# SUB 0.15 LB/MBTU NOx EMISSIONS ACHIEVED WITH ALTA ON A 500 MW CYCLONE-FIRED BOILER

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## ABSTRACT

A four week testing program was recently completed to assess the ability of the combination of deep staging, Rich Reagent Injection (RRI), and Selective Noncatalytic Reduction (SNCR) to reduce NOx emissions below 0.15 lb/MBtu in a cyclone fired boiler. The host site for the tests was AmerenUE's Sioux Unit 1, a 540 MW cyclone fired boiler located near St. Louis, MO. This layered approach to NOx reduction is termed the Advanced Layered Technology Approach (ALTA). Installed RRI and SNCR port locations were guided by computational fluid dynamics (CFD) based modeling conducted by REI. During the parametric testing, NOx emissions of 0.12 lb/MBtu were achieved consistently from OFA-only baseline NOx emissions of 0.25 lb/MBtu or less, when firing the typical 80/20 fuel blend of Powder River Basin (PRB) and Illinois #6 coals. From OFA-only baseline levels of 0.20 lb/MBtu, NOx emissions of 0.12 lb/MBtu were also achieved, but at significantly reduced urea flow rates. Under the deeply staged conditions that were tested, RRI performance was observed to degrade as higher blends of Illinois #6 were used. NOx emissions achieved with ALTA while firing a 60/40 blend were approximately 0.15 lb/MBtu. NOx emissions while firing 100% Illinois #6 were approximately 0.165 lb/MBtu. This project was funded by USDOE National Energy Technology Laboratory's Innovations for Existing Plants Program.

## INTRODUCTION

Cyclone fired boilers have historically been characterized as high NOx emitting units due to the very high combustion temperatures that are produced in the primary combustion zone. Uncontrolled NOx emissions ranging from 0.8 to 1.9 lb/MBtu have been typical. Due to the design characteristics of cyclone fired units, they are not conducive to the application of conventional low NOx burner technology. Prior to 1997, the conventional wisdom was that cyclone fired boilers could not be practically operated under two stage combustion conditions due to concerns about the reducing conditions in the cyclone barrel leading to corrosion. Gas reburn technology and SCR were considered to be the technologies of choice in cyclone units for NOx reduction (Stultz, 1992).

To evaluate alternative options for NOx control in cyclone fired boilers in anticipation of Title IV Phase II NOx limits, Reaction Engineering International (REI) participated with EPRI and their Cyclone NOx Control Interest Group (CNCIG) starting in 1995. There were three significant outcomes of this work: 1) Development of a CFD based model of cyclone barrel combustion for evaluation of cost-effective options for NOx reduction (Adams, 1997), 2) Demonstration of two stage combustion in cyclone boilers as a cost-effective NOx reduction strategy (Smith, 1997), and 3) Demonstration of Rich Reagent Injection (RRI) in combination with OFA for significant additional NOx reduction in cyclone boilers (Cremer, 2001, 2002). The successes of the CNCIG group led to the installation of OFA in the majority of cyclone boilers currently operating in the United States allowing them to meet the Title IV NOx limit of 0.86 lb/MBtu at capital and operating costs significantly lower than that of gas reburn or SCR.

For the majority of cyclone fired boilers currently equipped with OFA, it is not expected that NOx emissions below a 0.15 lb/MBtu target will be achievable without installation of additional NOx controls. An attractive option for meeting sub 0.15 lb/MBtu NOx limits in cyclone fired units is the combination of deep staging combined with reagent injection as part of the Rich Reagent Injection (RRI) and Selective Noncatalytic Reduction (SNCR) processes. This layered approach to NOx reduction is termed the Advanced Layered Technology Approach (ALTA). This paper presents the results of a recent Department of Energy (DOE) National Energy Technology Laboratory (NETL) funded program to evaluate ALTA in a full-scale cyclone fired boiler. The field testing was conducted in AmerenUE's Sioux Unit 1, a 540 MW cyclone fired boiler located near St. Louis, MO.

