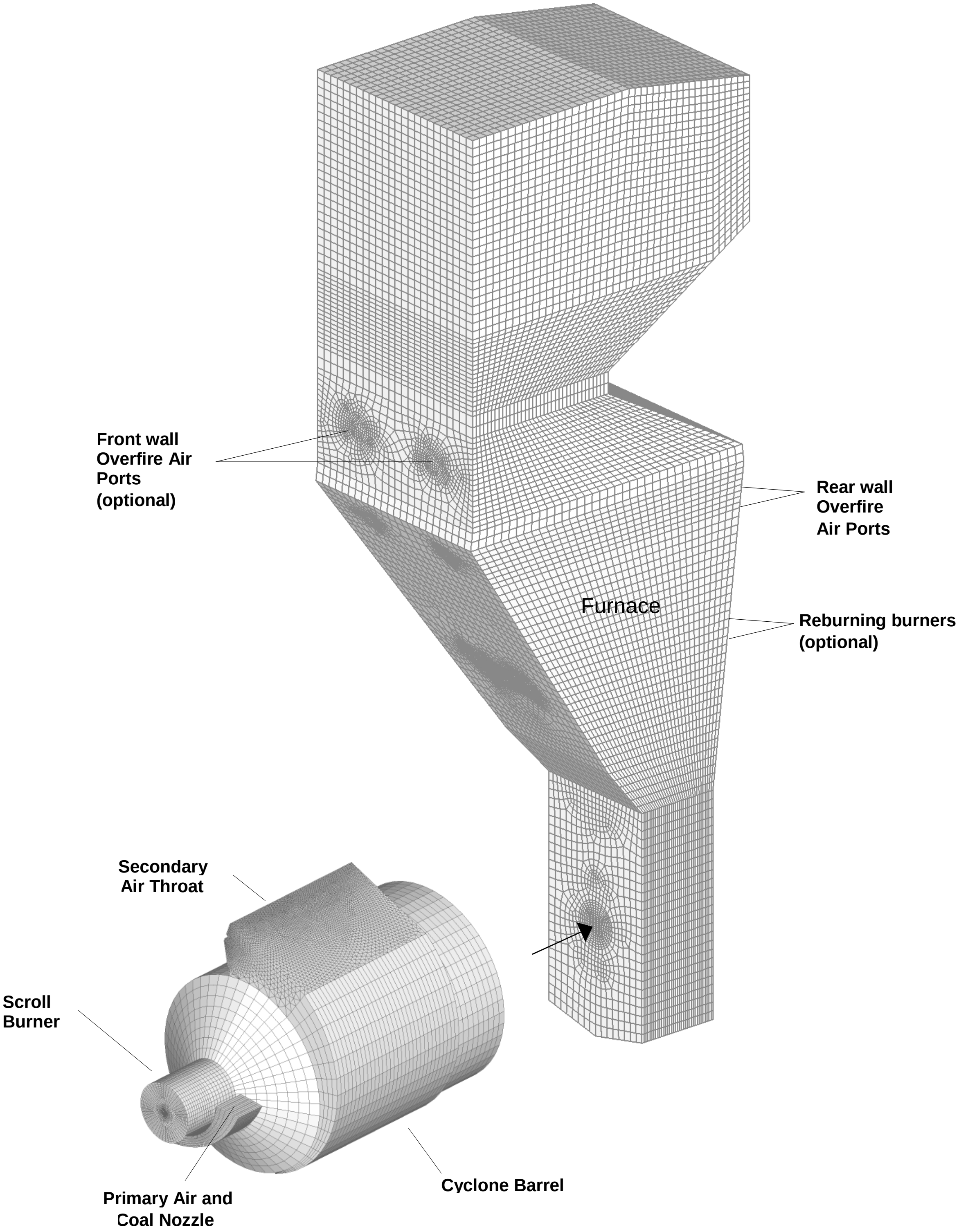

Figure 2. Computer model of the cyclone combustor and furnace

Table 1. Pittsburgh #8 Coal Analysis for Modeling Simulations

Proximate	Value
Fixed Carbon (%)	50.53
Volatile Matter (%)	37.63
Moisture (%)	3.50
Ash (%)	8.35
Ultimate	
Carbon (%)	74.91
Hydrogen (%)	4.59
Nitrogen (%)	1.42
Sulfur (%)	2.62
Chlorine (%)	0.11
Oxygen (%)	4.51
Heating Value (Btu/lb)	13,366

Table 2. Assumed Pulverized Pittsburgh #8 Coal Size Distributions

Mesh Designation and Size Screen # (µm)	Percent Smaller		
	Burner PC	Cyclone PC	Reburn PC
16 (1190)	100.0	100.0	100.0
30 (595)	100.0	99.4	100.0
50 (297)	99.9	93.5	99.9
70 (210)	99.3	84.2	99.4
100 (149)	96.9	72.0	98.0
140 (105)	87.6	57.9	94.0
200 (74)	70.3	45.0	85.0

Computations were carried out for 5 million Btu/hr firing at 0.80 combustion zone stoichiometry and 17% overall excess air. Baseline runs consisted of staged, air-blown operation, without reburning. Parametric simulations explored the effects of oxygen enrichment in the main combustion zone, and coal reburning with primary air (PA), oxygen, and recycled flue gas in the reburn zone. Extent of coal reburning and oxygen flow were set at 30% and 10% (of total O_2 flow in the boiler), respectively. For the reburning scenarios, the thermal load was split between the main combustion zone (3.5 million Btu/hr) and the reburn burners (1.5 million Btu/hr). FGR use was varied from 0 to 20%. All modeled cases and their results are summarized in Appendices I & II and discussed below.

At an early point during modeling, it became apparent that the computed NO_X levels could not be used reliably for choosing the best hardware due to their insensitivity to operational changes. So instead of using the NO_X results, we based the selection of optimum cases on proper flame attachment, reburn flame penetration, and mixing patterns of the main combustion zone effluents with the reburn zone by-products. Our goal was to create a large, high-temperature, and oxygen-deficient reaction zone within the furnace prior to the OFA ports. Such criteria have been known to be responsible for minimizing NO_X emissions.

<u>*Wall-Fired PC Cases*</u> - Selected results for three wall-fired arrangements are shown in Figures 3-5. Predicted furnace flow patterns, temperature, oxygen, and CO profiles are plotted for vertical planes passing through the centerlines of the main burner (top) and an OFA port (bottom), 1 ft away laterally from the main burner. In general, the high-momentum swirling flow of the main burner created a well-defined flame structure. Temperature peaked in the near-burner zone and around the flame envelope as oxygen was consumed rapidly following fuel devolatilization, giving rise to high CO levels further downstream of the burner. Addition and mixing of OFA with the combustion by-products oxidized the CO and char. In the baseline case (PC2), the in-furnace oxygen concentration was locally above 3% as seen in Figure 3, despite the sub-stoichiometric (fuel-rich) operation. Proper implementation of oxy-coal reburning in this region can decrease the oxygen availability, thereby reducing the NO_X formation potential.

Figure 4 shows a set of plots for case PC6 where 30% of the coal was fired with oxygen and FGR (each at 10% of the total throughput) via two 2-zone reburn burners. O_2 injection was accomplished with a centerline lance and its velocity was optimized over a wide range. With reburn burners operating at 0.63 stoichiometry, the combined combustion zone stoichiometry before adding OFA was about 0.75, which is just slightly less than the corresponding baseline stoichiometry of 0.80. Compared with the baseline air-blown operation, coal reburning with oxygen created a hotter and larger oxygen-depleted zone between the main burner and the OFA ports with greater potential for NO_X minimization. Both the main flame and the reburn flames appear well-attached. Figure 5 shows a similar set of results for 10% O_2-enrichment of the main burner (case PC25) by partial substitution of air. Here, two 1-zone (premixed PC/PA/O_2/FGR) oxy-coal reburn burners fired the supplementary fuel. Addition of oxygen to the main burner resulted in a locally higher flame temperature while maintaining the aforementioned favorable NO_X minimization characteristics.

<u>*Cyclone-Fired Cases*</u> - For cyclone combustors, it is imperative to attain high combustion temperatures to melt most of the coal-ash and tap it out to a slag tank. Oxygen-enrichment is one way to facilitate the flow of molten ash by increasing the combustion temperature, especially at part load operation. Two methods for oxygen enrichment were simulated. One involved a single-hole centerline lance and the other was a multi-hole secant injector at the secondary air entrance to the cyclone barrel. O_2 injection velocity was varied over a wide range. Oxy-coal reburning was achieved via two 1-zone (premixed PC/PA/O_2/FGR) burners. Among all cyclone-fired arrangements, case CY1 (air-staged cyclone plus oxy-coal reburn & FGR) and case CY9 (oxygen-enriched cyclone plus oxy-coal reburn & FGR) demonstrated the greatest potential for adequate slag tapping, high combustion efficiencies, and low NO_X emission. Again these cases were determined to be optimal by the virtue of their large and hot fuel-rich zones prior to reaching the OFA ports. Figure 6 compares the baseline (case CY10) and oxy-coal reburn (cases CY1 and CY9) predictions of temperature, O_2, and CO in the cyclone. Point sources of locally high O_2 concentrations are evident at the secondary air inlet to the cyclone for case CY9 where oxygen was injected via a multi-hole lance. Figures 7-9 illustrate the corresponding flow patterns, temperature, oxygen, and CO profiles in the furnace. For cases CY1 and CY9, the reburn flame is stabilized in the high-temperature and oxygen-deprived zone. There is also good penetration and mixing of the OFA in the burnout zone as seen in Figures 8 and 9. Use of FGR in the cyclone furnace was found to be undesirable due to its quenching effect on combustion temperature.

In retrospect, several promising cases for both wall-fired and cyclone-fired arrangements have emerged from the computer modeling efforts that warrant further evaluation for testing. In particular, cases involving oxy-coal reburn with 10% FGR, 10% O_2, with or without O_2-

enrichment of the main combustion zone can be conducive to significant NO_X reduction relative to baseline operation. Based on the modeling results, reburn burners, OFA ports, and oxygen injectors were designed for fabrication and testing. Special attention was devoted in the design efforts for maximum operational flexibility in interchanging various O_2 lances, adjusting their position, traversing the PC nozzle, and controlling O_2/PC/PA/FGR mixing patterns within the reburn burners.

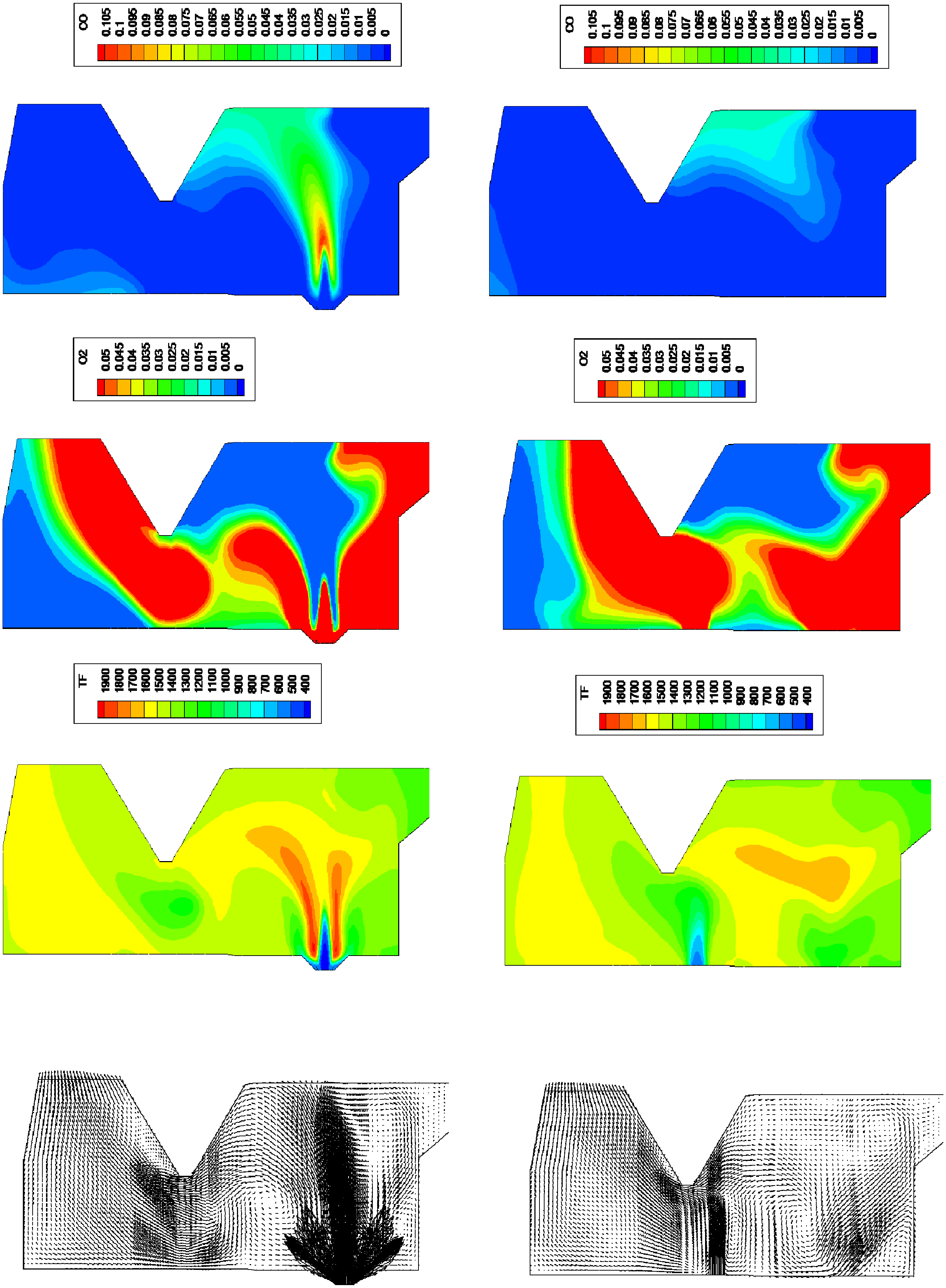

Figure 3. Computed velocity fields and contour plots of temperature (K), and O$_2$ and CO mole fractions for the baseline (case PC2) wall-fired operation at 0.80 PC burner stoichiometry and 17% overall excess air. Top and bottom plots represent the main burner and OFA centerline planes, respectively

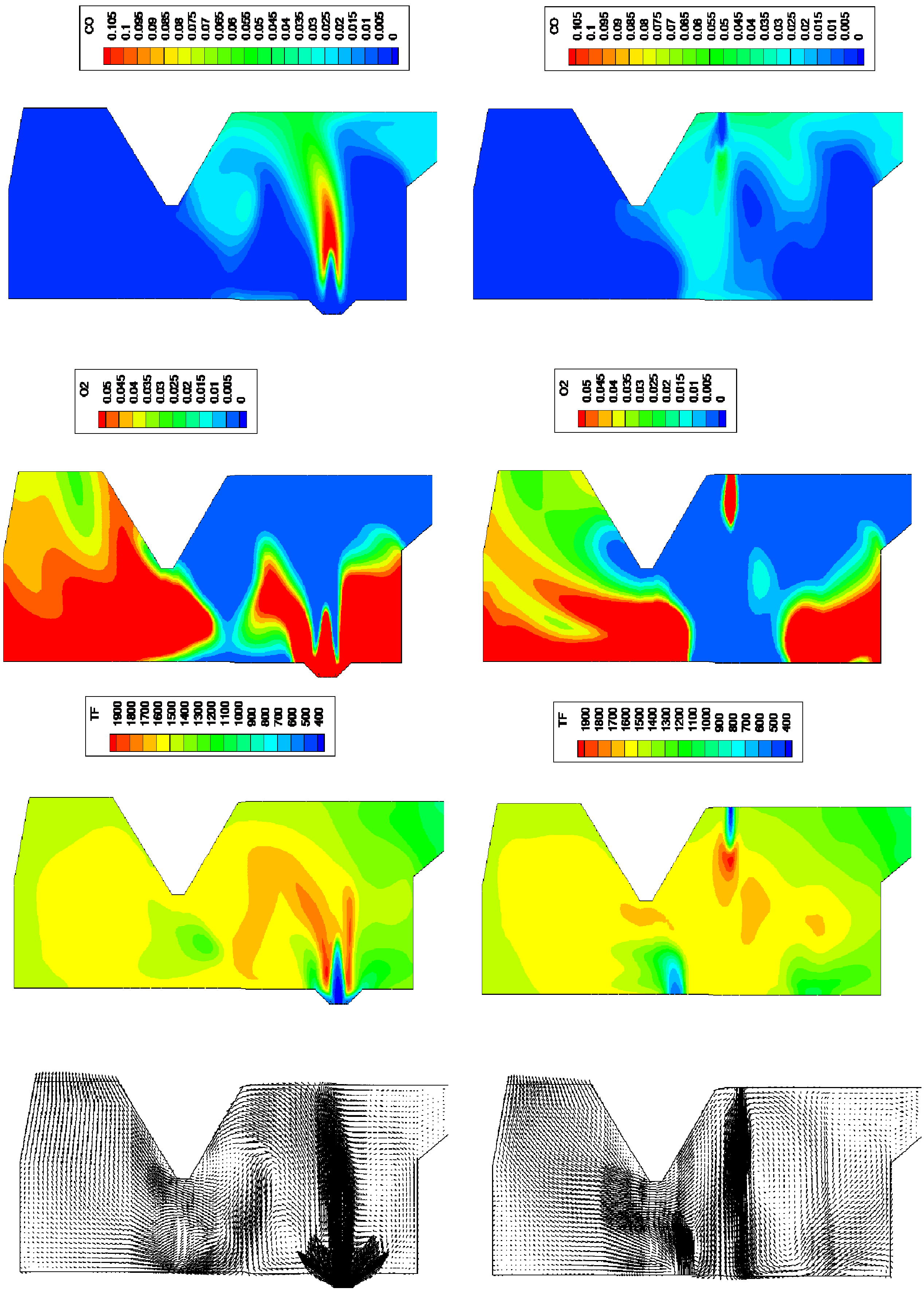

Figure 4. Computed velocity fields and contour plots of temperature (K), and O_2 and CO mole fractions for the wall-fired operation at 0.80 PC burner stoichiometry and 17% overall excess air with 30% coal & PA, 10% O_2, and 10% FGR to reburn burners (case PC6). Top and bottom plots represent the main burner and OFA centerline planes, respectively

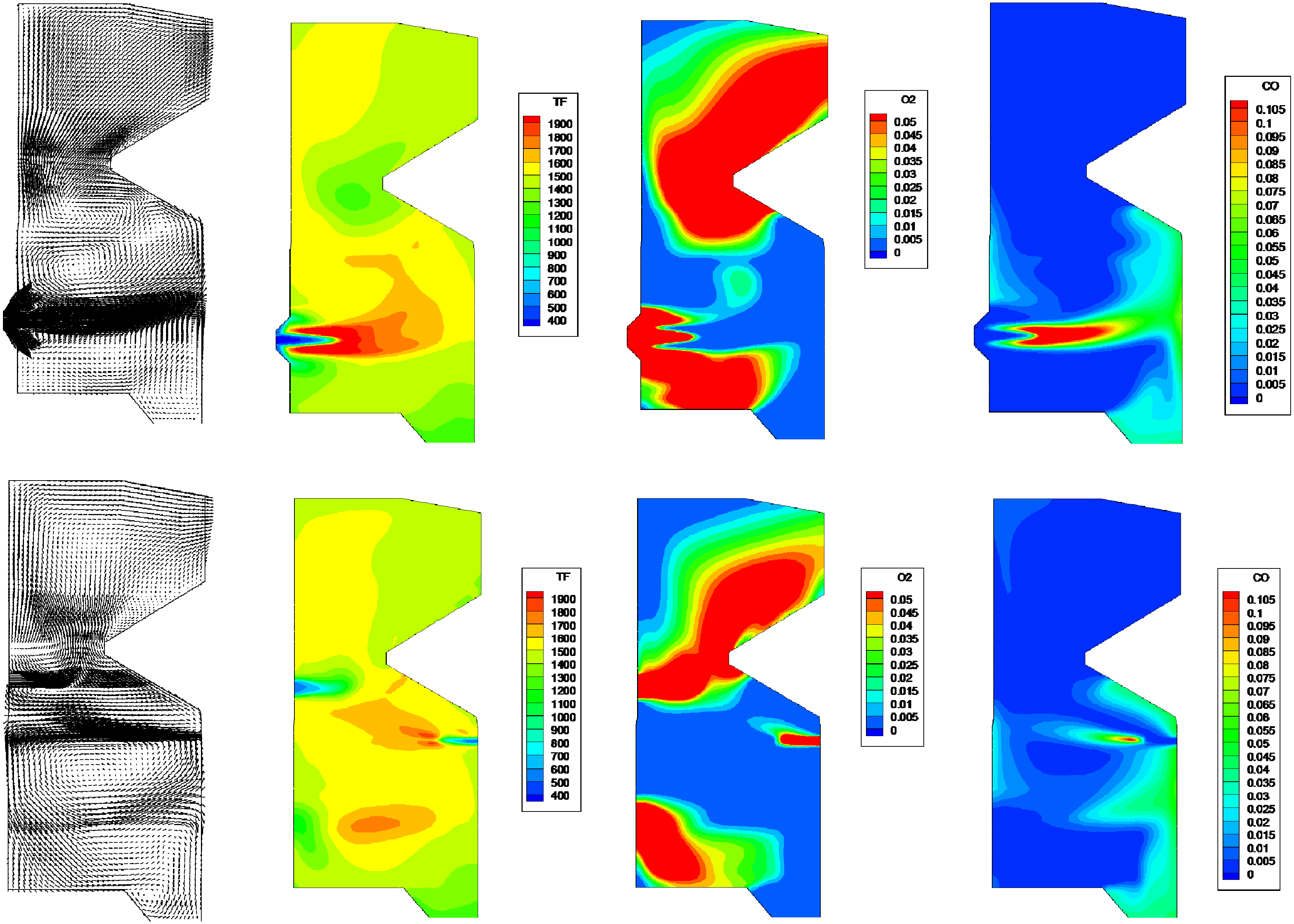

Figure 5. Computed velocity fields and contour plots of temperature (K), and O_2 and CO mole fractions for the 10% oxygen-enriched wall-fired operation at 0.80 PC burner stoichiometry and 17% overall excess air with 30% coal & PA, 10% O_2, and 10% FGR to reburn burners (case PC25). Top and bottom plots represent the main burner and OFA centerline planes, respectively

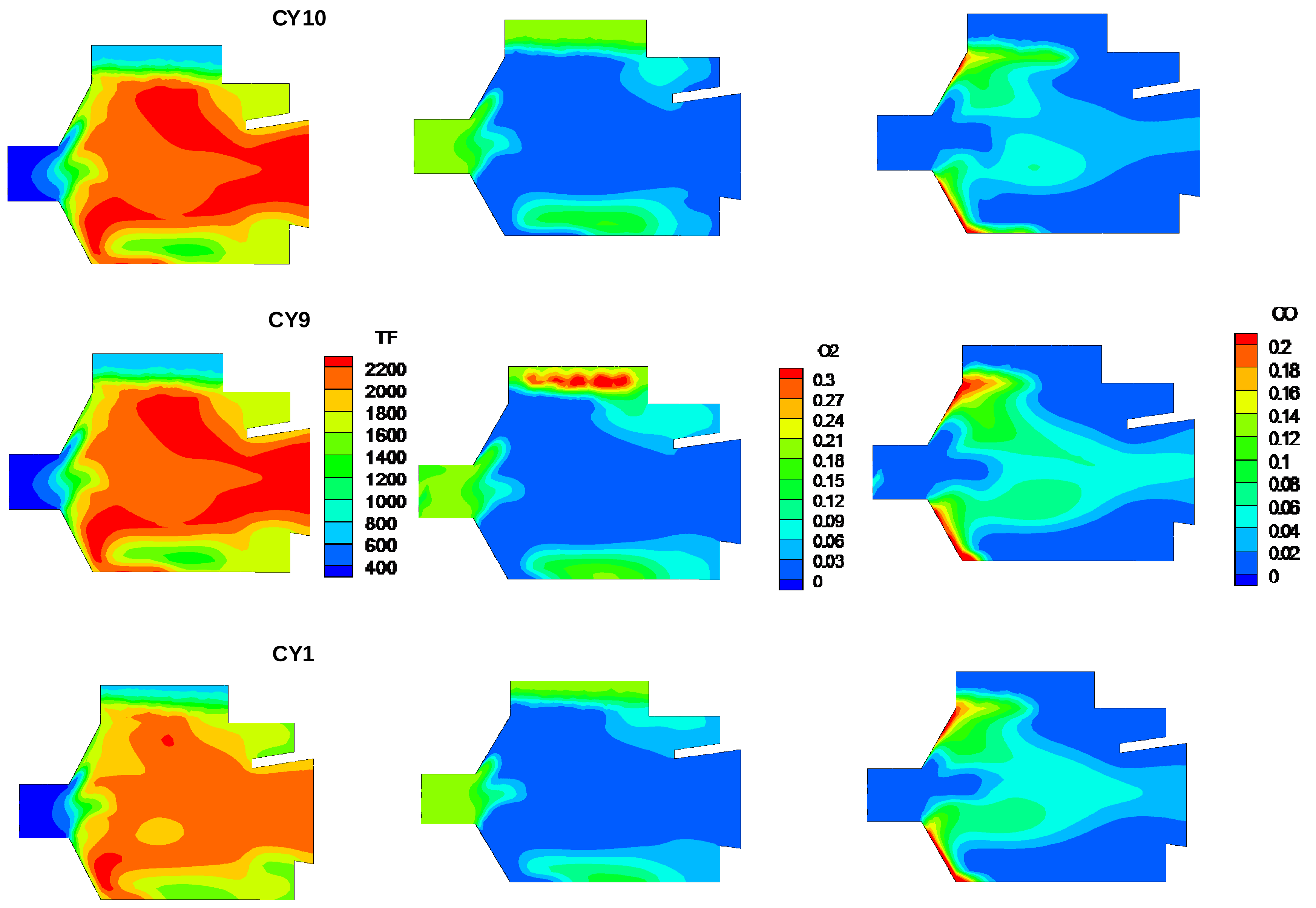

Figure 6. Computed cyclone centerline plane contour plots of temperature (K) , and O_2 and CO mole fractions for staged operation at 0.80 stoichiometry and 17% overall excess air. Case CY10: baseline (no reburning); case CY1: 30% coal reburn with 10% O_2 and 10% FGR; case CY9: same as case CY1 for reburn zone plus 10% O_2-enrichment in cyclone

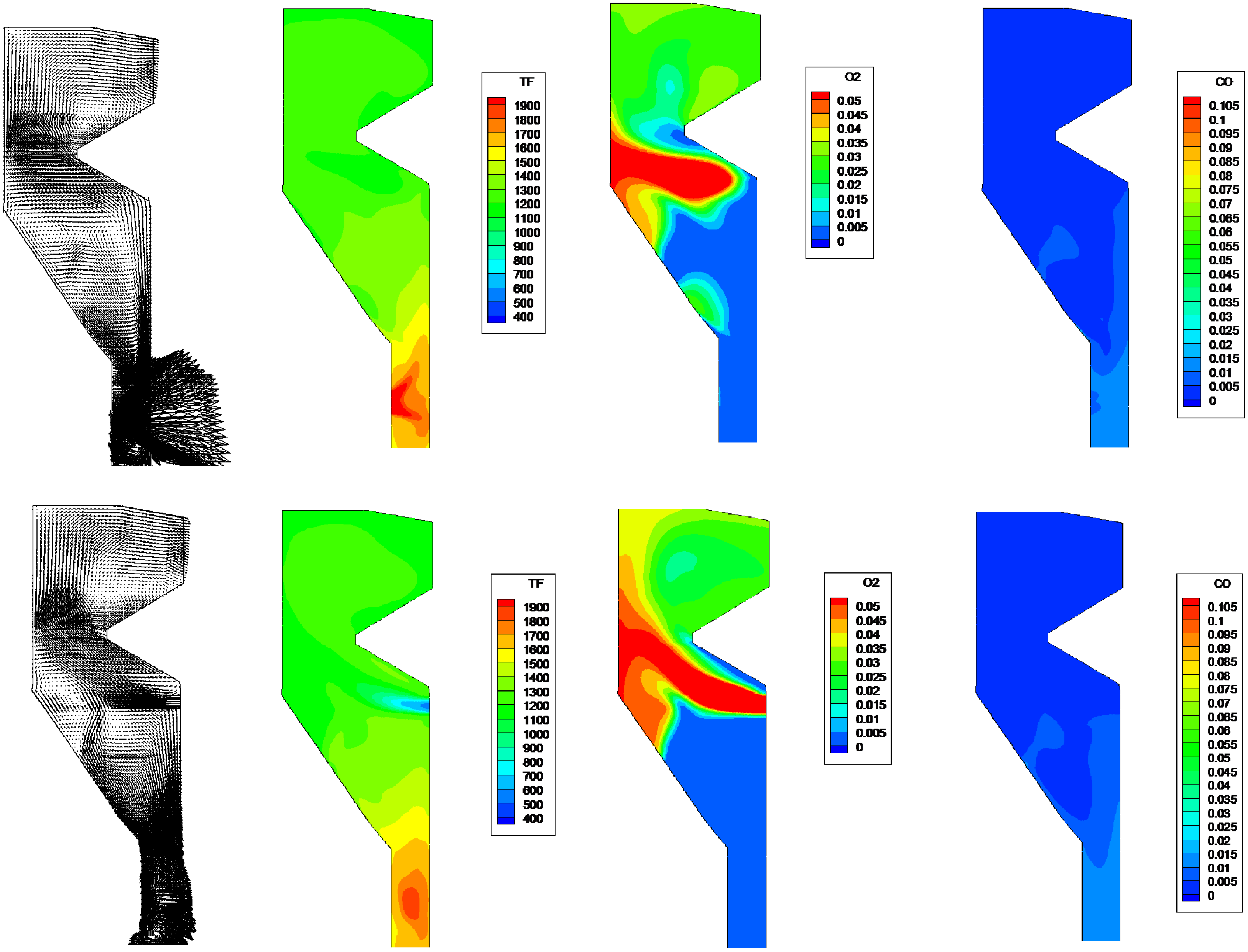

Figure 7. Computed furnace centerline (top) and OFA mid-plane (bottom) contour plots of temperature (K), and O_2 and CO mole fractions for staged cyclone operation at 0.80 stoichiometry and 17% overall excess air. Case C10: baseline (no reburning)

