Assessment of Enhanced Rich Reagent Injection Performance

Reagent Atomization with Natural Gas or Nitrogen

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Technical Update, February 2008

EPRI Project Manager

R. Himes

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

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Reaction Engineering International
77 West 200 South, Suite 210
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Principal Investigator
A. Fry

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PRODUCT DESCRIPTION

Rich reagent injection (RRI) is an alternative for in-furnace NO_x control. In this process, an amide reagent, typically urea, is injected into the fuel rich region of the furnace to accelerate the rate of NO_x reduction through the reaction of NO with NHi and HNCO/NCO to form N_2. In pulverized coal boilers with low-NO_x burners (LNBs) pockets of oxygen rich gas may consume the reagent without achieving any NO_x reduction benefit. This project studied the use of either an inert atomization medium or natural gas to consume oxygen in the atomization air and enhance the NO_x benefits of RRI.

Background

Introduction of the amide reagent into the boiler is generally achieved using injection lances with a two-fluid nozzle at the tip. A concentrated, aqueous solution of urea is atomized using pressurized air. The mass ratio of gas to liquid used in these injections systems is typically 0.8 or less. With air typically used as the atomization medium for RRI, it is necessary to know the conditions where the oxygen in the injection gas limits the effectiveness of RRI. Using an inert atomization medium or introducing natural gas to consume oxygen in the atomization air may enhance the NO_x benefits of RRI.

Objectives

To determine the impact of atomization gas composition on RRI for NO_x reduction in coal combustion systems.

Approach

The project team conducted tests on the pilot-scale pulverized coal fired furnace at the University of Utah Combustion Research Center. The first set of experiments examined the effect of reagent dilution at the injection lance and oxygen content of the atomization gas. A second round of experiments detailed the reduction of NO with RRI while using a stoichiometric mixture of air and methane as the atomization gas. The team also performed computational fluid dynamics (CFD) modeling to further investigate the impact of O_2 to urea ratio on NO_x reduction with RRI.

Results

The experimental data indicate that maximum reagent utilization and NO_x reduction by RRI occur when no O_2 is present in the injection atomization gas. However, model predictions indicate that at O_2 to urea ratios of less than 0.62, there is no negative impact of O_2 on NO_x reduction by RRI. An inert gas such as nitrogen or recycled flue gas may be used as the atomization gas for RRI to achieve the maximum benefit of RRI. In applications where utilization of an inert gas is not possible, the mass ratio of O_2 to urea should be limited to less than one, through appropriate nozzle selection, liquid reagent concentration, and gas to liquid ratio.

It was also demonstrated that adding methane to the atomization air in a stoichiometric ratio would consume the oxygen. For these conditions NO_x reduction by RRI was almost as great as when atomizing with nitrogen. Using predominantly methane as the atomization gas was attempted in one experiment. It was expected that this might help overcome burner stratification and enhance RRI. The amount of methane added represented nearly 5% of the total pilot-scale furnace heat input, however; and the results are not viewed as representative.

EPRI Perspective

While natural gas may be used in stoichiometric ratios with air as the atomization gas to remove the adverse effects of O_2 on RRI, site-specific economics should be evaluated to determine its overall cost effectiveness. More investigation is required where the atomization gas is operated with a slightly fuel rich ratio of methane with air. These conditions may provide some benefit in the presence of stratified combustion gases for RRI.

Keywords

NO_x reduction
Rich reagent injection (RRI)
Cyclone boilers
Low NO_x burners

ABSTRACT

Rich reagent injection (RRI) is a NO_x control method in which an amide reagent is injected into the fuel rich region of a coal-fired furnace to accelerate the rate of NO_x reduction through reactions that form N_2. RRI technology has been demonstrated on cyclone boilers to achieve NO_x emission rates at or below 0.12 lb/MMBtu when combined with overfire air (OFA) and selective non-catalytic reduction (SNCR). Pockets of oxygen rich gas or oxygen introduced with the atomization air, however, can consume the reagent without achieving any NO_x benefit. Experiments at the pilot-scale combustor at the University of Utah Combustion Research Center were conducted to elucidate potential impacts of the use of atomization air in twin fluid atomizers for injecting reagent in the RRI process. In addition, the use of an inert atomization medium or introducing natural gas to consume oxygen in the atomization air were investigated for their potential in enhancing the NO_x benefits of RRI. Computational fluid dynamics (CFD) modeling was also performed to further investigate the impact of atomization air O_2 to urea ratio on NO_x reduction with RRI.

The experimental data indicate that maximum reagent utilization and NO_x reduction by RRI occur when no O_2 is present in the injection atomization gas. However, model predictions indicate that at O_2 to urea ratios of less than 0.62, there is no negative impact of O_2 on NO_x reduction by RRI. An inert gas such as nitrogen or recycled flue gas may be used as the atomization gas for RRI to achieve the maximum benefit of RRI. It was also demonstrated that adding methane to the atomization air in a stoichiometric ratio would consume the oxygen. For these conditions NO_x reduction by RRI was almost as great as when atomizing with nitrogen.

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1
INTRODUCTION

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 high capital investment required limits its applicability to larger capacity boilers. 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 so as to delay the mixing of air with fuel-rich regions, limiting the formation of NO_x. LNBs may be coupled with overfire 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 for added NO_x reduction. Urea is introduced in the upper furnace to react with NO to form N_2 without an accelerating catalyst.

An additional alternative for in-furnace NO_x control, similar to SNCR, is rich reagent injection (RRI). RRI requires the promotion of a deeply staged and homogeneous lower furnace, with a stoichiometric ratio in the region of 0.9 to 0.65. An amide reagent, typically urea, is injected into this fuel rich region in the furnace to accelerate the rate of NO_x reduction through the reaction of NO with NHi and HNCO/NCO to form N_2. Application of RRI requires complex optimization of the combustion and layering configuration and strategic placement of reagent injection location to target appropriate stoichiometry and temperature regions in the furnace. RRI technology has been demonstrated on cyclone boilers to achieve NO_x emission rates at or below 0.12 lb/MMBtu1.

Cyclone units provide an ideal environment for RRI, because the coal is devolatilized and partially combusted in the cyclone barrels, before it enters the furnace. When staged, this environment is fuel rich, hot and near homogeneous, providing all of the characteristics necessary for NO_x reduction by RRI. RRI has not previously been applied to a pulverized coal unit. Typical operation of burners in a pulverized coal unit, especially low- NO_x burners, delays the mixing of fuel and air and results in stratification of the combustion gases. Particle residence time and char burnout are also important considerations for the application of RRI in a pulverized coal 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 fuel from the char particles has reached the gas phase. For application of RRI to a pulverized coal unit, a hot, rich and homogeneous environment must be developed quickly to allow RRI to be applied prior to the introduction of OFA and the burnout zone.

Pilot-scale experiments have been performed to investigate the applicability of RRI in a pulverized coal environment2. The homogenization of near-burner combustion gases has been promoted through modifications to burner design and operation. These experiments have demonstrated that RRI is capable of reducing NO_x emission from a pulverized coal boiler, even below what can be achieved with low- NO_x burners and staging alone. The effects of stratification of combustion gases have also been investigated. When the burner is operated to produce homogeneous conditions at the injection conditions, up to 78% reduction in NO_x can be achieved. When the low- NO_x burner is operated to delay mixing of the fuel and air, conditions typical of a low- NO_x burner, no reduction of NO_x is realized with RRI. This indicates that pockets of oxygen rich gas consume the reagent without achieving any NO_x benefit.

Introduction of the amide reagent into the boiler is generally achieved using injection lances with a two-fluid nozzle at the tip. A concentrated, aqueous solution of urea is atomized using pressurized air. The mass ratio of gas to liquid used in these injections systems is typically 0.8 or less. With air typically used as the atomization medium for RRI, it is necessary to know the conditions where the oxygen in the injection gas limits the effectiveness of RRI. Using an inert atomization medium or introducing natural gas to consume oxygen in the atomization air may enhance the NO_x benefits of RRI. These techniques may also have some ability to overcome oxygen-rich pockets of near burner stratification. Experiments to elucidate these effects have been performed at pilot-scale and are presented here.

2
EXPERIMENTAL

The pilot-scale combustor at the University of Utah Combustion Research Center is a pulverized coal fired furnace that was designed to simulate low emission, pulverized coal-fired boilers. This unit has contributed to 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 (1 meter), square cross section and is approximately 46 feet (14 meters) in length. The length is divided into ten 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. A schematic of the pilot-scale combustor is shown in Figure 2-1 with some of its features, test locations, and sample locations detailed.