## APPROACH

The DOE-NETL program was divided into two components: 1) Model-based design, and 2) Field Testing. CFD based modeling was conducted by REI to guide the RRI and SNCR process design and to locate new RRI and SNCR injection ports. The focus of this paper is the field testing component. The field testing was divided into two phases: 1) Parametric testing, and 2) Continuous Testing. The duration of the parametric testing was 14 days, beginning on May 16, 2005 and extending through June 3, 2005. Continuous testing of the temporary ALTA system was initiated on June 6, 2005 and proceeded through the morning of June 9, 2005.

## RRI and SNCR Injection Locations

RRI and SNCR were previously tested in Sioux Unit 1 during the fall of 2001 and spring of 2002. At that time, 20 RRI ports and 4 SNCR ports were installed for those tests. For the recent DOE-NETL program, 8 additional RRI ports were installed during the spring 2005 outage: 1) 1 on each side wall, and 2) 3 each on the front and rear walls. Physical obstructions in the windbox required that the 6 injector sleeves for the front and rear wall ports penetrate through the windbox at a 20º downward angle. A total of 14 SNCR ports were installed during the spring 2005 outage. These included 5 front wall ports and 9 ports at the center of the front and rear wall gas tempering (GT) ports. Physical obstructions within the gas tempering windbox required that the 9 injector sleeves be oriented at a $20^{o}$ downward angle for the 9 GT ports.

## Reagent Injection Equipment

REI subcontracted the supply and operation of the temporary reagent injection equipment to FuelTech, Inc., Batavia, IL. This included the supply of injectors, lances, hoses, distribution modules (DMs), air compressors, liquid pumps, metering equipment, reagent tanks, and heaters. Liquid and air lines supplied diluted urea and atomization and cooling air to each injector. The atomized liquid as well as cooling air was then transported through a variable-length lance that consisted of both a liquid line and an outer cooling tube. A threaded nozzle tip was then connected to the end of the liquid line. The orifice through the end of the threaded tip controlled the shape and direction of the liquid spray. Diluted urea and air were supplied to the RRI and SNCR injectors through rubber hoses connected to six distribution modules (DM). The DMs were equipped with valves and pressure gauges on the air lines and valves, rotameters, and pressure gauges on the liquid lines in order to measure and throttle both the air and liquid flows to the injectors. The RRI system included 4 5-pack DMs. Similarly, diluted urea and air to the SNCR injectors were supplied through rubber hoses connected to 1 9-pack and 2 4-pack DMs. The DMs were supplied by heat resistant rubber hoses carrying diluted urea and air. The air lines were connected to two electric air compressors.

Diluted urea flow rates to the DMs were controlled by Fuel Tech's mobile test trailer (MTT), a purpose-built Kentucky air-ride semi-trailer approximately 48' long, 8' wide and 12' high. At Sioux Plant, the urea dilution water was supplied from demineralized water tanks. This supply line was connected to a bulkhead fitting array mounted on the exterior of the trailer. Water was distributed to either or both of two turbine water booster pumps. Output of the two water pump systems was directed to a choice of three injection zones (output pipes). For the ALTA testing, SNCR and RRI flows were treated as two separate injection zones.

Commercial grade 50% aqueous urea was delivered by 5000 gallon tanker trucks by Terra Industries, Sioux City, IA. FuelTech provided a portable wheeled horizontal tank (Frac Truck), with a storage capacity of approximately 21,000 gallons, to store the aqueous urea. Aqueous urea from the Frac Truck was circulated continuously through a supply piping loop by two one-HP self-priming centrifugal pumps and through a thermostatically controlled electric inline heater to keep the concentrated urea solution in the Frac Truck at a temperature above $62^{o}$F, the saltation temperature. Both the concentrated urea and the dilution water were piped to the metering module in the MTT where they were mixed to the desired final concentration.

Plant signals, including boiler load and NOx emissions, were hardwired to the PLC in the trailer in order to accommodate automated operation of the system. In addition, these plant signals were also hardwired to a desktop computer in order to observe boiler operational data from the plant Pi system.

