AC22-92PC92159

CONF-9603233--1

ADVANCEMENTS IN LOW NOx TANGENTIAL FIRING SYSTEMS

Institute of Clean Air Companies Forum 96
March 1996 - Baltimore

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Abstract

The most cost effective method of reducing nitrogen oxide emissions when burning fossil fuels, such as coal, is through in-furnace NOx reduction processes. ABB Combustion Engineering, Inc. (ABB CE), through its ABB Power Plant Laboratories has been involved in the development of such low NOx pulverized coal firing systems for many years. This development effort is most recently demonstrated through ABB CE's involvement with the U.S. Department of Energy's (DOE) "Engineering Development of Advanced Coal Fired Low-Emission Boiler Systems" (LEBS) project.

The goal of the DOE LEBS project is to use "near term" technologies to produce a commercially viable, low emissions boiler. This paper addresses one of the key technologies within this project, the NOx control subsystem. The foundation for the work undertaken at ABB CE is the TFS 2000™ firing system, which is currently offered on a commercial basis. This system encompasses sub-stoichiometric combustion in the main firing zone for reduced NOx formation. Potential enhancements to this firing system focus on optimizing the introduction of the air and fuel within the primary windbox to provide additional horizontal and vertical staging. As is the case with all in-furnace NOx control processes, it is necessary to operate the system in a manner which does not decrease NOx at the expense of reduced combustion efficiency. The objective of developmental work on the low NOx firing system is to reduce NOx emissions levels leaving the boiler to 0.10 pounds NOx / MMBtu while maintaining carbon in ash at acceptably low levels (<5%) for high sulfur, mid-western and eastern bituminous coals.

The approach used to evaluate the various firing systems concepts included kinetic and computational modeling, small scale experimental testing in a Fundamental Scale Burner Facility (FSBF), and larger scale combustion testing in a Boiler Simulation Facility (BSF.) Both modeling and experimental testing were applied to better understand the mechanisms governing in-furnace NOx reduction and to identify potential enhancements to the TFS 2000™ firing system. This paper presents an overview of the approach used in the development of an advanced low NOx firing system and results from the experimental testing of that system.

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Introduction

Combustion Engineering, Inc. (ABB CE) is one of three contractors participating in the DOE's LEBS project. The overall objective of this project is the improvement of the environmental performance of pulverized coal fired power plants, without adversely impacting efficiency or the cost of electricity. One of the key elements within the LEBS project is the NOx control subsystem, for which the specific goals are the reduction of nitrogen oxides (NOx) emissions leaving the primary furnace to 0.10 pounds/ MMBtu or lower while maintaining carbon in ash levels at 5% or less.

For the LEBS project, the DOE has specified the use of near term technologies, which are at least partially developed, to provide these overall emissions reductions. Based on technical and economic feasibility, advanced tangential firing was selected as the primary means of NOx emissions control [1,2] for ABB CE's LEBS boiler design. Specifically, ABB CE's TFS 2000™ firing system, which is a proven technology and commercially available, represents the technology selected as the basis for in-furnace NOx reduction. This firing system design has been demonstrated to provide NOx emissions of 0.20 pounds/ MMBtu in prior laboratory and full scale, retrofit, utility boiler applications [3,4].

Briefly, the TFS 2000™ firing system has been developed for minimum NOx emissions from pulverized coal fired boilers, accomplished by way of combustion techniques only. Specific features of this system include the use of concentric firing system (CFS) air nozzles, where the main windbox secondary air jets are introduced at a larger firing circle than the fuel jets; close coupled over fire air (CCOFA) for improved carbon burnout; and multi-staged separated over fire air (SOFA) to provide for complete combustion while maintaining an optimum global stoichiometry history for NOx control. In addition, the TFS 2000™ firing system includes flame attachment coal nozzle tips for rapid fuel ignition and a pulverizer configured with a Dynamic™ Classifier to produce fine coal to minimize carbon losses under these staged combustion conditions.

Approach

The plan for reducing NOx emissions under the LEBS project was to enhance the TFS 2000™ firing system, focusing on optimizing the introduction of the air and fuel within the primary windbox. These enhancements were based on controlling the combustion of the coal in a more local sub-stoichiometric environment. That is, in addition to the global staging currently applied, improved NOx reduction was sought by controlling and optimizing the mixing of the fuel and air locally within the main firing zone through vertical and horizontal staging techniques. Vertical staging was done by biasing the air and fuel within the main windbox to control/ optimize the rate of the vertical stoichiometry build-up in this region. Similarly, horizontal staging was done by biasing the air and fuel distribution between each of the four windbox corners as a means of controlling the horizontal stoichiometry build-up from corner to corner within the firing zone. As a result of these enhancements, the residence time/ stoichiometry history of the coal combustion is controlled on a more local scale and the resultant formation of NOx minimized. In addition to these enhancements, newer, more novel firing systems such as two corner firing (the injection of air and coal through only two of the normal four corners in a tangentially fired system) were evaluated as a means of providing additional NOx reduction.

The processes used in the development and evaluation of the various firing system concepts/ configurations included an integrated approach of chemical kinetic and computational modeling, small scale experimental testing in a Fundamental Scale Burner Facility (FSBF), and larger scale experimental testing in a Boiler Simulation Facility (BSF).

A 1-D (time) chemical kinetics reaction model was used to evaluate and screen the effects of vertical staging within the main windbox on overall NOx production in order to optimize the vertical stoichiometry build up. Results from this modeling were applied to the development of advanced fuel staging concepts which were subsequently evaluated in small scale combustion testing (6.1 MMBtu/ hour) performed in the FSBF. Additional screening and development of new, novel firing systems employing horizontal staging in the main firing zone was accomplished using 3-D computational fluid dynamic (CFD) modeling. In this modeling, the furnace aerodynamics, mixing, and stoichiometry history (gas side performance) of these various concepts were evaluated to assess the potential for additional reduction in NOx emissions. The results from the kinetic modeling, small scale combustion testing, and CFD modeling were used to provide the information necessary for the development of the LEBS NOx control subsystem design strategy. These designs were subsequently tested and evaluated in larger, pilot scale testing (50 MMBtu/ hour) in the BSF. A flow diagram of this integrated approach is shown in Figure 1.

Discussion of Results

Kinetic Modeling

In order to evaluate the effects of various firing system arrangements on total NOx formation, a 1-D kinetic model which utilizes the CHEMKIN code was first applied. This model employs a series of plug flow reactors suitable for simulating the staged introduction of fuel and air within the main windbox. Chemical kinetic mechanisms of Miller and Bowman [5] were used in this model to evaluate the effects of stoichiometry, residence time and temperature history on NOx formation and destruction. The evaluation of these results, though qualitative, served as an important screening tool for identifying promising concepts.

Results from the chemical kinetic modeling work indicated that, although bulk main windbox stoichiometry is the primary influence on overall NOx emissions, the stoichiometric build up in the main windbox zone has a significant influence on NOx formation and reduction. That is, for similar bulk windbox stoichiometries, the cumulative sequencing of fuel and air in the main firing zone influences the overall NOx emissions. In other words, although it is the global stoichiometry history that dominates the overall NOx formation and reduction process, the build up of stoichiometry within the windbox zone is also a significant contributor. This is illustrated in Table 1, where the predicted NOx values are given for a series of configurations, each with the same main burner zone and global bulk stoichiometries. The only differences in each of these configurations is the stoichiometry build up within the main windbox zone. As can be seen from this data, a variation of nearly ±30% of the average predicted NOx was found to exist as the cumulative stoichiometry sequencing was varied. The results of vertical staging from this modeling were applied in firing system designs and subsequently evaluated / demonstrated in small scale combustion testing in the FSBF.