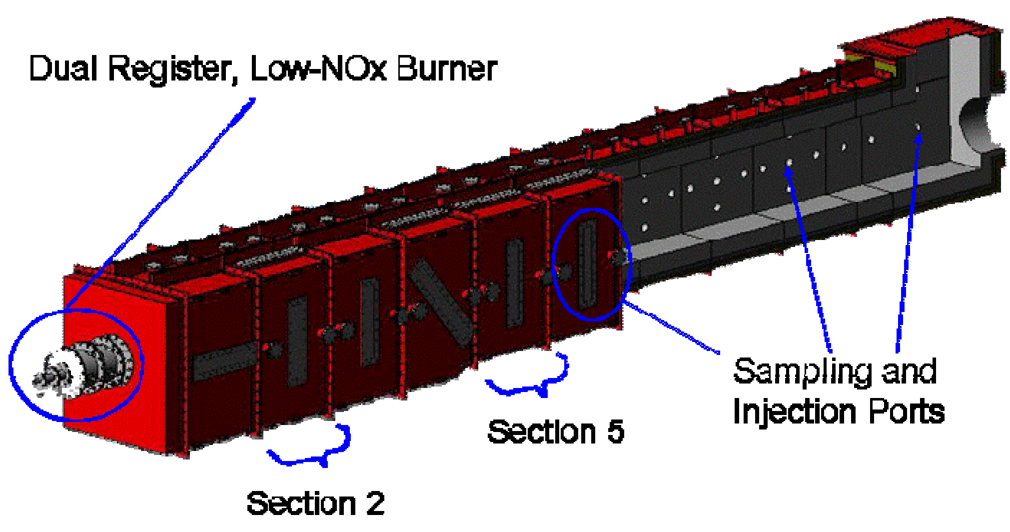

Figure 2-1
Schematic of Furnace Section of 4 MBtu/hr Pulverized Coal Combustion Test Facility

The furnace has a dual-register, dual-swirl burner that is 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 is able to operate across a range of primary air flows, down to air / fuel ratios of less than 1.5. The remainder of the burner air may be split between the inner and outer registers of the secondary, each with its own swirl settings. The air for the primary and the two secondary registers was supplied from two separate blowers. Each of the flows is metered using a v-cone and controlled with a valve. 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. The coal is supplied at a measured mass rate to an eductor to be entrained by the primary air. For these experiments the burner was not operated at conditions for optimal NO_x emission, but was adjusted to provide homogeneous, near-burner combustion gases for NO_x reduction by RRI.

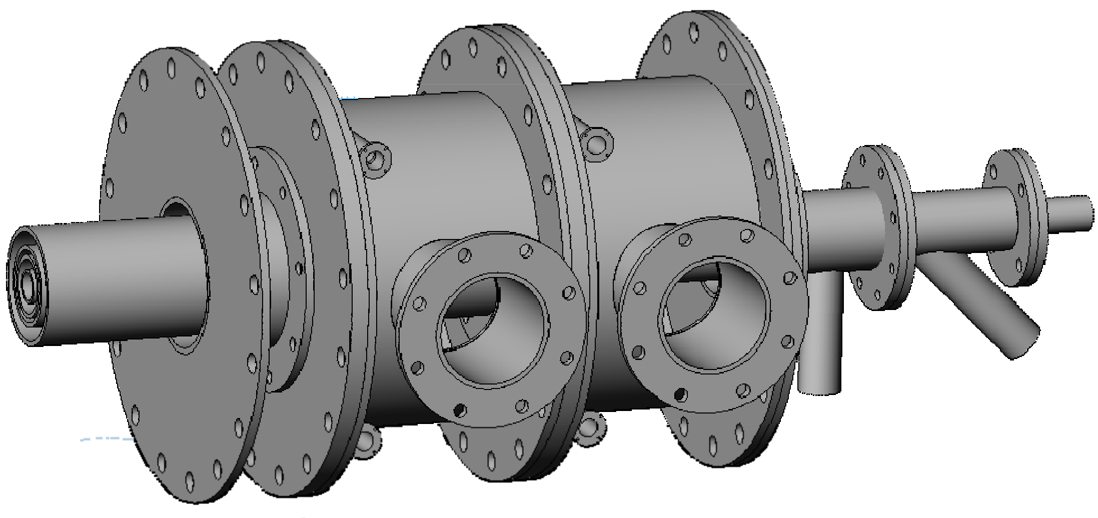

Figure 2-2
Moveable Block Swirl Burner used on Pilot-scale Facility

The combustion air can be preheated up to 800°F (427°C). 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.

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 ten 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. Figure 2-4 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 pulverized coal furnace. The average particle residence times, however, 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.

Table 2-1
Skyline Coal Analysis

Parameter	Feedstock
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	12,407
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

Table 2-1 (continued)
Skyline Coal Analysis

Parameter	Feedstock
Reducing Ash Fusion Temperature (˚F)	
Initial	2,118
Softening	2,189
Hemispheric	2,286
Fluid	2,469
Oxidizing Ash Fusion Temperature (˚F)	
Initial	2,193
Softening	2,250
Hemispheric	2,364
Fluid	2,545

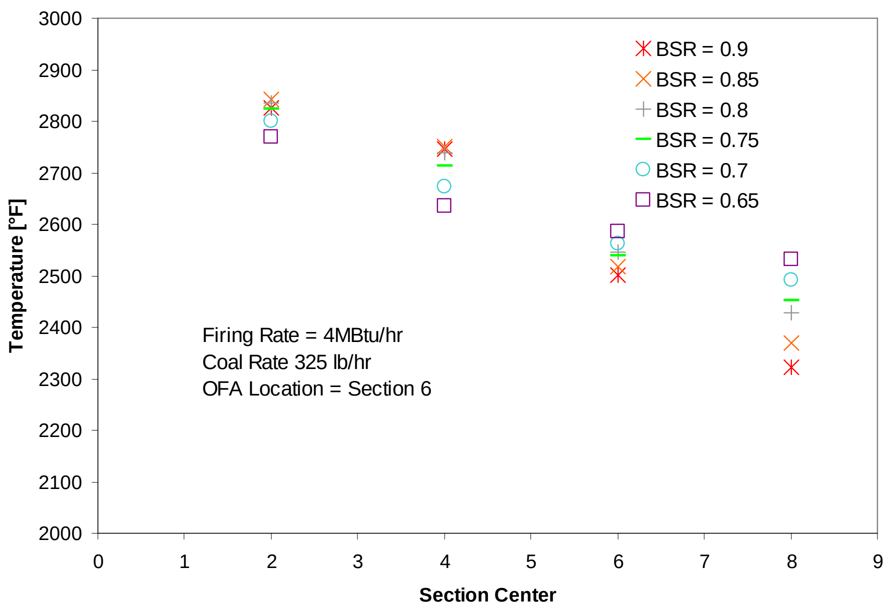

Figure 2-3
Temperature Profiles of the Pilot-Scale Furnace as a Function of Staging while Firing at 4 MBtu/hr

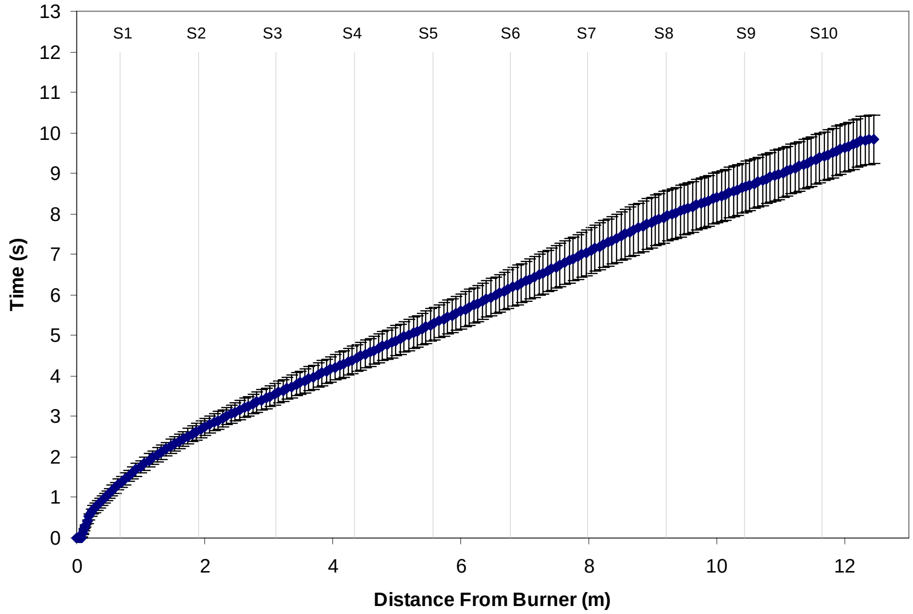

Figure 2-4
Predicted Average Gas Residence Time Profile in Pilot-Scale Furnace

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 Spraying Systems Model SU26 two-fluid nozzles, 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 three, 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 (15 lph) and the total nitrogen flow rate was held at 200 scfh (5.7 scmh). A representation of one of the two identical nozzles is contained in Figure 2-5.

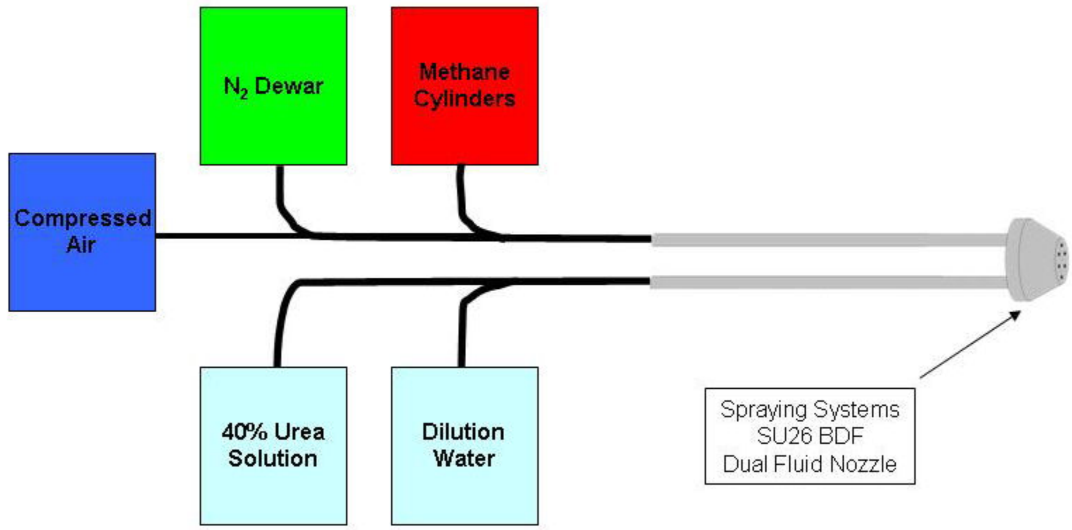

Figure 2-5
Rich Reagent Injection System Schematic

For these tests, reagent was injected into Section 4 and OFA was introduced into Section 6. CFD modeling shows that average particle residence times are 0.5 seconds to Section 4 and 1.4 seconds to Section 6. The short particle residence times from the burner to the OFA were representative of residence times found in commercial units. To provide the appropriate conditions for RRI, the reactor was operated at elevated temperatures, approaching a 2900°F (1593°C) wall temperature in Section 2. The wall temperature of Sections 2, 4, 6 and 8 were recorded and are presented in Figure 2-6. The data presented are the average temperatures for all operating conditions and the standard deviation is represented by the error bars.

