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ADVANCED TANGENTIALLY-FIRED COMBUSTION TECHNIQUES FOR THE REDUCTION OF NITROGEN OXIDE (NOx) EMISSIONS FROM COAL-FIRED BOILERS

Robert R. Hardman, Steve M. Wilson
Southern Company Services, Inc.
800 Shades Creek Parkway
Birmingham, Alabama 35209

J. D. McDonald
Gulf Power Company
6804 Highway 2300
Southport, Florida 32409

ABSTRACT

This paper discusses the technical progress of a U. S. Department of Energy Innovative Clean Coal Technology Project demonstrating advanced tangentially-fired combustion techniques for the reduction of nitrogen oxide (NOx) emissions from coal-fired boilers. The primary objective of the demonstration is to determine the performance of four low NOx combustion technologies applied in a stepwise fashion to a 180 MW boiler. A target of achieving fifty percent NOx reductions has been established for the project. The retrofit technologies being installed are discussed in detail including a comparison of NOx emissions results for those technologies that have been installed and tested to date. Details of the required instrumentation including acoustic pyrometers and continuous emissions monitoring systems are provided. Outage, manpower, and design requirements for the installation of new retrofit equipment are also presented. Finally, the most recent test data are presented and discussed.

INTRODUCTION

This paper discusses the technical progress of a U. S. Department of Energy (DOE) Innovative Clean Coal Technology (ICCT) Project demonstrating advanced tangentially-fired combustion techniques for the reduction of nitrogen oxide (NOx) emissions from coal-fired boilers. The project is being conducted at Gulf Power Company's Plant Lansing Smith Unit 2 near Panama City, Florida.

The project is being managed by Southern Company Services, Inc. (SCS) on behalf of the project co-funders: The Southern Company, the U. S. Department of Energy (DOE), and the Electric Power Research Institute. In addition to SCS, The Southern Company includes five electric operating companies: Alabama Power, Georgia Power, Gulf Power, Mississippi Power, and Savannah Electric and Power. SCS provides engineering and research services to the Southern Company. Through cost sharing in the installed low NOx retrofit technology, Asea Brown Boveri Combustion Engineering (ABB CE) is also participating as a project co-funder.

The ICCT Program is a jointly funded effort between government and industry to move the most promising advanced coal-based technologies from the research and development stage to the commercial marketplace. The clean coal effort sponsors projects which are different from traditional research and development programs sponsored by the DOE. The traditional projects focused on long-range, high-risk, high-payoff technologies with the DOE providing the majority of the funding. In contrast, the goal of clean coal projects is to demonstrate commercially feasible advanced coal-based technologies which have already reached the "proof-of-concept" stage. As a result, the clean coal projects are jointly funded endeavors between the government and the private sector which are conducted as Cooperative Agreements in which the industrial participant contributes at least fifty percent of the total project cost.

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The primary objective of the Plant Lansing Smith demonstration is to determine the long-term effects of commercially available tangentially-fired low NOx combustion technologies on NOx emissions and boiler performance. Short-term tests of each technology are also being performed to provide engineering information about emissions and performance trends. A target of achieving fifty percent NOx reduction using combustion modifications has been established for the project. The project seeks to address the following objectives:

1. Demonstrate in a logical stepwise fashion the short-term NOx reduction capabilities of the following advanced low NOx combustion technologies:

   a. Low NOx Bulk Furnace Staging (LNBFS)
   b. Low NOx Concentric Firing System (LNCFS) Levels I, II, and III

2. Determine the dynamic long-term emissions characteristics of the LNCFS Levels. I, II, and III using sophisticated statistical techniques.

3. Evaluate the progressive cost effectiveness (i.e., dollars per ton NOx removed) of the low NOx combustion techniques tested.

4. Determine the effects on other combustion parameters (e.g., CO production, carbon carryover, particulate characteristics) of applying the NOx reduction methods listed above.

PROJECT DESCRIPTION

The stepwise approach to evaluating the NOx control technologies requires that three plant outages be used to successively install (1) the test instrumentation and new air heater baskets, (2) the LNCFS Level II, and (3) the LNCFS Levels I and III. These outages were scheduled to coincide with existing plant outages in the fall of 1990, spring of 1991, and the fall of 1991.