Table 1 - Predicted NOx for Similar Main Burner Stoichiometries

Description	Predicted NOx
Configuration 1	74
Configuration 2	79
Configuration 3	88
Configuration 4	92
Configuration 5	135

Small Scale Combustion Testing

In order to evaluate the effects of integrating advanced fuel staging scenarios in the main windbox, and to explore additional preliminary concepts of vertical staging, small scale combustion testing was performed in ABB Power Plant Laboratories Fundamental Scale Burner Facility (FSBF). The objective of the FSBF testing was to evaluate the NOx emissions and combustion performance from firing systems that capitalize on the reburn process within the main windbox zone. Additionally, testing was performed to evaluate the effects of residence time on NOx reduction on the test coal, analysis shown in Table 2, and to screen concepts for larger scale pilot testing in the Boiler Simulation Facility (BSF).

The FSBF is a horizontally fired cylindrical test furnace, with adjustable length, capable of firing up to 9.9 MMBtu/ hour thermal input. For this testing, the furnace was configured for four corner, tangential firing. Three elevations each of coal and auxiliary air comprised the main burner region, and up to five elevations of over fire air were available to model various globally staged furnace configurations. A furnace firing rate of nominally 6.1 MMBtu/ hour and overall length were selected to simulate the mixing history (residence time and temperature) representative of typical commercial applications. A schematic of this facility is shown in Figure 2.

Low NOx firing typically requires that combustion in the main burner zone (MBZ) be performed under sub-stoichiometric conditions. In addition, the available residence time under these sub-stoichiometric conditions is an important factor in determining the magnitude of these NOx emission. As such, various conventional global air staging techniques were tested to benchmark their effectiveness on NOx reduction for the test fuel. Outlet NOx emissions as a function of staged residence time and bulk MBZ stoichiometry, on this test fuel in the FSBF, are presented in Figure 3. As expected, lower outlet NOx emissions are achieved under sub-stoichiometric combustion conditions in the MBZ, with up to a 70% reduction when compared against baseline, unstaged conditions. In addition to stoichiometry, it is also seen in this Figure that the location of the over fire air injection is an important factor in determining the magnitude of NOx emissions. Specifically, lower NOx emissions were obtained under similar levels of staging (same MBZ stoichiometry) when the introduction of over fire air is moved further downstream from the final coal elevation, thereby increasing sub-stoichiometric residence times in the furnace.

Additional testing was performed to determine the effects of over fire air residence time on overall NOx emissions. This was accomplished by maintaining the bulk main burner zone stoichiometry constant while varying the location of a single elevation of separate over fire air (SOFA). Results from this testing, shown in Figure 4, indicate that the largest reduction rate in NOx emissions occurs over a short bulk residence time (determined from the upper elevation of fuel injection), with diminishing returns in overall NOx reduction as the over fire air residence times are increased.

After having benchmarked various global staging arrangements in the FSBF for this test fuel, testing was performed to evaluate the effects of vertical staging in the main windbox zone on overall NOx formation. MBZ vertical staging was accomplished by strategically biasing the air and fuel distribution within the windbox, thus controlling the stoichiometry sequencing in the main combustion zone, while holding the bulk main burner zone stoichiometry constant, and was performed for several staged furnace arrangements. Results from this testing indicate that controlling the stoichiometry sequencing in the main burner zone had a significant impact on outlet NOx emissions, as shown in Figure 5. Specifically, limiting the peak stoichiometries within the main windbox zone was shown to be important in controlling overall NOx formation. As seen in this Figure, outlet NOx emissions varied by more than 20% for similar globally staged furnace arrangements. These variances were due to the differences in the rate of change of the MBZ stoichiometry only, and correspond with the prediction of the chemical kinetic modeling.

The results from this FSBF testing were used to identify potential enhancements to the TFS 2000™ firing system and later employed in the pilot scale combustion testing.

<u>Computational Fluid Dynamic Modeling</u>

3-D computational fluid dynamic modeling (CFD) was also used in the development and evaluation of advanced firing system concepts. CFD modeling allows advanced firing system concepts to be evaluated in a more cost effective manner than pilot-scale testing. The insight gained from the computational models helps to screen potential firing system concepts and better focus the experimental testing. As part of this project, CFD modeling was used to evaluate advanced horizontally staged firing concepts, such as two (2) corner coal firing. All CFD simulations were performed with the FLUENT code using the coal combustion and radiative heat transfer submodels.

Proprietary user-defined subroutines developed for use with the FLUENT code were also used in the CFD analyses.

Prior to evaluating any of the advanced firing system concepts, a CFD simulation of an existing TFS 2000™ firing arrangement, in the BSF, was performed. Results from this simulation were compared to previously obtained experimental data, and the model's thermal boundary conditions modified to assimilate the furnace temperature history. Once the model was representative of the experimental data for this TFS 2000™ configuration, all subsequent modeling results were benchmarked against this arrangement. In each subsequent case, boundary conditions were held constant in order to qualitatively evaluate the effects of the various new firing systems on the furnace gas side performance.

As part of the screening process, various combinations of vertically and horizontally staged furnace arrangements were computationally modeled. Results from each of these simulations were analyzed and benchmarked against the TFS 2000™ simulation. The primary objective of this modeling was to evaluate the impacts of firing system modifications on furnace aerodynamics and emissions reduction potential. Specifically, the gas flow, gas species, and temperature distributions within the furnace, along with furnace outlet temperatures, were examined for each of the arrangements and compared to the TFS 2000™ configuration. In addition, coal particle trajectories from each of the individual coal nozzles were examined. Included in this analysis were the coal particle stoichiometry, temperature, and residence time histories to assess the impacts of the various firing system modifications on reduced NOx emissions potential. Typical BSF coal particle trajectories for a single coal nozzle are shown in Figure 6. These simulations were also used to assess effects of the advanced firing system arrangements on wall heat flux distributions and their potential impacts on waterwall circulation in order to guide in the selection of optimum firing system designs. Finally, the potential for water wall corrosion/ slagging for each of these systems was examined by way of the predicted particle concentrations and gas phase stoichiometry along the furnace walls for additional guidance in the firing system design.

Briefly, the modeling results indicated that many of the proposed horizontal firing arrangements were viable when applied to the BSF geometry, though visible differences in the gas flow, species and temperature distributions in the main windbox zone were predicted, when compared against the TFS 2000™ arrangement. As a result of these differences, significant changes in wall heat flux patterns and particle concentrations at the wall resulted. However, modifications to the promising new firing system concepts were performed which resulted in peak values that, although appearing at different locations in the furnace, were not much different than those for the TFS 2000™ arrangement.

In summary, the modeling results suggested several of the horizontal staging concepts showed potential for reduce NOx formation, without negatively affecting furnace performance, and warranted further evaluation in ensuing combustion testing in the

BSF. In addition, the modeling provided general insight into the performance of these systems, better focusing the experimental testing.

Pilot Scale Combustion Testing

Pilot scale combustion testing of in-furnace NOx control systems was performed in ABB Power Plant Laboratories' Boiler Simulation Facility (BSF). The objective of this testing was to evaluate enhancements to the existing NOx control technologies for improved NOx emissions performance, while providing the necessary information for supporting the design of the NOx control subsystem for the LEBS Proof of Concept Test Facility (POCTF).