## Test Measurements

The test measurements of primary importance during the ALTA testing included: 1) Stack NOx emissions, 2) Ammonia slip, and 3) Unburned carbon in fly ash. During the ALTA testing, stack NOx emissions were determined using the existing continuous emissions monitors

(CEMs). Daily unburned carbon in ash measurements were taken by sampling flyash from hoppers in the inlet precipitator field and measuring the carbon content using a Leco carbon analyzer. These measurements were logged during the ALTA testing to provide estimates of unburned carbon in the fly ash. Since these are not isokinetic measurements, a high unburned carbon measurement could be due to operational conditions that existed several days previous.

Since ammonia measurements in the ductwork between the economizer and air heater are not typically made in Sioux Unit 1, efforts were made to do so during the ALTA testing. Ideally, continuous measurements of ammonia over the entire duct cross section would be made to determine an average ammonia concentration in the flue gas for each test. However, the costs associated with that level of effort are extremely high and it was decided that a reduced level of effort would suffice to provide estimates of ammonia slip. The approach used in this program was to make near wall measurements at two different axial locations in the ductwork between the economizer and air heater using two different measurement methods. Batch extractive measurements combined with wet chemical analysis as well as continuous laser based measurements were made. FuelTech performed the extractive ammonia sampling and analysis. EPRI and personnel from University of California Riverside performed the tunable diode laser (TDL) measurements.

## Furnace Operational Conditions

ALTA testing was performed for four different combinations of coal blends and gross loads as shown in Table 1. The majority of the tests were performed using a blend of 80% Powder River Basin (PRB) coal and 20% Illinois #6 (i.e. 80/20) at 480 MW. This represents the typical maximum load condition for this fuel blend. For this load and coal blend, ALTA testing was conducted nominally under two levels of staging to achieve NOx emissions with OFA alone of approximately 0.25 lb/MBtu and 0.20 lb/MBtu.

**Table 1:** Operational conditions for RRI and SNCR at Sioux Unit 1

| Coal | | Generation | Baseline NOx (lb/MBtu) | |
|---|---|---|---|---|
| **PRB** | **Bituminous** | **Load (MW)** | **Staged** | **Deeply Staged** |
| 80% | 20% | 480 | 0.25 | 0.20 |
| 80% | 20% | 425 | 0.23 | N/A |
| 60% | 40% | 530 | 0.26 | N/A |
| 0% | 100% | 540 | 0.33 | 0.27 |

# RESULTS

## Parametric Test Results

*RRI Results*

Parametric tests to evaluate RRI in the absence of SNCR were conducted to quantify impacts of: 1) Injector location, 2) Normalized stoichiometric ratio (NSR), and 3) Staging level (baseline NOx level). Figure 1 shows the measured NOx reductions due to the combination of OFA and RRI for all tests under conditions of 480 MW with the 80/20 (PRB/bit.) coal blend. Baseline NOx emissions with OFA alone during these tests ranged from approximately 0.205

lb/MBtu to 0.285 lb/MBtu. NOx emissions with application of RRI were as low as 0.147 lb/MBtu. NOx reduction varied from 15 % to 39%, primarily as a function of reagent flow rate and injector location. The TDL based measurements of ammonia slip taken during some of the RRI-only tests are also shown in Figure 1. These measurements showed values of 1 ppm or less during all of the tests. These values were typically indistinguishable from the background measurements that were taken while no reagent was being injected.

