Pilot-Scale Demonstration of ALTA for NO_x Control in Pulverized Coal-Fired Boilers

Final Technical Report

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ABSTRACT

This report describes computational fluid dynamics (CFD) modeling and pilot-scale testing conducted to demonstrate the ability of the Advanced Layered Technology Approach (ALTA) to reduce NO_x emissions in a pulverized coal (PC) boiler. Testing specifically focused on characterizing NO_x behavior with deep burner staging combined with Rich Reagent Injection (RRI).

Tests were performed in a 4 MBtu/hr pilot-scale furnace at the University of Utah. Reaction Engineering International (REI) led the project team which included the University of Utah and Combustion Components Associates (CCA). Deep burner staging and RRI, combined with selective non-catalytic reduction (SNCR), make up the Advanced Layered Technology Approach (ALTA) for NO_x reduction. The application of ALTA in a PC environment requires homogenization and rapid reaction of post-burner combustion gases and has not been successfully demonstrated in the past. Operation of the existing low-NO_x burner and design and operation of an application specific ALTA burner was guided by CFD modeling conducted by REI. Parametric pilot-scale testing proved the chemistry of RRI in a PC environment with a NO_x reduction of 79% at long residence times and high baseline NO_x rate. At representative particle residence times, typical operation of the dual-register low-NO_x burner provided an environment that was unsuitable for NO_x reduction by RRI, showing no NO_x reduction. With RRI, the ALTA burner was able to produce NO_x emissions 20% lower than the low-NO_x burner, 76 ppmv vs. 94 ppmv, at a burner stoichiometric ratio (BSR) of 0.7 and a normalized stoichiometric ratio (NSR) of 2.0. CFD modeling was used to investigate the application of RRI for NO_x control on a 180 MW_e wall-fired, PC boiler. A NO_x reduction of 37% from baseline (normal operation) was predicted using ALTA burners with RRI to produce a NO_x emission rate of 0.185 lb/MBtu at the horizontal nose of the boiler. When combined with SNCR, a NO_x emission rate of 0.12-0.14 lb/MBtu can be expected when implementing a full ALTA system on this unit. Cost effectiveness of the full ALTA system was estimated at $2,152/ton NO_x removed; this was less than 75% of the cost estimated for an SCR system on a unit of this size.

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ALTA	Advanced Layered Technology Approach
BSR	Burner Stoichiometric Ratio
CFD	Computational Fluid Dynamics
FMAB	Full-scale Modified ALTA Burner
GPH	Gallons per Hour
LNB	Low-NO_x Burner
MAB	Modified ALTA Burner
NSR	Normalized Stoichiometric Ratio
OFA	Over-Fire Air
PC	Pulverized Coal
PDF	Probability Density Function
REI	Reaction Engineering International
RRI	Rich Reagent Injection
SCFH	Standard Cubic Feet per Hour
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction

1.0 Executive Summary

This report describes pilot-scale testing and computational fluid dynamic (CFD) simulations conducted to demonstrate the ability of the Advanced Layered Technology Approach (ALTA) to reduce NO_x emissions in a pulverized coal (PC) boiler. Testing specifically focused on characterizing NO_x behavior with deep burner staging combined with Rich Reagent Injection (RRI), two key components of PC-ALTA. Tests were conducted in a 4 MBtu/hr, pilot-scale, pulverized coal furnace at the University of Utah, which was designed to simulate combustion in low emission, pulverized coal-fired boilers and has contributed to many investigations of technologies for NO_x and particulate control, including: staging, reburning, reagent injection, and burner development. In this study the furnace was fired with both a dual-register, low-NO_x burner and a prototype ALTA burner designed to provide conditions favorable for application of Rich Reagent Injection while firing pulverized coal. CFD simulations were used to identify the burner settings and furnace operating conditions necessary to produce rich and homogeneous near-burner combustion gases from a PC burner. The developed burner technology and furnace operational characteristics were used to model deep burner staging and RRI in a 180 MW_e wall-fired PC boiler.

ALTA involves the combination of deep furnace staging with overfire air (OFA), Rich Reagent Injection (RRI), and Selective Non-Catalytic Reduction (SNCR) for NO_x reduction. The three components of ALTA work together in a synergistic manner. Deeper staging through the use of OFA not only reduces NO_x emissions by itself, but also provides a more favorable environment for the RRI process in the furnace. Reducing the stoichiometric ratio (SR) in the lower furnace by staging the lower furnace causes the local flue gas to become more fuel rich, thereby reducing the potential for NO_x formation and increasing the extent of NO_x reduction in the flue gas. As the RRI reagent is injected into the fuel-rich flue gas, NO_x reductions are further enhanced. Thus, the combination of deeper staging with RRI leads to additional NO_x reductions that could not be achieved separately. The SNCR system further reduces NO_x remaining in the flue gas after the OFA is added to complete combustion.

ALTA has been previously demonstrated and commercially installed on cyclone boilers[1], but presents a particular challenge with application to PC furnaces. Whereas SNCR is a proven NO_x control technology for PC boilers, the effectiveness of RRI has not yet been demonstrated. For application of RRI in a PC environment, the combustion gases must be quickly homogenized and reacted with available oxygen. This is challenging because even when deeply staged, post-flame combustion gases in a PC furnace are, for a time, oxygen rich as unburned particle char is oxidized. In addition, typical low-NO_x burners further stratify the gases to delay mixing of the coal and air. Thus for PC units, successful burner design and operation become critical to successful application of RRI, and by extension, the ALTA technology.

Program funding was provided primarily by U.S. DOE National Energy Technology Laboratory (NETL) and Combustion Components Associates (CCA), with cost sharing by the University of Utah and CCA. Program period was from October 1, 2005 to April 30, 2008, with the pilot-scale testing occurring in August 2006 and February and April of 2007. Team members for the project were:

- Reaction Engineering International (REI) – prime contractor, computational fluid dynamics (CFD) modeling, test plan, testing oversight, data review, reporting.
- University of Utah – operation of pilot-scale furnace, data collection.
- Combustion Components Associates (CCA) – burner design and construction.

The overall objectives of the DOE funded program were to:

1. Demonstrate at pilot-scale that the combination of combustion modifications, deeper staging, and Rich Reagent Injection (RRI) can yield NO_x emissions lower than the combination of traditional low-NO_x burners with OFA.
2. Demonstrate that under deeply staged conditions, well-mixed, near-burner combustion can be used to reduce NO_x emissions below those achievable with traditional, delayed-mixing low-NO_x burners.
3. Demonstrate that the utilization of well-mixed combustion under deeply staged conditions works synergistically with RRI to further reduce NO_x emissions.
4. Use CFD modeling of a full-scale pulverized coal (PC) boiler to demonstrate that the combination of simple but novel burner modifications, deep staging with OFA, and RRI can reduce NO_x emissions from a PC unit firing bituminous coal to below 0.15 lb-NO_x/MBtu without increasing waterwall corrosion or unburned carbon in ash.
5. Demonstrate that this NO_x control technology in achieving NO_x emissions below 0.15 lb/MBtu can reduce the levelized cost of NO_x compliance below 75% of that of a current state-of-the-art SCR system.

REI modeled and tested performance of three different burners with and without RRI for a variety of operating and staging conditions. The three burners were: 1) an existing, dual-register, low-NO_x burner (LNB); 2) an ALTA burner based on modifications to a burner previously used for natural gas designed to produce a homogenous environment for RRI without a high penalty in baseline NO_x concentration, 3) a modified ALTA burner (MAB) that focused coal distribution away from the burner core and enhanced coal-air mixing.

The LNB was shown to behave as expected, that is, to produce low NO_x concentrations at burner stoichiometric ratios (BSR) less than one, to produce decreasing NO_x concentrations with decreasing BSR to a minimum near BSR of 0.70, and to produce a stratified fuel-air environment near the burner that was not conducive to NO_x reduction with RRI.

At long residence times (where RRI and OFA were in furnace sections 6 and 9, respectively, far from the burner), experiments showed that LNB operation (e.g., swirl, primary air ratio, secondary air splits) had little impact on baseline NO_x or RRI performance. However, staging had a dramatic effect on NO_x. With no RRI, NO_x concentration was 798 ppmv with a BSR of 1.05 and 36 ppmv with a BSR of 0.65. The impact of RRI was favorable at BSRs of 0.85 and 0.95, with reductions in NO_x concentrations of 79% and 56%, respectively, for NSR of 3.0.

When the RRI and OFA were moved closer to the burner to represent more realistic residence times (furnace sections 4 and 6, respectively), the effects of burner operation became more apparent and the effectiveness of RRI decreased. This was primarily due to the stratification of combustion gases close to the burner. As the percentage of burner air in the primary increased, the baseline NO_x and the NO_x reduction from RRI increased.

This trend was consistent with modeling results and re-emphasized that NO_x can be effectively reduced by RRI in a PC environment; however, conditions where RRI was most effective at reducing NO_x also provided the highest baseline NO_x concentrations. When firing with a typical low-NO_x burner, the final NO_x concentrations were essentially the same when the burner was operated either for low NO_x or for homogeneous conditions with RRI.

The initial ALTA burner was found to behave similarly to the LNB due to unexpected and incorrect coal distribution in the burner. This burner was subsequently modified to correct the coal distribution and was then referred to as the modified ALTA burner (MAB).

Performance of the modified ALTA burner (MAB) and the low-NO_x burner (LNB) were directly compared with RRI and OFA placed in furnace sections 4 and 6, respectively (4/6 configuration), and again with RRI and OFA placed in sections 3 and 5, respectively (3/5 configuration). Residence time, as represented by RRI and OFA placement, was shown to impact NO_x levels from the burners.

For the 4/6 configuration, the LNB showed 10-30% NO_x reductions with RRI for BSR≥0.75 and no reductions for lower BSR. The MAB showed 20-50% reductions with RRI for BSR≥0.75 and no reductions for lower BSR. NO_x concentrations were similar for LNB without RRI and MAB with RRI over the range of BSRs. Minimum NO_x of 75 ppmv was at BSR=0.70, achieved with both LNB and MAB.

For the shorter residence time 3/5 configuration, the LNB showed no NO_x reduction with RRI whereas the MAB still produced ~50% reduction with RRI for

BSR>0.75. More significantly, the MAB with RRI produced 15-20% lower NO_x than the LNB for BSR≤0.75. Lowest LNB NO_x was 94 ppmv at BSR=0.70; lowest MAB (with RRI) NO_x was 76 ppmv, also at BSR=0.70.

These results suggest that the modified ALTA burner was able to produce a fuel-rich homogeneous environment (favorable to RRI and lower NO_x) near the burner whereas the fuel and air from low-NO_x burner remained stratified for some distance downstream of the burner.

CFD simulations were performed to predict the effectiveness of deep staging with the modified ALTA burner combined with RRI on a 180 MW_e, front-wall fired, pulverized coal-fired utility boiler. This furnace had been previously modeled to evaluate the effectiveness of RRI for NO_x control. The results of that past effort suggested no more than 10% reduction in NO_x emission. For this investigation, the existing, dual-register, low-NO_x burners were replaced by full-scale modified ALTA burners (FMAB), the OFA ports were modified and the unit was staged more deeply at a BSR of 0.80. Modeling results showed the FMAB were effective in improving the homogeneous, fuel-rich environment in the lower furnace. When four levels of RRI injection were used with a total NSR of 2.0, modeling predicted an average NO_x concentration of 122 ppmv (0.185 lb/MBtu) at the furnace nose, a 37% reduction in NO_x from the existing baseline. This included a 7% increase in baseline NO_x with the FMAB (no RRI) followed by a 41% NO_x reduction from the FMAB baseline with RRI.

Modeling results also suggested that the OFA design should be optimized for this boiler to reduce unburned carbon-in-ash (or LOI) and corrosion potential due to unreacted material deposits, and that the FMAB design should be reviewed for LOI performance before it is implemented for commercial use.

A key result from full-scale boiler modeling was that deep staging with the modified ALTA burner combined with RRI was capable of producing NO_x levels of approximately 0.185 lb/MBtu on a 180 MW_e utility boiler. Further, combining this performance with the 25%-35% NO_x reduction expected from commercially available SNCR systems suggests that overall NO_x emissions with the full PC-ALTA system could be in the 0.12-0.14 lb/MBtu range, well below the 0.15 lb/MBtu target.

The cost effectiveness of the PC-ALTA system for the 180 MW unit was estimated at $2152/ton NO_x removed, less than 75% of the referenced cost of $3,000/ton NO_x removed for an SCR system.

The next step toward commercialization of the PC-ALTA technology is to establish a small, utility-scale demonstration project where the ALTA burners, OFA system, RRI injectors and SNCR system can be optimized using CFD and demonstrated in the unit.

2.0 Introduction

2.1 Background

The approach for NO_x management in coal-fired utility boilers has evolved over many years. Selective catalytic reduction (SCR) offers a sound solution to NO_x control, but the considerable capital investment limits its applicability to large units. Current technology allows significant reduction of NO_x from an uncontrolled level with small modifications to the furnace and operating conditions. Low-NO_x burners (LNBs) stratify the combustion gases as they delay the mixing of air with fuel-rich regions, limiting the formation of NO_x. LNBs may be coupled with over-fire air (OFA) to stage the lower furnace to a stoichiometric ratio of 0.95 to 0.85. This addition promotes a hot, rich lower furnace and causes further NO_x reduction. Selective non-catalytic reduction (SNCR) is often applied to the upper furnace (in the temperature range of 2200 to 1500˚F) for added NO_x reduction. An amine reagent is introduced to react with NO to form N_2 without an accelerating catalyst.

Reaction Engineering International (REI) has developed an alternative for in-furnace NO_x control called Advanced Layered Technology Approach (ALTA). ALTA requires the creation of a deeply staged and homogeneous lower furnace, with a stoichiometric ratio in the region of 0.9 to 0.65. An amine reagent is injected into this rich region (at temperatures approximately of 2600 to 2900˚F) to accelerate the rate of NO_x reduction through the reaction of NO with NH_i to form N_2. SNCR is also applied in the upper furnace for added NO_x reduction. Application of ALTA requires optimization of the combustion and layering configuration and strategic placement of reagent injection to target appropriate stoichiometry and temperature. ALTA has been demonstrated on cyclone boilers to achieve NO_x emission rates at or below 0.12 lb/MMBtu.[1]

Cyclone units provide an ideal environment for Rich Reagent Injection (RRI), because the coal is devolitalized and partially combusted in the cyclone barrels, before it enters the furnace. When staged, this environment is rich, hot and homogeneous, providing optimal characteristics for NO_x reduction by RRI. ALTA has not previously been successfully applied to a PC unit due to the stratification of the near-burner gases. Particle residence time and char burnout are also important considerations for the application of RRI in a PC environment. Burner operating conditions can be adjusted to provide a desired staging condition, i.e. near-burner stoichiometric ratio, but these conditions will not be met until sufficient fuel from the char particles has reached the gas phase. For application of RRI to a pulverized coal (PC) unit, a hot, rich and homogeneous environment must be developed quickly to allow RRI to be applied before the OFA zone.

2.2 Objectives

The objectives of this project were aimed at demonstrating the applicability of ALTA for NO_x control in a PC environment through pilot-scale testing and computational fluid dynamics (CFD) modeling. A summary of the specific objectives are as follows:

1) Demonstrate at pilot-scale that the combination of combustion modifications, deeper staging, and Rich Reagent Injection (RRI) can yield NO_x emissions lower than the combination of traditional low-NO_x burners with OFA.
2) Demonstrate that under deeply staged conditions, well-mixed, near-burner combustion can be used to reduce NO_x emissions below those achievable with traditional, delayed-mixing low-NO_x burners.
3) Demonstrate that the utilization of well-mixed combustion under deeply staged conditions works synergistically with RRI to further reduce NO_x emissions.
4) Use CFD modeling of a full-scale pulverized coal (PC) boiler to demonstrate that the combination of simple but novel burner modifications, deep staging with OFA, and RRI can reduce NO_x emissions from a PC unit firing bituminous coal to below 0.15 lb-NO_x/MBtu without increasing waterwall corrosion or unburned carbon in ash.
5) Demonstrate that this NO_x control technology in achieving NO_x emissions below 0.15 lb/MBtu can reduce the levelized cost of NO_x compliance below 75% of that of a current state-of-the-art SCR system.

These objectives were to be met through the following tasks:

- Evaluation of RRI in the pilot-scale furnace while firing with a conventional dual-register burner. This task included CFD modeling to guide the test effort and determine burner operating parameters of particular importance.
- Design, construction and evaluation of a new burner, intended to provide homogeneous flue gas conditions suitable for NO_x reduction by deep staging and RRI. This task consisted of CFD modeling to support the design effort, and pilot-scale testing of the ALTA burner to characterize its performance under staged and injection conditions.
- Retrofit of existing low-NO_x burners for application of deep staging and RRI. This task was adjusted to investigate modifications to the ALTA burner due to observations during previous modeling and pilot-scale testing indicating best ALTA conditions.
- CFD analysis of deep burner staging with RRI at full-scale. This task was performed by applying the modified ALTA burner design parameters to CFD modeling of a 180 MW_e wall-fired, pulverized coal boiler under staged and RRI conditions.

- Assessment of levelized costs for the RRI and full PC-ALTA NO_x control strategies compared to referenced SCR cost effectiveness.

2.3 Pilot-Scale Test Facility

The pilot-scale combustor at the University of Utah Combustion Research Center is a PC-fired furnace that was designed to simulate combustion in low emission, pulverized coal-fired boilers. This unit has been used for many investigations of technologies for NO_x and particulate control, including: staging, reburning, SNCR and burner development. The reaction zone of this furnace has a 3.2 foot, square cross section and is approximately 46 feet in length. The length is divided into 10 sections, each with various sampling and injection ports. The furnace is refractory lined due to its 10-fold greater surface-to-volume ratio relative to commercial water wall boilers. The refractory is necessary to keep the heat from dissipating which could result in flame extinguishing and an unrealistic time-temperature relationship. Thermocouples are embedded just under the surface of the inside ceramic walls at several axial locations down the furnace for wall temperature determination. Multiple ports are located in each of the reactor sections, allowing for numerous configurations of sampling, reagent injection and overfire air. The pilot-scale combustor is represented in Figure 2-1 with some of its features and sample locations detailed.

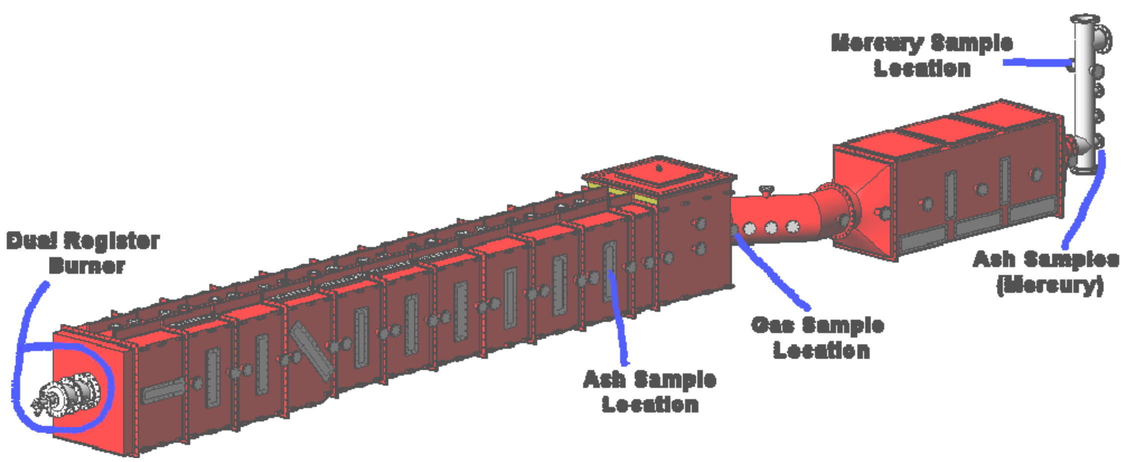

Figure 2-1. University of Utah 4 MBtu/hr pulverized coal combustion test facility

The furnace has a dual-register, dual-swirl burner very typical of commercial low-NO_x burners in utility boilers. The burner has adjustable air flow rates for the inner and outer secondary air registers and variable swirl to adjust flame shape and stability. The burner settings used during these tests have similar velocities, particle loading, temperatures and momentum ratios as commercial burners. The burner is detailed in Figure 2-2.

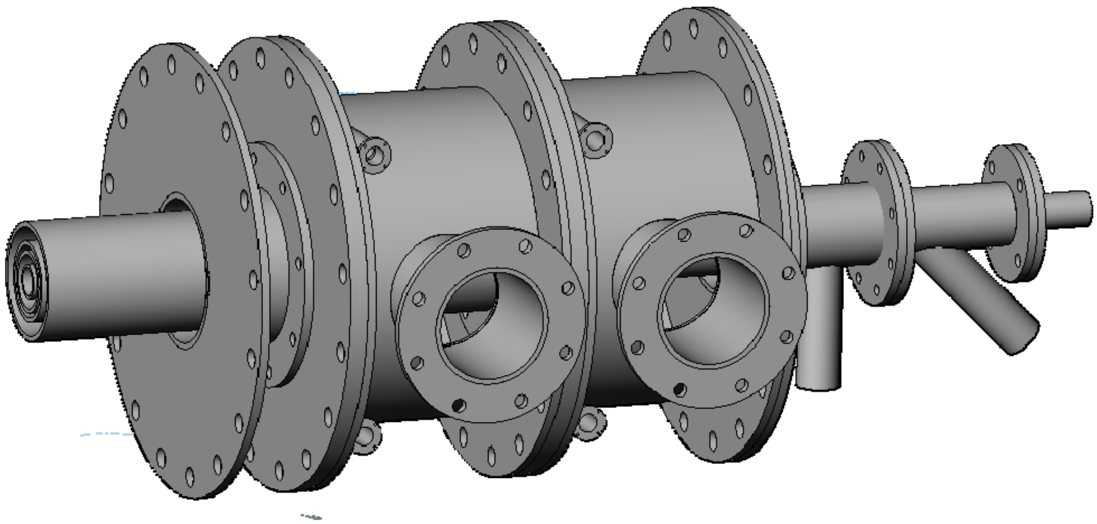

Figure 2-2. Moveable block swirl burner used on pilot-scale facility.

The combustion air can be preheated up to 800 °F. The solid feeding system includes a feeder, hopper and eductors to deliver pulverized coal to the burner at a measured rate. The unit is controlled via an Opto 22 distributed control system. This control system automatically collects data from emission monitoring equipment, including measurements of O_2, CO_2, CO, SO_2 and NO_x.

The fuel used for this investigation is a bituminous coal from Skyline Mine in central Utah. Table 2-1 contains a chemical analysis of this coal.