The BSF is a pilot scale test furnace, nominally rated at 50 MMBtu/ hour (5 MWe) for coal firing, that reliably duplicates the combustion characteristics of a tangentially fired utility boiler. All major aspects of a typical tangentially fired utility boiler are duplicated in the BSF including a "V" hopper for bottom ash collection, the use of multiple burner elevations, and an arch with subsequent backpass convective "superheat," "reheat," and "economizer" surfaces. Selective refractory lining over atmospheric pressure "waterwalls" allows the matching of the residence time / temperature history of large scale utility boilers, including the horizontal furnace outlet plane (HFOP) gas temperature, within the BSF.

The BSF is fully instrumented to monitor the combustion process. Instruments for measuring coal feed rate, primary and individual secondary air mass flow rates, outlet emissions (O2, CO2, CO, SO2, NO, and NOx), and convective pass heat flux distribution are tied into a combined DCS / data acquisition system to allow for control and logging of these and other important operational parameters. For the subject testing, the BSF was operated in a tangentially fired mode with multiple levels of available separated over fire air (SOFA), as depicted in Figure 7. Prior laboratory test programs have shown that BSF test results can be reliably translated to the field for use in firing system design, and subsequent performance prediction [3].

Performance targets for the BSF combustion testing were consistent with those for the LEBS program; NOx emissions <0.10 pounds/ MMBtu and carbon in the fly ash <5% for high sulfur, mid-western and eastern bituminous coals. In addition, the lower furnace heat absorption profiles and convective pass heat flux distribution were to remain similar to or improved over the existing system. The coal utilized during the BSF testing was the high sulfur, medium volatile, eastern bituminous Viking coal from Montgomery, Indiana. An analysis of the Viking coal is given in Table 3.

Prior to the initiation of NOx control subsystem testing, the firing system for the BSF was modified to take advantage of current and previous R&D project findings. First, ABB CE's Aerotip™ coal nozzle tip design was utilized as the base from which the BSF coal nozzles were constructed. The Aerotip™ design embodies improved aerodynamic features to minimize tip distortion, overheating, and coal deposition related problems. Also, it supports the test programs need for a low NOx coal nozzle tip through its control over near field stoichiometry.

In addition to the incorporation of an Aerotip™ based coal nozzle tip, the main windboxes of the BSF were designed to accommodate a range of vertical and horizontal air and coal staging scenarios. The design of the secondary air nozzles was based on the need to maintain proper jet momenta, while having sufficient flexibility to test variations in vertical and horizontal air staging. In addition, excess coal nozzle capacity was incorporated to allow the testing of various coal staging scenarios, including two corner coal firing. With this foundation, each of the "base" (r.e. benchmark) firing system designs tested in the BSF, including the TFS 2000™ firing system, was able to incorporate the results of the prior chemical kinetic and small scale (FSBF) combustion testing with respect to main windbox vertical air staging.

One goal of the BSF testing was to generate design data in support of achieving NOx emissions of 0.10 pounds/ MMBtu through in-furnace firing system modifications (i.e. prior to any post combustion process NOx reduction system). Toward this end, various "conventional" global air staging techniques were tested in order to benchmark their NOx reduction potential on the test fuel. This work included investigations of close coupled over fire air (CCOFA), upper and lower (single) elevations of separated over fire air (SOFA), and an implementation of ABB CE's TFS 2000™ technology. All of the varied over fire air configurations utilized the same main windbox arrangement, and all were performed with high fineness (90% - 200 mesh) coal grind, which is consistent with TFS 2000™ firing system design standards.

A summary of the results from testing various over fire air configurations with the test coal are given in Figure 8. As anticipated, the implementation of global air staging results in a significant reduction in furnace outlet NOx emissions. Beginning with NOx emissions of 0.52 pounds/ MMBtu with a typical "baseline" (post-NSPS) firing system arrangement, NOx reductions continued to a low of 0.13 pounds/ MMBtu for an "optimized" TFS 2000™ firing system arrangement (Note: similar 0.13 pounds/ MMBtu outlet NOx emissions were obtained with the upper SOFA only, but this was at slightly degraded carbon in the fly ash performance). The "optimized" TFS 2000™ system incorporates improvements to the bulk stoichiometry history over the initial TFS 2000™ test, with identical main and over fire air windbox configurations. In all, a 75% reduction in NOx from baseline levels was achieved with the "optimized" TFS 2000™ system. As expected, carbon in the fly ash increased as the global staging was increased, but remained below the performance limit of 5%.

Having benchmarked the effects of global staging on firing system performance, both vertical and horizontal staging techniques within the main firing zone were subsequently tested to evaluate their effects on NOx performance. The objectives of this work were to confirm the results of prior main windbox vertical air staging work, and to further reduce outlet NOx emissions from the previously demonstrated "best" level of 0.13 pounds/ MMBtu through the application of horizontal, and integrated vertical and horizontal main windbox staging techniques. As such, these methodologies were applied in concert with the optimized TFS 2000™ firing system, keeping the global stoichiometry history constant to allow meaningful comparisons.

First, vertical air staging within the main windbox was independently varied to demonstrate its effect on NOx formation at this large pilot scale. Results from this testing, given in Figure 9, show that significant variation in NOx emissions occur as main windbox vertical air staging is changed. In this case variations to the vertical air staging produced a +/- 13% deviation in outlet NOx about the mean. This result confirms that the main windbox vertical stoichiometry history is an important contributor to overall NOx formation, even with significant levels of global air staging. Overall, NOx emissions increased when variations to the main windbox vertical stoichiometry build-up were applied to the previously optimized TFS 2000™ arrangement. This result is, however, expected since the "optimized" TFS 2000™ system incorporates the results of prior chemical kinetic and small scale combustion test vertical air staging work into the configuration of its main windbox as noted above.

Next, horizontal staging, used to control the horizontal "build-up" of stoichiometry (corner to corner) within the main burner zone, was evaluated. This was accomplished by biasing the fuel and air between one or more of the four corners. Tested subsets of this technique are two corner firing, where all of the air and fuel are injected through two of four corners in a tangential arrangement, and opposed corner firing where the coal is injected from two corners, and the air from the remaining two. In general, independent implementation of horizontal staging techniques resulted in neutral to degraded NOx emissions performance over that of the optimized TFS 2000™ firing system during the subject testing. This is seen in Figure 10, which shows the effect of independent variation of either fuel or air (horizontal staging) on overall NOx emissions performance. These results demonstrate that, similar to the prior vertical staging experiments, outlet NOx emissions can be affected by horizontal fuel and air distributions. However, these results also demonstrate that the global time - stoichiometry history (i.e. the TFS 2000™ stoichiometry profile) dominates the NOx formation and reduction processes at these levels of global air staging.

Finally, several configurations which applied integrated vertical and horizontal staging techniques as a means of "optimizing" the stoichiometry of combustion within the main windbox were evaluated. Integrated vertical and horizontally staged firing systems were extensively evaluated using CFD modeling prior to the BSF test. In contrast to their independent performance, Figure 11 shows that when suitably combined, an integrated vertical and horizontal staging strategy offers a small, but consistent improvement to the NOx emissions performance of the optimized TFS 2000™ system. At a NOx emission level of 0.11 pounds/ MMBtu, the "best" integrated system (shown on Figure 11 as "Integrated Config. 6") produced a greater than 10% reduction in NOx over the previously optimized TFS 2000™ system. Carbon loss results (not shown) were also similar for the two firing systems.

