NO_x Control for Utility Boiler Ozone Transport Rule Compliance

Hamid Farzan and Jennifer L. Sivy
The Babcock & Wilcox Company
Research & Development Center
1562 Beeson St.
Alliance, OH 44601
HFarzan@Babcock.com
(330) 860-6628

John Boyle, Hank Xu
Fuel Tech, Inc.
512 Kingsland Drive
Batavia, IL 60510

and

Bruce Lani
U.S. Department of Energy (USDOE)
National Energy Technology Laboratory
P.O. Box 10940
Pittsburgh, PA 15236

ABSTRACT

With sponsorship from the USDOE National Energy Technology Laboratory's Innovations for Existing Plants Program, The Babcock & Wilcox Company (B&W) and Fuel Tech, Inc. (Fuel Tech) teamed to evaluate an integrated solution for NO_x control. This system was comprised of B&W's DRB-4Z® low-NO_x pulverized coal (PC) burner technology and Fuel Tech's NO_xOUT®, a selective non-catalytic reduction (SNCR) technology, capable of meeting a target emission limit of 0.15 lb $NO_x/10^6$ Btu with ammonia slip of less than 5 ppm. Commercial installations of B&W's low-NO_x burner, in combination with overfire air ports using PRB coal, have demonstrated a NO_x level of 0.15 to 0.2 lb/10^6 Btu under staged combustion conditions. The proposed goal of the combustion system (no SNCR) for this project was a NO_x level at 0.15 lb/10^6 Btu. The NO_x reduction goal for SNCR was 25% below the low-NO_x combustion emission levels. Therefore, overall NO_x emissions would approach a level of 0.11 lb/10^6 Btu.

Promising results were obtained with this technology from large-scale testing in B&W's 100-million Btu/hr Clean Environment Development Facility (CEDF) which simulates the conditions of large coal-fired utility boilers. NO_x emissions were reduced with urea injection at full load via a convective pass multiple nozzle lance (MNL) in front of the superheater tubes or in the convective tube bank. The goals of the program were met. At 100% load, using the MNL for very low baseline NO_x (0.094 to 0.162 lb/10^6 Btu depending on burner stoichiometry), an approximately 25% NO_x reduction was achieved (0.071 to 0.124 lb/10^6 Btu) while maintaining NH_3 slip less than 6.4 ppm. At 60% load, using MNL or only wall-injectors for very low baseline NO_x levels, more than 30% NO_x reduction was achieved.

1 INTRODUCTION

The Babcock & Wilcox Company (B&W) and Fuel Tech, Inc. (Fuel Tech), through sponsorship of the U.S. Department of Energy (DOE), teamed together to further investigate an integrated solution for nitrogen oxides (NO_x) control. This system was comprised of B&W's DRB-4Z® low-NO_x pulverized coal (PC) burner and Fuel Tech's NO_xOUT® SNCR (selective non-catalytic reduction) technology. The program built on previous testing that utilized wall injectors for NO_x control. During the previous test program, positive results were obtained, achieving low NO_x with the DRB-4Z® burner (without air staging) and achieving significant further NO_x reduction with Fuel Tech's SNCR technology while controlling the ammonia slip to less than 5 ppm. However, the overall NO_x emissions fell short of the previous project goal. During the previous testing, limited cases were performed with a multiple nozzle lance that was installed into the convective pass. Although conditions were not optimized, promising results were obtained. Building on this data, B&W and Fuel Tech believed that improved performance could be obtained with convective pass injection at full load via a convective pass multiple nozzle lance (MNL) in front of the superheater tubes. The technology has the following advantages: 1) lower injection temperature; 2) improved mixing between urea and boiler gases; and 3) achievement of very fine urea particles that evaporate quickly and engage in reducing NO_x. Therefore, a new program was developed that evaluated the full potential of NO_x reduction utilizing the convective pass MNL with the DRB-4Z® low-NO_x burner.

2 OBJECTIVE

The objective of the program was to achieve a NO_x level below 0.15 lb/10^6 Btu (with ammonia slip of less than 5 ppm) in the CEDF using Powder River Basin (PRB) coal and B&W's DRB-4Z® low-NO_x pulverized coal (PC) burner in combination with dual zone overfire air ports and Fuel Tech's NO_xOUT® System. Commercial installations of B&W's low-NO_x burner in combination with overfire air ports using PRB coal have demonstrated a NO_x level of 0.15 to 0.2 lb/10^6 Btu under staged combustion conditions. The proposed goal of the combustion system (no SNCR) for this project was a NO_x level at 0.15 lb/10^6 Btu. The NO_x reduction goal for SNCR was 25% from the low-NO_x combustion emission levels. Therefore, overall NO_x emissions would approach a level of 0.11 lb/10^6 Btu in commercial installation.