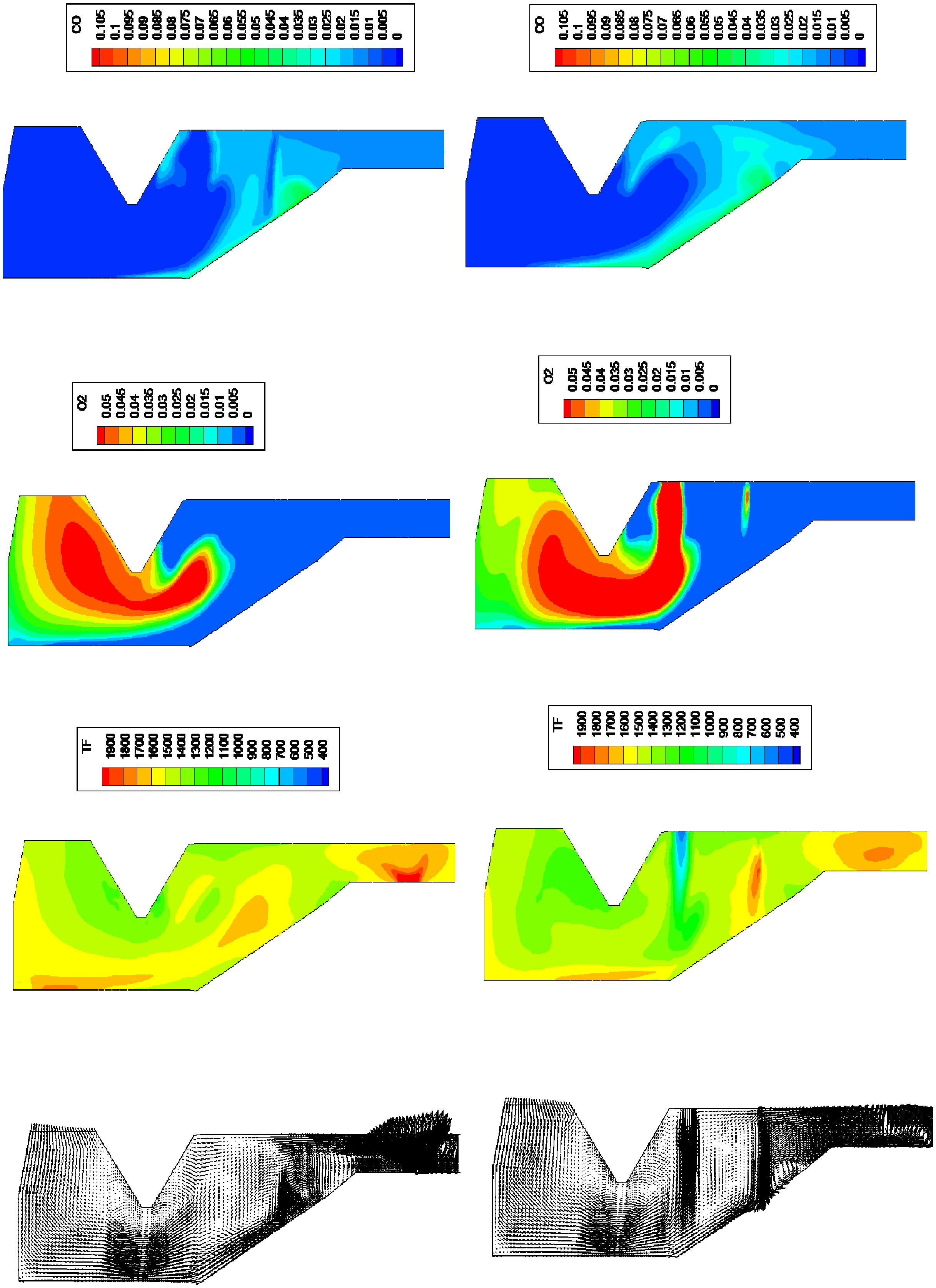

Figure 8. Computed furnace centerline (top) and OFA mid-plane (bottom) contour plots of temperature (K), and O_2 and CO mole fractions for staged cyclone operation at 0.80 stoichiometry, oxy-coal reburn, and 17% overall excess air. Case CY9: 30% coal & PA, 10% O_2, and 10% FGR to reburn burners without cyclone O_2-enrichment

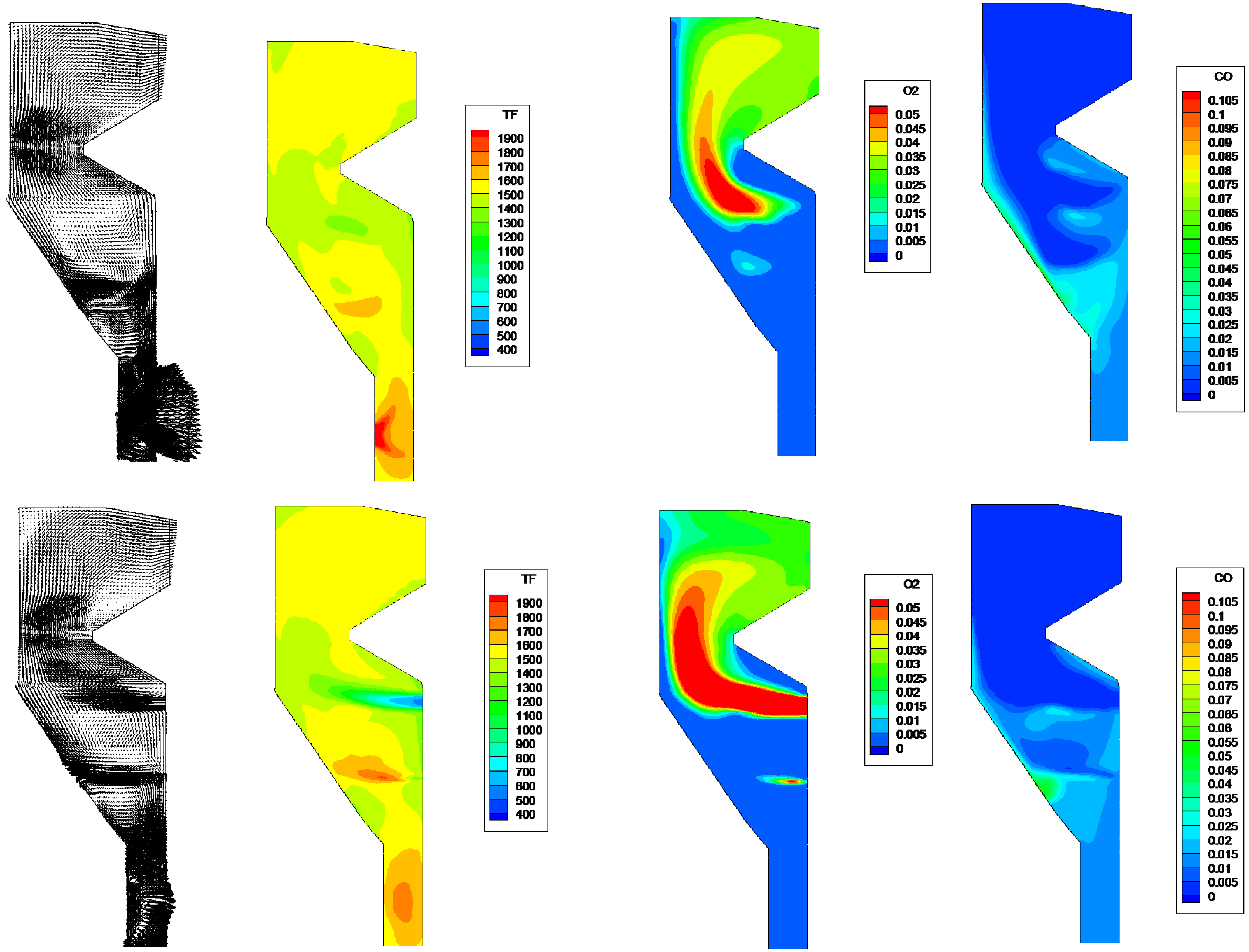

Figure 9. Computed furnace centerline (top) and OFA mid-plane (bottom) contour plots of temperature (K), and O_2 and CO mole fractions for staged cyclone operation at 0.80 stoichiometry, oxy-coal reburn, and 17% overall excess air. Case CY9: 30% coal & PA, 10% O_2, and 10% FGR to reburn burners with 10% cyclone O_2-enrichment

FACILITY MODIFICATIONS AND UPGRADES FOR PILOT-SCALE TESTING

In March 2006, B&W and Air Liquide began to modify and upgrade the pilot-facility. Below is the list of major activities that were completed in preparation for testing.

- Installation of reburn coal feed system to facilitate simultaneous firing of PC in the main combustion zone and the reburn zone
- Fabrication of two 2-zone reburn burners based on modeling recommendations
- Connection of coal supply, FGR, and oxygen lines to the reburn burners
- Construction of oxygen injection devices for the main burner, reburn burners, and cyclone furnace
- Fabrication and installation of flow dispersion devices for all burners and OFA ports
- Modification of existing oxygen delivery system to enable oxygen-enrichment in the cyclone burner and in reburn burners at desired flow rates
- Purchase and installation of three corrosion sensors including noise modules and electronics from Reaction Engineering International
- Installation of optical diagnostics sensors in appropriate furnace zones for combustion monitoring and optimization
- Programming new equations into the data acquisition system

Evaluation and optimization of NO_X control by deep staging, oxygen enrichment, and coal reburn were the main focus of pilot-scale test plans. Those plans included comparisons of baseline combustion and emissions data from conventional air-blown operation with oxygen-enhanced test results by the following measurements.

- Gas species concentrations (NO_X, CO, CO_2, O_2, and SO_2) and loss on ignition (LOI) at the convective pass section exit.
- Quantitative heat transfer determination by a combination of optical flame temperature mapping, furnace exit gas temperature (FEGT) probing, and incident and spectral measurements of the radiant heat flux.
- Collection and analysis of the convection pass exit gas-phase and particulate-phase mercury under optimum operations (minimal NO_X and maximum combustion efficiency).

PILOT-SCALE FACILITY DESCRIPTION

Small Boiler Simulator – Pilot-scale tests were performed in The Babcock & Wilcox Company's (B&W's) Small Boiler Simulator (SBS) facility, located in Alliance, Ohio. The water-cooled SBS furnace measures 4.5 ft wide by 7 ft deep by 17 ft high. When operated at its design capacity, the calculated furnace residence time is about 2 seconds. The interior surface of the SBS furnace is insulated to yield a furnace exit gas temperature of 2100 to 2300°F when firing a high-volatile bituminous coal at full load. In this project, the unit was configured separately for wall-firing and cyclone-firing, with and without coal reburning and oxygen enrichment.

For staged combustion, the main combustion zone was operated sub-stoichiometrically to minimize NO_X formation. Staging air was introduced at two elevations each equipped with 2 overfire air (OFA) ports downstream of the last combustion zone to burn out any remaining combustibles (i.e., CO and char). In the reburning arrangement, two single-register burners fired pulverized coal above the main combustion zone for NO_X control. Damper control and pressure drop indicators across the in-duct orifice plates are used to balance the airflow to each OFA port. Regardless of the firing mode, the combustion products exited the furnace and entered a convection pass where cooling water was circulated to the tube banks and walls. Deposits on the tubes and walls were removed by sootblowers. After leaving the convection pass, the flue gas was cooled further in a heat exchanger before entering a baghouse for capturing the particulate matter.

Cyclone Firing Configuration – Figure 10 illustrates the cyclone firing configuration of the SBS. A calibrated gravimetric feeder controlled the coal flow to the cyclone. Coarse pulverized coal (typically 44% through 200 mesh) was carried by heated primary air in the transport pipeline and into a scroll burner at the front center of the cyclone. Tertiary air was introduced from the center of the scroll burner to control the position of the main flame in the cyclone. As the coal/air mixture entered the cyclone barrel, it encountered a high-speed vortex from the 800°F secondary oxidant. Both the primary and secondary air streams swirled in the same direction. Fine coal particles burned in suspension and exited the center cone with hot gases. Due to centrifugal action, large particles were captured and burned in a molten layer of slag that formed on the inner walls of the cyclone. The molten mineral matter exited the cyclone furnace from a tap below the cyclone throat and dropped into a water-filled slag tank. About 80% of the coal ash left the cyclone as slag.

Figure 11 shows two possible ways of injecting oxygen into the cyclone. Several oxygen distribution lances with different discharge openings were constructed for testing the O_2-enrichment effects in the cyclone-fired mode.

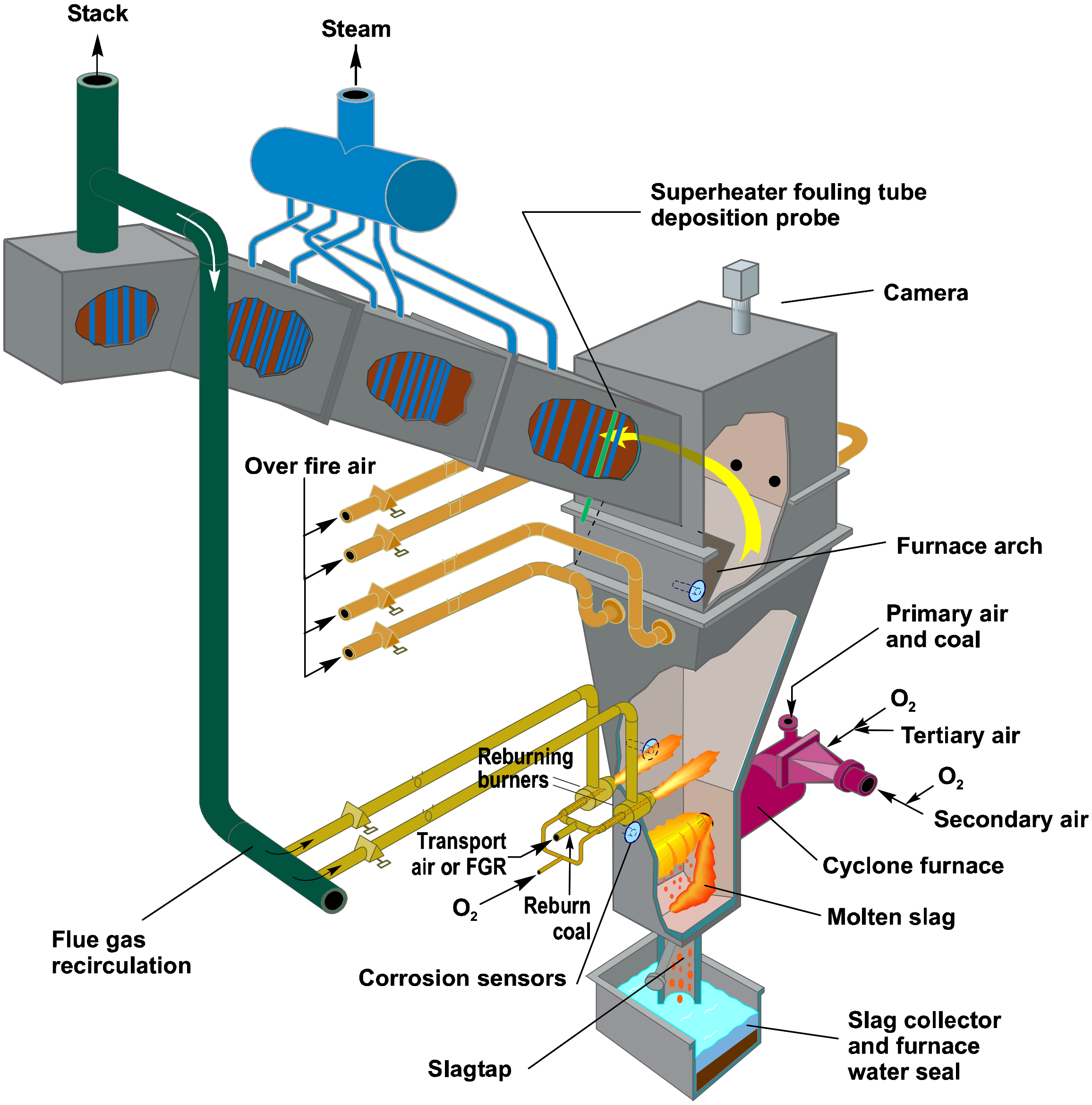

Figure 10. Cyclone-fired configuration of SBS

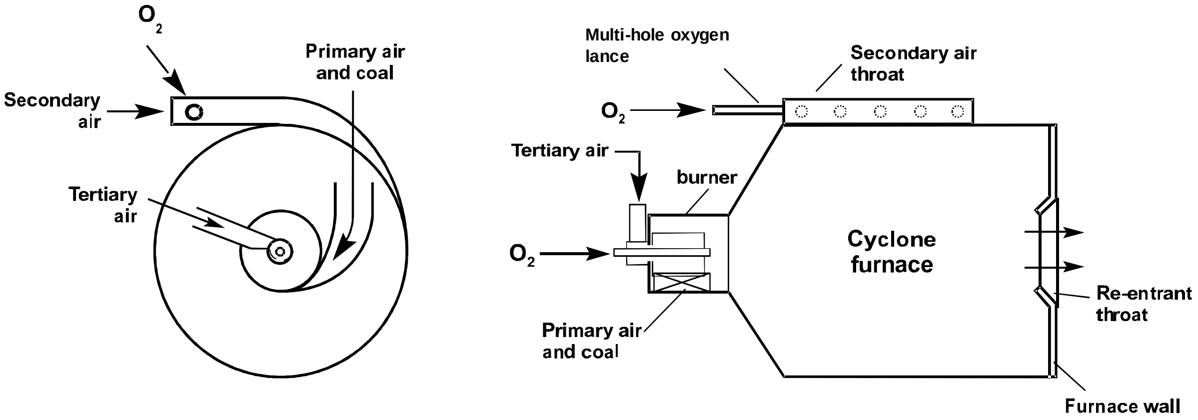

Figure 11. Oxygen enrichment in the cyclone furnace

Wall-Firing Configuration - Figure 12 shows the arrangement for the main burner, reburning burners and OFA ports. A 5 million Btu/hr, air-staged, geometrically scaled-down version of B&W's commercial ultra low-NO_X DRB-4Z® PC burner design was installed for the wall-firing tests. Figure 13 shows the standard components of the burner, schematically. The burner operates on the principle of controlled separation, distribution, and mixing of the oxidizer and fuel to minimize NO_X and unburned carbon emissions. Pulverized coal (70-75% through 200 mesh screen) feed rate from a storage bin was controlled and measured by a calibrated weigh feeder. The coal was then transported by heated air (120°F) to the burner. Secondary airflow was preheated indirectly by a gas-fired heater to 600°F. About 80% of the coal-ash exited the furnace as fly ash during PC firing. Oxygen was injected along the burner centerline into the fuel-rich combustion zone to accelerate the coal devolatilization. Lances with unique drilling patterns were used for optimum dispersion and mixing of the oxygen in the fuel-rich zone.

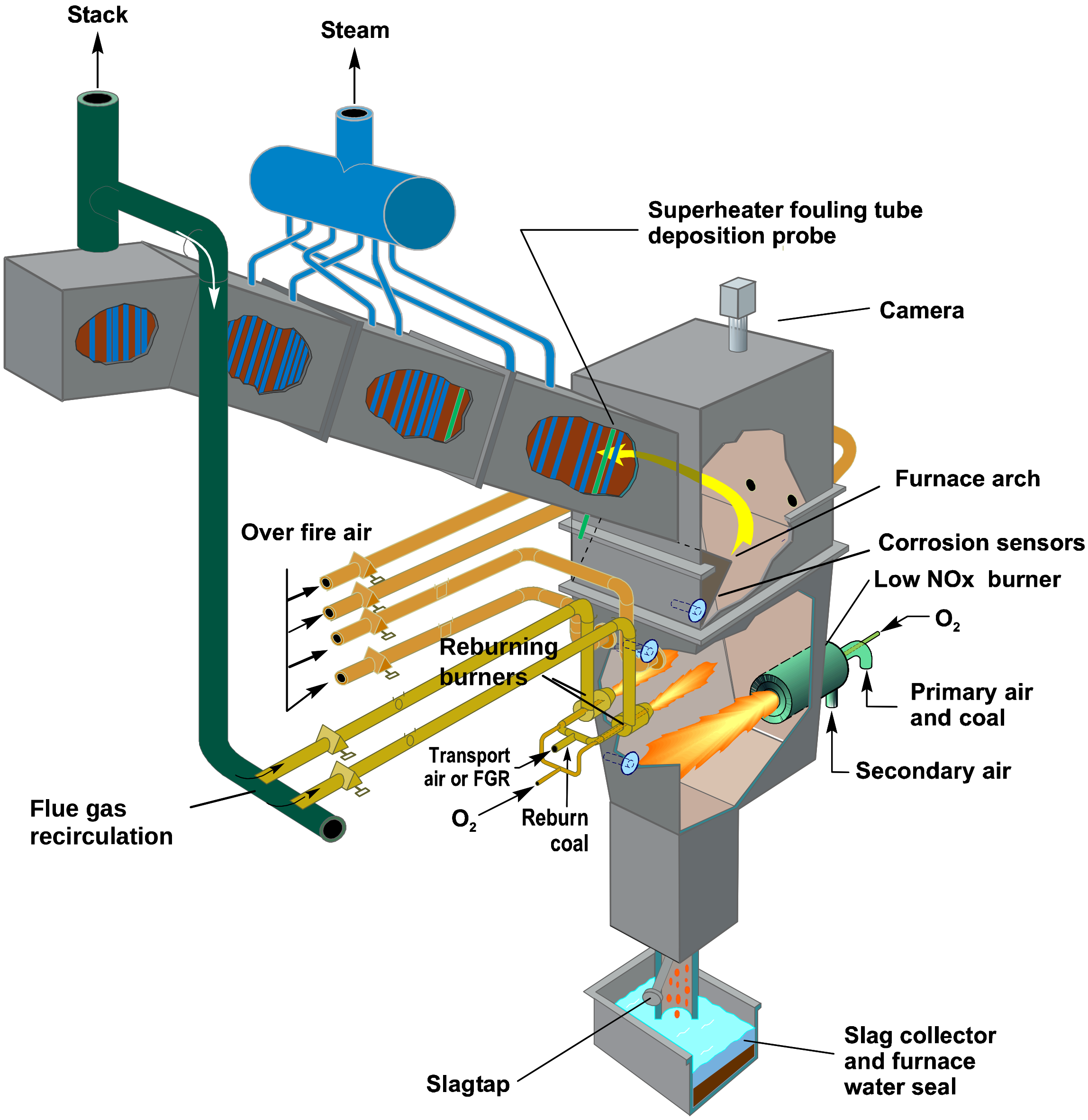

Figure 12. Wall-fired burner configuration of SBS

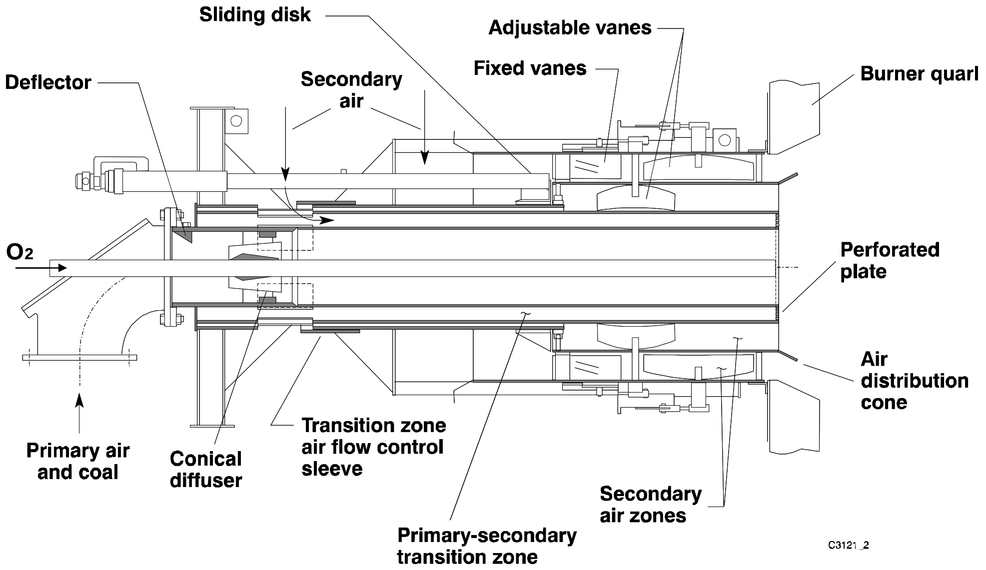

Figure 13. Oxygen enrichment in the low-NO_X DRB-4 Z® pulverized coal burner

Reburn Burner Arrangement – Computer modeling played a key role in designing the reburn burner shown in Figure 14. Two single-register reburn burners were installed as shown in Figures 10 and 12. For maximum operational flexibility, the reburn burner design featured a moveable coal nozzle, PC dispersion device, and oxygen lance. Reburn coal feed rate was controlled by a calibrated screw feeder. Figure 15 shows the screw feeder calibration curve. Compressed primary air (PA) transported the pulverized coal to the reburn burners. Flue gas recirculation (FGR) from the convection pass exit flowed into the reburner burners and traveled through moveable swirlers to enhance mixing in the furnace.

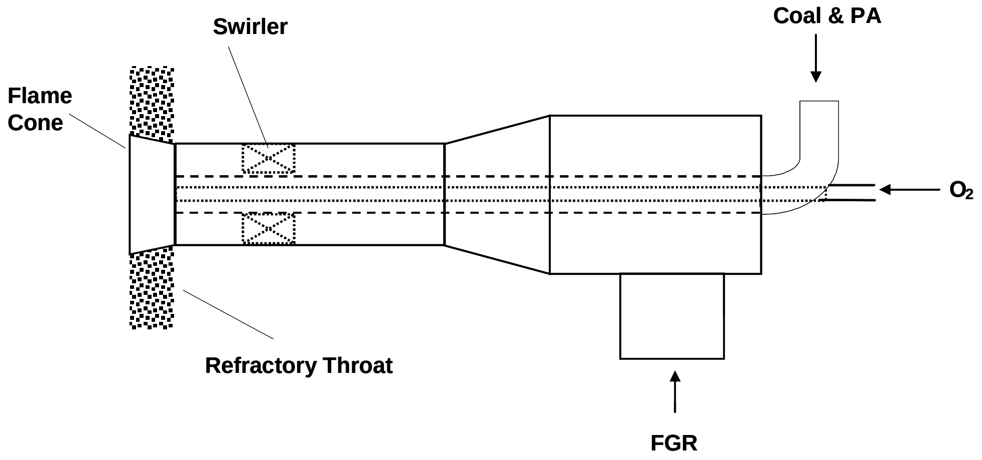

Figure 14. Oxy-coal reburn burner schematic

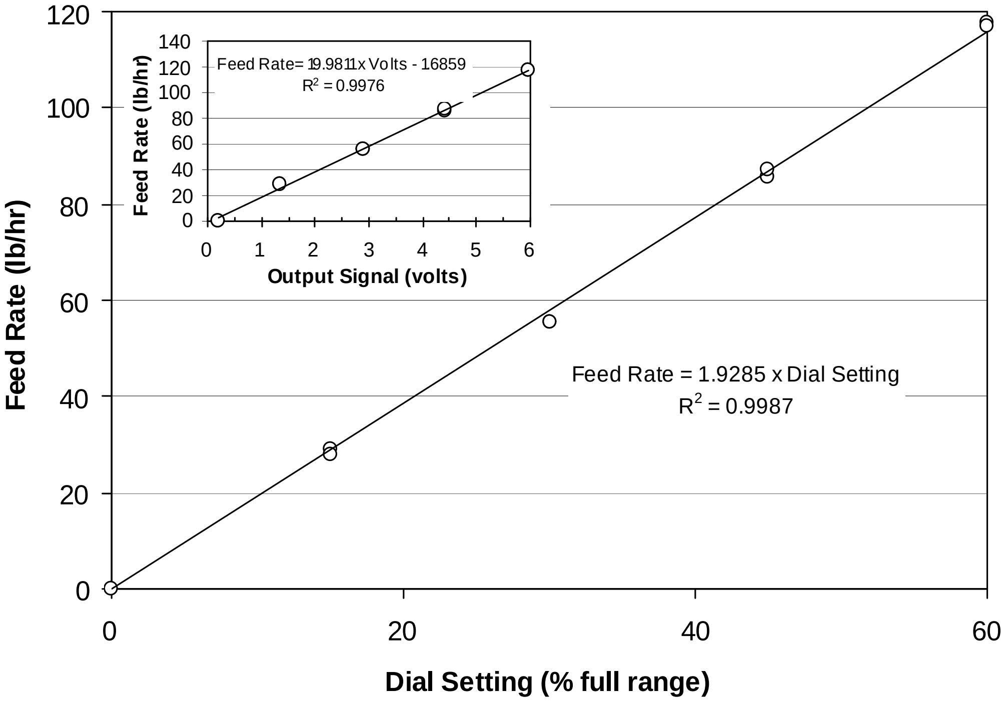

Figure 15. Reburn coal screw feeder calibration curve for 90% through 200 mesh PC

SBS Instrumentation - Measurements of the primary combustion air, secondary air, etc., relied on calibrated pressure transducers, thermocouples, and flow metering devices. Stack gases were sampled continuously from the convection pass section outlet at about 600°F through a heated sample line. After filtering and drying, CO, CO_2, O_2, SO_2, and NO_X concentrations were measured by calibrated analyzers. Table 3 lists the gas analysis instrumentation and their measurement principles.

