babcock & wilcox power generation group

NO_x Control for Utility Boiler OTR Compliance

Final Report

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June 2008

US DOE NETL Contract No.: DE-FC26-03NT41722
B&W Contract No.: RCD-1449

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DATE ISSUED: JUNE 2008

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ABSTRACT

Babcock & Wilcox Power Generation Group (B&W) and Fuel Tech, Inc. (Fuel Tech) teamed to evaluate an integrated solution for NO_x control 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. In a previous project sponsored by the U.S. Department of Energy (DOE), 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. Under the most challenging boiler temperatures at full load conditions, NO_x emissions of 0.19 lb/10^6 Btu were achieved firing Powder River Basin coal while controlling ammonia slip to less than 5 ppm. At a 40 million Btu/hr firing rate, NO_x emissions were as low as 0.09 lb/10^6 Btu. Improved performance with this system was proposed for this new program with injection at full load via a convective pass multiple nozzle lance (MNL) in front of the superheater tubes or in the convective tube bank. Convective pass lances represent the current state-of-the-art in SNCR and needed to be evaluated in order to assess the full potential of the combined technologies.

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 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 is a NO_x level at 0.15 lb/10^6 Btu. The NO_x reduction goal for SNCR is 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.

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.

Although site specific economic evaluation is required for each unit, our economic evaluation of DRB-4Z® burner and SNCR for a 500 MW_e plant firing PRB shows that the least cost strategy is low-NOx burner and OFA at a cost of $210 to $525 per ton of NO_x removed. Installation of SNCR allows the utilities to sell more NO_x credit and it becomes economical when NO_x credit cost is more than $5,275 per ton of NO_x.

TABLE OF CONTENTS

<u>**LIST OF TABLES**</u>

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

LIST OF PICTURES

1 INTRODUCTION

Under sponsorship of the U.S. Department of Energy's National Energy Technology Laboratory (NETL), Babcock & Wilcox Power Generation Group (B&W) and Fuel Tech, Inc. (Fuel Tech) teamed to evaluate an integrated solution for NO_x control for coal burning wall-fired boilers. 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. The technology's emission target was to achieve 0.15 lb $NO_x/10^6$ Btu. In a previous project, 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. Under the most challenging boiler temperatures at full load conditions, NO_x emissions of 0.19 lb/10^6 Btu were achieved firing Powder River Basin coal while controlling ammonia slip to less than 5 ppm. At a 40 million Btu/hr firing rate, NO_x emissions were as low as 0.09 lb/10^6 Btu.[(1)]

Limited testing was performed with SNCR injection in the convective pass during this previous testing, which showed good potential for NO_x reduction. B&W and Fuel Tech proposed that improved performance could be achieved with injection at full load via a convective pass multiple nozzle lance (MNL) in front of the superheater tubes or in the convective tube bank. Convective pass lances represent the current state-of-the-art in SNCR and needed to be evaluated in order to assess the full potential of the combined technologies. A description of the test program and the results obtained are detailed in this report.

1.1 BACKGROUND

Coal-fired electric utilities are facing a serious challenge with regards to curbing their NO_x emissions. The proposed Ozone Transport Rule (OTR) affects 22 states in the ozone transport region plus the District of Columbia. It requires them to develop a State Implementation Plan (SIP) for curbing the NO_x emissions from their boilers during the ozone season to 0.15 lb $NO_x/10^6$ Btu. Presently, no boiler vendor has a commercial burner for coal-burning wall-fired boilers that can consistently achieve 0.15 lb $NO_x/10^6$ Btu, even with a Powder River Basin

(PRB) coal. While the continuing low-NO_x burner and advanced staging R&D shows promise of achieving 0.15 lb $NO_x/10^6$ Btu for PRB and high volatile bituminous coals, post combustion technologies will be required with medium to low volatile coals. Figure 1.1 shows the historical NO_x emission levels from different B&W burners. Figure 1.1 shows that based on three large-scale commercial installations of the DRB-4Z® burners in combination with OFA ports, using Western subbituminous coal, the NO_x emissions ranged from 0.16 to 0.18 lb/10^6 Btu. It appears that with continuing research and development, the Ozone Transport Rule (OTR) emission level of 0.15 lb $NO_x/10^6$ Btu is within the reach of combustion modification techniques for boilers using western U.S. subbituminous coals. Although NO_x emissions from the DRB-4Z® burner are nearing OTR emission level with subbituminous coals, the utility boiler owners that use bituminous coals can still benefit from the addition of an SNCR and/or SCR system in order to comply with the stringent NO_x emission levels facing them.

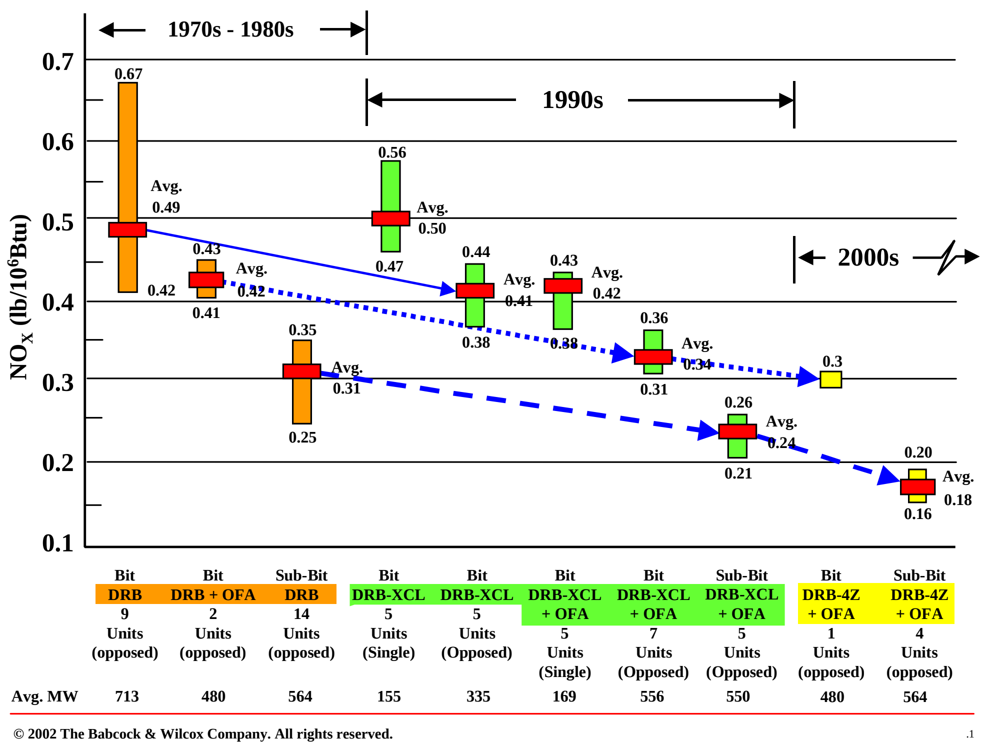


FIGURE 1.1 B&W LOW-NO_X BURNER ADVANCEMENTS

Babcock & Wilcox Power Generation Group (B&W) and Fuel Tech, Inc. (Fuel Tech) have previously teamed to evaluate an integrated solution for NO_x control utilizing B&W's DRB-4Z® low-NO_x pulverized coal (PC) burner technology and Fuel Tech's NO_xOUT® selective non-catalytic reduction (SNCR) technology, which is capable of meeting a target emission limit of 0.15 lb $NO_x/10^6$ Btu. The B&W/Fuel Tech approach combines the best available combustion and post-combustion NO_x control technologies. Large scale testing has previously been conducted in B&W's 100-million Btu/hr Clean Environment Development Facility (CEDF) which simulates the conditions of large wall-fired utility boilers. This previous testing provided an evaluation and optimization of the integrated NO_x control system. Three coals were burned during the previous test campaign: a Western subbituminous coal, a high volatile bituminous coal and a medium-volatile bituminous coal. These coals ranged in fixed carbon-to-volatile matter ratios (FC/VM) of 1.2 to 2.4. The Western subbituminous coal was a Spring Creek coal from the Powder River Basin (PRB). This coal was typical to other PRB coals tested in the CEDF and in the field with the DRB-4Z® burner. A Pittsburgh #8 coal was chosen to represent typical high-volatile bituminous coals. It is harder to obtain low NO_x emissions with the high-volatile coals than it is with a Western subbituminous. A Middle Kittanning coal was chosen for the middle-volatile bituminous coal. This coal had a FC/VM of approximately 2.4. A middle-volatile coal was chosen to serve as a challenging coal to meet the NO_x emissions.

During the 2000-2001 test program and under the most challenging boiler temperatures at full load conditions, baseline (unstaged, no air staging) NO_x emissions were 0.26 lb/10^6 Btu for PRB, 0.30 for Pittsburgh #8, and 0.40 for Middle Kittanning coal. The SNCR system reduced NO_x emission levels to 0.19, 0.22, and 0.32, respectively. Under the more favorable reduced load conditions, NO_x emissions were lower for both baseline (burner only) and SNCR operation. Baseline NO_x emissions of 0.17 lb/10^6 Btu for PRB coal at 60 million Btu/hr were reduced to 0.13 lb/10^6 Btu by SNCR. The lowest NO_x of 0.09 lb/10^6 Btu was achieved at a 40 million Btu/hr firing rate. These data were obtained while the ammonia slip was below 5 ppm. In summary, the results of testing were positive. The DRB-4Z® low-NO_x burner produced low NO_x without air staging. Significant NO_x reductions were demonstrated from very low baselines by SNCR application while controlling ammonia slip to less than 5 ppm.

The previous development work was performed with urea using wall-injectors. Improved performance with convective pass injection at full load via a convective pass multiple nozzle lance (MNL) in front of the superheater tubes was studied in the current project. This technique 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.

Furthermore, since SNCR performs very well in low load conditions, a hybrid selective catalytic reduction (SCR)/SNCR technology could be commercialized to take advantage of the strength of both technologies. The full-load conditions of utility boilers are very challenging environments for SNCR technology, since temperatures are high and residence time is low for reaction. SCR, on the other hand, can achieve over 90% reduction at full load, but there are concerns about catalyst poisoning at low loads due to ammonium bisulfate deposits on the catalyst. If SNCR is utilized for low load and SCR for full load conditions, the hybrid system will use the strength of both technologies. Aqueous ammonia injection at low load was considered as a potential SNCR augmentation to NH_3-SCR performance when the gas temperature at the catalyst reactor causes deposit formation. However, after reviewing the safety requirements, it was noted that when working with aqueous ammonia, all of the equipment must be explosion proof. This is because a spill, or leak, of ammonia may create a cloud of ammonia that may be ignited by the SNCR equipment. Replacement of the SNCR equipment with explosion proof devices did not fit within the schedule and/or budget constraints. The coverage concerns that become important with ammonia on large boilers can be addressed with modeling on a site specific basis.

1.2 IMPROVEMENT OVER EXISTING TECHNOLOGIES

The cost of the low-NO_x burner/SNCR technology is less than three-quarters of the cost of SCR. Economic analyses have shown that the total levelized costs of low-NO_x burner/SNCR and SCR for a 500 MWe wall-fired boiler firing PRB coal with a baseline NO_x emission of 0.5 lb/10^6 Btu are \$784 and \$1715/ton of NO_x removed, respectively.

A hybrid SCR/SNCR system will reduce the operating and capital costs if it can be located as an in-duct system. Operating cost savings will be realized, since it is well known that when a boiler utilizes an economizer by-pass to maintain catalyst temperature, the boiler suffers an efficiency loss of up to 0.5%. Also, the operating cost will be lower since this proposed technology will prevent a potential maintenance problem with bisulfate deposits. Capital cost saving will be realized by reduction of flue work, dampers, etc. since the economizer by-pass will not be required. As mentioned earlier, this concept was not tested in the CEDF because of safety concerns associated with handling ammonia.

Prior to commercializing the DRB-4Z®, the commercially available low-NO_x burner technologies were capable of controlling NO_x emissions to 0.25-0.40 lb/10^6 Btu depending on coal, combustion equipment, and boiler design. The staged DRB-4Z® burner has been demonstrated using PRB coal in several commercial units and shows a NO_x level of 0.15 to 0.20 lb/10^6 Btu. Therefore, for PRB coal in a worst case scenario, a 25% NO_x reduction is required (from 0.20 to 0.15 lb/10^6 Btu) by SNCR. The 0.15 lb/10^6 Btu NO_x emission level has not been achieved with wall-injectors at the full load conditions. The urea injection via lance was tested in this program to achieve this target level.

It should be mentioned that the advances with combustion modifications such as burner improvements, staging using two rows of OFA ports, and sophisticated boiler control systems may enable improvements to the burner technology to the point that the NO_x limit of 0.15 lb/10^6 Btu can be achieved with not only PRB coal, but also with eastern bituminous coals. In addition, a lower NO_x emission level of 0.11 lb/10^6 Btu has been proposed with Clear Skies regulations that can be met with SNCR.

2 EXECUTIVE SUMMARY

Babcock & Wilcox Power Generation Group (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 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 technology. The program built on previous testing that utilized wall-injection lances 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 injected 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 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.

2.1 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 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 has 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.

2.2 TESTING

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 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. 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 2.1 shows the injection system and furnace schematic.

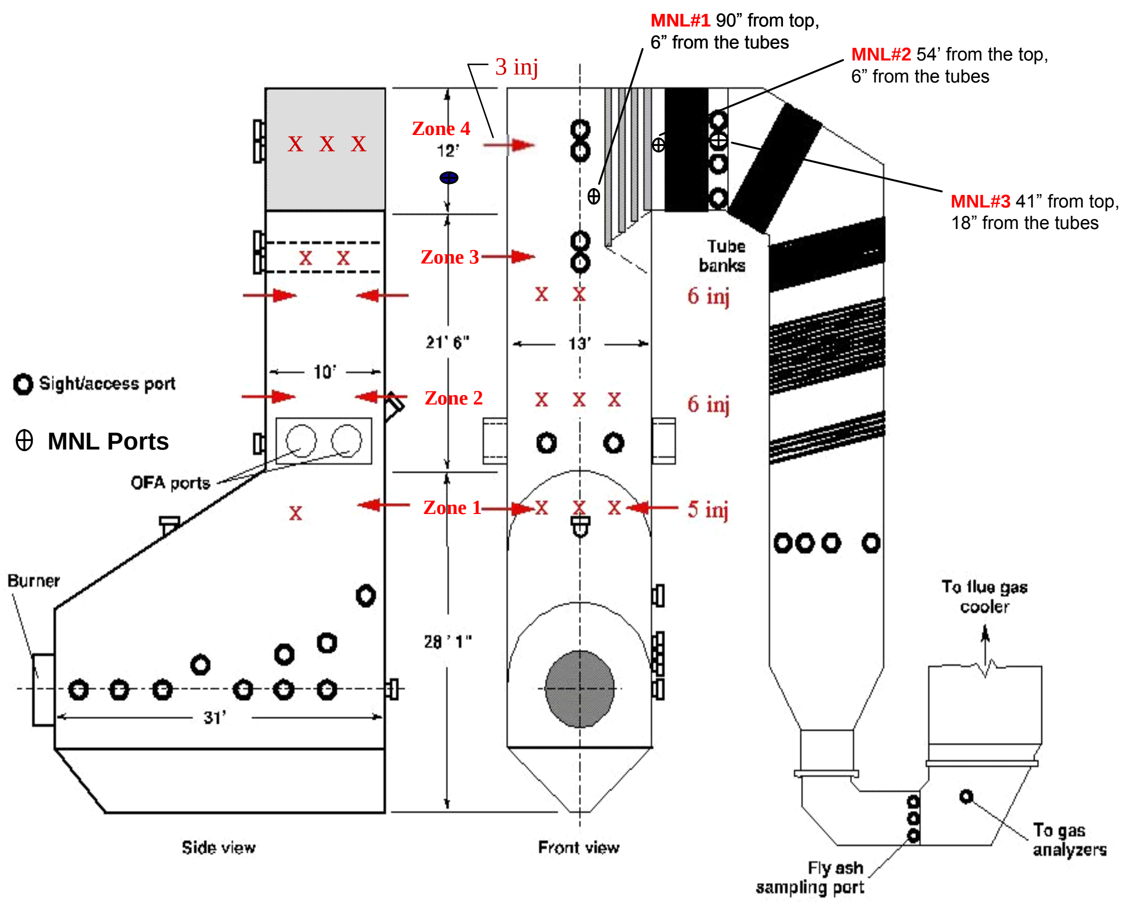


FIGURE 2.1 CEDF SCHEMATIC WITH SNCR INJECTION LOCATIONS

2.3 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 (overall excess O_2 was maintained at 3%). The baseline NO_x values from this round of testing were found to be slightly lower than the previous SNCR test campaign(1) and more comparable to typical values seen during other CEDF test programs and field results. The previous work was performed with a new boiler refractory that increased boiler temperatures and higher NO_x. A comparison of the baseline values is shown in Figure 2.2.

As shown in Figure 2.1, 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 2.3 shows that the MNL-Port 2 was determined to be optimum location. 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.

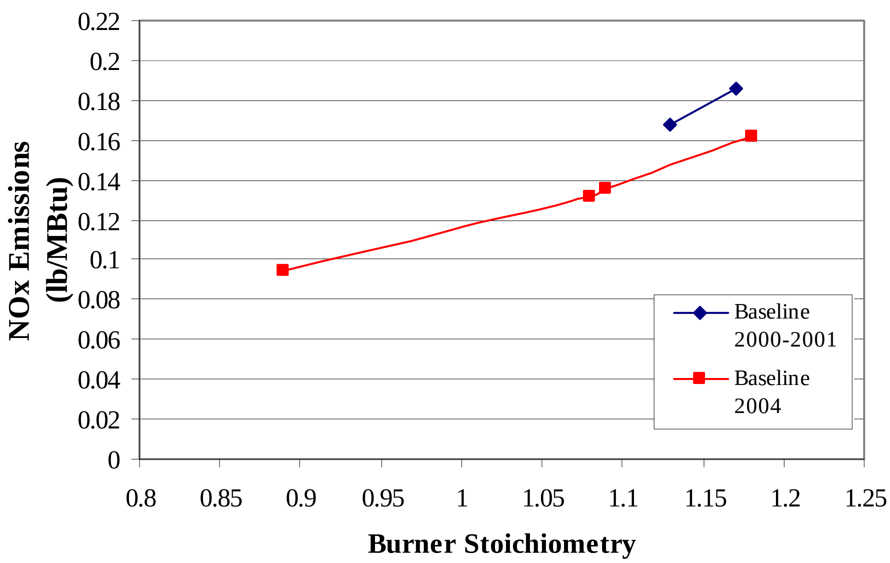


FIGURE 2.2 COMPARISON OF BASELINE NO_x VALUES FROM PREVIOUS SNCR TEST PROGRAM TO CURRENT SNCR TEST PROGRAM IN THE CEDF

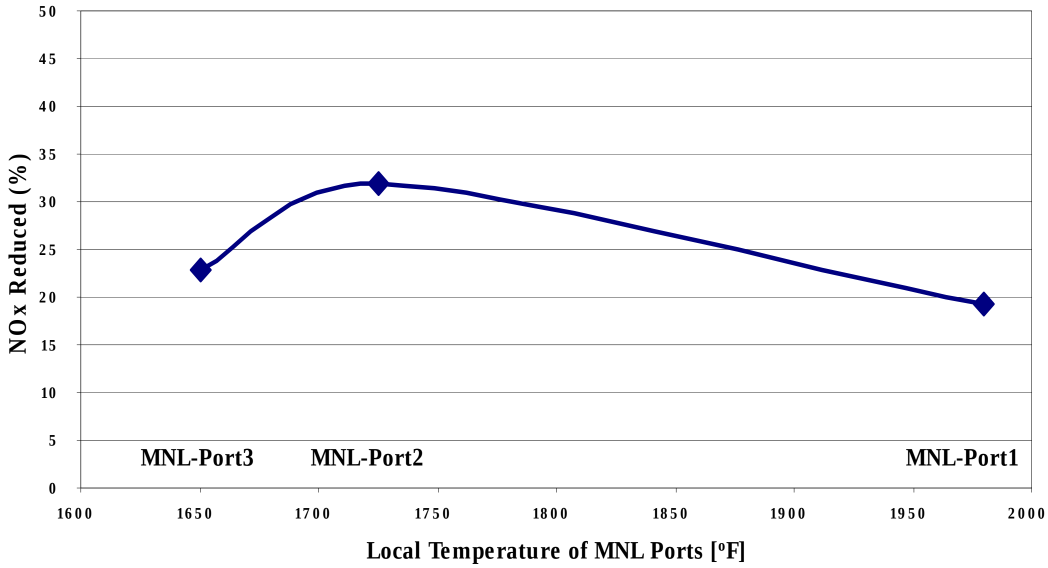


FIGURE 2.3 TEMPERATURE EFFECT ON NO_X REDUCTION FOR MNL PORT LOCATIONS FOR THE CEDF TEST SERIES

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 2.4 shows these results. The MNL-Port 2 location shows good urea utilization due to good chemical coverage and the right temperatures.