Table 2-1. Skyline coal analysis

Parameter	Value
Proximate, wt % (as received)	
Moisture	9.52
Volatile Matter	37.83
Fixed Carbon	44.56
Ash	8.10
Ultimate, wt% (dry)	
Carbon	73.52
Hydrogen	5.19
Nitrogen	1.32
Sulfur	0.58
Oxygen	10.46
Chlorine	NA
Ash	8.95
Heating Value, Btu/lb (dry)	
HHV	12407
Ash Elemental, wt % of ash	
SiO_2	53.90
AlO_2	14.06
TiO_2	0.73
CaO	5.65
SO_3	7.77
CaO	10.76
K_2O	0.65
MgO	2.17
Na_2O	1.22
Fe_2O_3	5.54
PO_2	0.57
MnO_2	2.17
SrO	0.08
BaO	0.03
Undetermined	2.51
Reducing Ash Fusion Temperature (˚F)	
Initial	2118
Softening	2189
Hemispheric	2286
Fluid	2469
Oxidizing Ash Fusion Temperature (˚F)	
Initial	2193
Softening	2250
Hemispheric	2364
Fluid	2545

The pilot-scale furnace is well equipped to investigate the impacts of staged combustion on NO_x emissions. The sampling and injection ports in each of the 10 sections of the furnace may be used to introduce OFA into the furnace, allowing for wide variations in residence time from burner to RRI and from RRI to OFA. The burner stoichiometry may be varied from deeply rich at a burner stoichiometric ratio (BSR) of 0.6 to various fuel lean conditions constrained by flame stability. The temperature profile of the furnace is impacted by the degree of staging and location of OFA. Measured wall temperatures across a range of staging conditions, while firing at 4 MBtu/hr are presented in Figure 2-3. As expected, the near burner wall temperatures are higher when the unit is less staged. For these conditions, most of the combustion is occurring in the first sections of the furnace. As the unit is staged more deeply, the temperature profile becomes more flat. This occurs when only part of the combustion is happening in the near burner sections with burnout occurring after the OFA is introduced.

The gas and particle residence times in the pilot scale furnace have been quantified using CFD modeling. The residence times of the gases and particles can differ greatly in this pilot-scale furnace. The char and ash particles are entrained primarily in high velocity gases near the centerline of the furnace providing short particle residence times. Slower moving gases near the walls and zones of gas recirculation result in calculated average gas residence times that are longer than expected in utility boilers. The average gas residence time as a function of location in the furnace is provided in Figure 2-4. The error bars in this figure indicate the standard deviation across a range of typical staging conditions while firing at 4 MBtu/hr. The center of each section of the furnace is also identified. This figure indicates an average gas residence time of 4.4 seconds to section 4 and 6.2 seconds to section 6. These times appear very long compared to the residence time of a typical PC furnace. The average particle residence times are more meaningful for these experiments. Predicted average particle residence times are 0.5 seconds at section 4 and 1.4 seconds at section 6.

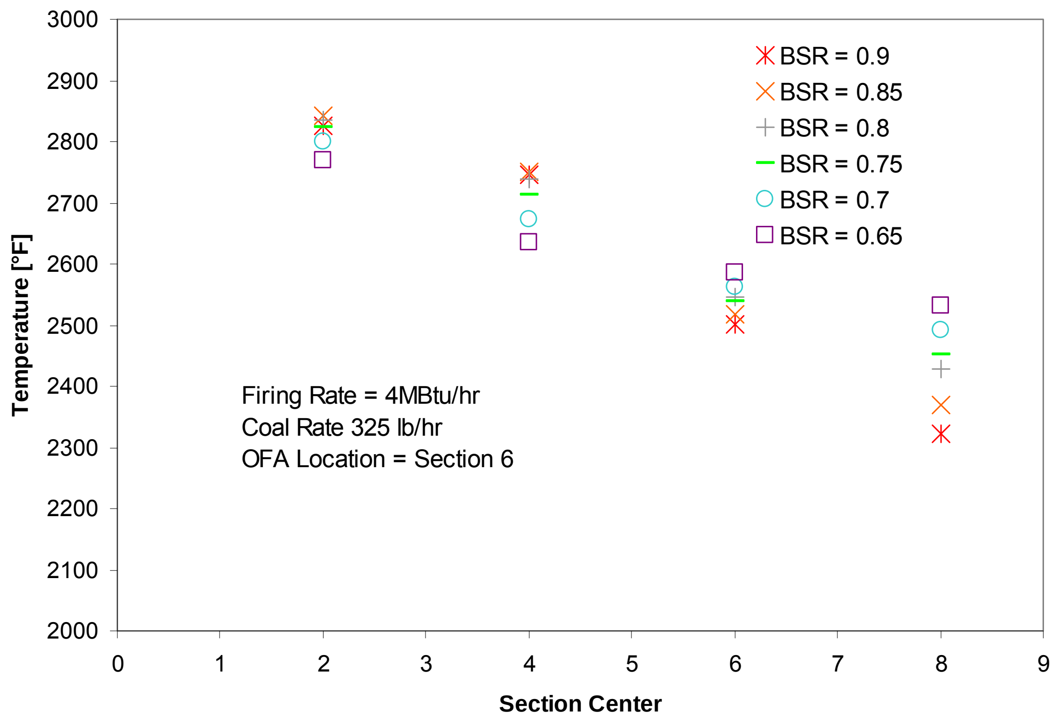

Figure 2-3. Temperature profiles of the pilot-scale furnace as a function of staging while firing at 4 MBtu/hr

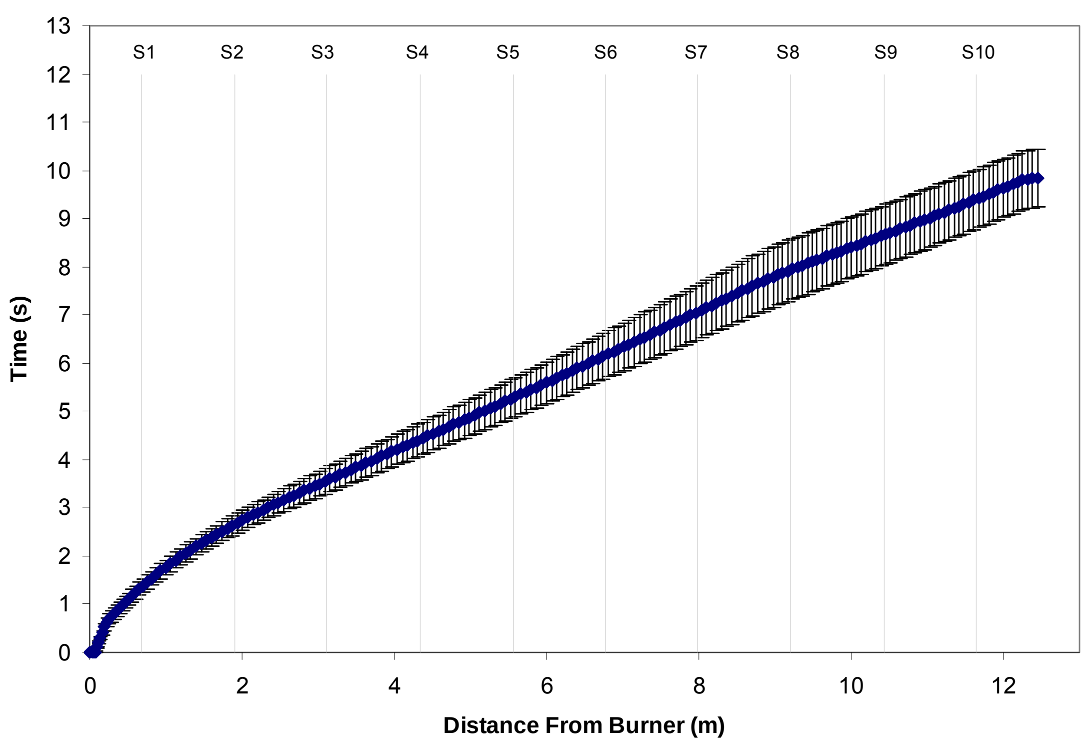

Figure 2-4. Predicted average gas residence time profile in pilot-scale furnace. Variability due to operating conditions noted by error bars; "S" denotes furnace sections.

Reagent can be injected into the pilot-scale furnace through any of the sampling and injection ports. For the purposes of this testing, injection was always performed through two horizontally opposed ports at the centerline of the furnace. Urea was mixed into water as a 40 weight percent solution. A reservoir of this solution was housed in two air pressurized canisters each supplying one of two injection probes. Flow of solution from each canister was controlled by a needle valve and metered using a calibrated rotameter. The urea solution was diluted with water, also controlled and metered with a needle valve and rotameter, before the liquid solutions entered the injection probes. The nozzles used to produce the atomized spray were model SU26 from Spraying systems and are two-fluid, requiring a pressurized gas for atomization. The atomization gas used in this study was nitrogen supplied by a Dewar for each injection nozzle. Each of the two injection lances was housed inside the annulus of a water-cooled probe to protect the nozzle.

This system was designed to supply urea into the furnace, at normalized stoichiometric ratios (NSRs) up to 3, across a broad range of baseline NO_x concentrations while maintaining a constant flow of liquid and gas to the nozzle, therefore maintaining constant atomization characteristics. The constant liquid flow to the nozzles was 4 GPH and the total nitrogen rate was held at 200 SCFH. Ammonia slip was not measured in these experiments because the FTIR at the University of Utah was out of service and alternative methods were not possible due to budget constraints. A representation of one of the two identical nozzles is contained in Figure 2-5.

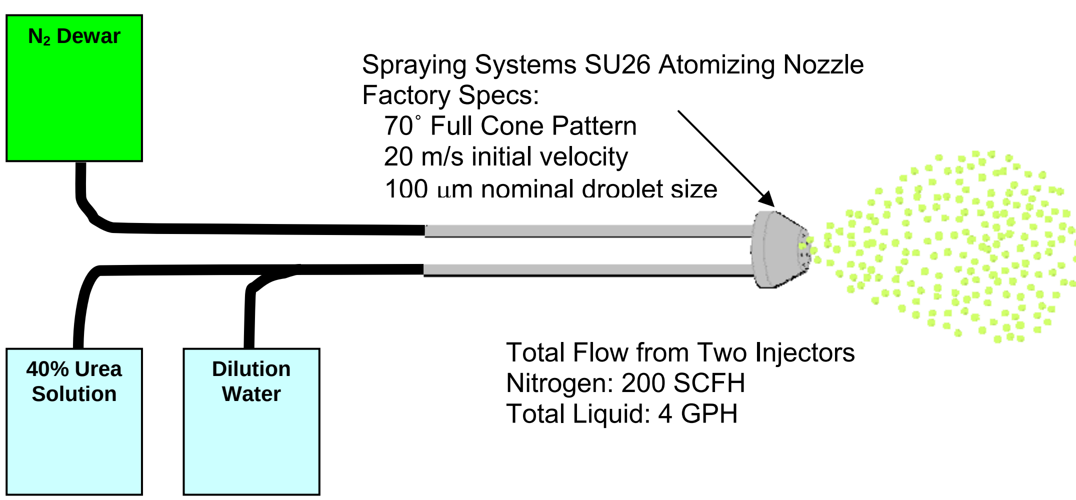

Figure 2-5. Reagent injection system used with the pilot-scale facility

2.4 CFD Model

Glacier Model Overview

The computer model to be used for this study is a CFD-based reacting flow code, *GLACIER*, developed by REI over the past 18 years. The code couples together the effects of turbulent fluid mechanics, gas-phase combustion chemistry, turbulent particle dispersion, heterogeneous particle reactions, and convective and radiative heat transfer. The REI combustion code assumes that the flow field is a continuum field that can be described locally by general conservation equations. The flow is assumed to be steady state and gas properties are determined through local mixing calculations. The fluid is assumed to be Newtonian and dilatation is neglected. The comprehensive model uses an Eulerian framework and handles either Reynolds- or Favre-averaging. The code couples the turbulent fluid mechanics and the chemical reaction process, using progress variables to track the turbulent mixing process and equilibrium chemistry to describe the chemical reaction process.

Within the model, the rate at which the primary combustion reactions occur is assumed to be limited by the rate of mixing between the fuel and the oxidizer, which is a reasonable assumption for the chemical reactions governing heat release. The thermodynamic state at each spatial location is a function of the enthalpy and the degree of mixing of two mixture fractions, one of which corresponds to the coal off-gas. The effect of turbulence and mixing on mean chemical composition is incorporated by assuming that the mixture fractions are defined by a “clipped Gaussian” probability density function (PDF) having a spatially varying mean and variance. The mean and variance are computed numerically at each grid point and mean chemical species concentrations are obtained by convolution over the PDF. Species concentrations are calculated as properties based on the local stream mixture and enthalpy. This is much more computationally efficient than tracking individual species. The exceptions to this are NO_x species, which are calculated using finite-rate chemistry.

Particle mechanics are solved by following the mean path or trajectory for a discretized group or ensemble of particles in a Lagrangian reference frame. Particle mass and momentum sources are converted from a Lagrangian to an Eulerian reference frame where they are coupled with gas phase fluid mechanics. The radiative intensity field is solved using the discrete ordinates method based on properties of the surfaces and participating medium and the resulting local flux divergence appears as a source term in the gas-phase energy equation. More detailed information regarding the computational model has been previously published.

NO_x Model Overview

Since the reduction of NO_x is often a major objective of combustion modeling programs, significant effort has been focused on producing an accurate method for predicting NO_x formation/reduction as part of the combustion simulations.

When predicting the mean concentrations of NO_x in coal-fired combustors, the effects of both turbulence and finite-rate chemistry are important. *GLACIER* can compute the relative effects of fuel and thermal NO_x as a function of local stoichiometry and temperature. The *GLACIER* NO_x submodel includes the following components:

- The flow field and local temperatures are computed from the coupled heat transfer and reaction models.
- A reduced kinetic mechanism is used based on the detailed mechanism of Miller & Bowman[2] with recent literature modification.[3] This detailed mechanism contains over 60 chemical species and 250 reversible elemental reactions. The approach that we have taken to develop a reduced description of the detailed NO_x chemistry is to use conventional reduced mechanism methods.[4, 5] This methodology is based on the assumption that certain species contained within a complete detailed chemical mechanism are in steady state (i.e. their rate of production is equal to their rate of destruction). This is a more rigorous and universal approach than curve-fitting type approaches which were used to generate simple global mechanisms. The total number of transfer equations that must be solved within the CFD simulation is equal to the number of major non-steady state species. The reduced mechanism involves 12 species.
- Fuel nitrogen from the coal volatiles evolves as mostly HCN with some NH_3, which feeds into the reduced mechanism.
- Coal volatile fuel nitrogen is tracked separately from char nitrogen. The char nitrogen is assumed to have a known conversion to NO with the balance converted to N_2.

3.0 Simulation and Testing Approach and Results

3.1 Evaluation of Conventional Dual-Register (Low-NO_x) Burner

CFD Simulation

CFD modeling was performed on the pilot-scale furnace while firing the bituminous coal detailed in Table 2-1, with the conventional dual register (Low-NO_x burner) at a firing rate of 3.8 MBtu/hr. Most of the parameters of interest for the CFD modeling of RRI in the pilot-scale furnace concern operation of the burner to produce a homogeneous environment at the injection location. A diagram of the Low-NO_x burner is provided in Figure 3-1 along with the inlet mesh for the CFD modeling.

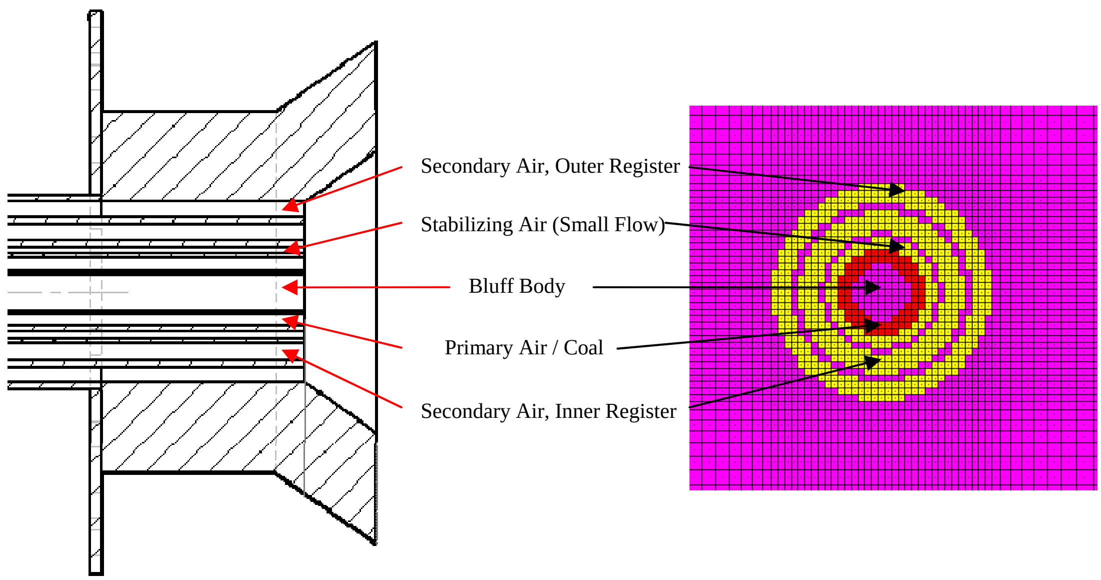

Figure 3-1. Low-NO_x burner configuration

The modeling parameters that were investigated for their impact on homogeneity and therefore effectiveness of RRI were as follows:

- RRI and OFA locations
- Staging / burner stoichiometric ratio (BSR)
- Primary air as % of total burner air
- Primary air velocity (by changing the size of bluff body)
- Secondary air, inner / outer register ratio
- Secondary air swirl, both inner and outer registers

Modeling results where RRI was placed in section 4, OFA in section 6 and a constant BSR of 0.85 were of particular interest. In these computations the distribution and velocity of air exiting the burner was varied, while all other parameters were held constant. A summary of inputs for these calculations is presented in Table 3-1. These simulations initiated at the burner face with an even distribution of air and coal in each of the burner outlets as prescribed in Table 3-1. The model was terminated at the end of section eight of the furnace, a sufficient distance downstream of the OFA that mixing and NO concentrations were static. These simulations demonstrated that there is a significant difference in homogeneity of the post-flame gases, depending on the air distribution in the burner. These differences are detailed in Figure 3-2 where CO profiles in the furnace for Cases 2 and 5 from Table 3-1 are compared.

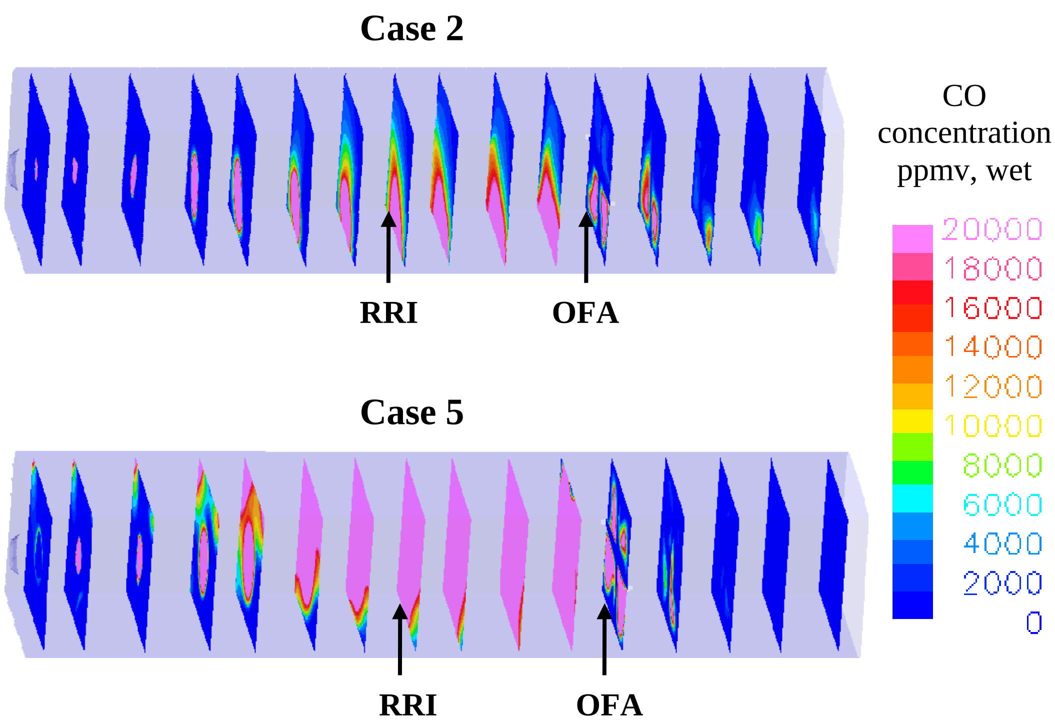

Figure 3-2. CO distribution in the pilot-scale furnace while firing with the Low-NOx burner

For the conditions of Case 2, 15% of total burner air is introduced through the primary with the remainder in the secondary. The secondary air is split with a 50/50 ratio between the inner and outer registers. For Case 5, 47% of the burner air is introduced in the primary. In this simulation the remaining air is also distributed evenly across the inner and outer registers of the secondary. It is evident from these CO profiles that as air is moved from the burner primary into the secondary, the post-flame combustion gases become more stratified.

Table 3-1. Conditions modeled in the pilot-scale furnace with BSR at 0.85

Case	Stoichiometric Ratio	Burner Stoichiometric Ratio	Coal [lb/hr]	Firing Rate [MBtu/hr]	Excess O2 [%, wet]	Primary Air [lb/hr]	Primary Air [% of total burner air]	Primary Air / Fuel	Secondary Air (Inner Register) [lb/hr]	Secondary Air (Outer Register) [lb/hr]	Secondary in Inner Register [%]	Secondary Swirl (Inner Register) [%]	Secondary Swirl (Outer Register) [%]	RRI Location	OFA Location	OFA [lb/hr]
1	1.20	0.85	324	3.79	3.28	367	15%	1.1	1664	416	80%	50	50	S 4	S 6	1007
2	1.20	0.85	324	3.79	3.28	367	15%	1.1	1040	1040	50%	50	50	S 4	S 6	1007
3	1.20	0.85	324	3.79	3.28	367	15%	1.1	416	1664	20%	50	50	S 4	S 6	1007
4	1.20	0.85	324	3.79	3.28	1150	47%	3.5	1037	259	80%	50	50	S 4	S 6	1007
5	1.20	0.85	324	3.79	3.28	1150	47%	3.5	648	648	50%	50	50	S 4	S 6	1007
6	1.20	0.85	324	3.79	3.28	734	30%	2.3	1370	343	80%	50	50	S 4	S 6	1007
7	1.20	0.85	324	3.79	3.28	734	30%	2.3	856	856	50%	50	50	S 4	S 6	1007
8	1.20	0.85	324	3.79	3.28	734	30%	2.3	343	1370	20%	50	50	S 4	S 6	1007

These data suggest that typical operation of the Low-NO_x burner will not provide optimal conditions for NO_x reduction with RRI. Moving combustion air from the secondary back into the primary would produce a more homogeneous environment for RRI injection in section 4 of the pilot-scale furnace with a Low-NO_x burner. The drawback to operation of the Low-NO_x burner in this manner is the penalty in baseline NO_x concentrations. Predicted NO_x concentrations at the exit of section 8 for Cases 2 and 5 are 191 and 356 ppmv, respectively. Even more dramatic are the predicted post-flame NO_x concentrations at about 300 and 800 ppmv. These data suggest that by producing conditions that are more favorable for RRI, the uncontrolled NO_x rate increases.