Table 3. Gas Analysis Instrumentation

Gas Species	Analyzer	Model Number	Measurement Principle
O_2	Rosemount	NGA-PND	Paramagnetic
CO_2	Rosemount	NGA-NDIR	NDIR
CO	Rosemount	NGA-NDIR	NDIR
NO_X	Rosemount	NGA-CLD	Chemiluminescence
SO_2	Rosemount	NGA-NDIR	NDIR

Fly ash was sampled across the convection pass section exit via an isokinetic probe. Representative samples at each test condition were collected on a glass fiber filter and analyzed for loss on ignition (LOI). Previous work at B&W has shown that LOI measurements closely approximate the fly ash unburned carbon levels.

Mercury Sampling and Measurement System - Coal-mercury transformation was quantitatively determined by Western Kentucky University according to the Ontario Hydro procedure[†]. Cumulative batch samples at the convection pass outlet were obtained by radial traverses of an isokinetic stack sampler (EPA Method 17: In-stack Filtration Method). Mercury contents of the collected particulate matter and the absorbed gas phase in impinger solutions, including elemental and oxidized fractions, were measured by cold vapor atomic absorption spectroscopy (CVAAS). The fate of coal-mercury and its transformation were determined from material balance calculations.

Temperature and Heat Absorption Measurement Equipment - Oxygen injection to various combustion zones is likely to influence the heat capacities and radiative properties of the gas phase. Heat transfer variations can be quantified by several complementary methods. Furnace exit gas temperatures were measured by a K-type, water-cooled, high-velocity-thermocouple (HVT) probe. Non-intrusive flame temperature mapping was done with an optical pyrometry system from Diamond Power Specialty Company called FLAMEVIEW^{TM}. The unit comprises a CCD (Charge Coupled Device) array camera mounted on the roof of the SBS and directly above the flame with a 50° field of view. Two-dimensional temperature maps were generated from the live flame image via a patented process utilizing two-color pyrometry in the visible and near infrared (IR) region.

Total radiation emitted from a known flame region was measured with a thermopile detector. Thermopile detectors have a spectrally flat response to thermal radiation over the wavelength range of about 0.2 to 50 micrometers. The detector approximates a “grey body” in which the absorptance (emittance) is constant with wavelength. A protective window reduces the responsive wavelength range to about 0.6 to 18 micrometers. For temperatures in the range of 1500°F to 3000°F, this wavelength range contains about 95% or more of the total thermal radiation.

Spectral radiance was measured using a computer-controlled scanning monochromator. The monochromator is equipped with multiple photodetectors and gratings that can span a measurement range of about 0.2 to 15 micrometers. Silver-coated first surface mirrors directed the flame radiation to the thermopile and to the scanning monochromator. An off-axis parabolic mirror (fastened to a rotating mount) collected the light. This arrangement permitted the selection of thermal radiation from a blackbody calibration source or flame by simply rotating a single mirror. Figure 16 shows the equipment. The thermopile detector was mounted at the same optical height as the monochromator, thus, it could be simply inserted into the path of the collected light to make a measurement. The light entering the monochromator was modulated with a chopper wheel, and the electronic signal from the photodetectors was amplified and processed with a lock-in amplifier. The lock-in amplifier and monochromator were interfaced to a computer which operated the equipment.

[†] ASTM D6784-02 “Standard Test Method for Elemental, Oxidized, Particle-Bound and Total Mercury in Flue Gas Generated from Coal-Fired Stationary Sources (Ontario Hydro Method),” American Society for Testing and Materials, 2002.

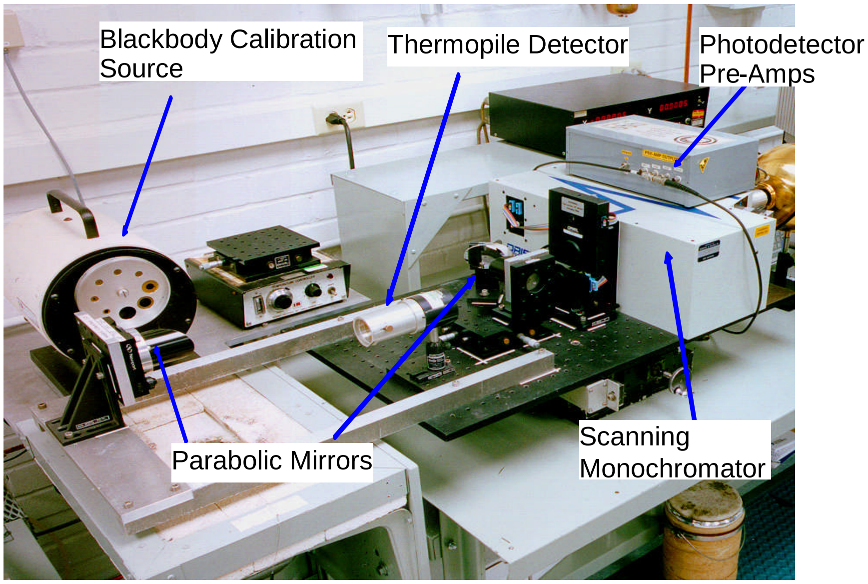

Figure 16. Photograph of the thermopile detector, scanning monochromator and light collection mirrors

Oxygen Supply System - Liquid oxygen was delivered by trucks and stored in a 9,000 gallon tank. The liquid oxygen was vaporized in an ambient vaporizer. Gaseous oxygen was then regulated to an appropriate pressure (50 psig) and delivered to the test area via a copper line. Air Liquide modified an existing oxygen valve skid to enable oxygen-enrichment in the cyclone burner and in reburn burners according to National Fire Protection Association (NFPA 86) standard, CGA G4.1 and G4.4 guidelines and Air Liquide's internal Oxygen Piping Design Standard Practices. The PLC and HMI (human – machine interface) systems were upgraded and integrated into the SBS safety interlock system, allowing oxygen flows to be safely and accurately controlled and monitored from a central location. Figure 17 shows photographs of the liquid oxygen tank, vaporizer, and O_2 valve skid.

Figure 17. Photographs of the liquid oxygen tank and evaporator (top), and the valve skid (bottom)

Advanced Combustion Monitoring and Optimization System - Silicon photodiode optical sensors were mounted on the main burner, cyclone, reburn burners or in the vicinity of the overfire air ports. B&W uses these sensors routinely on commercial boilers or plants that do not have flame scanners. A portable Flame Doctor® system, typical of units used by B&W field service engineers for flame diagnostics and burner tuning, was set up to receive signals from various combustion zones. Existing algorithms in the Flame Doctor® system provided a quantitative indication of combustion stability for each hardware configuration and operating condition. Together with emissions data and 2-color pyrometer temperature mapping, optimum combustion conditions were identified. Raw signal and processed data from the Flame Doctor® were archived to the system computer hard drive for further analysis.

Electrochemical Noise (EN) Corrosion Monitoring Sensors - EN sensors utilize non-perturbative measurements to evaluate electrochemical activity associated with corrosion and degradation processes as they occur at the furnace wall. By analyzing the fluctuations in current and voltage occurring between nominally identical elements, the electrochemical condition at a corroding interface can be characterized.

Three probes equipped with EN sensors were installed by the Reaction Engineering International (REI) in three different locations based on prior test facility operating experience and modeling recommendations. These locations were on the main combustion zone target wall, reburn burner plane, and the interface between the reburn zone and first row of OFA ports. Photographs of the corrosion monitoring probes are shown in Figure 18.

Figure 18. Before-installation photographs of three corrosion monitoring probes. Sensor surfaces can be seen on the front faces of the probes in picture on the right.

Figure 19 shows two of the installed probes and associated electrical and air connections. The EN sensors were positioned flush with the surface of the furnace refractory wall and the electrical and air connections were verified. After that, the sensor surface temperature set point was chosen to be 450°C (840°F) and the probes' surface temperatures were monitored. Once the face temperature was maintained, the electrochemical noise data were recorded continuously and plotted. All data were stored on computer disks and analyzed using standard statistical procedures.

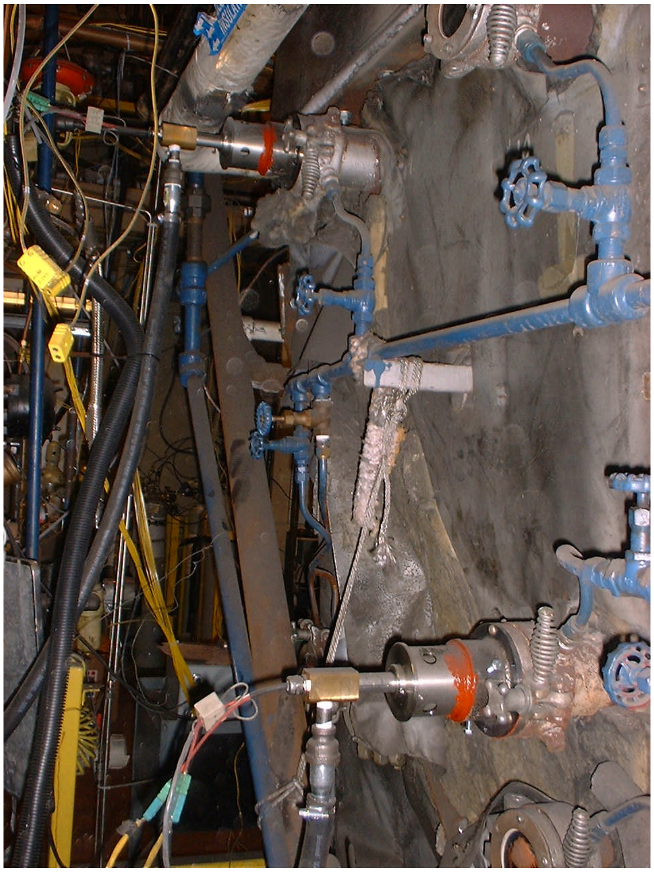

Figure 19. Photograph of two corrosion monitoring probes installed at different elevations on the furnace side wall.

TEST RESULTS

Coal Procurement and Analysis - A high-volatile, eastern bituminous Pittsburgh #8 coal was purchased for testing. Table 4 lists the proximate and ultimate analyses, heating value, and chlorine content of the as-received coal sample. Ash composition and trace elements for the Pittsburgh #8 coal are listed in Tables 5 and 6, respectively. Pulverizer settings were adjusted to produce the desired fineness. Pulverized coal samples were extracted from the PC-laden stream after the mill and checked for fineness using stacked sieves of 200 to 8 mesh screens (74 to 2380 µm). Table 7 tabulates representative as-fired pulverized coal fineness for the low-NO_x burner, reburn burners, and the cyclone furnace. Leftover Black Thunder Powder River Basin coal from another project was also used for a one-day cyclone firing test. Coal analysis and PC fineness results for the Black Thunder coal are also shown in Tables 4, 5, and 7. In order to facilitate the wet Black Thunder coal handling by the fuel preparation equipment, its moisture content was reduced by partial drying from 25.92% to 18.16%.

Table 4. As-Received Coal Analyses

Constituents	Pittsburgh #8	Black Thunder
Proximate		
Fixed Carbon (%)	47.17	37.43
Volatile Matter (%)	37.34	30.84
Moisture (%)	6.10	25.92
Ash (%)	9.39	5.81
Ultimate		
Carbon (%)	71.14	50.57
Hydrogen (%)	4.94	3.66
Nitrogen (%)	1.18	0.56
Sulfur (%)	3.53	0.30
Oxygen (%)	3.72	13.18
Miscellaneous		
Chlorine (ppm)	507	NM
Heating Value (Btu/lb)	12,695	8,718

Table 5. Ash Composition Analyses (weight %)

Constituents	Pittsburgh #8	Black Thunder
SiO_2	42.94	38.23
Al_2O_3	20.49	17.76
Fe_2O_3	24.23	6.46
CaO	2.98	16.19
MgO	0.64	4.09
Na_2O	0.49	1.03
K_2O	1.67	0.67
P_2O_5	0.51	1.52
TiO_2	1.60	1.01
BaO	-	0.57
SrO	-	0.30
SO_3	2.29	9.84

Table 6. Trace Elements in Pittsburgh #8 Coal

Element	(ppmw dry)
Arsenic	10.5
Barium	56.1
Beryllium	0.450
Cadmium	0.075
Chromium	14.3
Lead	3.34
Manganese	20.6
Mercury	0.13
Nickel	18.8
Selenium	2.51
Vanadium	25.3
Zinc	13.1

Table 7. As-Fired Coal Fineness

Mesh Designation and Size	Percent Smaller				
	Pittsburgh #8				Black Thunder
Screen # (µm)	Cyclone	Low-NO$_x$ Burner	Reburn Burner		Cyclone
			Standard	Fine	
8 (2380)	100.00	100.00	100.00	100.00	100.00
16 (1190)	99.96	100.00	100.00	100.00	99.96
30 (595)	99.36	100.00	100.00	100.00	98.73
50 (297)	93.82	99.96	99.96	100.00	87.03
70 (210)	84.02	99.82	99.82	99.92	72.18
100 (149)	71.22	98.13	98.13	99.57	57.71
140 (105)	46.10	88.55	88.55	97.07	43.74
200 (74)	45.44	73.37	73.37	90.08	34.66

<u>Pilot-Scale Test Procedures</u> - Each test day began with a 2-hour warm-up period that involved heating the combustion air and firing natural gas through the igniter. Instrument calibration and general system checks were done during this period and re-examined periodically throughout the day. Once suitable furnace conditions for coal firing were reached, coal and air were introduced gradually into the boiler and ignited by the natural gas pilot flame. Shortly after, the pilot flame was shut off, and the coal feed rate was increased progressively over another hour until the desired load was established. The furnace was then allowed to warm up for at least one more hour until the convection pass exit temperature and species concentrations reached steady state levels.

During each test, analog data from pressure transducers, thermocouples, and gas analyzers were sampled electronically every 10-15 seconds and averaged over a preset time span. Commercially available LabView® software was used for data acquisition. Performance reproducibility was verified by repeating selected tests. About 10 hours after the initial startup, the facility was shut down and allowed to cool for a couple of hours before it was left unattended until the next test day.

Wall Firing Tests

In these series of tests, the SBS furnace was configured for wall-firing of Pittsburgh #8 coal in an air-staged, scaled-down version of the B&W commercial DRB-4Z® low-NO_X PC burner. Test results from baseline air-blown operation and oxygen-enriched combustion including coal reburning are described next.

Baseline Wall-Fired Coal Combustion - Baseline performance data were collected without oxygen enrichment or reburning. Burner settings (spin vane angles and air damper throttle) were optimized at full load (5 x 10^6 Btu/hr), 0.80 burner stoichiometry, and 1.17 overall stoichiometry. The burner stoichiometry was then varied from 0.7 to 1.0 by splitting the total secondary airflow between the burner and the OFA ports. Figure 20 compares the effect of burner stoichiometry on NO_X, CO, and LOI at a fixed overall excess air level of 17% where all of the staging air was diverted to the lower level OFA ports on the furnace rear wall. With the DRB-4Z® burner, NO_X emissions dropped with decreasing burner stoichiometry and oxygen availability in the flame zone, reaching the lowest level at 0.80 stoichiometry. But further reduction of burner stoichiometry below the 0.80 value actually generated more NO_x due to the oxidation of certain nitrogenous species (e.g., HCN and char-N) in the overfire air zone. LOI and CO levels tracked each other closely and varied modestly with burner stoichiometry variations.

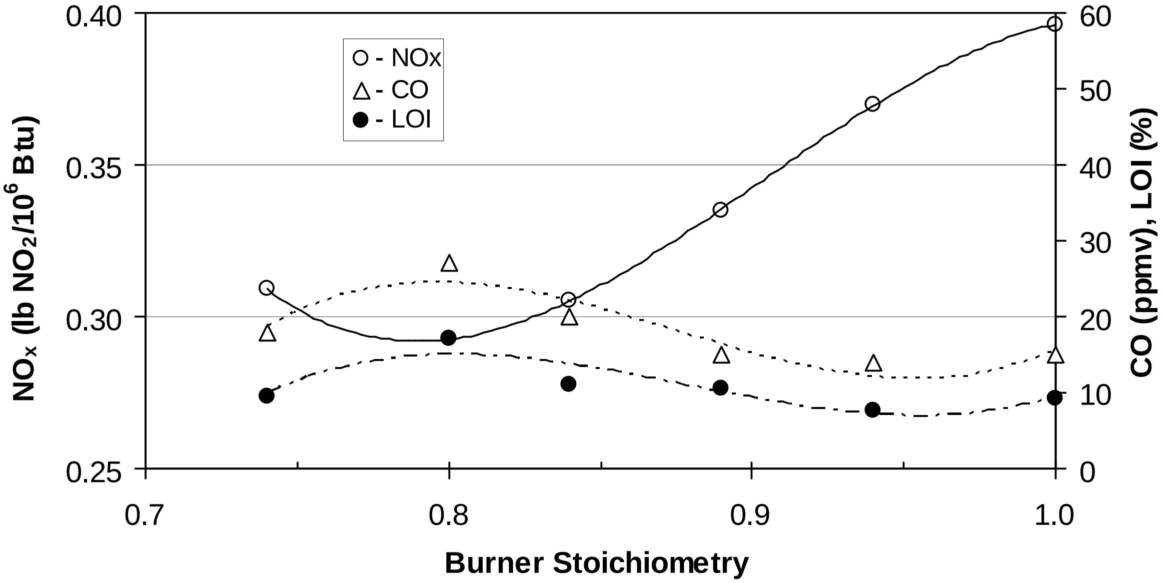

Figure 20. Burner stoichiometry effects on NO_x, CO, and LOI for the DRB-4Z® burner using lower level OFA ports. Nominal operating conditions: 5 million Btu/hr, 17% overall excess air, and 73% through a 200 mesh screen Pittsburgh #8 coal fineness.

Figure 21 shows the still images of the staged flames and corresponding 2-D temperature maps at different burner stoichiometries. As expected, the flame luminosity and temperature increased when the burner stoichiometry was raised from 0.80 to 1.00.

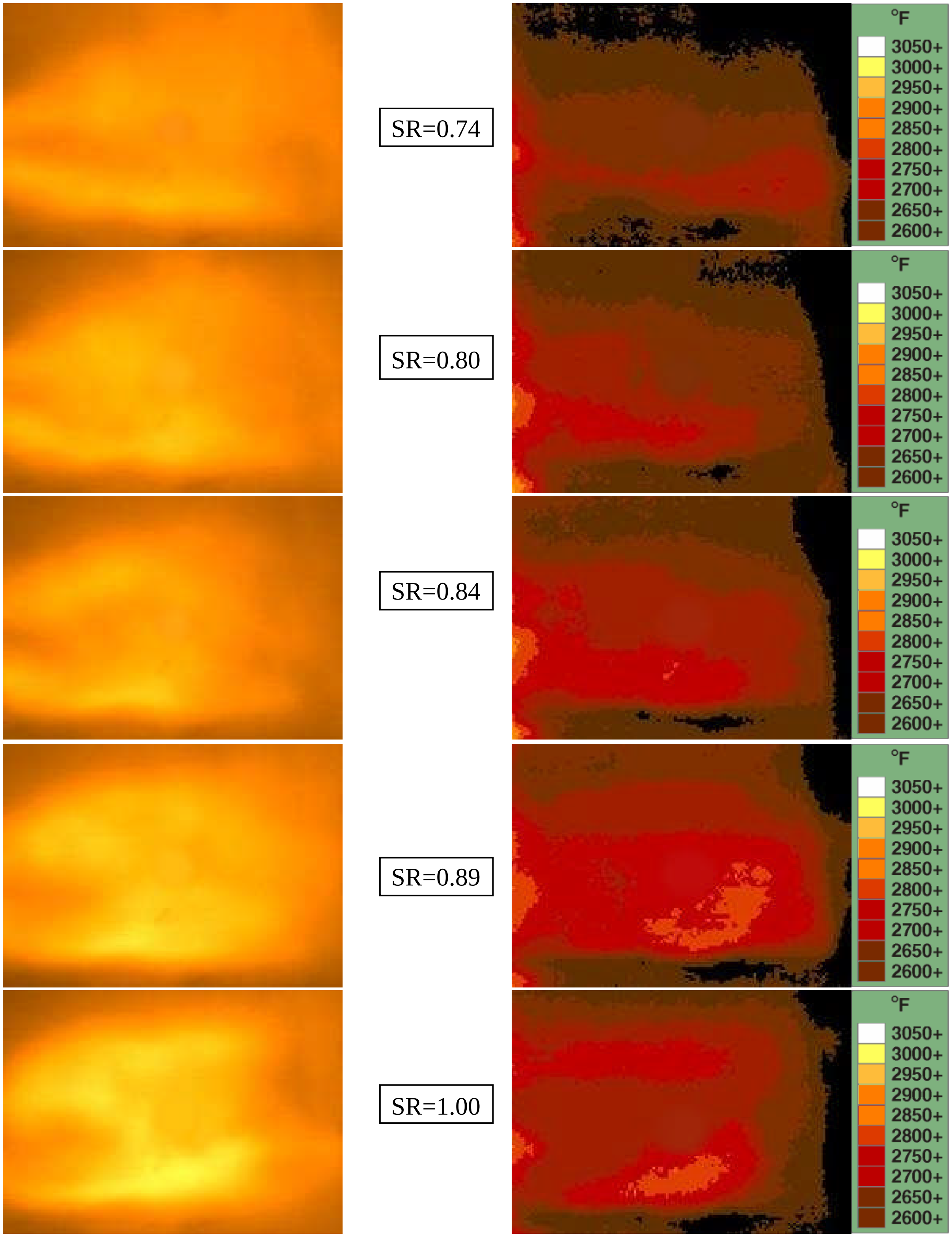

Figure 21. Flame images and 2-D temperature maps of the DRB-4Z® burner exit obtained by the FLAMEVIEW™ optical pyrometry system while burning Pittsburgh #8 coal at different stoichiometric ratios (SR). Flow direction is from left to right.

Overall combustion stoichiometry and firing rate effects were examined at burner settings more favorable to lowering the CO emissions rather than NO_x and different than those corresponding to the Figure 20 data. Increasing the overall excess air level at a fixed burner stoichiometry of 0.80 had the expected effect of higher NO_x but lower CO and LOI levels as illustrated in Figure 22. Part and minimum load operations generally resulted in lower NO_x and higher CO levels due to cooler furnace environment as shown in Figure 23.

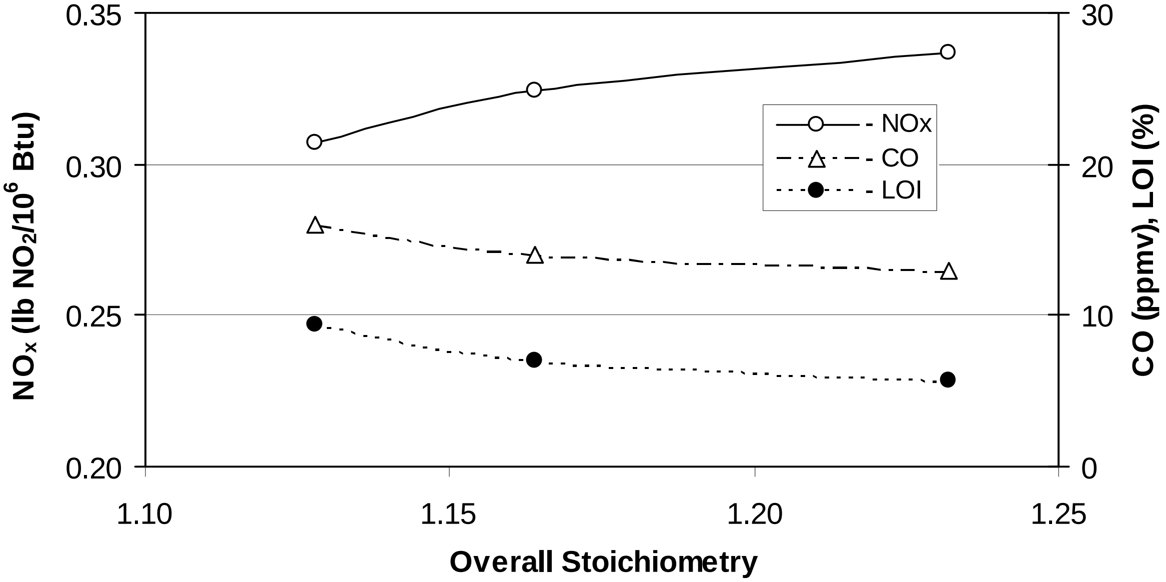

Figure 22. **Overall combustion stoichiometry effect on NO_x, CO, and LOI for the DRB-4Z® burner using <u>lower level</u> OFA ports. Nominal operating conditions: 5 million Btu/hr, 0.80 burner stoichiometry, and 73% through a 200 mesh screen Pittsburgh #8 coal fineness.**

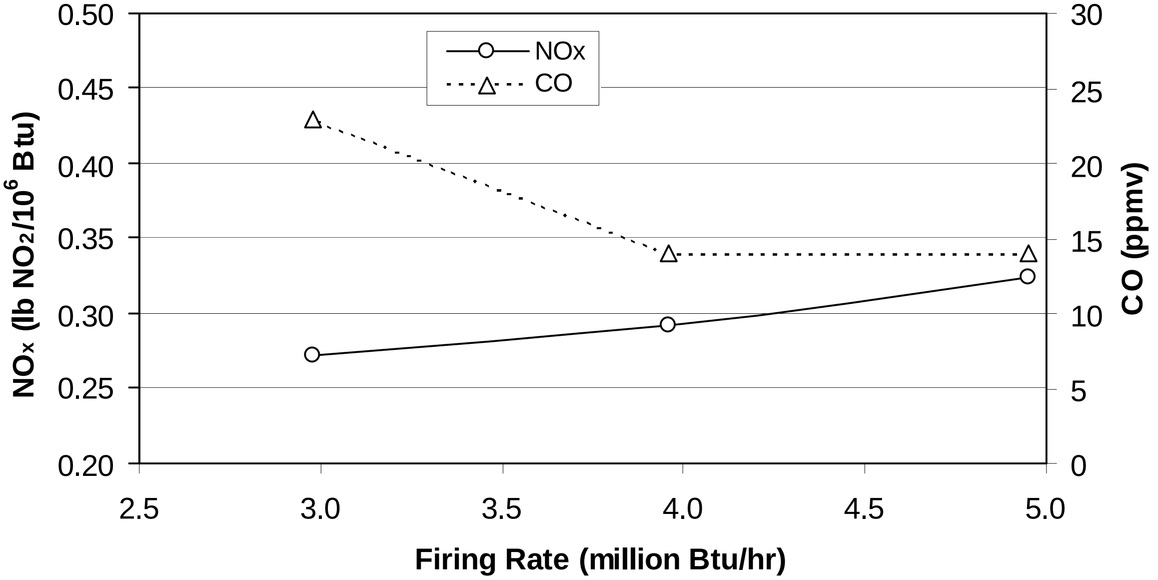

Figure 23. **Firing rate effects on NO_x and CO emissions for the DRB-4Z® burner using <u>lower level</u> OFA ports. Nominal operating conditions: 0.80 burner stoichiometry, 1.17 overall stoichiometry, and 73% through a 200 mesh screen Pittsburgh #8 coal fineness.**

Two-Level Versus Single-Level OFA - In deeply staged combustion, lowest NO_x levels are achieved when burner-to-OFA residence times for flue gas mixing and reaction are optimized. Single level OFA ports provide good jet penetration and mixing but they also cause rapid oxidation of nitrogen-carrying species in the flue gas stream. Multi-level staging of air can be more effective for NO_x minimization than single-level because the gradual addition of OFA above the main combustion zone reduces the oxidation of nitrogenous species. In our tests, staging air was introduced through two elevations each equipped with 2 overfire air ports. Figure 24 shows the impact of OFA distribution on NO_x and LOI. Lowest NO_x concentrations were measured when the flow was split equally to both levels. When all of the staging air was blown through the upper OFA ports, the LOI also increased due to gas temperature cooling near the furnace exit.