For reduced operation at 60% load, using the MNL ports provided to not be as effective as utilizing wall-injectors only. Figure 2.5 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.

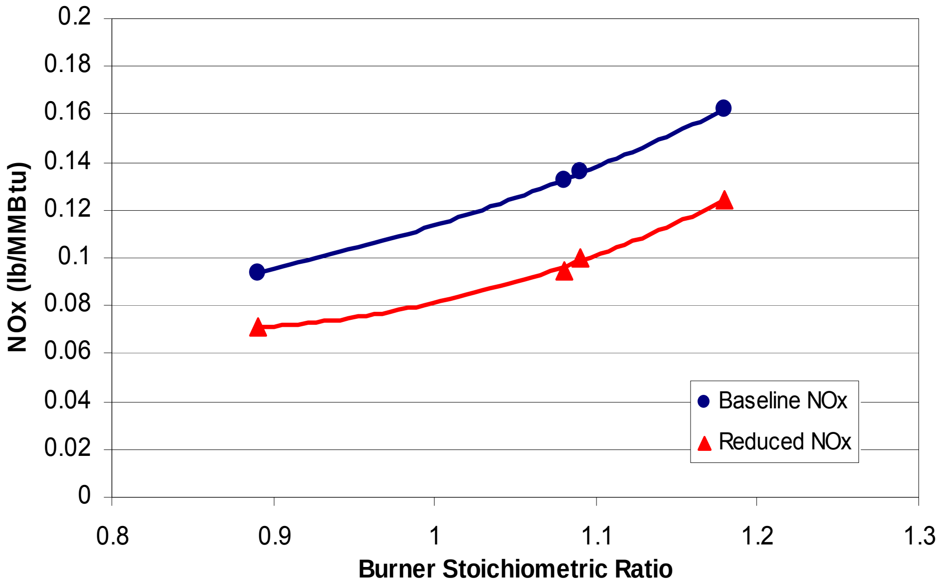


FIGURE 2.4 NO_X REDUCTION WITH UREA INJECTION AT FULL LOAD CONDITIONS IN THE CEDF

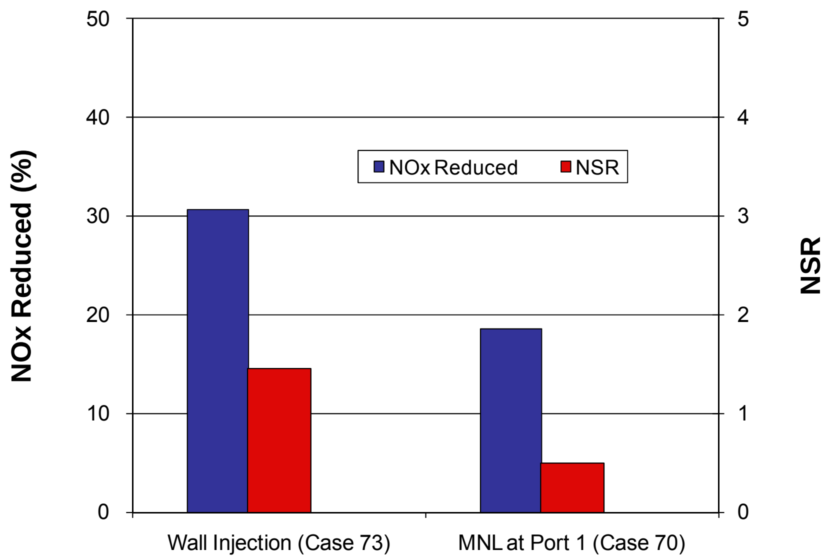


FIGURE 2.5 COMPARISON OF WALL-INJECTORS AND MNL AT PORT 1 FOR 60% LOAD OPERATION AT THE CEDF

2.4 ECONOMICS

To demonstrate the application and benefits of various NO_x control options, their cost-effectiveness was calculated for a reference 500 MWe wall-fired, coal-burning boiler. 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) to determine cost-effectiveness of these technologies to address the EPA SIP call for achieving the 0.15 lb NO_x /10^6Btu limit.

Based on the CEDF testing and commercial experience, several integrated NO_x control options were considered in this evaluation with the goal of reducing the baseline emissions from 0.5 to 0.15 lb NO_x/10^6 Btu or lower. For units using PRB, the options are:

1) LNB with OFA when the DRB-4Z® burner with OFA ports NO_x emission level is 0.125 lb NO_x/10^6 Btu, enabling the utility to sell extra credit
2) LNB with OFA plus NO_XOUT® when the DRB-4Z® burner with OFA ports NO_x emission level is 0.125 lb NO_x/10^6 Btu, and sell credit
3) SCR-only systems with a 90% removal efficiency enabling the utility to sell extra credits, or
4) SCR/SNCR hybrid using SCR at full load and SNCR at loads below 60% load, enabling to reduce the overall cost.

The SCR-only scenario as specified in the DOE's program solicitation represents the base case for comparing with the costs of other cases.

Table 2.1 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. It was assumed that the NOx control equipment will be in operation only during ozone season (5 months per year). The most important assumption was the NO_x credit cost determined from the market trading on SIP NO_x credits. The current price for NO_x 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 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.

TABLE 2.1 INTEGRATED SYSTEM ECONOMICS FOR A 500 MW BOILER

		Burner NO_x	NO_x	Levelized Cost
		$lb/10^6Btu$	$lb/10^6Btu$	$/ton of NO_x Removed
1	**LNB + OFA+Sell Credit**	0.125	0.125	$210 to $525
2	**LNB + OFA + SNCR+Sell Credit**	0.125	0.0937	$456 to $1171
3	**SCR + Sell Credit**	0.5	0.05	$1805 to $4007
4	**SCR/SNCR Hybrid**	0.5	0.05/0.375	$1895 to $3783

Our 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 ($210 to $525 per ton of NO_x). Since low-NO_x burners are more cost-effective on a $/ton of NO_x basis than SNCR or SCR technologies in general, there is a great incentive for using them in combination with post-combustion NO_x control methods. The combination of LNB/OFA plus the NO_xOUT® cost is slightly higher $456 to $1,171 per ton of NO_x removed but the final NOx emission is lower and more credit can be sold. Both systems compare well with SCR. However, if a utility decides to install SCR, they could benefit from a combination of SCR and SNCR if installation of SNCR system simplifies the SCR. Our evaluation showed that the SCR/SNCR combination is more economical if SCR capital cost reduces by $13/kW when SNCR is used in lower loads. It should be mentioned that these costs are site specific, and the results may change from unit to unit.

The NO_x credit price volatility is one of the biggest variables in this analysis. Our evaluation shows when the NO_x credit cost increases to $5,275 per ton of NO_x, the combination of low-NO_x burner and SNCR becomes the least cost strategy ($12/ton of NO_x removed) and at $9,940 per ton of NO_x credit, SCR becomes the least cost alternative (-$321/ton of NO_x removed). 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. As the commercial market has witnessed, utilities have asked vendors for the lowest NO_x (0.06 lb/10^6 Btu) on their largest boilers. Some utilities that are concerned about the increase of the NO_x credit costs could install SNCR to reduce their risk.

2.5 CONCLUSIONS & RECOMMENDATIONS

- 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. The chemical kinetic modeling (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.
- 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 (burner stoichiometry of 0.89 to 1.18), resulting in NO_x values of 0.07 to 0.12 lb/10^6 Btu. These NO_x levels were obtained when the MNL has been installed inside the convective tube bank, agreed with modeling predictions very well indicating that the chemical coverage of the flue gas was excellent.
- Using the MNL, a lower baseline NO_x led to a lower final NO_x concentration, which meant that re-optimizing OFA was not needed when adding the SNCR system.
- 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. At this reduced load, chemical release temperatures from the MNL were within the effective temperature window, but the gases at the top of the furnace exit were not treated effectively.
- Although site specific economic evaluation is required for each unit, our economic evaluation of DRB-4Z® and SNCR for a 500 MW_e plant firing PRB shows:

- the NO_x levels with DRB-4Z® and OFA is very close to 0.125 lb/10^6 Btu (commercial experience 0.13 – 0.2 lb/10^6). The least cost strategy is low-NOx burner and OFA at a cost of $210 to $525 per ton of NO_x removed.
- Installation of SNCR allows the utility to reduce NO_x beyond OTR limit and to sell more NO_x credit and it becomes economical when NO_x credit cost is more than $5,275 per ton of NO_x.

3 EXPERIMENTAL

The B&W/Fuel Tech integrated low-NO_x control system is comprised of B&W's DRB-4Z® low-NO_x pulverized coal (PC) burner and Fuel Tech's NO_xOUT® SNCR technology. B&W has a long history of successfully reducing NO_x emissions on coal-fired boilers. The DRB-4Z® burner is the most advanced coal burner yet commercialized by B&W. The advanced DRB-4Z® is designed to produce lower emissions by featuring a patented transition zone (shown later in Figure 3.1). This zone acts as a buffer between the fuel rich flame core and secondary combustion air streams. This design improves mixing and flame stability by limiting recirculation between air streams. These recirculation regions transport combustion products back toward the oxygen lean zone for NO_x reduction.

The DRB-4Z® low NO_x burner was developed as a result of extensive development utilizing computer modeling, prototype design, and large scale testing[(2,3)]. Development testing was performed in B&W's CEDF. The DRB-4Z®, without use of NO_x ports, reduced emissions to less than 0.25 lb/million Btu for a variety of bituminous coals, and less than 0.20 lb/million Btu with subbituminous coals. The DRB-4Z® burner design is solidly based upon the proven performance and experience of B&W's history with low NO_x combustion equipment. Later in the commercial applications of the technology, the DRB-4Z® was used with an OFA system, resulting in the NO_x emission levels of 0.15-0.2 lbs/10^6 Btu for PRB and 0.28-0.36 lb/10^6 Btu for high volatile bituminous coals.

Building on Fuel Tech's extensive SNCR experience, improvements to Fuel Tech's NO_xOUT® SNCR technology were envisioned through use of a multiple nozzle lance in front of the superheater tubes. The injection in front of the superheater is not a new concept and has been previously done by Fuel Tech. During previous research by B&W and Fuel Tech, it was identified that the combination of lower initial NO_x and higher utility boiler temperature requires injection at a lower temperature that had been tested to-date. The CEDF temperature profile closely simulates large utility boilers, and it is believed that a similar urea injection approach would be necessary in large utility boilers (with low initial NO_x levels). The lance injection would give better results because: 1) injection temperature is lower; 2) the spray is via a lance with multiple injection ports, which better increases mixing between the gas and urea; and 3) the fine urea can vaporize fast and react with NO_x in an optimum condition. The wall-mounted injectors produce larger particles for penetration into the boiler, and then it evaporates slowly and reacts with NO_x and O_2 to reduce or generate NO_x. Therefore, the urea injection lance has an advantage for reducing NO_x. The lance is particularly applicable to ultra-low NO_x applications. As the baseline NO_x drops, the target temperature required for NO_x reduction decreases and the window becomes narrower. The lance not only offers injection at lower temperature (in the convective pass) but also provides a tight distribution of droplet sizes to target the chemical release.

In commercial applications today, in-furnace multi-nozzle lances (MNLs) have been installed in many utility boilers when using SNCR systems. NO_x reduction can be improved by more than 5-10%, compared with using wall injection only. However, MNLs are more costly.

A description of the various components of the B&W/Fuel Tech system is given below.

3.1 DRB-4Z® PC LOW-NO_X BURNER

NO_x formation during the combustion process occurs mainly through the oxidation of nitrogen in the combustion air (thermal NO_x) or from oxidation of nitrogen bound to the organic matter in the coal (fuel NO_x). Thermal NO_x is the dominant formation mechanism for natural gas and for fuel oils with little or no fuel nitrogen. Thermal NO_x increases exponentially with temperature and is suppressed by techniques which reduce flame temperature and reduce the concentration of oxygen. Fuel NO_x formation, while complex, can be inhibited by the reduction of oxygen concentration and temperature during the early stages of combustion. Fuel NO_x is the primary formation mechanism during coal combustion, and is highly dependent on coal properties. Highly reactive coals, with low fixed carbon to volatile matter ratio, and coals with low nitrogen content display lower NO_x forming tendencies.

Low NO_x burners regulate the rate of air introduced during the early stages of combustion, usually by use of multiple air zones and hardware to control mixing rates. This reduces oxygen availability as the coal devolatizes and reduces peak flame temperatures, limiting NO_x formation.

The DRB-4Z® pulverized coal burner, shown in Figure 3.1, is designed to reduce NO_x by diverting air away from the core of the flame, reducing the local stoichiometry during coal devolatilization, and thereby reducing initial NO_x formation. Limited recirculation zones between the primary and secondary stream also act to transport evolved fuel NO_x back toward the oxygen lean devolatilization zone for reduction to molecular nitrogen. The coal stream is transported by air in the central primary zone. The air/coal mixture in this zone is set to create a fuel-rich core region. Encircling the primary zone is the transition and secondary air streams to control near-burner and downstream mixing. Combustion air can be diverted from the secondary air stream to the transition zone, or the zone can operate without combustion air. A sliding damper is located over the openings of the transition zone to regulate the flow of air into this zone. Fixed or adjustable vanes can be used to impart proper spin to the transition air for flame stability and additional near-burner mixing control. The majority of the combustion air is supplied through the dual inner/outer secondary zones to complete burnout in the downstream fuel-lean zone. The burner is equipped with a set of fixed pre-spin vanes located in the outer air zone to enhance distribution of air around the periphery of the burner. Adjustable vanes are located in both the inner and outer air zones to impart proper spin to the secondary air for flame stability and optimum mixing of fuel and air. Curved adjustable and fixed vanes were added to the inner secondary air zone to lower the pressure drop through the burner. Secondary air to the inner and outer zones is controlled independently of the spin vanes by means of a sliding damper blocking the inner zone. An inner air distribution cone (IADC) device may be added to enhance flame stability. An outer air distribution cone (OADC) can also be used to change the secondary airflow for mixing control. Devices can also be placed in the transition zone to change the air patterns, thus affecting the air/fuel mixing.

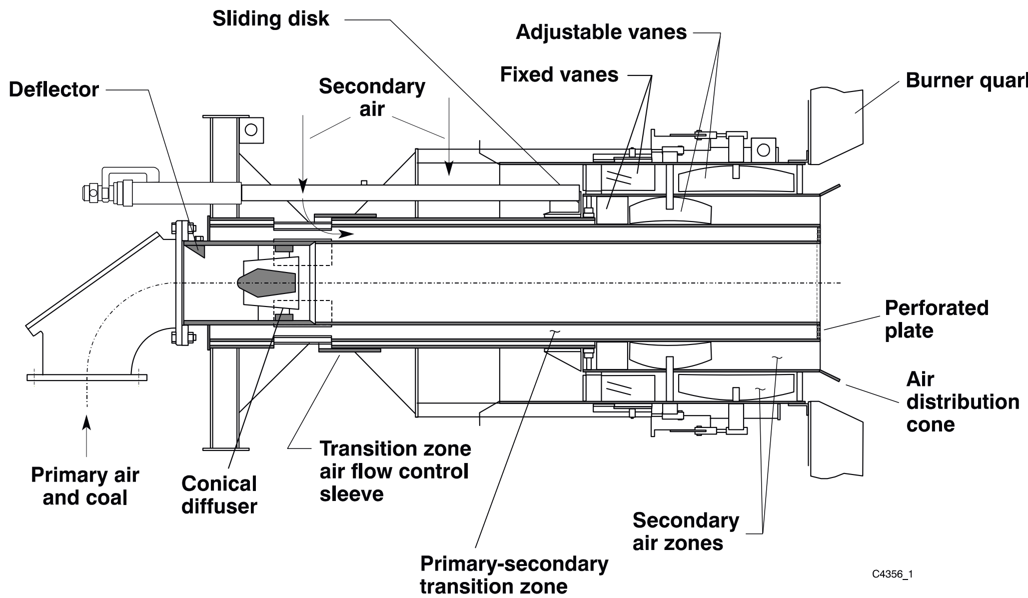


FIGURE 3.1 SCHEMATIC OF THE DRB-4Z® PC BURNER

3.2 SNCR PROCESS

In 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, water, and carbon dioxide. The overall chemical reaction for reducing NO_x with urea is:

$$NH_2CONH_2 + 2\ NO + ½\ O_2 \text{ ---> } 2\ N_2 + CO_2 + 2\ H_2O$$

A range of temperatures where significant NO_x reductions are obtained is called the temperature window. The effective window is a result of chemical kinetics, which is strongly related to initial NO_x levels, CO concentrations, the Normalized Stoichiometric Ratio (NSR) and residence time. At temperatures lower than this window, the reaction requires longer reaction time than is typically available in most commercial combustion systems and thus reductions are negligible and ammonia slip is high. At temperatures higher than this window, the oxidation reactions of urea to NO_x become a significant path and compete with NO_x reduction reactions for reagent. These oxidation reactions increase with temperature and thus NO_x reduction decreases with increasing temperature, while ammonia slip is negligible. A further increase in temperature increases NO_x above the baseline value.

Thus, releasing chemical reagent within the effective temperature window is a key to improve NO_x removal efficiency. Fuel Tech provided performance design tools that increased confidence in the SNCR application. Process performance was analyzed using Fuel Tech's chemical kinetics computer model (CKM). Process conditions were evaluated using computational fluid dynamics (CFD) modeling techniques. B&W had previously provided the CFD modeling results, which enabled the simulation of injector design configurations to evaluate chemical dispersion effectiveness. Used together, the CKM and CFD models provided a sound basis for predictions of expected performance.

3.3 FACILITY DESCRIPTION

The Clean Environment Development Facility (CEDF), located at the Babcock & Wilcox Research Center in Alliance, Ohio, was utilized for optimization of the Effective Control of NO_x with Integrated Ultra Low-NO_x PC Burners and SNCR program. This large scale, 100 million Btu/hr, state-of-the-art test facility integrates combustion and post-combustion testing capabilities to provide the products and processes needed to meet or exceed the current air emission requirements. This scale test facility allows for testing equipment with a minimum of scale-up for commercialization.

Test Facility Description

The CEDF is sized for a fuel heat input of 100 million Btu/hr when burning a wide range of pulverized coals, #2 and #6 oils, and natural gas. In smaller facilities, the complex flow and mixing patterns, coal pyrolysis, and char combustion reactions occurring at the flame front do not always result in predictable geometric scaling. The CEDF has been designed to accommodate either a single burner of 100 million Btu/hr or multiple burners of equivalent total capacity. Previous testing has already been performed in the CEDF with a single, 100 million Btu/hr B&W DRB-XCL® commercial burner and a single 100 million Btu/hr DRB-4Z® ultra low-NO_x burner, the latter of which was utilized for this program. A description of this burner was given in Section 3.3.