Summary

Chemical kinetic modeling, computational fluid dynamics (CFD) and small scale combustion testing in ABB Power Plant Laboratories' Fundamental Scale Burner Facility (FSBF) have demonstrated that, in addition to global stoichiometry, the build-up of the stoichiometry within the main windbox zone influences the overall NOx formation for a given firing system configuration. By controlling and optimizing the mixing of the fuel and air in the main windbox zone, improved NOx performance can be achieved.

During the pilot scale NOx control subsystem testing in the ABB Power Plant Laboratories' Boiler Simulation Facility (BSF), in-furnace NOx reductions of 75%, compared to the baseline, unstaged firing system, were demonstrated for an "optimized" TFS 2000™ firing system on the test, Viking coal. Additional enhancements to this system in the form of integrated vertical and horizontal staging of the coal and air within the main windbox region, identified through the use of CFD modeling, demonstrated the potential to produce an additional 10% reduction in NOx emissions over the previously optimized TFS 2000™ system. During the BSF testing, a test period "best" NOx emissions level of 0.11 pounds/ MMBtu was achieved with integrated vertical and horizontal staging superimposed on a TFS 2000™ globally staged firing system.

Additional pilot scale testing of potential NOx control subsystems in the BSF is currently planned for early 1996 under this project. This testing will serve to further confirm the performance of the integrated vertical and horizontal staging technique, focusing on the repeatability of the present test results, while generating design information for this and other, promising, firing system concepts for eventual full scale utility boiler application.

Acknowledgements

The authors would like to acknowledge the following individuals who contributed to the work in this paper: N. Nsakala, S. Srinivasachar, D. Thornock, and J. Walker.

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	AS RECEIVED	MOISTURE FREE	MOISTURE & ASH FREE
PROXIMATE ANAL., WT. %			
MOISTURE (TOTAL)	3.0		
VOLATILE MATTER	33.3	34.4	36.3
FIXED CARBON (DIFF.)	58.6	60.4	63.7
ASH	5.1	5.2	
TOTAL	100.0	100.0	100.0
HHV, BTU/LB	13,288	13,699	14,455
LB ASH/ MMBTU	3.8		
ULTIMATE ANAL., WT. %			
MOISTURE (TOTAL)	3.0		
HYDROGEN	4.0	4.1	4.3
CARBON	75.2	77.6	81.8
SULFUR	0.7	0.8	0.8
NITROGEN	1.8	1.8	1.9
OXYGEN (DIFF)	10.2	10.5	11.2
ASH	5.1	5.2	
TOTAL	100.0	100.0	100.0

PARTICLE MESH SIZE	SIZE % RETAINED
+ 50	trace
+ 70	0.2
+100	0.5
+140	2.6
+200	6.7
-200	90.1

Table 2 - REND LAKE COAL ANALYSIS

	AS RECEIVED	MOISTURE FREE	MOISTURE & ASH FREE
PROXIMATE ANAL., WT. %			
MOISTURE (TOTAL)	4.1		
VOLATILE MATTER	35.2	36.7	40.7
FIXED CARBON (DIFF.)	51.3	53.5	59.3
ASH	9.4	9.8	
TOTAL	100.0	100.0	100.0
HHV, BTU/LB	12,572	13,109	14,529
LB ASH/ MMBTU	7.5		
ULTIMATE ANAL., WT. %			
MOISTURE (TOTAL)	4.1		
HYDROGEN	5.4	5.6	6.2
CARBON	68.9	71.9	79.6
SULFUR	2.6	2.7	3.0
NITROGEN	1.6	1.6	1.8
OXYGEN (DIFF)	8.0	8.4	9.4
ASH	9.4	9.8	
TOTAL	100.0	100.0	100.0