3 RESEARCH FACILITY

Large-scale testing was performed in B&W's 100 million Btu/hr Clean Environment Development Facility (CEDF), which simulates the conditions of large scale coal-fired utility boilers. This one-of-a-kind facility is equipped with one near full-scale B&W DRB-4Z® burner. The CEDF was constructed with water walls and insulated with refractory to simulate the thermal conditions of the middle row burner in a commercial boiler. The CEDF has also been equipped with dual-zone overfire air ports. These ports were strategically located to allow for introduction of combustion air for carbon burnout and further NO_x reduction without interfering with the gas flow patterns in the burner tunnel of the furnace. The convective pass was designed to simulate the flue gas time-temperature pattern found in commercial boilers. In the SNCR process, the products of combustion are treated with an aqueous urea solution, which combines in reduction reactions with NO_x to yield molecular nitrogen. The convective pass was equipped with three new ports for the SNCR multiple nozzle lance. The gas temperature at these three locations ranged from 2000 to 1650°F, providing a large temperature window for optimizing the SNCR reactions. Figure 1 shows the injection system and furnace schematic.

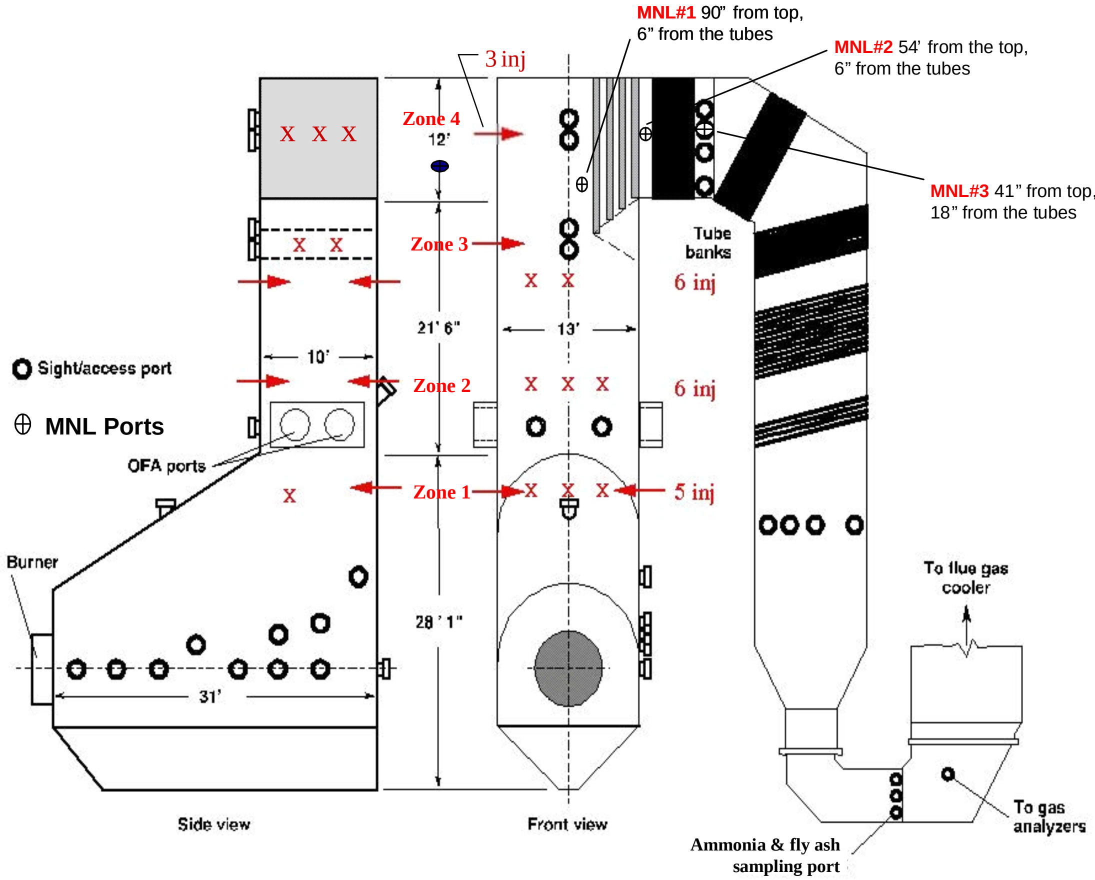

FIGURE 1 CEDF SCHEMATIC WITH SNCR INJECTION LOCATIONS

4 EXPERIMENTAL RESULTS

Low NO_x emissions were achieved during CEDF testing. While firing a Black Thunder PRB coal, baseline NO_x values at full load conditions were found to range from 0.09 to 0.16 lb/10^6 Btu depending on burner stoichiometry. The baseline NO_x values from this round of testing were found to be slightly lower than the previous SNCR test campaign and more comparable to typical values seen during other CEDF test programs and field results. A comparison of the baseline values is shown in Figure 2.

As shown in Figure 1, three MNL ports were utilized during testing. The effect of temperature on the SNCR chemistry was demonstrated during testing by varying the injection location between the ports and measuring the gas temperature in those locations. Figure 3 shows that the MNL-Port 2 was determined to be optimum location at the full load conditions of the CEDF. Temperatures near MNL-Port 1 were found to be higher than desired, which caused the oxidation reaction of urea to NO_x to become a significant path and compete with NO_x reductions for the reagent. The MNL-Port 3, however, was to be on the edge of the lower limit of the effective temperature window. At the lower temperature, the oxidation reaction of urea requires a longer reaction time and therefore reductions are not as great and ammonia slip can become high.