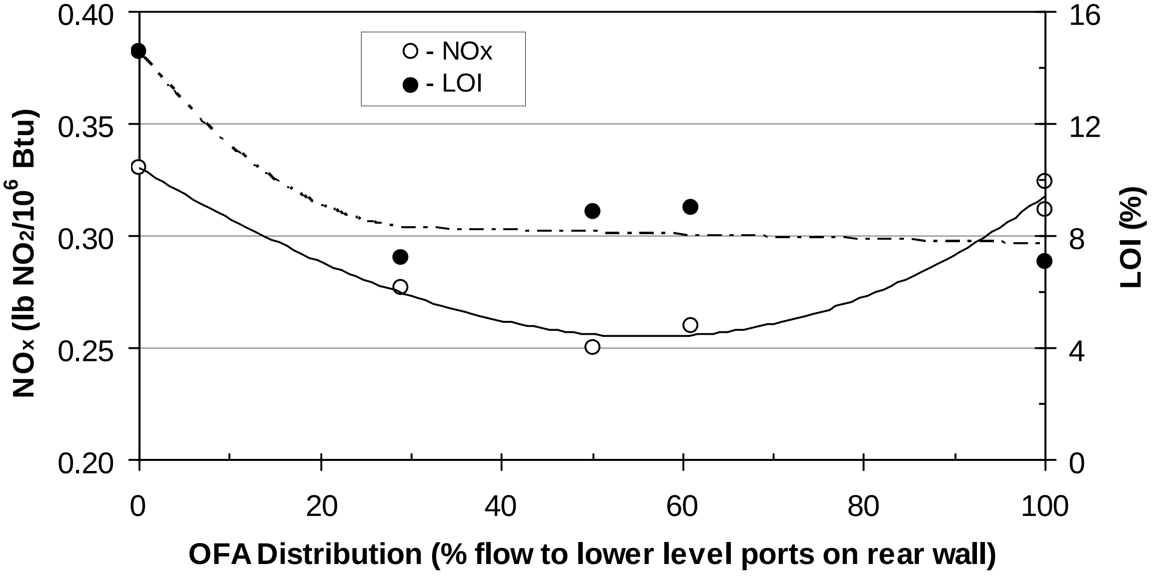

Figure 24. Effect of overfire air distribution on NO_x and LOI for the DRB-4Z® burner. Nominal operating conditions: 5 million Btu/hr, 0.80 burner stoichiometry, 1.17 overall stoichiometry, and 73% through a 200 mesh screen Pittsburgh #8 coal fineness.

Oxygen Enrichment of Low-NO_x Wall-Fired Burner – Oxygen enrichment in the main combustion zone was accomplished by various O_2 lances at levels up to 10% of the total oxidant input to the boiler. Initial O_2 enrichment tests were conducted without coal reburning. Major test parameters included O_2 injector design, burner stoichiometry, and oxygen enrichment level. Figure 25 shows the oxygen enrichment effect on flame shape and temperature at a fixed burner stoichiometry of 0.70. As seen in the images, the flame became smaller, brighter, and hotter with increasing oxygen injection along the burner centerline.

Figure 26 shows the stoichiometry effect on NO_x and LOI when the DRB-4Z® burner was enriched with 8.9% O_2 and the lower OFA ports were in service. Similar to the baseline results, NO_x emissions decreased as the burner stoichiometry dropped from 0.95 to 0.70, but rose again as the stoichiometry approached 0.60. As before, oxidation of nitrogen-carrying species by the overfire air is believed to be responsible for the rising NO_x concentrations below the 0.70 optimum burner stoichiometry. LOI values on the other hand remained relatively constant over the 0.6 to 0.95 range.

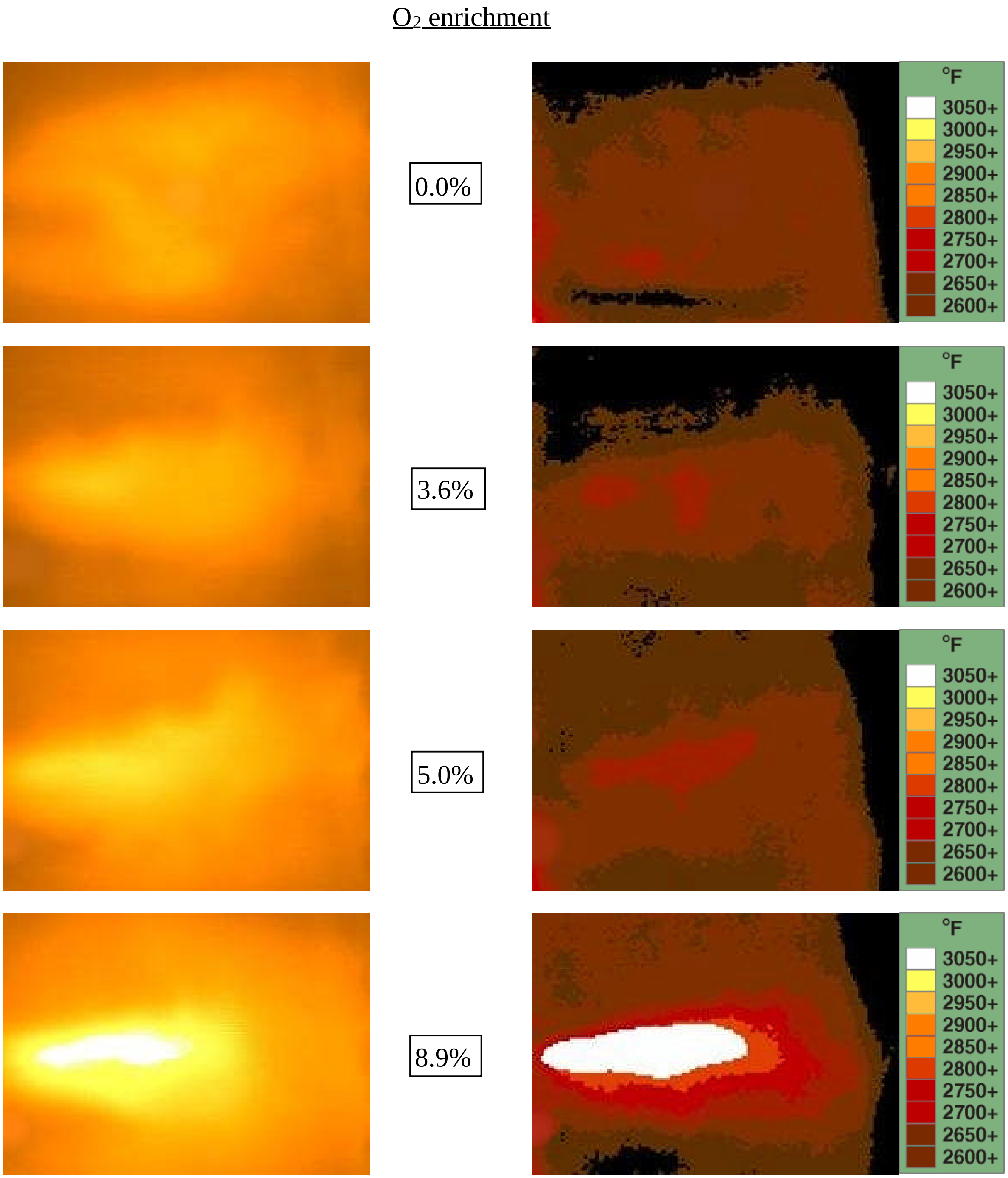

Figure 25. O_2 enrichment effects on the DRB-4Z® burner flame luminosity and temperature while burning 73% through 200 mesh screen Pittsburgh #8 coal at 0.70 stoichiometry. Flow direction is from left to right.

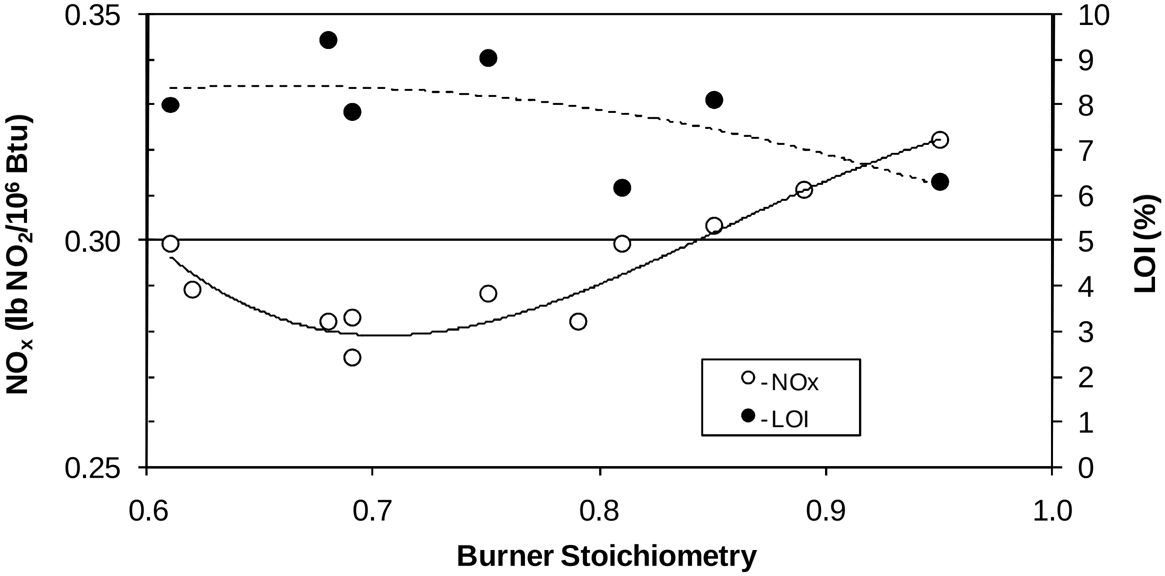

Figure 26. Burner stoichiometry effects on NO_x and LOI for the O_2-enriched DRB-4Z® burner using <u>lower level</u> OFA ports. Nominal operating conditions: 5 million Btu/hr, 1.17 overall stoichiometry, 8.9% O_2 enrichment via a single-hole centerline lance, and 73% through a 200 mesh screen Pittsburgh #8 coal fineness.

Two-level overfire air distribution effect was evaluated at the optimum 0.70 burner stoichiometry with 8.9% O_2-enrichment and the NO_x and LOI results are plotted in Figure 27. Diverting half of the overfire air from the lower level ports to the upper ports brought down the NO_x levels by 25% but increased the LOI by 19%. Oxygen enrichment of the burner enhanced the coal devolatilization and NO_x reduction during sub-stoichiometric operation.

Combined effects of O_2 enrichment and OFA distribution on NO_x emissions were evaluated further at 0.7 stoichiometry (OFA split equally to lower and upper ports) and 0.8 stoichiometry (100% OFA to lower ports). Figure 28 illustrates a linear reduction in NO_x emissions with increasing oxygen enrichment in the DRB-4Z® burner.

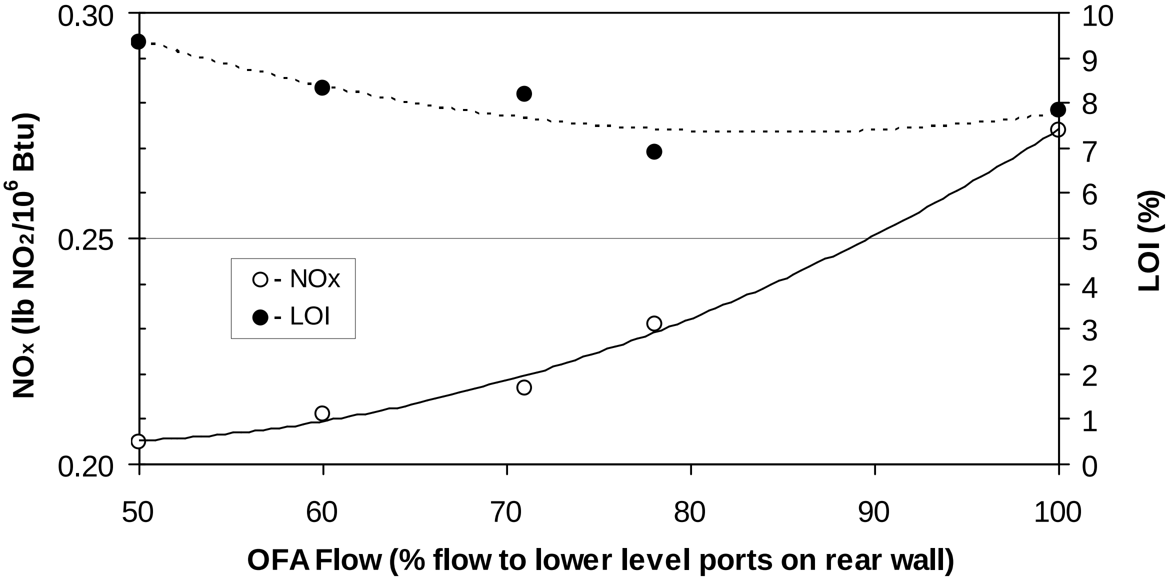

Figure 27. **Effect of air distribution to upper and lower OFA ports on NO_x and LOI for the O_2-enriched DRB-4Z® burner. Nominal operating conditions: 5 million Btu/hr, 0.70 burner stoichiometry, 17% overall excess air, 8.9% O_2-enrichment with a single-hole centerline lance, and 73% through a 200 mesh screen Pittsburgh #8 coal fineness.**

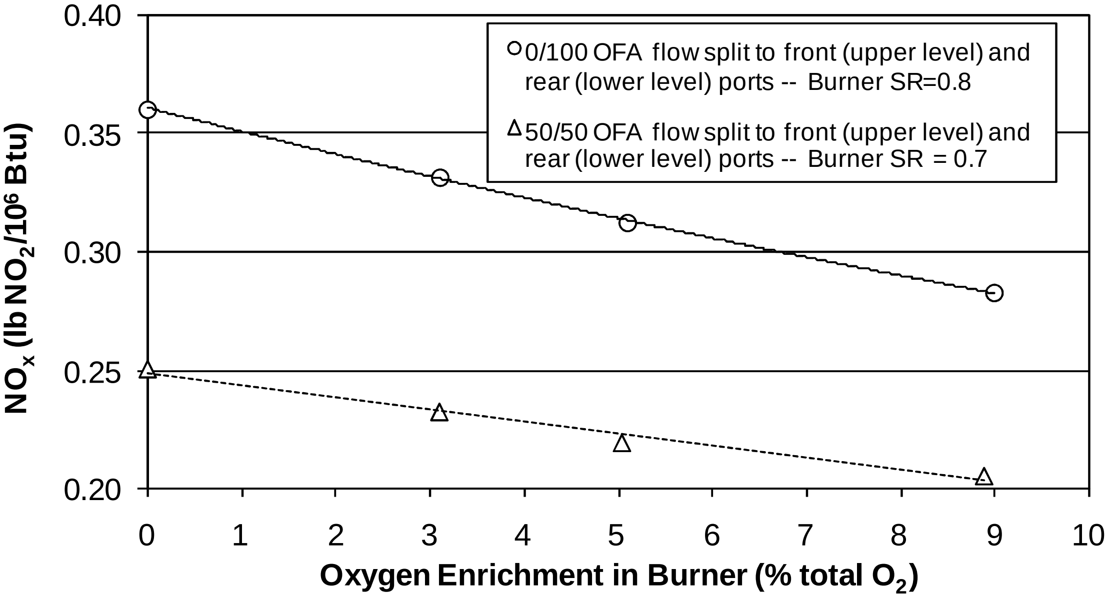

Figure 28. **O_2 enrichment effects on NO_x and LOI using a single-hole centerline lance in the DRB-4Z® burner. Circles denote 100% OFA flow to <u>lower level</u> ports and triangles designate equally split OFA flow to <u>lower and upper level</u> ports. Nominal operating conditions: 5 million Btu/hr, 1.17 overall stoichiometry, and 73% through a 200 mesh screen Pittsburgh #8 coal fineness.**

Oxy-Coal Reburn Application in Wall-Fired Combustion - Effects of simultaneous oxygen enrichment in the main burner and reburn burners were examined following the favorable O_2-enriched combustion tests with the DRB-4Z® burner. For oxy-coal reburn tests, pulverized coal was fired by two reburn burners at an equivalent rate of 10-30% of the boiler heat input. Total air flow to the boiler was distributed to the DRB-4Z® burner, reburn burners, and OFA zones. To avoid excessive CO and unburned carbon levels, the coal fineness for reburn burners was about 90% through a 200 mesh screen. Oxygen flow rate was varied over an equivalent range of 0 to 10% of total O_2 input to the boiler. Several O_2 injection lances with different discharge patterns were used interchangeably during testing. Up to 20% of the flue gas was recycled and introduced through the swirling zone of the reburn burners for better penetration and mixing of the fuel/oxidizer jet with the bulk flow gases.

In one series of tests, 19% coal reburn was established at 0.41 stoichiometry using oxygen, air, and FGR while the O_2-enriched DRB-4Z® was operated in the 0.73 to 1.0 stoichiometry range by changing the secondary air flow to the burner. Figure 29 shows that for the overall combustion stoichiometry of 1.17, NO_x levels declined with decreasing DRB-4Z® burner stoichiometry. CO concentrations dipped to their lowest values around the 0.80 to 0.88 burner stoichiometry. More CO was emitted at 1.0 burner stoichiometry due to lower OFA flow penetration and mixing with the DRB-4Z® burner combustion by-products. CO levels also rose due to higher formation of combustibles from fuel-rich combustion at 0.73 burner stoichiometry, despite a better OFA flow penetration and mixing in the furnace.

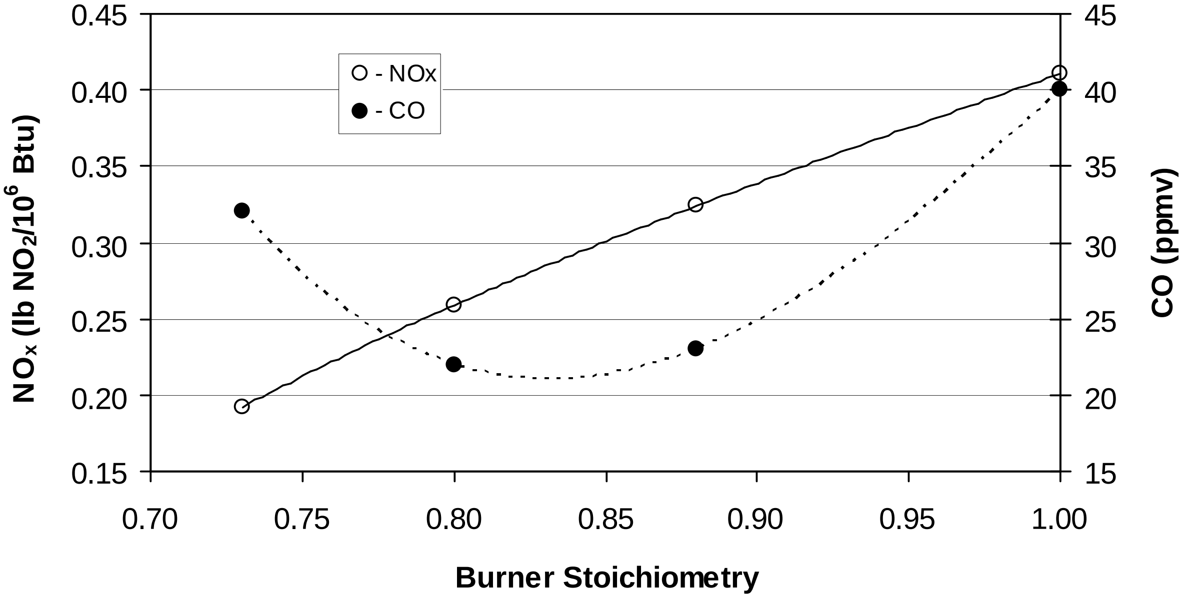

Figure 29. DRB-4Z® burner stoichiometry effect on NO_x and CO. Nominal operating conditions: 5 million Btu/hr, 1.17 overall stoichiometry, 19% PC reburn, O_2 enrichment at 6.3% for the DRB-4Z® burner and 2.5% for the reburn burners, two-level OFA distribution, and Pittsburgh #8 coal fineness of 73% and 90% through a 200 mesh screen for DRB-4Z® burner and reburn burners, respectively.

Oxygen-enriched coal reburning at 19% of full load lowered the NO_x by 10% below the no-reburn operation value. At the higher coal reburn extent of 29% where the reburn zone stoichiometry was 0.61 (weighted average of DRB-4Z® at SR=0.73 and reburn burners at SR=0.34), more nitrogen-carrying species oxidized to NO_x in the overfire air mixing zone. Figure 30 shows the variation of NO_x with the extent of reburning.

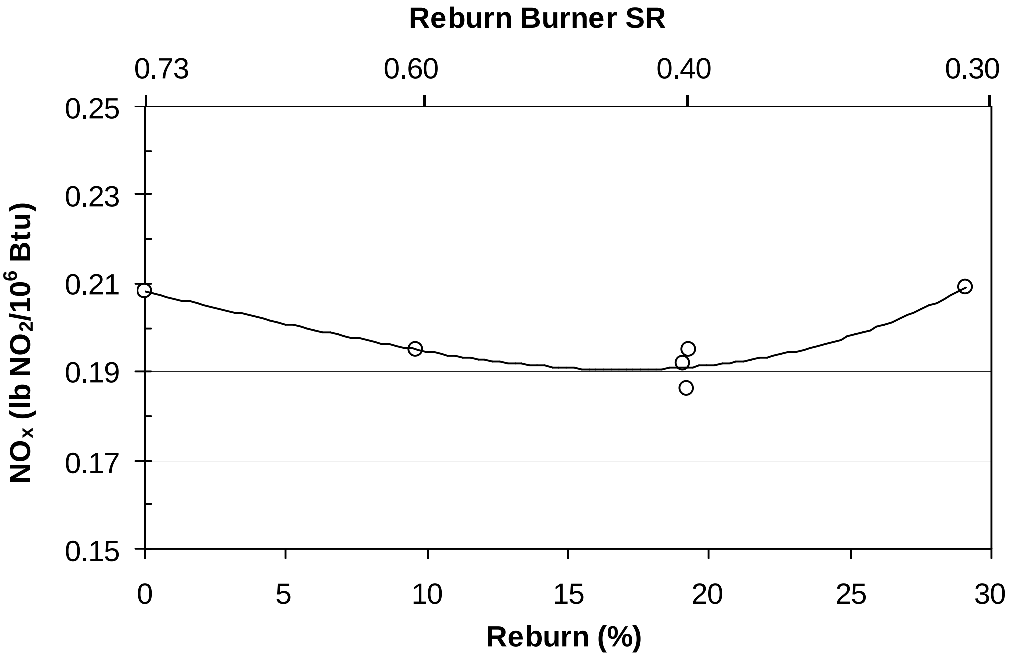

Figure 30. **Extent of coal reburning effect on NO_x emissions. Nominal operating conditions: 5 million Btu/hr, 0.70-0.75 DRB-4Z® burner stoichiometry, 1.17 overall stoichiometry, O_2 enrichment at 6.3% for the DRB-4Z® burner and 2.4% for reburn burners (0% without reburn), 11% FGR flow to reburn burners, two-level OFA distribution, and Pittsburgh #8 coal fineness of 73% and 90% through a 200 mesh screen for DRB-4Z® burner and reburn burners, respectively.**

Recycling flue gas to the reburn burners activates several competing processes. Without FGR, the NO_x destruction efficiency is lower due to the reduction of mixing between the reburn burner flames and the main combustion zone by-products. High FGR flow on the other hand can quench the fuel-rich reburn zone and increase the NO_x and CO levels. In our tests, 0 to 21% of the total flue gas was recycled to the reburn burners and the lowest CO and NO_x concentrations were measured when the FGR level was close to 10% as seen in Figure 31. Overall combustion stoichiometry effects on NO_x and CO levels for 19% coal reburn with oxygen and 10% FGR in a two-level OFA arrangement are illustrated in Figure 32.

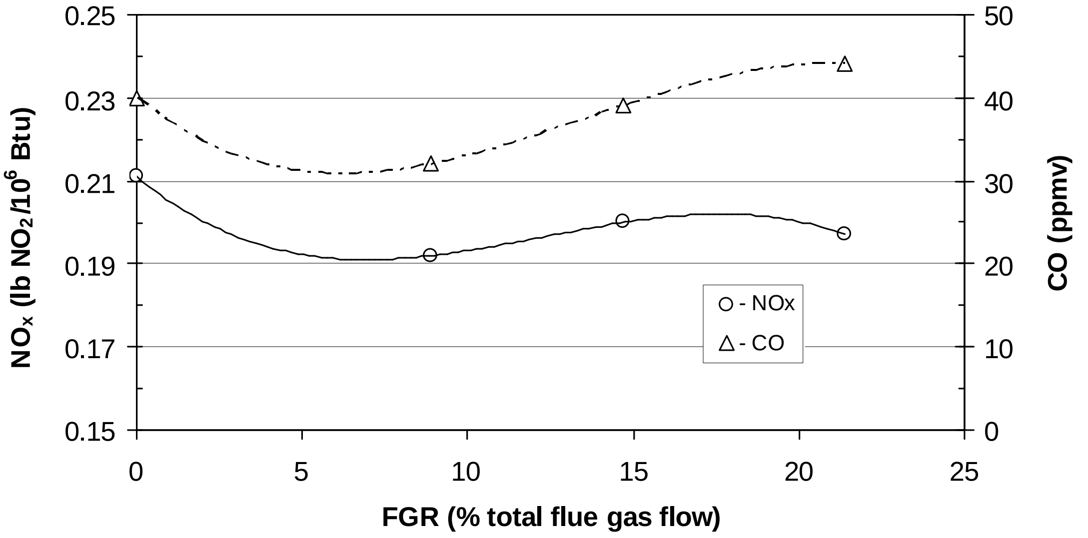

Figure 31. Reburn burner flue gas recirculation flow effect on NO_x and CO. Nominal operating conditions: 5 million Btu/hr, 0.70-0.75 DRB-4Z® burner stoichiometry, two-level OFA distribution, 1.17 overall stoichiometry, 19% PC reburn, O_2 enrichment at 6.3% for the DRB-4Z® burner and 2.4% for the reburn burner, DRB-4Z® burner and reburn burner Pittsburgh #8 coal fineness of 73% and 90% through a 200 mesh screen, respectively.

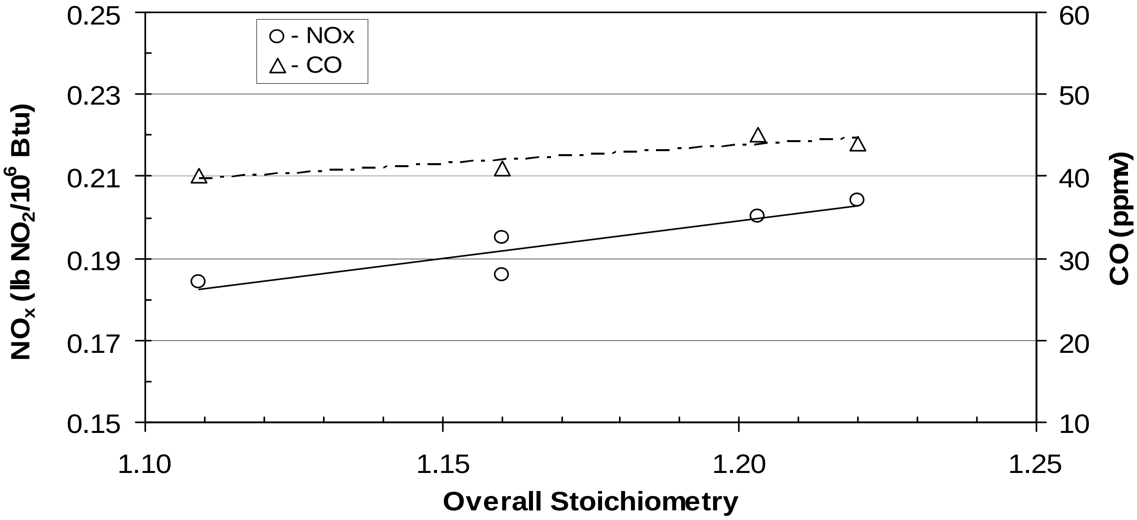

Figure 32. Overall combustion stoichiometry effect on NO_x and CO. Nominal operating conditions: 5 million Btu/hr, 0.70-0.75 DRB-4Z® burner stoichiometry, two-level OFA distribution, 19% PC reburn, 10% FGR, O_2-enrichment at 6.3% for the DRB-4Z® burner and 2.4% for the reburn burner, DRB-4Z® burner and reburn burner Pittsburgh #8 coal fineness of 73% and 90% through a 200 mesh screen, respectively.

Furnace Exit Gas Temperature – Figure 33 compares the average uncorrected furnace exit gas temperature (FEGT) measurements by the HVT probe for the air-blown (baseline) and oxy-coal reburn operations. Calculated heat absorptions in the furnace and convective pass sections of the boiler for the baseline and oxy-coal reburn operations are compared in Figure 34. Baseline furnace heat absorption and FEGT values were slightly higher than the oxy-reburn results, but a similar rise in the convection pass heat absorption in the latter case (with the added FGR flow) kept the overall heat transfer characteristics unchanged.

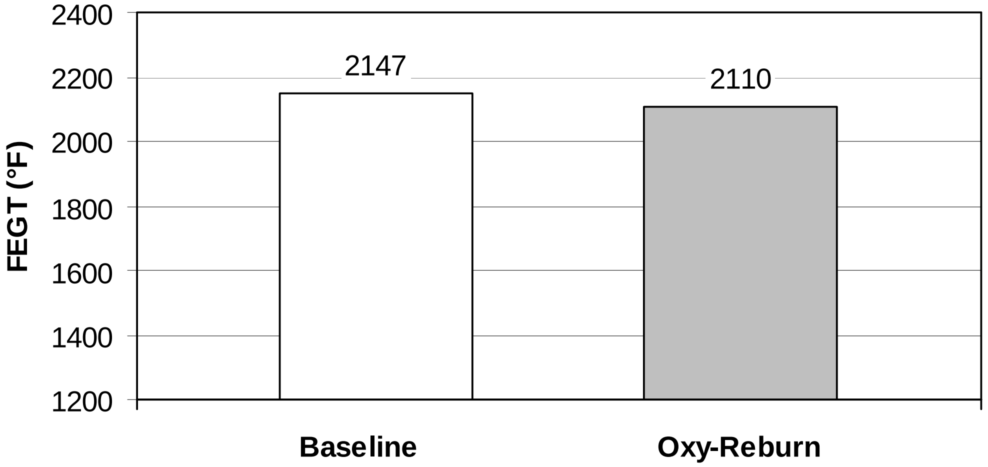

Figure 33. Furnace exit gas temperature measurements for Pittsburgh #8 coal combustion in air-blown (baseline) and oxy-reburn modes. See Table 8 for nominal operating conditions.