The design of the furnace and convection pass is shown in Figure 3.2. The shape of the furnace results from rotating the firing axis of the large burner 90 degrees from the firing axis of the small burners and furnace exit. The furnace is designed as a water-jacketed box with a refractory lining to maintain the proper combustion zone temperature. The vertical part of the furnace is 13 feet deep by 10 feet wide inside the refractory, and about 44 feet high from the centerline of the large burner to the centerline of the gas exit duct. The furnace tunnel for the single burner is 13 feet wide and extends an additional 20 feet from the furnace shaft to prevent flame impingement on the side of back walls. The furnace extends about 9 feet below the burner centerline and terminates in a hopper. The water jacket extends approximately 4 feet above the top of the furnace to provide for steam/water separation in the jacket. Thus, the total external height of the furnace from the apex of the hopper to the top of the water jacket is approximately 62 feet.

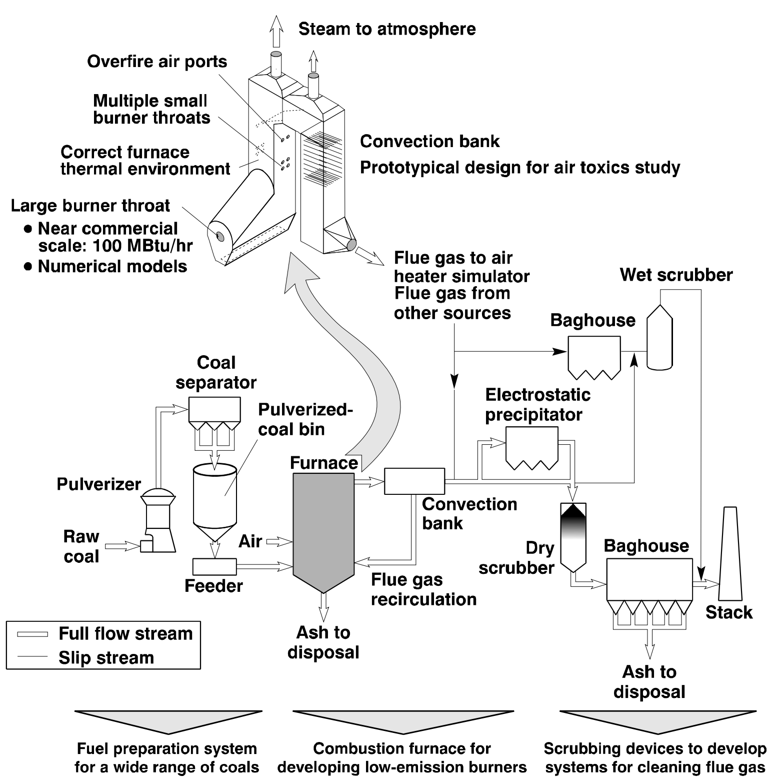


FIGURE 3.2 CLEAN ENVIRONMENT DEVELOPMENT FACILITY FURNACE AND CONVECTION PASS

The single 100 million Btu/hr ultra low-NO_x burner was mounted on the north wall of the lower furnace as an extended zone. This zone is 13 feet wide by about 15 feet high at the burner. The roof of this zone is arch shaped and slopes upward toward the vertical shaft by about 30 degrees. The sloped arch roof is required to provide room for gas recirculation above the burner and to accommodate the natural buoyancy of the flame. Beneath the large burner and furnace shaft there is a hopper and slag tank with a water-impounded drag chain conveyor for removing ash and slag. The windbox, which is about 10 feet square, is not shown but extends out about 6 feet from the front of the furnace.

Overfire air ports are located in the furnace side wall at approximately 3 feet above the transition from the burner tunnel to the furnace shaft. This location allows for introduction of the overfire air for carbon burnout without interfering with the gas flow patterns in the burner tunnel. In these tests, the NO_x concentrations were further reduced by the use of overfire air to create deeper staging of the combustion. The residence time at high temperatures must be kept within critical limits when using overfire air. This residence time may not be easily achieved with the large single burner because of the width and depth established by flame impingement limits with the single burner. The actual residence time in the CEDF with the upper OFA ports is slightly longer than that of typical commercial operation. New boiler configurations could be built with longer residence times; however, this would not occur in retrofit applications. During testing, NO_x levels were purposely increased to values typical of field operation to see the effect of SNCR. Burner performance, stability, and NO_x reduction trends at low stoichiometries were still able to be explored with this OFA port arrangement.

B&W's unique dual-zone overfire air ports provide even distribution of overfire air. The ports are equipped with sliding dampers, spin vanes and air flow measurement devices to enable flow balancing during commissioning of the equipment. The sliding air damper may be automated to control the air through each port. The spin vanes control the swirl or tangential velocity and flare of the air pattern through the OFA port and into the furnace. The air for the OFA ports is taken from the secondary (or combustion) air. Metering devices are installed to control the airflow to the burner and to the OFA ports. The metering devices are connected to the data acquisition system for data collection.

The flue gas from the furnace passes over a nose or arch that protrudes approximately 35% into the furnace. The nose provides sufficient flow resistance to develop the proper gas flow patterns in the vertical shaft and at the entrance of the convection pass for the large single burner. The gas exit is the full width of the furnace, 10 feet by 12 feet high. When the single burner is in use, the evolution of flame-generated volatile organic compounds (VOCs) and air toxics can be followed as the flue gas cools from flame temperature to a typical emission control device temperature. This is accomplished by taking measurements at various points along the flue gas path from the furnace exit to the inlet of the SO_2 emission control device. Careful control of the gas cooling rate is required to provide a gas time-temperature profile that is similar to commercial units. In this way, a representative reaction environment is created for the formation and destruction of NO_x-related species and air toxics. A two-stage cooling process is used to achieve the desired time-temperature history. The first stage is a simulated convection bank while the second stage more closely simulates an air heater.

The convection bank is a 10 x 12-foot water-cooled duct. In order to make the best use of the available space, the convection pass has a horizontal section followed by a down flow vertical section. A large number of water-cooled tubes run from the floor to the ceiling of the horizontal section and side to side with an incline of about 15 degrees in the vertical section. The tubes are spaced uniformly across the duct in any given row, but the number of tubes per row and the row spacing along the duct is very irregular. This non-uniform tube spacing is designed to simulate the flue gas time-temperature pattern found in commercial boilers. Tube spacing is also influenced by the need to accommodate coals with strong fouling tendencies. Sootblowers are installed to keep the convection pass tubes clean. The flue gas cools rapidly in the initial section of the bank but more slowly in the later parts that simulate the economizer. Sufficient heat transfer surface is provided to cool the flue gas from the furnace exit temperature to about 700°F at the exit.

Following the convection pass, the flue gas enters a combination flue gas cool and air heater. The gas temperature leaving this unit is controlled to a suitable value for the gas clean-up systems. The flue gas is primarily cooled with secondary air through preheating of the air. The outlet temperature is adjusted by independently adjusting the airflow through the upper modules. The simulation of the burner and furnace test zone terminates at the flue gas cooler. Numerous sample connections are located along gas flow path to follow the formation and destruction of VOCs and other air toxics.

Boiler convection pass and air heater simulators maintain representative conditions through the entire boiler system to facilitate studies of air toxics capture in the dry scrubber and baghouse. Representative gas phase time-temperature profiles and surface metal temperatures are maintained throughout the convection pass. Convection pass metal temperatures are maintained in the 600-1000°F range by way of a novel double-walled tube design.

Air and Coal Supply

Pulverized coal is supplied to the burner by an indirect or "bin feed" system so that a wide range of air-to-fuel ratios and fuel moistures can be studied. Separating the pulverizer and burner also allows limited periods of independent operation of the coal preparation and burning units. A B&W EL-56 pulverizer is equipped with a dynamically staged, variable speed classifier so that the effects of coal fineness on NO_x production and unburned carbon can be evaluated. Preheated primary air picks up the coal and transfers it to a small baghouse that vents the wet air and drops the coal into a pulverized coal storage bin. The bin is equipped with a nitrogen inerting system to prevent bin fires. The pulverized coal can also be sent directly from the pulverizer to the burner when burning fuels for which the pulverizer output matches the required feed rate and air/fuel ratio.

Pulverized coal is withdrawn from the bottom of the bin by a flow control device and picked up in a transport air stream that carries it to the burner. Spraying water into the transport air upstream of the pick-up point can vary the as-fired moisture level. In order to obtain maximum flexibility and control, separate fans and air preheaters are used for the primary air to the pulverizer, transport air from the pulverizer to the burner, and secondary air to the burner and overfire airports.

Post-Combustion Emission Control

From the flue gas cooler, the gas enters a dry scrubber to control sulfur dioxide emissions. Although this system can be used to advance dry scrubber technology, its current primary purpose is to allow the facility to meet air emission regulation. The dry scrubber is a vertically oriented, 14-foot diameter by 60-foot tall tower (including inlet and exit transition sections) constructed of carbon steel. Flue gas enters the top through an expansion containing flow straightening devices.

Atomized slurry is introduced through a single B&W DuraJet™ atomizer located to provide uniform spray coverage in the vessel. The B&W DuraJet™ atomizer is used in commercial dry scrubbing and humidification systems. The atomizer not only provides finely atomized slurry, but also acts as a mixer to ensure intimate contact between the hot entering flue gas and slurry, maximizing SO_2 removal and drying. The atomizer is mounted in a shield air tube at the scrubber inlet allowing for naturally aspirated vent airflow. A reagent preparation system is designed to wet hydrated lime and prepare slurry for injection into the dry scrubber. The flue gas, along with the dried particulate, travels down the chamber and turns 180° into an air outlet duct. The outlet duct is fitted with a sloped cone to minimize solids dropout in the duct.

Flue gas exiting the dry scrubber is ducted to a pulse-jet fabric filter baghouse. The baghouse consists of six modules arranged in a three-by-two array. Each of the six modules contains 42 full-size bags for a total of 252 bags in the baghouse. The air-to-cloth ratio is adjustable from 4:1 to 6:1 at full load by blanking off modules. The entering flue gas is distributed to the bottom of each of the six modules through a tapered inlet manifold. Manually operated butterfly dampers are used for module isolation. The clean gas exits each module at the top and is collected in a tapered clean gas manifold. Pneumatically operated poppet values are utilized for module outlet isolation.

The pulse-jet cleaning system is designed to permit either on-line or off-line cleaning in either manual of automatic operating modes. For additional flexibility in the automatic mode, the fully adjustable cleaning cycle may be initiated on either baghouse pressure differential, timed, or combined pressure differential/timed basis. The solid by-product dislodged from the bags is transferred from the baghouse by a pneumatic conveyor system to an ash silo for disposal.

Existing post combustion emissions control instrumentation includes: dry scrubber and baghouse outlet temperature, dry scrubber skin thermocouples to monitor deposition, atomizer slurry and air pressure gauges, baghouse pressure drop across each of the six baghouse modules, and a continuous emissions monitor at the stack.

Instrumentation

Calibrated pressure transducers, thermocouples, and flow metering and control devices are integral to the CEDF. Voltage signals from instruments, sensors, and metering devices are collected, converted to a digital signal, and stored by the Data Acquisition System (DAS). STARS/LabVIEW software is utilized to convert these signals to engineering units for on-line real time display in tabular or graphical form at time intervals specified by the operator. Derived quantities such as fuel input (load) and airflow are calculated utilizing other measured instrument values converted to engineering units. The fuel and combustion flows are measured by the DAS electronically utilizing pressure transducers and thermocouples at the flow orifices. Raw voltages from these devices are converted to static pressure, pressure drop, and flow temperature at the orifice by utilizing calibrations based on reference signals. Engineering units for flow are calculated with a calibrated flow orifice equation expressing flow as a function of the above variables.

Convective pass section outlet gaseous species are sampled continuously through a heated sample line. After filtering and drying, CO, CO_2, O_2, NO_x, and SO_2 concentrations are measured and recorded. All analyzers are calibrated daily with certified gas standards.

SNCR Equipment

The SNCR equipment included all necessary equipment for treating the CEDF test unit: pumps, solution, lances, etc. The maximum chemical flow rate, water flow rate, and air pressure were 16 gph, 3.6 gpm, and 70 psig. A storage tank capable of holding up to 4000 gallons of reagent was on site. Portable chemical distribution panels for controlling the injectors were located as practical near the injection location. Pictures 3.1 and 3.2 show the urea injection controls and the MNL inserted into the furnace.

Four injection zones were previously installed in the CEDF to provide sufficient flue gas treatment for 100%, 60% and 40% load operations. The detailed configuration of these injection zones is shown in Figure 3.3. Zone 1 consisted of five wall-mounted injectors located near the furnace shaft transition. Zone 2 was located below the furnace nose with three injectors on both front and rear wall for a total of six injectors. Zones 1 & 2 were not used during this series of testing because minimum load conditions (40% load) were not tested. Zone 3 was located at about the same elevation as the furnace nose. There were six injectors in total: two on the front wall and two on each side wall. Zone 4 was located above the level of the furnace nose. There were three wall injectors on the front wall in Zone 4. A new zone, Zone 5, was added during this test program. An in-furnace multi-nozzle lance (MNL), as shown in Figure 3.4, was built and installed into the furnace exit or the convective pass. The MNL was 8 feet long and had 4 pairs of nozzles. The flue gases at the furnace exit could be treated more effectively than wall injection which was used in the previous test program because using the MNL in Zone 5 allowed the chemical reagent to be sprayed more easily across the convective pass. Three ports along the convective pass were prepared for this MNL. Depending on load operation, the optimum location for the MNL is shifted.

PICTURE 3.1 UREA INJECTION CONTROL SYSTEM

PICTURE 3.2 MNL INSERTED INTO FURNACE

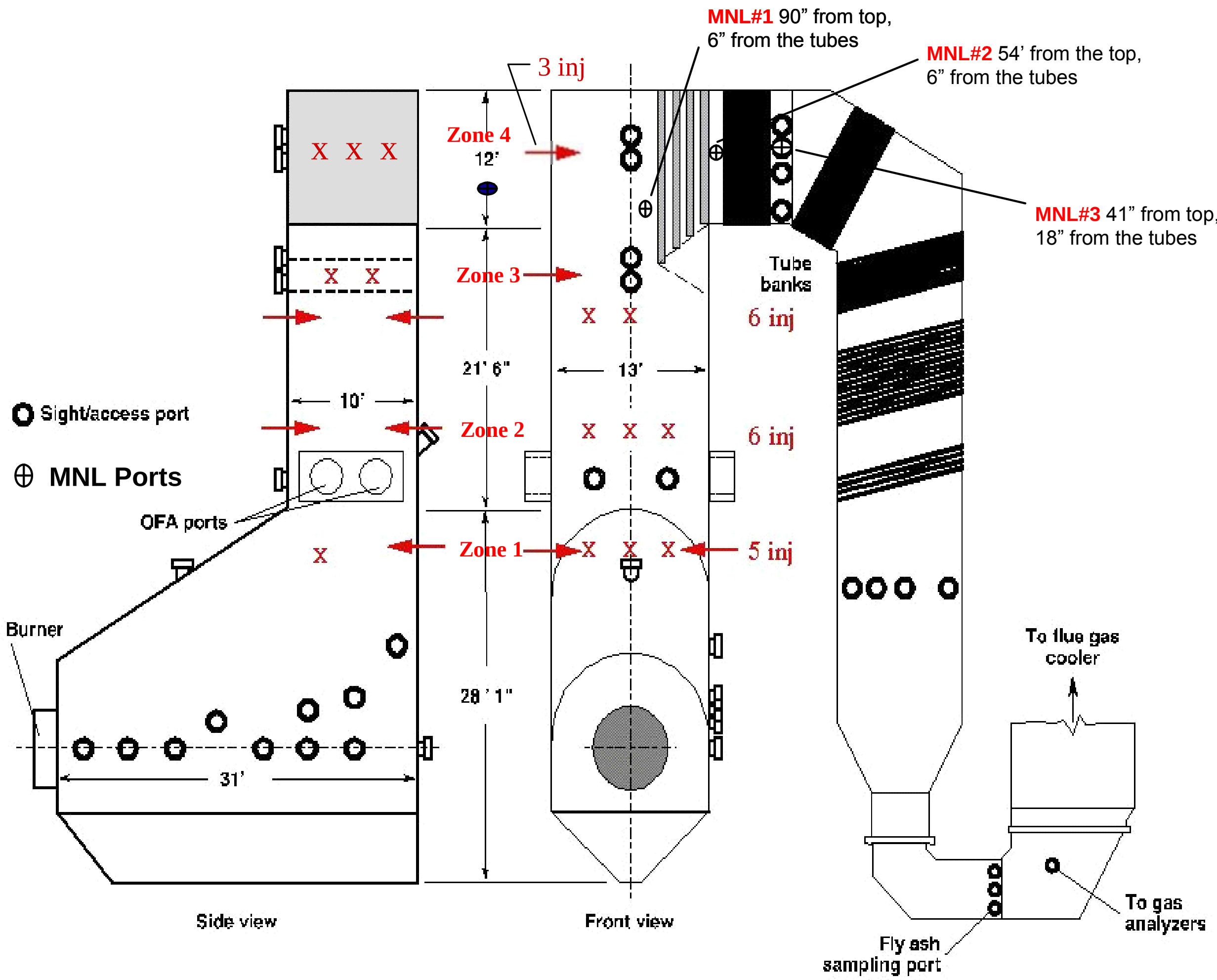


FIGURE 3.3 INJECTOR AND FURNACE LAYOUT

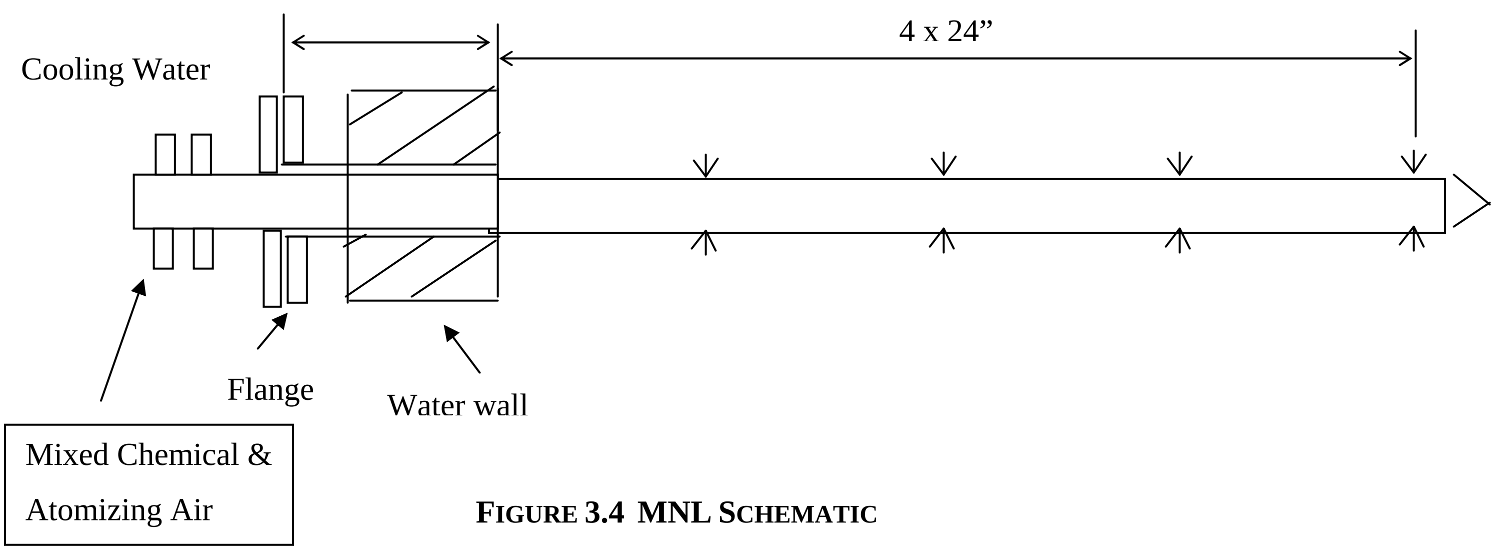


FIGURE 3.4 MNL SCHEMATIC

The preparation for aqueous ammonia, injection at low load was considered as a potential SNCR augmentation to NH_3-SCR performance when the gas temperature at the catalyst reactor causes deposit formation. However, after reviewing the safety requirements, it was noted that when working with aqueous ammonia, all of the equipment must be explosion proof. This is because a spill, or leak, of ammonia may create a cloud of ammonia that may be ignited by the SNCR equipment. Replacement of the SNCR equipment with explosion proof devices did not fit within the schedule and/or budget constraints.