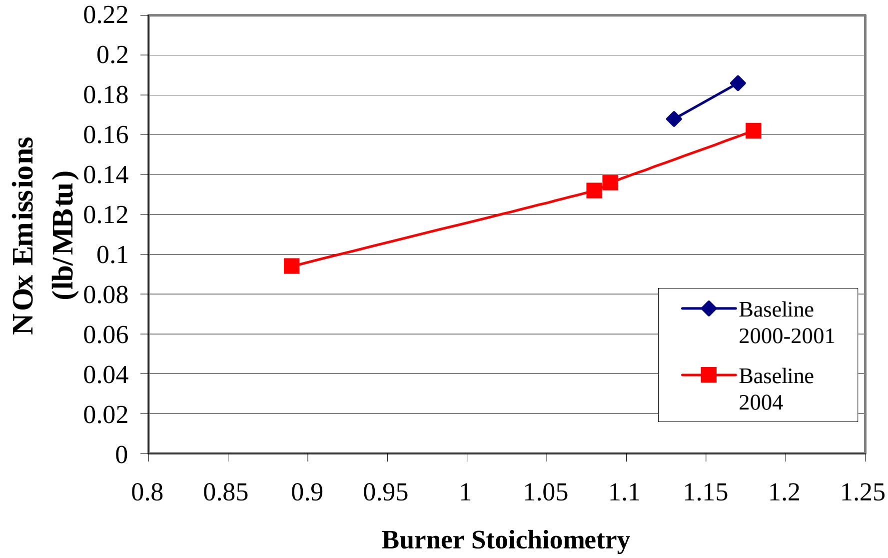

FIGURE 2 COMPARISON OF BASELINE NO_X VALUES FROM PREVIOUS SNCR TEST PROGRAM TO CURRENT SNCR TEST PROGRAM IN THE CEDF

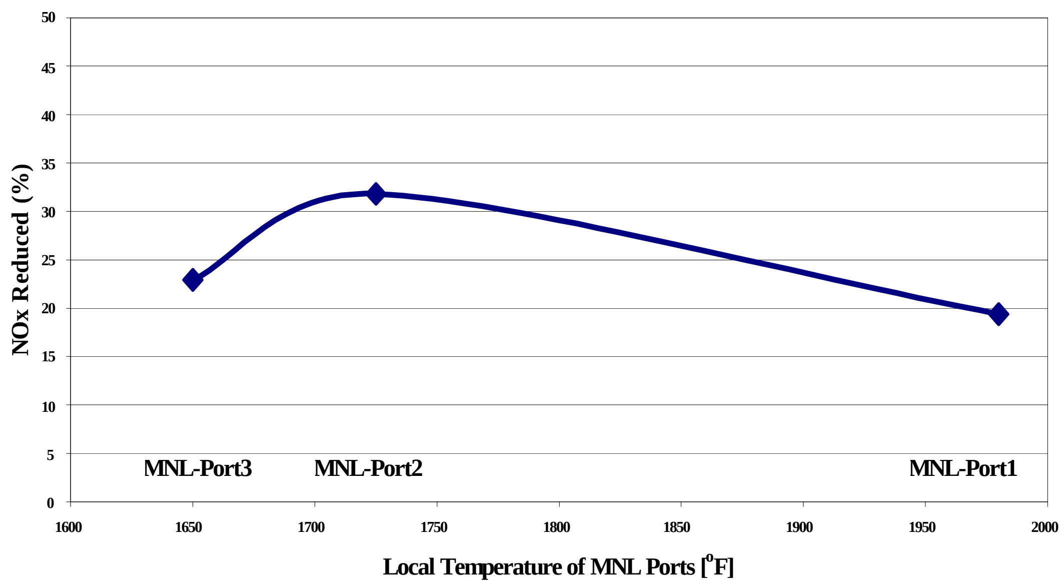

FIGURE 3 TEMPERATURE EFFECT ON NO_X REDUCTION FOR MNL PORT LOCATIONS FOR THE CEDF AT FULL LOAD CONDITIONS

NO_x values representing an approximately 25% reduction were achieved when the MNL was utilized for urea injection in the convective pass. These reduced NO_x values ranged from 0.071 to 0.124 lb/10^6 Btu, while maintaining NH_3 slip less than 6.4 ppm. Figure 4 shows these results. The MNL-Port 2 location shows good urea utilization due to good chemical coverage and the right temperatures.