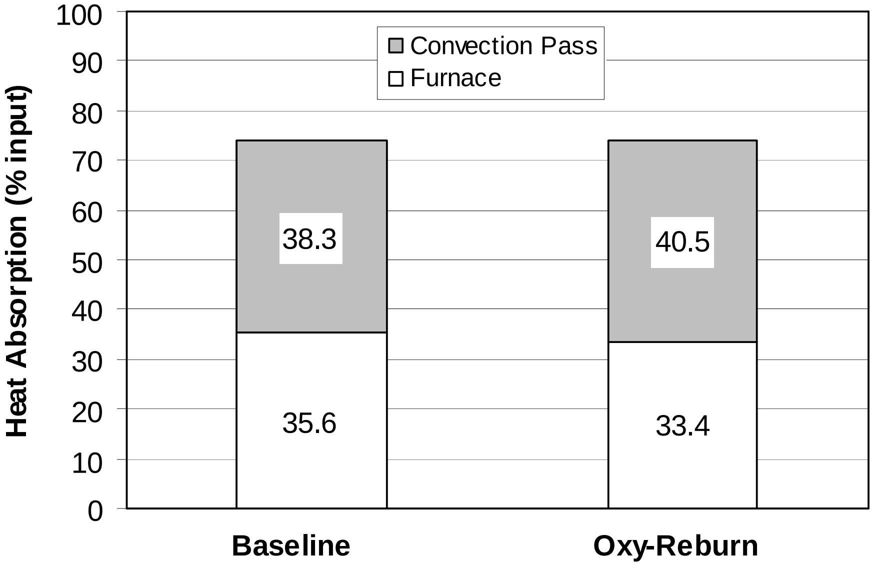

Figure 34. Furnace and convection pass heat absorption comparisons for Pittsburgh #8 coal combustion in air-blown (baseline) and oxy-reburn modes. See Table 8 for nominal operating conditions.

Mercury Emissions - Mercury speciation measurements at the convection pass outlet for selected air-blown and oxy-reburn tests along with pertinent operating conditions are listed in Table 8. Among the three measured forms, the elemental (Hg^0) and particulate (Hg^P) mercury fractions were the most and least abundant constituents, respectively. The oxidized component (Hg^{+2}) of total mercury ranged from 6% for the air-blown operation to 29% for the oxy-reburn. Consistent with other reported oxy-combustion investigations, oxy-reburn operation seems to enhance the Hg^{+2} formation. In a practical application, transformation of the water insoluble Hg^0 to the soluble Hg^{+2} is highly desirable since it facilitates partial removal of coal mercury in the flue gas desulfurization equipment. Material balance calculations indicate good coal-mercury recovery at the sampling location downstream of the convection pass. Unaccounted mercury was most likely adsorbed on the relatively cold (~212°F) convection pass walls and tubes, and/or captured by the carbonaceous residues in fly ash deposits on metal surfaces. Figure 35 shows the average mercury emissions at the convection pass outlet.

Table 8. Mercury Speciation for Wall-Fired Air-Blown (Baseline) and Oxy-Reburn Operations at 1.17 Overall Stoichiometry with Pittsburgh #8 Coal

Measurements	Baseline	Oxy-Reburn
Firing rate (MBtu/hr)	5.0	4.9
Burner stoichiometry	0.80	0.75
Total coal flow (lb/hr)	379	377
Coal reburn (%)	0	19
O_2 flow to reburn burner (% total)	0	2.4
O_2 flow to DRB-4Z® burner (% total)	0	6.3
Flue gas flow at stack (lb/hr)	4960	4681
Flue gas flow at boiler exit (lb/hr)	4960	5207
Sampling location temperature (°F)	822	757
Hg^{Coal} (lb/10^{12} Btu)‡	10.24	10.24
Hg^0 (µg/Nm^3)	8.84	7.80
Hg^{+2} (µg/Nm^3)	0.60	3.18
Hg^P (µg/Nm^3)	1.3E-04	7.0E-05
Hg^{Total} (lb/10^{12} Btu)	7.67	9.44
Recovered Hg (%)	75	92

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‡ Based on as-fired coal heating value of 13,384 Btu/lb and 0.11 ppmw Hg content

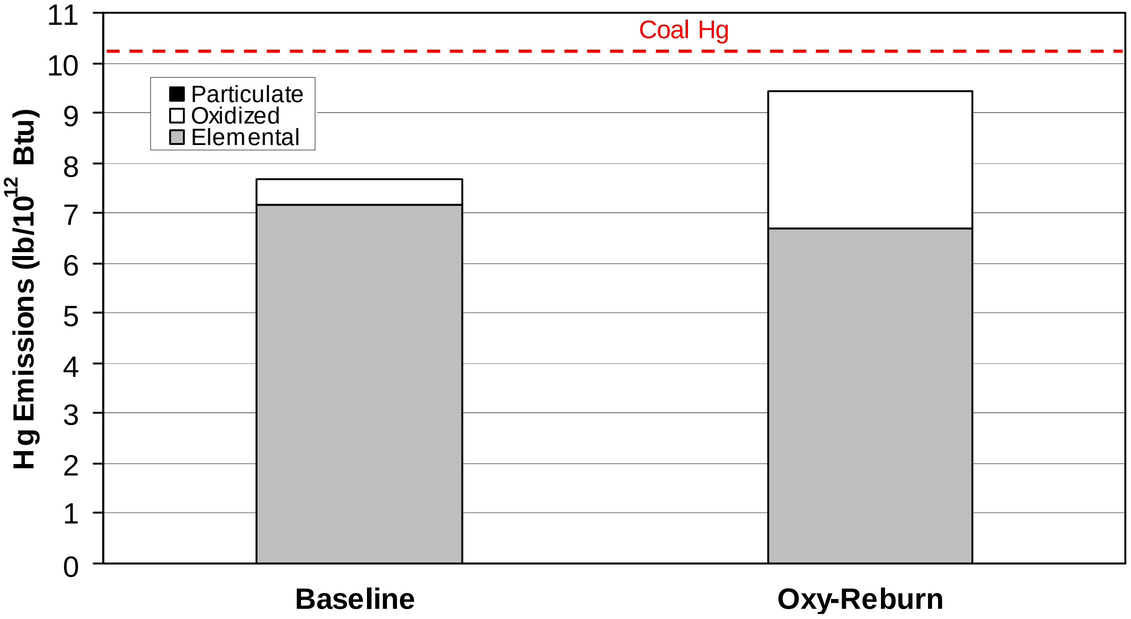

Figure 35. Mercury emissions from the combustion of Pittsburgh #8 coal in air-blown (baseline) and oxy-reburn modes. See Table 8 for nominal operating conditions.

Flame Spectral Emittance - Flame radiance was measured by the thermopile detector during an optimized oxygen-enriched firing test. Figure 36 shows good reproducibility in the spectral emittance measurements at a fixed operating condition. Integrated spectral emittance was 0.87 and 0.88 and the estimated local flame temperatures were 2800°F and 2940°F which are in reasonable agreement with the independent 2-color pyrometry measurements. Sharp peaks and valleys in the spectral emittance at 1.55 and 4.3 microns are attributable to the strong H_2O and CO_2 absorption bands at those respective wavelengths.

Corresponding spectral distributions of flame radiation for the oxygen-enriched firing test are shown in Figure 37. The plots exhibit good repeatability and resemble the classic radiation spectra from a blackbody (Planck's law). Again, the notable spikes at 1.55 µm and the dips at 4.3 µm wavelengths are most likely due to the presence of water vapor and carbon dioxide, respectively. Average radiative heat flux was 167,000 to 200,000 Btu/hr-ft^2. Attempts at making comparable measurements under air-fired operation were not successful due to repeated soot deposition on the parabolic mirror that collected the flame radiation.

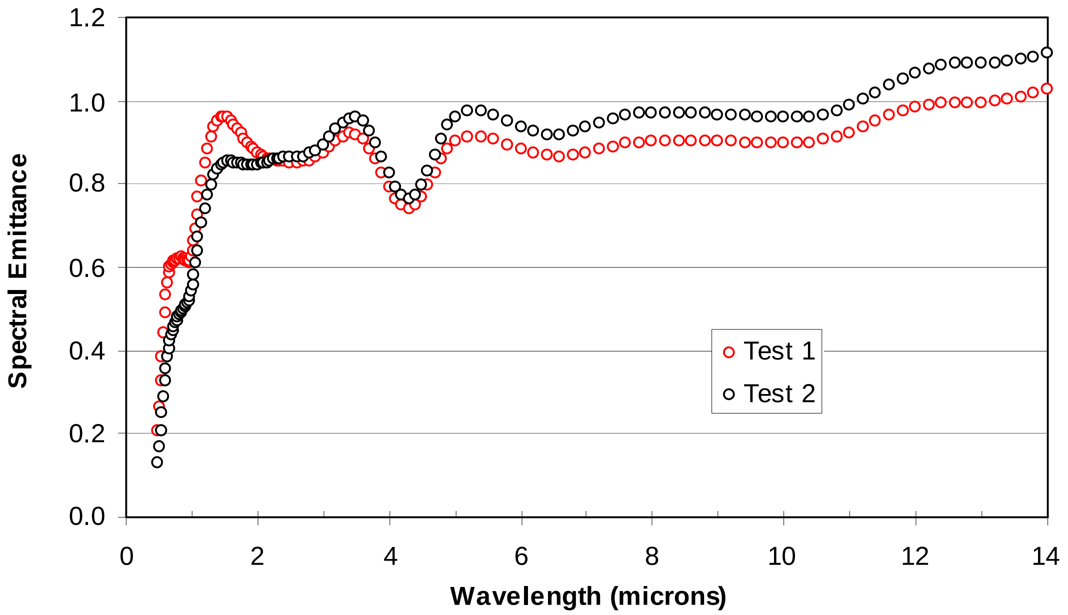

Figure 36. **Flame spectral emittance for oxygen-enriched (6.3%) combustion of 73% through 200 mesh screen Pittsburgh #8 coal at 0.75 stoichiometry in the DRB-4Z® burner.**

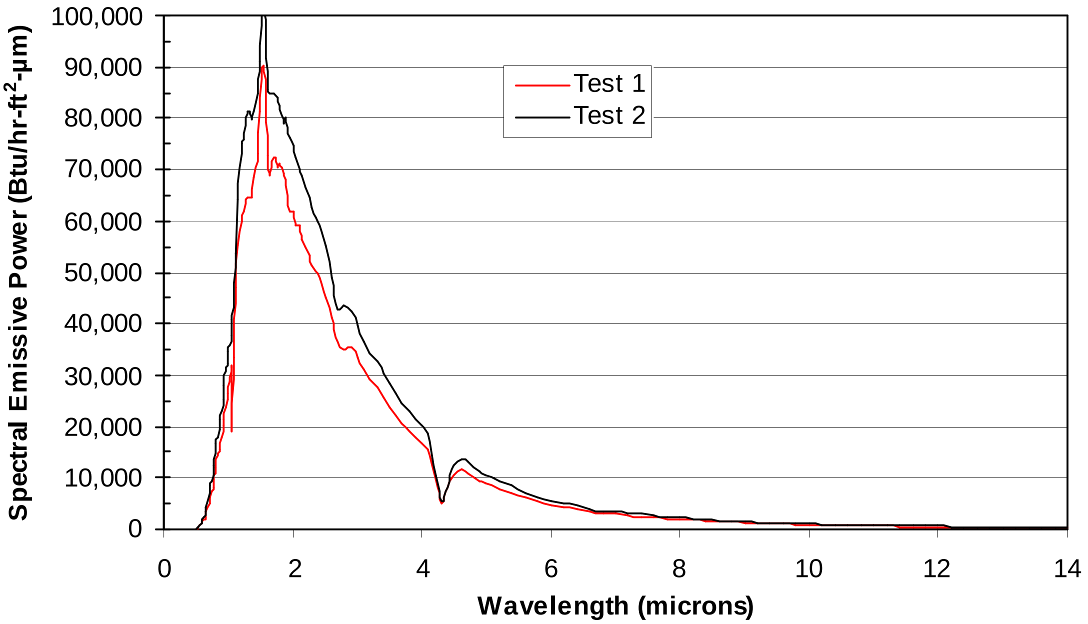

Figure 37. **Spectral distributions of flame radiation for oxygen-enriched (6.3%) combustion of 73% through 200 mesh screen Pittsburgh #8 coal at 0.75 stoichiometry in the DRB-4Z® burner.**

Corrosion Measurements in Wall-Fired Operation - In-situ corrosion rate measurements for selected operating conditions are plotted in Figure 38. Due to the semi-quantitative nature of the measurement technique, the data are normalized relative to the baseline staged operation at 0.80 burner stoichiometry and with lower level OFA ports in service. Corrosion rates in the sub-stoichiometric main combustion and reburn zones were either the same or double the baseline values. In the burnout zone where overfire air mixed with gases from the sub-stoichiometric combustion zones, the average corrosion rates were up to 3 times faster.

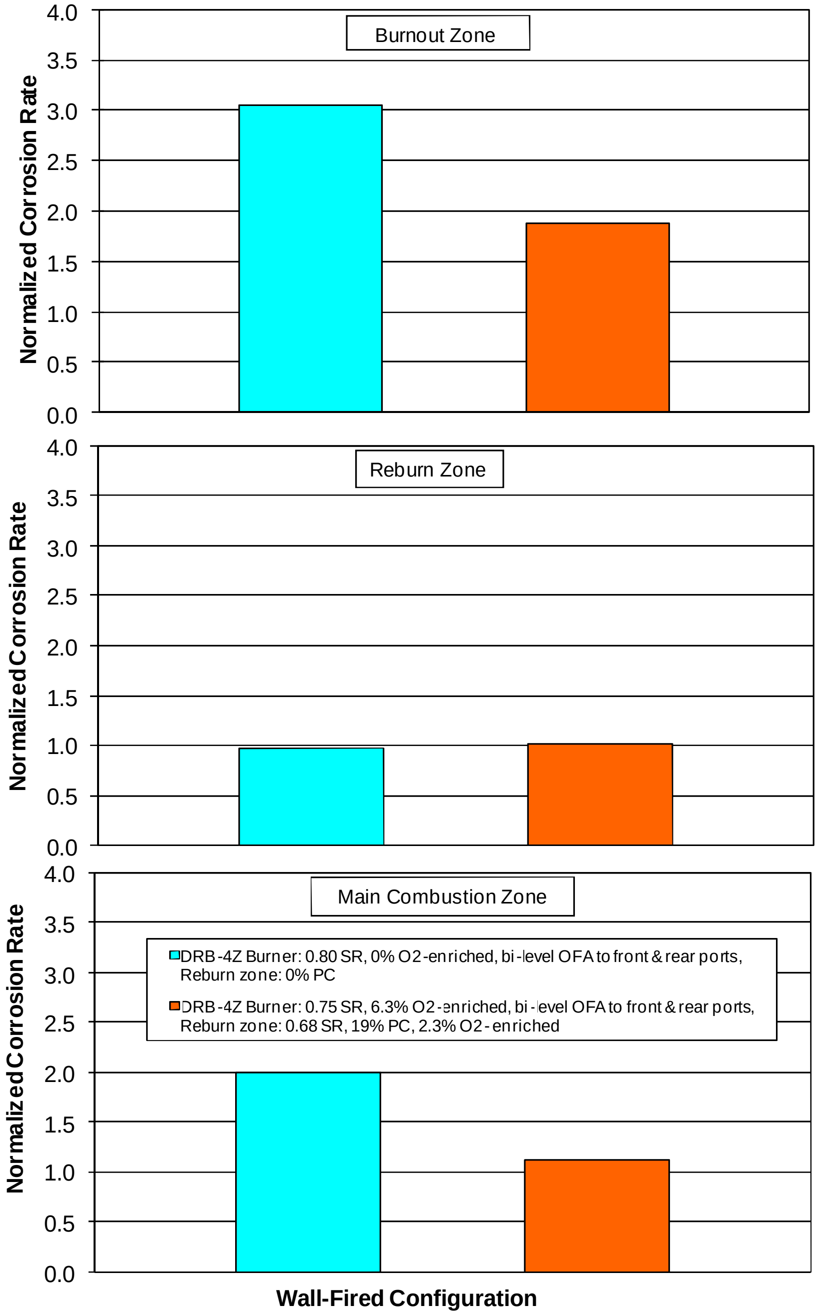

Figure 38. Normalized corrosion rates (relative to staged operation at 0.80 burner stoichiometry with lower-level OFA ports in service) for different wall-fired operating conditions. Nominal operating conditions: Pittsburgh #8 coal combustion at 5 million Btu/hr and 1.17 overall stoichiometry.

Optimum NO$_x$ Values for Wall-Fired Configurations - NO$_x$ emissions test results are summarized in Figure 39. At a fixed overall excess air level of 17%, NO$_X$ emissions with single-level OFA ports were around 0.32 lb/million Btu at 0.80 burner stoichiometry. Two-level OFA operation lowered the NO$_x$ levels to 0.25 lb/million Btu. Oxygen enrichment at 8.9% level in the staged burner (SR=0.7) reduced the NO$_x$ values to 0.21 lb/million Btu. Coal reburning in conjunction with oxygen enrichment range further trimmed the NO$_x$ emissions to 0.18-0.19 lb/million Btu (142-151 ppmv). Based on the short residence times in the sub-stoichiometric combustion zones and the low-NO$_x$ burner mixing characteristics, it was concluded that these results were nearly the best performance that could be obtained under such conditions. Therefore, the remaining tests were instead devoted to the cyclone mode of firing where intense mixing in the staged combustion zone is followed by a longer cyclone-to-OFA residence time.

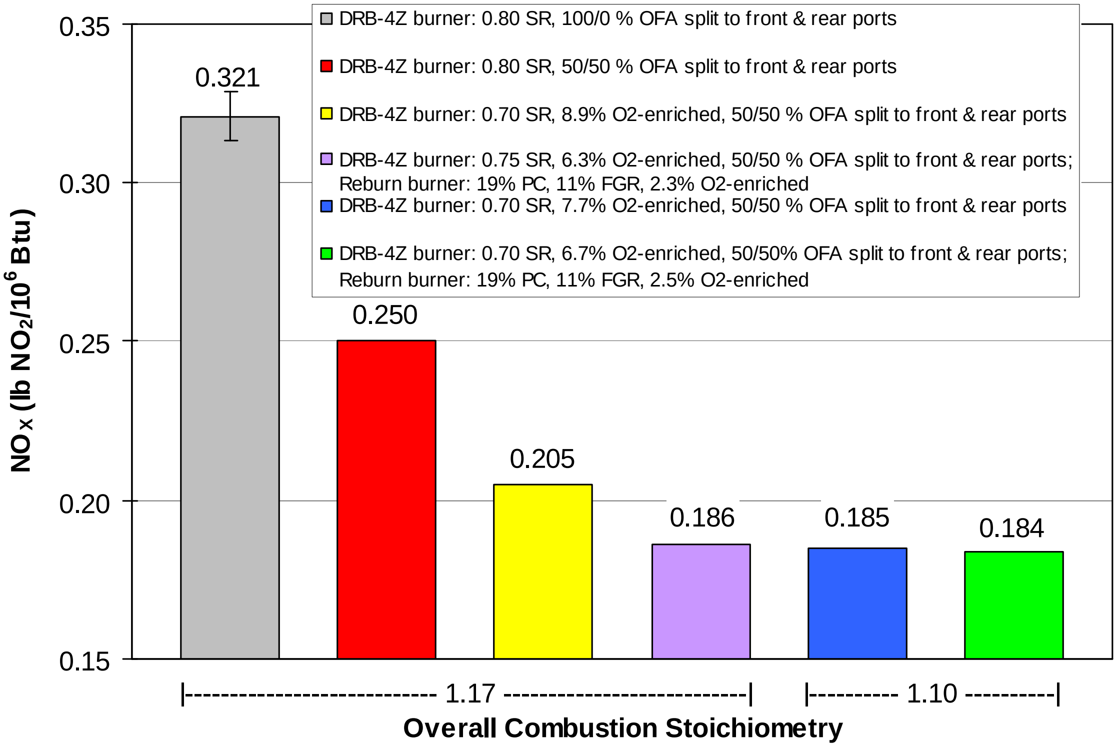

Figure 39. Wall-fired configuration and operating conditions effects on NO$_x$. Nominal operating conditions: 5 million Btu/hr and DRB-4Z® burner and reburn burner Pittsburgh #8 coal fineness of 73% and 90% through a 200 mesh screen, respectively.

Cyclone Firing Tests

Baseline Cyclone-Fired Coal Combustion - Baseline performance data were collected without oxygen enrichment or reburning. Optimum secondary air damper settings for steady slag tapping and minimum pollutant emissions (NO_x and CO) were determined at full load (5 x 10^6 Btu/hr) and 3.2% O_2 at furnace exit (corresponding to 1.17 overall stoichiometry, or 17% excess air in the air-blown case). Depending on the cyclone combustor stoichiometry and OFA distribution, the NO_x levels ranged from 0.2 to 1.4 lb NO_x/million Btu as shown in Figure 40. NO_x emissions were lower when the staging air was split equally between the rear (lower) and front (upper) OFA ports.

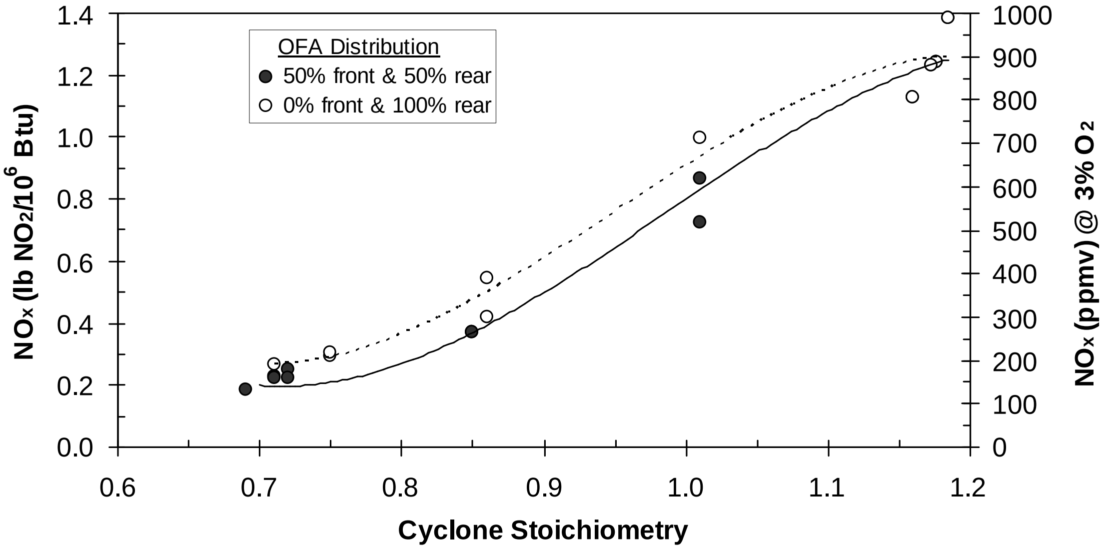

Figure 40. Cyclone combustor stoichiometry and OFA distribution effects on NO_x emissions from the combustion of Pittsburgh #8 coal. Nominal operating conditions: 5 million Btu/hr and 1.17 overall stoichiometry.

Soot formation tendency for Pittsburgh #8 coal was generally strong and it increased as the combustion stoichiometry was lowered. At high combustion temperatures, soot particle radiation gave the luminous flame appearance. Birdseye view flame images and 2-D temperature maps of the cyclone combustor exit are shown in Figure 41. Flame luminosity and combustion temperature peaked at stoichiometric operation (SR=1.0) but decreased at 0.85 and 1.17 stoichiometries. Optical viewing of the cyclone exit zone became more challenging at 0.70 combustion stoichiometry due to the dimming effects of lower combustion temperature and obscuration by soot.

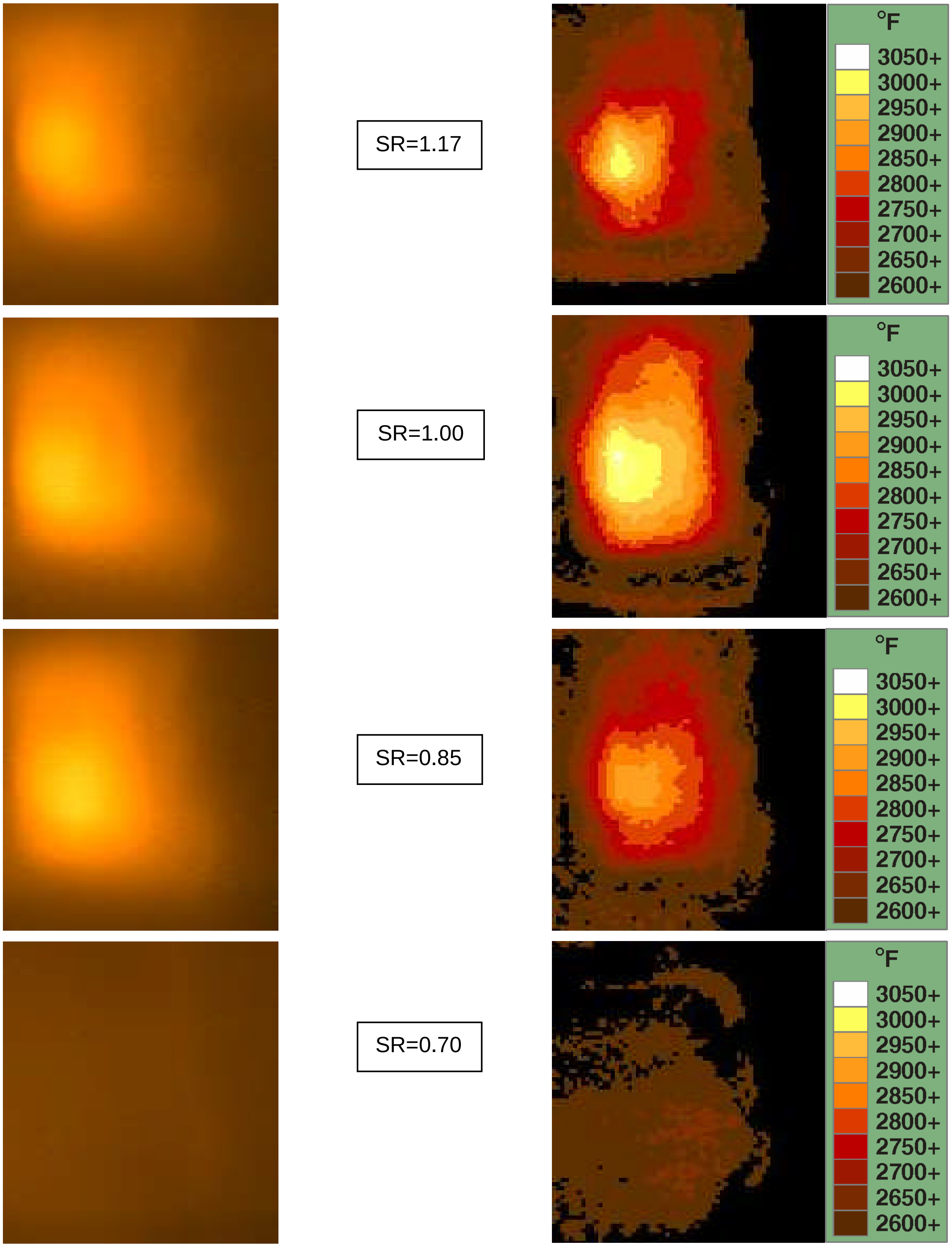

Figure 41. **Flame images and 2-D temperature maps of the cyclone combustor exit obtained by the FLAMEVIEW™ optical pyrometry system while burning Pittsburgh #8 coal at different stoichiometric ratios (SR). Flow direction is from left to right.**

FGR Application in Cyclone Combustion - Flue gas recirculation is an effective technique for in-flame NO_x reduction in natural gas flames. For one thing, it curtails the oxidation of nitrogenous species by reducing the partial pressure of oxygen in the oxidant stream. It also quenches the flame and averts peak temperatures and thermal-NO_x formation. Previous applications of FGR in PC-fired burners have not been successful due to their adverse effects of quenching on flame attachment, opacity, and char burnout. We tested the effects of FGR addition to the coal-burning cyclone furnace under staged and unstaged conditions and the emission results are shown in Figures 42 and 43. Flue gas was added to the secondary air stream entering the cyclone, downstream of the OFA takeoff point. In the unstaged mode and with 19% flue gas recycle, the volumetric O_2 concentration in the secondary oxidant stream to the cyclone furnace dropped from 20.8% to 17.5% (on a wet basis) resulting in 11% lower NO_x emissions relative to no recycle operation. Thermal quenching and lower oxygen partial pressure are the most likely reasons for the observed NO_x suppression. Recycling of 13.5% flue gas into the staged cyclone lowered the secondary oxidant stream O_2 concentration from 20.8% to 16.9%. But due to its cooling effect on the sub-stoichiometric NO_x destruction zone, the NO_x emissions increased by 5%. In both cases (staged and unstaged), CO emissions increased only slightly and slag tapping was not noticeably affected by flue gas recirculation.