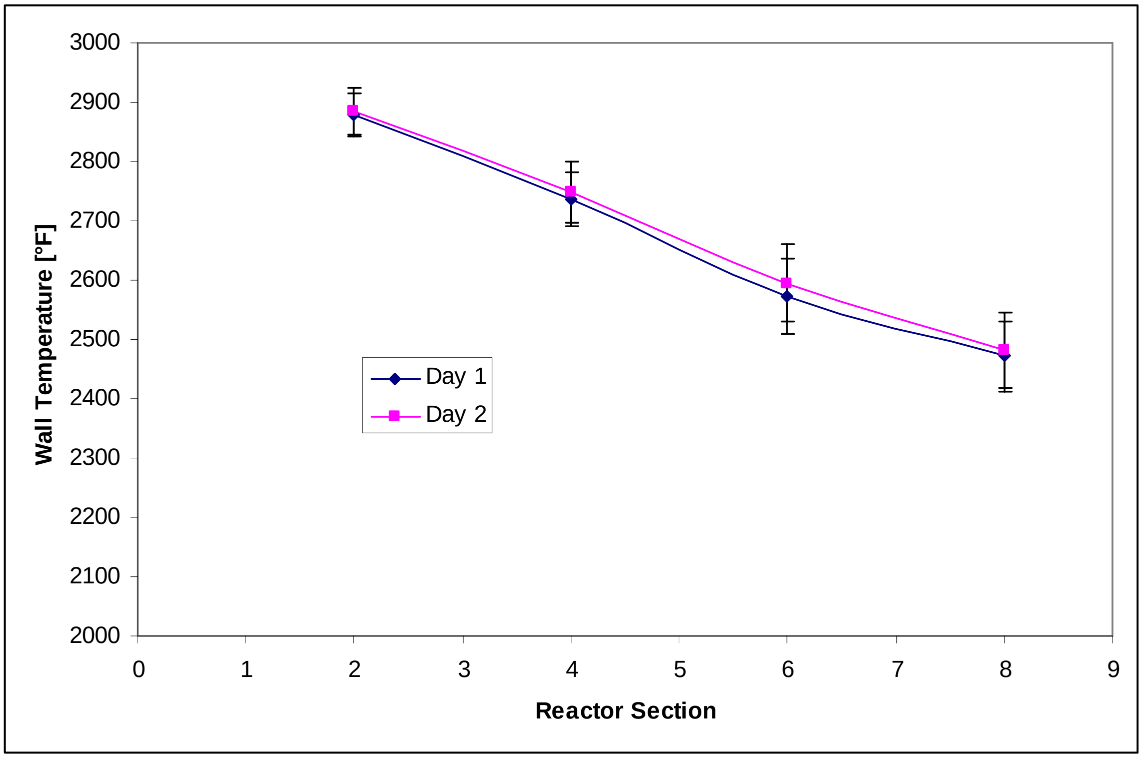

Figure 2-6
Wall Temperature Profile in the Pilot-Scale Facility with Current Test Conditions

3
RESULTS

The LNB was operated at conditions that were favorable for NO_x reduction by RRI. Coal was fired at a rate of 320 lb/hr with a primary air to fuel mass ratio of 1.8. The secondary air was split between the registers with 66% in the inner and the remainder in the outer. The swirl was set to zero for both of the secondary registers. For these conditions, baseline NO_x concentration was in the range of 150 ppmv to 180 ppmv, which corresponds to approximately to 0.15 to 0.18 lb/MBtu.

The first set of experiments examined the effect of reagent dilution at the injection lance and oxygen content of the atomization gas. For these experiments, the mass ratio of atomizing gas to liquid injected was maintained at 0.8. For urea concentrations in solution of 9 and 13 weight percent, the atomization gas mixture was varied from total nitrogen to total air, spanning a range of 0 to 21 volume percent oxygen in the atomization gas. The results of these experiments are presented in Figure 3-1.

Maximum NO reduction is represented by cases where there is no oxidant in the atomization gas. As the O_2 concentration in the atomization gas increases, the NO reduction decreases. This indicates that the reagent is being consumed by O_2 instead of consuming NO, as intended. The effect of O_2 on reduction through RRI is more pronounced at lower urea concentrations. When urea is more diluted from the original 40 weight percent solution at the injection lance, and the gas to liquid ratio is maintained, the oxidant to reagent ratio is increased. These data indicate that while gas to liquid ratio is important for proper atomization, oxidant to reagent ratio may have a great effect on reagent utilization.

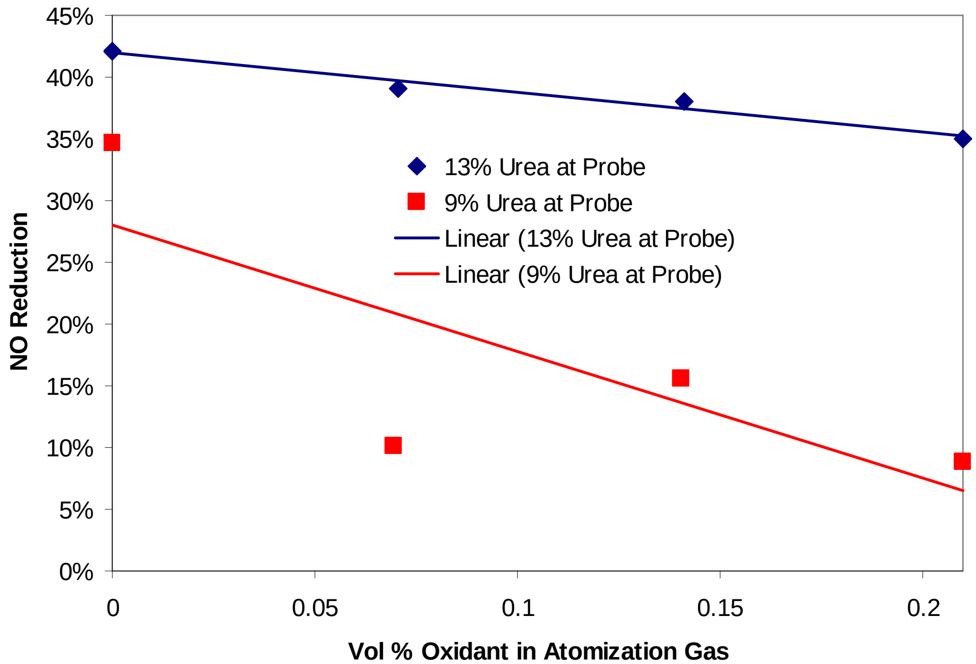

Figure 3-1
NO_X Reduction by RRI as a Function of O_2 and Urea Concentrations in the Injection Stream

The second round of experiments detailed the reduction of NO with RRI while using a stoichiometric mixture of air and methane as the atomization gas. For these experiments, a baseline NO concentration was recorded. RRI was then introduced at an NSR of 2 with nitrogen as the atomization gas. Nitrogen was then replaced with air and then with a stoichiometric mixture of air and methane. The reagent was then removed while the air and natural gas were continued. The final condition was a baseline with air injection and no reagent. For these experiments, the injection gas to liquid mass ratio was maintained at 0.8 and the urea concentration at the injector was diluted to 5 weight percent. At these conditions we would expect the ratio of oxidant to reagent to significantly impact the NO reduction by RRI. The results of these experiments are presented in Figure 3-2.

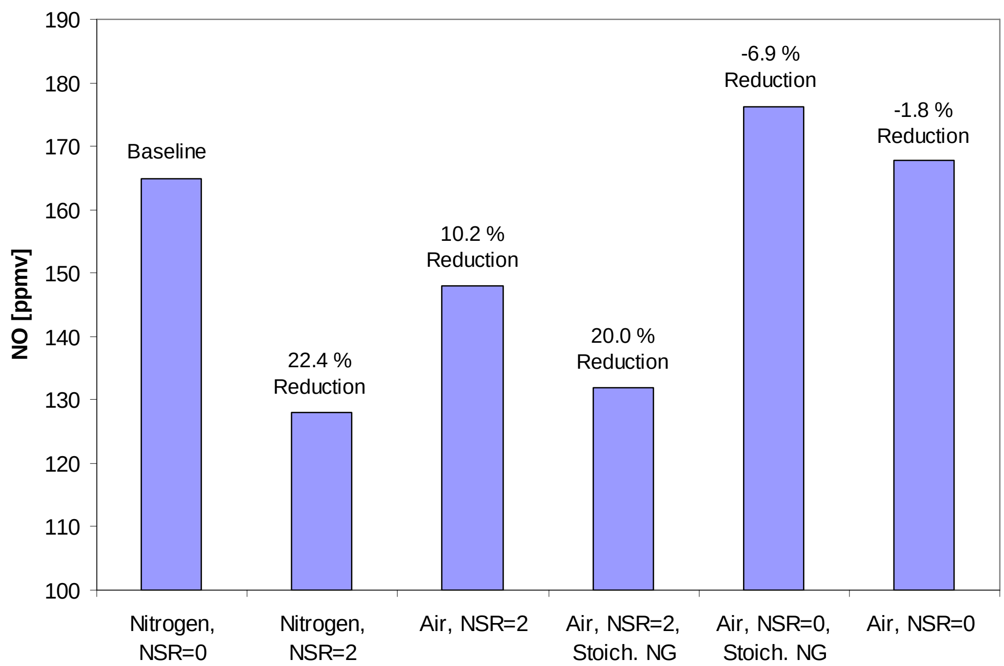

Figure 3-2
NO Concentrations While Using Various Atomization Gases - Including Nitrogen, Air and a Stoichiometric Mixture of Air and Methane

Figure 3-2 shows that the maximum NO reduction of 22.4% occurs when nitrogen is used as the atomization gas. Using air as the atomization gas limits the NO reduction to only 10.2%. Introducing methane at a stoichiometric ratio consumes the O_2 in air and returns the NO reduction almost back to the maximum at 20.0%. Operating the injector without reagent, but with the mixture of methane and air, increases the NO above its baseline value. The baseline across the range of conditions tested remained unchanged.