3.4 OPTIMIZATION TESTING

Since the burner hardware was optimized during the previous test program, further burner optimization was not required with the DRB-4Z® burner. The burner settings determined during the previous test series were utilized as the optimum setting. Baseline data was collected for comparison to SNCR optimization. A Western subbituminous Black Thunder coal from the Powder River Basin was utilized for this test program. Proximate, ultimate, and heating value analyses of the as-received coal were determined. Table 3.1 shows the representative analyses of the coal along with the analyses from the previous test program for comparison. The Black Thunder PRB coal utilized during the current test campaign had a lower FC/VM (1.18) than the previous Spring Creek coal, subsequently resulting in lower NO_x emissions. The Black Thunder coal is typical to other PRB coals tested in the CEDF and in the field with the DRB-4Z® burner.

Pulverizer settings were adjusted to produce a desired PC fineness of about 70% through a 200-mesh screen. Pulverized coal samples were extracted from the PC-laden stream after the mill (before the filterhouse) according to the ASME PTC 4.2 procedure. Mass percentage of as-fired PC particles passing through stacked sieves of 30 to 200 mesh screens (600 to 75 μm) were checked each day the coal was pulverized. The particle size distribution can be seen in Table 3.2. As seen in the table, the actual PC size distribution was closer to 52% through 200-mesh, thus a coarser coal than optimally desired. This increase in coal size could contribute to increased CO and LOI values due to slower fuel oxidation. However, since the CO values were not significantly higher, it was determined to stay with the coarser coal than to try to play with the fineness settings and delay testing. We did not measure the fly ash unburned combustibles since it has been under 2% with PRB coal in the CEDF.

Baseline NO_x values were obtained before and after a series of urea injection tests. For SNCR optimization, an aqueous urea solution was sprayed into the furnace or the convective pass. Injection levels and number of ports for different load operations were selected with the aid of numerical modeling and in-furnace temperature and species measurement. Injection of a chemical reagent requires sufficient jet momentum for cross flow penetration. Atomizing air flow requirements for maximum NO_x removal were determined by the way of optimizing the spray pattern, droplet size distribution, evaporation, and mixing. Since the SNCR performance is sensitive to load variations and initial NO_x levels, the gross heat input and burner stoichiometric ratio (BSR) were varied to cover typical conditions. The change of BSR affects the burner/overfire air ratio, which changes the initial NO_x level and CO concentration. Optimizing OFA through the change of BSR provides the best conditions for NO_x control, which may not be true when the SNCR system was added. It was particularly valuable in this testing to see how the combination of OFA and SNCR system affects the NO_x removal efficiency.

TABLE 3.1 PRB COAL ANALYSES

	Subbituminous ***Black Thunder 2004 Test***	**Subbituminous** ***Spring Creek 2000-2001 Test***
PROXIMATE (as rec'd)		
Fixed Carbon (%)	34.99	39.10
Volatile Matter (%)	29.77	31.05
Moisture (%)	29.53	26.21
Ash (%)	5.72	3.64
Fixed Carbon/Volatile Matter	1.18	1.26
ULTIMATE (as rec'd)		
Carbon (%)	48.68	53.10
Hydrogen (%)	3.46	3.78
Nitrogen (%)	0.75	0.64
Sulfur (%)	0.30	0.23
Oxygen (%)	11.58	12.40
As-Fired Moisture (%)	13.56	13.56
Heating Value (Btu/lb) (as rec'd)	8392	9110

TABLE 3.2 PRB COAL SIZE DISTRIBUTION

Mesh Designation & Size (µm)	(Percent Smaller)	
	Black Thunder (2004 Test)	Sprink Creek (2000-2001 Test)
30	99.98	100.00
50	98.18	99.77
70	92.31	98.56
100	80.28	90.00
140	64.46	79.51
200	51.66	63.10

From the previous tests[1], the wall injection zones have been investigated closely and understood well. The SNCR system with wall-injectors provided control to 0.195 lb $NO_x/10^6$ Btu or 25% reduction from the baseline NO_x concentration of 0.260 lb $NO_x/10^6$ Btu at the full load conditions at the CEDF. However, 0.150 lb $NO_x/10^6$ Btu NO_x emission level has not been achieved with wall injectors only. Fuel Tech designed a multi-nozzle lance (MNL) this time to make it possible to access more effective region and provide better chemical coverage of the flue gases. In this testing, more time was spent to test the behavior of the MNL.

Temperature and gas species mapping were made in the upper furnace and convection pass area to document the actual flue gas conditions and to correlate to optimal injection location. Figure 3.5 shows the temperature mapping for the Black Thunder coal during this test series. For comparison, the temperature mapping from the previous test series in 2000-2001 is shown in Figure 3.6. As illustrated, the furnace temperatures from the previous test campaign were found to be hotter, which had been attributed to the newly installed refractory at the time of testing.

Gas species measurements were also made in the furnace to map the CO and O_2 concentrations in the MNL injection area. These furnace mappings are shown in Figures 3.7 and 3.8 for the 2004 and 2000-2001 test campaigns, respectively. Note that the CO concentrations were measured and are presented here as measured. The oxygen levels are high and we believe there is an air leakage in these local measurements. These measurements were obtained while the convection pass outlet O_2 was approximately 3%. Figure 3.7 that CO is decreasing substantially from MNL-Port 1 to MNL-Port 2. The CO measurement at MNL-Port 3 was not attempted because the temperature was low for the SNCR reaction.

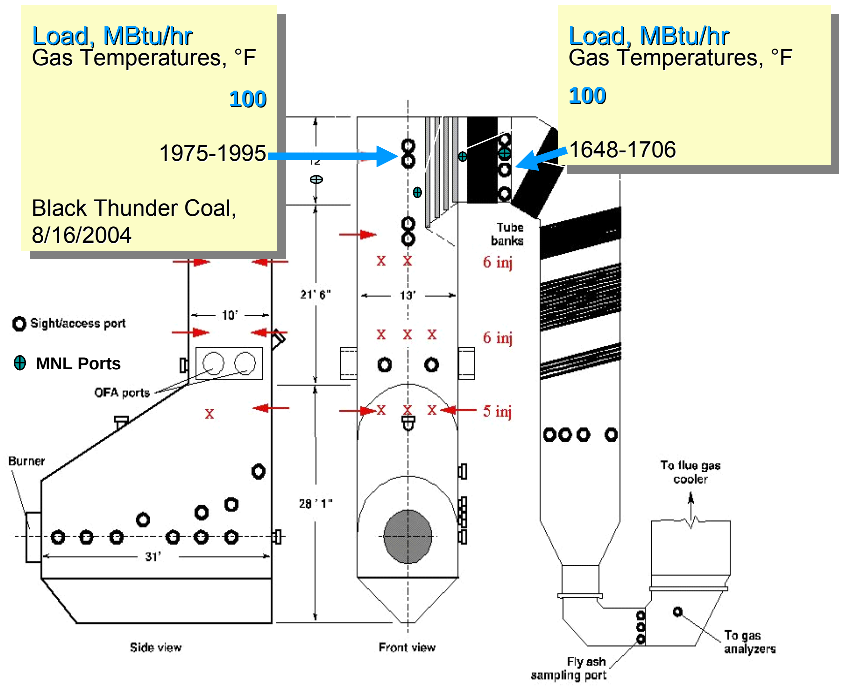


FIGURE 3.5 GAS TEMPERATURE (°F) MAPPING OF CEDF FURNACE FIRING BLACK THUNDER PULVERIZED COAL WITH THE ULTRA LOW-NO_X DRB-4Z® BURNER FROM THE 2004 TEST CAMPAIGN

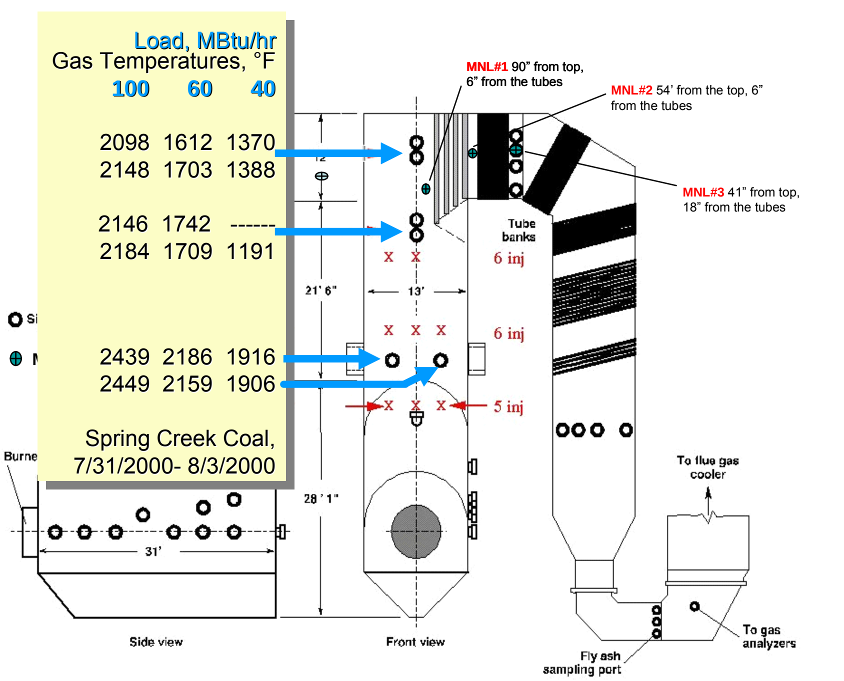


FIGURE 3.6 GAS TEMPERATURE (°F) MAPPING OF CEDF FURNACE FIRING SPRING CREEK PULVERIZED COAL WITH THE ULTRA LOW-NO_X DRB-4Z® BURNER FROM THE 2000-2001 TEST CAMPAIGN

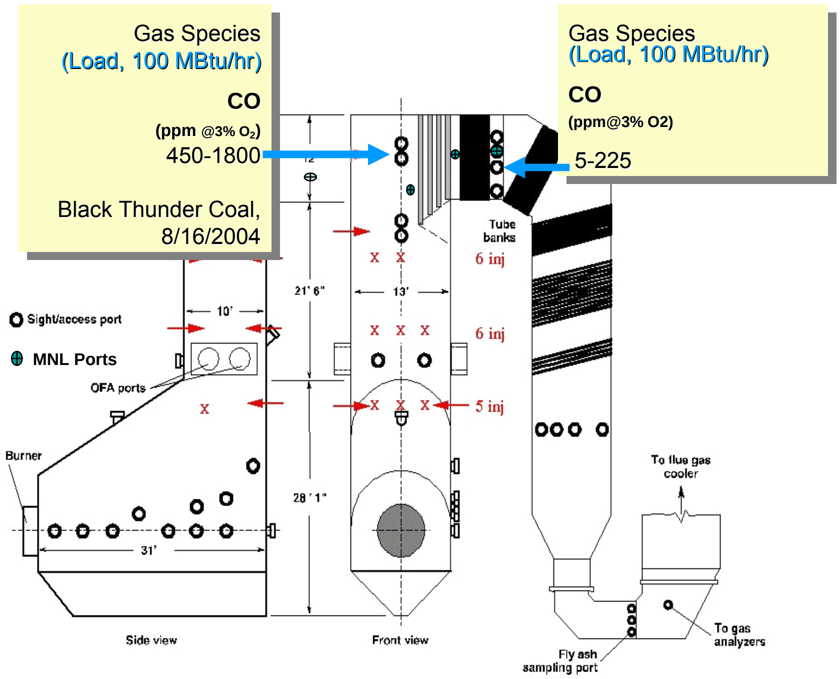


FIGURE 3.7 GAS SPECIES FURNACE MAPPING OF CEDF FURNACE FIRING BLACK THUNDER PULVERIZED COAL WITH THE ULTRA LOW-NO_X DRB-4Z® BURNER FROM THE 2004 TEST CAMPAIGN (CONVECTION PASS O2 AT 3%)

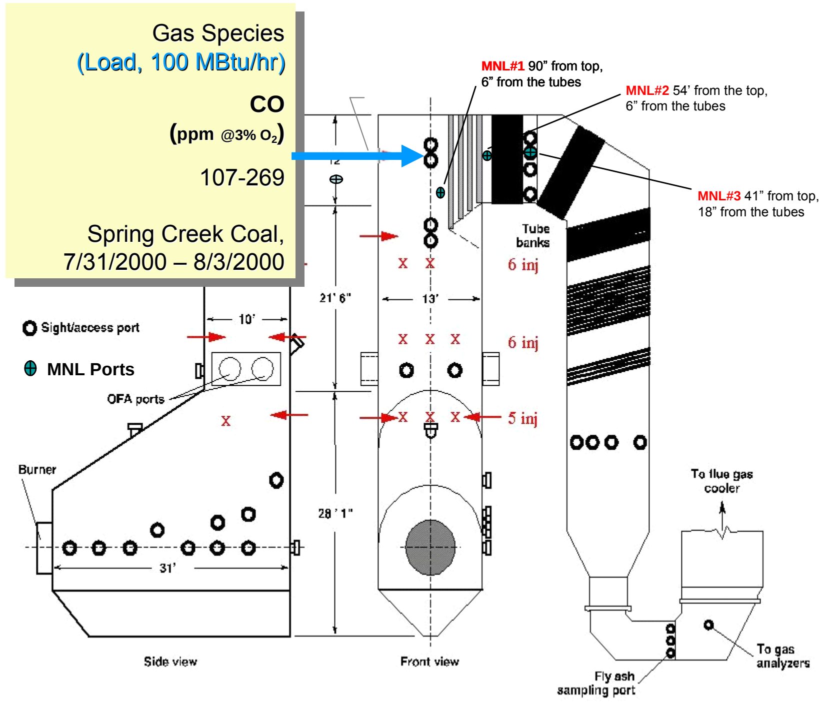
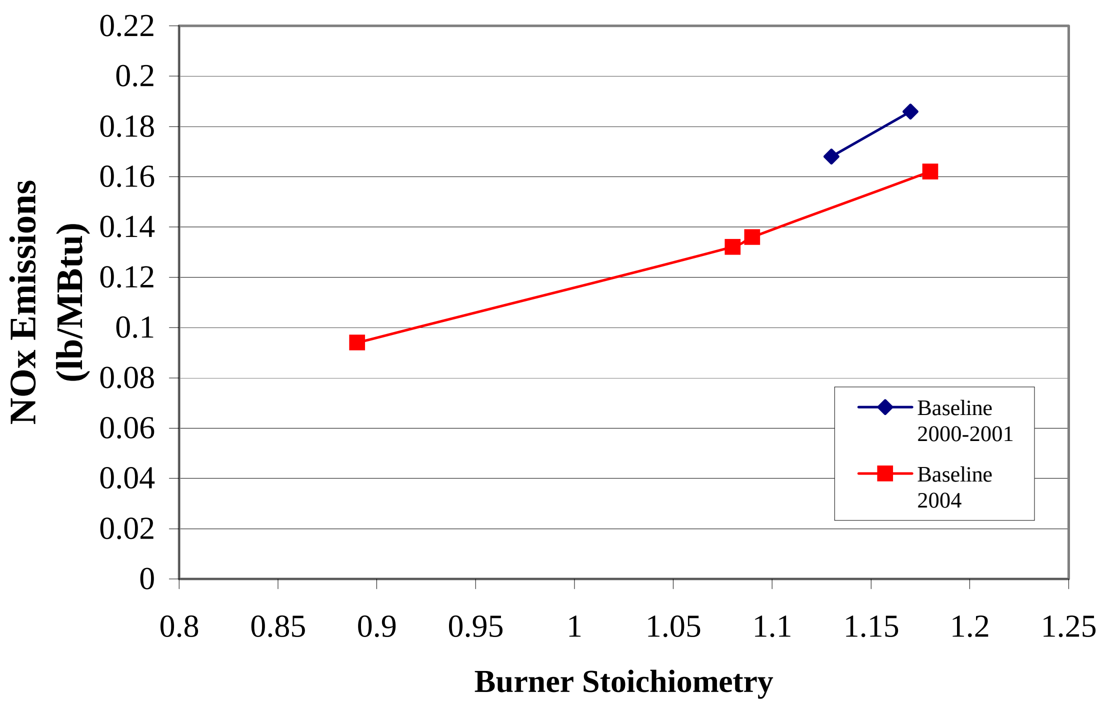


FIGURE 3.8 GAS SPECIES FURNACE MAPPING OF CEDF FURNACE FIRING SPRING CREEK PULVERIZED COAL WITH THE ULTRA LOW-NO_X DRB-4Z® BURNER FROM THE 2000-2001 TEST CAMPAIGN

4 RESULTS AND DISCUSSION

During start-up, the optimum hardware positioning was quickly re-checked through systematic adjustment of spin vane angles and secondary and transition zone air damper positioning. The results obtained were compared to previous test results and are shown in Figure 4.1. The CEDF baseline ranged from 0.09 to 0.16 lb/million Btu (overall excess O_2 was maintained at 3%), allowing the effectiveness of the SNCR to be tested at these conditions. The baseline results obtained during this round of testing more closely represent earlier test campaigns in the CEDF[(1)], which are slightly lower than the baseline results obtained in the 2000-2001 test period. As previously discussed, the refractory in the CEDF had just been replaced and the unit had been found to run hotter than typical during the 2000-2001 test campaign, thus resulting in higher than expected NO_x emissions. The coal had changed but as mentioned in section 3-4, the Black thunder coal had a higher FC/VM ratio which increases the NO_x emissions. CO levels were below 100 ppm. Fly ash unburned carbon was not measured but the CEDF data-base shows with PRB coals fly ash combustibles are below 2%.

FIGURE 4.1 COMPARISON OF BASELINE NO_X EMISSIONS BETWEEN TEST PROGRAMS



4.1 EXPERIMENTAL TESTING

Three ports were selected for the multiple nozzle lance (MNL) injection from the furnace exit to convective pass in this testing. The MNL-Port 1 was the hottest port located upstream of the superheater. The MNL-Port 2 was located downstream of the superheater, and was followed by MNL-Port 3. At full load and a burner stoichiometric ratio (BSR) of 1.08, the CO concentrations and temperatures at MNL Port 1 and Port 3 were measured. This furnace setting resulted in a NO_x value that was approximately 0.15 lb/10^6 Btu, which is similar to NO_x levels with the DRB-4Z® and PRB coal in commercial installations. At MNL-Port 1, the temperature was about 1980°F and CO concentration was at 450-900 ppm (@ 3% O_2). The temperature at MNL-Port 3 was about 1650°F. The temperature and CO concentration at MNL-Port 2 were not measured, but believed to be around 1700-1750°F and < 100 ppm, respectively.

During testing, different injection combinations and the change of NSR were tested at 100% and 60% loads while burning PRB coal. At 100% load with a low baseline NO_x of 0.124~0.136 lb NO_x/10^6 Btu, three MNL ports were tried. It was found that MNL-Port 2 was the best for NO_x reduction. The SNCR system was also tested with and without the MNL at Port 2 for two other baseline NO_x (i.e., 0.094 and 0.162 lb NO_x/10^6 Btu) conditions resulting from the change of BSR (or OFA ratio). Burner stoichiometry was generally 1.08 to 1.10 for a NO_x level approximately 0.15 lb/ 10^6 Btu. At 60%load, MNL-Port 1 was the best port for NO_x reduction. The burner stoichiometry at reduced load increased to 1.16 to mimic the commercial operation. In commercial boiler operation, as load is reduced, some burners are withdrawn from service and excess oxygen increases. A detailed description of these results is provided below. Table 4.1 contains some of the testing cases and results for various conditions. The complete tabulation of test data is located in Appendix A.