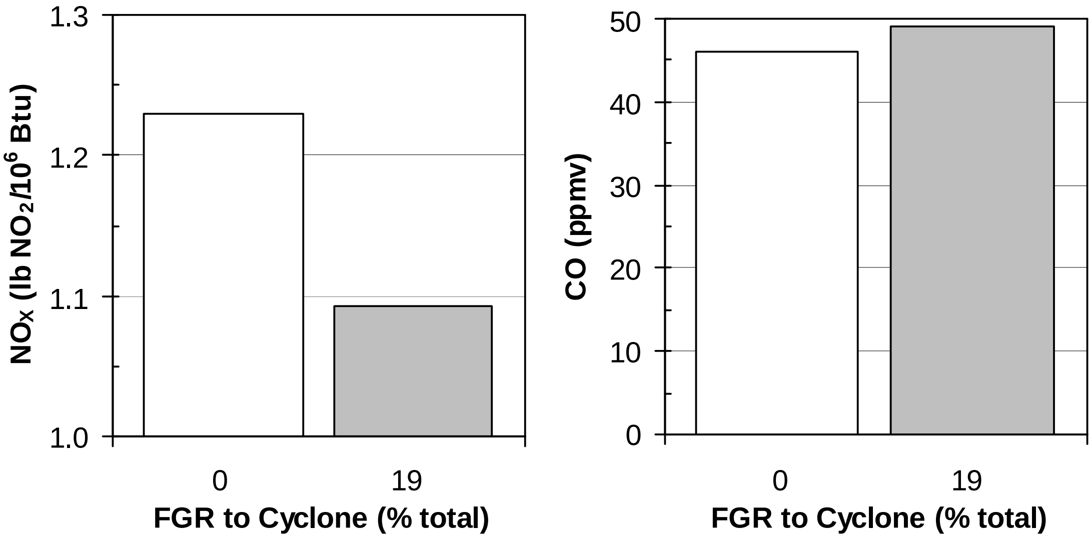

Figure 42. Effect of flue gas recycle into the cyclone combustor on NO_x and CO emissions during unstaged operation with Pittsburgh #8 coal at 1.17 stoichiometry and 5 million Btu/hr.

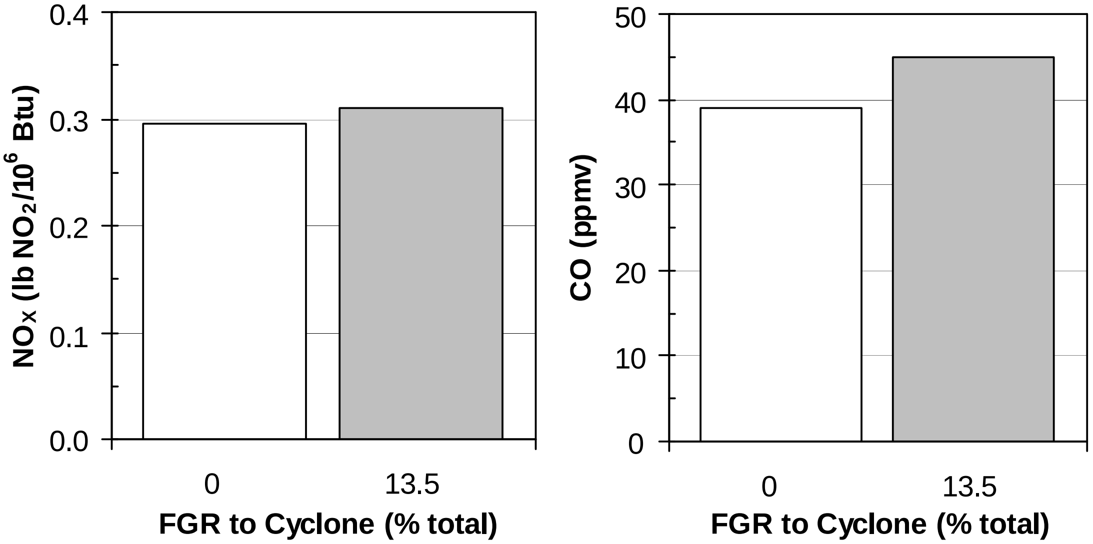

Figure 43. Effect of flue gas recycle into the cyclone combustor on NO_x and CO emissions during staged operation with Pittsburgh #8 coal at 0.75 stoichiometry using lower level OFA ports. Nominal operating conditions: 5 million Btu/hr and 1.17 overall stoichiometry.

Coal Reburning Application During Staged Cyclone-Fired Operation - Coal reburning of up to 27% was done downstream of the staged cyclone combustor (0.70 stoichiometry with two-level OFA addition). Despite the already reducing conditions of the main combustion zone, coal reburning was able to further trim the NO_x emissions to their lowest values in the 9-18% coal reburn range as shown in Figure 44. Within this range, the combined cyclone furnace and reburn burner stoichiometry in the reburn zone was 0.63 to 0.68. At 27% coal reburn, the reburn zone stoichiometry dropped slightly below 0.60 and some of the evolving nitrogenous species were oxidized by the overfire air to NO_x. Utilization of a coarser reburn PC (73% versus 90% through a 200 mesh screen) under the air-blown mode of operation had a negligible effect on NO_x emissions but CO was elevated by 5% due to incomplete burnout of larger particles as seen in Figure 45. Figure 46 provides further verification that equal distribution of the OFA at two levels was more effective than single-level operation with or without any coal reburn.

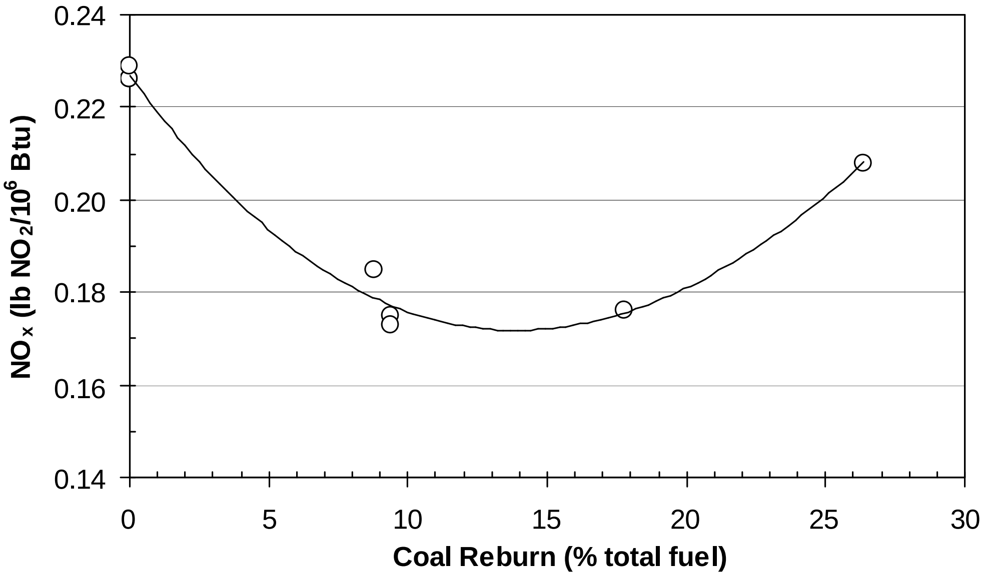

Figure 44. **Extent of coal reburning effect on NO_x emissions from the combustion of Pittsburgh #8 coal. Nominal operating conditions: 5 million Btu/hr, 0.70 cyclone stoichiometry, 17% overall excess air, and reburn coal fineness of 90% through a 200 mesh screen.**

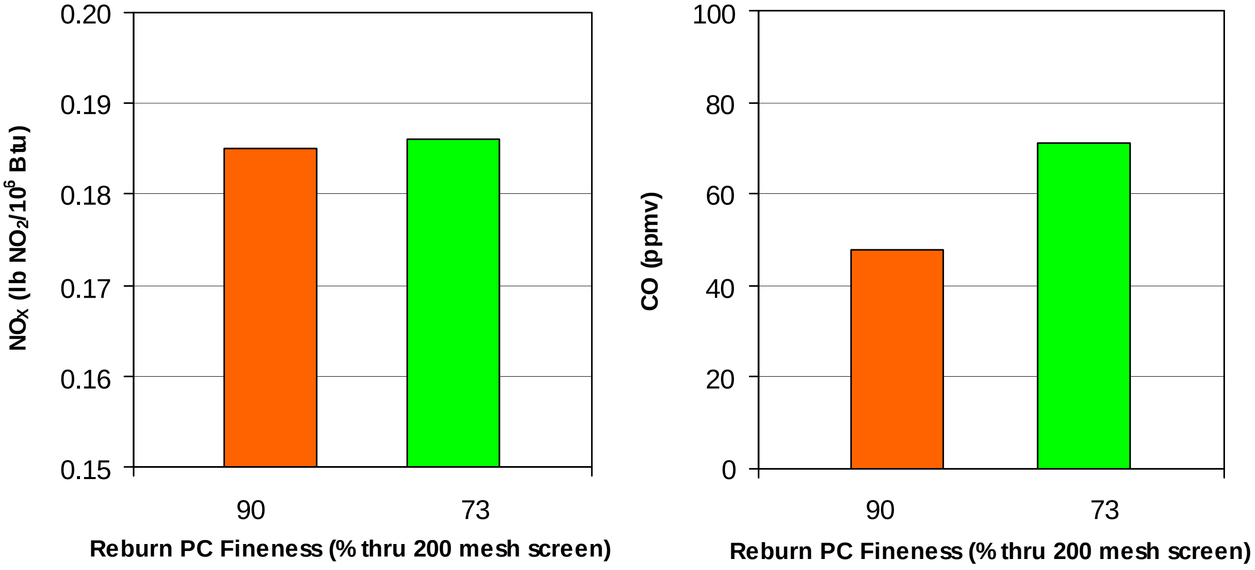

Figure 45. **Reburn coal fineness effect on NO_x and CO emissions. Nominal operating conditions: 5 million Btu/hr, 0.7 cyclone stoichiometry, two-level OFA ports with equally split flows, 9% reburn, 1.17 overall stoichiometry, and 45% through a 200 mesh screen Pittsburgh #8 coal fineness.**

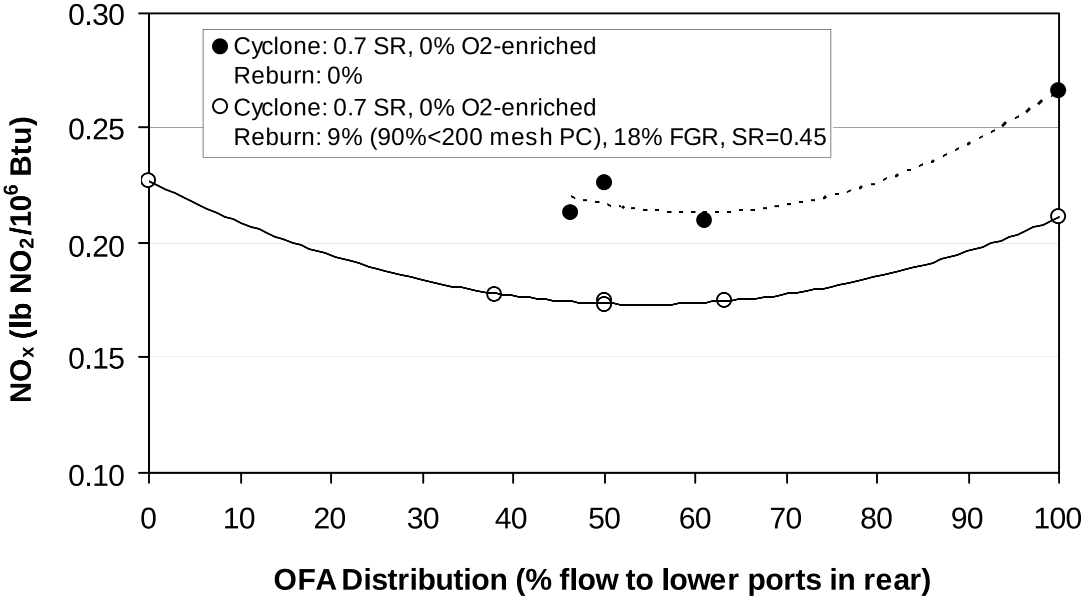

Figure 46. Effect of air distribution to upper and lower OFA ports on NO_x for staged cyclone combustion with and without reburning. Nominal operating conditions: 5 million Btu/hr, 0.70 cyclone stoichiometry, 17% overall excess air, and 45% through a 200 mesh screen cyclone Pittsburgh #8 coal fineness.

Coal Reburn and Oxygen-Enriched Cyclone Combustion - After optimizing the OFA distribution and extent of coal reburn, oxygen enrichment of the staged cyclone furnace was evaluated by partial substitution of air with O_2. Various O_2 lances were installed sequentially through the scroll burner and the secondary air entrance to the cyclone barrel. Consistent with the computer modeling predictions, oxygen enrichment by way of a multi-hole lance at the secondary air inlet to the cyclone barrel was more effective than the centerline scroll burner lance. Without coal reburn, oxygen enrichment of the staged cyclone furnace (SR=0.7) at 2-10% of the total O_2 flow into the boiler resulted in 0.17-0.18 lb $NO_x/10^6$ Btu. With 10% coal reburn and 5-7% oxygen enrichment in the cyclone furnace, the NO_x levels were 0.15 lb/10^6 Btu or lower as shown in Figure 47. In both cases, the unburned combustibles remained unchanged over the entire range of pure O_2 flow to the cyclone furnace.

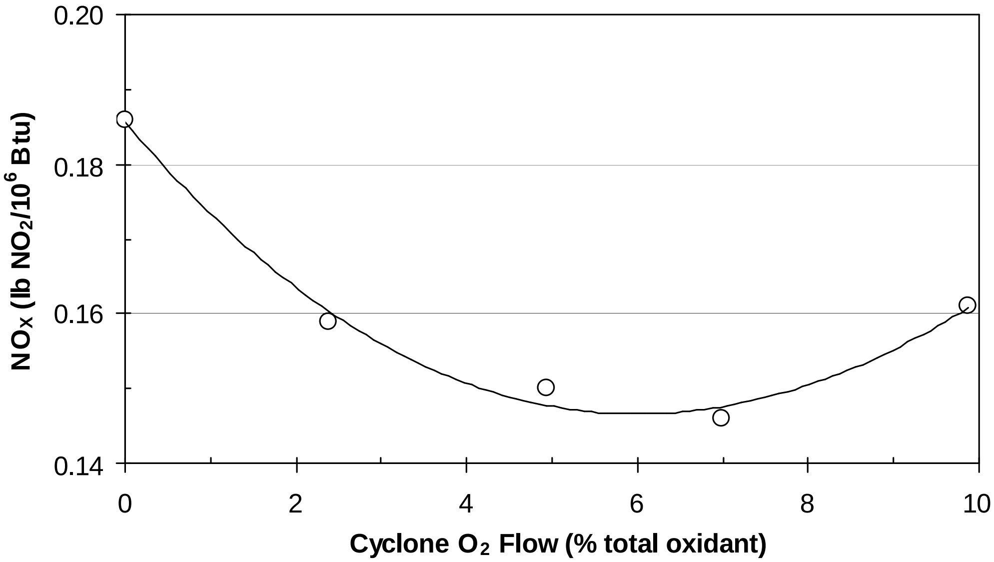

Figure 47. **O_2 enrichment effects on NO_x emissions from burning Pittsburgh #8 coal in the cyclone furnace. Nominal operating conditions: 5 million Btu/hr, 0.70 cyclone stoichiometry, 1.17 overall stoichiometry, 21% FGR flow to reburn burners, and 10% reburn with 73% through a 200 mesh screen PC fineness.**

Optimum NO_x Values for Cyclone-Fired Configurations - Optimum cyclone firing performance results at 5 million Btu/hr firing rate and 1.17 overall stoichiometry for the staged combustion of Pittsburgh #8 using two-level OFA configuration, with and without oxygen enrichment or coal reburn, are summarized in Figures 48 and 49. Without oxygen enrichment, the minimum stoichiometry to avoid slag buildup and plugging in the cyclone throat was 0.7. Adding 10% oxygen to the cyclone furnace enabled high-temperature and deep-staged operation at 0.6 stoichiometry and good slag tapping from the bottom of the primary furnace. Under these conditions, average NO_x levels were 134 ppmv (0.172 lb/million Btu) with 80 ppmv CO. But as stated earlier, the best combustion and emission performance results were measured at 0.7 cyclone furnace stoichiometry, 10% coal reburning, 21% FGR, and 5-7% oxygen enrichment. In fact, the lowest measured NO_x emissions of 113 ppmv (0.146 lb/million Btu) and the corresponding 59 ppmv CO were measured at 7% oxygen enrichment in the cyclone furnace.

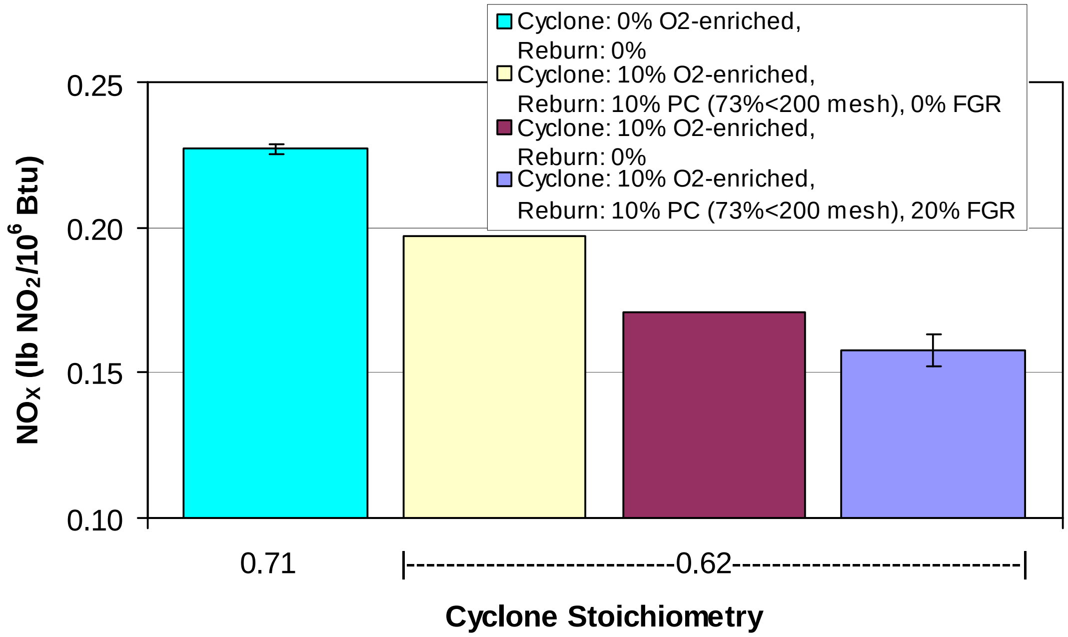

Figure 48. Cyclone firing configuration and operating conditions effect on NO_x. Nominal operating conditions: 5 million Btu/hr, 17% overall excess air, 45% through a 200 mesh screen cyclone Pittsburgh #8 coal fineness.

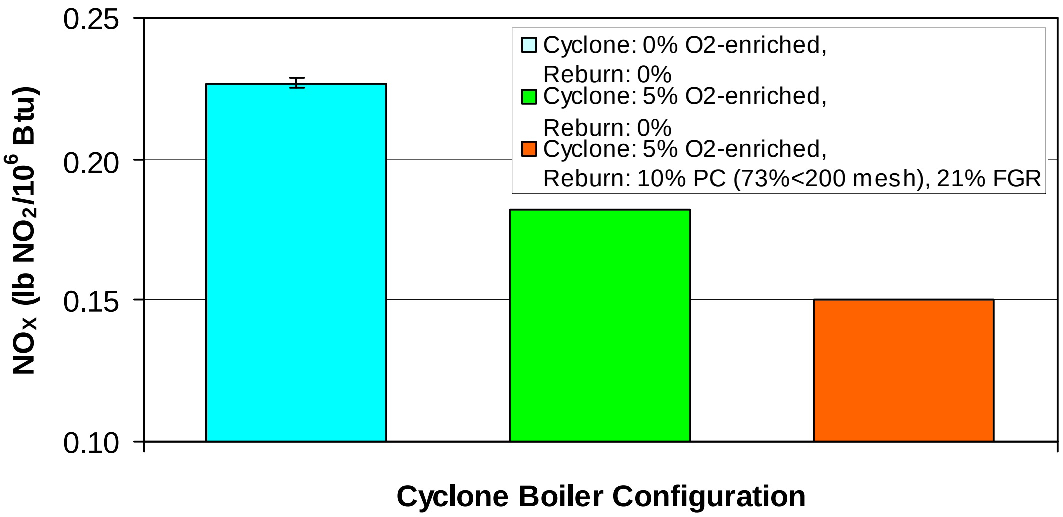

Figure 49. Cyclone firing configuration and operating condition effects on NO_x. Nominal operating conditions: 5 million Btu/hr, 0.7 cyclone furnace stoichiometry, 17% overall excess air, 45% through a 200 mesh screen cyclone Pittsburgh #8 coal fineness.

Corrosion Measurements in Cyclone-Fired Operation - Figure 50 shows the semi-quantitative corrosion rate measurements for selected operating conditions. In-furnace corrosion rates are normalized relative to unstaged operation at 1.17 cyclone stoichiometry. Typical values ranged from unchanged to 3 times faster than the baseline numbers.

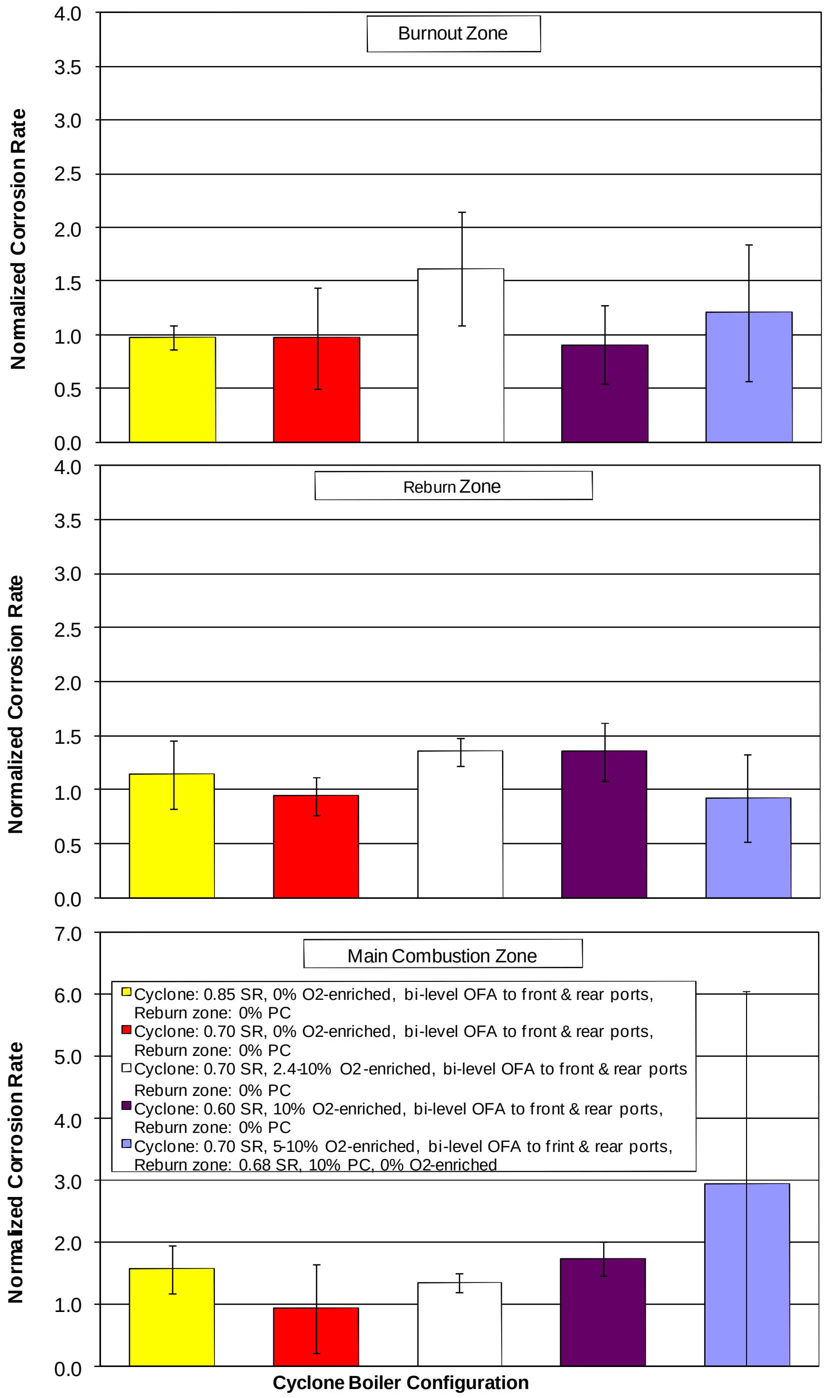

Figure 50. Normalized corrosion rates (relative to unstaged cyclone operation at 1.17 stoichiometry) for different cyclone-fired conditions. Nominal operating conditions: Pittsburgh #8 coal combustion at 5 million Btu/hr and 1.17 overall stoichiometry.

Fuel Switching Effects- At the conclusion of Pittsburgh #8 coal firing tests, an extra test day was devoted to investigating fuel switching effects. For this purpose, a Powder River Basin Black Thunder coal was burned in the cyclone furnace while being staged with two levels of OFA ports but without coal reburning or FGR. Firing the high-moisture and low-nitrogen content Black Thunder coal produced a cooler flame with lower NO_x emissions relative to an eastern bituminous coal performance. Without oxygen enrichment, the lowest cyclone stoichiometry for continuous slag tapping was 0.7. Under this condition and 1.17 overall stoichiometry, the NO_x concentration was 108 ppmv (0.148 lb/million Btu), and the CO level was 24 ppmv. Un-staged NO_x and CO emissions levels were 759 ppmv (1.04 lb/million Btu) and 27 ppmv, respectively. Increasing the cyclone stoichiometry increased the fuel-N oxidation and resulted in higher NO_x emissions as seen in Figure 51. LOI levels were lowest around the cyclone stoichiometry of 1.0 where peak combustion temperatures are expected. Birdseye view flame images and 2-D temperature maps of the cyclone combustor exit are shown in Figure 52. Exit gas luminosity and combustion temperature peaked at around 3000°F (1650°C) at stoichiometric operation (SR=1.0) but decreased at 1.17 and 0.85 stoichiometries. Lowering the cyclone combustor stoichiometry to 0.70 further cooled the flame to about 2750°F (1510°C) with minimal obscuration by soot and fly ash.

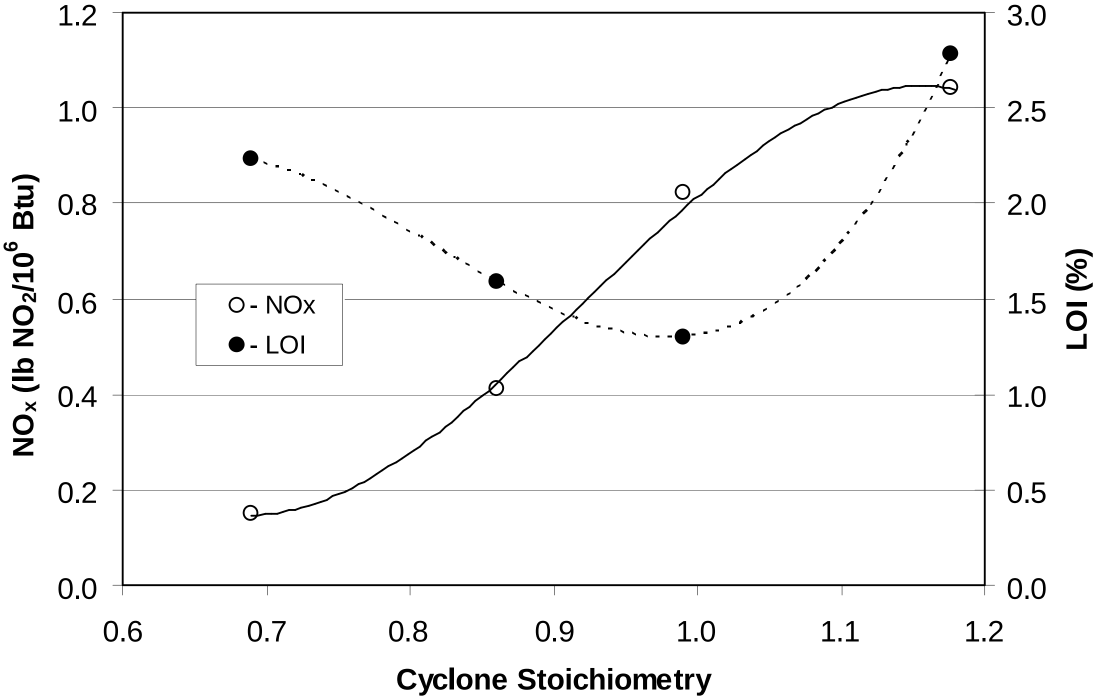

Figure 51. Cyclone combustor stoichiometry effects on NO_x and LOI. Nominal operating conditions: 5 million Btu/hr, 17% overall excess air, two-level OFA ports, and 35% through a 200 mesh screen Black Thunder coal fineness.