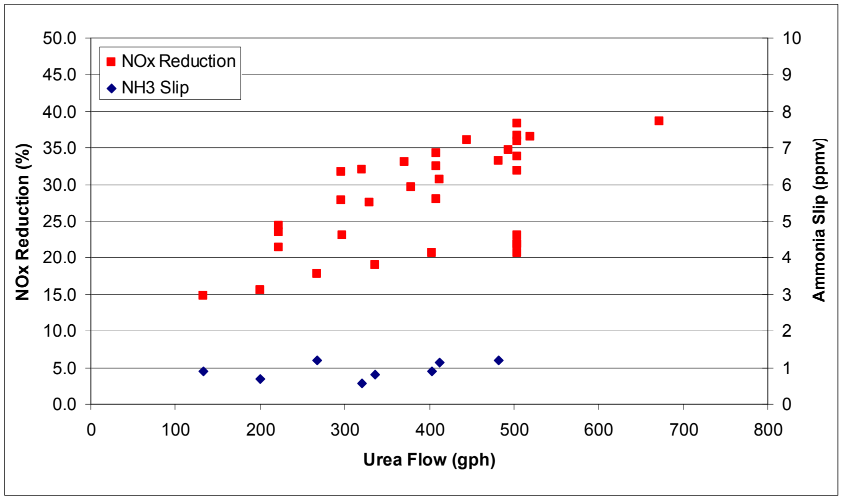


**Figure 1:** Measured NOx reduction due to RRI plotted as percentage NOx reduction from OFA alone.

The scatter in the measured NOx reductions was due primarily to: 1) injector location, and 2) staging level (i.e. lower furnace SR). Early on in the parametric testing, several tests were completed to evaluate impacts of using different combinations of the RRI injection locations. The results demonstrated that a combination of 16 injectors, including six of the newly installed port locations achieved the best performance. Subsequent RRI tests utilized only that 16 injector configuration. Figure 2 shows only the 16 injector data from Figure 1, plotted as a function of NSR and baseline NOx level. Note that much of the scatter in the NOx reductions observed in Figure 1 has been eliminated by holding the RRI injection configuration constant. As expected, the NOx reduction increases as a function of NSR. It is also apparent that particularly for deeply staged conditions corresponding to baseline NOx emissions below 0.25 lb/MBtu, there is a decrease in NOx reduction compared to less deeply

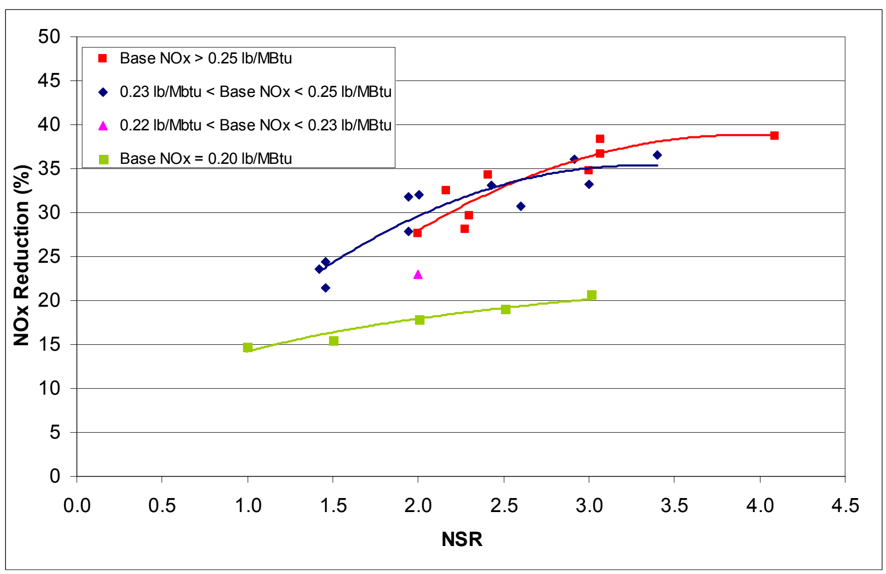


**Figure 2:** Measured NOx reductions due to RRI versus normalized stoichiometric ratio (NSR) and as a function of baseline NOx level.

staged conditions. The baseline NOx emissions are a good indication of average lower furnace SR, where lower NOx emissions correlate with reduced lower furnace SR (deeper staging). Figure 2 shows that at a given NSR, NOx reduction from baseline NOx levels less than 0.23 lb/MBtu is reduced from that achieved from baseline NOx levels greater than 0.23 lb/MBtu. Specifically, the figure shows that at NSR=2, the NOx reduction due to RRI ranges from 18% to 32% as the baseline NOx increases from 0.20 lb/MBtu to 0.25 lb/MBtu. This corresponds to a range of reagent utilizations from approximately 9% to 16%. The observed decrease in NOx reduction due to staging is consistent with the results of REI's previous CFD model based analyses.