In the first set of experiments, represented in Figure 3-1, the total gas flow was varied from 142 scfh for the 9 weight percent urea condition to 125 scfh in the 13 weight percent condition. This represents a turndown of the nozzle and may have independent impact on NO reduction. No information on the impact of turndown on atomization and droplet size distribution was available from the nozzle manufacturer. The 142 scfh total atomization gas flow is on the low end of the range recommended by the manufacturer. Experiments were performed to determine the effect of nozzle turndown on NO reduction. For these experiments, the mass ratio of gas to liquid was maintained at 0.8. The NSR was held constant at a value of two while the total gas and dilution water was reduced. The results of this experiment are presented in Figure 3-2.

Figure 3-3 details the profound impact of nozzle turndown on NO_x reduction by RRI. This effect may be explained by two causes. Turndown also impacts reagent penetration into the combustion gasses and may impact droplet-size distribution. This experiment suggests that there should be a difference in NO_x reduction, due to turndown, by only 2% between the two experimental conditions detailed in Figure 3-3.

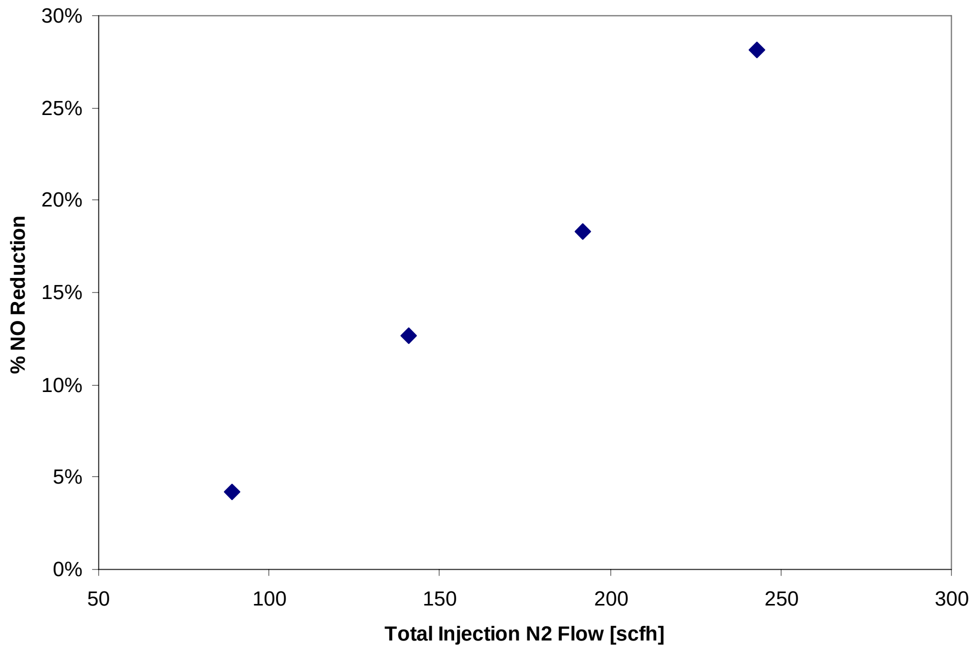

Figure 3-3
NO_X Reduction as a Function of Nozzle Turndown

4
MODELING

Computational fluid dynamics (CFD) modeling was performed to further investigate the impact of O_2 to urea ratio on NO_x reduction with RRI. This modeling was performed using REIs proprietary reacting CFD code, Glacier. The pilot-scale furnace conditions described in section 3.0, without reagent injection, were modeled and used as baseline for several injection scenarios. The predicted NO_x profile in the furnace for the baseline conditions is presented in 4-1. In this figure, a profile plot is presented for the axial NO_x distribution in a vertical plane through the furnace. There are also two cross sectional planes detailed which are upstream of the reagent injection location and downstream of the OFA. For all subsequent modeling, solutions were generated for only the region between these two planes. The initial conditions at the inlet plane were assigned from baseline modeling results. In addition, this region was split in two, by a vertical symmetry plane running axially down the center of the furnace. These steps were implemented to reduce the computational investment.

The droplet size characterization from the Spraying Systems nozzle is unknown to the vendor. To determine a reasonable characterization for modeling, the droplet size distribution was adjusted in the model inputs for constant injection conditions used in the experiment. From these computations, it was determined that a droplet size with the Sauter Mean Diameter (SMD) of 50 •m produced NO_x reduction that was observed in the experiments. This droplet size was then held constant while varying the ratio of air and nitrogen used for atomization. The four injection conditions investigated are summarized in Table 4-1. These conditions cover a range of O_2 to Urea mass ratios that were used in the experimental investigation.

The results of modeling for each of the conditions presented in Table 4-1 are summarized in Table 4-2. The predicted distribution of NO_x for each of these cases is presented in Figure 4-2 and reagent distribution is exhibited in Figure 4-3.

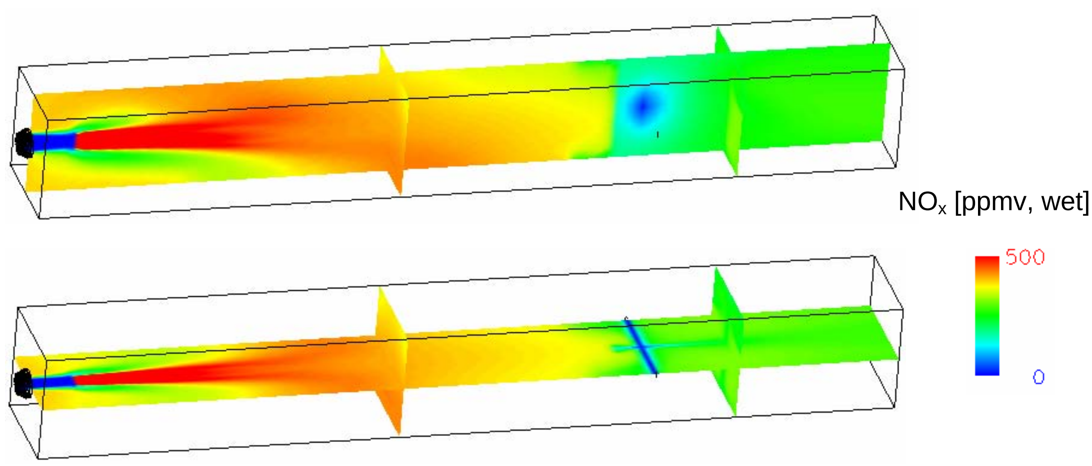

Figure 4-1
Predicted Baseline NO Profile in the Pilot-scale Furnace

Table 4-1
Reagent Injection Conditions Used for Modeling

Case	Uncontrolled NO_x [lb/MBtu]	Section of RRI	Section of OFA	NSR	Urea Conc. In Solution [% Mass]	Urea Solution Flow [gph]	Urea Droplet SMD [mm]	Atomization Gas Flow [scfh]	Gas/Liquid [mass ratio]	Air in Gas [mass fraction]	O_2/Urea [mass ratio]
1	0.37	4	6	2.0	8.9%	2.52	50	240	0.80	0.0	0.00
2	0.37	4	6	2.0	8.9%	2.52	50	240	0.80	0.3	0.62
3	0.37	4	6	2.0	8.9%	2.52	50	240	0.80	0.7	1.45
4	0.37	4	6	2.0	8.9%	2.52	50	240	0.80	1.0	2.08

Table 4-2
Summary of Modeling Results

	Case 1	Case 2	Case 3	Case 4
Baseline NO_x concentration [ppm, wet]	236	236	236	236
Baseline NO_x emission [lb/MBtu]	0.367	0.367	0.367	0.367
RRI NO_x concentration [ppm, wet]	136	131	156	196
RRI NO_x emission [lb/MBtu]	0.212	0.204	0.242	0.306
RRI NO_x Reduction	42.3%	44.4%	34.0%	16.7%
RRI NH_3 slip [ppm, wet]	0.0	0.0	0.0	0.0

The data presented in Table 4-2 show that the O_2 to urea ratio has significant bearing on the effectiveness of RRI for NO_x reduction. However, for ratios below at least 0.62, NO_x reduction by RRI was reasonably flat. Increasing from an O_2 to urea mass ratio of 0.62 to 2.08 curbed the NO_x reduction by nearly 28%. Figure 4-3 indicates that as the O_2 to urea ratio increases from 0.62 to 2.08, the reagent is consumed more rapidly, likely through reactions with O_2.