100% Load

Wall injection in only Zone 3 and Zone 4 was tested first. The maximum NO_x reduction was from 0.129 to 0.103 lb NO_x/10^6 Btu (Case 09), or about 20% reduction with an ammonia slip less than 5 ppm with an NSR of 2.51. When the MNL was used at MNL-Port 1, together with wall injection in Zone 4, the NO_x emission was reduced from 0.129 to 0.104 lb NO_x/10^6 Btu (Case 12), which was very close to the reduction with using wall injection only in Case 09. This also indicated that the temperatures near Port 1 were a little higher than desired for the best temperature window. The local temperature was at 1980°F, which was slightly higher than optimum temperatures, where the oxidation reaction of urea to NO_x becomes a significant path and competes with NO_x reductions for reagent. The MNL was then moved to MNL-Port 2 in Case 23. The performance improved. The NO_x emission was reduced from 0.132 to 0.095 lb $NO_x/10^6$ Btu. The MNL was also tested later at MNL-Port 3 in Case 37. Together with wall injection in Zone 4, the NO_x reduction was from 0.131 to 0.101 lb $NO_x/10^6$ Btu with an ammonia slip of 11.5 ppm, which meant that MNL-Port 3 was on the edge of the lower limit of the effective temperature window at 100% load. This is because the reaction requires longer reaction time and thus, reductions are negligible and ammonia slip is high. The effect of temperature on NO_x reduction is shown in Figure 4.2 for the MNL ports in the CEDF test.

TABLE 4.1 EXPERIMENTAL CASES FOR VARIOUS CONDITIONS

Case No.	Load (%)	Zones	NSR	BSR	Baseline NO_x (lb/10^6 Btu)	Final NO_x (lb/10^6 Btu)	NH_3 Slip (ppm)
09	100	3, 4	2.51	1.08	0.129	0.103	0.7
12	100	4,5 (Port 1)	2.51	1.09	0.129	0.104	1.1
23	100	4,5 (Port 2)	2.43	1.08	0.132	0.095	6.7
27	100	5 (Port 2)	1.03	1.09	0.136	0.095	9.3
30	100	5 (Port 2)	0.84	1.09	0.136	0.100	5.4
34	100	5 (Port 3)	0.86	1.08	0.131	0.101	14.2
37	100	4,5 (Port 3)	2.18	1.09	0.131	0.101	11.5
42	100	4,5 (Port 2)	2.30	1.08	0.124	0.085	7.9
45	100	5 (Port 2)	0.91	0.89	0.094	0.071	6.4
52	100	5 (Port 2)	0.58	1.18	0.162	0.124	6.1
55	60	5 (Port 2)	0.51	1.16	0.140	0.125	26.8
60	60	3	1.03	1.16	0.140	0.098	3.9
64	60	3,4	1.61	1.16	0.133	0.082	6.7
65	60	3,4	1.44	1.16	0.133	0.081	---
70	60	5 (Port 1)	0.50	1.13	0.124	0.101	8.4
72	60	3,4	1.45	1.16	0.124	0.090	5.6
73	60	3,4	1.46	1.14	0.124	0.086	6.2

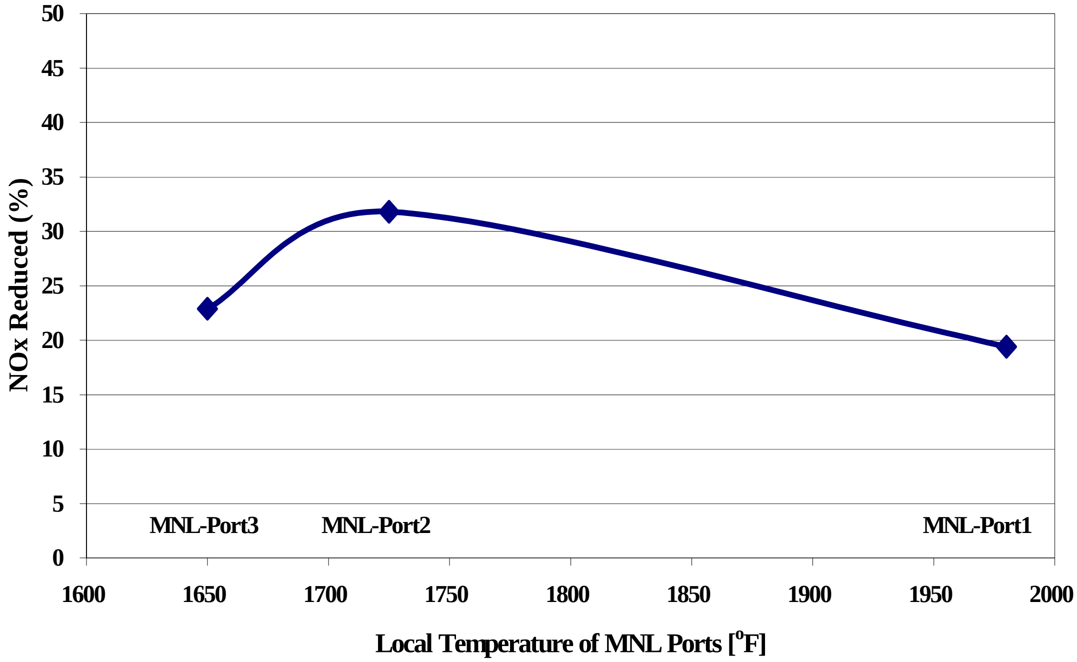


FIGURE 4.2 NO_X REDUCTION VERSUS MNL LOCATION AND TEMPERATURE EFFECT FOR THE CEDF TEST SERIES

When only using the MNL at Port 2 in Case 27, 30% reduction was achieved with an NSR of 1.03, as shown in comparison to Case 9 with wall injection only in Figure 4.3. Clearly, at 100% load, when using the MNL, the efficiency of NO_x reduction was significantly improved. In order to achieve the same or higher NO_x reduction, less reagent was required when using the MNL than using wall injection.

To further test utilization, the MNL was also tested at MNL-Port 2 without any wall injection (Case 30). With one-third of chemical reagent (i.e., NSR of 0.84 in Case 30 vs. 2.43 in Case 23), the NO_x reduction was from 0.136 to 0.100 lb $NO_x/10^6$ Btu, which was about the same as Case 23 with wall injection in Zone 4 and MNL at Port 2. It indicated that the utilization of chemical reagent in Zone 5 at MNL-Port 2 was significantly higher than wall injection in Zone 4. Excellent chemical coverage and right local temperatures at Port 2 are the main reasons for good utilization.

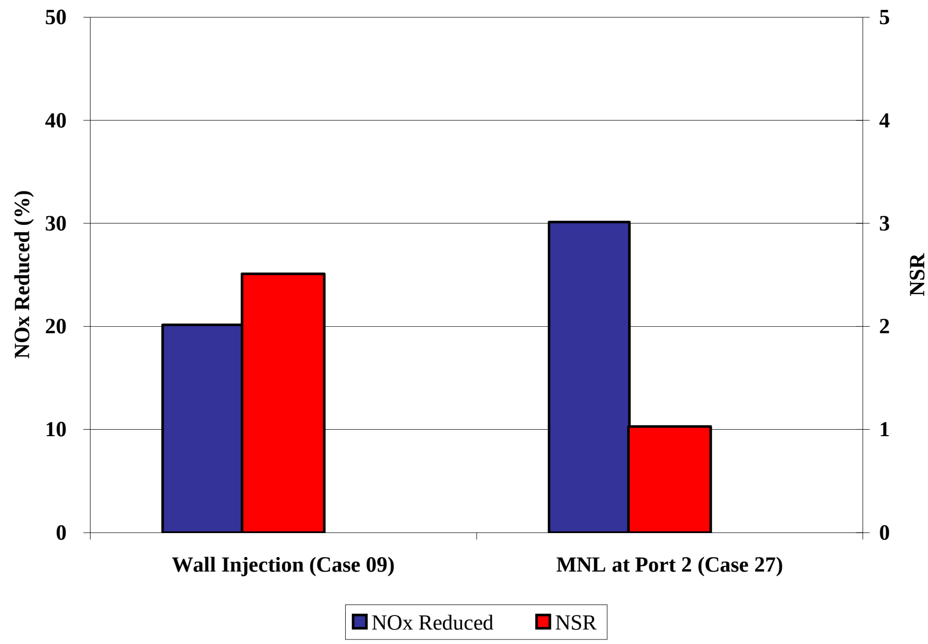


FIGURE 4.3 COMPARISON OF WALL INJECTION WITH MNL AT 100% LOAD FOR CEDF TEST SERIES (CASES 9 AND 27)

As expected, higher BSR led to a lower OFA flow rate, which resulted in a higher baseline NO_x. Three low baseline NO_x cases have been tested with using only the MNL at Port 2, as Case 45, Case 30 and Case 52 to investigate the effect of baseline NO_x on the SNCR NO_x reduction effectiveness. As shown in Figure 4.4, baseline NO_x levels increased with BSR. Using MNL at Port 2, NO_x emission could be reduced from 0.094 to 0.071 lb $NO_x/10^6$ Btu (Case 45), 0.136 to 0.100 lb $NO_x/10^6$ Btu (Case 30), and 0.162 to 0.124 lb $NO_x/10^6$ Btu (Case 52), or about 23.5%-26% reduction, while maintaining an ammonia slip at 5.4-6.7 ppm. In this test, lower initial NO_x led to a lower final NO_x concentration, which meant that it was not necessary to re-optimize OFA when adding the SNCR system because the furnace temperatures and CO concentrations were controlled very well at the CEDF. In commercial installation, the burner and OFA design should be optimized to reduce the CO concentration at the SNCR injection point.

From the test data, it can be seen that the utilization of chemical reagent was improved significantly when using the MNL at Port 2. Like Cases 27 and 30, NSR of 0.84 and 1.03 were required to achieve more than 26% of NO_x reduction. When using wall injection with or without the MNL at Port 2, more than 2.0 NSR was needed to achieve the same amount of NO_x reduction, such as Cases 9, 12, 23, and 42.

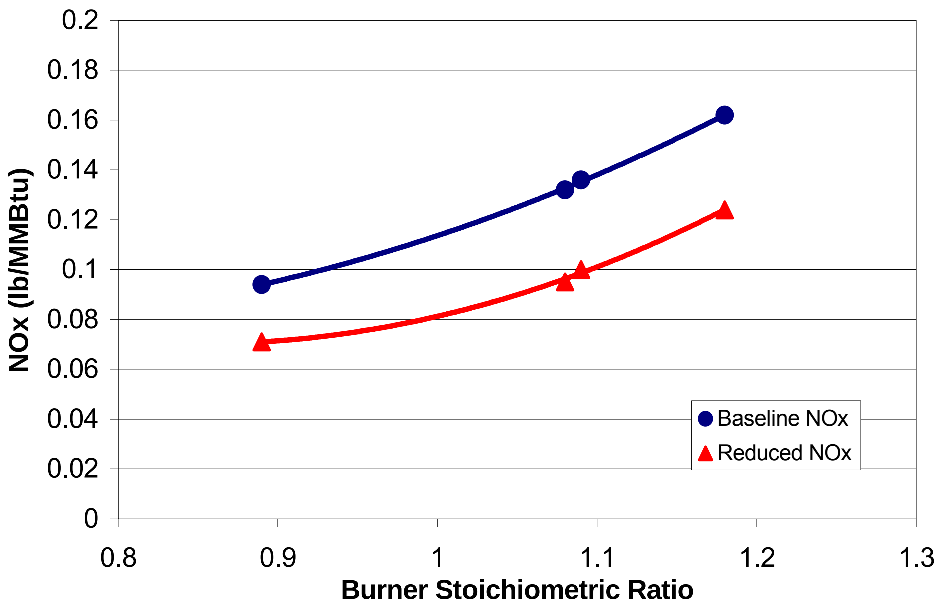


FIGURE 4.4 BASELINE NO_X VS. BURNER STOICHIOMETRY RATIO

The performance with a relaxation of the ammonia slip limit was also investigated at 100% load. In Case 27, improved performance, from 0.136 to 0.095 lb $NO_x/10^6$ Btu or 30% reduction, was achieved as NH_3 slip increased to 9.3 ppm, compared to 26% reduction in Case 30. Using MNL at Port 3, NO_x could be reduced from 0.131 to 0.101 lb $NO_x/10^6$ Btu (Case 37), or 23% with a high NH_3 slip (i.e., 11.5 ppm), which indicated the MNL-Port 3 was too cool for the SNCR system and would be good for an SCR/SNCR hybrid application.

60% Load

Using wall injection in Zone 3 alone, the NO_x emission was reduced from 0.140 to 0.096 lb $NO_x/10^6$ Btu (Case 60), or 31% reduction, while maintaining ammonia slip less than 5 ppm. Using wall injection in Zone 3 and Zone 4 (Case 64), the NO_x emission was reduced from 0.133 to 0.082 lb $NO_x/10^6$ Btu, or 38 % reduction with an ammonia slip of 6.7 ppm.

Using only the MNL at Port 2 (Case 55), the NO_x emission was reduced from 0.140 to 0.125 lb $NO_x/10^6$ Btu, or 11% reduction, while ammonia slip reached up to 26.8 ppm even with a low NSR of 0.51. This indicated that Port 2 was too cool for the SNCR system at 60% load. When using the MNL at Port 1 in Case 70, the NO_x reduction was about 18%. Even with a low NSR of

0.50, the ammonia slip was slightly high, i.e., 8.4 ppm, which indicated that the temperature at Port 1 was a little low for the SNCR system. In Case 73, without the MNL, NO_x reduction was 31% with a higher NSR of 1.46. A comparison of Cases 70 and 73 is given in Figure 4.5. The MNL at Port 3 was not tested because local temperatures in Port 3 would be lower than that at Port 2. It could be concluded that at 60% load, wall injection in Zones 3 and 4 reduced NO_x very well, and the MNL was not very helpful.

The performance with the relaxation of the ammonia slip limit was also tested at 60% load. In Case 57, up to 38% of reduction could be reached with 13.9 ppm ammonia slip. In Case 71, 33% of reduction was achieved with 17.9 ppm ammonia slip.

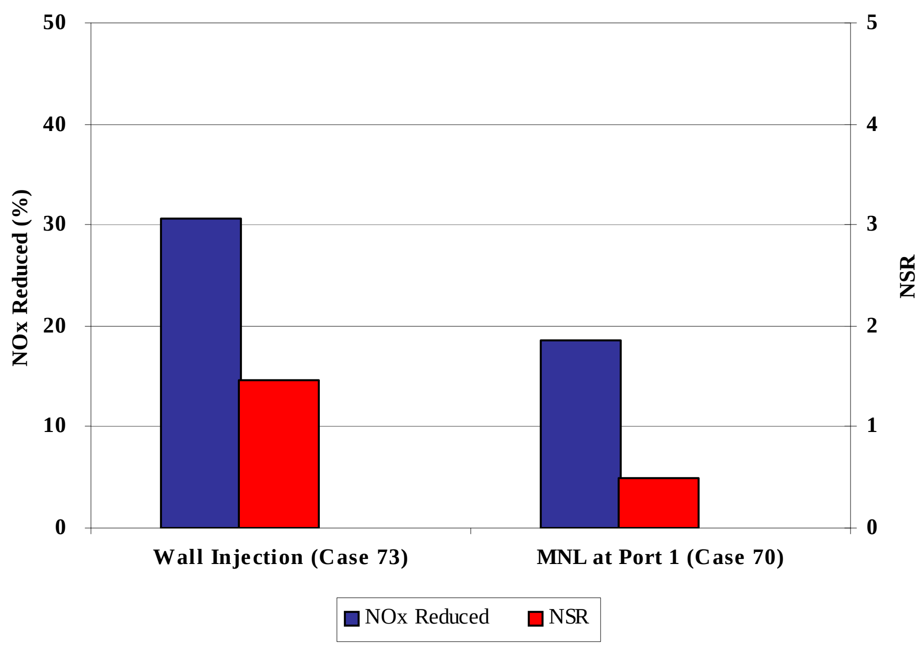


FIGURE 4.5 COMPARISON OF WALL INJECTION WITH THE MNL AT 60% LOAD FOR CEDF TEST SERIES, (CASES 70 AND 73)

Testing Summary

In summary, at 100% load, most of variables affecting SNCR performance have been investigated, including the location of the MNL and three low baseline NO_x levels. At 60% load, more limited tests were completed.

At 100% load:

- Using wall injection alone, the NO_x emission was reduced from 0.129 to 0.103 lb $NO_x/10^6$ Btu (20%) while maintaining NH_3 slip less than 5 ppm.
- Using the MNL for three low baseline NO_x cases (0.094, 0.124 and 0.162 lb $NO_x/10^6$ Btu), ~25% reduction was achieved while maintaining NH_3 slip less than 6.4 ppm.
- The MNL was the most efficient in Port 2. Port 1 and Port 3 were somewhat effective, but not ideal.
- Using the MNL, a lower baseline NO_x led to a lower final NO_x concentration, which meant that re-optimizing OFA was not needed when adding the SNCR system.
- Higher NO_x reduction could be achieved with relaxation of ammonia slip limit.

At 60% load:

- Only one low baseline NO_x was tested.
- Using wall injection only, the maximal NO_x reduction was about 38% with an ammonia slip of 6.7 ppm.
- The MNL was not helpful for further NO_x reduction.

4.2 NUMERICAL MODELING

The flow pattern, gas velocity, and gas temperatures for CEDF at 100% load and 60% load have been predicted using the CFD model developed by B&W in the previous project[(1)]. We decided that we did not need to model the boiler because the changes in the flow patterns would not significantly affect the existing position of injectors. The OFA changes the flow patterns in the lower furnace but as it reaches upper furnace they would tend to straighten out when it makes the turn and enters the convection pass. Also, we decided to use the measured temperatures for modeling. The results of CFD were then provided to Fuel Tech, Inc. for its subsequent postprocessing to determine optimum areas for SNCR urea injection. From these estimates, Fuel Tech's proprietary Chemical Kinetics Model (CKM) results were generated which were used to predict the performance of the $NO_xOUT^{®}$ process and identify the optimum temperature ranges in which chemicals should be released. Injection strategies were developed which disperse chemicals as near as possible to the optimal zones for various operating conditions. These strategies are expected to provide the best opportunity for maximum NO_x reduction while minimizing by-product emissions. In the previous testing, four levels of wall injection have been installed and were kept at the same locations in this testing.

Due to the use of MNL in this testing, a couple of cases with and without MNL at 100% load and 60% load were modeled. The modeling results were then compared with the experimental data. 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.

Several chemical release locations, starting points for the NO_x reduction reactions, were evaluated for those cases. The different locations were investigated in order to determine the optimum injection location for each streamline. The results were plotted as a function of chemical release temperature. Initial values of NO_x, CO, and chemical ratio (NSR) were specified at the point of chemical release. The remaining starting species concentrations were the equilibrium concentrations found at the origin of each streamline.

Fuel analysis data were used to generate an expected flue gas composition as required for CKM analysis. Modeling was performed to evaluate the effect of load, chemical injection rate, and chemical location on process effectiveness. The CKM results were obtained under the ideal assumption that there was complete chemical coverage of the flue gas.

Before this testing, the ports for MNL have been located carefully by the aid of CFD injection modeling analysis. Chemical coverage was excellent at MNL-Port 1, Port 2 and Port 3. In the CKM modeling, 100% of chemical coverage over flue gas was assumed with using MNL at Port 1, 2, and 3.

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.