Three days of parametric tests were devoted to evaluation of ALTA performance while firing 100% Illinois #6 coal as well as a "sweetened" blend of 40% Illinois #6 coal. Although the Sioux plant typically fires a blend of 80% PRB, they will periodically increase the fraction of Illinois coal up to 40% in order to reach peak load of approximately 540 MW. The testing with 100% Illinois coal was performed as a requirement of the DOE program. The boiler load during the tests with 100% Illinois #6 and 40% Illinois #6 coal was in the range from 530 – 540 MW. Baseline NOx emissions with the 100% Illinois fuel were found to be in the range of 0.26 to 0.34 lb/MBtu, higher than the typical baseline NOx emissions obtained with the 80/20 blend. Figure 3 shows the measured NOx reductions resulting from application of RRI for the three fuel blends, as a function of reagent usage. Note that the observed dependence of NOx emissions on fuel type was significant. The lowest NOx emissions achieved through deep staging and RRI with 100% Illinois #6 fuel was approximately 0.24 lb/MBtu. During the limited testing with the 60/40 blend, emissions as low as 0.205 lb/MBtu were obtained with RRI. For the 80/20 blend, the NOx emissions obtained with RRI were as low as 0.147 lb/MBtu.

In consideration of the data plotted previously in Figure 2, the data suggest a strong dependency of NOx reduction with RRI on the baseline NOx emissions (i.e. degree of staging). This dependency is clearly shown in Figure 3 where the NOx reduction achieved with RRI is plotted vs. the baseline (OFA only) NOx emissions for the three coal blends. For the 80/20 blend, there is a clear trend showing a decrease in percentage NOx reduction due to RRI for baseline NOx emissions below 0.25 lb/MBtu. For the 100% Illinois fuel, it appears that the same trend is observed, but is apparent at baseline NOx emissions in the range from 0.26 to 0.34 lb/MBtu. No such trend can be shown for the 60/40 blend due to insufficient data, but it would be expected that similar behavior

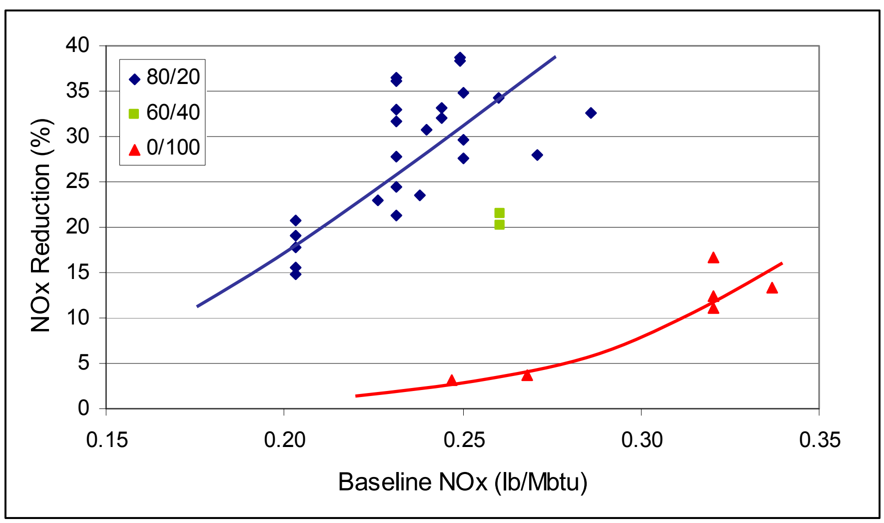


**Figure 3:** NOx reduction due to RRI for three coal blends of PRB/Ill. #6 plotted as a function of the baseline NOx emissions

would be exhibited. For the 100% Illinois coal, it is apparent that RRI is nearly ineffective when applied under baseline furnace conditions where NOx emissions of 0.25 lb/MBtu have been achieved. However, for baseline NOx levels of 0.34 lb/MBtu, RRI achieved approximately 17% NOx reduction. Note that previous RRI testing at Conectiv's B.L. England Station showed 30% NOx reduction from a baseline NOx level of 0.55 lb/MBtu when firing Eastern bituminous coal [Cremer, 2001].

*SNCR Results*

SNCR tests were carried out to evaluate performance in the absence of or in combination with RRI. Most of the SNCR testing was conducted while firing the typical 80/20 fuel blend at a boiler load of nominally 480 MW. In addition, test results were achieved for the 80/20 fuel blend at 425 MW as well as with 100% Illinois #6 at 530-540 MW.