CFD modeling was performed for the conditions presented in Table 3-1 with reagent injection at a NSR of 2.0. These simulations were expected to determine whether the reduction due to RRI can overcome the increased baseline NO_x concentrations and provide favorable reductions. For all of the conditions listed in Table 3-1, the NO_x reduction with RRI was calculated and is plotted against baseline NO_x concentration in Figure 3-3. In this figure the data are separated into color by the amount of burner air in the primary.

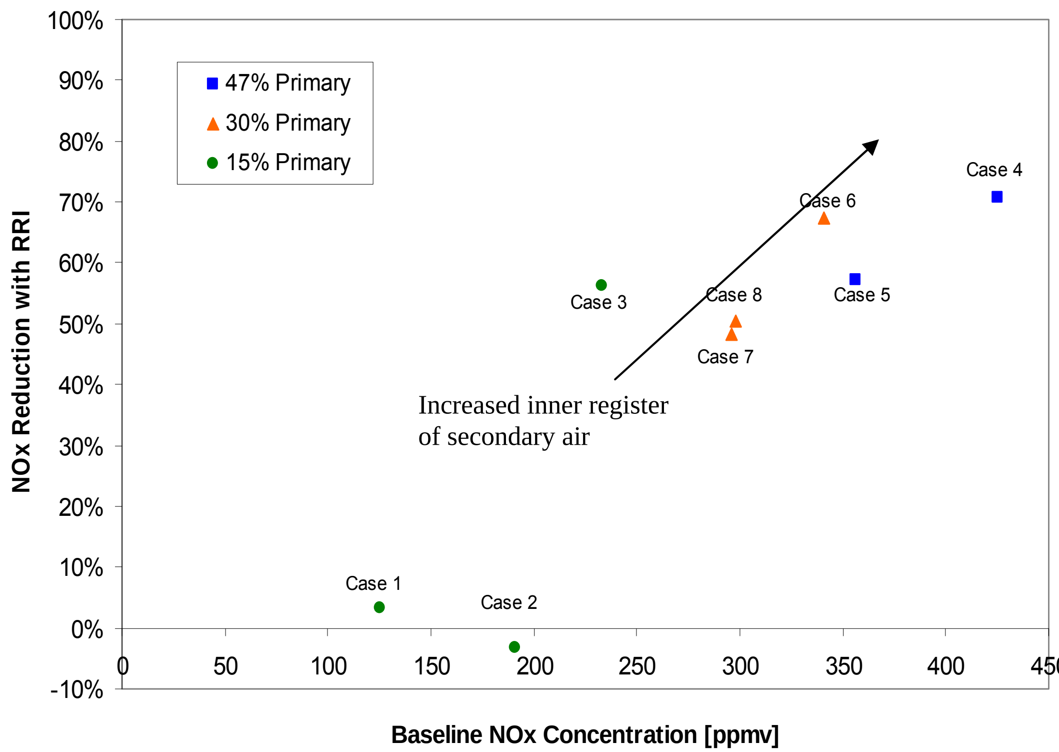

Figure 3-3. CFD model predictions for the impact of baseline NO_x concentration on NO_x reduction with RRI.

Figure 3-3 illustrates that as air is moved from the outer register of the secondary into the primary and inner register, the NO_x reduction increases as did the baseline NO_x concentration. It can also be seen that for the more stratified conditions, Cases 1 and 2, there was little or no NO_x reduction expected when the reagent is injected. The important metric for evaluating the effectiveness of RRI at reducing NO_x is the concentration. Figure 3-4 is a plot of reduced (with RRI) NO_x concentration against baseline NO_x concentration.

The data in Figure 3-4 shows impressive NO_x reduction from baseline for the conditions expected to give more homogeneous gases at the injection location, but the reduced NO_x concentrations are similar across all conditions, indicating that the NO_x reduction with RRI is only enough to offset the penalty for producing homogeneous conditions. This is demonstrated more effectively where the NO_x reduction and concentrations are averaged for each primary air condition and plotted as in Figure 3-5.

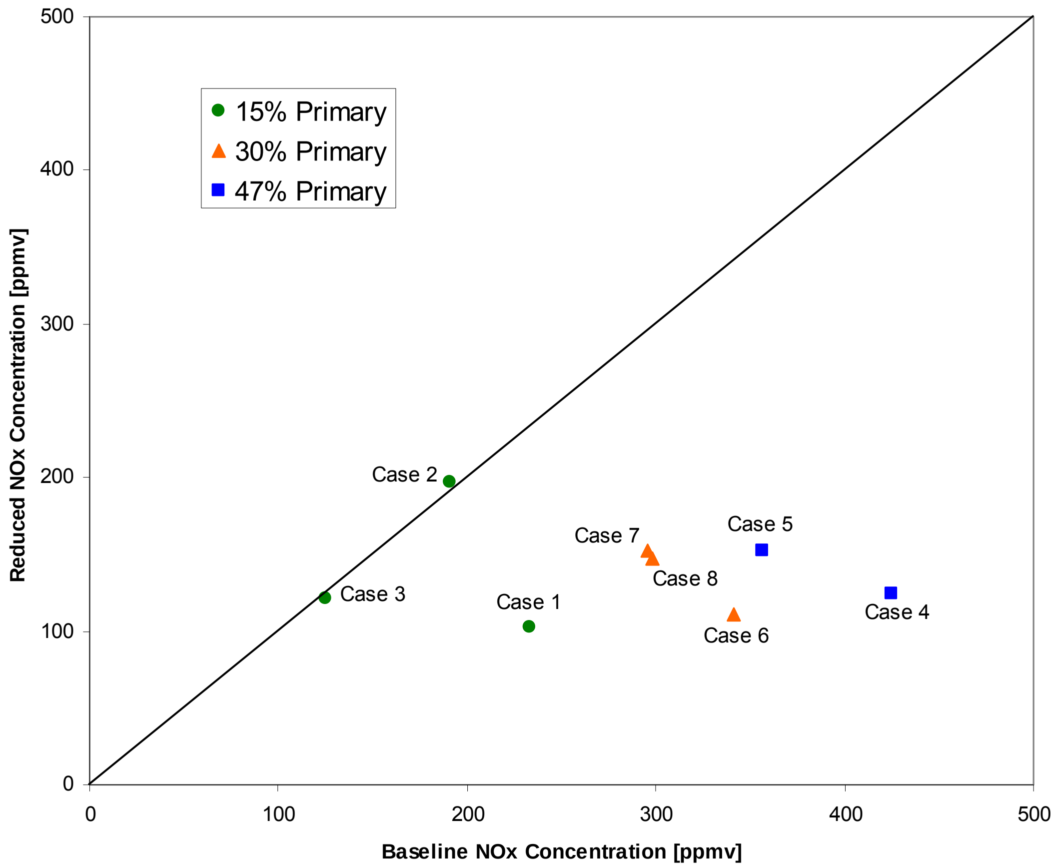

Figure 3-4. CFD model predictions for the relationship between reduced and baseline NO_x concentration

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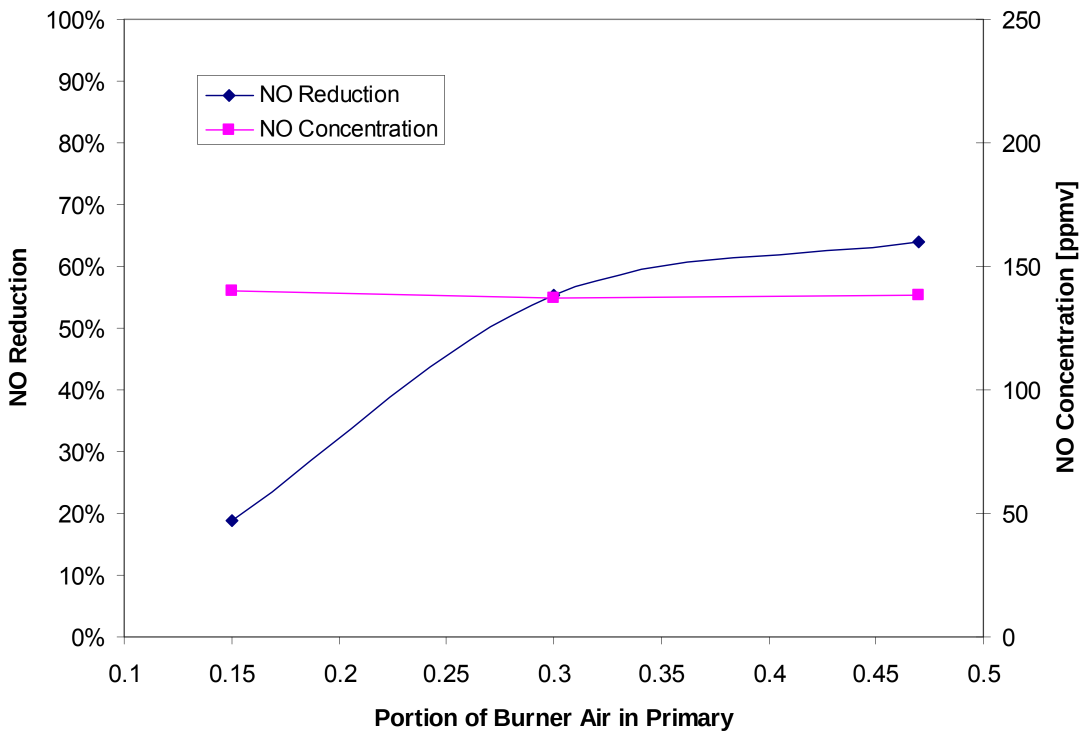


Figure 3-5. CFD predicted relationship between burner operation, NO_x reduction and NO_x concentration

These simulations suggest that with a Low-NO_x PC burner it is possible to produce conditions favorable for reduction of NO_x with RRI, but that due to the baseline NO_x penalties of homogeneous conditions, NO_x reduction with RRI may not be particularly beneficial.

Pilot-Scale Experimentation

The initial pilot-scale experiments were focused on long residence times, with RRI in section 6 and OFA in section 9 of the pilot-scale furnace. With this configuration, the average gas residence time was on the order of 6 and 8.5 seconds to the location of RRI and OFA respectively. These first tests were designed to prove that RRI chemistry works in a PC environment. With RRI and OFA thus located, the furnace was fired across staging conditions, with burner stoichiometric ratio (BSR) ranging from 1.05 to 0.65. At each of these conditions the NSR was set to 0, 1, 2 and 3. Early in the experiments it was determined that burner settings had little impact at such long residence times. For these experiments, the burner was operated with a primary air / fuel ratio of 1.8. The Secondary air was operated with a 33/67 split between the inner and outer registers. The swirl was set at 50% for both the inner and outer register. Table 3-2 contains a detailed description of each of these conditions.

Table 3-2. Pilot-scale test conditions with RRI in Section 6 and OFA in section 9

Condition	Stoichiometric Ratio	Burner Stoichiometric Ratio	Coal [lb/hr]	Firing Rate [lb/MBtu]	O2 [%, wet]	Primary Air [lb/hr]	Primary Air [% of total burner air]	Primary Air / Fuel	Secondary Air (Inner Register) [lb/hr]	Secondary Air (Outer Register) [lb/hr]	Secondary in Inner Register [%]	Secondary Swirl (Inner Register) [%]	Secondary Swirl (Outer Register) [%]	RRI Location	OFA Location	OFA [lb/hr]	NSR
1	1.21	1.06	319	3.73	3.8	605	19%	1.9	866	1714	34%	50	50	S6	S9	466	0
2	1.19	1.05	326	3.81	3.2	600	19%	1.8	863	1710	34%	50	50	S6	S9	466	1
3	1.21	1.06	323	3.78	3.5	598	19%	1.9	870	1721	34%	50	50	S6	S9	452	2
4	1.20	1.05	325	3.80	3.4	595	19%	1.8	869	1713	34%	50	50	S6	S9	452	3
5	1.20	1.05	326	3.81	3.4	602	19%	1.8	876	1713	34%	50	50	S6	S9	479	0
6	1.19	0.94	324	3.79	3.4	600	21%	1.9	740	1472	33%	50	50	S6	S9	748	0
7	1.19	0.94	324	3.79	3.6	603	21%	1.9	745	1478	34%	50	50	S6	S9	745	1
8	1.18	0.93	323	3.78	3.3	602	21%	1.9	743	1468	34%	50	50	S6	S9	734	2
9	1.18	0.93	321	3.76	3.4	595	21%	1.9	742	1471	34%	50	50	S6	S9	730	3
10	1.17	0.93	324	3.79	3.3	605	21%	1.9	746	1468	34%	50	50	S6	S9	738	0
11	1.18	0.84	321	3.76	3.7	601	24%	1.9	643	1281	33%	50	50	S6	S9	1033	0
12	1.18	0.84	320	3.74	3.6	593	24%	1.9	640	1265	34%	50	50	S6	S9	1018	1
13	1.18	0.84	322	3.77	3.5	595	24%	1.8	643	1272	34%	50	50	S6	S9	1033	2
14	1.18	0.84	324	3.79	3.5	599	24%	1.8	649	1276	34%	50	50	S6	S9	1025	3
15	1.18	0.84	327	3.83	3.4	592	23%	1.8	650	1278	34%	50	50	S6	S9	1028	0
16	1.18	0.74	325	3.80	3.5	602	27%	1.9	548	1076	34%	50	50	S6	S9	1328	0
17	1.19	0.74	326	3.81	3.6	600	27%	1.8	548	1082	34%	50	50	S6	S9	1388	1
18	1.19	0.75	323	3.78	3.8	600	27%	1.9	550	1079	34%	50	50	S6	S9	1316	2
19	1.19	0.75	323	3.78	3.7	598	27%	1.9	550	1081	34%	50	50	S6	S9	1308	3
20	1.18	0.74	327	3.83	3.5	598	27%	1.8	553	1086	34%	50	50	S6	S9	1304	0
21	1.18	0.64	326	3.81	3.8	599	31%	1.8	447	901	33%	50	50	S6	S9	1592	0
22	1.18	0.65	323	3.78	3.8	603	31%	1.9	448	897	33%	50	50	S6	S9	1587	1
23	1.18	0.65	323	3.78	3.7	594	31%	1.8	449	897	33%	50	50	S6	S9	1587	2
24	1.17	0.64	326	3.81	3.4	600	31%	1.8	447	896	33%	50	50	S6	S9	1571	3
25	1.18	0.65	322	3.77	3.6	593	31%	1.8	446	890	33%	50	50	S6	S9	1562	0

As expected these experiments show that staging alone has a dramatic effect on NO_x. With no RRI, NSR equal to 0, the NO_x concentration measured at the transition section of the furnace was 798 ppmv with a BSR of 1.05 and 36 ppmv with a BSR of 0.65. The impact of RRI was very favorable at BSRs of 0.85 and 0.95, with reductions in NO_x concentration of 79% and 56% respectively, with an NSR of 3. The results of this series of tests are presented in Figure 3-6.

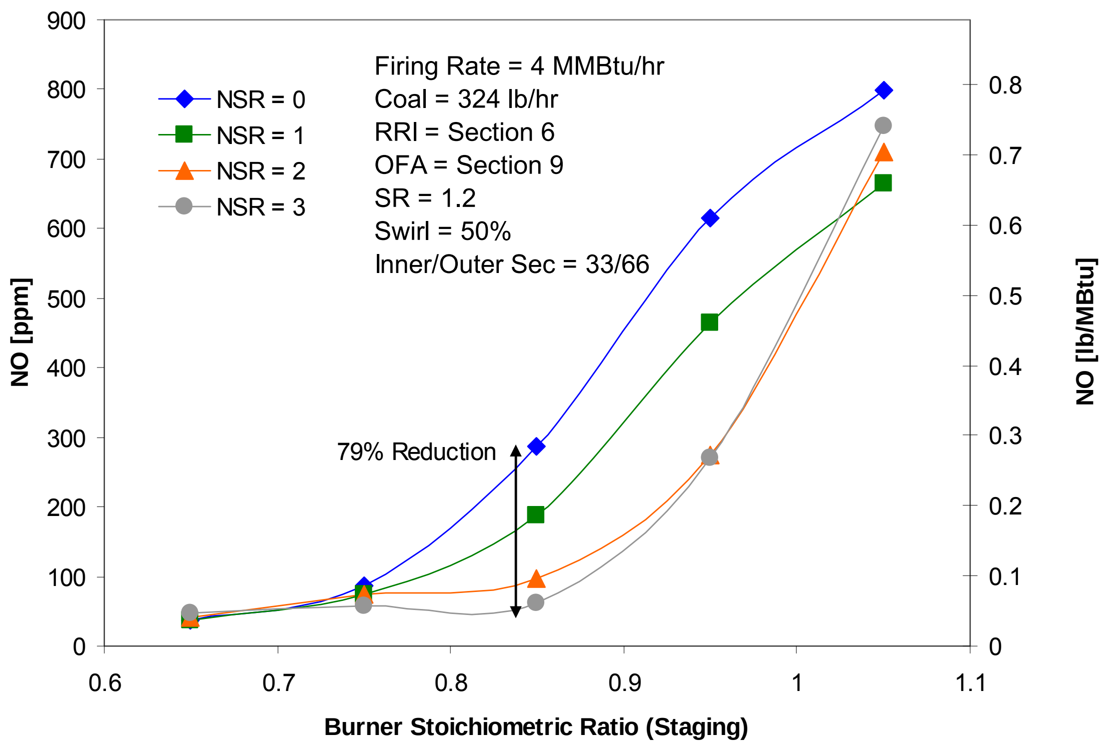


Figure 3-6. Staging curve detailing a 79% reduction in NO_x emission with RRI.

While the chemistry associated with RRI has been proven to work in a PC environment, it is necessary to experiment with RRI at residence times that are more reasonable for real combustion systems. The next set of experiments was designed to observe the NO_x reduction due to RRI as the injection and OFA locations are moved toward the burner.

For these experiments the BSR was set at 0.85, the staging condition that provided maximum reduction in the previous experiments. All other burner settings remained as they were in the previous set of experiments. The locations of RRI and OFA were moved to section 6 and section 8 then section 4 and section 7 and finally section 3 and section 6 respectively. The test condition details are provided in Table 3-3. For this series of tests, the reduction of NO_x due to RRI reduced significantly. For the first set of paired locations, RRI in section 6 and OFA in section 8, the NO_x reduction was 82% with an NSR of 3. At the second set of paired locations, the reduction was 59% at an NSR of 3; for the last set of paired locations, the reduction was 26% at an NSR of 3. The results of these tests are presented in Figure 3-7.

Table 3-3. Pilot-scale test conditions to investigate RRI and OFA location

Condition	Stoichiometric Ratio	Burner Stoichiometric Ratio	Coal [lb/hr]	Firing Rate [MBtu/h]	O_2 [%, wet]	Primary Air [lb/hr]	Primary Air [% of total burner air]	Primary Air / Fuel	Secondary Air (Inner Register) [lb/hr]	Secondary Air (Outer Register) [lb/hr]	Secondary in Inner Register [%]	Secondary Swirl (Inner Register) [%]	Secondary Swirl (Outer Register) [%]	RRI Location	OFA Location	OFA [lb/hr]	NSR
1	1.22	0.86	324	3.99	3.5	596	23%	1.8	655	1349	33%	50	50	6	8	1039	0
2	1.21	0.86	324	4.00	3.3	600	23%	1.9	654	1346	33%	50	50	6	8	1049	1
3	1.21	0.86	325	4.02	3.2	594	23%	1.8	659	1349	33%	50	50	6	8	1052	2
4	1.20	0.86	325	4.02	3.2	594	23%	1.8	663	1354	33%	50	50	6	8	1063	3
5	1.20	0.85	323	4.00	3.3	592	23%	1.8	658	1345	33%	50	50	6	8	1049	0
6	1.19	0.84	324	4.00	3.7	593	23%	1.8	645	1289	33%	50	50	4	7	1050	0
7	1.19	0.85	320	3.95	3.7	597	24%	1.9	645	1290	33%	50	50	4	7	1050	1
8	1.19	0.84	326	4.02	3.5	592	24%	1.8	642	1281	33%	50	50	4	7	1034	2
9	1.18	0.84	324	4.00	3.7	593	24%	1.8	643	1287	33%	50	50	4	7	1038	3
10	1.18	0.84	326	4.00	3.6	599	24%	1.8	644	1281	33%	50	50	4	7	1035	0
11	1.18	0.84	324	3.99	3.6	597	24%	1.8	646	1290	33%	50	50	3	6	1036	0
12	1.27	0.84	325	4.04	3.8	597	23%	1.8	657	1302	34%	50	50	3	6	1057	1
13	1.21	0.84	322	4.00	3.7	595	23%	1.8	646	1299	33%	50	50	3	6	1050	2
14	1.20	0.86	324	3.95	3.6	605	24%	1.9	644	1299	33%	50	50	3	6	1058	3
15	1.20	0.84	328	4.04	3.6	601	24%	1.8	643	1293	33%	50	50	3	6	1055	0

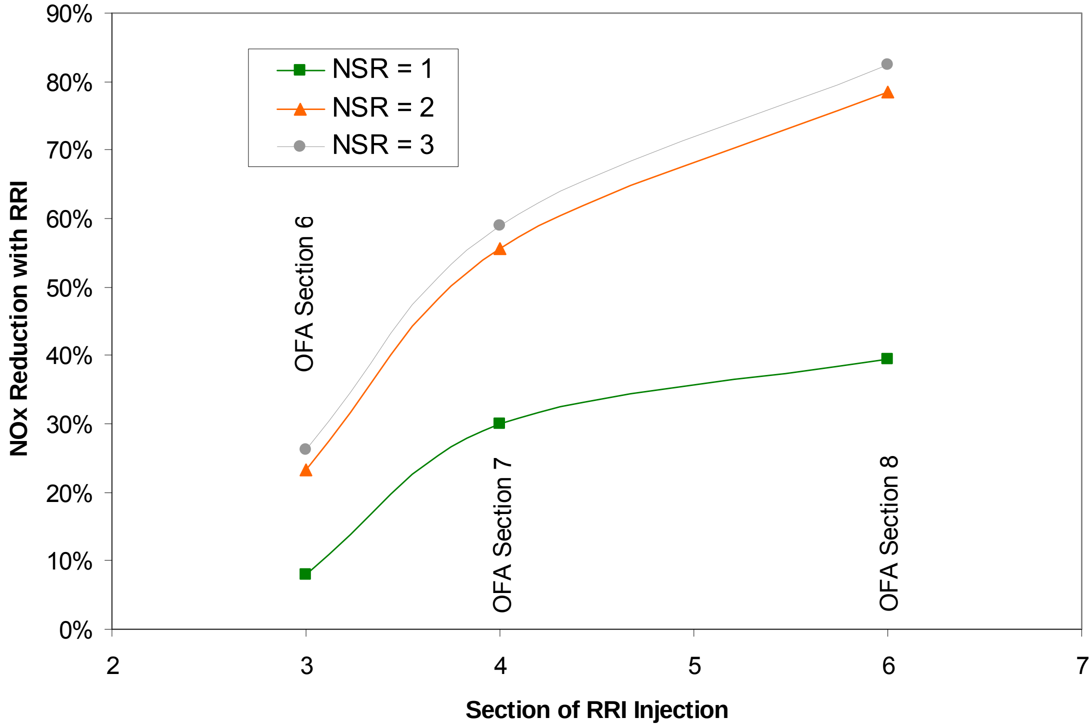


Figure 3-7. NO_x reduction with RRI decreases as injection location moves closer to the flame

Figure 3-7 suggests that as the injection location moves toward the burner, the reduction in NO_x due to RRI is less significant. This is primarily due to the stratification of combustion gases close to the burner not providing an environment favorable to RRI reactions.