Four operating conditions were considered: three different baseline NO_x at 100% load and one baseline NO_x at 60% load. 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 71 lb/10^6 Btu to 0.071 lb/10^6 Btu at an NSR of 0.91 (Case 45), and from 0.132 lb/10^6 Btu to 0.095 lb/10^6 Btu at an NSR of 2.43 (Case 23), and from 0.162 lb/10^6 Btu to 0.124 lb/10^6 Btu at an NSR of 0.58 (Case 52). 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 (Case 65).

Figure 4.6 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 (refer to Case 45). 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 (Case 45) 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.

Figures 4.7 and 4.8 show the results of CKM at 100% load for different baseline NO_x concentrations of 0.132 lb/10^6 Btu and 0.162 lb/10^6 Btu, respectively. At an NSR of 2.43, 100 ppm CO and 1700°F as Case 23, NO_x reduction from 0.132 lb/10^6 Btu to 0.90 lb/10^6 Btu is predicted. At an NSR of 0.58, 100 ppm CO and 1700°F as Case 52, NO_x reduction from 0.162 lb/10^6 Btu to 0.120 lb/10^6 Btu is predicted. These two final NO_x concentrations are very close to the testing data, i.e., 0.095 lb/10^6 Btu (Case 23) and 0.124 lb/10^6 Btu (Case 52), respectively.

Figure 4.9 shows the comparison of experimental data with modeling results for Cases 23, 45, and 52. As discussed above, final NO_x measured for all three cases match modeling predictions very well.

Figure 4.10 shows the CKM results at 60% load. At 1.50 NSR, 100 ppm CO and 1700°F as Case 65, 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, comparing Case 70 with Case 73.

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% reduction was achievable, while maintaining NH_3 slip controlled.

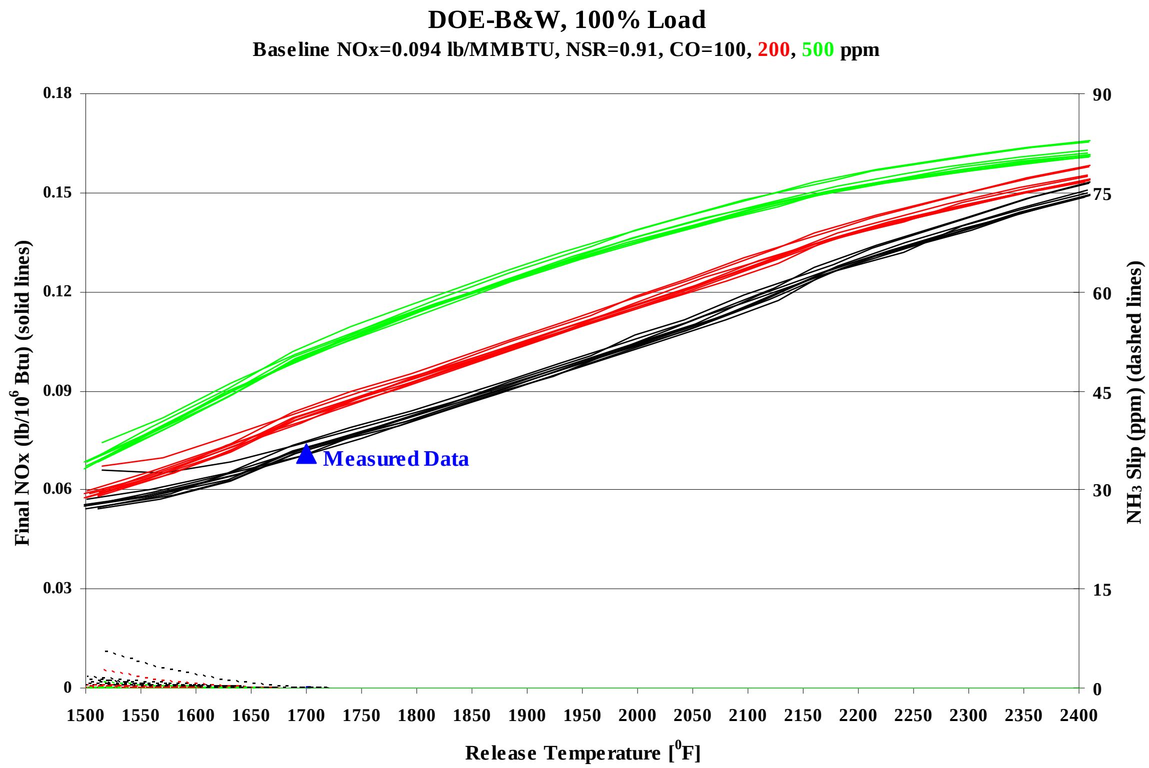


FIGURE 4.6 CKM RESULTS FOR 100% LOAD AND BASELINE NO_X=0.094 LB/10^6 BTU

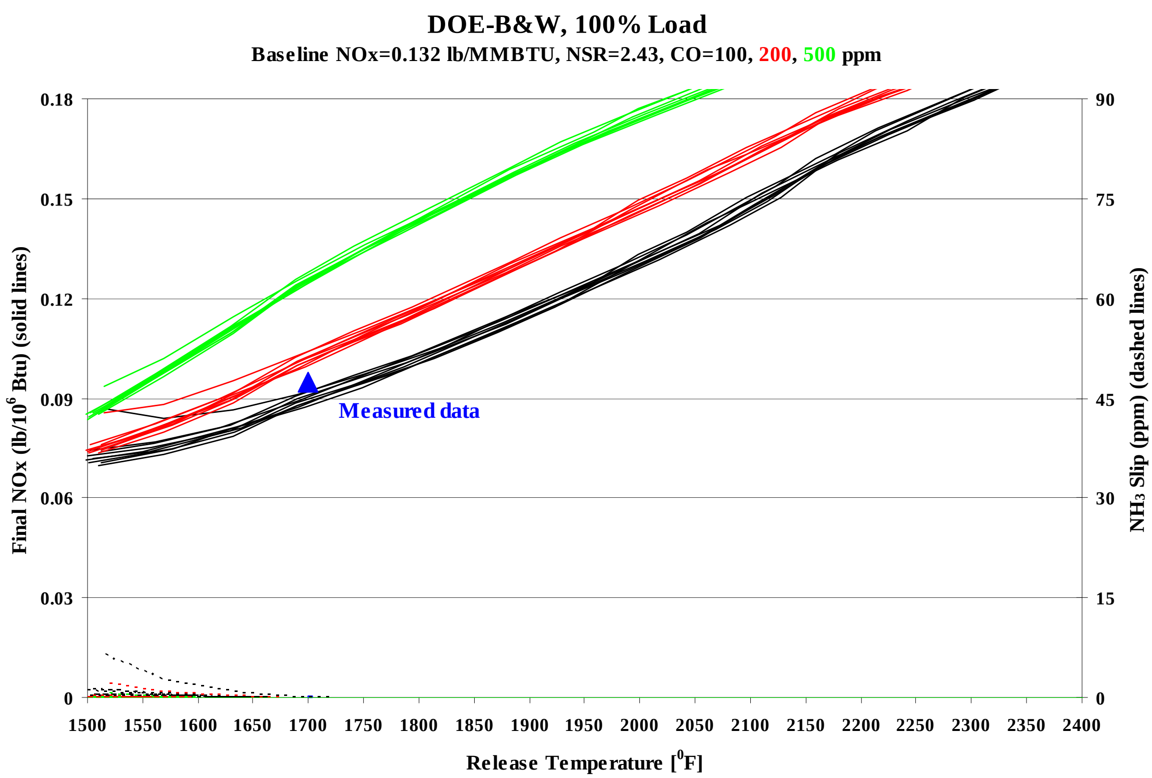


FIGURE 4.7 CKM RESULTS FOR 100% LOAD AND BASELINE NO_X=0.132 LB/10^6 BTU

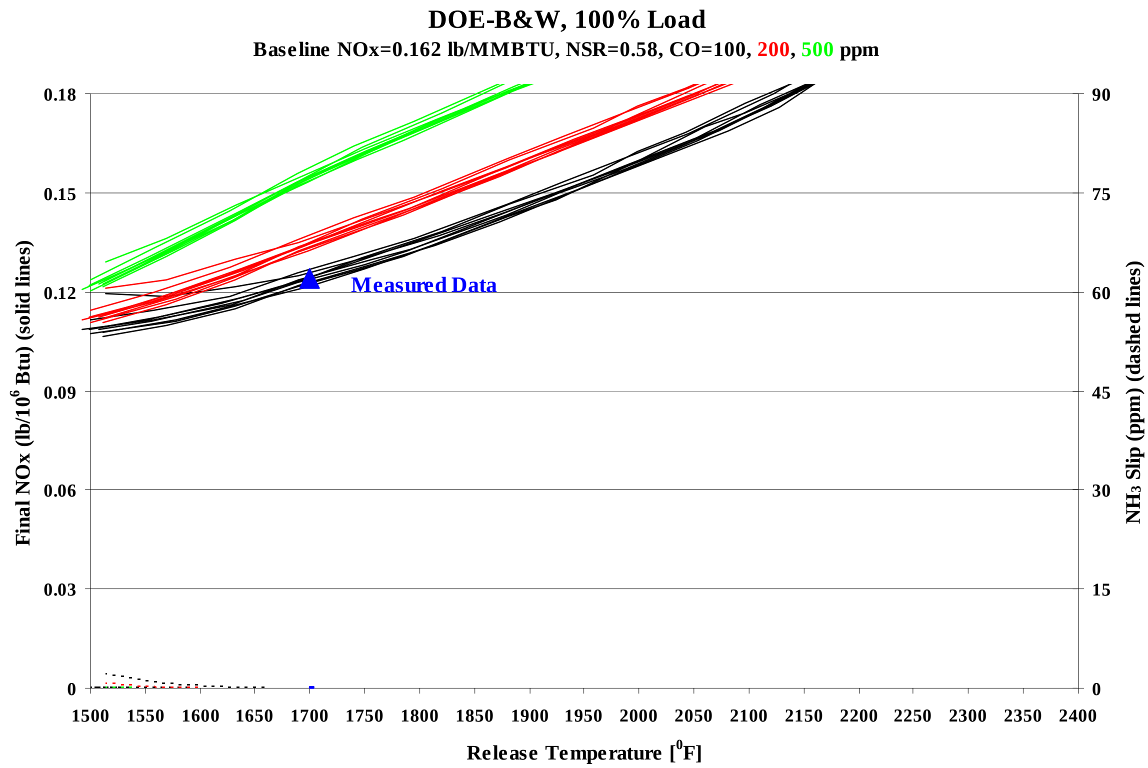


FIGURE 4.8 CKM RESULTS FOR 100% LOAD AND BASELINE NO_X=0.162 LB/10^6 BTU

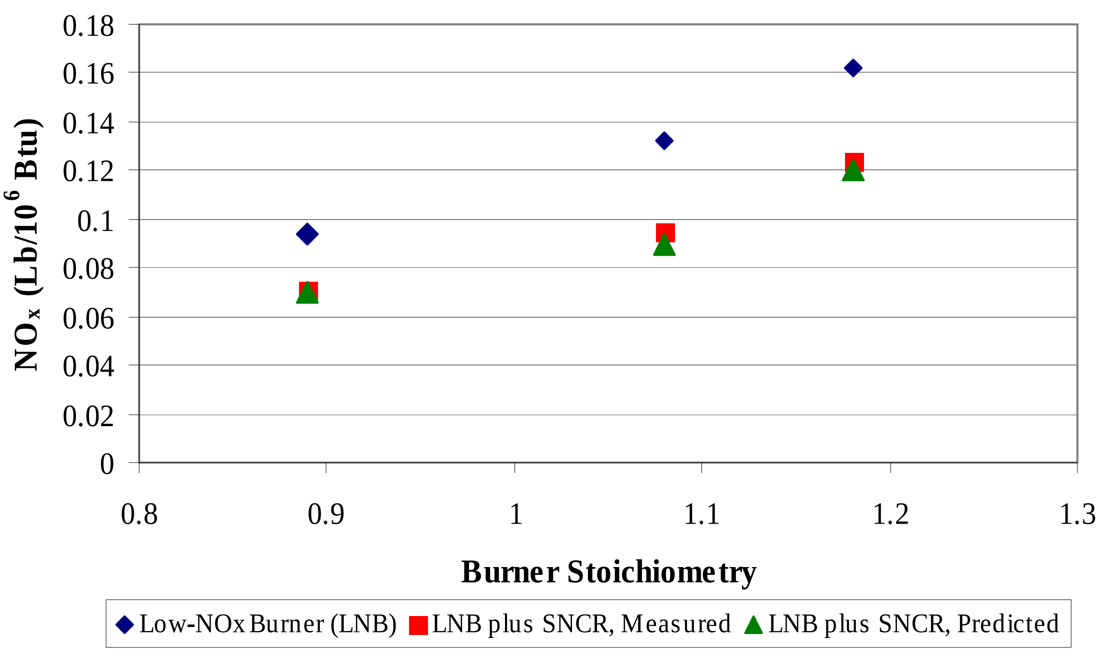


FIGURE 4.9 COMPARISON OF EXPERIMENTAL DATA WITH MODELING PREDICTIONS

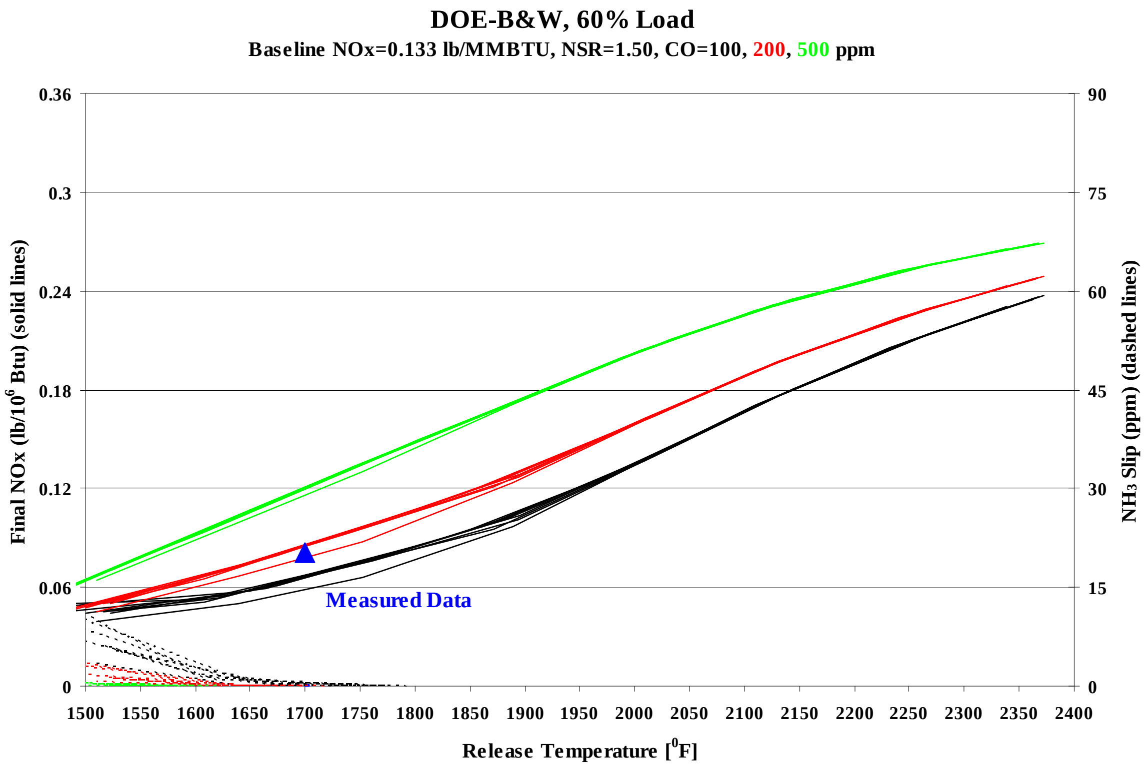


FIGURE 4.10 CKM RESULTS FOR 60% LOAD AND BASELINE NO_X=0.133 LB/10^6 BTU

4.3 ECONOMICS

4.3.1 ECONOMIC COMPARISON WITH EXISTING TECHNOLOGIES

This project was aimed at providing NO_x control options for existing power plants to keep coal both economically and environmentally competitive as a boiler fuel. Further, 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) to determine cost-effectiveness of these technologies to address the EPA SIP call for achieving the 0.15 lb NO_x /10^6Btu limit.

NOx Reduction Strategies - Achieving the target NO_x emission level of 0.15 lb/10^6 Btu presents a challenge to pulverized coal (PC) wall-fired utilities. Presently, combustion modification techniques alone cannot achieve this target emission level in most PC boilers. Based on several field applications of B&W's DRB-4Z® burner with OFA ports firing PRB coal, the NO_x

emission levels has ranged from 0.15 to 0.2 lb/10^6 Btu. B&W's newest low-NO_x burner, AeroJet® burner, in combination with overfire air (OFA) ports, has shown a NO_x emission level of 0.13 lb/10^6Btu with PRB coal. The CEDF data indicate a range of NO_x emissions depending on burner stoichiometry and conservatively a baseline of 0.125 lb/MBtu can be achieved. Therefore, with continuing commercial application of low-NO_x combustion technology, it may prove to be a viable stand-alone option for boilers using PRB coal. The combination of the combustion modification and post-combustion NO_x removal systems can further reduce the NO_x emissions enabling utilities to sell credit. If a utility decides for any reason to keep their combustion equipment, then Selective Catalytic Reduction (SCR) of NO_x, which is a commercially available technology, can be installed as a stand-alone system. If a utility selects SCR as their compliance strategy, it may be advantageous to use SCR at the full load and switch to SNCR at lower loads. This hybrid SCR/SNCR may reduce the overall cost of NO_x compliance. When these technologies are combined prudently, a low-cost NO_x control strategy can be developed for boilers in the 19 states that are affected by Title I compliance.

Based on the CEDF testing and commercial experience, several integrated NO_x control options were considered in this evaluation with the goal of reducing the baseline emissions from 0.5 to 0.15 lb NO_x/10^6 Btu or lower.

For units using PRB, the options are:

1) LNB with OFA when the DRB-4Z® burner with OFA ports NO_x emission level is 0.125 lb NO_x/10^6 Btu, enabling the utility to sell extra credit
2) LNB with OFA plus NO_XOUT® when the DRB-4Z® burner with OFA ports NO_x emission level is 0.125 lb NO_x/10^6 Btu, and sell credit
3) SCR-only systems with a 90% removal efficiency enabling the utility to sell extra credits, or
4) SCR/SNCR hybrid using SCR at full load and SNCR at loads below 60% load, enabling to reduce the overall cost.

Economic Evaluation - To demonstrate the application and benefits of various NO_x control options, their cost-effectiveness was calculated for a 500 MWe wall-fired, coal-burning boiler using the technology for the ozone season. Table 4.2 presents the major economic assumptions.

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 heat rate of 10,500 Btu/kWhr, and a 66.67% capacity factor. A 20-year project life and 20-year book life were selected. It was assumed that the NO_x control equipment will be in operation only during ozone season (5 months per year). Typical state and property taxes of 4% and 2% were used in this economic evaluation. A federal tax savings of 34% on depreciated value of the equipment was also considered in this evaluation. A 7% interest rate and escalation of 3% were used. The most important assumption was the NO_x credit cost of $2,500 derived from the market trading on SIP NO_x credits. However, the publicly available data showed the cost of NO_x credits varies from $7,900 to $4,300 per ton for 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). SCR efficiency of 90%, which is available commercially, was considered. The SCR catalyst vendors provide a guarantee for a life of 20,000 hours at a typical cost of $6,000 per cubic meter. In commercial utility practice, one third of the catalyst surface is added after the 20,000 hour service.

Table 4.3 compares the annual levelized costs of NO_x control for different options. The annual levelized cost is derived from both capital cost and operational cost. The levelized costs are illustrated as a range, since these costs can be different in different boilers. For example, the SCR capital cost is strongly dependent on the retrofit difficulties such as availability of space for the SCR reactor, and the need for fan modification or 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 is reported here, which is according to multiple commercial installations of low-NO_x burners (10 to 20 $/kW) and SCR systems (70 to140 $/kW). Based on the commercial experience of Fuel Tech, the SNCR capital cost is 8 $/kW for units with wall-fired injectors and increases to 12 $/kW for units that use MNL.