The measured NOx reductions for the SNCR-only tests are plotted vs. NSR in Figure 4. Also shown are ammonia slip measurements from both the TDL and wet chemistry (extractive) approaches. The highest NOx reductions, approximately 30%, were achieved using only the five front wall injectors at El 576'. The majority of the ammonia slip measurements showed 10 ppmv or less. However, one of the extractive measurements showed ammonia slip as high as 20 ppmv during testing with the five front wall injectors. The TDL based measurement during the same test was 5 ppm, indicating a significant amount of stratification of ammonia within the duct at the economizer exit. The results indicate that similar SNCR performance was achieved over a range of loads from 425 to 535 MW. The 100% Illinois data suggest that even at peak load, the upper front wall level injectors were able to achieve slightly better than 30% NOx reduction with less than 5 ppm ammonia slip from baseline NOx levels of 0.25 lb/MBtu. The ammonia slip measurements show a dramatic increase in ammonia slip when the NSR is increased above 1.5.

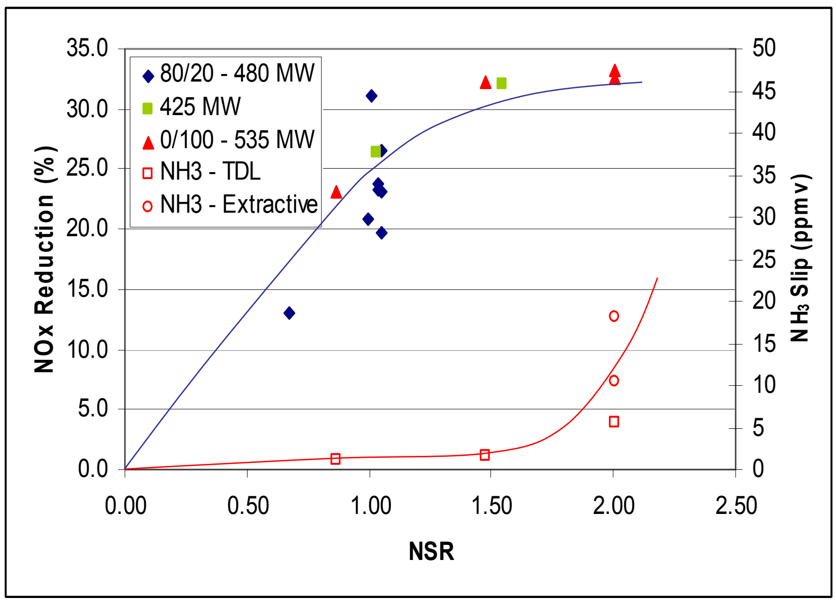


**Figure 4:** Measured NOx reduction and ammonia slip plotted vs NSR as a function of load and fuel blend. Ammonia slip measurements are shown only for the 0/100 blend.

*ALTA Results*

The parametric tests that were completed to separately assess RRI and SNCR performance were used to determine optimal injector locations as well as optimal injector parameters to use when combining RRI and SNCR. Figure 5 shows the NOx emissions resulting from all tests involving the combination of staging, RRI, and SNCR under conditions of nominally 480 MW and 80/20 coal blend. For comparison, OFA-only, RRI-only, and SNCR-only test results employing the optimized RRI and SNCR injection strategies are also shown. The ammonia slip measurements for the ALTA tests are also included. Baseline NOx emissions during the testing were controlled by putting the OFA damper positions in manual. During the ALTA testing, the baseline NOx emissions varied from approximately 0.205 lb/MBtu to 0.255 lb/MBtu. NOx emissions achieved with ALTA varied from 0.117 to 0.15 lb/MBtu depending on the reagent flow (NSR). NOx emissions of approximately 0.12 lb/MBtu were typical and reproducible. The continuous TDL based ammonia slip measurements showed concentrations less than 10 ppm for all tests, and measurements below 5 ppmv were typical.