PARTICLE MESH SIZE	SIZE % RETAINED
+ 50	trace
+ 70	0.2
+100	0.7
+140	2.7
+200	6.0
-200	90.3

Table 3 - VIKING COAL ANALYSIS

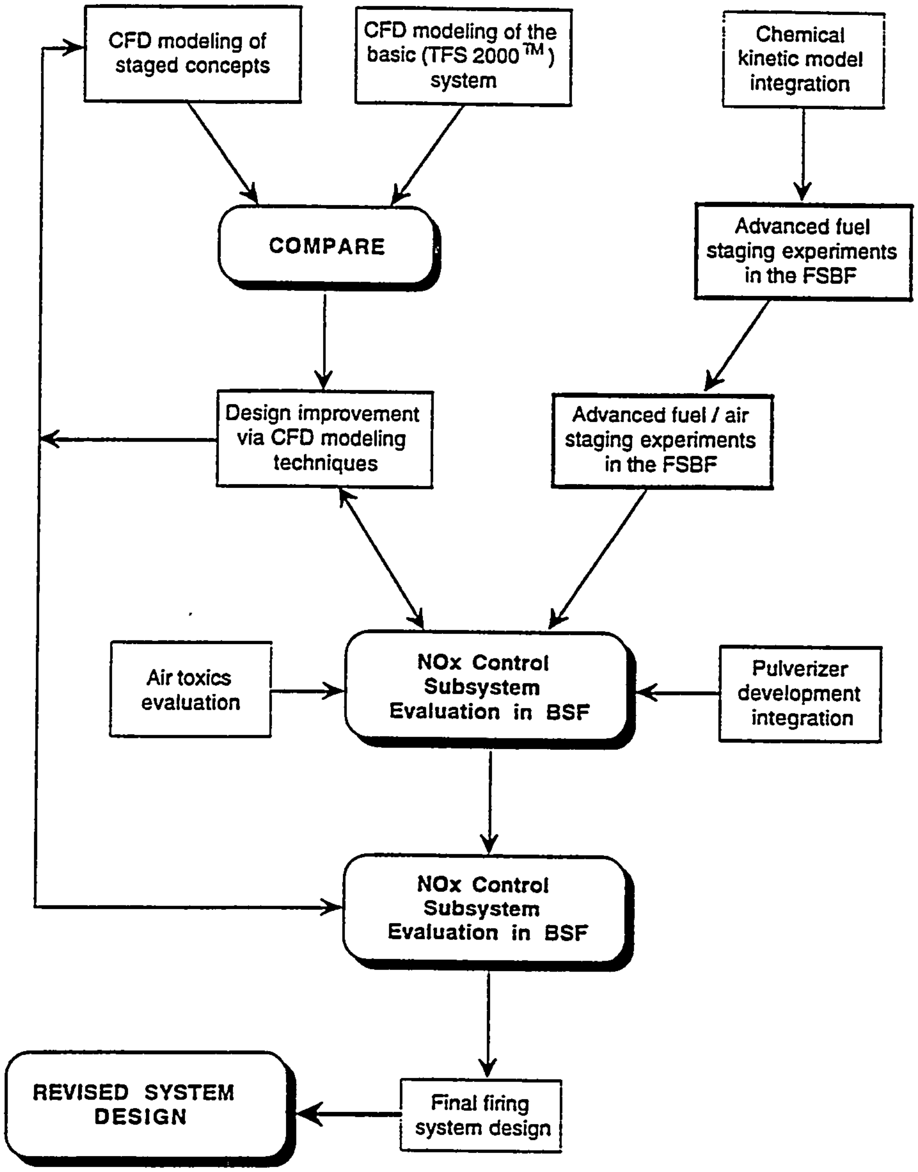

Figure 1 - LEBS NOx Control Subsystem Work Flow Chart

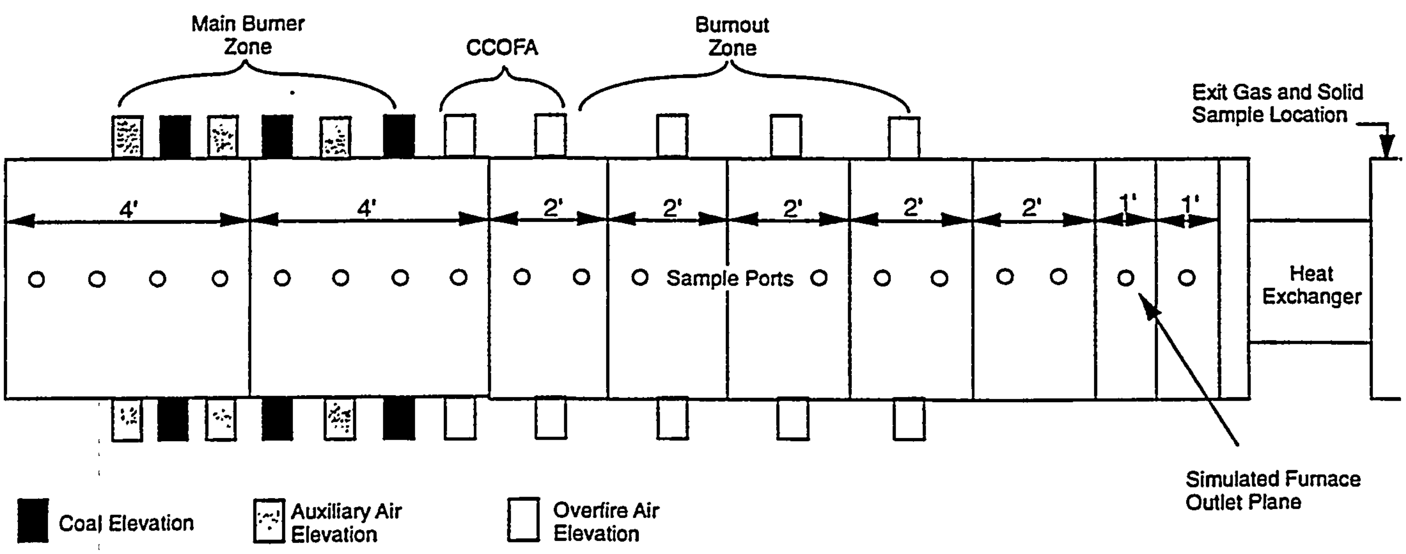

Figure 2 - Schematic of FundamentalScale Burner Facility