Following each outage, a series of four groups of tests are performed. These are (1) diagnostic, (2) performance, (3) long-term, and (4) verification. The diagnostic, performance, and verification tests consist of short-term data collection during carefully established operating conditions. The diagnostic tests are designed to map the effects of changes in boiler operation on NOx emissions. The performance tests evaluate a more comprehensive set of boiler and combustion performance indicators. The results from these tests will include particulate characteristics, boiler efficiency, and boiler outlet emissions. Coal pulverizer (mill) performance and air flow distribution are also tested. The verification tests will be used to characterize any changes that might have occurred during long-term testing.

As stated previously, the primary objective of the demonstration is to collect long-term, statistically significant quantities of data under normal operating conditions with and without the various NOx reduction technologies. Earlier demonstrations of emissions control technologies have relied solely on data from a matrix of carefully established short-term (one to four hour) tests. However, boilers are not typically operated in this manner considering plant equipment inconsistencies and economic dispatch strategies. Therefore, statistical analysis methods for long-term data have been developed that can be used to determine the achievable emissions limit or emission tonnage of a control technology. These analysis methods have been developed over the past fifteen years by the Control Technology Committee of the Utility Air Regulatory Group (UARG). Because the uncertainty in the analysis methods is reduced with increasing data set size, UARG recommends that acceptable results can be achieved with data sets of at least fifty-one days with each day containing at least eighteen valid hourly averages.

UNIT DESCRIPTION

Plant Lansing Smith is located in Lynn Haven, Florida, near Panama City, and is owned and operated by Gulf Power Company. Unit 2 utilizes a tangentially-fired boiler rated at 180 MW with the capability to provide loads of up to 200 MW. The boiler is a Combustion Engineering radiant reheat, natural circulation steam generator which came on line in 1967. It is designed for continuous indoor service to deliver 1,306,000 pounds of steam per hour at normal rated load, a pressure of 1800 psig, and a temperature of 1000°F at the superheater and the reheater outlets. Typical excess oxygen levels range from 4.5 percent at full load (200 MW) to 6.5 percent at minimum load (55 MW). It is fired with pulverized coal (67.4% C, 9.0% H_2O, 4.6% H, 1.4% N, 2.8% S, 6.0% O, 8.7% ash, 0.1% Cl; FC/VM = 1.3) through twenty tangential coal nozzles with five nozzles at each corner. Five Combustion Engineering Raymond Bowl mills equipped with exhausters at the outlet of each mill deliver coal to the furnace. The unit is equipped with Ljungstrom air preheaters and two forced-draft fans which deliver all the combustion air to the boiler. Exhaust gases are treated with both hot- and cold-side electrostatic precipitators. Although originally designed for pressurized furnace operation, the unit was converted to balanced-draft operation in 1976.