As in the CFD simulations discussed previously, experiments were performed with RRI in section 4 and OFA in section 6 of the furnace. These experiments were designed to use the same conditions as the modeling and expected to produce results verifying the trends captured in those simulations. For these experiments, the burner stoichiometry was set at 0.85. Burner air distributions included 47, 30 and 15% of the air in the primary. At each of these primary air rates, the distribution of air in the secondary was set to 80% in the inner register. At these conditions the baseline NO_x concentration was measured and then reagent was injected at an NSR of 2. The secondary air was varied from 80% in the inner register to 20% in the inner register with values of 67, 50 and 33% also being evaluated with the same reagent injection rate. Once this curve was produced, the reagent injection was stopped and a baseline was taken with 20% of the secondary air in the inner register. This method is not exactly the same as the conditions modeled, where NSR of 0 and 2 was investigated at every condition. The detailed conditions for this experimental effort are presented in Table 3-4.

Table 3-4. Pilot-scale test conditions to investigate the impact of burner air distribution on NO_x reduction by RRI

Condition	Stoichiometric Ratio	Burner Stoichiometric Ratio	Coal [lb/hr]	Firing Rate [MBtu/hr]	O_2 [%, wet]	Primary Air [lb/hr]	Primary Air [% of total burner air]	Primary Air / Fuel	Secondary Air (Inner Register) [lb/hr]	Secondary Air (Outer Register) [lb/hr]	Secondary in Inner Register [%]	Secondary Swirl (Inner Register) [%]	Secondary Swirl (Outer Register) [%]	RRI Location	OFA Location	OFA [lb/hr]	NSR
1	1.22	0.85	326	4.03	3.5	388	15%	1.2	1704	432	80%	49	49	4	6	1028	0
2	1.22	0.85	326	4.03	3.5	388	15%	1.2	1704	432	80%	50	50	4	6	1028	2
3	1.19	0.85	324	4.00	3.3	386	15%	1.2	1421	705	67%	50	50	4	6	1011	2
4	1.20	0.86	323	3.97	3.6	384	15%	1.2	1068	1069	50%	50	50	4	6	1024	2
5	1.20	0.85	324	4.00	3.4	382	15%	1.2	709	1416	33%	50	50	4	6	1021	2
6	1.20	0.85	324	4.00	3.4	383	15%	1.2	425	1695	20%	50	50	4	6	1033	2
7	1.20	0.85	324	4.00	3.4	383	15%	1.2	425	1695	20%	51	51	4	6	1033	0
8	1.17	0.83	323	4.00	3.6	1172	48%	3.6	1027	251	80%	49	49	4	6	1005	0
9	1.17	0.83	323	4.00	3.6	1172	48%	3.6	1027	251	80%	50	50	4	6	1005	2
10	1.17	0.83	325	4.01	3.2	1162	48%	3.6	855	421	67%	50	50	4	6	1032	2
11	1.17	0.83	324	4.00	3.3	1165	48%	3.6	631	640	50%	50	50	4	6	1006	2
12	1.17	0.83	325	4.01	3.1	1165	47%	3.6	429	876	33%	50	50	4	6	1005	2
13	1.20	0.84	327	4.03	3	1162	46%	3.6	284	1065	21%	50	50	4	6	1006	2
14	1.20	0.84	327	4.03	3	1162	46%	3.6	284	1065	21%	51	51	4	6	1006	0
15	1.20	0.86	324	4.01	3.5	790	30%	2.4	1435	373	79%	49	49	4	6	1025	0
16	1.20	0.86	324	4.01	3.5	790	30%	2.4	1435	373	79%	50	50	4	6	1025	2
17	1.20	0.86	324	4.01	3.2	786	30%	2.4	1198	602	67%	50	50	4	6	1021	2
18	1.19	0.85	324	3.99	3.5	755	30%	2.3	905	877	51%	50	50	4	6	1030	2
19	1.20	0.85	325	4.01	3.3	755	30%	2.3	602	1197	33%	50	50	4	6	1034	2
20	1.20	0.85	324	4.00	3.1	764	30%	2.4	365	1429	20%	50	50	4	6	1039	2
21	1.20	0.85	324	4.00	3.1	764	30%	2.4	365	1429	20%	51	51	4	6	1039	0

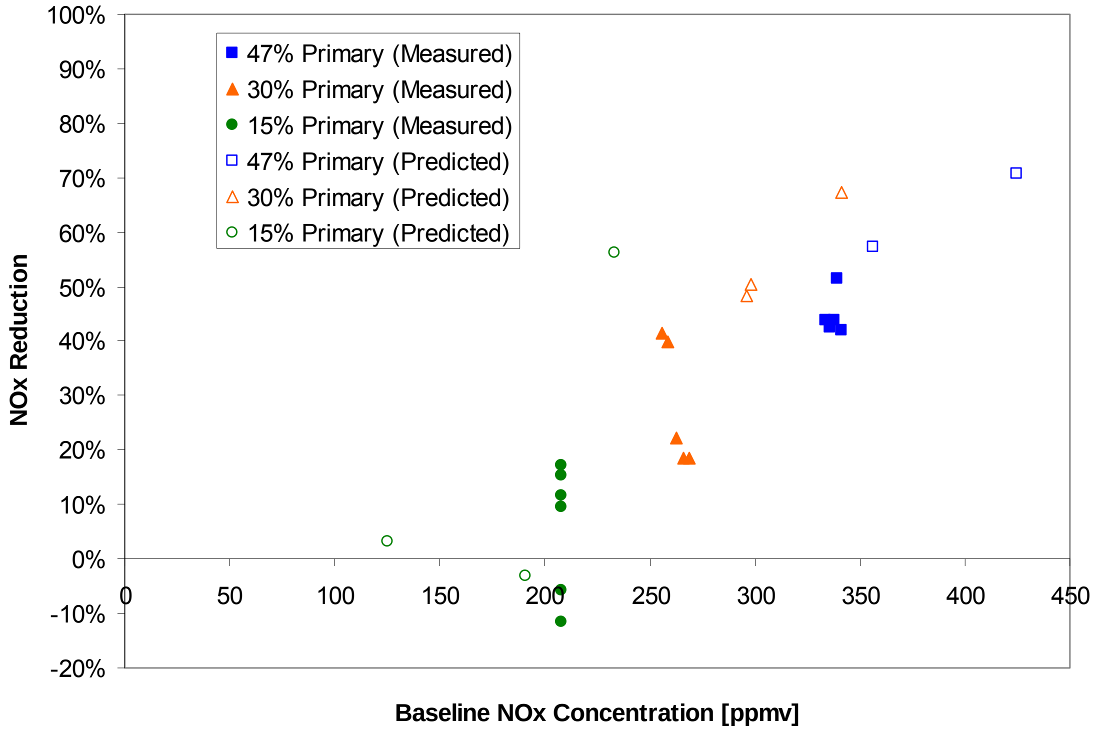


Figure 3-8. Experimental results showing the impact of baseline NO_x concentration on NO_x reduction with RRI

Figure 3-8 shows the behavior of NO_x reduction due to RRI as a function of each of the primary air rates. These data are compared with the modeling results for the same conditions that were presented in Figure 3-4. The model and measured results match very well in their trends. This figure shows that the NO_x reduction and the baseline concentration are both higher for the conditions where more air is introduced in the primary. The measured data do not show a strong trend with the distribution of air in the secondary as expected from the modeling. Also, the measured baseline NO_x concentrations and the NO_x reductions are both lower than those predicted. The discrepancies between measured and predicted data can be explained in part by differences in the geometry modeled (ideal furnace) and the actual furnace geometry (e.g., significant ash deposits on floor and walls from previous testing), differences in modeled and actual BSR and flow inputs, and differences in modeled and actual reagent droplet size distribution.

Figure 3-9 presents these same data where reduced NO_x concentration is plotted as a function of baseline NO_x concentration. This plot may be compared with modeling results presented in Figure 3-4. The reduced NO_x concentrations displayed behavior that was identical to that in the simulation. Although the NO_x reduction by RRI increased when there was more air in the primary, the reduced NO_x concentration remained fairly constant over all primary air conditions. This is even more evident in Figure 3-10 where NO_x reduction and concentrations are averaged for each primary air condition and plotted.

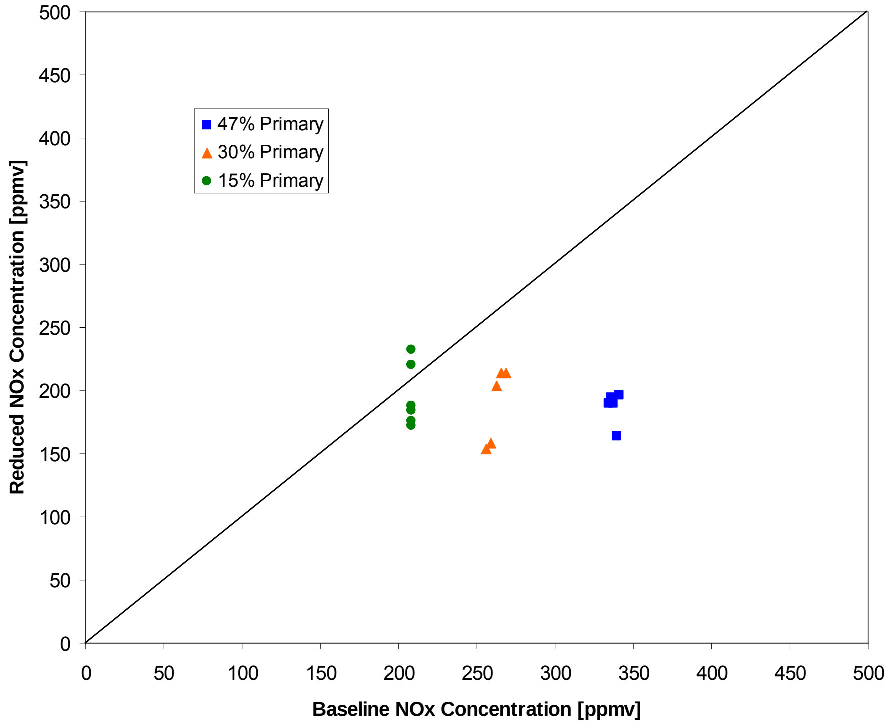


Figure 3-9. Experimental results for the relationship between reduced and baseline NO_x concentration

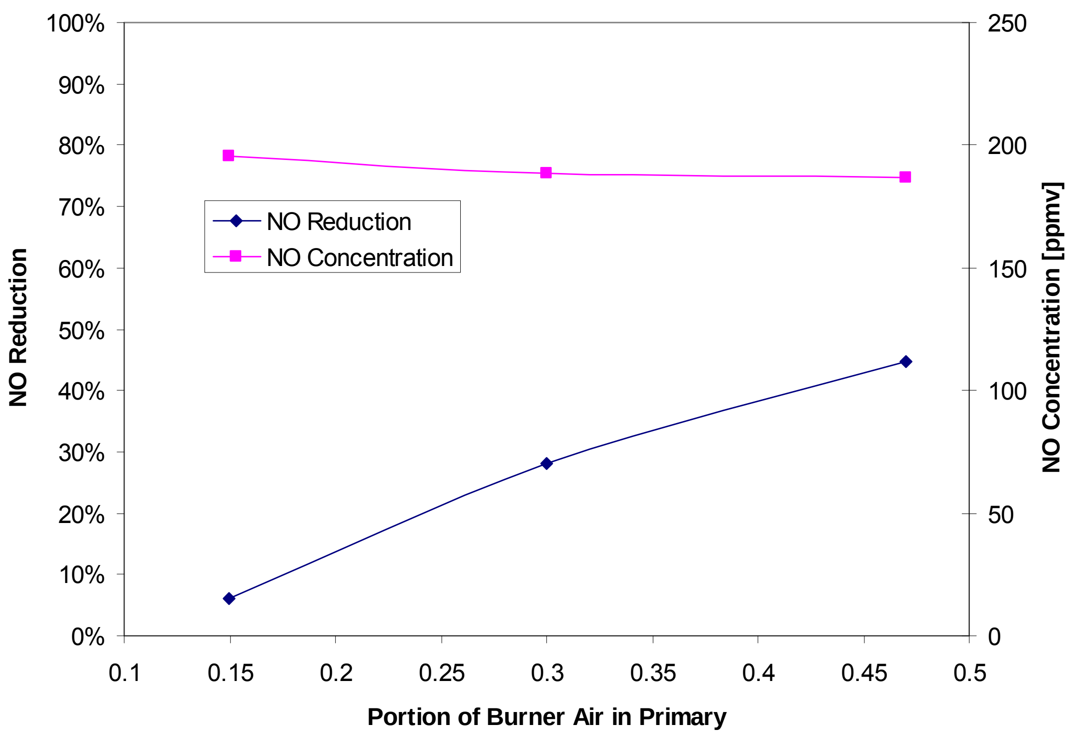


Figure 3-10. Relationship between burner operation, NO_x reduction and NO_x concentration while firing the Low-NO_x Burner

Both the CFD model result and the experimental data agree that NO_x can be effectively reduced by RRI in a PC environment. It has also been shown that conditions where RRI is most effective at reducing NO_x also provide the highest baseline NO_x concentrations. When firing with a typical Low-NO_x burner, the NO_x concentrations are essentially the same when the burner is operated for Low-NO_x or for homogenous conditions with RRI. These observations are motivation to find a burner design that provides homogeneous flue gas conditions without the high penalty in baseline NO_x concentration.

3.2 Evaluation of ALTA Burner

CFD Simulations

A burner suitable for firing pulverized coal and producing conditions favorable for RRI must provide two conditions. The flue gas must become homogeneous rapidly in the post-flame region and the homogenous residence time must be sufficiently long to optimize release of carbon from the solid phase, producing rich conditions. These conditions must be met while producing a stable flame. Based on these specifications, REI worked with Combustion Components Associates (CCA) to modify a burner previously used for natural gas. In this design, the fuel and primary air is distributed throughout the secondary air cross section, a design that accelerates the rate of fuel and air mixing. A diagram showing the configuration of the resulting ALTA burner is shown in Figure 3-11.

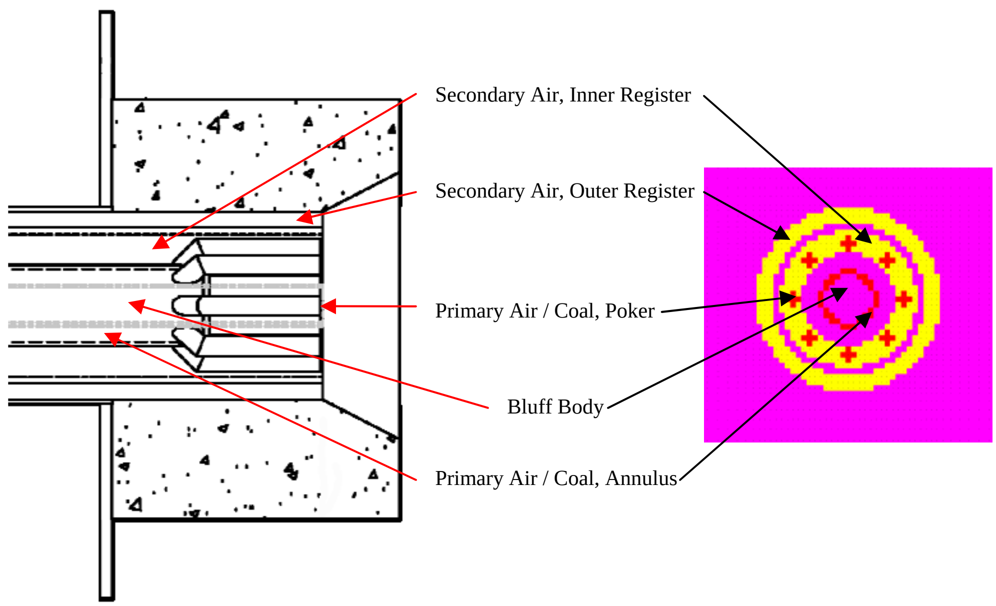


Figure 3-11. ALTA burner configuration

Part of the design consideration for the ALTA Burner was to replace as few components in the Low-NO_x burner (LNB) as possible, while maintaining functionality. The installation of the ALTA burner required removal of the primary air annulus, bluff body, and the secondary inner register swirl block from the existing LNB. These components were replaced with an assembly that would slide into the existing burner giving the configuration detailed in Figure 3-11. With this understanding, the ALTA burner may be accepted as a significant modification to the existing LNB.

CFD modeling was performed to determine the mixing characteristics of the ALTA burner. For these simulations, the BSR was set to 0.7. The burner air was distributed with 30% in the primary and the remainder in the secondary with a 60/40 split between the inner and outer registers. A uniform coal particle and air distribution was assumed across the primary outlets, including the inner annulus and the distributed nozzles or “pokers”. The OFA was introduced in section 6. As with previous modeling, a CO profile plot of the furnace was produced as an indicator of stratification or homogenization at various planes. The plot for this modeling effort is detailed in Figure 3-12.

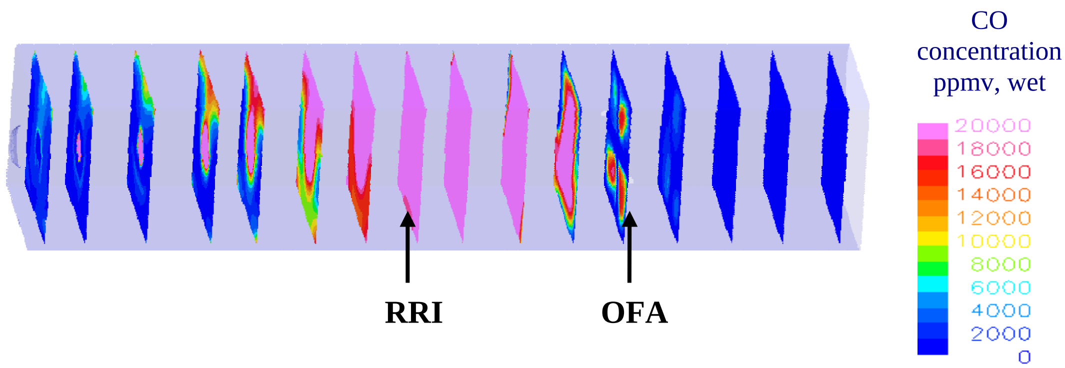


Figure 3-12. CO distribution in the L-1500 while firing the ALTA burner

The CO profile in Figure 3-12 shows homogeneity at the reagent injection location. For this simulation, the post-flame NO_x concentration was approximately 450 ppmv and the post-OFA concentration was just over 200 ppmv in section 8. These NO_x concentrations are significantly lower than those predicted for the Low-NO_x burner using the most homogeneous conditions detailed in Figure 3-2. The contour plot of CO suggests that the plane of injection is more homogeneous than the conditions presented in Figure 3-2. These modeling results imply conditions for favorable NO_x reduction from the ALTA burner.

Pilot-Scale Experimentation

The first experiments with the ALTA burner were designed to establish the behavior of the burner under staged conditions, without RRI. For these experiments the BSR was set at 0.85, 0.75 and 0.65 and the distribution of the burner air was varied. Detailed conditions for these tests can be found in Table 3-5 and a summary of the test results can be found in Figure 3-13.