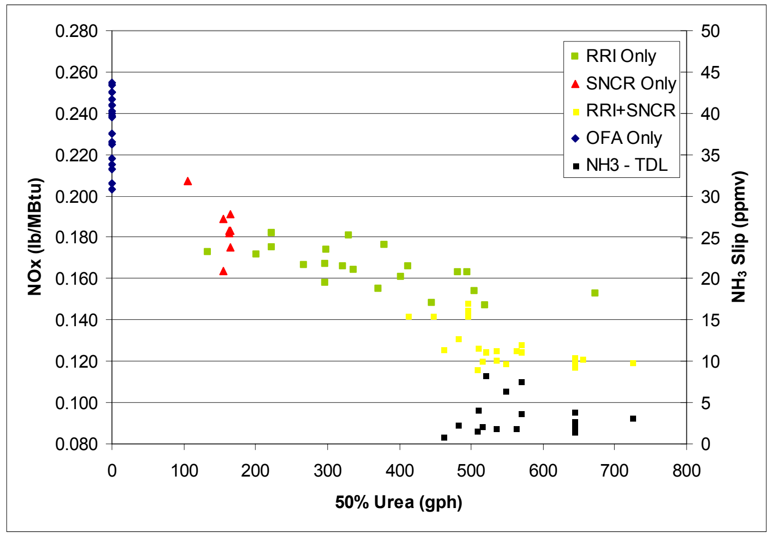


**Figure 5:** NOx emissions and measured ammonia slip plotted as a function of 50% urea flow rate for the components of ALTA. Ammonia slip measurements are only shown for the ALTA results.

The daily LOI measurements during the three weeks of continuous testing showed relatively high values, averaging approximately 25%. In contrast, measurements that were previously reported in Sioux Unit 1 for the time period of June, 2003 through July, 2004 (Cremer, et. al. 2004) averaged approximately 10-15%, although NOx emissions were similar for both time periods. Following the spring 2005 outage, UBC in fly ash in unit 1 was uncharacteristically high. This issue had not been resolved prior to the onset of the ALTA parametric testing. During the three week testing effort, the data showed no discernible correlation strictly between OFA damper position (or NOx emissions) and UBC in the fly ash. Thus, there is no indication that the ALTA testing was responsible for the uncharacteristically high UBC in fly ash during the test period.

## Continuous Test Results

Following the 14 day parametric testing phase of this program, a simple control scheme was implemented to run the combined RRI and SNCR system in a continuous manner over a three day period from June 6 through June 8, 2005. The goal of this test was not to achieve maximum NOx reduction, but to assess whether any problems developed which would provide hints regarding operational problems that would occur when the system was operated continuously. Specific issues that were of interest prior to the testing were:

- Ammonia slip (air heater pluggage)
- Injector failures

The control system was set up in a conservative fashion regarding NOx reduction. The target NSRs were 2.5 and 0.6 for RRI and SNCR, respectively. The urea flows were setup to vary proportionally according to the boiler load. In addition, AmerenUE implemented a control strategy to vary OFA damper position as a function of boiler load in an attempt to retain a baseline (OFA-only) NOx emission of 0.25 lb/MBtu. Since the chemical flows assume a given NSR based on a baseline NOx emission of 0.25 lb/MBtu, higher NOx baseline levels result in a lower overall NSR and vice versa.

The RRI and SNCR injector system was first run in automatic mode overnight from June 2 to June 3, 2005. Figure 6 shows the NOx emissions and the boiler load during that time period. As expected, NOx emissions dropped within the range from 0.12 to 0.13 lb/MBtu while at 480 MW. However, during reduced load operation of approximately 325 MW, NOx emissions decreased further to approximately 0.10 lb/MBtu. The following morning, reagent injection was terminated, verifying that the baseline NOx emissions were in the range from 0.25 to 0.26 lb/MBtu.

Monday morning, June 6, 2005, the reagent injection system was again placed into automatic operation, per the simple control system described above. For all continuous testing, the 16 injector RRI configuration and the five injector SNCR configuration were used exclusively. The NOx emissions for the first two days of continuous testing were in the range from 0.15 to 0.18 lb/MBtu during boiler loads of 480 MW. These emission rates are higher than previously measured values of 0.12 lb/MBtu. The higher emissions during that time-frame were due to higher than anticipated baseline NOx emission. The spikes in NOx levels, seen periodically during the first two days of testing show that the baseline NOx emissions were in the range from 0.28 to 0.30 lb/MBtu. Since the urea flow rate was fixed with boiler load, the actual NSR during this time-frame was significantly lower