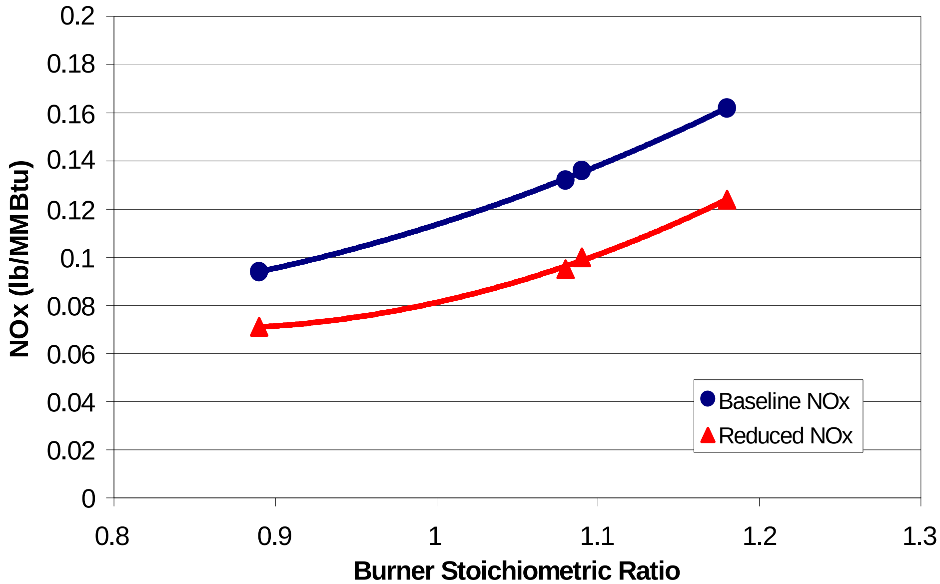

FIGURE 4 NO_x REDUCTION WITH UREA INJECTION AT FULL LOAD CONDITIONS IN THE CEDF

For reduced operation at 60% load, using the MNL ports proved to be not as effective as utilizing wall-injectors only. Figure 5 shows a comparison of wall-injection versus MNL injection at 60% load operation. Wall-injection alone was able to achieve a 31% reduction in NO_x levels compared to only an 18% NO_x reduction when utilizing only the MNL at Port 1.

5 MODELING

Fuel Tech's proprietary Chemical Kinetics Model (CKM) results were used to predict the performance of the NO_xOUT® process and identify the optimum temperature ranges in which chemicals should be released. Temperature-residence time data were computed from the CFD streamlines as input to the chemical kinetics model. A number of streamlines were generated for each of the cases. The streamlines follow the modeled furnace flow beginning at an elevation in the lower furnace. A representative sample of the streamlines was selected and considered to sufficiently describe the temperature distribution within the boiler. CKM modeling was performed on these representative profiles for each of the three cases.

Achievable NO_x reduction is typically limited at low temperatures by ammonia slip and at high temperatures by a lack of significant NO_x reduction. The identification of temperature limits for desired NO_x control is an important result of CKM analysis.

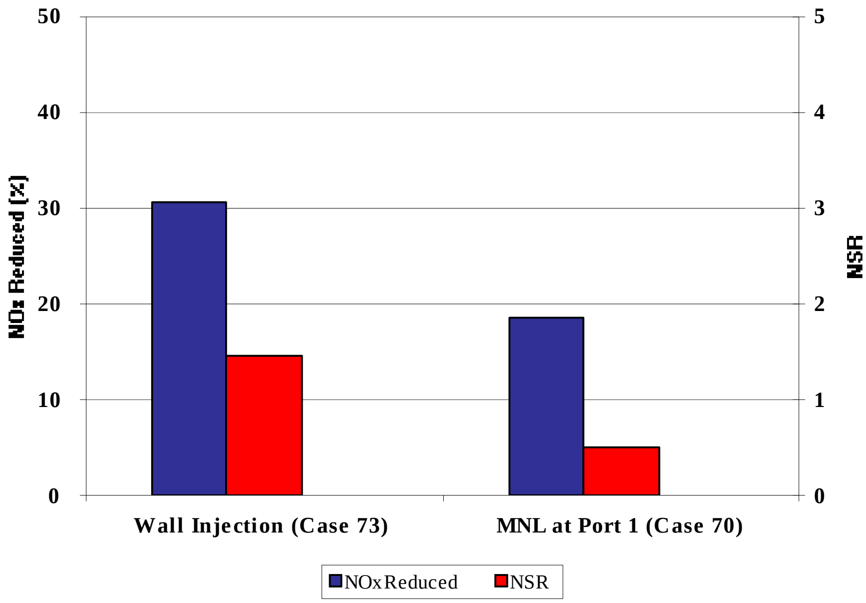

FIGURE 5 **COMPARISON OF WALL-INJECTORS AND MNL AT PORT 1 FOR 60% LOAD OPERATION AT THE CEDF**

Based on the measured data during the testing, at 100% load, the chemical release temperature from the MNL at Port 2 was about 1700°F, and local CO concentration was less than 100 ppm. The testing data showed that the NO_x concentrations were reduced from 0.094 lb/10^6 Btu to 0.071 lb/10^6 Btu at a nitrogen stoichiometry ratio (NSR) of 0.91, and from 0.132 lb/10^6 Btu to 0.095 lb/10^6 Btu at an NSR of 2.43, and from 0.162 lb/10^6 Btu to 0.124 lb/10^6 Btu at an NSR of 0.58. Using the MNL at Port 2, the chemical coverage of the flue gas was excellent. At 60% load, from the wall injection in Zone 3 and Zone 4, chemical reaction occurred near the furnace exit, where based on the previous testing data, the temperature was about 1700°F and CO concentration was less than 100 ppm. The chemical coverage was good but may miss some coverage of the flue gases. The testing data showed the NO_x concentration was reduced from 0.133 lb/10^6 Btu to 0.081 lb/10^6 Btu.

Figure 6 is a plot of the results of CKM analysis at 100% load across varied initial chemical release temperatures for an assumed baseline NO_x concentration of 0.094 lb/10^6 Btu. The figure indicates the results of furnace injection at an NSR of 0.91, with initial CO concentrations of 100 ppm, 200 ppm and 500 ppm. At 100 ppm CO, the effective chemical release temperature window for NO_x reduction is between 1600°F and 1900°F. At 100 ppm CO and 1700°F matching the combustion conditions at MNL- Port 2, the CKM results show that final NO_x concentration of 0.072 lb/10^6 Btu is achievable, which matches the measured data (i.e., 0.071 lb/10^6 Btu as marked in the figure) very well. The CKM results indicated that better NO_x reduction can be achieved if the chemical release temperature is lower. However, in practice, large droplets may not be able to evaporate completely at a lower temperature, which leads to ammonia slip.