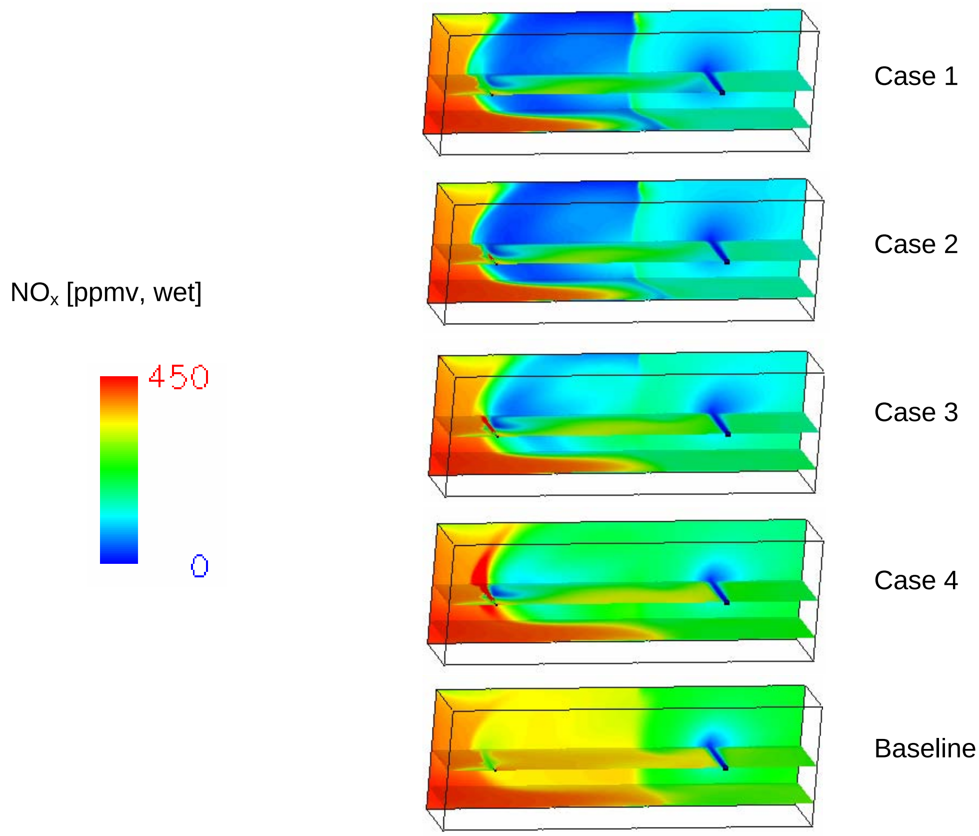

Figure 4-2
NO_X Concentration Profile for Reagent Injection Cases and Baseline

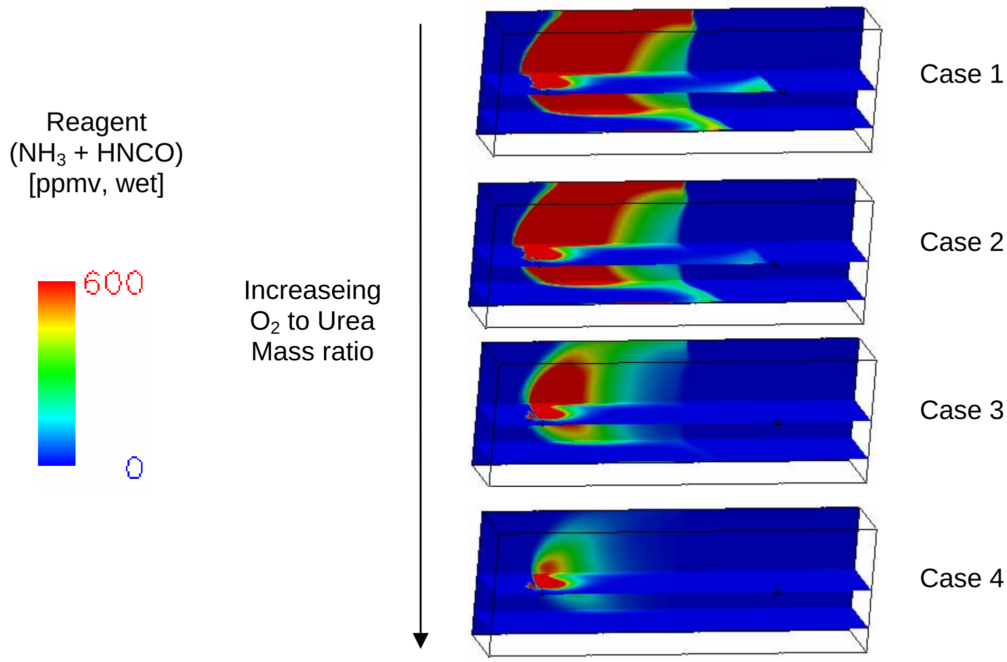

Figure 4-3
Reagent Concentration Profile for All Injection Cases and Baseline

5
SUMMARY

Experiments and CFD modeling were performed at pilot-scale to determine the impact of atomization gas composition on Rich Reagent Injection for NO_x reduction in coal combustion systems. RRI is typically performed by using a two-fluid atomization nozzle where a solution of urea is atomized with air. In these experiments, O_2 in the atomization gas was demonstrated to deter the reduction of NO_x by RRI. When injecting a solution diluted to 9 weight percent urea, the NO_x reduction was demonstrated to be 34.6% with nitrogen atomization and only 8.7% with air atomization at the same conditions. To better understand the relationship between NO_x reduction and the ratio of oxygen in the atomization gas and urea, these values were plotted for all of the data collected over the two days of testing along with the predicted values. This information is presented as Figure 5-1.

Figure 5-1 indicates that the maximum possible NO_x reduction decreases as the O_2 to Urea mass ratio increases. With no oxygen in the atomization gas, the NO_x reduction is approximately 55% for the operating conditions investigated here. The variability of the data collected is a function of all other operating conditions including baseline NO_x, injector turndown and burner operating parameters. When the ratio of O_2 to urea is increased to about 4.5, the NO_x reduction goes to zero. Greater O_2 to urea ratios cause an increase in NO_x concentration. The predicted NO_x reduction, as a function of O_2 to urea ratio, confirm the trend demonstrated in experiment. Although the simulations suggest that at ratios below 0.62, there is no negative impact of O_2 on NO_x reduction by RRI.

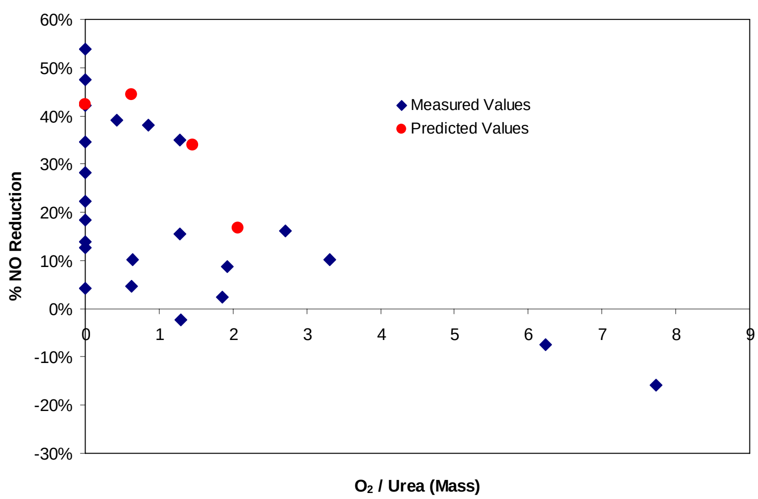

Figure 5-1
Predicted and Measured NO_X Reduction as a Function of the Mass Ratio of O_2 to Urea

It was also demonstrated that adding methane to the atomization air in a stoichiometric ratio would consume the oxygen. For these conditions NO_x reduction by RRI was almost as great as when atomizing with nitrogen. Using predominantly methane as the atomization gas was attempted in one experiment. It was expected that this may help overcome burner stratification and enhance RRI. The amount of methane added represented nearly 5% of the total furnace heat input. It was quickly evident that this type of experiment impacted too many variables to draw any meaningful conclusions and this avenue was abandoned.

Injection nozzle turndown was also investigated. Data suggested that turndown will significantly limit NO_x reduction by RRI. For the conditions investigated, the NO_x reduction decreased from almost 30% to no impact on NO_x emission while the atomization gas and dilution water was decreased, but maintaining the rate of urea input.

6
CONCLUSIONS AND RECOMMENDATIONS

The experimental data indicate that maximum reagent utilization and NO_x reduction by RRI occur when no O_2 is present in the injection atomization gas. However, model predictions indicate that at O_2 to urea ratios of less than 0.62, there is no negative impact of O_2 on NO_x reduction by RRI. An inert gas such as nitrogen or recycled flue gas may be used as the atomization gas for RRI to achieve the maximum benefit of RRI. In applications where utilization of an inert gas is not possible, the mass ratio of O_2 to urea should be limited to less than one, through appropriate nozzle selection, liquid reagent concentration and gas to liquid ratio.

To facilitate identification of appropriate RRI injector operating regimes, Figure 6-1 provides a series of curves at different atomizing air to urea solution mass ratios as a function of urea weight percent. For example, injection of a 20 percent by weight urea solution with an air to liquid mass ratio of 0.8 yields an oxygen to urea mass ratio of just under 1.0.