Table 3-5. Pilot-scale test conditions to investigate the staging behavior of the ALTA burner

Condition	Stoichiometric Ratio*	Burner Stoichiometric Ratio*	Coal [lb/hr]*	Firing Rate [lb/MBtu]*	O2 [%, wet]	Primary Air [lb/hr]*	Primary Air [% of total burner air]*	Primary Air / Fuel*	Secondary Air (Inner Register) [lb/hr]*	Secondary Air (Outer Register) [lb/hr]*	Secondary in Inner Register [%]*	Secondary Swirl (Inner Register) [%]	Secondary Swirl (Outer Register) [%]	RRI Location	OFA Location	OFA [lb/hr]*
1	1.2	0.75	325	3.8	3.3	666	30%	2.1	1244	311	80%	--	100%	--	6	1333
2	1.2	0.75	325	3.8	3.4	666	30%	2.1	1026	529	66%	--	100%	--	6	1333
3	1.2	0.75	325	3.8	3.7	666	30%	2.1	777	777	50%	--	100%	--	6	1333
4	1.2	0.75	325	3.8	4.0	666	30%	2.1	513	1042	33%	--	100%	--	6	1333
5	1.2	0.75	325	3.8	3.8	666	30%	2.1	311	1244	20%	--	100%	--	6	1333
6	1.2	0.65	325	3.8	3.0	578	30%	1.8	1078	270	80%	--	100%	--	6	1629
7	1.2	0.65	325	3.8	3.2	578	30%	1.8	889	458	66%	--	100%	--	6	1629
8	1.2	0.65	325	3.8	3.3	578	30%	1.8	674	674	50%	--	100%	--	6	1629
9	1.2	0.65	325	3.8	3.5	578	30%	1.8	445	903	33%	--	100%	--	6	1629
10	1.2	0.65	325	3.8	3.3	578	30%	1.8	270	1078	20%	--	100%	--	6	1629
11	1.2	0.85	325	3.8	3.8	1183	47%	3.6	1067	267	80%	--	100%	--	6	1037
12	1.2	0.85	325	3.8	4.0	1183	47%	3.6	667	667	50%	--	100%	--	6	1037
13	1.2	0.85	325	3.8	4.2	1183	47%	3.6	267	1067	20%	--	100%	--	6	1037
14	1.2	0.75	325	3.8	3.8	1044	47%	3.2	942	235	80%	--	100%	--	6	1333
15	1.2	0.75	325	3.8	3.8	1044	47%	3.2	589	589	50%	--	100%	--	6	1333
16	1.2	0.75	325	3.8	4.0	1044	47%	3.2	235	942	20%	--	100%	--	6	1333
17	1.2	0.65	325	3.8	3.4	905	47%	2.8	816	204	80%	--	100%	--	6	1629
18	1.2	0.65	325	3.8	3.8	905	47%	2.8	510	510	50%	--	100%	--	6	1629
19	1.2	0.65	325	3.8	4.0	905	47%	2.8	204	816	20%	--	100%	--	6	1629
20	1.2	0.85	325	3.8	3.2	755	30%	2.3	1410	352	80%	--	100%	--	6	1037
21	1.2	0.85	325	3.8	3.8	755	30%	2.3	881	881	50%	--	100%	--	6	1037
22	1.2	0.85	325	3.8	3.4	755	30%	2.3	352	1410	20%	--	100%	--	6	1037

* Set point

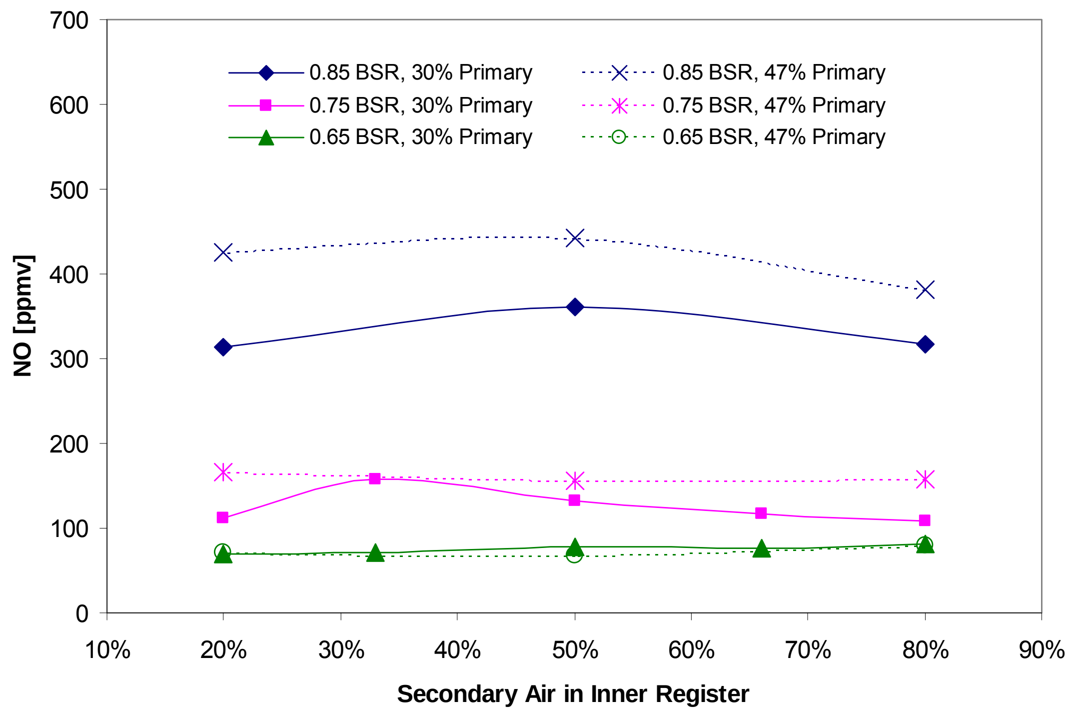


Figure 3-13. Characterization of ALTA burner under various staging conditions and burner air distributions

Figure 3-13 shows a significant effect of staging on the NO_x concentration when firing with the ALTA burner. The NO_x concentrations achieved here with the OFA in section 6 are nearly as low as those produced with the Low-NO_x burner when the OFA was in section 9. It is also evident from these data that the distribution of air in the secondary registers has only a limited effect on NO_x concentration, particularly at the lower burner stoichiometries.

The next set of tests was designed to elucidate the behavior of the ALTA burner as a function of the distribution of burner air. For these tests the BSR was set at 0.85. The portion of burner air that was introduced through the primary was set at 22 and 30%. For each of these conditions the secondary air was moved from the inner to outer register in increments. The NSR was varied between 0 and 2 to determine baseline and reduced NO_x numbers. For the conditions where the baseline NO_x was not directly measured it was linearly interpolated from the baseline NO_x at similar conditions. Details of these test conditions can be found in Table 3-6. The effect of distribution of burner air on NO_x baseline concentration, reduction with RRI and reduced concentration is presented in Figure 3-14.

Table 3-6. Pilot-scale test conditions to investigate the effect of burner air distribution on the ALTA burner

Condition	Stoichiometric Ratio*	Burner Stoichiometric Ratio*	Coal [lb/hr]*	Firing Rate [MBtu/hr]*	O2 [%, wet]	Primary Air [lb/hr]*	Primary Air [% of total burner air]	Primary Air / Fuel	Secondary Air (Inner Register) [lb/hr]*	Secondary Air (Outer Register) [lb/hr]*	Secondary in Inner Register [%]	Secondary Swirl (Inner Register) [%]	Secondary Swirl (Outer Register0 [%]	Injection Location	OFA Location	OFA [lb/hr]*
1	1.2	0.85	320	3.7	3.52	744	30%	2.3	1736	0	100%	--	100%	4	6	1021
2	1.2	0.85	320	3.7	3.67	744	30%	2.3	1389	347	80%	--	100%	4	6	1021
3	1.2	0.85	320	3.7	3.6	744	30%	2.3	1736	0	100%	--	100%	4	6	1021
4	1.2	0.85	320	3.7	3.2	744	30%	2.3	1389	347	80%	--	100%	4	6	1021
5	1.2	0.85	320	3.7	3.6	744	30%	2.3	868	868	50%	--	100%	4	6	1021
6	1.2	0.85	320	3.7	3.4	744	30%	2.3	347	1389	20%	--	100%	4	6	1021
7	1.2	0.85	320	3.7	3.56	744	30%	2.3	347	1389	20%	--	100%	4	6	1021
8	1.2	0.85	320	3.7	3.85	565	22%	1.8	1916	0	100%	--	100%	4	6	1021
9	1.2	0.85	320	3.7	3.6	565	22%	1.8	1916	0	100%	--	100%	4	6	1021
10	1.2	0.85	320	3.7	3.5	565	22%	1.8	1532	383	80%	--	100%	4	6	1021
11	1.2	0.85	320	3.7	3.4	565	22%	1.8	958	958	50%	--	100%	4	6	1021
12	1.2	0.85	320	3.7	3.5	565	22%	1.8	383	1532	20%	--	100%	4	6	1021
13	1.2	0.85	320	3.7	3.6	565	22%	1.8	383	1532	20%	--	100%	4	6	1021

*Set point

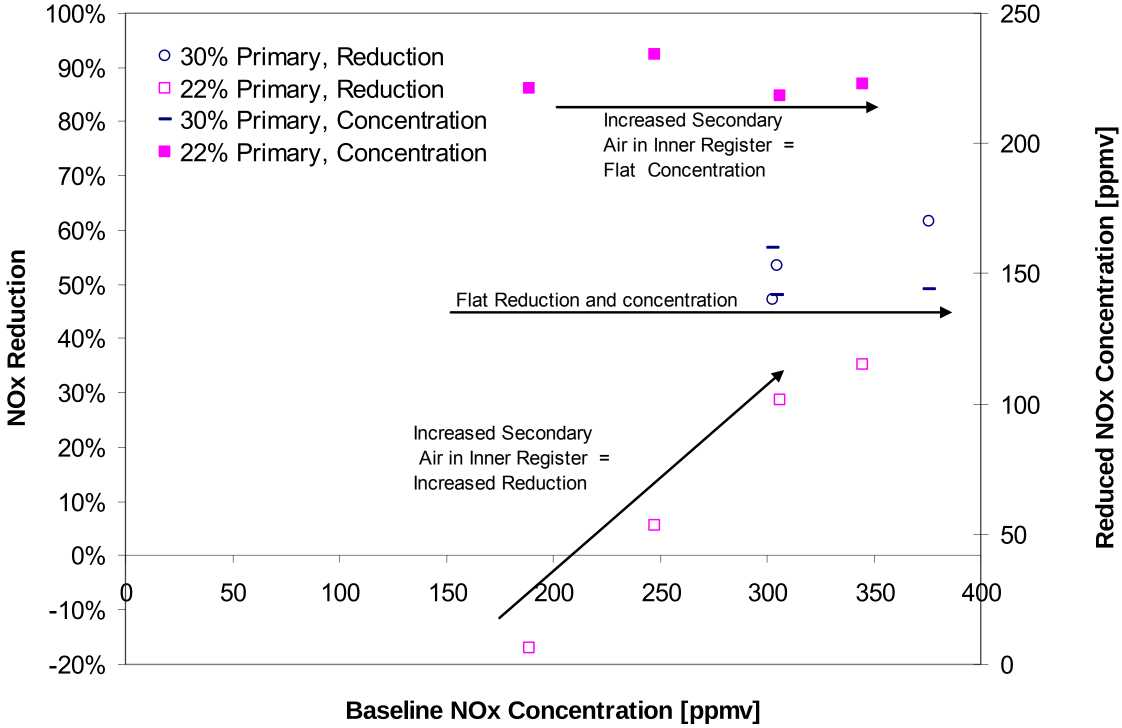


Figure 3-14. Effect of burner air distribution on NO_x baseline concentration, reduction with RRI and reduced concentration

Figure 3-14 shows that there is a significant difference between the behavior of the ALTA burner with 30 and 22% of the burner air in the primary. At 22% primary air, the burner behavior is like the Low-NO_x burner where stratified conditions give low baseline NO_x concentrations and low reductions. In addition homogeneous conditions give high baseline NO_x concentrations and high reductions. The behavior is much different when the primary air is brought up to just 30% of the total air. The NO_x reduction due to RRI and the reduced NO_x concentration are fairly flat across the distribution of air in the secondary. This is more like the ALTA burner is expected to behave - independent of primary air rate.

Through investigation of this discontinuity in burner behavior, a potential improvement in burner design was identified. The primary air and coal in the ALTA burner have two possible routes to the furnace as seen in Figure 3-11. They may run through the annulus, or they can turn and discharge through the “pokers”. It is expected that at low primary air rates, the pressure drop at the annulus constriction is not great enough to direct flow through the pokers. At higher primary air rates the pressure drop increases and some of the coal and air is directed to the pokers and distributed into the secondary air as intended. This issue and the resulting modifications implemented in the ALTA burner are discussed further in Section 3.3.

The last set of tests with the ALTA burner was to investigate the effects of reduced residence time to the injection location. For this test, the BSR was varied from 0.95 to 0.65 at 0.05 increments with RRI in section 4 and OFA in section 6. This set of tests was repeated with RRI in section 3 and OFA in section 5. Reagent was injected at an NSR of 0 and 2 at each condition to get baseline and reduced NO_x. Details of the conditions used for these tests are provided in Table 3-7. A summary of the data from these tests is provided in Figure 3-15.

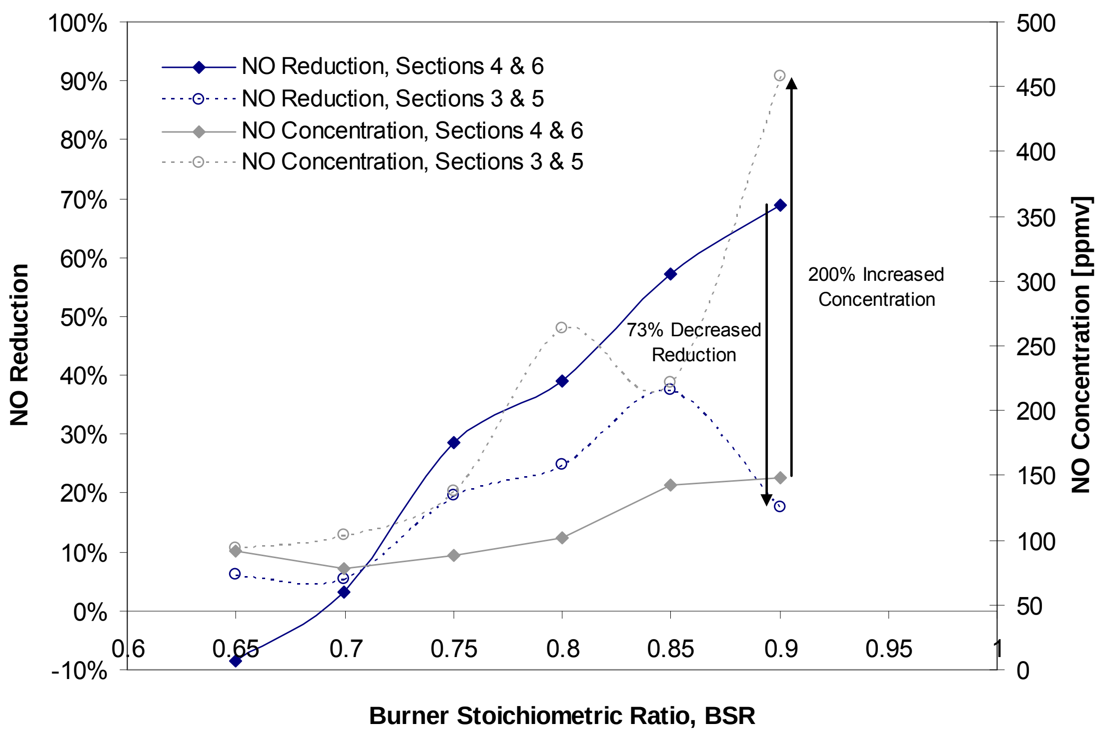


Figure 3-15. Performance of the ALTA burner decreases as the injection location moves closer to the burner

These data show a decline in effectiveness of RRI at reducing NO_x when the injection location is moved one section closer to the burner. Most significant is the 200% increase in NO_x concentration at a BSR of 0.9. This corresponds to a 73% loss in NO_x reduction. Other significant aspects of these data are the unusually low NO_x concentrations with RRI in section 4 and BSRs ranging from 0.7 to 0.8. These concentrations are 78, 88 and 102 ppmv respectively.

Table 3-7. Pilot-scale test conditions to investigate the effect staging and injection and OFA locations

Condition	Stoichiometric Ratio*	Burner Stoichiometric Ratio*	Coal [lb/hr]*	Firing Rate [MBtu/hr]	O2 [%, wet]	Primary Air [lb/hr]*	Primary Air [% of total burner air]	Primary Air / Fuel	Secondary Air (Inner Register) [lb/hr]*	Secondary Air (Outer Register) [lb/hr]	Secondary in Inner Register [%]	Secondary Swirl (Inner Register) [%]	Secondary Swirl (Outer Register) [%]	RRI Location	OFA Location	OFA [lb/hr]*
1	1.2	0.9	323	3.8	3.1	1176	44%	3.6	1473	0	100%	--	50%	4	6	883
2	1.2	0.9	323	3.8	3.31	1176	44%	3.6	1473	0	100%	--	50%	4	6	883
3	1.2	0.85	323	3.8	3.34	1126	45%	3.5	1376	0	100%	--	50%	4	6	1030
4	1.2	0.85	323	3.8	3.3	1126	45%	3.5	1376	0	100%	--	50%	4	6	1030
5	1.2	0.8	323	3.8	2.88	1060	45%	3.3	1295	0	100%	--	50%	4	6	1177
6	1.2	0.8	323	3.8	2.9	1060	45%	3.3	1295	0	100%	--	50%	4	6	1177
7	1.2	0.75	323	3.8	3.15	993	45%	3.1	1214	0	100%	--	50%	4	6	1325
8	1.2	0.75	323	3.8	3.1	993	45%	3.1	1214	0	100%	--	50%	4	6	1325
9	1.2	0.7	323	3.8	3.29	927	45%	2.9	1133	0	100%	--	50%	4	6	1472
10	1.2	0.7	323	3.8	3.2	927	45%	2.9	1133	0	100%	--	50%	4	6	1472
11	1.2	0.65	323	3.8	3.3	861	45%	2.7	1052	0	100%	--	50%	4	6	1619
12	1.2	0.65	323	3.8	3.1	861	45%	2.7	1052	0	100%	--	50%	4	6	1619
13	1.2	0.85	323	3.8	3.48	1126	45%	3.5	1376	0	100%	--	50%	3	5	1030
14	1.2	0.85	323	3.8	3.5	1126	45%	3.5	1376	0	100%	--	50%	3	5	1030
15	1.2	0.85	323	3.8	3.8	1126	45%	3.5	1376	0	100%	--	50%	3	5	1030
16	1.2	0.9	323	3.8	3.82	1192	45%	3.7	1457	0	100%	--	50%	3	5	883
17	1.2	0.9	323	3.8	3.8	1192	45%	3.7	1457	0	100%	--	50%	3	5	883
18	1.2	0.8	323	3.8	4.13	1060	45%	3.3	1295	0	100%	--	50%	3	5	1177
19	1.2	0.8	323	3.8	3.8	1060	45%	3.3	1295	0	100%	--	50%	3	5	1177
20	1.2	0.75	323	3.8	3.52	993	45%	3.1	1214	0	100%	--	50%	3	5	1325
21	1.2	0.75	323	3.8	3.5	993	45%	3.1	1214	0	100%	--	50%	3	5	1325
22	1.2	0.7	323	3.8	3.25	927	45%	2.9	1133	0	100%	--	50%	3	5	1472
23	1.2	0.7	323	3.8	3.2	927	45%	2.9	1133	0	100%	--	50%	3	5	1472
24	1.2	0.65	323	3.8	3.47	861	45%	2.7	1052	0	100%	--	50%	3	5	1619
25	1.2	0.65	323	3.8	3.5	861	45%	2.7	1052	0	100%	--	50%	3	5	1619

3.3 Evaluation of Modified ALTA Burner

Pilot-Scale Experimentation

It was decided that to improve the performance of RRI, it was prudent to modify the ALTA burner. This modification would be to block the inner annulus of the primary air, forcing the primary flow through the pokers. This modification would force coal distribution into the secondary air as was intended. It was further speculated that the burner should operate at lower primary air rates to devolatilize the coal nearer the burner.

Following modification of the ALTA burner, a series of experiments were designed to evaluate its effectiveness. For these experiments, the modified ALTA burner (MAB) was compared directly to the Low-NO_x Burner (LNB). Each of the burners was operated with air distribution that would produce the lowest NO_x concentration with reagent injection. The LNB was operated at conditions "typical" for Low-NO_x burners and have been proven in this facility to produce the lowest NO_x. The modified ALTA burner was operated with a conventional Primary Air / Fuel ratio of 1.8 and all of the secondary air in the inner register. These conditions were thought to provide the most homogeneous conditions possible in close proximity to the burner. Each of the burners was fired across a range of BSRs and at each condition the NSR was set to 0 and 2. A series of tests was performed with each of the burners while the reagent was injected in section 4 and the OFA in section 6 and while the reagent was injected in section 3 and the OFA in section 5. The detailed conditions for each of these tests appear in Table 3-8 through Table 3-11. Figure 3-16 and Figure 3-17 compare NO_x emissions and reduction from the modified ALTA burner and the Low-NO_x burner with reagent injection in section 4 and OFA in section 6 of the furnace.

Table 3-8. Pilot-scale test conditions to investigate the modified ALTA burner with RRI in section 4 and OFA in Section 6

Condition	Stoichiometric Ratio*	Burner Stoichiometric Ratio*	Coal [lb/hr]*	Firing Rate [MBtu/hr]	O2 [%, wet]	Primary Air [lb/hr]*	Primary Air [% of total burner air]	Primary Air/Fuel	Secondary Air (Inner Register) [lb/hr]*	Secondary Air (Outer Register) [lb/hr]*	Secondary in Inner Register [%]	Secondary Swirl (Inner Register) [%]	Secondary Swirl (Outer Register) [%]	RRI Location	OFA Location	OFA [lb/hr]*	NSR*
1	1.2	0.9	330	3.9	3.05	601	24%	1.82	1944	0	100%	--	50%	4	6	848	0
2	1.2	0.9	330	3.9	2.9	601	24%	1.82	1944	0	100%	--	50%	4	6	848	2
3	1.2	0.85	330	3.9	2.97	601	25%	1.82	1803	0	100%	--	50%	4	6	990	0
4	1.2	0.85	330	3.9	3.2	601	25%	1.82	1803	0	100%	--	50%	4	6	990	2
5	1.2	0.8	330	3.9	3.5	601	27%	1.82	1661	0	100%	--	50%	4	6	1131	0
6	1.2	0.8	330	3.9	3.1	601	27%	1.82	1661	0	100%	--	50%	4	6	1131	2
7	1.2	0.75	330	3.9	3.14	601	28%	1.82	1520	0	100%	--	50%	4	6	1272	0
8	1.2	0.75	330	3.9	3.1	601	28%	1.82	1520	0	100%	--	50%	4	6	1272	2
9	1.2	0.7	330	3.9	3.09	601	30%	1.82	1379	0	100%	--	50%	4	6	1414	0
10	1.2	0.7	330	3.9	3.2	601	30%	1.82	1379	0	100%	--	50%	4	6	1414	2
11	1.2	0.65	330	3.9	3.24	601	33%	1.82	1237	0	100%	--	50%	4	6	1555	0
12	1.2	0.65	330	3.9	3.2	601	33%	1.82	1237	0	100%	--	50%	4	6	1555	2
13	1.2	0.95	330	3.9	3.39	601	22%	1.82	2086	0	100%	--	50%	4	6	707	0
14	1.2	0.95	330	3.9	3	601	22%	1.82	2086	0	100%	--	50%	4	6	707	2

*Set point

Table 3-9. Pilot-scale test conditions to investigate the modified ALTA burner with RRI in section 3 and OFA in Section 5

Condition	Stoichiometric Ratio*	Burner Stoichiometric Ratio*	Coal [lb/hr]*	Firing Rate [MBtu/hr]	O2 [%, wet]	Primary Air [lb/hr]*	Primary Air [% of total burner air]	Primary Air/Fuel	Secondary Air (Inner Register) [lb/hr]*	Secondary Air (Outer Register) [lb/hr]*	Secondary in Inner Register [%]	Secondary Swirl (Inner Register) [%]	Secondary Swirl (Outer Register) [%]	RRI Location	OFA Location	OFA [lb/hr]*	NSR*
1	1.2	0.95	340	4.0	3.18	619	22%	1.82	2143	0	100%	--	50%	3	5	727	0
2	1.2	0.95	340	4.0	2.9	619	22%	1.82	2143	0	100%	--	50%	3	5	727	2
3	1.2	0.9	340	4.0	3.33	619	24%	1.82	1998	0	100%	--	50%	3	5	872	0
4	1.2	0.9	340	4.0	3.1	619	24%	1.82	1998	0	100%	--	50%	3	5	872	2
5	1.2	0.85	340	4.0	3.01	619	25%	1.82	1853	0	100%	--	50%	3	5	1018	0
6	1.2	0.85	340	4.0	2.9	619	25%	1.82	1853	0	100%	--	50%	3	5	1018	2
7	1.2	0.8	340	4.0	3.32	619	27%	1.82	1707	0	100%	--	50%	3	5	1163	0
8	1.2	0.8	340	4.0	3.2	619	27%	1.82	1707	0	100%	--	50%	3	5	1163	2
9	1.2	0.75	340	4.0	3.4	619	28%	1.82	1562	0	100%	--	50%	3	5	1308	0
10	1.2	0.75	340	4.0	2.8	619	28%	1.82	1562	0	100%	--	50%	3	5	1308	2
11	1.2	0.7	340	4.0	2.95	619	30%	1.82	1416	0	100%	--	50%	3	5	1454	0
12	1.2	0.7	340	4.0	3	619	30%	1.82	1416	0	100%	--	50%	3	5	1454	2
13	1.2	0.65	340	4.0	3.16	619	33%	1.82	1271	0	100%	--	50%	3	5	1599	0
14	1.2	0.65	340	4.0	3.2	619	33%	1.82	1271	0	100%	--	50%	3	5	1599	2