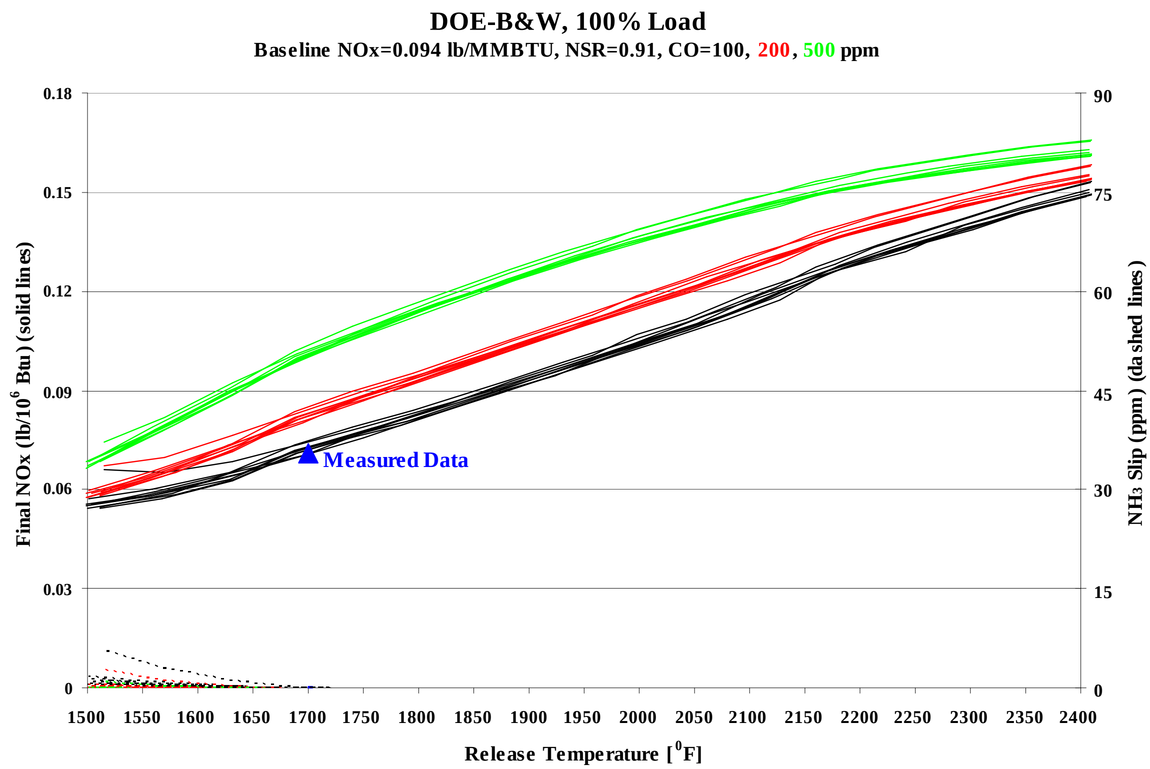

FIGURE 6 CKM RESULTS FOR 100% LOAD AND BASELINE NO_x=0.094 LB/10^6 BTU

Figure 7 shows the comparison of experimental data with modeling results with different baseline NO_x levels. As discussed above, final NO_x levels measured for all three cases match modeling predictions very well.

Figure 8 shows the CKM results at 60% load. At 1.50 NSR, 100 ppm CO and 1700°F, NO_x reduction from 0.133 to 0.065 lb/10^6 Btu is predicted, compared to the measured data from 0.133 to 0.081 lb/10^6 Btu. Incomplete chemical coverage of the gases may cause the difference between the prediction and experiment when only wall injection was used. At this load, chemical release temperatures from the MNL at Port 1 were within the effective temperature window, but the gases at the top of the furnace exit were not treated effectively. This explained why NO_x reduction using MNL could not exceed the performance using wall injection only.

From the discussion above, it was found that the CKM modeling could accurately predict experimental data. With the aid of CKM and CFD modeling, the injection design for this unit, including the MNL, provided very good chemical coverage and releases chemical reagent within effective temperature windows. At low initial NO_x concentrations, 20-30% reductions were achievable, while maintaining control of NH_3 slip.