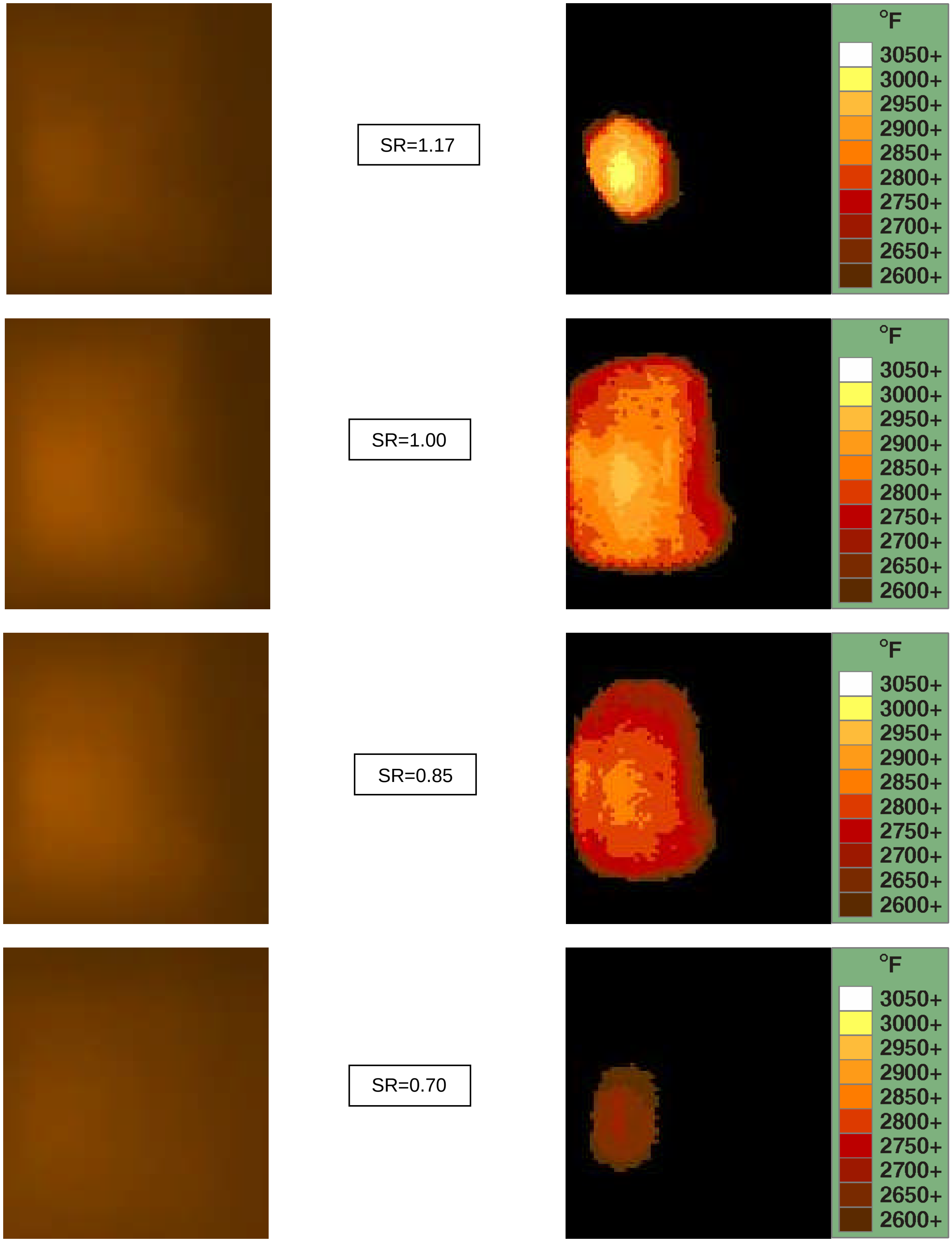

Figure 52. **Cyclone stoichiometry effects on the cyclone combustor exit gas luminosity and temperature while burning 35% through 200 mesh screen PRB Black Thunder coal at 0.70 stoichiometry. Flow direction is from left to right.**

Partial substitution of secondary air flow to the cyclone combustor with oxygen was tested at a constant combustion stoichiometry of 0.70 using up to 10% O_2 enrichment and an overall stoichiometry of 1.17. Figure 53 shows the oxygen enrichment effects on NO_x, CO, and LOI values during staged operation. CO and LOI levels decreased with increasing oxygen enrichment. Within the 0-10% oxygen enrichment range, the lowest NO_x concentration of 109 ppmv (0.142 lb/10^6 Btu) and the corresponding 23 ppmv CO and 2.2% LOI were measured at the 5% enrichment level. At this enrichment level, the sub-stoichiometric combustion zone may have reached the optimum temperature for NO_x destruction. Increasing NO_x emissions at higher oxygen (greater than 5%) enrichment levels is most likely linked to enhanced "fuel-bound nitrogen" oxidation and "prompt" NO contribution.

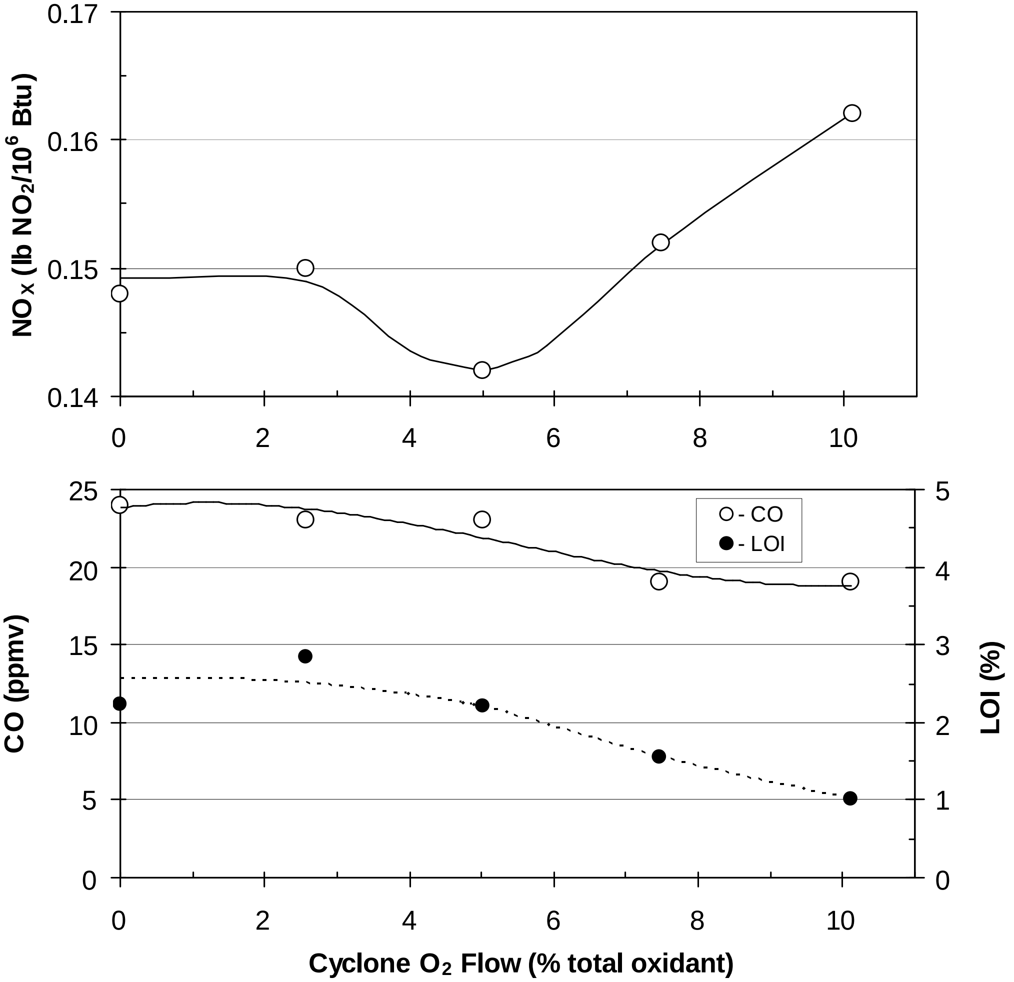

Figure 53. **O_2-enrichment effects on NO_x and LOI using a multi-hole lance in the cyclone furnace. Nominal operating conditions: 5 million Btu/hr, 0.70 cyclone stoichiometry, two-level OFA ports, 1.17 overall boiler stoichiometry, and 35% through a 200 mesh screen Black Thunder coal fineness.**

As seen in Figure 54, the cyclone combustor exit gas luminosity and temperature increased progressively with rising oxygen enrichment. With 10% oxygen enrichment, the cyclone exit gas temperature rose by about 250°F (140°C) to 2950°F (1620°C), approaching the non-enriched stoichiometric operation values.

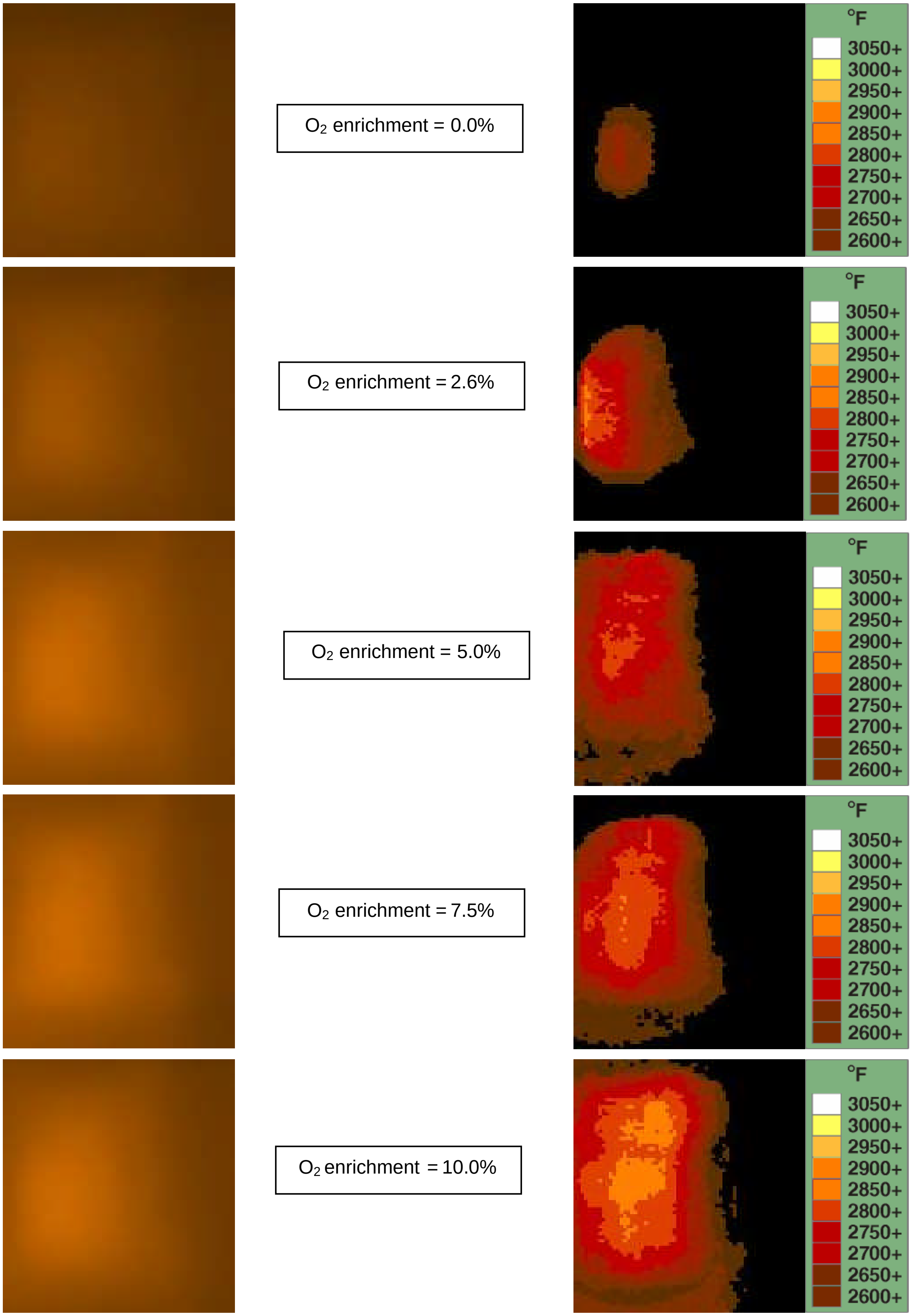

Figure 54. O$_2$ enrichment effects on the cyclone combustor exit gas luminosity and temperature while burning 35% through 200 mesh screen PRB Black Thunder coal at 0.70 stoichiometry. Flow direction is from left to right.

Oxygen enrichment of the cyclone combustor at the 5% level extended the lower stoichiometry limit to 0.6 while maintaining good slag tapping. At 0.6 cyclone furnace stoichiometry, 5% oxygen enrichment and 1.11 overall boiler stoichiometry, the NO_x and CO emission levels were 96 ppmv (0.120 lb/million Btu) and 66 ppmv, respectively. At 1.17 overall combustion stoichiometry, the average NO_x concentration was 95 ppmv (0.126 lb/million Btu), and the average CO was 17 ppmv when the cyclone was staged close to 0.7 stoichiometry and the pure oxygen flow to the cyclone was equivalent to 5% of the total oxidizer flowing into the furnace. Figure 55 provides a graphical summary of the results. For reference, the best results from firing the eastern bituminous Pittsburgh #8 coal were 112 ppmv NO_x (0.146 lb/million Btu) and 59 ppmv CO and they were achieved at 0.7 cyclone stoichiometry, 10% coal reburning, and 7% oxygen flow to the boiler.

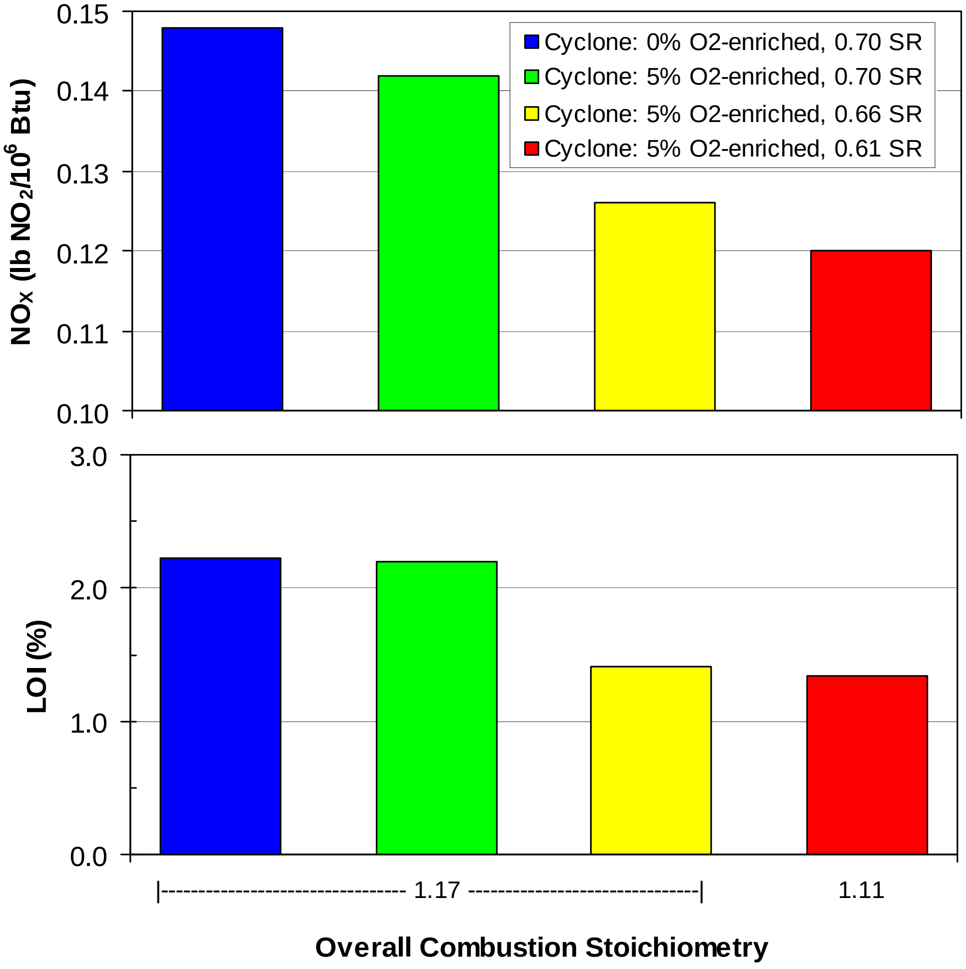

Figure 55. Cyclone firing configurations and operating conditions effects on NO_x and LOI. Nominal operating conditions: 5 million Btu/hr firing of Black Thunder coal.

ECONOMIC ANALYSIS

An economic analysis was conducted in order to compare the best-performing NO_x removal technologies from pilot-scale testing with the state-of-the-art SCR systems for wall-fired and cyclone-fired commercial power plants. Major parameters included combustion-generated NO_x levels (wall-fired versus cyclone-fired), stack emissions, and plant size (150, 400, and 800 MW_e gross). Baseline and in-furnace controlled NO_x levels were taken from pilot-scale test results and are shown in Table 9. Table 10 lists the key assumptions. SCR catalyst replacement expenses were sourced from a 2008 article [3] and converted to 2009 dollars. Incremental fuel costs for non-SCR technologies with slightly higher unburned carbon loss were also estimated.

Table 9. Technologies considered based on NO_X levels achieved in pilot-scale testing

Technology	NO_x Emissions ($lb\ NO_x/10^6$ Btu)	Change from Baseline ($lb\ NO_x/10^6$ Btu)
Wall-fired		
Baseline: Low-NO_x Burner + Single Level OFA	0.35	-
Low-NO_x Burner + 2 Level OFA	0.25	0.10
Low-NO_x Burner + 2 Level OFA + 8.9% O_2 Enrichment	0.21	0.14
Low-NO_x Burner + 2 Level OFA + 6.3% O_2 Enrichment + Coal Reburn	0.19	0.16
SCR (0.1 lb $NO_X/10^6$ Btu)	0.10	0.25
SCR (0.05 lb $NO_X/10^6$ Btu)	0.05	0.30
Cyclone-Fired		
Baseline: Single Level OFA	0.50	-
2 Level OFA	0.23	0.27
2 Level OFA + 5% O_2 Enrichment	0.18	0.32
2 Level OFA + 5% O_2 Enrichment + Coal Reburn	0.15	0.35
SCR (0.1 lb $NO_x/10^6$ Btu)	0.10	0.40
SCR (0.05 lb $NO_x/10^6$ Btu)	0.05	0.45

Table 10. Key assumptions of the economics assessment

Assumptions	Value		
Plant Output (MW_e, gross)	150	400	800
Heat Rate (Btu/kWh)	10000	9600	9300
Capacity Factor	0.8	0.85	0.9
Fraction of coal used by coal reburn burners (wall-fired)	0.2		
Fraction of coal used by coal reburn burners (cyclone-fired)	0.1		
Incremental unburned carbon loss (percentage points) increase:			
2 Level OFA	1.5		
2 Level OFA + O_2 Enrichment	1.0		
2 Level OFA + O_2 Enrichment + Coal Reburn	1.5		
Capitalization Factor (20 years @ 7%, 3% escal, taxes)	0.1407		
Coal Cost ($\$/10^6$ Btu)	2.50		
SCR Catalyst Volume (ft^3/MW)	49.44		
New SCR Catalyst Price ($\$/ft^3$)	190		
SCR Management Strategy	100% regenerated (no disposal cost)		
Annual SCR Catalyst Replacement	25%		
Regenerated SCR Catalyst Price (% of new catalyst price)	60%		
Coal	Bituminous		
Currency	2009 US Dollars		
Credits Not Included			

Results and Discussion of Economic Assessment

Estimated costs of adding the selected NO_x control technologies to a baseline plant are shown in Table 11 and Table 12 for wall and cyclone-fired units, respectively. Here, technology costs are in thousands of dollars. Technology effectiveness is listed as $/kW for capital and $/ton of NO_x removed using the annual O&M plus levelized annual capital cost.

Table 11. Summarized results of economic assessment for wall-fired units

Unit Size (MW_e, gross)	LNB† + 2 level OFA		LNB + 2 level OFA + 8.9% O_2 Enrichment		LNB + 2 level OFA + 6.3% O_2 Enrichment + Coal Reburn		SCR (0.1 lb $NO_x/10^6$Btu)		SCR (0.05 lb $NO_x/10^6$Btu)	
Technology Cost ($K)										
	Capital	Annual O&M	Capital	Annual O&M	Capital	Annual O&M	Capital	Annual O&M	Capital	Annual O&M
150	1,395	394	23,278	2,380	34,602	2,482	59,119	649	61,653	714
400	2,200	1,072	45,420	3,093	71,180	3,356	81,205	1,562	85,858	1,726
800	3,000	2,200	72,540	4,278	103,700	4,810	109,411	3,058	117,661	3,387
Technology Effectiveness										
	Capital [$/kw]	[$/ton-$NO_X$ Removed]	Capital [$/kw]	[$/ton-$NO_X$ Removed]	Capital [$/kw]	[$/ton-$NO_X$ Removed]	Capital [$/kw]	[$/ton-$NO_X$ Removed]	Capital [$/kw]	[$/ton-$NO_X$ Removed]
150	9.30	1,123	155	7,685	231	8,741	394	6,824	411	5,954
400	5.50	967	114	4,738	178	5,845	203	3,634	215	3,219
800	3.75	894	91	3,528	130	4,134	137	2,517	147	2,266

Table 12. Summarized results of economic assessment for cyclone-fired units

Unit Size (MW_e, gross)	Cyclone + 2 level OFA		Cyclone + 2 level OFA + 5% O_2 Enrichment		Cyclone + 2 level OFA + 5% O_2 Enrichment + Coal Reburn		SCR (0.1 lb $NO_x/10^6$Btu)		SCR (0.05 lb $NO_x/10^6$Btu)	
Technology Cost ($K)										
	Capital	Annual O&M	Capital	Annual O&M	Capital	Annual O&M	Capital	Annual O&M	Capital	Annual O&M
150	1,256	394	16,493	2,316	31,978	2,461	61,304	776	63,520	837
400	1,980	1,072	31,800	2,916	65,880	3,297	86,478	1,935	90,683	2,095
800	2,736	2,200	51,016	3,919	95,176	4,690	117,997	3,806	125,498	4,127
Technology Effectiveness										
	Capital [$/kw]	[$/ton-$NO_X$ Removed]	Capital [$/kw]	[$/ton-$NO_X$ Removed]	Capital [$/kw]	[$/ton-$NO_X$ Removed]	Capital [$/kw]	[$/ton-$NO_X$ Removed]	Capital [$/kw]	[$/ton-$NO_X$ Removed]
150	8.37	402	110	2,757	213	3,784	409	4,472	423	4,132
400	4.95	350	80	1,615	165	2,511	216	2,466	227	2,309
800	3.42	326	64	1,182	119	1,761	147	1,740	157	1,651

Figure 56 shows the levelized annual capital and O&M costs of NO_x control for all case studies. Addition of a second OFA level is by far the lowest cost technology. Use of O_2 enrichment with 2-level OFA results in a higher capital cost largely due to the requirement for an air separation unit (ASU). But when coal reburning burners are added, the ASU accounts for a significantly smaller fraction of the capital cost (in some cases less than half).

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† LNB: Low-NO_x Burner

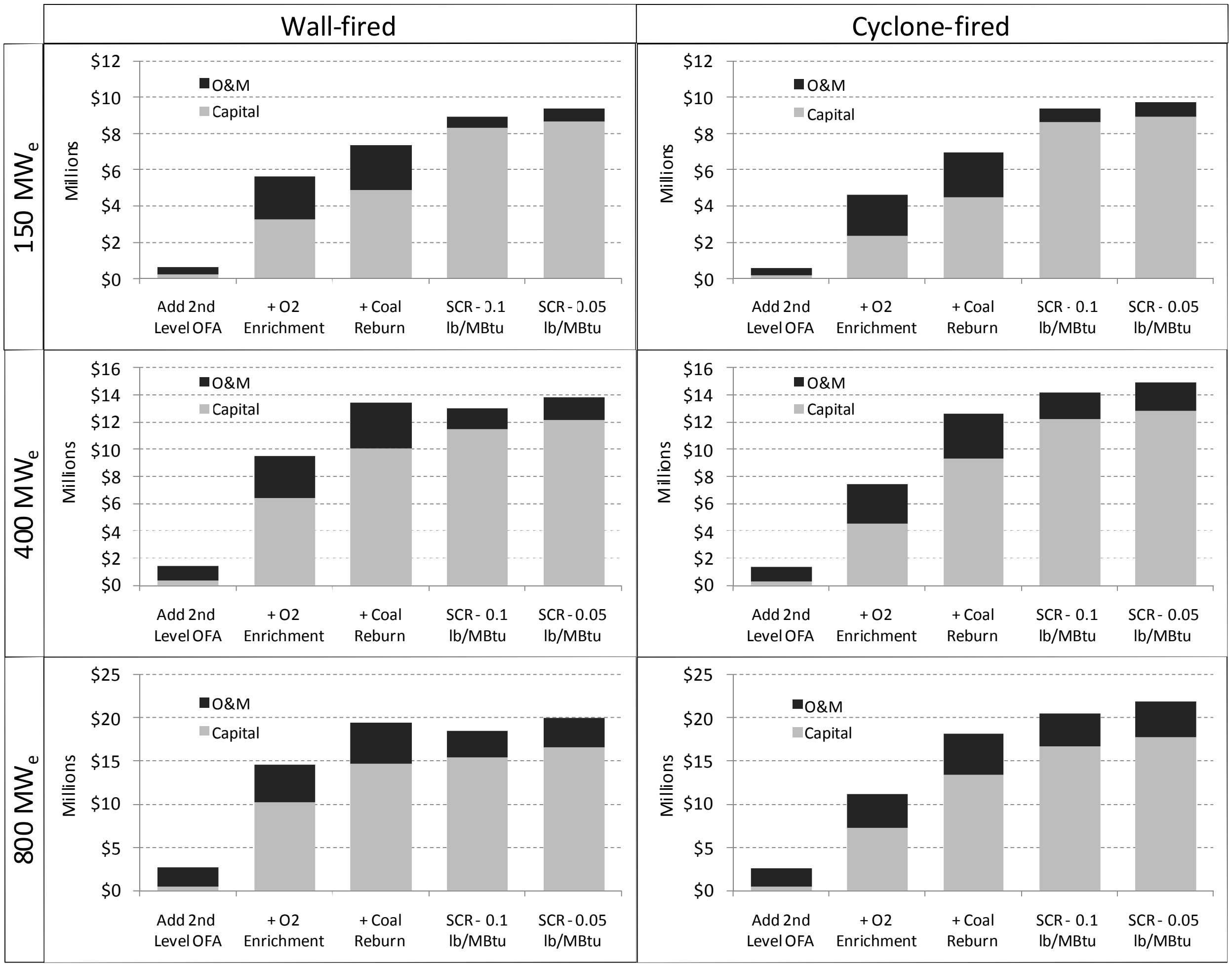

Figure 56. Levelized annual capital and O&M costs for various NO_x control technologies assuming a capitalization factor of 0.1407 (20 years).

In this analysis, the O&M cost of a 2-level OFA system relates to higher fuel charges due to rising unburned carbon losses from the implementation of in-furnace NO_x control methods in plants where available residence times for efficient NO_x destruction and carbon burnout may be insufficient. For O_2 enrichment technologies, the O&M cost is dominated by the ASU operation. Ammonia and catalyst replacement (with regenerated catalyst) contribute almost equally to the O&M expenses for the SCR options. SCR replacement costs are a strong function of the coal type and SCR management strategy. Our analysis was based on a bituminous coal. Burning of lower rank coals in some utility boilers has required more frequent catalyst replacements. For those units, the O&M costs would increase above the reported values.

Figure 57 shows the same information as Figure 56, but calculated with a capitalization factor representative of financing over 10 years (0.259) rather than 20. In general, the relative attractiveness of each technology remains unchanged, except for the 400 MW_e wall-fired with the coal reburning case which turned out to be slightly more expensive than the SCR (0.1 lb/10^6 Btu) option when financed over a longer period. The lack of sensitivity to the capitalization factor in this study is due to all technologies being relatively similar in capital intensity (excepting the lowest cost 2-level OFA option). Therefore, the more common capitalization factor of 0.1407 was used in all subsequent analysis.