These capital costs include purchase and installation of hardware (e.g., LNB, or urea or ammonia delivery systems, catalyst) and controls. For the SCR, a 15-day ammonia storage, inlet NO_x level of 0.5 lb/10^6 Btu and outlet NO_x level of 0.05 lb/10^6 Btu was assumed.

TABLE 4.2 MAJOR ECONOMIC ASSUMPTIONS

2004 Dollars	
Generating Capacity, MW_e	500
Pre-Retrofit NO_x, lb/10^6Btu	0.5
Capacity Factor	0.6667
Plant Heat Rate, Btu/kWh	10500
Project Life, Years	20
Book Life, Years	20
Interest Rate	7%
Escallation, %	3%
State Tax	4%
Property Tax	2%
Federal Tax Saving	34%
Capitalization Factor	0.1407
SCR Efficiency, %	90
SCR Cathalyst life Guarantee, Hours	20,000
Catalyst Cost, $/M3	6,000
NO_x Credit, $/Ton of NO_x	2,500
Urea Cost, $/gal	1.1
Urea Overall Utilization (SNCR only), %	30%

TABLE 4.3 INTEGRATED SYSTEM ECONOMICS FOR A 500 MW BOILER

	1	2	3	4
	LNB+OFA & Sell Credit	LNB+OFA +SNCR & Sell Credit	SCR & Sell Credit	SCR/SNCR Hybrid
Coal	PRB	PRB	PRB	N/A
Burner NO_x, lb/MBtu	0.125	0.125	0.5	0.5
Controlled NO_x, lb/MBtu	0.125	0.094	0.05	0.06333333
LNB+OFA Capital Cost, $/kW (10-20)	10	10	0	0
LNB+OFA Capital Cost, $	5,000,000	5,000,000	0	0
SNCR Capital Cost, $ (8 to 12 $/kW)	0	6,000,000	0	4,000,000
SCR Capital Cost, $ (70 t0 140 $/kW)	0	0	35,000,000	30,000,000
Total Capital Cost, $	5,000,000	11,000,000	35,000,000	34,000,000
LNB Operating Cost, $/Year	166,000	166,000	0	0
SNCR Operating Cost, $/Year	0	200,671	0	160,537
SCR Operating Cost, $/Year	0	0	707,143	677,143
NO_x Credit needed, tons/OTR Season	-160	-358	-639	-554
NO_x Credit, $/Year	-399,239	-894,295	-1,596,955	-1,384,028
Total Operating Cost, $/Year	-233,239	-527,623	-889,812	-546,347
Total Operating Cost, mills/kWh	-0.19	-0.43	-0.73	-0.45
Total Levelized Cost, $/Year	470261	1020077	4034688	4237453
Levelized Cost, $/ton of NO_x Removed	$210	$456	$1,805	$1,895
Levelized Cost, mills/kWh	0.39	0.84	3.32	3.48
LNB/SCR Capital Cost increases 100%	($20/kW for LNB and $140/kW for SCR)			
Levelized Cost, $/ton of NO_x Removed	$525	$1,171	$4,007	$3,783

Our 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 ($210 to $525 per ton of NO_x). Since low-NO_x burners are more cost-effective on a $/ton of NO_x basis than SNCR or SCR technologies in general, there is a great incentive for using them in combination with post-combustion NO_x control methods. The combination of LNB/OFA plus the NO_xOUT® cost is slightly higher $456 to $1,171 per ton of NO_x removed but the final NOx emission is lower and more credit can be sold. Both systems compare well with SCR. However, if a utility decides to install SCR, they could benefit from a combination of SCR and SNCR if installation of the SNCR system simplifies the SCR. Our evaluation showed that the SCR/SNCR combination is more economical if SCR capital cost reduces by $13/kW when SNCR is used in lower loads. It should be mentioned that these costs are site specific, and the results may change from unit to unit.

The NO_x credit price volatility is one of the biggest variables in this analysis. Our evaluation shows when the NO_x credit cost increases to $5,275 per ton of NO_x, the combination of low-NO_x burner and SNCR becomes the least cost strategy ($12/ton of NO_x removed) and at $9,940 per ton of NO_x credit, SCR becomes the least cost alternative (-$321/ton of NO_x removed). 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. As the commercial market has witnessed, utilities have asked vendors for the lowest NO_x (0.06 lb/10^6 Btu) on their largest boilers. Some utilities that are concerned about the increase of the NO_x credit costs could install SNCR to reduce their risk.

This annual levelized cost includes both capital and operating costs. Operating cost of LNB plus OFA is minimal. Low NO_x burners could increase the unburned combustibles and the pressure drop across the burner. Although the DRB-4Z® low-NO_x burner was designed to maintain an acceptable pressure drop and has shown very low unburned combustibles, for the purpose of this analysis, an extra operating cost of $166,000 was added. SNCR operating cost was $200,671 for urea usage, and no additional operating cost was considered. SCR operating cost was $707,143 from which $407,143 was for ammonia usage and $300,000 for catalyst replacement. For SCR/SNCR combination, potential saving on the catalyst was $30,000 per year but had an added cost of 160,535 for ammonia cost. All four systems produced NO_x revenue that could be sold and offset the overall operating costs. The overall operating cost for all four systems is negative. For example, SCR produced 639 tons of NO_x credits that produced $1,596,955 of income. The operating costs of these options are based on the five months of the ozone transport season.

4.3.2 MARKET POTENTIAL

Market Niche - Results from evaluation of the DRB-4Z® low-NO_x PC burner/NO_xOUT® Process under this project are directly applicable to front and opposed wall-fired pulverized coal boilers within the 19 states that are facing strict NO_x emissions regulations. A portion of the affected utilities can reduce their emissions substantially by retrofitting their pre-NSPS and post-NSPS units that generate 0.5 lb/10^6 Btu of NO_x or higher with the DRB-4Z® ultra low-NO_x PC burners plus the NO_xOUT® Process. Cell-fired, roof-fired, and arch-fired boilers are also among potential candidates for employing LNB/NO_xOUT® technology. Tangential-fired and cyclone-fired boilers cannot use the LNB technology, but they can benefit from the NO_xOUT® technology.

Impact on Commercialization - The CEDF results help answer a critical question: Can SNCR be efficiently applied to a wall-fired pulverized coal boiler equipped with low-NO_x burner that emits as low 0.2 lbs of NO_x per 10^6 Btu? Prior to this project, SNCR was primarily applied to a boiler with NO_x levels above 0.3 lb/10^6 Btu. The NO_x reduction potential of SNCR technology when the low-NO_x burner emission levels are low (e.g. 0.2 lbs of NO_x per 10^6 Btu) was not known and was expected to be lower. As a result, SNCR was not considered to be a viable option and the utility boiler owners that were interested in the combination of LNB/SNCR technology could not use SNCR without substantial risk of performance. This project shows that SNCR can reduce a nominal 25% NO_x from very low baseline levels (e.g. 0.09 – 0.18 lbs/10^6 Btu) by using a multiple lance nozzle and providing technical justification for considering SNCR as one of the alternative options when NO_x compliance is considered for a wall-fired boiler.

Market Potential - Cost-effectiveness calculations have shown that the LNB/NO_xOUT® is economically attractive at the current low NO_x credit cost of approximately 2,500 per ton of NO_x. However, low-NO_x burner NO_x emissions must be less than or equal to 0.3 lb/10^6Btu.

Burner NO_x emissions are a function of the boiler design, fuel type, and other site-specific variables such as boiler heat release rate. Fuel rank in particular is an important parameter. Our near full-scale low-NO_x performance data from the CEDF, as well as several commercial units, indicate that utilities that burn subbituminous (e.g., PRB) coals would emit low NO_x levels and, thus, can greatly benefit from utilizing the LNB/NO_xOUT® technology.

Market Size - Total coal-fired power plant population in the U.S. is 332,600 MWe including approximately 200,000 MWe pre-NSPS units[4, 5]. Coal-burning, wall-fired boilers represent 140,000 MWe capacity. As discussed before, the LNB technology is applicable to all wall-fired and roof-fired boilers. Tangential-fired and cyclone boilers can benefit from NO_xOUT® technology alone. Title IV affects about 37,300 MW capacity of wall-fired PC boilers that are not currently in compliance. Title I could impact a much larger population of boilers, if the proposed rules are enforced. For example, the Ozone Transport Rule could affect most of the 115,000 MW_e wall-fired, PC boilers within 19 states. The LNB/SNCR combination will be the least cost option for a majority of these boilers. Boilers that burn medium volatile bituminous coals can choose other technologies such as SCR or may opt to change coal (if possible) to minimize their NO_x removal costs. This coal-switching trend has been seen recently in the utility market. Many utilities have switched to PRB coal mainly for SO_X compliance, and the PRB usage is on the rise due to its low-sulfur content and low cost including transportation. Therefore, we estimate the market size for the LNB/SNCR technology to be approximately 86,000 MWe. This is 75% of the 115,000 MWe wall-fired PC boilers within the 19 states.

Commercial Deployment Timeline - A key advantage of this technology is its near-term commercial readiness. Performance evaluation of the integrated LNB and SNCR system has been carried out at the near full-scale level in B&W's 100 million Btu/hr test facility. Past experience has shown that a large prototype, 100 million Btu/hr burner design, can be readily scaled with minimal risk for commercial retrofit where a typical burner size is about 150 to 200 million Btu/hr. A scale-up concern is the varying flow patterns and temperature profiles in the urea injection zone of the CEDF versus commercial boilers. The CEDF was fired with one burner, whereas the commercial units are fired by multiple burners and with front-wall and opposed-wall firing configurations. The application of SNCR to commercial boilers could result in different flow patterns than occur in the CEDF, and the SNCR system design has to be on a site-specific basis. Commercial offers can be made currently.

5 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. The chemical kinetic modeling (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.

- 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 (burner stoichiometry of 0.89 to 1.18), resulting in NO_x values of 0.07 to 0.12 lb/10^6 Btu. These NO_x levels were obtained when the MNL has been installed inside the convective tube bank, agreed with modeling predictions very well, indicating that the chemical coverage of the flue gas was excellent.

- Using the MNL, a lower baseline NO_x led to a lower final NO_x concentration, which meant that re-optimizing OFA was not needed when adding the SNCR system.

- 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 expected to be the reason. At this reduced load, chemical release temperatures from the MNL were within the effective temperature window, but the gases at the top of the furnace exit were not treated effectively.

- Although site specific economic evaluation is required for each unit, our economic evaluation of DRB-4Z® and SNCR for a 500 MW_e plant firing PRB shows:
  - the NO_x levels with DRB-4Z® and OFA is very close to 0.125 lb/10^6 Btu (commercial experience 0.13 – 0.2 lb/10^6). The least cost strategy is low-NOx burner and OFA at a cost of $210 to $525 per ton of NO_x removed.
  - Installation of SNCR allows the utility to reduce NO_x beyond OTR limit and to sell more NOx credit and it becomes economical when NO_x credit cost is more than $5,275 per ton of NO_x.

6 REFERENCES

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7 List of Acronyms and Abbreviations

B&W	-	Babcock & Wilcox Power Generation Group
BSR	-	burner stoichiometric ratio
CEDF	-	B&W's Clean Environment Development Facility
CFD	-	computational fluid dynamics
CKM	-	chemical kinetics model
DAS	-	data acquisition system
DOE	-	The U.S. Department of Energy
Fuel Tech	-	Fuel Tech, Inc.
IADC	-	inner air distribution cone
MNL	-	multiple nozzle lance
NETL	-	Nation Energy Technology Laboratory
NSR	-	normalized stoichiometric ratio
OADC	-	outer air distribution cone
OFA	-	overfire air
OTR	-	Ozone Transport Rule
PC	-	pulverized coal
PRB	-	Powder River Basin
SCR	-	selective catalytic reduction
SIP	-	State Implementation Rule
SNCR	-	selective non-catalytic reduction
VOCs	-	volatile organic compounds

8 ACKNOWLEDGEMENTS

This work was sponsored by the U.S. Department of Energy's National Energy Technology Laboratory (NETL), Babcock & Wilcox Power Generation Group, and Fuel Tech, Inc. Many thanks are due to Mr. Bruce Lani of the NETL for his guidance throughout the program. The authors would also like to thank the technical and commercial support of Albert LaRue from B&W. Many thanks due to numerous B&W and Fuel Tech employees for their help in the site preparation, burner and SNCR evaluation, and operation of the test facility.

APPENDICES

B&W
CEDF **PRB Coal**

MK	9876	
PRB	9731	new*
P#8	9864	

Date: 8/16/2004--8/17/2004

Test No.	Test Type	Start Test Time	Boiler Load: Gross Load %	Boiler Load: Load MMBtu per hr	MM Zone 1 – Zone 2 (or 4) Injection: # of Inj's	Tip Type	Water Flow [gpm]	Flow / inj [gpm]	Air P [psig]	Chem Flow [gph]	31% NSR	MM Zone 2 – Zone 3 (or 5) Injection: # of Inj's	Tip Type	Water Flow [gpm]	Flow / inj [gpm]	Air P [psig]	Chem Flow [gph]	31% NSR	Analyzers: NOx ppmd	B&W CO ppmd	O2 %(dry)	NH3 ppm	Summary of Results: NOx ppmdc	Calc # NOX /MMBtu	CEMS	BL # NOX /MMBtu	Total NSR	% Red	B&W CEMS Red %	% Util	Conv Pass Out Temp F	Test No.	COMMENTS
1.001	Baseline	12:06	100.54	100.54	0	inj	--	N/A	--	--.-	0.00	0	inj	--	N/A	--	--.-	0.00		99		--	0	0.1280	0.1280	0.128	0.00	0.0%	0.0%	N/A	921	1.001	
1.001b	Baseline new	17:38	100.40	100.40	0	inj	--	N/A	--	--.-	0.00	0	inj	--	N/A	--	--.-	0.00	91	99	3.40	--	93	0.1263	0.1250	0.125	0.00	-1.0%	0.0%	N/A	899	1.001b	
1.001c	Baseline more	18:01	101.65	101.65	0	inj	--	N/A	--	--.-	0.00	0	inj	--	N/A	--	--.-	0.00	90	244	3.30	--	92	0.1242	0.1240	0.125	0.00	0.7%	0.8%	N/A	901	1.001c	
1.002	Repeat 2.48	21:47	101.79	101.79	3	F45	0.60	0.23	35.0	4.88	1.65	6	inj	2.46	0.42	30	2.74	0.93	83	193	3.75		87	0.118	0.117	0.125	2.58	6.0%	6.4%	2.3%	901	1.002	
1.002b	BnW data 01b	22:06	101.17	101.17	3	F45	0.59	0.22	35.0	4.91	1.67	6	inj	2.47	0.42	30	2.71	0.92	82	115	3.77	7.7	86	0.116	0.115	0.125	2.60	7.0%	8.0%	2.7%	902	1.002b	7.99% based on B&W data
1.003	try to reduce NH3 slip	23:33	103.89	103.89	3	F45	0.49	0.19	40	4.91	1.63	6	inj	2.49	0.42	30	2.70	0.90	83	69	3.40	3.3	85	0.115	0.115	0.125	2.53	7.9%	8.0%	3.1%	917	1.003	
1.004	repeat 1.003	1:44	101.86	101.86	3	F45	0.51	0.20	40	4.90	1.54	6	inj	2.49	0.42	30	2.70	0.85	85	172	3.50	--	87	0.119	0.117	0.135	2.38	12.1%	13.3%	5.1%	918	1.004	after changing operating condition,
1.005	mv chem from Z3 to Z4	2:34	101.72	101.72	3	F45	0.50	0.20	40	5.91	1.86	6	inj	2.50	0.42	30	1.70	0.53	84	151	3.56	3.0	87	0.118	0.116	0.135	2.39	12.8%	14.0%	5.4%	918	1.005	mv Chem from 3 to 4
1.006	A,B,E,F in Z3 off	4:15	101.90	101.90	3	F45	0.52	0.20	40	4.90	1.54	2	inj	1.04	0.54	30	2.70	0.85	81	128	3.59	4.2	84	0.114	0.113	0.135	2.38	15.8%	16.2%	6.6%	928	1.006	OK, 3ABEF now OOS
1.007	baseline test	5:16	101.92	101.92	-	inj		N/A			0.00		inj		N/A			0.00	96	181	3.62		99	0.135	0.134	0.135	0.00	0.0%	0.7%	N/A	936	1.007	