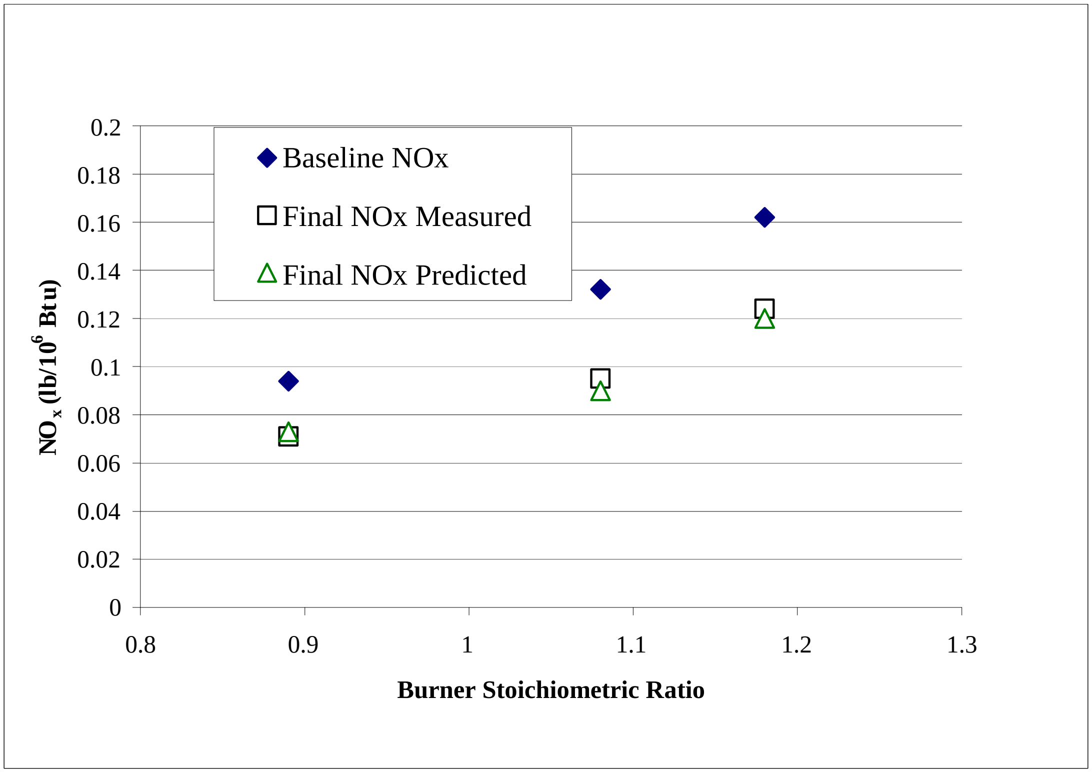

FIGURE 7 COMPARISON OF EXPERIMENTAL DATA WITH MODELING PREDICTIONS

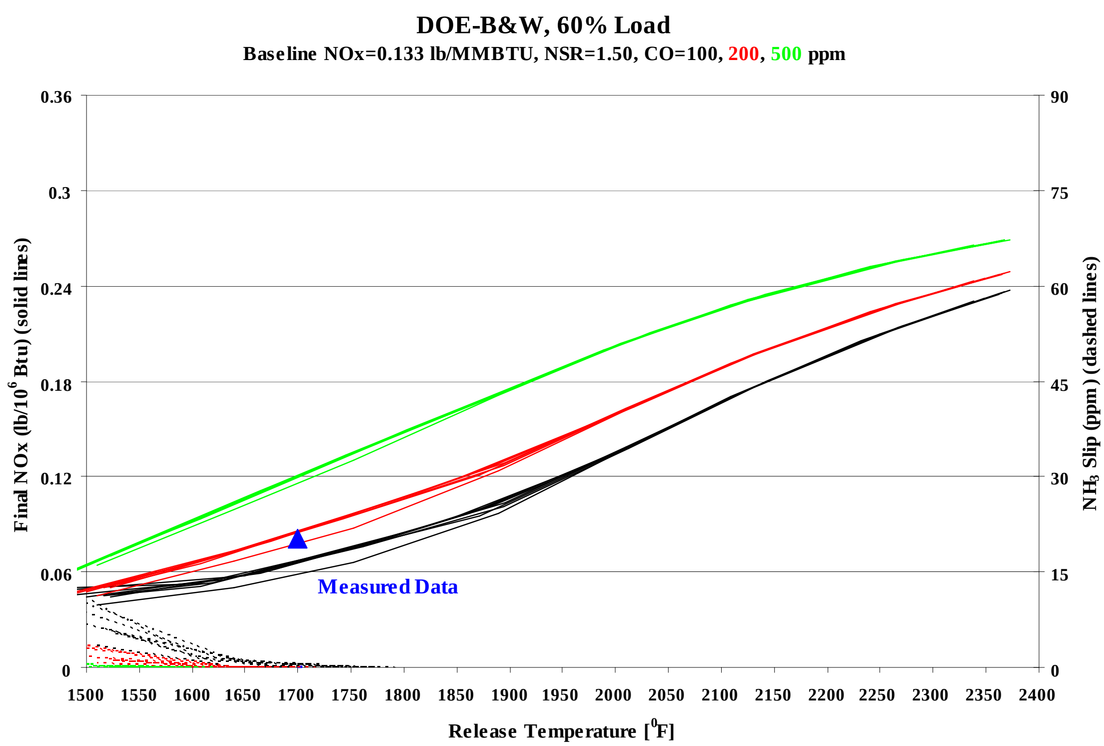

FIGURE 8 CKM RESULTS FOR 60% LOAD AND BASELINE NO_X=0.133 LB/10^6 BTU

6 ECONOMICS

Economic evaluation of integrating the individually demonstrated low NO_x burner (LNB) with overfire air ports (OFA) and selective non-catalytic reduction (SNCR) systems was compared to commercially available selective catalytic reduction (SCR) for a 500 MWe wall-fired, coal-burning boiler for achieving the 0.15 lb NO_x /10^6Btu. Since DRB-4Z® burner NO_x emission is affected by coal rank, different options were considered for boilers using PRB, high volatile bituminous coal, and medium volatile coal.