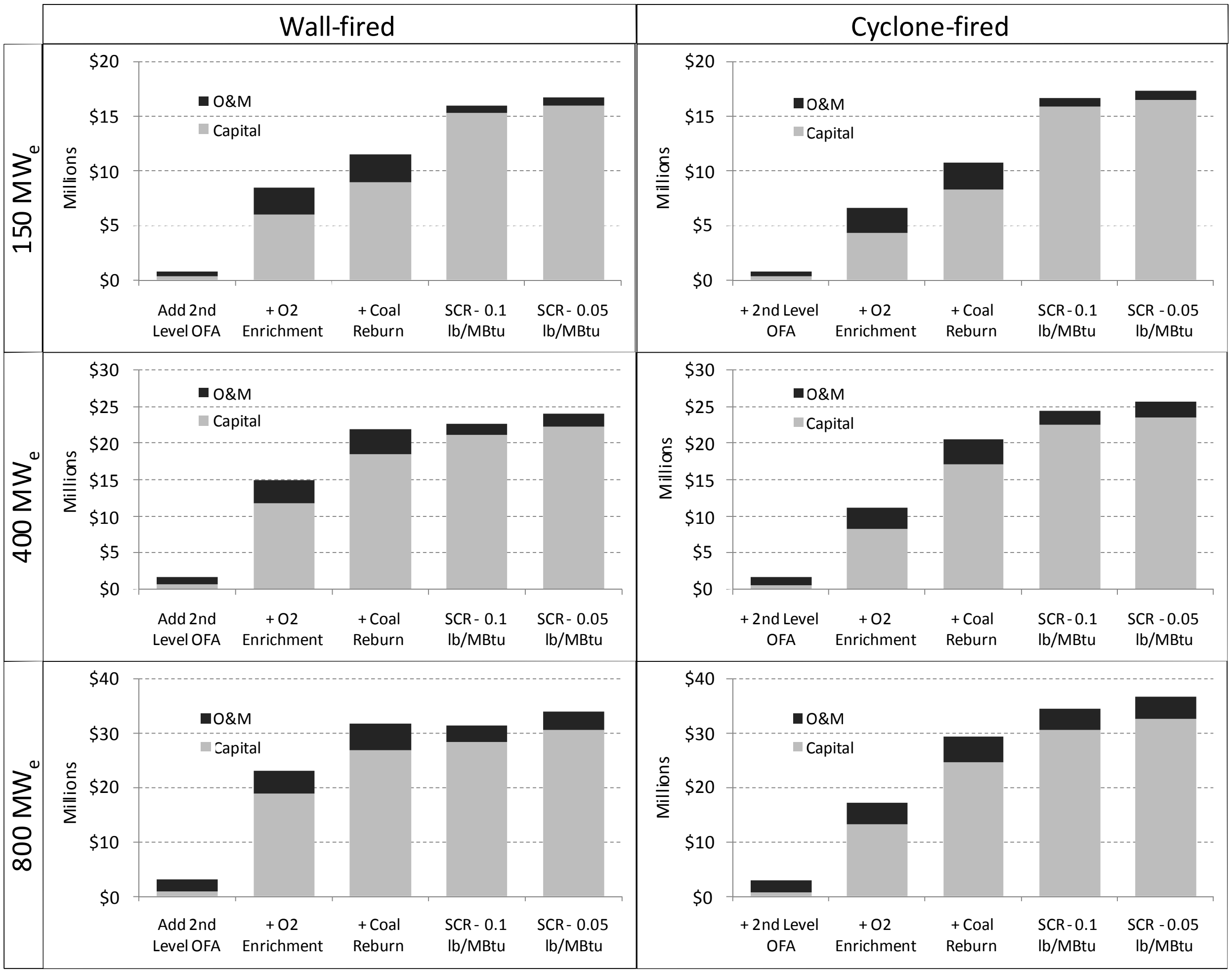

Figure 57. Levelized annual capital and O&M costs for various NO_x control technologies assuming a capitalization factor of 0.259 (10 years).

Figure 58 and Figure 59 compare the effectiveness of the NO_x control scenarios in terms of \$/ton-NO_x removed for the wall and cyclone-firing configurations, respectively. Expected NO_x reduction performance is also plotted for these arrangements. For wall-fired units that are already equipped with low-NO_x burners and single-level OFA ports, the most cost-effective measure is the installation of new OFA ports at a second level. Reductions in NO_x emissions for these units will, however, be small given that existing combustion modifications have already minimized the NO_x emissions. Our analysis indicates that the cost effectiveness of SCR for wall-fired plants is better than O_2 enrichment strategies with or without coal reburning. Both SCR and O_2 enrichment methods become more attractive economically at larger scales (400 and 800 MWe). Two-level OFA is the only low cost NO_x control option for smaller scales (150 MWe). The least effective technology is the combined use of 2-level OFA, O_2 enrichment, and coal reburning due to significant capital costs.

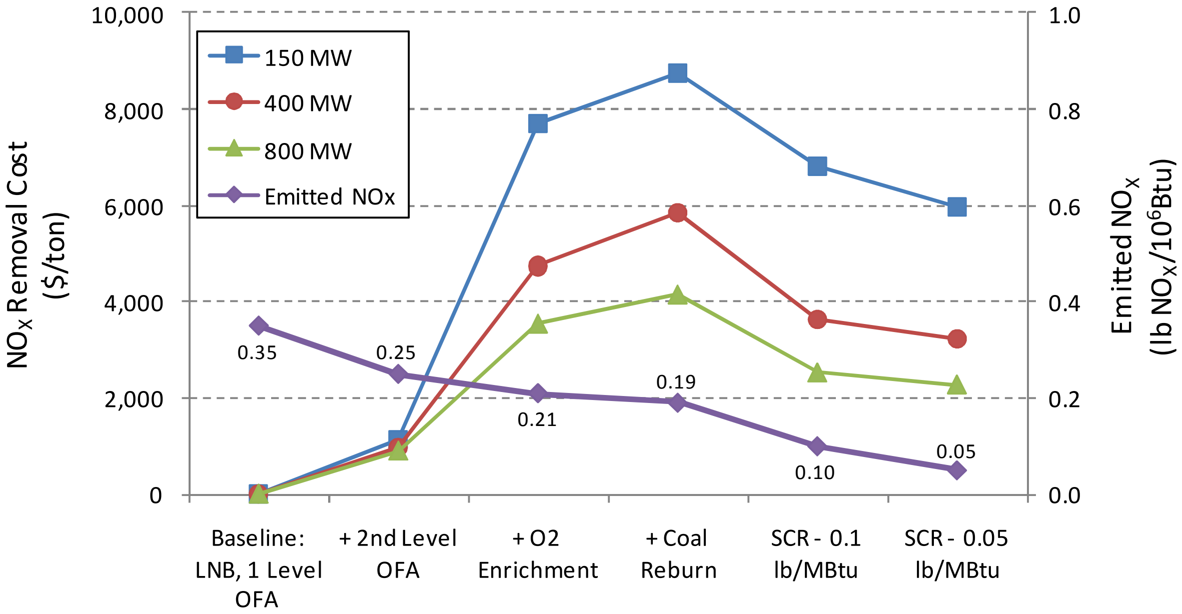

Figure 58. **Estimated NO_x removal costs following installations of various in-furnace control methods in reference wall-fired units previously equipped with low-NO_x burners and single-level OFA ports. Plotted NO_x emission levels are based on pilot-scale testing.**

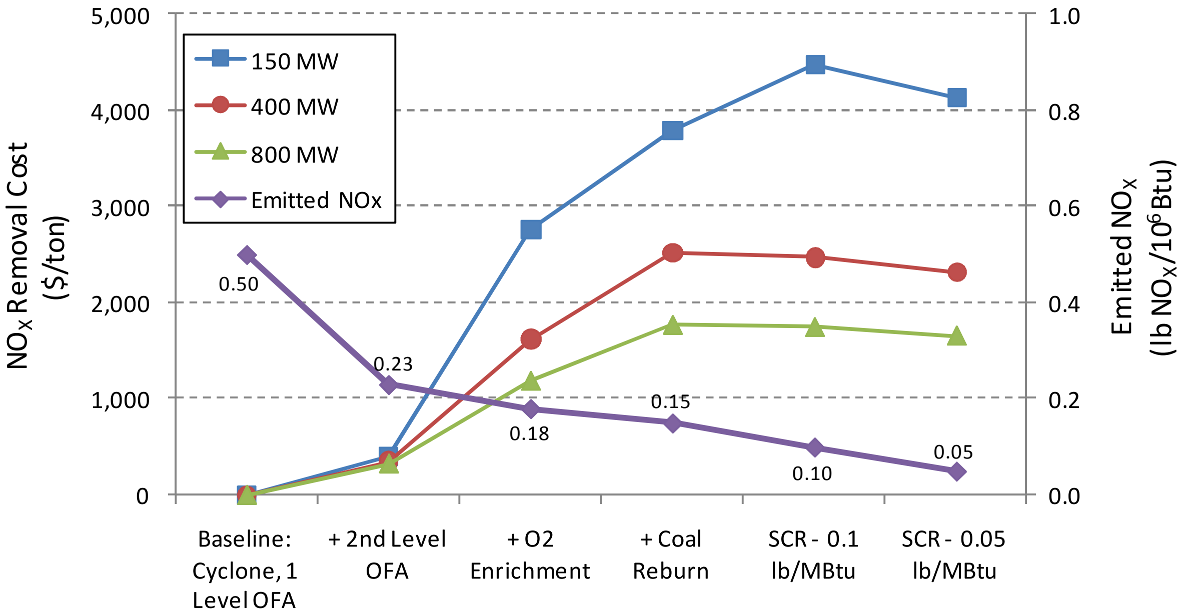

Figure 59. **Estimated NO_x removal costs following installations of various in-furnace control methods in reference staged cyclone-fired units previously equipped with single-level OFA ports. Plotted NO_x emission levels are based on pilot-scale testing.**

Staged cyclone furnaces typically produce more NO_x relative to staged wall-fired units. Pilot-scale tests demonstrated a significant decrease in NO_x emissions when the cyclone furnace was operated with two-level OFA ports. Referring to Figure 59, 2-level OFA plus O_2 enrichment is more cost effective per ton of NO_x removed than SCR. Similar to the wall-firing analysis, coal reburning is a relatively expensive option for the modest achievable NO_x reductions. Application of SCR or O_2 enrichment benefits from economies of scale which favors the selection of 2-level OFA for smaller units. The improvement in NO_x with 2-level OFA is rather dramatic for the minimal cost. It should be noted that while the combined use of 2-level OFA and SCR could reduce the ammonia flow rate required at the SCR, the associated cost of increased unburned carbon in this analysis is greater than the expected savings in ammonia. It should be emphasized that the achievable NO_x emissions are different among the technologies that were evaluated in this economic analysis. SCR technology is more expensive for smaller units relative to other technologies, but does offer the highest level of NO_x reduction.

Figures 60 and 61 compare the normalized levelized costs (relative to those of SCR systems achieving 0.1 lb $NO_x/10^6$ Btu) for additional NO_x removal by various in-furnace control methods in reference wall-fired or cyclone-fired units already equipped with single-level OFA ports. As noted earlier, two-level OFA ports offer the most economical approach for moderate NO_x control, especially for smaller units. O_2 enrichment in combination with 2-level OFA is not cost effective for wall-firing (Figure 60). But for cyclone units, its NO_x removal rate is at 80% of an SCR system performance at less than 75% of the levelized cost as seen in Figure 61. Combined deployment of coal reburning, 2-level OFA, and O_2-enriched combustion in wall-fired plants achieves only 64% of the SCR NO_x removal performance and as such it would be more expensive. But the NO_x removal performance by this approach for cyclone-fired units is equivalent to 88% of the SCR system and the analysis shows that the costs are comparable.

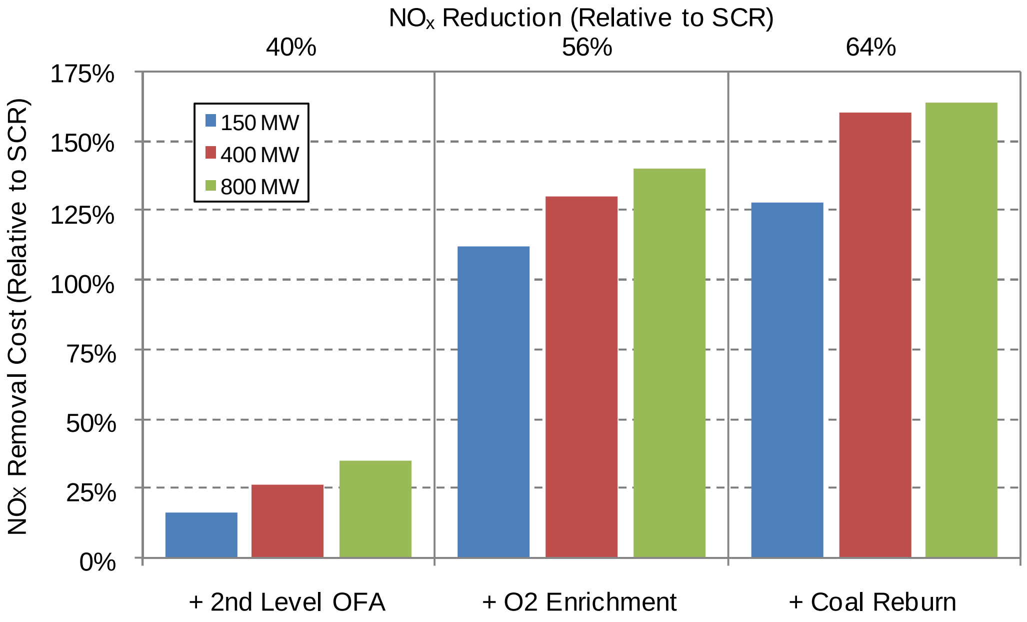

Figure 60. Levelized costs (relative to SCR) for additional NO_X removal by various in-furnace control methods in reference wall-fired units previously equipped with low-NO_x burners and single-level OFA ports.

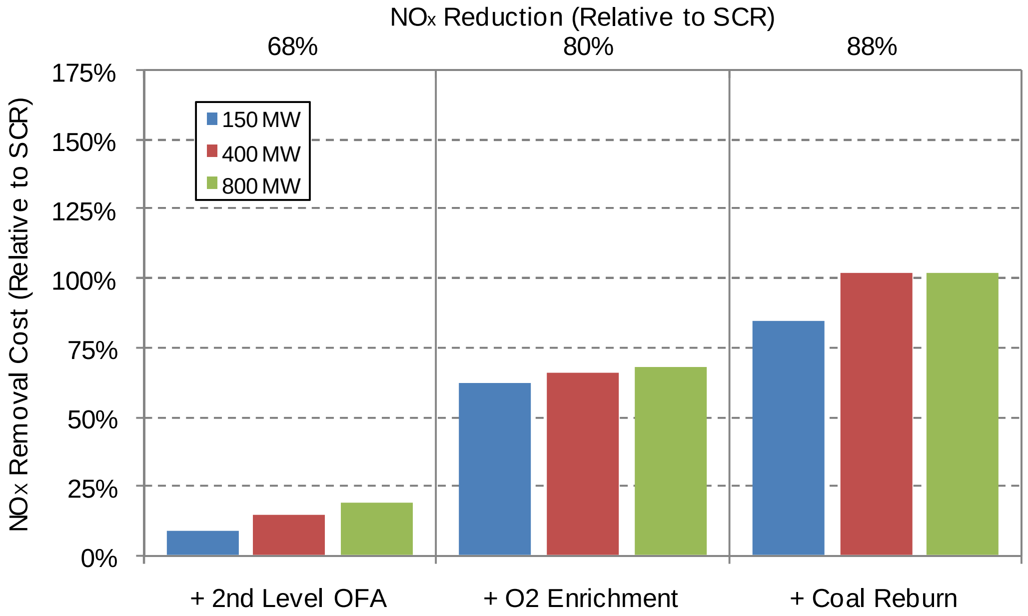

Figure 61. **Levelized costs (relative to SCR) for additional NO_X removal by various in-furnace control methods in reference cyclone-fired units previously equipped with single-level OFA ports.**

SUMMARY AND CONCLUSIONS

A NO_x minimization strategy for cyclone and pulverized coal-burning utility boilers was developed that includes deep air staging, innovative oxygen use, reburning, and advanced combustion control enhancements. Computational fluid dynamics modeling was applied to refine and select the best arrangements. Pilot-scale tests were conducted by firing an eastern high-volatile bituminous Pittsburgh #8 coal at 5 million Btu/hr in a facility that was set up with two-level overfire air ports. Oxygen enrichment enabled high-temperature and deeply staged operation for lowering NO_x emissions. One of the key findings in this work was the superior NO_x reduction performance of the cyclone-fired arrangement relative to the wall-fired configurations. Intense flow mixing characteristics of the cyclone furnace together with the longer residence time in the oxygen-enriched but sub-stoichiometric combustion zone were mainly responsible for the outcome. Although the program target of 0.10 lb $NO_X/10^6$ Btu was not met, significant progress was made toward developing a NO_x minimization approach for coal-burning utility boilers. Major highlights are summarized below.

Wall-Fired DRB-4Z® Burner Operation

- At a fixed overall excess air level of 17%, NO_X emissions with single-level OFA ports were around 0.32 lb/million Btu at 0.80 burner stoichiometry.
- Two-level OFA operation lowered the NO_x levels to 0.25 lb/million Btu.
- Oxygen enrichment at 8.9% level in the staged burner (SR=0.7) reduced the NO_x values to 0.21 lb/million Btu.
- Coal reburning in the 9-19% range in conjunction with oxygen enrichment further trimmed the NO_x emissions from 0.21 to 0.19 lb/million Btu.
- O_2 enrichment plus reburning and 2-level OFA operation curbed the NO_x emissions by 41% relative to conventional air-staged operation with single-level OFA ports.

- Measured corrosion rates were up to three times faster relative to conventional staged operation.
- Oxy-reburn had no adverse effect on heat transfer characteristics.
- Transformation of elemental to oxidized mercury and the potential for removing the water soluble Hg^{2+} in a wet scrubber was increased with oxy-reburn.
- Two-level OFA ports offer the most economical approach for moderate NO_x control, especially for smaller units.
- O_2 enrichment in combination with 2-level OFA and/or coal reburning is not cost effective.

Cyclone-Fired Operation

- Unstaged combustion of the high-volatile bituminous Pittsburgh #8 coal with air in the 1.16 to 1.18 stoichiometry range produced 1.13 to 1.39 lb NO_x/million Btu.
- Switching from the Pittsburgh #8 coal to the Powder River Basin Black Thunder coal generated 1.04 lb/million Btu at 1.17 combustion stoichiometry.
- Staged combustion at 0.7 stoichiometry while using 2-level OFA ports to maintain an overall stoichiometry of 1.17 resulted in 0.23 lb NO_x/million Btu for the Pittsburgh #8 coal and 0.15 lb NO_x/million Btu for the Black Thunder coal.
- With 5% oxygen enrichment of the cyclone furnace under otherwise similar conditions as stated above, the NO_x emissions were reduced to 0.18 lb/million Btu for the Pittsburgh #8 coal and 0.13 lb/million Btu for the Black Thunder coal while maintaining good slag tapping.
- By combining oxygen enrichment of the staged cyclone, 2-level OFA operation, and 10% coal reburning, NO_x levels for the Pittsburgh #8 coal dropped to 0.15 lb/million Btu.
- Optimum results for the Pittsburgh #8 and Black Thunder coals represent 88% NO_x reduction from the uncontrolled operation.
- Measured corrosion rates were up to three times faster relative to conventional un-staged operation.
- Two-level OFA and O_2-enrichment achieved 80% of SCR NO_x removal performance but at less than 75% of the SCR levelized cost.

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APPENDICES

Appendix I. Summary of the Computer Modeling Results for PC-Fired Simulations[1]

Case	Main Combustion Zone					OFA Ports		Reburn Zone									Highlights of Modeling Predictions
		O_2 to main zone						Reburn Burner						O_2 to Reburn Burner			
	SR	% flow to boiler	Injection location	Velocity (ft/min)	% FGR to SA	Swirl No.	Swirl direction	No. of zones	Swirl No.	Swirl direction	SR	% fuel reburn	% FGR	% flow to boiler	Injection location	Velocity (ft/min)	
PC1	0.80	0	--	0	0	0	N/A	--	--	--	--	0	0	0	--	--	Large oxidizing zone immediately above burner exit, poor OFA mixing, O_2 and temperature stratifications at furnace exit
PC2	0.80	0	--	0	0	0.4	CCW/CW	--	--	--	--	0	0	0	--	--	Large oxidizing zone immediately above burner exit, some O_2 and temperature stratifications at furnace exit
PC3	0.80	0	--	0	0	0	N/A	2	0.7	CW/CW	0.63	30	10	10	centerline	2500	Small oxidizing zone immediately above burner exit, some O_2 stratification at furnace exit
PC4	0.80	0	--	0	0	0	N/A	2	0.7	CW/CW	0.63	30	10	10	centerline	5000	Large flow recirculation and small oxidizing zone immediately above burner exit, some O_2 stratification at furnace exit
PC5	0.80	0	--	0	0	0.9	CW/CW	2	0	N/A	0.63	30	10	10	centerline	5000	Strong main flame propagation toward the nose, reducing zone confined to rear wall and nose area, poor OFA penetration
PC6	0.80	0	--	0	0	0.4	CCW/CW	2	0.7	CW/CCW	0.63	30	10	10	centerline	5000	Good configuration for producing a hot, O_2-deficient, combustion zone at the reburn plane, more uniform O_2 and T at furnace exit
PC7	0.80	0	--	0	0	0	N/A	2	0.7	CW/CW	0.63	30	10	10	centerline	5000	Good configuration for producing a hot, O_2-deficient, combustion zone at the reburn plane, but high-T above the nose
PC8	0.80	0	--	0	0	0.9	CW/CW	2	0.7	CW/CW	0.63	30	10	10	centerline	5000	Oxidizing zone at the burner and OFA walls, poor OFA penetration
PC9	0.80	0	--	0	0	0	N/A	2	0	N/A	0.63	30	10	10	centerline	7500	Good configuration for producing a hot, O_2-deficient, combustion zone at the reburn plane, but locally hot zone above the OFA ports
PC10	0.80	0	--	0	0	0.9	CW/CW	2	0	N/A	0.69	30	20	10	centerline	5000	Short main flame, strong recirculation zone between main flame and reburn flame, largest O_2-deficient zone, possible reburn flame detachment
PC11	0.80	0	--	0	0	0.9	CW/CW	2	0.7	CW/CW	0.69	30	20	10	centerline	5000	Long main flame, oxidizing zone on the burner and OFA walls, poor OFA penetration, some temperature stratification at furnace exit
PC12	0.80	0	--	0	0	0.4	CCW/CW	2	0.7	CW/CCW	0.43	30	10	5	centerline	5000	Small oxidizing zone immediately above burner exit, locally hot zones above the OFA ports
PC13	0.80	0	--	0	0	0.4	CCW/CW	1	0.4	CW/CCW	0.63	30	10	10	premixed	same as mixture	Well-attached reburn flame, an oxidizing zone immediately above burner exit
PC14	0.80	0	--	0	0	0.4	CCW/CW	1	0	N/A	0.63	30	10	10	premixed	same as mixture	Well-attached reburn flame, a small oxidizing zone in middle of lower furnace between reburn and main flame
PC15	0.80	10	centerline	2,150	20	0.4	CCW/CW	1	0.4	CW/CCW	0.63	30	10	10	premixed	same as mixture	Well-attached reburn flame, an oxidizing zone immediately above burner exit, hotter main flame
PC17	0.80	10	centerline	2,150	20	0.4	CCW/CW	1	0	N/A	0.63	30	10	10	premixed	same as mixture	Well-attached reburn flame, an oxidizing zone immediately above burner exit, locally hot zone in upper furnace, O_2 stratification at furnace exit, hot main flame
PC18	0.80	10	centerline	4,300	20	0.4	CCW/CW	1	0.4	CW/CCW	0.63	30	10	10	premixed	same as mixture	Well-attached reburn flame, an oxidizing zone immediately above burner exit, O_2 stratification at furnace exit, hot main flame
PC19	0.80	10	centerline	4,300	20	0.4	CCW/CW	1	0	N/A	0.63	30	10	10	premixed	same as mixture	Well-attached reburn flame, an oxidizing zone immediately above burner exit, locally hot zone in upper furnace, O_2 stratification at furnace exit, hot main flame

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[1] Reburn zone swirl for centerline oxygen injection refers to FGR flow in outer zone

Appendix I. Summary of the Computer Modeling Results for PC-Fired Simulations[1] (continued)

Case	Main Combustion Zone					OFA Ports		Reburn Zone									Highlights of Modeling Predictions
	SR	O_2 to main zone						Reburn Burner						O_2 to Reburn Burner			
		% flow to boiler	Injection location	Velocity (ft/min)	% FGR to SA	Swirl No.	Swirl direction	No. of zones	Swirl No.	Swirl direction	SR	% fuel reburn	% FGR	% flow to boiler	Injection location	Velocity (ft/min)	
PC20	0.80	10	centerline	6,450	20	0.4	CCW/CW	1	0.4	CW/CCW	0.63	30	10	10	premixed	same as mixture	Well-attached reburn flame, an oxidizing zone immediately above burner exit, O_2 stratification at furnace exit, hot main flame
PC21	0.80	10	centerline	6,450	20	0.4	CCW/CW	1	0	N/A	0.63	30	10	10	premixed	same as mixture	Well-attached reburn flame, hot & O_2-deficient, combustion zone at the reburn plane, locally hot zone in upper furnace, O_2 stratification at furnace exit, hot main flame
PC22	0.80	10	centerline	2,150	0	0.4	CCW/CW	1	0.4	CW/CCW	0.63	30	10	10	premixed	same as mixture	Wide and well-attached reburn flame, hot & O_2-deficient, combustion zone at the reburn plane, a small oxidizing zone immediately above burner exit, some O_2 stratification at furnace exit, hot main flame
PC23	0.80	10	centerline	2,150	0	0.4	CCW/CW	1	0	N/A	0.63	30	10	10	premixed	same as mixture	Wide and well-attached reburn flame, hot & O_2-deficient, combustion zone at the reburn plane, local O_2 stratification at furnace exit, hot main flame
PC24	0.80	10	premixed with PA	4,300	20	0.4	CCW/CW	1	0	N/A	0.63	30	10	10	premixed	same as mixture	Well-attached reburn flame, hot & O_2-deficient, combustion zone at the reburn plane, locally hot zone above the nose, local O_2 stratification at furnace exit, hot main flame
PC25	0.80	10	premixed with PA	4,300	0	0.4	CCW/CW	1	0	N/A	0.63	30	10	10	premixed	same as mixture	Well-attached reburn flame, hot & O_2-deficient combustion zone at the reburn plane, good OFA penetration, hot main flame

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[1] Reburn zone swirl for centerline oxygen injection refers to FGR flow in outer zone

Appendix II. Summary of the Computer Modeling Results for Cyclone-Fired Simulations[1]

Case	Main Combustion Zone					OFA Ports		Reburn Zone									Highlights of Modeling Predictions
		O_2 to main zone						Reburn Burner						O_2 to Reburn Burner			
	SR	% flow to boiler	Injection location	Velocity (ft/min)	% FGR to SA	Swirl No.	Swirl direction	No. of zones	Swirl No.	Swirl direction	SR	% fuel reburn	% FGR	% flow to boiler	Injection location	Velocity (ft/min)	
CY1	0.80	0	--	0	0	0	N/A	1	0	N/A	0.63	30	10	10	premixed	same as mixture	Hot flame near cyclone barrel wall, good slag tapping indication, hot & O_2-deficient combustion zone at the reburn plane, good OFA penetration
CY2	0.80	10	centerline	2,150	20	0	N/A	1	0	N/A	0.63	30	10	10	premixed	same as mixture	High-T localized around cyclone centerline, potential slagging problem, reburn flame impingement on wall, locally high-T zone in upper furnace
CY3	0.80	10	centerline	4,300	20	0	N/A	1	0	N/A	0.63	30	10	10	premixed	same as mixture	High-T localized around cyclone centerline, potential slagging problem, hot & O_2-deficient combustion zone at the reburn plane
CY4	0.80	10	centerline	6,450	20	0	N/A	1	0	N/A	0.63	30	10	10	premixed	same as mixture	High-T localized around cyclone centerline, potential slagging problem, hot & large O_2-deficient combustion zone at the reburn plane, large O_2 and temperature stratifications at furnace exit
CY5	0.80	10	centerline	2,150	0	0	N/A	1	0	N/A	0.63	30	10	10	premixed	same as mixture	Hot flame near cyclone barrel wall, good slag tapping indication, hot & large O_2-deficient combustion zone at the reburn plane, local O_2 stratification at furnace exit
CY6	0.80	10	SA to cyclone	5,000	20	0	N/A	1	0	N/A	0.63	30	10	10	premixed	same as mixture	High-T localized around cyclone centerline, potential slagging problem, hot & O_2-deficient combustion zone at the reburn plane
CY7	0.80	10	SA to cyclone	10,000	20	0	N/A	1	0	N/A	0.63	30	10	10	premixed	same as mixture	High-T localized around cyclone centerline, potential slagging problem, locally hot zone above the nose, local O_2 stratification at furnace exit, small O_2-deficient combustion zone at the reburn plane
CY8	0.80	10	SA to cyclone	15,000	20	0	N/A	1	0	N/A	0.63	30	10	10	premixed	same as mixture	High-T localized around cyclone centerline, potential slagging problem, locally hot zone above the nose, hot & O_2-deficient combustion zone at the reburn plane, local O_2 stratification at furnace exit
CY9	0.80	10	SA to cyclone	5,000	0	0	N/A	1	0	N/A	0.63	30	10	10	premixed	same as mixture	Hot flame near cyclone barrel wall, good slag tapping indication, hot & O_2-deficient combustion zone at the reburn plane, good OFA penetration
CY10	0.80	0	N/A	0	0	0	N/A	N/A	N/A	N/A	N/A	0	0	0	N/A	N/A	Hot flame near cyclone barrel wall, good slag tapping indication, hot & O_2-deficient combustion zone in primary furnace, good OFA penetration

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[1] Reburn zone swirl for centerline oxygen injection refers to FGR flow in outer zone