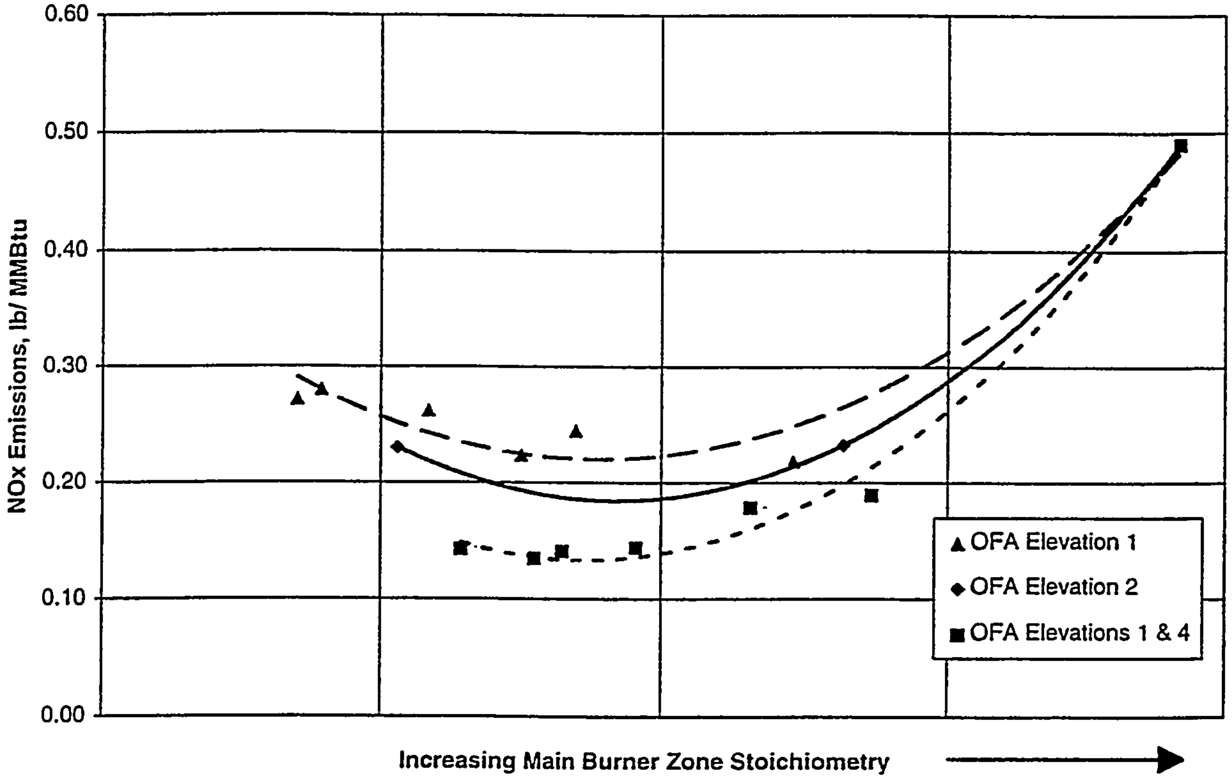

Figure 3 - NOx vs. Main Burner Zone Stoichiometry

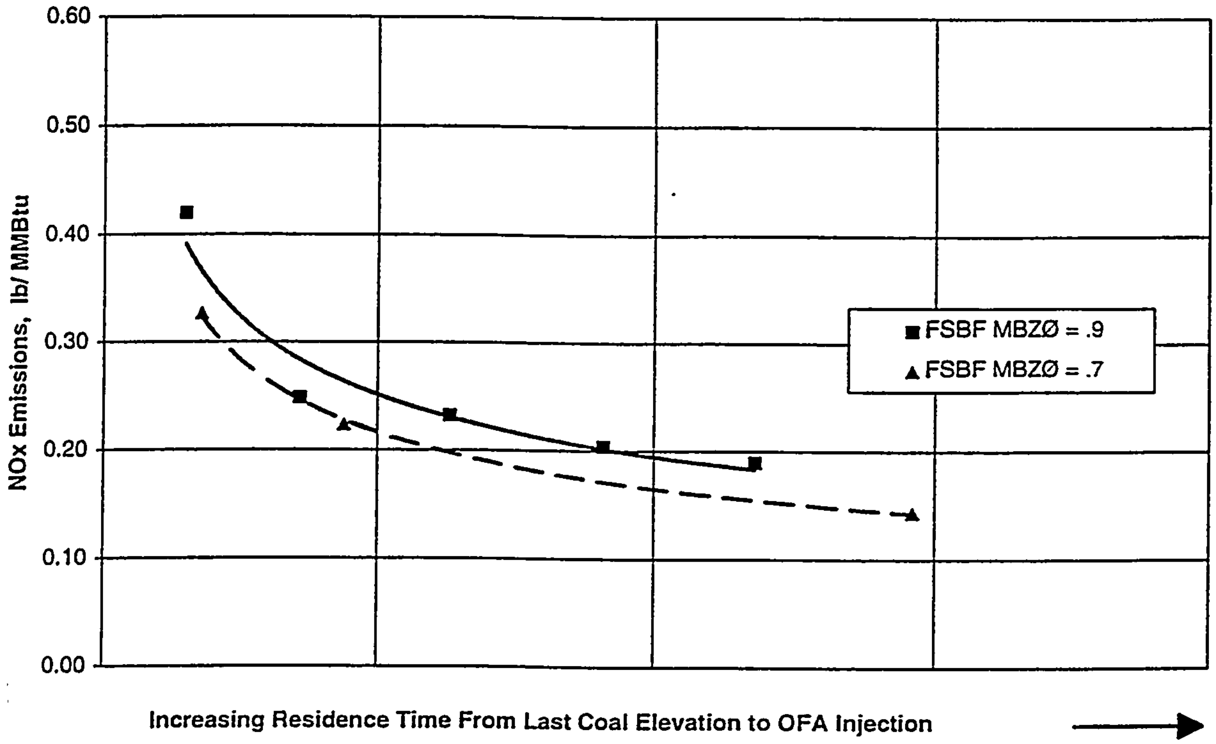

Figure 4 - Effect of Residence Time on Flue NOx

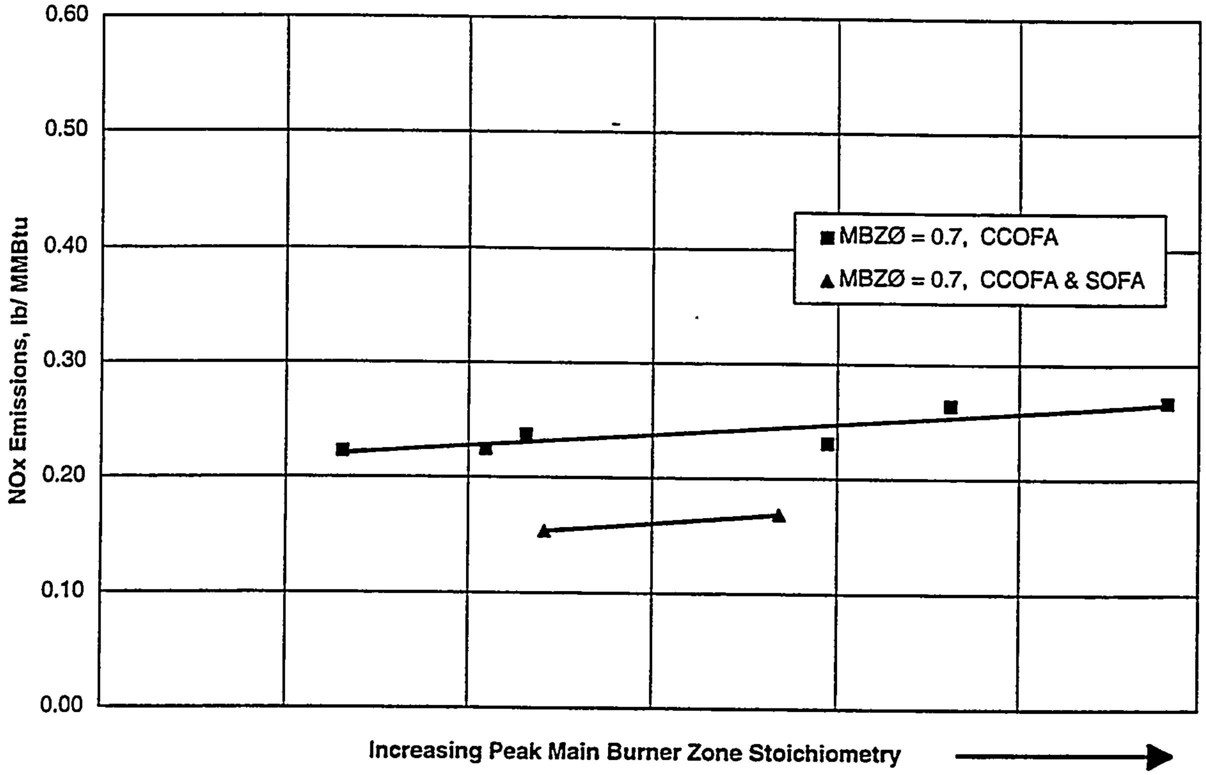

Figure 5 - Outlet NOx vs Maximum Bulk Windbox Stoichiometry