For units using PRB, the options are:

1) LNB with OFA when the DRB-4Z® burner with OFA ports NO_x emission level is 0.15 lb NO_x/10^6 Btu,
2) LNB with OFA plus NO_XOUT® when the DRB-4Z® burner with OFA ports NO_x emission level is 0.2 lb NO_x/10^6 Btu,
3) LNB with OFA and purchasing NO_x credit when the DRB-4Z® burner with OFA ports NO_x emission level is 0.2 lb NO_x/10^6 Btu,
4) NO_xOUT CASCADE®, or
5) SCR-only systems with a 90% removal efficiency enabling the utility to sell extra credits.

For units burning high volatile bituminous coal, NO_x achieved with the DRB-4Z® burner is approximately 0.3 lb/10^6 Btu. The control options are:

1) LNB+OFA+SNCR and purchasing NO_x credit for compliance,
2) Use LNB+OFA+CASCADE, or

For units burning medium volatile matter coal, NO_x achieved with the DRB-4Z® burner was estimated at 0.4 lb NO_x/10^6 Btu. The control option is LNB+OFA+ Cascade.

Fuel Tech investigated the NO_xOUT CASCADE® for cases with high reagent injection rates (burner $NO_x \geq 0.3$ lb/10^6 Btu) where ammonia slip can be reduced with a catalyst. There was no catalyst available in the CEDF to promote reaction between ammonia and NO_x which is the basis for NO_xOUT CASCADE® technology. For the purpose of this economic analysis, the NO_xOUT CASCADE® NO_x reduction was estimated based on Fuel Tech's experience. The capital cost of NO_xOUT CASCADE® is lower because it is assumed that the NO_xOUT CASCADE® will be an in-duct system and therefore cost saving over a standard SCR system can be realized.

Table 1 compares the annual levelized costs of NO_x control for different options. The costs are based on 2004 dollars for a 500 MW_e boiler with a pre-retrofit NO_x level of 0.5 lb/10^6Btu. A 20 year project life and 20 year book life were selected. The most important assumption was the NO_x credit cost determined from the market trading on SIP NO_x credits. The current price for NOx credit is approximately $2,500 per ton. However, the publicly available data showed the cost of NO_x credits varies from $7,900 to $4,300 per ton for the August 2001 through May 2003 period. Therefore, we performed a sensitivity study of this value to determine at what price an option is viable (see below). An SCR efficiency of 90%, which is available commercially, was considered.

The levelized costs are illustrated as a range, since these costs can be different in different boilers. The SCR capital cost is a strong function of retrofit difficulties such as availability of space for the SCR reactor, and the need for fan modifications or a new forced draft fan since SCR may increase the pressure drop beyond the capability of the existing fan. Low-NO_x burner cost is also very site specific and depends on many factors such as adequacy of air and coal measurements in the boiler, pulverizer performance and boiler control. Although the DRB-4Z® low-NO_x PC burner has been specifically developed for retrofit applications with potentially high throat velocity, the potential need for pressure part modifications impacts the cost of equipment. For these reasons, a range of capital costs was considered, which is according to multiple commercial installations of low-NO_x burners and SCR systems. The SNCR capital and operating costs were based on the commercial experience of Fuel Tech.

TABLE 1 INTEGRATED SYSTEM ECONOMICS FOR A 500 MW BOILER

		Coal	Burner NO_x (NOx, lb/10^6Btu)	Levelized Cost ($/ton of NOx Removed)
1	LNB + OFA	PRB	0.15	389 to 704
2	LNB + OFA + SNCR	PRB	0.2	784 to 1099
3	LNB + OFA + Purchase Credit	PRB	0.2	746 to 1061
4	SCR + Sell Credit	All	0.5	1715 to 3918
5	CASCADE®	All	0.5	1506
6	LNB + OFA +SNCR + Purcahse Credit	HVB	0.3	1392 to 1706
7	LNB + OFA + CASCADE®	HVB	0.3	1440 to 1755
8	LNB + OFA + CASCADE®	MVB	0.4	1667 to 1981

The analysis shows that for boilers firing PRB coal, the DRB-4Z® low-NO_x burner in combination with OFA has the lowest annual levelized cost ($389 per ton of NO_x) when the low-NO_x burner emissions are 0.15 lb/10^6 Btu. If the low-NO_x burner emissions are 0.2 lb/10^6 Btu, purchasing credit at $2,500 per ton of NO_x is the lowest combination cost alternative, $746 to $1,061 per ton of NO_x. Although LNB/OFA plus the NO_xOUT® combination cost is slightly higher, ($784 to $1,099 per ton of NO_x removed) SNCR becomes the lowest cost strategy if the NO_x credit cost increases to $2,765 per ton. Since the NO_x levels with wall-fired PRB firing units are very close to 0.15 lb/10^6 Btu, a utility may not choose to install SCR or SNCR on these units and use the DRB-4Z® low-NO_x burner with OFA on these units and rely on system wide NO_x emissions for compliance.