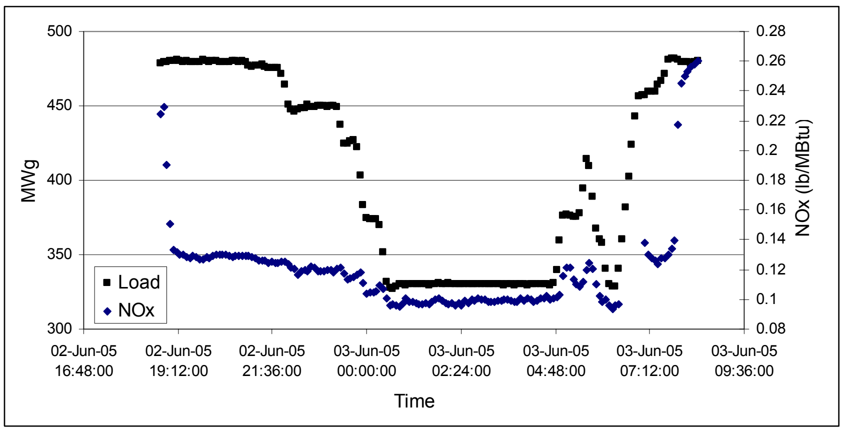


**Figure 6:** NOx emissions and boiler load during the evening of June 2 and morning of June 3, 2005 when the ALTA system was first entered into automatic operation.

than the target value of 3.1 (i.e. 2.6 to 2.8), yielding reduced performance. From the afternoon of June 8 onward, the boiler load was increased above 500 MW. At the same time, the fraction of Illinois #6 coal in the blend was increased above 20%. $SO_2$ concentrations during that time suggest that the coal blend was approximately 50/50. It is likely that the higher proportion of Illinois #6 coal during that time frame led to reduced RRI and overall ALTA performance.

Measured pressure drops across the two tubular air heaters in Sioux Unit 1 during the duration of the ALTA tests were seen to respond to the changes in flow that occur with boiler load, but there was no observable increase in pressure drop at a given load over the duration of the tests. It is noteworthy that tubular air heaters are not as susceptible to ammonium bisulfate (ABS) based pluggage as regenerative air heaters. Inspection of the RRI injector tips following the continuous tests verified that all but one of the tips was intact.

## CONCLUSIONS

The results of the field testing conducted in Sioux Unit 1 confirmed the model based predictions indicating that sub 0.15 lb/MBtu NOx emissions could be obtained with ALTA. Specific conclusions based on the results of the parametric and continuous tests of ALTA in Sioux Unit 1 are:

- The combination of RRI and SNCR is able to reduce NOx emissions to 0.12 lb/MBtu with less than 5 ppm ammonia slip in a reliable manner from baseline NOx emissions of 0.25 lb/MBtu or less when firing the typical 80/20 fuel blend at 480 MW or lower.
- RRI alone reduces NOx emissions to 0.16 to 0.17 lb/MBtu from baseline NOx levels of 0.25 lb/MBtu or lower with less than 1 ppm ammonia slip when firing the typical 80/20 fuel blend at 480 MW or lower.
- Increasing the percentage of Illinois #6 fuel in the PRB/Ill. #6 blend leads to a decrease in NOx reduction achievable with RRI when staging to achieve NOx emissions of 0.35 lb/MBtu and below.
    - The lowest NOx emissions achieved with a 60/40 blend were approximately 0.15 lb/MBtu.
    - The lowest NOx emissions achieved with 100% Illinois #6 were approximately 0.165 lb/MBtu
- There is no apparent decrease in SNCR performance with increasing percentages of Illinois #6.
- Continuous testing showed that the water-cooled stainless steel RRI injectors used during the testing can withstand the harsh high temperature environment. Several injector tip failures confirmed that air cooling alone is not sufficient to protect the RRI injectors once inserted past the waterwall.
- Continuous testing indicated that the levels of ammonia slip generated by the ALTA process will not lead to dramatic ammonia bisulphate deposition causing air heater pluggage in the tubular air heaters in Sioux Unit 1 over short time periods.

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