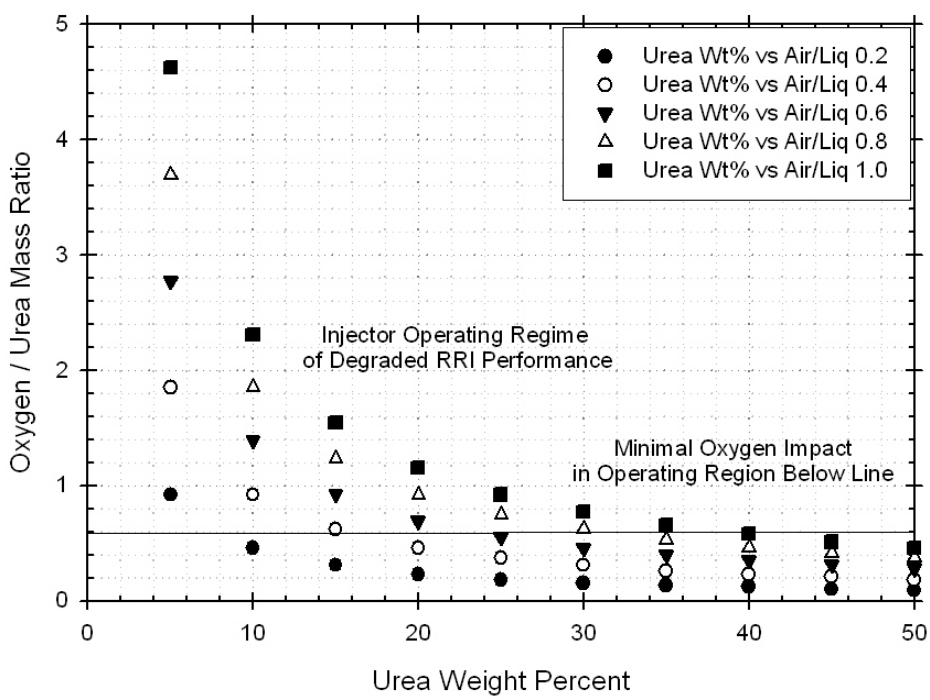

Figure 6-1
RRI Injector Oxygen to Urea Mass Ratio as a Function of Injected Urea Weight Percent and Injector Air to Liquid Mass Ratio

Appropriate nozzles should be used for RRI applications, providing appropriate drop size distributions and evaporation times without the use of excessive atomizing air that can impair RRI performance. If operation is necessary at flows that are outside of their nominal design specifications, different nozzles should be identified and installed. In addition, the design of the injection system should be accompanied by modeling to optimize the mixing characteristics into the combustion gases.

While natural gas may be used in stoichiometric ratios with air as the atomization gas to remove the adverse effects of O_2 on RRI, site specific economics should be evaluated to determine its overall cost effectiveness. More investigation is required where the atomization gas is operated with a slightly fuel rich ratio of methane with air. These conditions may provide some benefit in the presence of stratified combustion gases for RRI.

7
REFERENCES

1. Adams, B. R.; Cremer, M. A.; Chiodo, A. P.; Giesmann, C.; Stuckmeyer, K.; Boyle, J., Layered NO_x Reduction on a 500-MW Cyclone-Fired Boiler. Coal Power 2007, 27 – 33.
2. Fry, A.; Davis, K.; Cremer, M., NO_x Control Developments with ALTA in Pulverized Coal Units, The International Technical Conference on Coal Utilization & Fuel Systems, Clearwater, FL, June 10-15, 2007.

A
PIILOT SCALE DATA SHEETS

Test #	Date	Time of Data	Burner	Burner Distance [in.]	Overall SR	Burner SR	Air Pre-Heat [ºF]	Secondary Swirl	Inner Register Swirl	Outer Register Swirl	Primary Air to Fuel	Secondary	Tertiary	Injection Location	OFA Location	Sample Location	Temp Section 2 [ºF]	Temp Section 4 [ºF]	Temp Section 6 [ºF]	Temp Section 8 [ºF]
1	4/26/2007	10:07	LNB	NA	1.2	0.95	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans	2,631	2,612	2,384	2,218
2	4/26/2007	10:17	LNB	NA	1.2	0.95	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans	2,620	2,632	2,413	2,239
3	4/26/2007	10:23	LNB	NA	1.2	0.95	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans	2,618	2,655	2,449	2,254
4	4/26/2007	10:30	LNB	NA	1.2	0.95	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans	2,620	2,651	2,405	2,268
5	4/26/2007		LNB	NA	1.2	0.95	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans				
6	4/26/2007	10:52	LNB	NA	1.2	0.95	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans	2,627	2,685	2,475	2,291
7	4/26/2007		LNB	NA	1.2	0.95	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans				
8	4/26/2007		LNB	NA	1.2	0.95	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans				
9	4/26/2007		LNB	NA	1.2	0.90	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans				
10	4/26/2007		LNB	NA	1.2	0.90	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans				
11	4/26/2007		LNB	NA	1.2	0.90	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans				
12	4/26/2007		LNB	NA	1.2	0.90	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans				
13	4/26/2007		LNB	NA	1.2	0.90	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans				
14	4/26/2007		LNB	NA	1.2	0.90	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans				
15	4/26/2007		LNB	NA	1.2	0.90	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans				
16	4/26/2007		LNB	NA	1.2	0.90	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans				
17	4/26/2007		LNB	NA	1.2	0.85	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans				
18	4/26/2007	11:40	LNB	NA	1.2	0.85	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans	2,678	2,701	2,472	2,321
19	4/26/2007	11:46	LNB	NA	1.2	0.85	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans	2,680	2,710	2,469	2,327
20	4/26/2007	11:16	LNB	NA	1.2	0.85	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans	2,677	2,683	2,467	2,308
21	4/26/2007	11:24	LNB	NA	1.2	0.85	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans	2,667	2,686	2,462	2,320
22	4/26/2007		LNB	NA	1.2	0.85	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans				
23	4/26/2007	12:00	LNB	NA	1.2	0.85	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans	2,681	2,688	2,515	2,391
24	4/26/2007	12:08	LNB	NA	1.2	0.85	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans	2,686	2,687	2,496	2,414
25	4/26/2007		LNB	NA	1.2	0.85	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans				
26	4/26/2007		LNB	NA	1.2	0.85	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans				
27	4/26/2007		LNB	NA	1.2	0.85	500	--	75.0%	75.0%	1.80	33.0%	66.0%	4	6	Trans				
28	4/26/2007	1:06	LNB	NA	1.2	0.80	500	--	0.0%	0.0%	1.80	66.0%	33.0%	4	6	Trans	2,765	2,671	2,514	2,382
29	4/26/2007	1:27	LNB	NA	1.2	0.80	500	--	0.0%	0.0%	1.80	66.0%	33.0%	4	6	Trans	2,788	2,666	2,489	2,380
30	4/26/2007	1:34	LNB	NA	1.2	0.80	500	--	0.0%	0.0%	1.80	66.0%	33.0%	4	6	Trans	2,795	2,663	2,468	2,383
31	4/26/2007	1:43	LNB	NA	1.2	0.80	500	--	0.0%	0.0%	1.80	66.0%	33.0%	4	6	Trans	2,803	2,670	2,490	2,389
32	4/26/2007	1:52	LNB	NA	1.2	0.80	500	--	0.0%	0.0%	1.80	66.0%	33.0%	4	6	Trans	2,810	2,678	2,504	2,396
33	4/26/2007	1:58	LNB	NA	1.2	0.80	500	--	0.0%	0.0%	1.80	66.0%	33.0%	4	6	Trans	2,815	2,681	2,506	2,406
34	4/26/2007	2:05	LNB	NA	1.2	0.80	500	--	0.0%	0.0%	1.80	66.0%	33.0%	4	6	Trans	2,818	2,677	2,502	2,413
35	4/26/2007		LNB	NA	1.2	0.80	500	--	0.0%	0.0%	1.80	66.0%	33.0%	4	6	Trans				
36	4/26/2007	3:22	LNB	NA	1.2	0.80	500	--	0.0%	0.0%	1.80	66.0%	33.0%	4	6	Trans	2,832	2,707	2,509	2,391
37	4/26/2007	3:38	LNB	NA	1.2	0.80	500	--	0.0%	0.0%	1.80	66.0%	33.0%	4	6	Trans	2,842	2,707	2,511	2,397
38	4/26/2007	3:44	LNB	NA	1.2	0.80	500	--	0.0%	0.0%	1.80	66.0%	33.0%	4	6	Trans	2,844	2,709	2,508	2,406
39	4/26/2007	3:51	LNB	NA	1.2	0.80	500	--	0.0%	0.0%	1.80	66.0%	33.0%	4	6	Trans	2,845	2,712	2,492	2,418
40	4/26/2007	4:02	LNB	NA	1.2	0.80	500	--	0.0%	0.0%	1.80	66.0%	33.0%	4	6	Trans	2,849	2,712	2,520	2,420
41	4/26/2007	4:08	LNB	NA	1.2	0.80	500	--	0.0%	0.0%	1.80	66.0%	33.0%	4	6	Trans				
42	4/26/2007	4:22	LNB	NA	1.2	0.80	500	--	0.0%	0.0%	1.80	66.0%	33.0%	4	6	Trans	2,859	2,716	2,543	2,438
43	4/26/2007	4:30	LNB	NA	1.2	0.80	500	--	0.0%	0.0%	1.80	66.0%	33.0%	4	6	Trans	2,859	2,707	2,541	2,456
44	4/26/2007	4:36	LNB	NA	1.2	0.80	500	--	0.0%	0.0%	1.80	66.0%	33.0%	4	6	Trans	2,863	2,712	2,537	2,454
45	4/26/2007	4:46	LNB	NA	1.2	0.80	500	--	0.0%	0.0%	1.80	66.0%	33.0%	4	6	Trans	2,865	2,718	2,534	2,534
46	4/26/2007	4:53	LNB	NA	1.2	0.80	500	--	0.0%	0.0%	1.80	66.0%	33.0%	4	6	Trans	2,866	2,717	2,537	2,459
47	4/26/2007	4:59	LNB	NA	1.2	0.80	500	--	0.0%	0.0%	2.80	66.0%	33.0%	4	6	Trans				