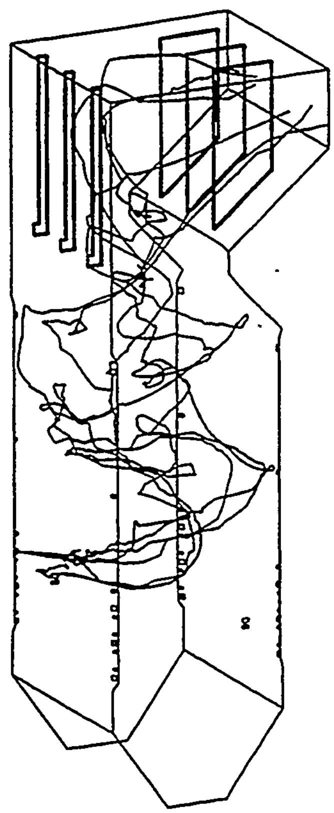

Figure 6 - Typical Coal Particle Trajectories

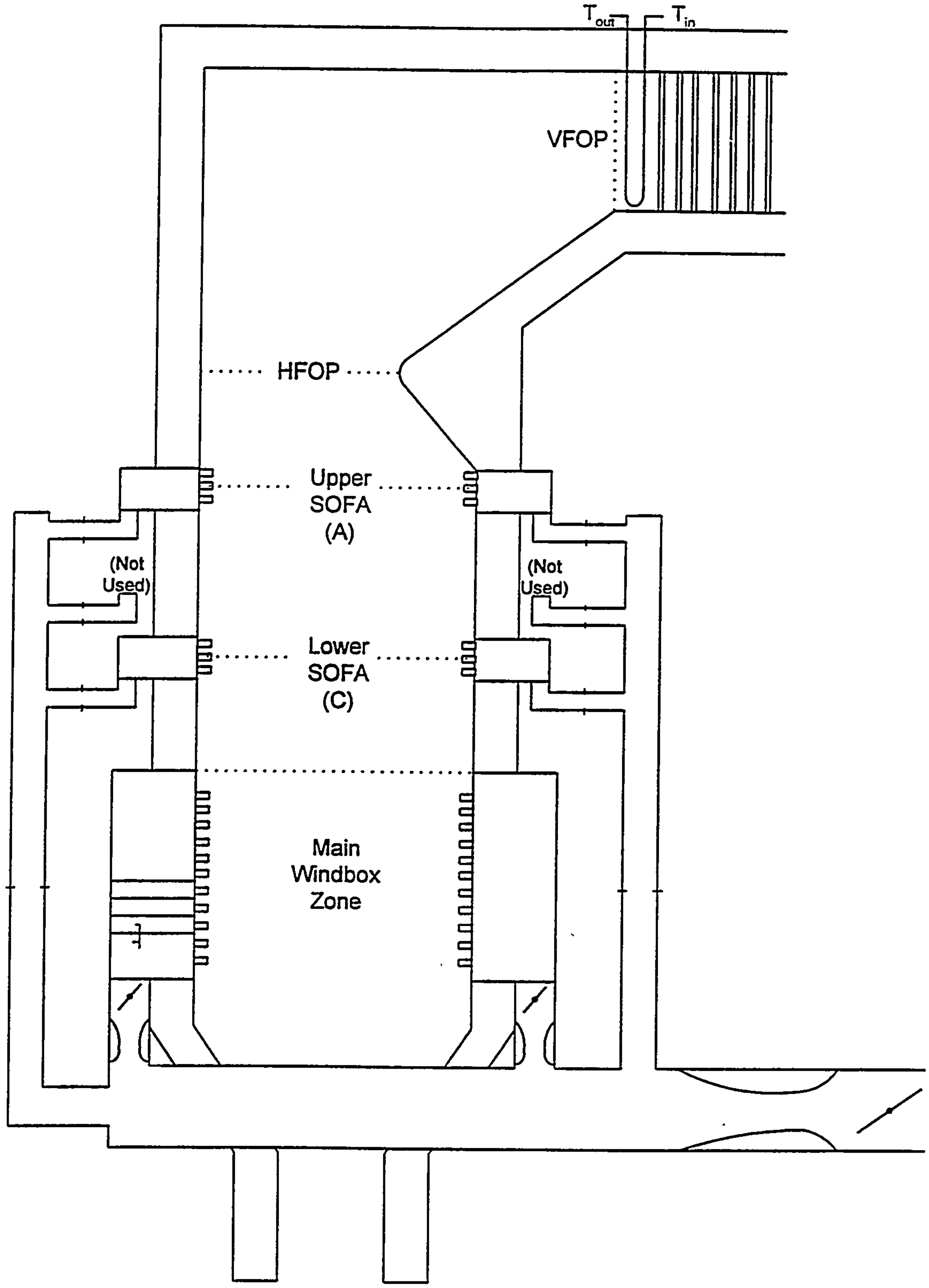

Figure 7 - ABB PPL's Boiler Simulation Facility (BSF)

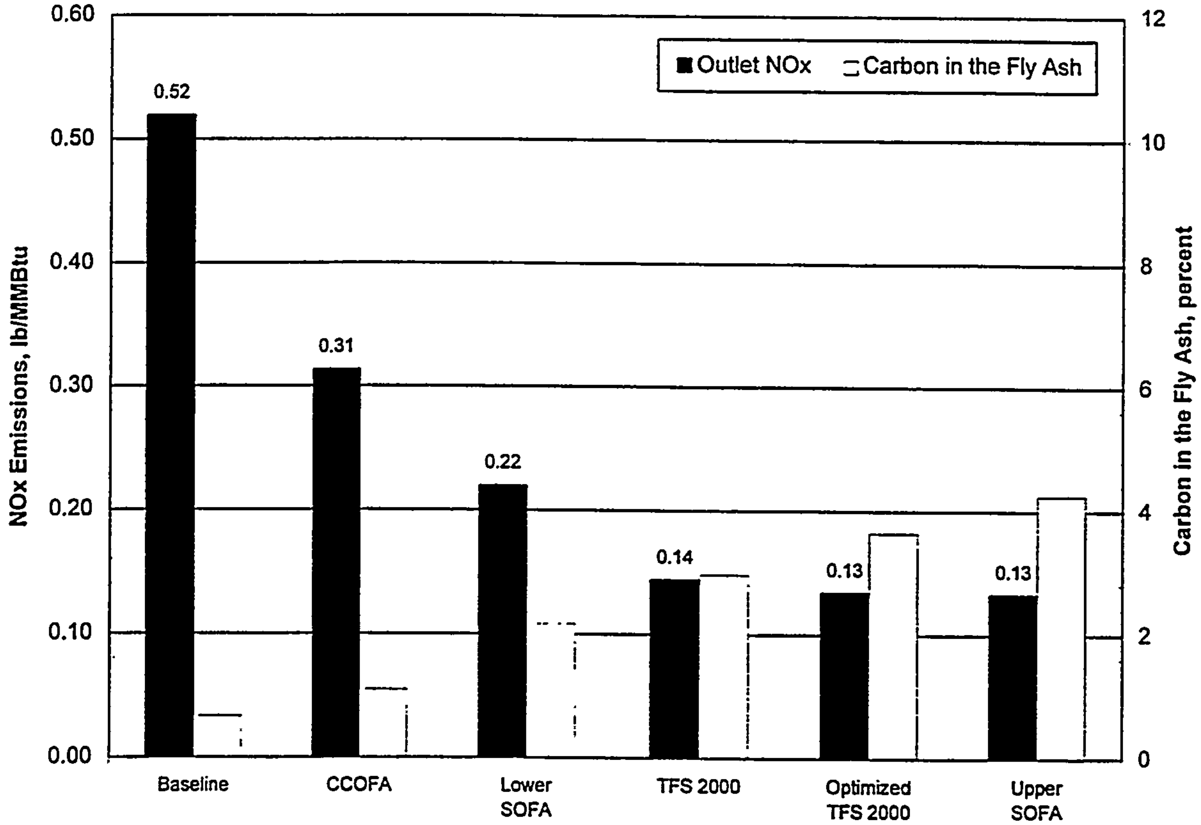

Figure 8 - Outlet NOx and Carbon in the Fly Ash versus Over Fire Air Configuration