*Set point

Table 3-10. Pilot-scale test conditions to investigate the Low-NO_x burner with RRI in section 4 and OFA in Section 6

Condition	Stoichiometric Ratio*	Burner Stoichiometric Ratio*	Coal [lb/hr]*	Firing Rate [MBtu/hr]	O2 [%, wet]	Primary Air [lb/hr]*	Primary Air [% of total burner air]	Primary Air/Fuel	Secondary Air (Inner Register) [lb/hr]*	Secondary Air (Outer Register) [lb/hr]*	Secondary in Inner Register [%]	Secondary Swirl (Inner Register) [%]	Secondary Swirl (Outer Register) [%]	RRI Location	OFA Location	OFA [lb/hr]*	NSR*
1	1.2	0.95	340	4.0	3.33	612	22%	1.8	710	1441	33%	75%	75%	4	6	727	0
2	1.2	0.95	340	4.0	3.3	612	22%	1.8	710	1441	33%	75%	75%	4	6	727	2
3	1.2	0.9	340	4.0	3.34	612	23%	1.8	662	1343	33%	75%	75%	4	6	872	0
4	1.2	0.9	340	4.0	3.3	612	23%	1.8	662	1343	33%	75%	75%	4	6	872	2
5	1.2	0.85	340	4.0	3.45	612	25%	1.8	614	1246	33%	75%	75%	4	6	1018	0
6	1.2	0.85	340	4.0	3.2	612	25%	1.8	614	1246	33%	75%	75%	4	6	1018	2
7	1.2	0.8	340	4.0	3.29	612	26%	1.8	566	1148	33%	75%	75%	4	6	1163	0
8	1.2	0.8	340	4.0	3.2	612	26%	1.8	566	1148	33%	75%	75%	4	6	1163	2
9	1.2	0.75	340	4.0	3.43	612	28%	1.8	518	1051	33%	75%	75%	4	6	1308	0
10	1.2	0.75	340	4.0	3.5	612	28%	1.8	518	1051	33%	75%	75%	4	6	1308	2
11	1.2	0.7	340	4.0	3.47	612	30%	1.8	470	954	33%	75%	75%	4	6	1454	0
12	1.2	0.7	340	4.0	3.1	612	30%	1.8	470	954	33%	75%	75%	4	6	1454	2
13	1.2	0.65	340	4.0	3.22	612	32%	1.8	422	856	33%	75%	75%	4	6	1599	0
14	1.2	0.65	340	4.0	3.2	612	32%	1.8	422	856	33%	75%	75%	4	6	1599	2

*Set point

Table 3-11. Pilot-scale test conditions to investigate the Low-NO_x burner with RRI in section 3 and OFA in Section 5

Condition	Stoichiometric Ratio*	Burner Stoichiometric Ratio*	Coal [lb/hr]*	Firing Rate [MBtu/hr]	O2 [%, wet]	Primary Air [lb/hr]*	Primary Air [% of total burner air]	Primary Air/Fuel	Secondary Air (Inner Register) [lb/hr]*	Secondary Air (Outer Register) [lb/hr]*	Secondary in Inner Register [%]	Secondary Swirl (Inner Register) [%]	Secondary Swirl (Outer Register) [%]	RRI Location	OFA Location	OFA [lb/hr]*	NSR*
1	1.2	0.95	340	4.0	3.1	612	22%	1.8	710	1441	33%	75%	75%	3	5	727	0
2	1.2	0.95	340	4.0	3.29	612	22%	1.8	710	1441	33%	75%	75%	3	5	727	2
3	1.2	0.9	340	4.0	3.04	612	23%	1.8	662	1343	33%	75%	75%	3	5	872	0
4	1.2	0.9	340	4.0	3	612	23%	1.8	662	1343	33%	75%	75%	3	5	872	2
5	1.2	0.85	340	4.0	3.1	612	25%	1.8	614	1246	33%	75%	75%	3	5	1018	0
6	1.2	0.85	340	4.0	3	612	25%	1.8	614	1246	33%	75%	75%	3	5	1018	2
7	1.2	0.8	340	4.0	3.18	612	26%	1.8	566	1148	33%	75%	75%	3	5	1163	0
8	1.2	0.8	340	4.0	3.2	612	26%	1.8	566	1148	33%	75%	75%	3	5	1163	2
9	1.2	0.75	340	4.0	3.16	612	28%	1.8	518	1051	33%	75%	75%	3	5	1308	0
10	1.2	0.75	340	4.0	2.9	612	28%	1.8	518	1051	33%	75%	75%	3	5	1308	2
11	1.2	0.7	340	4.0	3.22	612	30%	1.8	470	954	33%	75%	75%	3	5	1454	0
12	1.2	0.7	340	4.0	3	612	30%	1.8	470	954	33%	75%	75%	3	5	1454	2
13	1.2	0.65	340	4.0	2.93	612	32%	1.8	422	856	33%	75%	75%	3	5	1599	0
14	1.2	0.65	340	4.0	2.8	612	32%	1.8	422	856	33%	75%	75%	3	5	1599	2

*Set point

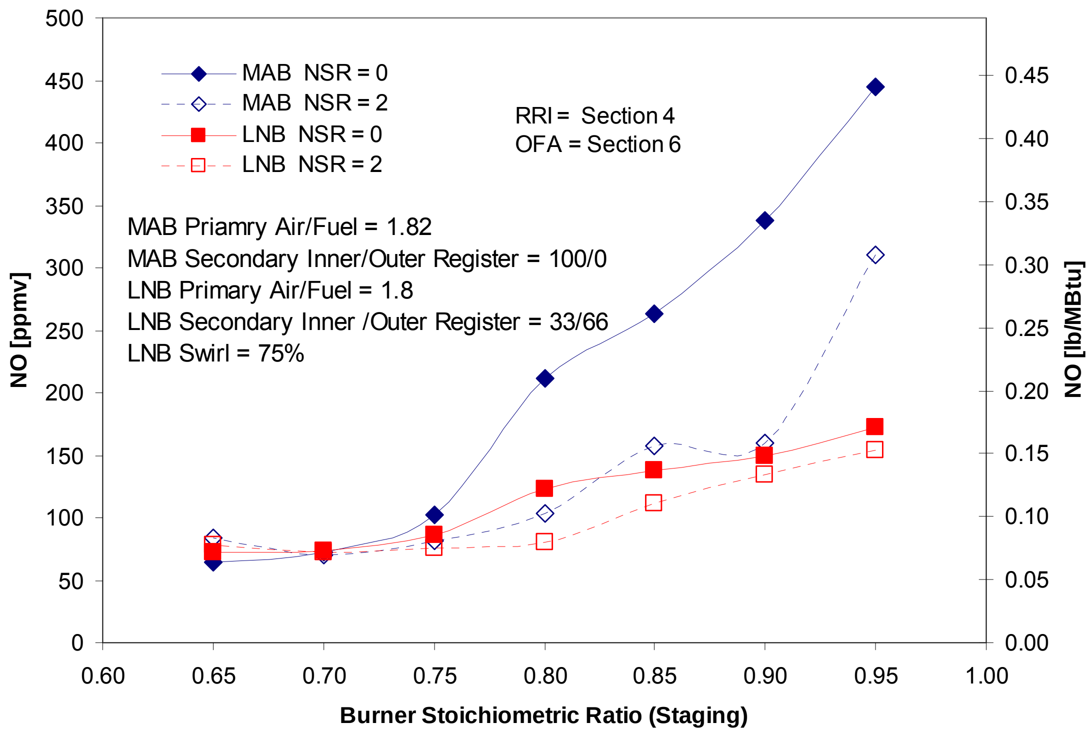


Figure 3-16. Staging curve using the modified ALTA burner (MAB), with RRI in section 4 and OFA in section 6 of the furnace

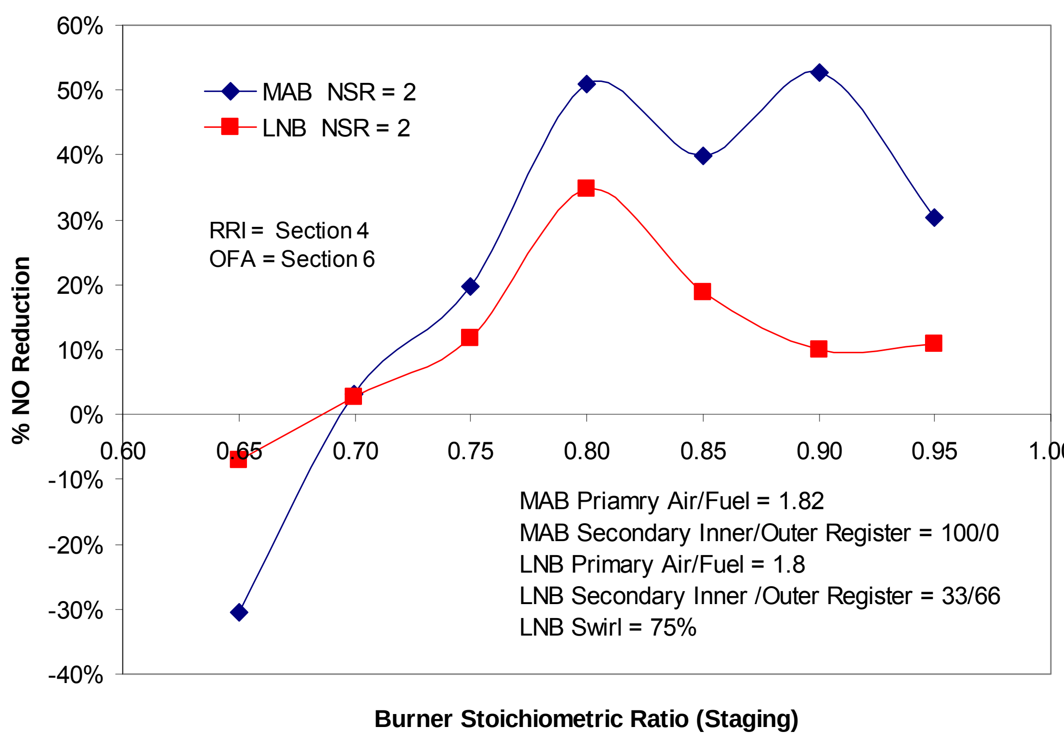


Figure 3-17. NO reduction comparison between modified ALTA burner (MAB) and Low-NO_x burner (LNB) as a function of staging with RRI in section 4 and OFA in section 6

These data demonstrate that residence time and mixing limitations can impede the effectiveness of RRI when using the existing LNB. Significant reductions in NO_x concentration could be achieved in this region when the modified ALTA burner was used. At a BSR of 0.80, NO_x was reduced from 212 ppmv (0.21 lb/MBtu) to 104 ppmv (0.10 lb/MBtu) for a reduction of 51%. These data suggest that the modified ALTA burner was operating as intended and causing homogeneity in the flue gas. Even with 51% reduction in NO_x concentration, the modified ALTA burner, which is designed to operate under deeply staged, short residence-time conditions, was not able to produce NO_x concentrations that were significantly lower than the LNB under the same conditions. NO_x concentrations from the LNB were also further reduced with RRI. This suggests that with RRI in section 4 and OFA in section 6, there was still enough residence time to overcome the effects of stratification before the OFA. This was also evident in the NO_x concentration at deeply staged conditions. As with the long residence time experiments, the NO_x values converged at a BSR of 0.7 for both burners, with and without RRI. Figure 3-18 shows NO_x reduction as a function of NSR for both burners at a BSR of 0.85. This figure suggests that additional reduction could be achieved at higher NSRs for the conditions tested with reagent injection in section 4 and OFA in section 6.

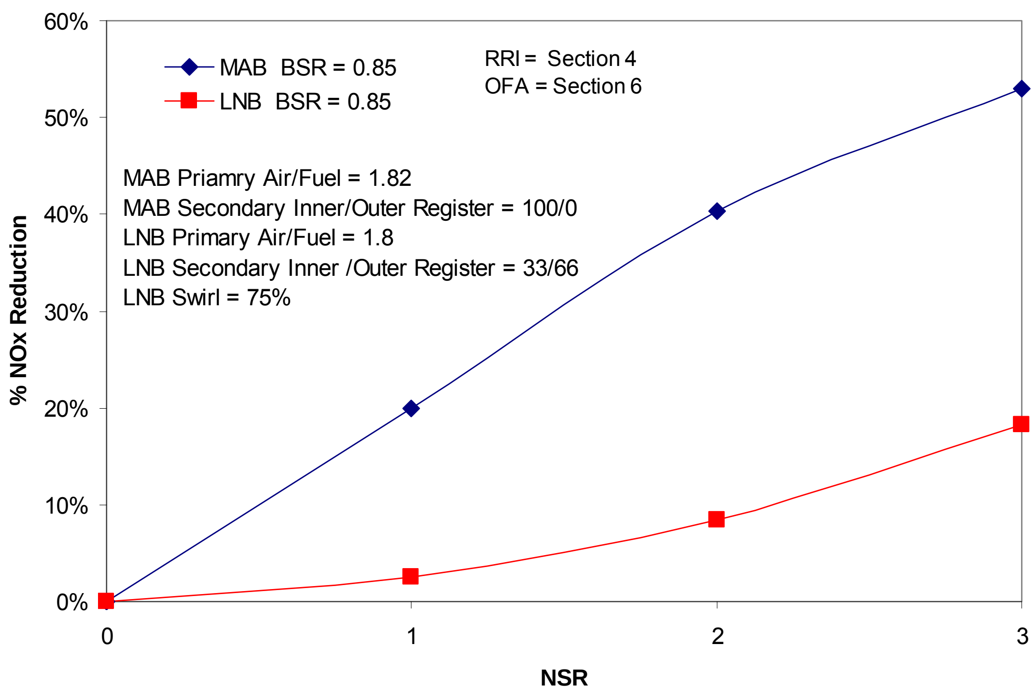


Figure 3-18. NSR curve with the modified ALTA burner (MAB) and reagent injection in section 4 and OFA in section 6

Figure 3-19 and Figure 3-20 compare NO_x emissions and reduction from the modified ALTA burner and the LNB with reagent injection in section 3 and OFA in section 5 of the furnace.

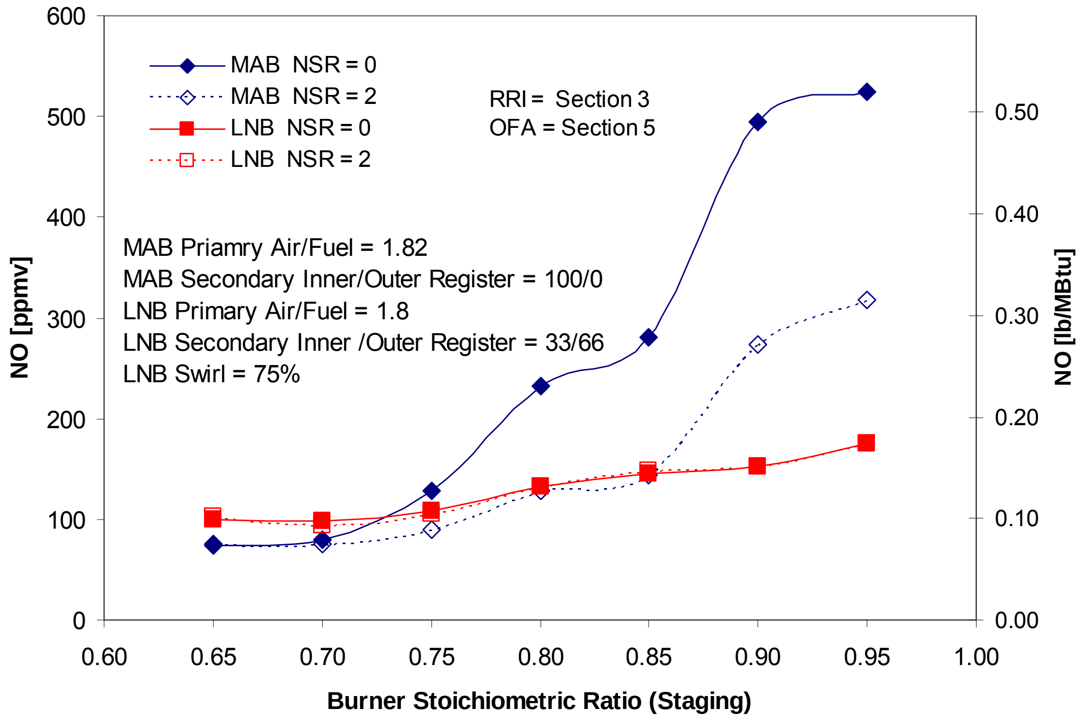


Figure 3-19. Staging curve comparison between the modified ALTA burner (MAB) and the Low-NO_x burner (LNB) with reagent injection in section 3 and OFA in section 5

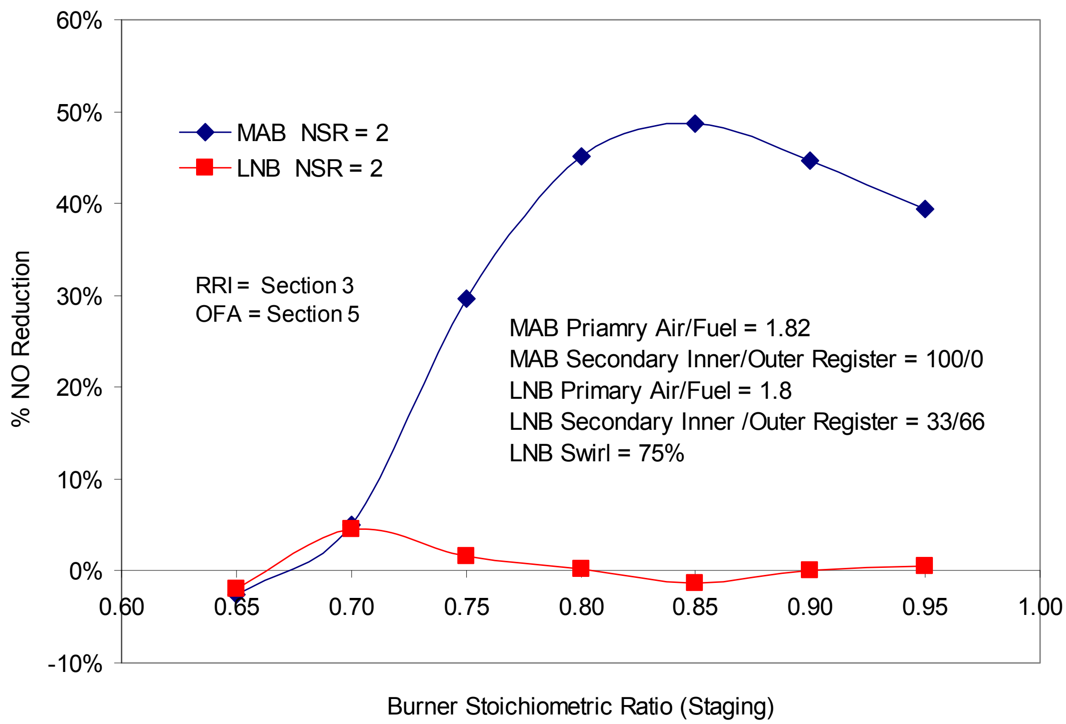


Figure 3-20. NO reduction comparison between modified ALTA burner (MAB) and Low-NO_x burner (LNB) as a function of staging with RRI in section 3 and OFA in section 5

Here, the NO_x values were the same with and without reagent injection, when using the LNB. However, the modified ALTA burner still showed almost 50% reduction in NO_x at a BSR of 0.85. Even more significant was the separation between the NO_x values produced by each of the burners under deeply staged conditions as seen in Figure 3-21. At a BSR of 0.75, the modified ALTA burner with reagent injection was able to produce 17 % lower NO_x concentrations than the LNB. At moderate staging the modified ALTA burner also showed lower NO_x concentration with RRI than could be produced with the LNB. This can more easily be seen in Figure 3-21.

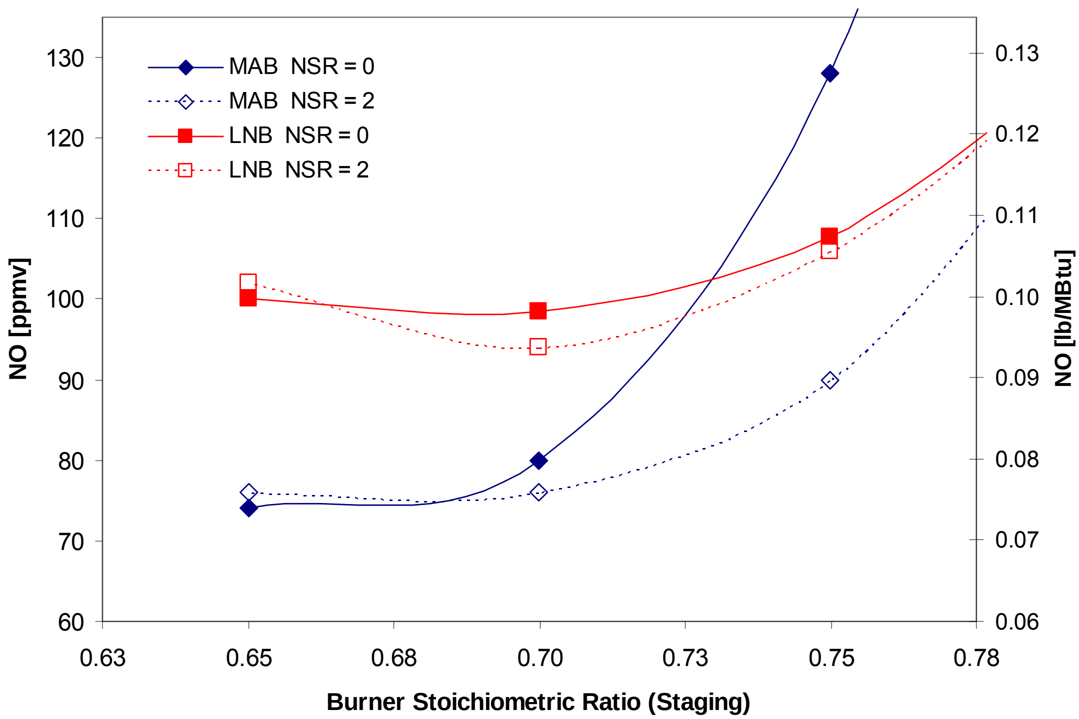


Figure 3-21. Staging curve comparison between the modified ALTA burner (MAB) and the Low-NO_x burner (LNB) with reagent injection in section 3 and OFA in section 5

The NSR curve in Figure 3-18 suggests that more reduction can be achieved with the modified ALTA burner, even at these conditions. Considering the behavior of the LNB with reagent injection in section 3, it is not expected to see any further reduction with increased NSR from this burner.