Test #	Date	Time of Data	NSR	CH_4 Flow [scfh]	N_2 Flow [scfh]	Air Flow [scfh]	Vol % O_2 In Gas	Gas Flow [lb/hr]	Urea Flow [GPh]	Dilution Flow [GPh]	Urea Conc. At the Probe [wt. %]	Liquid Flow (lb)	Gas/Liquid	NO [ppm]	Reduction	Urea [lb/hr]	Urea [lbmol/hr]	O2 [lb/hr]	O2 [lbmol/hr]	O2/Urea [mass]
1	4/26/2007	10:07	0					0.0	0.0	4.0	0.0%	37.46	0.00	148		0.00	0.00	0.00	0.00	
2	4/26/2007	10:17	0			200	0.210	15.0	0.0	4.0	0.0%	37.46	0.40	148		0.00	0.00	3.15	0.10	
3	4/26/2007	10:23	2			200	0.210	15.0		4.0	0.0%	37.46	0.40	158		0.00	0.00	3.15	0.10	
4	4/26/2007	10:30	0		200		0.000	14.5	0.0	4.0	0.0%	37.46	0.39	149		0.00	0.00	0.00	0.00	
5	4/26/2007		2		200		0.000	14.5		4.0	0.0%	37.46	0.39			0.00	0.00	0.00	0.00	
6	4/26/2007	10:52	0		460		0.000	33.3	0.0	4.0	0.0%	37.46	0.89	160		0.00	0.00	0.00	0.00	
7	4/26/2007		2		460		0.000	33.3		4.0	0.0%	37.46	0.89			0.00	0.00	0.00	0.00	
8	4/26/2007		0					0.0	0.0	4.0	0.0%	37.46	0.00			0.00	0.00	0.00	0.00	
9	4/26/2007		0					0.0	0.0	4.0	0.0%	37.46	0.00			0.00	0.00	0.00	0.00	
10	4/26/2007		0			200	0.210	15.0	0.0	4.0	0.0%	37.46	0.40			0.00	0.00	3.15	0.10	
11	4/26/2007		2			200	0.210	15.0		4.0	0.0%	37.46	0.40			0.00	0.00	3.15	0.10	
12	4/26/2007		0		200		0.000	14.5	0.0	4.0	0.0%	37.46	0.39			0.00	0.00	0.00	0.00	
13	4/26/2007		2		200		0.000	14.5		4.0	0.0%	37.46	0.39			0.00	0.00	0.00	0.00	
14	4/26/2007		0	200			0.000	8.3	0.0	4.0	0.0%	37.46	0.22			0.00	0.00	0.00	0.00	
15	4/26/2007		2	200			0.000	8.3		4.0	0.0%	37.46	0.22			0.00	0.00	0.00	0.00	
16	4/26/2007		0					0.0	0.0	4.0	0.0%	37.46	0.00			0.00	0.00	0.00	0.00	
17	4/26/2007		0					0.0	0.0	4.0	0.0%	37.46	0.00			0.00	0.00	0.00	0.00	
18	4/26/2007	11:40	0			460	0.210	34.5	0.0	4.0	0.0%	37.46	0.92	119		0.00	0.00	7.24	0.23	
19	4/26/2007	11:46	2			460	0.210	34.5	0.3	3.8	2.5%	37.46	0.92	138	-15.9%	0.94	0.02	7.24	0.23	7.73
20	4/26/2007	11:16	0		460		0.000	33.3	0.0	4.0	0.0%	37.46	0.89	109		0.00	0.00	0.00	0.00	
21	4/26/2007	11:24	2		460		0.000	33.3	0.2	3.8	2.2%	37.46	0.89	98		0.82	0.01	0.00	0.00	0.00
22	4/26/2007		0		460		0.000	33.3	0.0	4.0	0.0%	37.46	0.89	111		0.00	0.00	0.00	0.00	
23	4/26/2007	12:00	0	200			0.000	8.3		4.0	0.0%	37.46	0.22	84		0.00	0.00	0.00	0.00	
24	4/26/2007	12:08	2	200			0.000	8.3	0.0	4.0	0.0%	37.46	0.22	80		0.00	0.00	0.00	0.00	
25	4/26/2007		0					0.0	0.0	4.0	0.0%	37.46	0.00			0.00	0.00	0.00	0.00	
26	4/26/2007		0		200		0.000	14.5	0.0	4.0	0.0%	37.46	0.39			0.00	0.00	0.00	0.00	
27	4/26/2007		2		200		0.000	14.5		4.0	0.0%	37.46	0.39	117		0.00	0.00	0.00	0.00	
28	4/26/2007	1:06	0		460		0.000	33.3	0.0	4.0	0.0%	37.46	0.89	191		0.00	0.00	0.00	0.00	
29	4/26/2007	1:27	2		460		0.000	33.3	0.4	3.6	3.9%	37.46	0.89	88	53.8%	1.46	0.02	0.00	0.00	0.00
30	4/26/2007	1:34	2		200		0.000	14.5	0.4	3.6	3.9%	37.46	0.39	100	47.5%	1.46	0.02	0.00	0.00	0.00
31	4/26/2007	1:43	0		200		0.000	14.5	0.0	4.0	0.0%	37.46	0.39	170		0.00	0.00	0.00	0.00	
32	4/26/2007	1:52	0			460	0.210	34.5	0.0	4.0	0.0%	37.46	0.92	153		0.00	0.00	7.24	0.23	
33	4/26/2007	1:58	0			460	0.210	34.5	0.3	3.7	3.1%	37.46	0.92	164	-7.5%	1.16	0.02	7.24	0.23	6.23
34	4/26/2007	2:05	0			200	0.210	15.0	0.3	3.7	3.1%	37.46	0.40	128	16.1%	1.16	0.02	3.15	0.10	2.71
35	4/26/2007		0			200	0.210	15.0	0.0	4.0	0.0%	37.46	0.40			0.00	0.00	3.15	0.10	
36	4/26/2007	3:22	0		125		0.000	9.0	0.0	0.9	0.0%	7.96	1.14	197		0.00	0.00	0.00	0.00	
37	4/26/2007	3:38	2		125		0.000	9.0	0.4	0.9	13.0%	11.80	0.77	114	42.1%	1.54	0.03	0.00	0.00	0.00
38	4/26/2007	3:44	2		83	42	0.071	9.2	0.4	0.9	13.0%	11.80	0.78	120	39.1%	1.54	0.03	0.66	0.02	0.43
39	4/26/2007	3:51	2		41	84	0.141	9.3	0.4	0.9	13.0%	11.80	0.78	122	38.1%	1.54	0.03	1.32	0.04	0.86
40	4/26/2007	4:02	2			125	0.210	9.4	0.4	0.9	13.0%	11.80	0.79	128	35.0%	1.54	0.03	1.97	0.06	1.28
41	4/26/2007	4:08	0			125	0.210	9.4	0.0	0.9	0.0%	7.96	1.18	151		0.00	0.00	1.97	0.06	
42	4/26/2007	4:22	0		142		0.000	10.3	0.0	1.1	0.0%	10.40	0.99	147		0.00	0.00	0.00	0.00	
43	4/26/2007	4:30	2		142		0.000	10.3	0.3	1.1	8.7%	13.30	0.77	96	34.6%	1.16	0.02	0.00	0.00	0.00
44	4/26/2007	4:36	2		95	47	0.070	10.4	0.3	1.1	8.7%	13.30	0.78	132	10.1%	1.16	0.02	0.74	0.02	0.64
45	4/26/2007	4:46	2		47	95	0.140	10.5	0.3	1.1	8.7%	13.30	0.79	124	15.6%	1.16	0.02	1.49	0.05	1.29
46	4/26/2007	4:53	2			142	0.210	10.6	0.3	1.1	8.7%	13.30	0.80	134	8.8%	1.16	0.02	2.23	0.07	1.92
47	4/26/2007	4:59	0			142	0.210	10.6	0.0	1.1	0.0%	10.40	1.02	136	7.6%	0.00	0.00	2.23	0.07	

Test #	Date	Time of Data	O2/Urea [mol]	Corrected NO	CO_2 %	CO [ppm]	CO [%]	O_2 [%]
1	4/26/2007	10:07			15.54	13		3.12
2	4/26/2007	10:17			15.68	12		3.07
3	4/26/2007	10:23			15.60	13		2.90
4	4/26/2007	10:30			15.71	12		2.81
5	4/26/2007							
6	4/26/2007	10:52			15.68	13		2.97
7	4/26/2007							
8	4/26/2007							
9	4/26/2007							
10	4/26/2007							
11	4/26/2007							
12	4/26/2007							
13	4/26/2007							
14	4/26/2007							
15	4/26/2007							
16	4/26/2007							
17	4/26/2007							
18	4/26/2007	11:40			15.51	13		3.25
19	4/26/2007	11:46	14.64		15.60	13		3.10
20	4/26/2007	11:16			15.58	13		3.01
21	4/26/2007	11:24	0.00		15.70	13		2.90
22	4/26/2007							
23	4/26/2007	12:00			16.76	13		1.59
24	4/26/2007	12:08			16.80	14		1.50
25	4/26/2007							
26	4/26/2007							
27	4/26/2007				15.54	13		3.29
28	4/26/2007	1:06			15.68	12		3.30
29	4/26/2007	1:27	0.00		15.70	12		3.00
30	4/26/2007	1:34	0.00		15.80	12		3.00
31	4/26/2007	1:43			15.90	12		2.90
32	4/26/2007	1:52			16.23	12		2.79
33	4/26/2007	1:58	11.80		16.30	12		2.70
34	4/26/2007	2:05	5.13		16.30	12		2.70
35	4/26/2007							
36	4/26/2007	3:22			15.54	9		3.66
37	4/26/2007	3:38	0.00		15.50	9		3.40
38	4/26/2007	3:44	0.81		15.70	9		3.20
39	4/26/2007	3:51	1.63		15.80	9		3.10
40	4/26/2007	4:02	2.43		15.70	7		3.10
41	4/26/2007	4:08			15.78	7		3.18
42	4/26/2007	4:22			15.74	7		3.13
43	4/26/2007	4:30	0.00		15.70	8		3.00
44	4/26/2007	4:36	1.21		15.50	7		3.20
45	4/26/2007	4:46	2.44		15.60	7		3.00
46	4/26/2007	4:53	3.64		15.60	7		3.00
47	4/26/2007	4:59			15.70	7		3.00