For boilers using high volatile bituminous coal, the total levelized costs for LNB + OFA + SNCR+ NO_x credit (case 6) and LNB + OFA + CASCADE® (case 7) are $1,392 to

$1,706 and $1,440 to $1,755, respectively. At the $2,500 per ton of NO_x credit, these are both lower than the lower range of SCR cost of $1,715 per ton of NO_x removed. But the three options are close, and site specific considerations would determine the best technology. Ease of the SCR and/or burner retrofit could be a key to the determination of the selected technology.

As mentioned earlier, NO_x credit costs have been very volatile. Figure 9 shows the effect of NO_x credit cost. LNB + OFA + SNCR+ NO_x credit (case 6) is the least cost option when NO_x credit is less than $2,725 per ton of NO_x. When the NO_x credit cost increases above $2,725 per ton of NO_x, CASCADE® becomes the lowest cost strategy and at $3,460 per ton of NO_x, SCR will become the least cost alternative. SCR may be the choice for newer and larger boilers while SNCR can be used for smaller and older units that are scheduled to shut down within the 5-10 years.

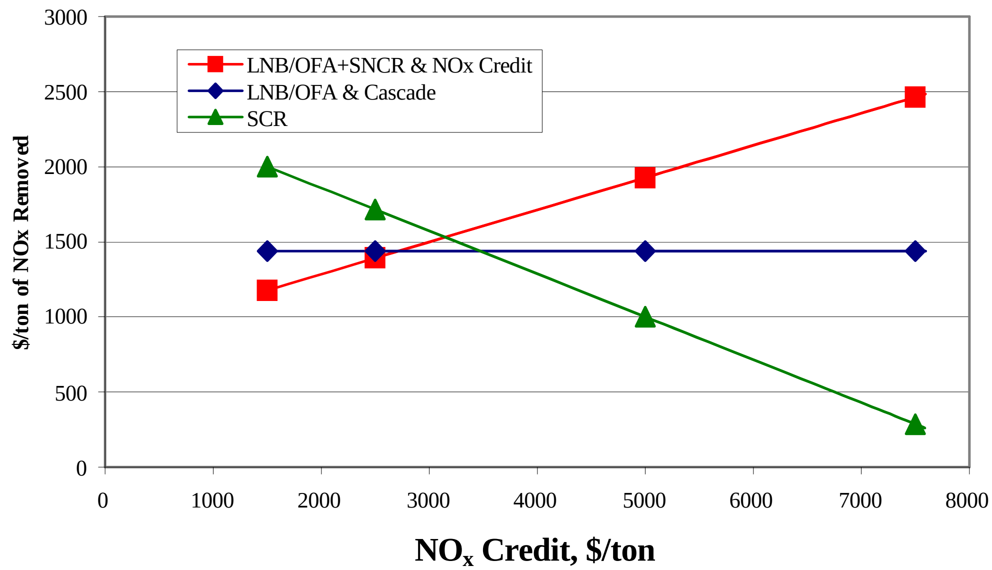

FIGURE 9 NO_X REDUCTION COST FOR UNITS FIRING BITUMINOUS COAL

For boilers using medium volatile bituminous (MVB) coal, LNB + OFA could be combined with CASCADE. The NO_x control cost for LNB + OFA + CASCADE® is $1,667 to $1,981 per ton of NO_x removed. Again, the site specific situations would determine the suitability of the technology.

7 CONCLUSIONS

- Substantial NO_x reductions were achieved utilizing B&W's DRB-4Z® low-NO_x PC burner and SNCR utilizing a multiple nozzle lance (MNL). At full load, the MNL was tested at a temperature range of 1650 to 1980°F. The optimum injection was 1700-1750°F. At the full load conditions using SNCR and firing a PRB coal, a nominal NO_x reduction of 25% was achieved from a range of baseline NO_x values of 0.09 to 0.16 lb/10^6 Btu resulting in NO_x values of 0.07 to 0.12 lb/10^6 Btu. At the reduced load (60%), the MNL was located at the furnace exit and reduced NO_x, but not as much as with the wall-injectors. Incomplete chemical coverage of the gases is expected to be the reason.

- Our economic evaluation of DRB-4Z® and SNCR for a 500 MW_e plant indicates that the technology is strongly dependent on the coal rank, cost of NO_x credit, and retrofit difficulty. A site specific economic evaluation is required for each unit.
  - For boilers firing PRB coal, the NO_x levels with DRB-4Z® and OFA are very close to 0.15 lb/10^6 Btu (commercial experience 0.15 – 0.2 lb/10^6). The least cost strategy is: 1) purchasing NO_x credit if the NO_x credit cost is less than $2,765 per ton of NO_x, 2) SNCR if the credit cost is more than $2,765 per ton of NO_x, 3) SCR if NO_x credit cost is more than $4,760 per ton of NO_x.
  - For boilers using high-volatile bituminous coals, the combination of DRB-4Z® and OFA + SNCR and purchasing credit could achieve a compliance strategy. The least cost strategy is dependent on the NO_x credit cost: 1) purchasing NO_x credit if the cost is less than $3,460 per ton of NO_x, 2) SCR if the credit cost is above $3,460 per ton of NO_x.
  - For boilers using medium volatile bituminous (MVB) coal, DRB-4Z® and OFA could be used to achieve a nominal NO_x level of 0.4 lb/10^6 Btu. Additional NO_x control equipment is required to achieve compliance. LNB + OFA + CASCADE® or an SCR system could be the least cost strategy depending on the site specific situations.