3.4 CFD Analysis of ALTA Burners and RRI at Utility-Scale

The final task of this project was to apply RRI for NO_x reduction on a full-scale PC boiler using CFD modeling tools. REI has previously modeled a 180 MW_e, front wall-fired, PC boiler including application of RRI. In this effort, RRI was applied at various locations along the rear wall. The level of staging was adjusted, but no other combustion modifications were made. NO_x reduction by RRI was predicted to be less than 10%. The unfavorable modeling results were verified in brief, limited testing of RRI injection at the plant. For this task, the furnace modeling was repeated, this time applying burner and OFA modifications to create a homogeneous, post-flame flue gas.

The full-scale furnace modeled is fired by fifteen burners in three columns and the modified OFA arrangement has six ports. The fire box is divided into three separate cavities by water wall partitions between each of the columns of burners. The geometry of the furnace as modeled is described in Figure 3-22. The burner and OFA port locations are given in Table 3-12. A western bituminous coal was used for the calculations to be consistent with pilot-scale testing.

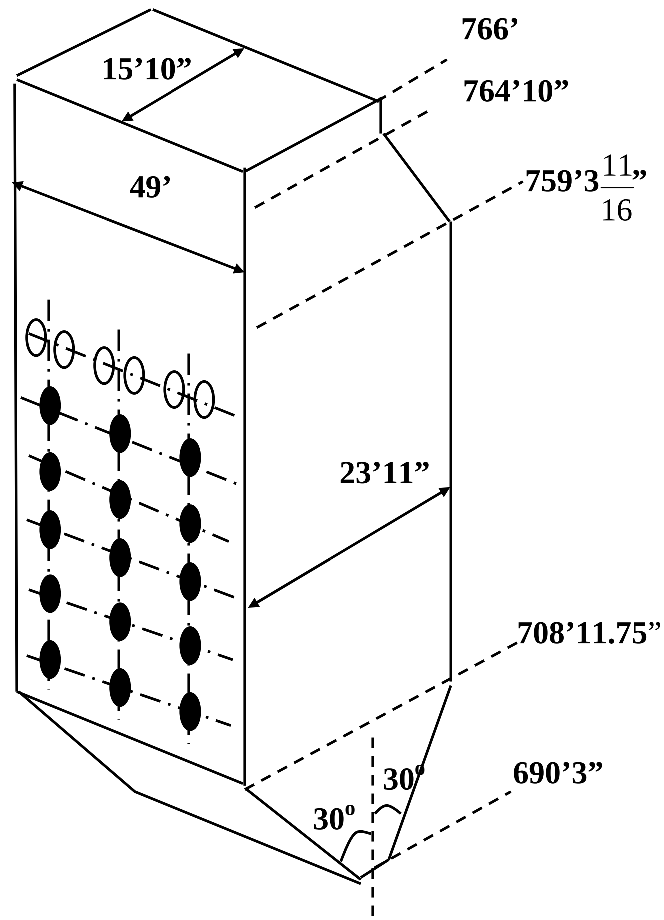


Figure 3-22. Full-scale furnace geometry

Table 3-12. Location of burners and OFA ports

Elevation	Burners	OFA Ports
690' – 3"	Bottom of Furnace	
715' – 0"	3	
721' – 6"	3	
729' – 6"	3	
737' – 6"	3	
744' – 0"	3	
754' – 11"		6

The burners installed and originally modeled in the furnace were dual register, low-NO_x burners, operated at a BSR of 0.9. These burners were replaced with full-scale modified ALTA burners (FMAB) for this modeling effort. The design of the FMAB used in the model was a scale-up of the modified ALTA burner as implemented in the last set of pilot-scale experiments. This burner configuration consists of a bluff body, a secondary air annulus and eight primary "pokers". The size of each of these features was constrained by the size of the opening for the original burner, commercially available materials (schedule 40 pipe) and the burner air distribution used in the original burners. Bluff body and "poker" pipe sizes were chosen such that the primary and secondary air velocities matched those in the pilot-scale modified ALTA burner. The FMAB configuration designed for the full-scale furnace simulations is detailed in Figure 3-23.

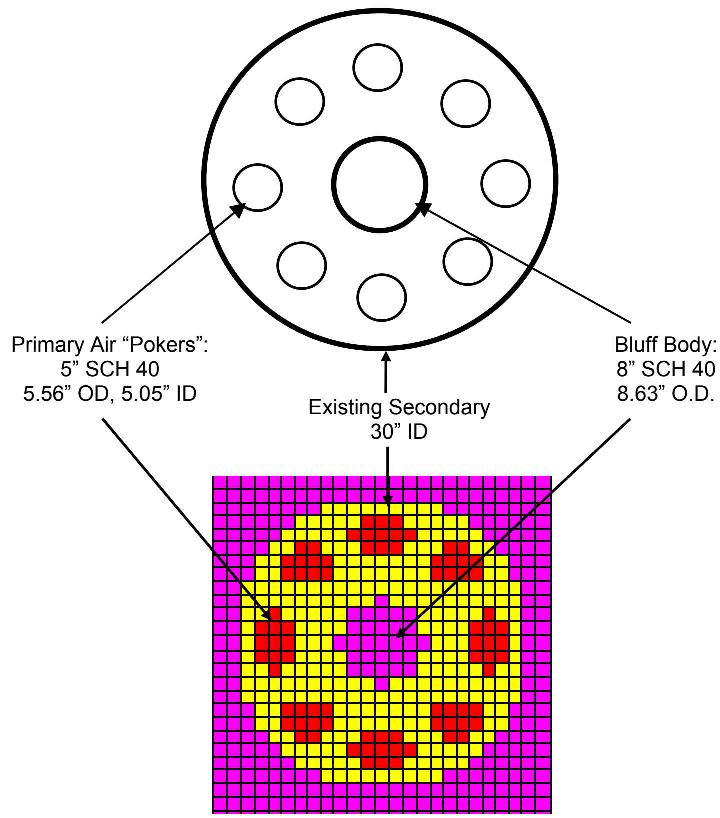


Figure 3-23. Full-scale modified ALTA burner (FMAB) geometry

The swirl in the secondary of the pilot-scale modified ALTA burner was induced by vanes near the burner tip. The same secondary air swirl was applied to the FMAB.

Four furnace configurations were modeled using the FMAB at a BSR of 0.8 – a baseline configuration with no RRI and three reagent injection configurations. This level of staging for the FMAB was chosen because of the excellent performance of RRI at that condition in the pilot-scale testing. The primary air / coal ratio was maintained at 1.8 as in the pilot-scale experiments with the modified ALTA burner. The amount of OFA was determined from the firing rate and assigned BSR, and the remaining air was introduced through the burner secondary. Details of the modeling conditions for BSRs of 0.9 and 0.8 are included in Table 3-13.

Table 3-13. Baseline modeling conditions for full-scale simulation

Parameter	BSR = 0.9	BSR = 0.8
Firing Rate (MBtu/hr)	1,735	1,735
Excess O_2 in Flue Gas (%, wet)	3.3	3.3
Overall Furnace Stoichiometry	1.2	1.2
Lower Furnace Stoichiometric Ratio	0.9	0.8
Total Coal Flow (lb/hr)	144,403	144,403
Total Combustion Air Flow (lb/hr)	1,580,150	1,580,150
Total Primary Air (dry) Flow (lb/hr)	259,925	259,925
Primary Air (dry)/Coal (as rec'd) Ratio	1.8	1.8
Primary Air Temperature (^oF)	130	130
Total Burner Secondary Air (BSA) (lb/hr)	925,506	795,109
Secondary Air Temperature (^oF)	590	590
Total Over Fire Air (OFA) (lb/hr)	394,718	525,116
OFA Temperature (^oF)	590	590
The fraction of OFA in total air	25%	33%
BSA+OFA (wind box air)	1,320,225	1,320,225
The fraction of OFA in (BSA+OFA)	30%	40%

For the three modeling cases performed with reagent injection, the injectors were placed on the rear wall with a six inch extension into the flue gas. An injector was placed on either side of each burner with the expected spray pattern just outside of the flame zone determined from baseline modeling. A 20% urea solution was used and spray characteristics typical of low-energy injection were assumed. The Sauter mean diameter (SMD) of the droplets was assumed to be 100 μm. The injectors were oriented horizontally and the spray pattern was 30° with a full cone.

The first modeling case located injectors at the elevation of the lowest row of burners and the third row from the bottom, for a total of 12. The second case had injectors located at the elevation of the bottom three rows of burners, for a total of 18. The last cases had 24 injectors distributed across the lower four rows of burners. In each of these cases the amount of reagent injected was the same at an NSR of two and the reagent was distributed equally to each injector. The inputs for these three cases are summarized in Table 3-14.

Table 3-14. Urea injection conditions for full-scale simulation

Parameter	Two Level Injection	Three Level Injection	Four Level Injection
Baseline NO_x emission (lb/MBtu)	0.32	0.32	0.32
Firing Rate (MBtu/hr)	1,735	1,735	1,735
NO_x flow rate (lb/hr)	548	548	548
NO_x flow rate (lbMol/hr)	11.9	11.9	11.9
NSR	2.00	2.00	2.00
Pure urea flow rate (lb/hr)	715	715	715
50% urea solution flow rate (lb/hr)	1430	1430	1430
50% urea solution density (lb/gal)	9.5	9.5	9.5
50% urea solution flow rate (gpm)	2.5	2.5	2.5
Urea solution concentration	20%	20%	20%
Urea solution density (lb/gal)	8.8	8.8	8.8
Urea solution density (kg/m^3)	1050	1050	1050
Urea solution flow rate (gpm)	6.8	6.8	6.8
Number of nozzle	12	18	24
Urea flow rate per nozzle (gpm)	0.57	0.38	0.28
Injected Urea soln flow rate per nozzle (kg/s)	0.04	0.04	0.04
Pure Urea flow rate (kg/s)	0.09	0.09	0.09

The predicted NO_x profiles for the FMAB baseline and three RRI injection cases are summarized in Figure 3-24. These results are also tabulated in Table 3-15 and compared to predicted NO_x emissions from the furnace with the existing low-NO_x burners staged at a BSR of 0.9. The existing low-NO_x burners were not simulated at lower BSR and typical furnace excess oxygen of 3.3% since the existing OFA ports are undersized for this condition. Thus, the OFA ports were modified in the FMAB cases to accommodate the higher OFA flow rates required at lower BSR. The simulated OFA configuration was chosen to represent a feasible arrangement, but was not an optimal arrangement with regards to control of LOI or CO emissions. Table 3-15 shows a notable increase in average CO concentrations *at the furnace nose* for the FMAB cases, and a smaller increase in LOI. These values will decrease through the convective section of the furnace. Further optimization of the OFA port configuration could also decrease LOI and CO emissions without significantly impacting the predicted NO_x reduction associated with RRI.

These model results show significant NO_x reduction with FMAB and RRI for all three injection cases. The 2 and 3-Level injection cases show similar NO_x reductions of 33% from the staged FMAB baseline and 28% from typical operating conditions (i.e., no ALTA). The 4-Level Injection case shows additional improvement in NO_x reduction with 41% from the staged FMAB baseline and 37% from typical operating conditions. The predicted ammonia slip was less than 5 ppm (at the furnace nose) for all injection configurations; these ammonia concentrations were expected to decrease to less than 1 ppm by the economizer outlet based on experience with RRI in other boiler simulations.

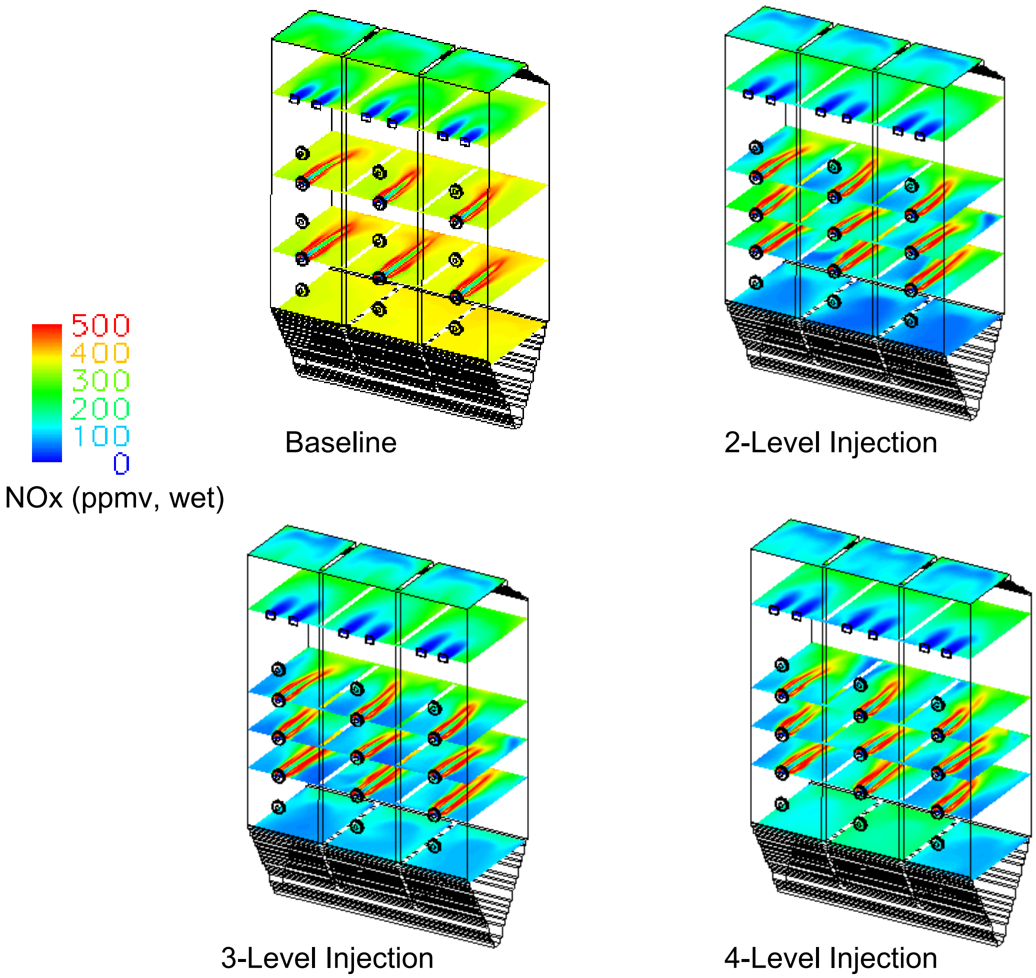


Figure 3-24. NO_x concentration profiles predicted by CFD modeling of full-scale furnace

Table 3-15. Predicted NO_x reduction due to RRI in full-scale furnace

	Existing Burner (SR=0.9)	Modified ALTA Burner (FMAB) (SR=0.8)	2-Level Injection	3-Level Injection	4-Level Injection
NO_x emission (ppmvw)	194	208	139	140	122
NO_x emission (lb/MBtu)	0.295	0.316	0.211	0.213	0.185
NO_x reduction (%) from Existing LNB at BSR=0.9	n/a	-7.1	28.4	27.8	37.1
NO_x reduction (%) from FMAB at BSR=0.8	6.6	n/a	33.2	32.7	41.4
Ammonia Slip (ppmv)	n/a	n/a	2	1	5
CO (ppmvd, furn. nose)	3,020	10,300	10,530	10,510	10,710
LOI (furnace nose)	10%	14%	13%	13%	12%

The results of Table 3-15 suggest that deep staging with the FMAB combined with RRI is capable of producing NO_x levels near 0.185 lb/MBtu on utility-scale boilers. These levels are not below the 0.15 lb/MBtu target, however, combining the RRI performance with the 25%-35% NO_x reduction expected from commercially available SNCR systems suggests that overall NO_x emissions with the full ALTA system (deep staging, RRI and SNCR) could be in the 0.12-0.14 lb/MBtu range, well below the 0.15 lb/MBtu target.

Figure 3-25 and Figure 3-26 show elevation profiles of NO_x rate and NO_x concentration respectively. Figure 3-25 indicates that the NO_x formation from each of the burner rows is considerably greater for the FMAB than for the existing low-NO_x burner. It is also apparent from the NO_x rate profile that the FMAB rapidly creates conditions between the burner rows that are ideal for NO_x reburning, likely an indication of the homogeneity of the gases. This is manifest by the decrease in NO_x flow rate after each of the burner rows for the staged baseline case. In Figure 3-26 it is apparent that the reagent injection at the fourth row of burners causes the 4-Layer Injection case to have significantly higher NO_x reduction. Prior to the fourth elevation of burners each of the three injection cases were similar in NO_x concentration.

The effectiveness of the FMAB in improving the homogeneous, fuel-rich environment in the lower furnace is also illustrated in Figure 3-27. The FMAB case shows more furnace regions at zero or near-zero oxygen concentrations than the existing low-NO_x burner case.

Although NO_x reduction was the key focus of these full-scale modeling studies, model results also provided insights to operational impacts from deep staging with the FMAB. Table 3-16 summarizes the LOI and corrosion behavior for the existing low-NO_x burners at BSR=0.9 and for the FMAB at BSR=0.8. LOI was higher for the FMAB (14% vs. 10% at the furnace nose), however this was somewhat misleading because the FMAB was operated at a lower BSR and the OFA was not optimized for optimal upper furnace mixing. As visible in Figure 3-27, air flow from the LNB OFA ports reaches the furnace rear wall, even "splashing" off the wall into the lower furnace, whereas flow from the FMAB OFA ports did not reach the rear furnace wall, allowing a path for unreacted particles to continue to the model exit. LOI for the FMAB case would be expected to decrease with optimized OFA, but these results also suggest that additional burner design work should be done to optimize LOI performance as part of any FMAB design for commercial application.

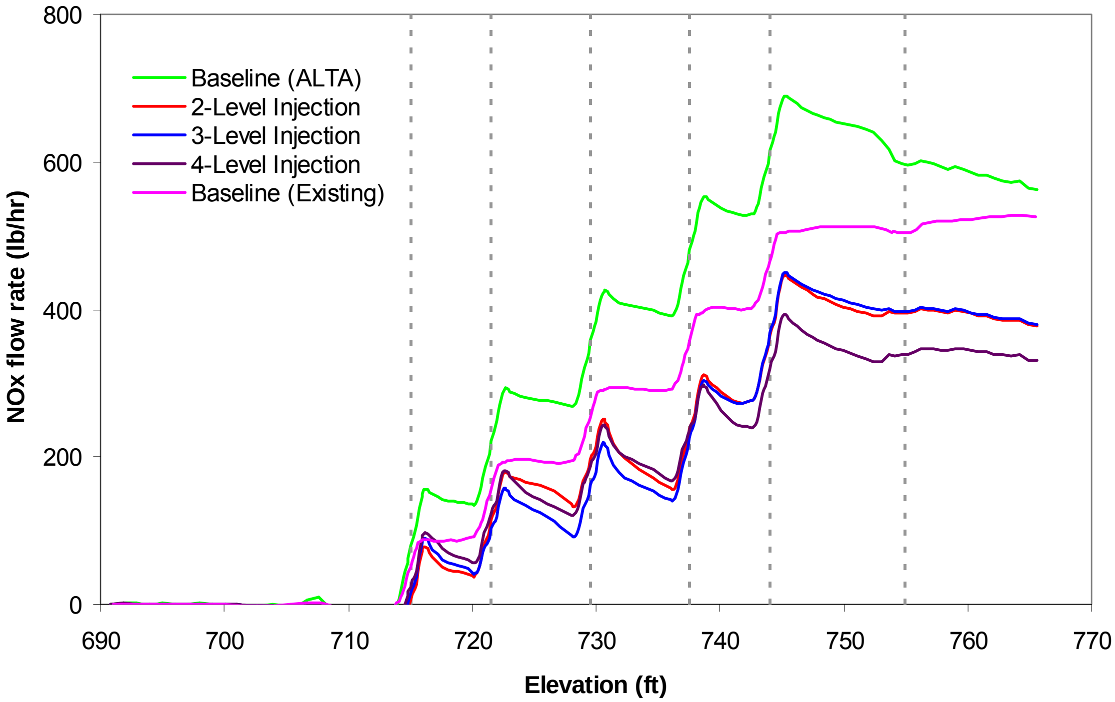


Figure 3-25. CFD predicted NO_x flow rates for various injection schemes

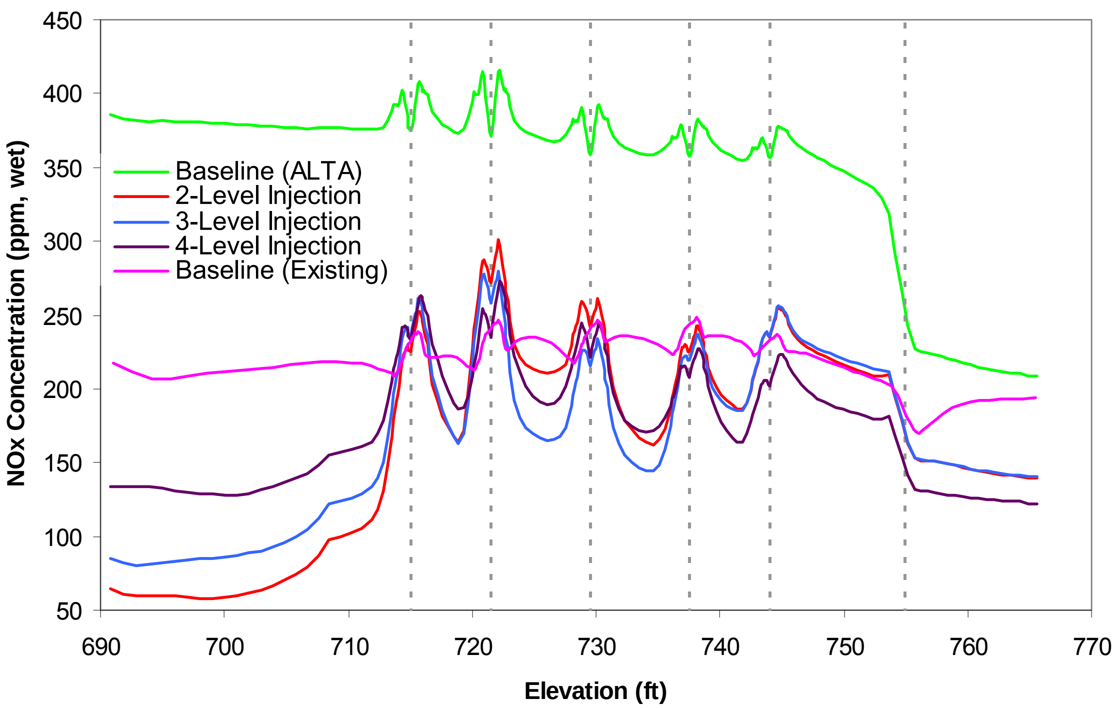
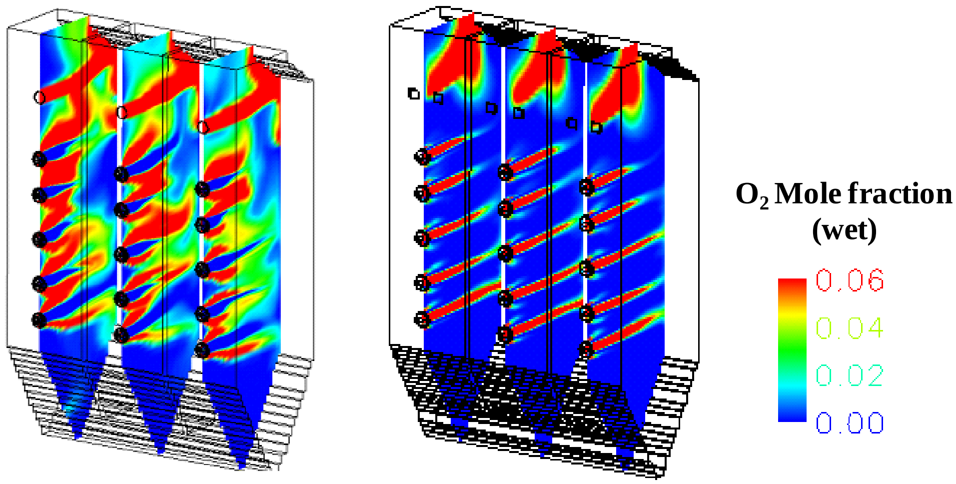


Figure 3-26. CFD predicted NO_x concentrations for various injection schemes



Existing LNB at BSR=0.9 **ALTA burners at BSR=0.8**

Figure 3-27. Predicted oxygen concentrations for existing LNB and FMAB configurations

Table 3-16 also indicates that furnace surfaces were predicted to experience relatively small changes in corrosion rates between operation with the existing LNB and the more deeply staged FMAB. One interesting trend was that the amount of surface area subject to corrosion increased with the FMAB, whereas the peak corrosion rates decreased. This suggested that more unburned particulate material was being deposited on boiler surfaces in the FMAB case, particularly in the OFA region, but that this increase in deposited material was more distributed, resulting in lower peak corrosion rates. The rate of deposition in the burner region was similar for both cases, indicating that the increased deposition was driven by the level of staging and not the burner modifications. The higher deposition of unburned material in the OFA region is consistent with the higher LOI predictions and suggests that optimized OFA may decrease regions exposed to unburned material deposits (and potential corrosion), but that burner modifications may also need to be considered to reduce unburned material leaving the flame zone. Corrosion calculations were based on correlations relating material loss with boiler tube temperature, amount of deposited material, composition of deposited material, and local gas composition.