Test #	Date	Time of Data	Burner	Burner Distance [in.]	Overall SR	Burner SR	Air Pre-Heat [°F]	Secondary Swirl	Inner Register Swirl	Outer Register Swirl	Primary Air to Fuel	Secondary	Tertiary	Injection Location	OFA Location	Sample Location	Temp Section 2 [°F]	Temp Section 4 [°F]	Temp Section 6 [°F]	Temp Section 8 [°F]
1	4/27/2007	9:40	LNB	NA	1.2	0.8	500	--	0.00%	0.00%	1.80	66%	33%	4	6	Trans	2,823	2,662	2,480	2,378
2	4/27/2007	9:52	LNB	NA	1.2	0.8	500	--	0.00%	0.00%	1.80	66%	33%	4	6	Trans	2,827	2,671	2,502	2,393
3	4/27/2007	9:58	LNB	NA	1.2	0.8	500	--	0.00%	0.00%	1.80	66%	33%	4	6	Trans	2,832	2,679	2,504	2,397
4	4/27/2007	10:04	LNB	NA	1.2	0.8	500	--	0.00%	0.00%	1.80	66%	33%	4	6	Trans	2,836	2,690	2,520	2,403
5	4/27/2007	10:10	LNB	NA	1.2	0.8	500	--	0.00%	0.00%	1.80	66%	33%	4	6	Trans	2,838	2,688	2,518	2,407
6	4/27/2007	10:16	LNB	NA	1.2	0.8	500	--	0.00%	0.00%	1.80	66%	33%	4	6	Trans	2,841	2,698	2,520	2,415
7	4/27/2007		LNB	NA	1.2	0.8	500	--	0.00%	0.00%	1.80	66%	33%	4	6	Trans				
8	4/27/2007	1:22	LNB	NA	1.2	0.8	500	--	0.00%	0.00%	1.80	66%	33%	4	6	Trans	2,901	2,750	2,615	2,503
9	4/27/2007	1:32	LNB	NA	1.2	0.8	500	--	0.00%	0.00%	1.80	66%	33%	4	6	Trans	2,903	2,775	2,624	2,498
10	4/27/2007	1:40	LNB	NA	1.2	0.8	500	--	0.00%	0.00%	1.80	66%	33%	4	6	Trans	2,907	2,768	2,622	2,505
11	4/27/2007	1:46	LNB	NA	1.2	0.8	500	--	0.00%	0.00%	1.80	66%	33%	4	6	Trans	2,910	2,769	2,632	2,511
12	4/27/2007	2:07	LNB	NA	1.2	0.8	500	--	0.00%	0.00%	1.80	66%	33%	4	6	Trans	2,909	2,777	2,630	2,512
13	4/27/2007	2:34	LNB	NA	1.2	0.8	500	--	0.00%	0.00%	1.80	66%	33%	4	6	Trans	2,916	2,783	2,631	2,509
14	4/27/2007		LNB	NA	1.2	0.8	500	--	0.00%	0.00%	1.80	66%	33%	4	6	Trans				
15	4/27/2007	3:08	LNB	NA	1.2	0.8	500	--	0.00%	0.00%	1.80	66%	33%	4	6	Trans	2,921	2,790	2,656	2,535
16	4/27/2007	3:14	LNB	NA	1.2	0.8	500	--	0.00%	0.00%	1.80	66%	33%	4	6	Trans	2,922	2,783	2,644	2,539
17	4/27/2007	3:19	LNB	NA	1.2	0.8	500	--	0.00%	0.00%	1.80	66%	33%	4	6	Trans	2,919	2,789	2,649	2,542
18	4/27/2007	3:27	LNB	NA	1.2	0.8	500	--	0.00%	0.00%	1.80	66%	33%	4	6	Trans	2,920	2,798	2,657	2,535
19	4/27/2007	3:32	LNB	NA	1.2	0.8	500	--	0.00%	0.00%	1.80	66%	33%	4	6	Trans	2,916	2,799	2,656	2,545
20	4/27/2007	3:36	LNB	NA	1.2	0.8	500	--	0.00%	0.00%	1.80	66%	33%	4	6	Trans	2,923	2,796	2,647	2,547

Test #	Date	Time of Data	NSR	CH_4 Flow [scfh]	N_2 Flow [scfh]	Air Flow [scfh]	Vol % O_2 In Gas	Gas Flow [lb/hr]	Urea Flow [GPh]	Dilution Flow [GPh]	Urea Conc. At the Probe [wt. %]	Liquid Flow (lb)	Gas/Liquid	NO [ppm]	Reduction	Urea [lb/hr]	Urea [lbmol/hr]	O2 [lb/hr]	O2 [lbmol/hr]	O2/Urea [mass]
1	4/27/2007	9:40	0		243		0.0%	17.6		2.34	0.00	21.96	0.80	142		0.00	0.00	0.00	0.00	
2	4/27/2007	9:52	2		243		0.0%	17.6	0.28	2.07	0.05	21.98	0.80	102	28.2%	1.05	0.02	0.00	0.00	0.00
3	4/27/2007	9:58	2		192		0.0%	13.9	0.28	1.57	0.06	17.35	0.80	116	18.3%	1.05	0.02	0.00	0.00	0.00
4	4/27/2007	10:04	2		141		0.0%	10.2	0.28	1.08	0.08	12.75	0.80	124	12.7%	1.05	0.02	0.00	0.00	0.00
5	4/27/2007	10:10	2		89		0.0%	6.4	0.28	0.58	0.13	8.06	0.80	136	4.2%	1.05	0.02	0.00	0.00	0.00
6	4/27/2007	10:16	0		89		0.0%	6.4		0.86	0.00	8.05	0.80	140		0.00	0.00	0.00	0.00	
7	4/27/2007															0.00	0.00	0.00	0.00	
8	4/27/2007	1:22	0		319		0.0%	23.1	0.00	3.08	0.00	28.82	0.80	165		0.00	0.00	0.00	0.00	
9	4/27/2007	1:32	2		319		0.0%	23.1	0.39	2.69	0.05	28.87	0.80	128	22.4%	1.46	0.02	0.00	0.00	0.00
10	4/27/2007	1:40	2			308	21.0%	23.1	0.39	2.69	0.05	28.87	0.80	148	10.2%	1.46	0.02	4.85	0.15	3.32
11	4/27/2007	1:46	2	30.6		291	19.0%	23.1	0.39	2.69	0.05	28.87	0.80	132	20.0%	1.46	0.02			
12	4/27/2007	2:07	0	30.6		291	19.0%	23.1	0.00	2.69	0.00	25.22	0.91	176		0.00	0.00	4.58	0.14	
13	4/27/2007	2:34	0			308	21.0%	23.1	0.00	3.08	0.00	28.82	0.80	168		0.00	0.00	4.85	0.15	
14	4/27/2007															0.00	0.00	0.00	0.00	
15	4/27/2007	3:08	0		174		0.0%	12.6	0.00	1.68	0.00	15.73	0.80	174		0.00	0.00	0.00	0.00	
16	4/27/2007	3:14	2		174		0.0%	12.6	0.38	1.30	0.09	15.74	0.80	150	13.8%	1.42	0.02	0.00	0.00	0.00
17	4/27/2007	3:19	2		117	57	6.9%	12.7	0.38	1.30	0.09	15.74	0.81	166	4.7%	1.42	0.02	0.90	0.03	0.63
18	4/27/2007	3:27	2		57	117	14.1%	12.9	0.38	1.30	0.09	15.74	0.82	178	-2.2%	1.42	0.02	1.84	0.06	1.29
19	4/27/2007	3:32	2			168	21.0%	12.6	0.38	1.30	0.09	15.74	0.80	170	2.4%	1.42	0.02	2.64	0.08	1.86
20	4/27/2007	3:36	0			168	21.0%	12.6	0.00	1.68	0.00	15.73	0.80	181		0.00	0.00	2.64	0.08	

Test #	Date	Time of Data	O2/Urea [mol]	Corrected NO	CO_2 %	CO [ppm]	CO [%]	O_2 [%]
1	4/27/2007	9:40			15.40	5		3.10
2	4/27/2007	9:52	0.00		15.60	5		3.00
3	4/27/2007	9:58	0.00		15.50	6		3.00
4	4/27/2007	10:04	0.00		15.50	6		3.10
5	4/27/2007	10:10	0.00		15.50	6		3.10
6	4/27/2007	10:16			15.53	5		3.05
7	4/27/2007							
8	4/27/2007	1:22			15.63	6		3.08
9	4/27/2007	1:32	0.00		15.50	7		3.10
10	4/27/2007	1:40	6.28		15.70	7		3.10
11	4/27/2007	1:46			15.60	7		3.10
12	4/27/2007	2:07			15.79	7		3.17
13	4/27/2007	2:34			16.02	7		3.02
14	4/27/2007							
15	4/27/2007	3:08			15.60	7		3.00
16	4/27/2007	3:14	0.00		15.50	7		3.00
17	4/27/2007	3:19	1.19		15.60	7		3.00
18	4/27/2007	3:27	2.45		15.90	8		3.00
19	4/27/2007	3:32	3.52		15.70	8		3.10
20	4/27/2007	3:36			15.66	7		3.18

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com