Date: 8/17/2004--8/18/2004

Test No.	Test Type	Start Test Time	Boiler Load: Gross Load %	Boiler Load: Load MMBtu per hr	MM Zone 1 – Zone 2 (or 4) Injection: # of Inj's	Tip Type	Water Flow [gpm]	Flow / inj [gpm]	Air P [psig]	Chem Flow [gph]	31% NSR	MM Zone 2 – Zone 3 (or 5) Injection: # of Inj's	Tip Type	Water Flow [gpm]	Flow / inj [gpm]	Air P [psig]	Chem Flow [gph]	31% NSR	Analyzers: NOx ppmd	B&W CO ppmd	O2 %(dry)	NH3 ppm	Summary of Results: NOx ppmdc	Calc # NOX /MMBtu	CEMS	BL # NOX /MMBtu	Total NSR	% Red	B&W CEMS Red %	% Util	Conv Pass Out Temp F	Test No.	COMMENTS
2.008	post-SB baseline	7:42	102.02	102.02	-	inj	--	N/A	--	--.-	0.00		inj		N/A			0.00	92	298	3.57		95	0.129	0.129	0.129	0.00	0.0%	0.0%	N/A	894	2.008	
2.009	repeat 1.006 with good B	8:40	101.28	101.28	3	F45	0.54	0.21	40	4.90	1.62	2	inj	1.07	0.56	30	2.70	0.89	74	253	3.46	0.7	76	0.103	0.103	0.129	2.51	20.2%	20.2%	8.0%	894	2.009	why so much better?
2.010	Zone 4 only	9:22	100.65	100.65	3	F45	0.54	0.21	40	4.90	1.63		inj		N/A			0.00	80	179	3.39		82	0.111	0.111	0.129	1.63	14.0%	14.0%	8.6%	895	2.010	
2.011	install MNL	10:35	101.78	101.78	3	F45	0.55	0.21	40	4.90	1.61	8	MNL-1	0.49	0.07	60	2.71	0.89	77	88	3.50		79	0.107	0.107	0.129	2.50	16.7%	17.1%	6.7%	905	2.011	
2.012	inc water to MNL	11:13	101.14	101.14	3	F45	0.55	0.21	40	4.91	1.62	8	MNL-1	0.75	0.10	60	2.69	0.89	74	89	3.54	1.1	76	0.104	0.104	0.129	2.51	19.8%	19.4%	7.9%	909	2.012	ok, nh3? (low util in Z5)
2.013	dec air P to lance to 45 ps	12:45	101.33	101.33	3	F45	0.56	0.21	40	4.91	1.62	8	MNL-1	0.75	0.10	46	2.70	0.89	75	252	3.57	2.6	77	0.105	0.105	0.129	2.51	18.5%	18.6%	7.4%	906	2.013	cal nox meter before test (fine)
2.014	NSR sweep	13:42	100.00	100.00	3	F45	0.59	0.21	40	2.90	0.97	8	MNL-1	0.77	0.10	46	1.91	0.64	79	219	3.67		82	0.111	0.111	0.129	1.61	13.7%	14.0%	8.5%	903	2.014	util not much better
2.015	MNL alone	14:17	101.00	101.00	3	F45	--	0.00	--	--	0.00	8	MNL-1	0.73	0.10	46	2.70	0.89	86	240	3.58		89	0.121	0.120	0.129	0.89	6.5%	7.0%	7.3%	906	2.015	hmmm…not so good.
2.016	Inc water once more	14:44	100.57	100.57	-	inj	--	N/A	--	--.-	0.00	8	MNL-1	1.08	0.14	46	2.71	0.90	84	260	3.62		87	0.118	0.117	0.129	0.90	8.5%	9.3%	9.4%	907	2.016	not heroic
2.017	dec air P to lance to 35 ps	15:06	101.30	101.30	-	inj	--	N/A	--	--.-	0.00	8	MNL-1	1.09	0.14	35	2.70	0.89	82	362	3.43		84	0.114	0.114	0.129	0.89	11.6%	11.6%	13.1%	910	2.017	it'll have to do…NH3?
2.018	add Z4 @ 4 gph	15:38	100.76	100.76	3	F45	0.67	0.25	40	4.02	1.33	8	MNL-1	1.08	0.14	35	2.70	0.90	75	298	3.43		77	0.104	0.104	0.129	2.23	19.2%	19.4%	8.6%	908	2.018	best? I don't think so…
2.019	shift chem to MNL (bet u	16:00	100.76	100.76	3	F45	0.68	0.25	40	3.31	1.10	8	MNL-1	1.07	0.14	35	3.30	1.09	75	231	3.59	6.0	78	0.105	0.104	0.129	2.19	18.4%	19.4%	8.4%	908	2.019	final test for this
2.020	baseline followed by CEN	16:35	100.89	100.89	-	inj	--	N/A	--	--.-	0.00		inj		N/A			0.00	95	170	3.53		98	0.133	0.132	0.132	0.00	-0.6%	0.0%	N/A	919	2.020	baseline
2.021	mv MNL to 1800F port	17:54	101.61	101.61	--	F45	-	N/A	-	-	0.00	8	MNL-2	0.47	0.06	60	2.73	0.88	68	93	3.47	6.9	70	0.095	0.094	0.132	0.88	28.2%	28.8%	32.2%	925	2.021	
2.022	inc P to MNL	18:59	99.91	99.91	--	F45	-	N/A	-	-	0.00	8	MNL-2	0.48	0.07	70	2.71	0.89	73	66	3.75	3.6	76	0.103	0.103	0.132	0.89	21.7%	22.0%	24.5%	935	2.022	conv pass outlet temp=935 F
2.023	MNL-2 + Z4	20:29	102.12	102.12	3	F45	0.55	0.21	40	4.90	1.57	8	MNL-2	0.47	0.06	70	2.70	0.86	69	244	3.39	6.7	71	0.096	0.095	0.132	2.43	27.5%	28.0%	11.3%	931	2.023	
2.024	MNL-2 alone inc chem	21:16	102.47	102.47	-	F45	--	N/A	-	-	0.00	8	MNL-2	0.48	0.07	70	3.32	1.06	72	327	3.37		74	0.100	0.097	0.132	1.06	24.4%	26.5%	23.1%	935	2.024	
2.025	baseline	21:39	101.98	101.98	-	inj	--	N/A	--	--.-	0.00		inj		N/A			0.00	96	255	3.45		98	0.134	0.133	0.133	0.00	-0.4%	0.0%	N/A	939	2.025	baseline before SB
2.026	post-SB baseline	22:56	101.51	101.51	-	inj	--	N/A	--	--.-	0.00		inj		N/A			0.00	97	179	3.53		100	0.136	0.136	0.136	0.00	0.3%	0.0%	N/A	897	2.026	
2.027	repeat 2.024	23:30	101.79	101.79	-	inj	--	N/A	--	--.-	0.00	8	MNL-2	0.49	0.07	70	3.30	1.03	68	188	3.54	9.3	70	0.095	0.095	0.136	1.03	30.1%	30.1%	29.3%	895	2.027	
2.028	reduce water	0:16	101.53	101.53	-	inj	--	N/A	--	--.-	0.00	8	MNL-2	0.43	0.06	70	3.31	1.03	69	156	3.65	7.9	72	0.097	0.097	0.136	1.03	28.6%	28.7%	27.7%	898	2.028	
2.029	increase water to see the e	0:58	101.54	101.54	-	inj	--	N/A	--	--.-	0.00	8	MNL-2	0.76	0.10	70	3.30	1.03	66	140	3.61		68	0.093	0.092	0.136	1.03	31.8%	32.4%	30.9%	899	2.029	NH3 should be higher after incr H2O, just want to see the effect
2.030	best ?	1:35	102.14	102.14	-	inj	--	N/A	--	--.-	0.00	8	MNL-2	0.52	0.07	65	2.70	0.84	72	189	3.54	5.4	74	0.101	0.100	0.136	0.84	25.9%	26.5%	31.0%	903	2.030	see 2.021 and 2.022. I guess this case will be the best?
2.031	decrease P	2:37	101.55	101.55	-	inj	--	N/A	--	--.-	0.00	8	MNL-2	0.50	0.07	45	2.70	0.84	67	60	3.62		69	0.094	0.093	0.136	0.84	30.8%	31.6%	36.5%	908	2.031	NH3 should be high, just see the effect
2.032	baseline	3:08	102.20	102.20	-	inj	--	N/A	--	--.-	0.00		inj		N/A			0.00	94	49	3.60		97	0.132	0.131	0.131	0.00	-0.7%	0.0%	N/A	918	2.032	baseline before moving the lance to port 3
2.033	mv MNL to 1600F port	4:43	102.53	102.53	--	F45	-	N/A	-	-	0.00	8	MNL-3	0.43	0.06	70	2.20	0.71	74	215	3.40		76	0.103	0.103	0.131	0.71	21.6%	21.4%	30.6%	921	2.033	long delay to test due to radical O2 swing cause unknown
2.034	increase chem to 2.7	5:13	102.92	102.92	--	F45	-	N/A	-	-	0.00	8	MNL-3	0.43	0.06	70	2.70	0.86	74	284	3.32	14.2	75	0.102	0.101	0.131	0.86	22.0%	22.9%	25.5%	924	2.034	CO levels increasing
2.035	increase water to see the e	5:52	102.78	102.78	--	F45	-	N/A	-	-	0.00	8	MNL-3	0.49	0.07	70	2.70	0.86	74	312	3.37		76	0.103	0.102	0.131	0.86	21.8%	22.1%	25.2%	925	2.035	
2.036	decrease air pressure	6:32	101.89	101.89	--	F45	-	N/A	-	-	0.00	8	MNL-3	0.43	0.06	65	2.70	0.87	76	188	3.60		79	0.107	0.107	0.131	0.87	18.6%	18.3%	21.3%	925	2.036	
2.037	add Z4 @ 4 gph (lite)	7:38	101.31	101.31	3	F45	0.55	0.21	40	4.00	1.30	8	MNL-3	0.24	0.04	75	2.70	0.88	72	207	3.58	11.5	74	0.101	0.101	0.131	2.18	22.9%	22.9%	10.5%	924	2.037	

Date: 8/18/2004--8/19/2004

			Boiler Load		MM Zone 1 Zone 2 (or 4) Injection							MM Zone 2 Zone 3 (or 5) Injection							Analyzers				Summary of Results										
Test No.	Test Type	Start Test Time	Gross Load %	Load MMBtu per hr	# of Inj's	Tip Type	Water Flow [gpm]	Flow / inj [gpm]	Air P [psig]	Chem Flow [gph]	31% NSR	# of Inj's	Tip Type	Water Flow [gpm]	Flow / inj [gpm]	Air P [psig]	Chem Flow [gph]	31% NSR	NOx ppmd	B&W CO ppmd	O2 %(dry)	NH3 ppm	NOx ppmdc	Calc # NOX /MMBtu	CEMS	BL # NOX /MMBtu	Total NSR	% Red	B&W CEMS Red %	% Util	Conv Pass Out Temp F	Test No.	COMMENTS
3.038	after SB	9:26	101.81	101.81	3	F45	0.56	0.21	40	4.00	1.40	8	MNL-3	0.25	0.04	75	2.70	0.94	70	143	3.50		72	0.098	0.097	0.121	2.34	19.3%	19.8%	8.2%	886	3.038	
3.039	Baseline	9:56	100.61	100.61	--	F45	--	N/A	--	--	0.00	-		--	N/A	--	--	0.00	86	49	3.71		90	0.121	0.121	0.121	0.00	-0.4%	0.0%	N/A	892	3.039	
3.040	Baseline after another cal	10:43	100.24	100.24	--	F45	-	N/A	-	-	0.00	8		--	0.00	70	--	0.00	88	44	3.68		91	0.124	0.124	0.124	0.00	-0.1%	0.0%	N/A	905	3.040	
3.041	move to best MNL2 (#2.0	11:26	101.59	101.59	--	F45	-	N/A	-	-	0.00	8	MNL-2	0.52	0.07	70	2.70	0.92	66	284	3.35	2.4	67	0.091	0.091	0.124	0.92	26.4%	26.6%	28.5%	905	3.041	conv pass outlet temp = 905 F
3.042	add Z4 w/o making slip?	12:16	101.20	101.20	3	F45	0.56	0.21	40	4.01	1.38	8	MNL-2	0.52	0.07	70	2.70	0.93	61	201	3.40	7.9	62	0.085	0.085	0.124	2.30	31.7%	31.5%	13.8%	898	3.042	NOx at exp of util.
3.043	remove MNL to check on	12:44	100.60	100.60	3	F45	0.57	0.21	40	4.00	1.38	8		--	0.00	--	--	0.00	84	289	3.51		86	0.117	0.117	0.124	1.38	5.4%	5.6%	3.9%	902	3.043	31.7-26.4=5.3% independent?, combined util looks right too.
note	quick baseline returned to	13:00	100.00	100.00	--	F45	--	N/A		--	0.00	8		--	0.00	--	--	0.00	90	307	3.46		92	0.125	0.124	0.124	0.00	-1.1%	0.0%	N/A		note	ok
3.044	move air to OFA:burner (	14:20	100.50	100.50	--	F45	--	N/A		--	0.00	8		--	0.00	--	--	0.00	67	114	3.55		69	0.094	0.094	0.094	0.00	0.2%	0.0%	N/A	904	3.044	lowest BL without using a wrench
3.045	repeat test 41 with new co	15:01	101.16	101.16	--	F45	--	N/A		--	0.00	8	MNL-2	0.53	0.07	70	2.00	0.91	51	168	3.48	6.4	52	0.071	0.071	0.094	0.91	24.4%	24.5%	26.9%	906	3.045	still good reduction (out temp = 904)
3.046	NSR sweep down	15:41	101.40	101.40	--	F45	--	N/A		--	0.00	8	MNL-2	0.54	0.07	70	1.30	0.59	55	92	3.48		57	0.077	0.077	0.094	0.59	18.4%	18.1%	31.4%	909	3.046	
3.047	NSR sweep up	16:15	101.13	101.13	--	F45	--	N/A		--	0.00	8	MNL-2	0.52	0.07	70	2.60	1.18	47	100	3.46	8.8	48	0.065	0.065	0.094	1.18	30.4%	30.9%	25.8%	912	3.047	not bad…nh3 is moderate
3.048	baseline	16:41	100.60	100.60	--	F45	--	N/A		--	0.00	8		--	--		--	0.00	66	63	3.54		68	0.092	0.092	0.094	0.00	1.8%	2.1%	N/A	916	3.048	
3.049	move stoich to get 0.15 B	17:36	101.25	101.25	--	F45	--	N/A		--	0.00	8		--	0.00	-	-	0.00	109	23	4.74		121	0.164	0.162	0.162	0.00	-1.1%	0.0%	N/A	936	3.049	
3.050	repeat test 41 with new co	18:33	101.33	101.33	--	F45	--	N/A		--	0.00	8	MNL-2	0.51	0.071	70	3.42	0.90	77	19	4.76	14.0	85	0.116	0.115	0.162	0.90	28.5%	29.0%	31.7%	944	3.050	
3.051	NSR sweep down	19:07	100.72	100.72	--	F45	--	N/A		--	0.00	8	MNL-2	0.51	0.068	70	2.19	0.58	83	40	4.82		92	0.125	0.124	0.162	0.58	22.6%	23.5%	39.1%	941	3.051	
3.052	repeat #51 get NH3 data	19:44	101.15	101.15	--	F45	--	N/A		--	0.00	8	MNL-2	0.52	0.070	70	2.20	0.58	83	46	4.75	6.1	92	0.125	0.124	0.162	0.58	23.0%	23.5%	39.7%	944	3.052	
3.053	drop load and blow soot	20:14	100.88	100.88	--	F45	--	N/A		--	0.00	8		--	0.000		--	0.00	109	20	4.85		122	0.165	0.163	0.162	0.00	-1.8%	-0.6%	N/A	947	3.053	
3.054	mid load baseline 60%	22:14	60.06	60.06	--	F45	--	N/A		--	0.00	-		--	N/A		--	0.00	94	11	4.77		104	0.142	0.140	0.140	0.00	-1.1%	0.0%	N/A	654	3.054	baseline taken after O2 settled
3.055	try MNL-2	23:05	60.47	60.47	--	F45	--	N/A		--	0.00	8	MNL-2	0.22	0.030	75	1.00	0.51	84	11	4.72	26.8	93	0.126	0.125	0.140	0.51	10.0%	10.7%	19.6%	651	3.055	
3.056	NSR up	23:32	59.73	59.73	--	F45	--	N/A		--	0.00	8	MNL-2	0.21	0.030	75	2.01	1.04	84	10	4.95		94	0.128	0.126	0.140	1.04	8.7%	10.0%	8.4%	650	3.056	NH3 must be very high
3.057	Z3 only	0:08	59.80	59.80	--	F45	--	N/A		--	0.00	6	C00	1.40	0.242	30	3.11	1.60	58	11	4.96	13.9	65	0.088	0.087	0.140	1.60	36.9%	37.9%	23.0%	648	3.057	repeat old case# 3.66
3.058	NSR down	0:48	59.88	59.88	--	F45	--	N/A		--	0.00	6	C00	1.42	0.242	30	2.00	1.03	63	10	4.94	7.8	71	0.096	0.094	0.140	1.03	31.5%	32.9%	30.7%	649	3.058	
3.059	inc P to A,B injectors	1:21	59.94	59.94	--	F45	--	N/A		--	0.00	6	C00	1.39	0.237	30, 40	2.00	1.03	60	10	4.96	7.6	67	0.091	0.090	0.140	1.03	34.7%	35.7%	33.8%	652	3.059	increase P at AB. AB at 40 psi, CDEF at 30 psi
3.060	inc P to C,D injectors	2:55	60.03	60.03	--	F45	--	N/A		--	0.00	6	C00	1.37	0.234	30, 40	2.01	1.03	66	13	4.73	3.9	73	0.099	0.098	0.140	1.03	29.2%	30.0%	28.3%	653	3.060	CD at 40 psi, and ABEF at 30 psi, check if slip is from C & D inj.
3.061	reduce water	3:28	60.94	60.94	--	F45	--	N/A		--	0.00	6	C00	0.98	0.169	30, 40	2.00	1.01	71	11	4.58		78	0.106	0.104	0.140	1.01	24.5%	25.7%	24.3%	657	3.061	
3.062	Z4 alone	4:09	60.86	60.86	3	F45	0.28	0.10	45	1.00	0.53	-		-	N/A	-	-	0.00	68	11	4.63	3.9	75	0.101	0.101	0.133	0.53	23.7%	24.1%	44.5%	666	3.062	Z4 is good
3.063	BL	4:51	61.46	61.46	--	F45	--	N/A		--	0.00	-		--	N/A		--	0.00	89	10	4.83		99	0.134	0.133	0.133	0.00	-1.1%	0.0%	N/A	675	3.063	
3.064	Z3 + Z4	5:35	60.56	60.56	3	F45	0.29	0.10	45	1.00	0.54	6	C00	1.00	0.172	30,40	2.00	1.07	55	12	4.70	6.7	61	0.082	0.082	0.133	1.61	38.0%	38.3%	23.7%	666	3.064	combine case 3.061 & 3.062
3.065	tune up	6:28	60.79	60.79	3	F45	0.27	0.10	50	1.20	0.64	6	C00	0.99	0.169	30,40	1.50	0.80	55	11	4.72	-	61	0.083	0.081	0.133	1.44	37.9%	39.1%	26.4%	670	3.065	decrease NSR, mv chem from Z3 to Z4, inc P at Z4

Date: 8/18/2004--8/19/2004

			Boiler Load		MM Zone 1 Zone 2 (or 4) Injection							MM Zone 2 Zone 3 (or 5) Injection							Analyzers				Summary of Results										
Test No.	Test Type	Start Test Time	Gross Load %	Load MMBtu per hr	# of Inj's	Tip Type	Water Flow [gpm]	Flow / inj [gpm]	Air P [psig]	Chem Flow [gph]	31% NSR	# of Inj's	Tip Type	Water Flow [gpm]	Flow / inj [gpm]	Air P [psig]	Chem Flow [gph]	31% NSR	NOx ppmd	B&W CO ppmd	O2 %(dry)	NH3 ppm	NOx ppmdc	Calc # NOX /MMBtu	CEMS	BL # NOX /MMBtu	Total NSR	% Red	B&W CEMS Red %	% Util	Conv Pass Out Temp F	Test No.	COMMENTS
	NOTE: recalibrate and repeat baseline (moving MNL), calibration was low (183 when it should have been 196)																																
4.066	mid load baseline 60%	8:26	60.84	60.84	--	F45	--	N/A		--	0.00	-		--	N/A		--	0.00	91	9	4.63		100	0.136	0.134	0.134	0.00	-1.4%	0.0%	N/A	683	4.066	long time since calibration
4.067	try MNL Port #1	9:18	60.47	60.47	--	F45	--	N/A		--	0.00	8	MNL-1	0.37	0.049	70	1.50	0.80	65	12	4.56	19.8	71	0.097	0.095	0.134	0.80	27.9%	29.1%	35.0%	683	4.067	first shot with MNL-1
	NOTE: Unit trip (lost burner) at 9:38, stopped test and NH3 (data should still be good) [Hamid will digitally remove the last few points to correct this data)																																
4.068	pre-baseline	12:16	59.29	59.29	--	F45	--	N/A		--	0.00	--		--	N/A		--	0.00	84	9	4.55		92	0.125	0.124	0.124	0.00	-0.6%	0.0%	N/A	673	4.068	
4.069	slip buster	13:12	60.75	60.75	--	F45	--	N/A		--	0.00	8	MNL-1	0.20	0.028	70	1.40	0.80	60	16	4.22	11.4	64	0.087	0.087	0.124	0.80	29.6%	29.8%	36.9%	672	4.069	decr slip?
4.070	drop NSR	14:00	62.64	62.64	--	F45	--	N/A		--	0.00	8	MNL-1	0.21	0.028	70	0.90	0.50	69	23	4.31	8.4	74	0.101	0.101	0.124	0.50	18.6%	18.5%	37.1%	689	4.070	
4.071	add Z4 like #65	14:48	61.48	61.48	3	F45	0.36	0.13	50	1.00	0.57	8	MNL-1	0.21	0.028	70	0.90	0.51	56	11	4.64	17.9	62	0.084	0.083	0.124	1.07	32.6%	33.1%	30.3%	691	4.071	hit Z4 too hard.
4.072	rep #65	15:53	60.66	60.66	3	F45	0.28	0.10	50	1.03	0.59	6	C00	1.03	0.176	30,40	1.50	0.86	60	10	4.80	5.6	67	0.090	0.090	0.124	1.45	27.0%	27.4%	18.6%	685	4.072	ok
4.073	shift chem from Z3 to Z4	16:40	61.70	61.70	3	F45	0.28	0.10	50	1.30	0.73	6	C00	1.03	0.175	30,40	1.30	0.73	58	11	4.52	6.2	63	0.086	0.085	0.124	1.46	30.7%	31.5%	20.9%	691	4.073	running out of coal
4.074	baseline	17:13	61.88	61.88		F45		N/A			0.00		C00		N/A			0.00	82	8	4.57		90	0.122	0.120	0.124	0.00	1.7%	3.2%	N/A		4.074	done.