Table 3-16. Summary of predicted LOI and corrosion rates with LNB vs. FMAB

Parameter	Existing LNB at BSR=0.9		FMAB at BSR=0.8	
	Burner Region	OFA Region	Burner Region	OFA Region
LOI at Furnace Nose (%)		10		14
FeS Corrosion (ft^3/yr)	2.999	1.842	4.121	1.596
FeS Corrosion (mils/yr)	38.242	37.839	42.147	32.024
Total Corrosion (ft^3/yr)	7.107	2.151	9.599	3.544
Peak Corrosion (mils/yr)	42.070	39.423	44.902	32.753

4.0 Simulation and Testing Summary

4.1 Conventional Low-NO_x Burner with Rich Reagent Injection

CFD modeling was performed to determine the feasibility of reducing NO_x with rich reagent injection while firing in a 4 MBtu/hr pilot-scale furnace. These simulations focused on creating a fuel-rich, homogeneous environment for reagent injection using an existing, dual-register, low-NO_x burner (LNB). Predicted results indicated behavior typical for a low-NO_x burner. With much of the burner air introduced through the outer register of the secondary, the gases were stratified and the baseline NO_x concentration was low. When air was moved from the secondary back into the primary, the post-flame gases were more homogenous across the furnace cross section, but the baseline NO_x concentration was high, about 800 ppmv in the post-flame region. Model predictions suggested that RRI would give effective NO_x reduction under these conditions, but that the greater baseline NO_x concentration would offset this reduction, leaving RRI with no advantage over typical operation of the low-NO_x burner.

Pilot-scale experiments showed that at long residence times (where RRI and OFA were in furnace sections 6 and 9, respectively, far from the burner), low-NO_x burner operation (e.g., swirl, primary air ratio, secondary air splits) had little impact on baseline NO_x or RRI performance. However, the extent of staging had a dramatic effect on NO_x. With no RRI, NO_x concentration was 798 ppmv with a BSR of 1.05 and 36 ppmv with a BSR of 0.65. The impact of RRI was favorable at BSRs of 0.85 and 0.95, with reductions in NO_x concentrations of 79% and 56%, respectively, for NSR of 3.0. When the RRI and OFA were moved closer to the burner to represent more realistic residence times (furnace sections 4 and 6, respectively), the effects of burner operation became more apparent and the effectiveness of RRI decreased. This was primarily due to the stratification of combustion gases close to the burner. As the percentage of burner air in the primary increased, the baseline NO_x and the NO_x reduction from RRI increased. This trend was consistent with modeling results and re-emphasized that NO_x can be effectively reduced by RRI in a PC environment; however, conditions where RRI was most effective at reducing NO_x also provided the highest baseline NO_x concentrations. When firing with a typical low-NO_x burner, the final NO_x concentrations were essentially the same when the burner was operated either for low NO_x or for homogeneous conditions with RRI.

4.2 ALTA Burner with Rich Reagent Injection

REI worked with CCA to modify a burner previously used for natural gas to produce a homogenous environment for RRI without such a high penalty in baseline NO_x concentration. The performance of this burner was modeled and tested in the pilot-scale facility.

Modeling of the initial ALTA burner suggested that it would provide a homogeneous environment for rich reagent injection by section 4 of the pilot-scale furnace. In addition, the post-flame uncontrolled NO_x concentration was predicted to be about 450 ppmv, almost half of what was predicted for the high primary, low-NO_x burner (LNB) conditions. These model results were dependent on the assumption that the coal particles were evenly distributed in the primary.

ALTA burner testing showed only minor improvement over the LNB for RRI performance. With RRI and OFA in sections 4 and 6 of the pilot-scale furnace, respectively, and at a BSR of 0.85, the reduced NO_x concentration of 143 ppmv was only a slight improvement over the LNB. Furthermore, the ALTA burner demonstrated similar behavior to the LNB, where high primary air rates were necessary to provide conditions where RRI performance was favorable. This observation was not expected, as homogeneous conditions should have been created even when low primary air rates were used. In addition, as RRI and OFA were moved closer to the burner, the reagent performance dropped off rapidly. This suggested that the ALTA burner was not functioning as expected.

4.3 Modified ALTA Burner with Rich Reagent Injection

Subsequent analysis of modeling and initial ALTA burner testing results showed that the assumption that the coal particles were evenly distributed throughout the primary was not correct for the ALTA burner. At low primary air rates, it was likely that most of the air and coal particles were released through the inner annulus, instead of through the distributed nozzles, or “pokers”. For subsequent testing, the ALTA burner was modified such that the inner annulus of the primary was blocked in order to produce the desired coal distribution. This helped react the coal nearer the burner and provide the most homogeneous conditions close to the burner.

Performance of the modified ALTA burner (MAB) and the low-NO_x burner (LNB) were directly compared with RRI and OFA placed in furnace sections 4 and 6, respectively (4/6 configuration), and again with RRI and OFA placed in sections 3 and 5, respectively (3/5 configuration). Residence time, as represented by RRI and OFA placement, was shown to impact NO_x levels from the burners.

For the 4/6 configuration, the LNB showed 10-30% NO_x reductions with RRI for BSR≥0.75 and no reductions for lower BSR. The MAB showed 20-50% reductions with RRI for BSR≥0.75 and no reductions for lower BSR. NO_x concentrations were similar for LNB without RRI and MAB with RRI over the range of BSRs. Minimum NO_x of 75 ppmv was at BSR=0.70, achieved with both LNB and MAB.

For the shorter residence time 3/5 configuration, the LNB showed no NO_x reduction with RRI whereas the MAB still produced ~50% reduction with RRI for

BSR>0.75. More significantly, the MAB with RRI produced 15-20% lower NO_x than the LNB for BSR≤0.75. Lowest LNB NO_x was 94 ppmv at BSR=0.70; lowest MAB (with RRI) NO_x was 76 ppmv, also at BSR=0.70.

These results suggest that the modified ALTA burner was able to produce a fuel-rich homogeneous environment (favorable to RRI and lower NO_x) near the burner whereas the fuel and air from low-NO_x burner remained stratified for some distance downstream of the burner.

4.4 RRI and ALTA Performance in Full-Scale PC Environment

CFD simulations were performed to predict the effectiveness of deep staging with a full-scale modified ALTA burner (FMAB) combined with RRI on a 180 MW_e, front-wall fired, pulverized coal-fired utility boiler. This furnace had been previously modeled to evaluate the effectiveness of RRI for NO_x control. The results of that past effort suggested no more than 10% reduction in NO_x emission. For this investigation, the existing, dual-register, low-NO_x burners were replaced by FMAB, the OFA ports were modified and the unit was staged more deeply at a BSR of 0.80. Modeling results showed the FMAB was effective in improving the homogeneous, fuel-rich environment in the lower furnace. When four levels of RRI injection were used with a total NSR of 2.0, modeling predicted an average NO_x concentration of 122 ppmv (0.185 lb/MBtu) at the furnace nose, a 37% reduction in NO_x from the existing LNB baseline. This included a 7% increase in baseline NO_x with the FMAB (no RRI) followed by a 41% NO_x reduction from the FMAB baseline with RRI.

Modeling results also suggested that the OFA design should be optimized for this boiler to reduce CO, LOI and corrosion potential due to unreacted material deposits. The predicted three-fold increase in CO concentration at the furnace nose with the deeper-staged FMAB is expected to decrease moving through the convective pass, however, the OFA ports should be optimized to reduce CO concentrations. Such an optimization would also be expected to reduce LOI and corrosion rates. Finally, since it was not the focus of the testing work in this program, the FMAB design should be reviewed for LOI performance before it is scaled-up for commercial use.

The key result from full-scale boiler modeling was that deep staging with the FMAB combined with RRI was capable of producing NO_x levels near 0.185 lb/MBtu on a 180 MW_e utility boiler. Further, combining this performance with the 25%-35% NO_x reduction expected from commercially available SNCR systems suggests that overall NO_x emissions with the full PC-ALTA system could be in the 0.12-0.14 lb/MBtu range, well below the 0.15 lb/MBtu target.

5.0 Assessment of Economic Viability

5.1 Economic Analysis Approach

This section provides a simple economic analysis of the PC-ALTA technology applied to a 180 MW_e utility boiler. The costing values discussed in this section will vary from unit to unit, but should provide a guideline for expected costs for the technology. Economic calculations for application of the FMAB combined with RRI for a pulverized-coal boiler were based on burner pricing estimates from Combustion Component Associates (CCA) and previous RRI pricing estimates from EPRI[6]. NO_x performance was based on CFD simulations of a utility-scale boiler.

Burner and RRI capital costs will be site-specific, but depend primarily upon:

- Boiler dimensions (quantity of burners and injectors, amount of reagent)
- Reagent storage capacity
- Control system complexity (e.g. continuous ammonia monitoring and feedback, furnace exit gas temperature monitoring, atomization air control)

Burner costs include equipment, services, installation and other fees as detailed in Table 5-1. Installation is roughly 0.75 times the burner supply cost. Freight and taxes are location dependent. Vendor contingency and mark-up can vary from 20-30% of equipment and services costs.

Table 5-1. ALTA Burner Capital Cost Components

Equipment Coal Burner Register Coal Pipe From New Elbow To Burner Outlet Coal Distributer Air Balancing Shroud With Electric Drive Throat Ring Throat Former Flame Stabilizer Front Plate With Sight Ports Igniter Guide Pipe Scanner Guide Pipe Thermocouples Coal Balancing Damper	Services Engineering Survey of the Unit Baseline Test CFD Model Design And Engineering Bill Of Materials Control Philosophy Training Support At Site Install Supervision Startup Testing Acceptance Testing Witness
Materials Typically Reused (not included) Scanner Igniter Throat Opening Tube Panel	Additional Costs Installation Freight and Taxes Vendor contingency and mark-up

The basis for a RRI capital cost estimate is typically broken down into the components shown in Table 5-2, and is based upon cost estimating procedures developed by EPRI[6].

Table 5-2. RRI Capital Cost Components

Capital Cost Component	Cost Estimation Detail
Modeling	$80,000 fixed cost, for situations where dynamic similarity from other studies cannot be assumed
Startup & Testing	$200,000 fixed cost (temperature characterization and system start-up optimization)
Reagent Storage (RS)	Reagent storage cost is a linear function of the initial NO_x level and projected NSR
Injection System (IS)	Injection system cost is a function of the unit size, number of wall injectors and/or lance injectors
Compressors (C)	$100,000 fixed cost
Installation	Estimated at 60% of (RS + IS + C)
Total Process Capital (TPC)	Sum of the above costs
Taxes	6% of TPC
Engineering & Procurement	10% of TPC
Field Supervision & In-directs	8% of TPC
Project Contingency	10% of TPC
Vendor Mark-Ups	15% of TPC
Total	Sum of TPC, taxes, engineering, field supervision, contingency, and vendor mark-ups

5.2 Economic Results and Discussion

Based on the above guidelines, capital cost estimates were prepared for a nominal 180 MW wall-fired boiler for ALTA burners, RRI and SNCR (see Table 5-3). SNCR costs were included to provide an analysis of the full PC-ALTA system (i.e., deeper-staged ALTA burners, RRI and SNCR). The ALTA burners and RRI system were estimated to have similar capital costs at $2.55M and $2.75M, respectively. The RRI system assumed an optimized injector configuration that required 12 injectors. Based on modeling experience at REI, this quantity of injectors was expected to be more typical of units this size than the 24 injectors simulated in this project. The approximately $15/kW capital costs for the burners and RRI system are in-line with industry values for units of this size. The SNCR capital cost of $7/kW was lower than normal due to the shared components with the RRI system and the fact that the SNCR system was based on an inexpensive SNCR technology such as SNCR Trim with a single level of injectors at the furnace exit. While this approach to SNCR may not provide maximum reductions, it provides sufficient performance cost-effectively. The estimated capital cost for the ALTA burners and RRI system was $5.3M or $29.5/kW; the estimated cost for a full ALTA system (including SNCR) was $6.56M or $36.4/kW.

Table 5-3. Capital cost estimates for ALTA Burners, RRI and SNCR on a 180 MW wall-fired boiler

	ALTA Burners	**RRI**		**SNCR**	
Boiler Capacity (MW)	180		180		180
Quantity of Burners	15				
Burner Equipment & Services (including contingency & mark-up)	$1,375,000				
Burner Installation	$1,031,000				
Taxes & Freight (6.1%)	$147,000				
Baseline NO_x (lb/MBtu)	0.295		0.316		0.186
Estimated Delta-NO_x	-7%		41%		30%
New NO_x (lb/MBtu)	0.316		0.185		0.130
Modeling			$80,000		included
Startup & Testing			$200,000		$200,000
Reagent Storage			$180,000		Included
Injection System		#Inj		#Inj	
Upper Level Inj.		3		8	$400,000
Mid Level Inj.		3		0	
Lower Level Inj.		6	$600,000	0	
Compressors			$100,000		Included
Continuous Ammonia Monitor			$80,000		Included
Continuous FEGT Monitor (2)			$80,000		Included
Installation			$528,000		$240,000
Total Process Capital (TPC)			**$1,848,000**		**$840,000**
Taxes		6%	$110,880	6%	$50,400
Engineering & Procurement		10%	$184,800	10%	$84,000
Field Supervision & In-directs		8%	$147,840	8%	$67,200
Project Contingency		10%	$184,800	10%	$84,000
Vendor Markups		15%	$277,200	15%	$126,000
Total Estimated Capital	**$2,553,000**		**$2,753,520**		**$1,251,600**
$/kW	**14.2**		**15.3**		**6.95**

Table 5-4 provides a summary of economic calculations for annual cost effectiveness of the RRI and PC-ALTA technologies applied to a 180 MW unit. Calculations assume a baseline NO_x emission level of 0.295 lb/MBtu for a standard low-NO_x burner installation operating at a burner stoichiometric ratio of 0.90. The costs of the ALTA burner and RRI system have been combined since they operate as a set, whereas costs for an add-on SNCR unit have been broken out. For the capacity factor, net heat rate, capital cost recovery factor and NO_x reductions shown in Table 5-4, the annual cost effectiveness of the ALTA burners and RRI system was estimated at $2,391 per ton of NO_x removed. Adding the SNCR system with a 30% NO_x reduction capacity resulted in a total annual cost of $2,152 per ton of NO_x removed. These costs are sensitive to changes in the plant capacity factor (drawn from the NETL database for the unit simulated), capital cost and cost recovery factor (similar to that used in previous costing studies), and reagent costs (which have varied significantly with feedstock prices).

Table 5-4. Cost effectiveness for ALTA Burner, RRI and SNCR on a 180 MW wall-fired boiler with baseline NO_x emissions of 0.295 lb/MBtu

		Burners+RRI	**SNCR**	**Sum**
Capacity (MWe)	180			
Capacity Factor	81%	(from NETL database)		
Baseline NO_x (lb/MBtu)		0.295	0.186	0.130
Net Heat Rate (Btu/kWh)	9850	(from NETL database)		
Heat Input	1773			
NO_x Removal		37%	30%	56%
Annual Tons NO_x Removed		688	350	1039
Capital Cost Recovery Factor	12.50%			
Capital Cost		$5,307,020	$1,251,600	$6,558,620
Annual Levelized cost		$663,378	$156,450	$819,828
Reagent Cost		$982,488	$432,687	$1,415,175
Annual Cost Estimate		$1,645,866	$589,137	$2,235,003
Annual Operation ($/ton NO_x)		**$2,391**	**$1,682**	**$2,152**
Reagent Cost ($/gal)		0.90	0.90	
NO_x Basis for NSR		0.316	0.186	
NSR		2.0	1.5	
50% Reagent Requirement (gph)		153.8	67.8	

One interesting result from this study was that neither the existing LNB technology combined with SNCR nor the ALTA burner combined with RRI was able to reduce NO_x levels below 0.15 lb/MBtu. Reaching this target required both the RRI and SNCR reductions. Although the ALTA burners and RRI technologies are a relatively expensive combination compared to LNB alone, they are an essential component of the layered PC-ALTA technology which combined can achieve the 0.15 lb/MBtu target.

One of the program objectives was to compare the cost effectiveness of the PC-ALTA NO_x control technology to SCR costs. The SCR numbers presented here were taken from a recent report by Cichanowicz[7]. That report notes that SCR capital costs have increased significantly over the past 10-15 years, particularly for smaller MW units, whereas catalyst costs have decreased. The overall trend is toward more expensive SCR installations due to a number of factors including materials, labor and difficulty of design. Allowing for the sensitivity to capital costs and reagent costs, estimated SCR cost effectiveness of $3000/ton of NO_x removed appears reasonable for the subject 180 MW unit firing bituminous coal (this cost increases to ~$5,000/ton for units firing PRB). The estimated cost effectiveness of the full PC-ALTA technology ($2152/ton NO_x) is less than 75% of such an SCR system.

6.0 Summary and Conclusions

Completion of the pilot-scale testing and CFD modeling in this program has achieved the project objectives and led to the following conclusions:

- The chemistry for reducing NO_x by RRI has been proven to work effectively in a pilot-scale PC environment, indicating no fundamental issues prohibiting application of ALTA on PC furnaces. However, results from the pilot-scale testing suggest that simple adjustments in traditional LNB operation and staging alone may not provide conditions necessary to reduce NO_x with RRI.
- The ALTA burner design successfully mixed coal and burner air rapidly, while maintaining velocities necessary for flame stability. This configuration produced homogeneous combustion gases suitable for NO_x reduction by RRI in close proximity to the burner, a region where RRI was not effective when used with the low-NO_x burner.
- For the shortest burner-to-RRI/OFA configurations tested, the combination of the ALTA burner with RRI produced NO_x reductions of 50% from baseline levels without RRI. Further, the ALTA burner with RRI produced NO_x concentrations 15-20% lower than a traditional low-NO_x burner for burner stoichiometric ratios (BSR) of 0.75 and lower.
- For BSR≥0.90, the baseline NO_x levels for the ALTA burner were so high that even with 50% RRI reduction there appeared to be no advantage to using the ALTA burner and RRI over the low-NO_x burner. This reinforces that the ALTA concept is best suited to deep staging (BSR<0.85) applications.
- Full-scale boiler modeling showed that deep staging with the modified ALTA burner combined with RRI was capable of producing NO_x levels of approximately 0.185 lb/MBtu on a 180 MW_e utility boiler. Further, combining this performance with the 25%-35% NO_x reduction expected from commercially available SNCR systems suggests that overall NO_x emissions with the full PC-ALTA system could be in the 0.12-0.14 lb/MBtu range, well below the 0.15 lb/MBtu target.
- These results indicated that the burner behavior and mixing principles learned in pilot-scale testing were applicable in a utility-scale, multiple burner configuration. Evidence of this was the predicted 37% reduction in NO_x emissions with RRI for this unit, compared to 10% from previous best efforts.
- Based on predicted NO_x reduction performance in a 180 MW unit, cost effectiveness of RRI with modified ALTA burners was $2,391/ton NO_x removed. Cost effectiveness of a full PC-ALTA system (deep staging with ALTA burners, RRI and simple SNCR) was estimated at $2,152, which met the project objective of being less than 75% of estimated SCR costs (estimated at $3,000/ton NO_x for this unit).

7.0 Recommendations

The next step toward commercialization of the PC-ALTA technology is to establish a demonstration project at a small utility boiler where the ALTA burners, OFA system, RRI injectors and SNCR system can be optimized using CFD and demonstrated in the unit. As part of this demonstration, additional research should be conducted on the ALTA burner design to ensure unburned carbon-in-ash and corrosion effects are minimized. Although these effects should be minimal for a rapid-mixing burner, they were not studied in-depth in this program. Also, there may be alternative and less intrusive modifications to a multi-burner array that can create conditions necessary for NO_x reduction by RRI. These options should be investigated through CFD modeling before demonstration at full-scale.

8.0 References

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