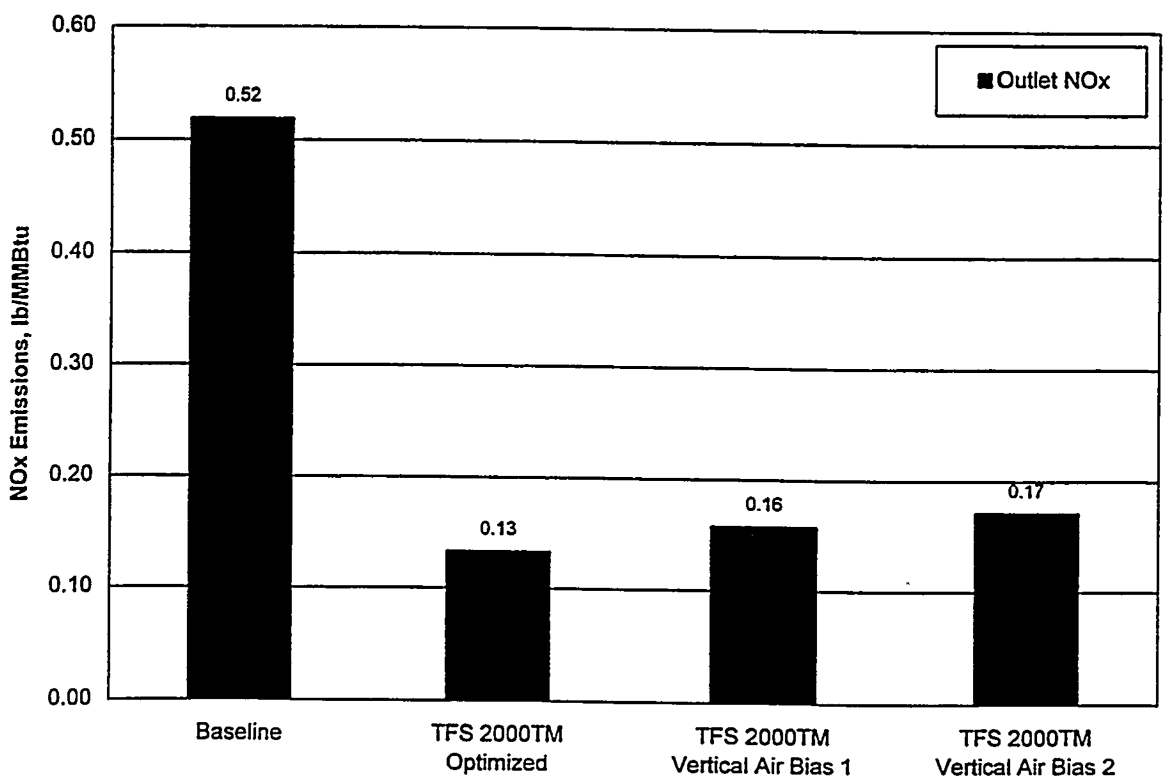

Figure 9 - Outlet NOx versus Main Windbox Vertical Air Staging

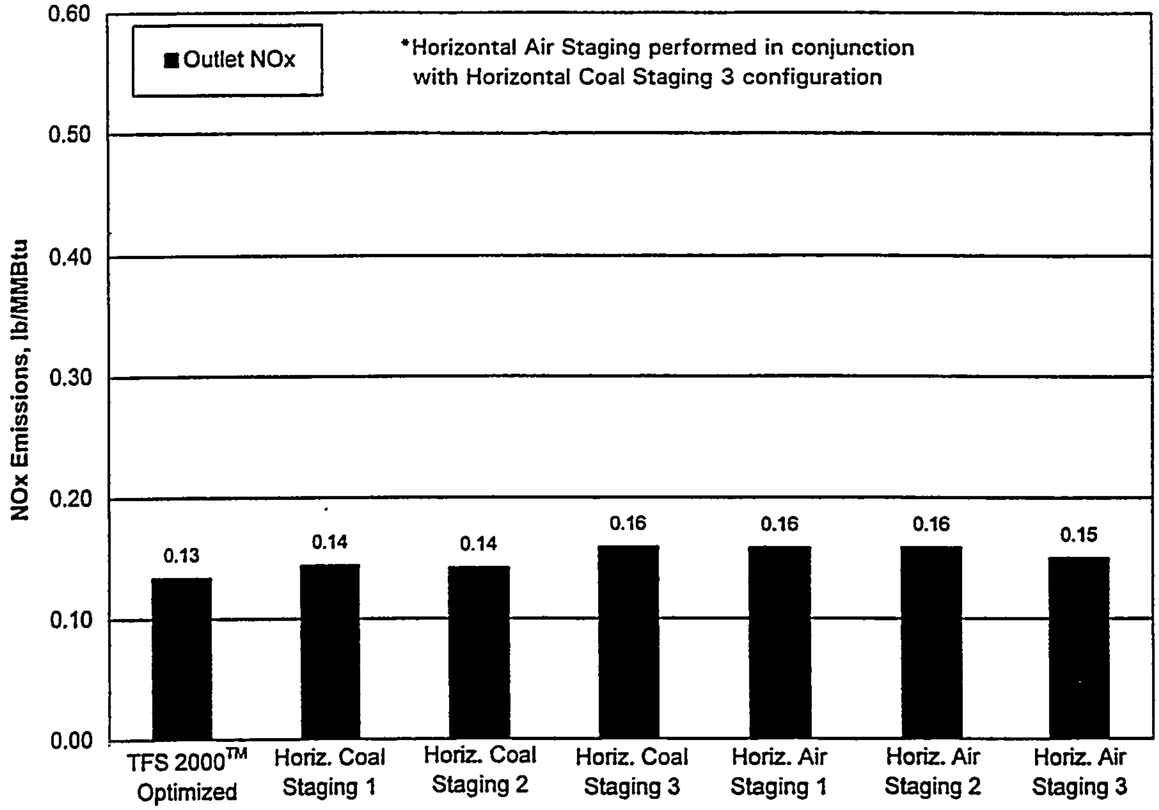

Figure 10 - Outlet NOx versus Main Windbox Horizontal Coal and Air Staging*

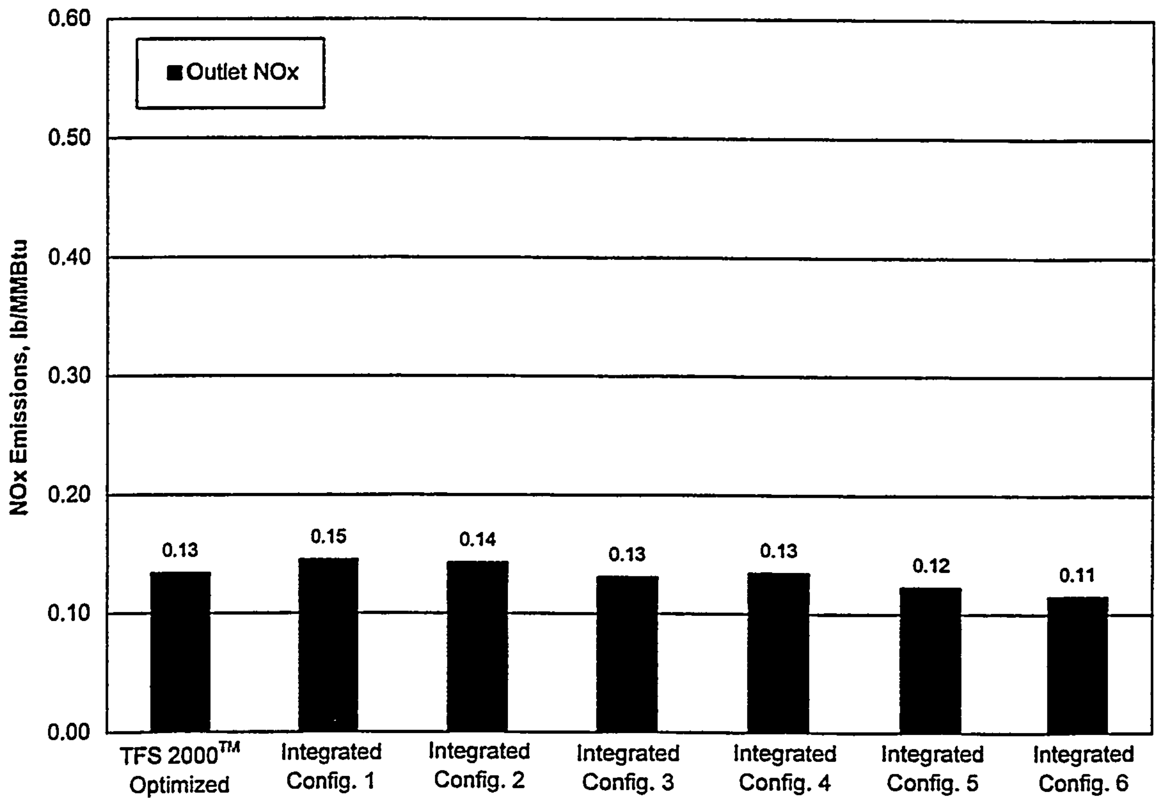

Figure 11 - Outlet NOx versus Integrated Main Windbox Vertical and Horizontal Staging