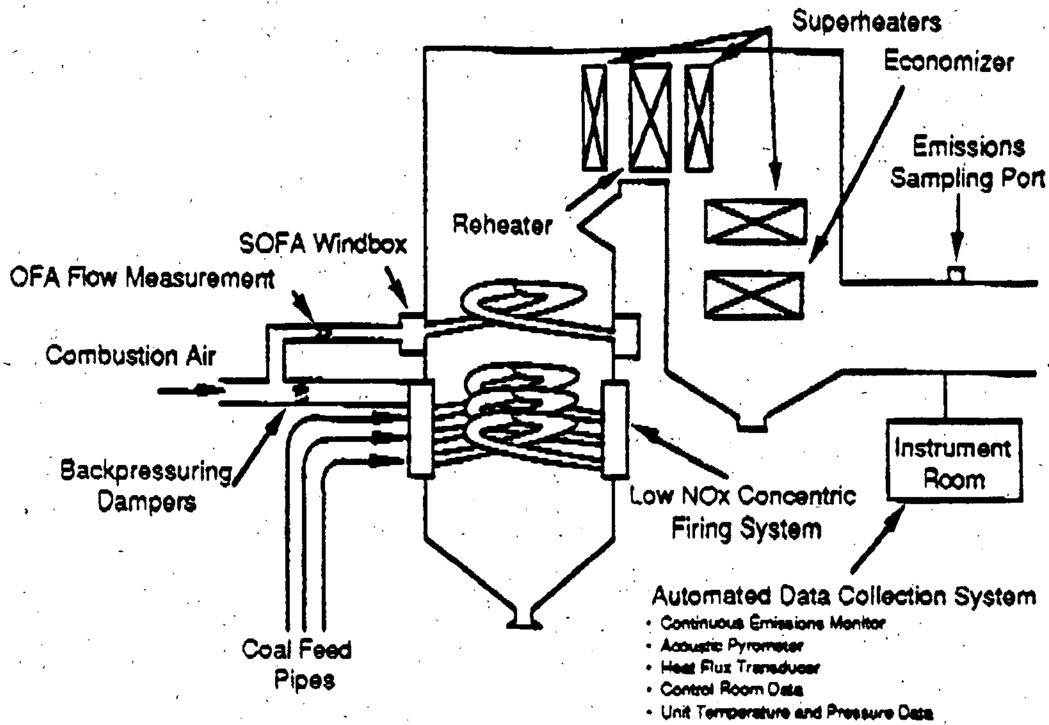

Figure 1. Modifications to the Plant Lansing Smith Unit 2 Boiler

RETROFIT REQUIREMENTS

As stated in the project objectives, four different low NOx combustion technologies for tangentially-fired boilers are planned for demonstration. In addition, an extensive data acquisition system has been installed to collect the required data for the project. Figure 1 provides a boiler schematic to assist in the following discussion of these technologies and the associated measurement equipment.

Test Instrumentation

Prior to baseline testing, an extensive instrumentation and data acquisition system was designed and placed into service at the test site. This system includes a continuous emissions monitoring system (NOx, SO2, O2, total hydrocarbons, CO) with a multi-point flue gas sampling and conditioning system, a data acquisition system, an acoustic pyrometer, and boiler efficiency instrumentation.

Data Acquisition System (DAS). The DAS is a custom designed microcomputer based system used to collect, format, calculate, store, and transmit data derived from power plant mechanical, thermal, and fluid processes. The 160 inputs to the DAS are scanned every five seconds, averaged and then stored to disk at five minute intervals. The stored averages are subsequently archived for future analysis. A summary of the inputs to the DAS is shown in Table 1.

Extractive Continuous Emissions Monitoring System (ECEM). The ECEM, purchased from KVB, provides the means of extracting gas samples for automatic chemical analysis from sample points at strategic locations in the boiler exhaust ducts. A total of forty-one different sampling locations can be monitored.

Table 1: DAS Input Summary

Boiler Drum Pressure	Stack NOx	Superheat Outlet Pressure
Cold Reheat Pressure	Stack O2	Hot Reheat Pressure
Barometric Pressure	Stack SO2	Superheat Spray Flow
Reheat Spray Flow	Stack Opacity	Main Steam Flow
Feedwater Flow	Relative Humidity	Coal Flows
Secondary Air Flows	Ambient Temperature	Primary Air Flows
Main Steam Temperatures	Overfire Air Flows	Cold Reheat Temperature
Hot Reheat Temperature	BFP Discharge Temp.	Feedwater Temperature
Desuperheater Outlet Temp.	Air Heater Air Outlet Temp.	Desuperheater Inlet Temp.
Economizer Outlet Temp.	Generation (Unit Load)	Air Heater Air Inlet Temp.

Acoustic Pyrometer System (APS). The APS provides furnace gas temperature for the analysis of variations in the combustion process. The APS is a microcomputer controlled system that transmits and receives sonic signals through the hot furnace gas from multiple locations around the girth of the boiler. The velocity of the sonic pulses can be computed and processed to provide a contour map of furnace temperatures at the level where the acoustic pyrometers are installed. A total of six acoustic pyrometer horns are installed on three walls (two per wall) of the Plant Lansing Smith boiler. The fourth wall was not used due to interference with the furnace nose arch.

Fluxdome Heat Flux Sensors. The DAS instrumentation includes heat flux sensors (Fluxdomes, manufactured by Land Combustion) that detect the heat absorption into the boiler's furnace wall tubes at strategic locations in the furnace. These flux measurements are intended to provide an indication of both the furnace combustion gas temperature and the condition of the wall ash deposits in the near-burner zone. Comparisons of the flux measurements during the various phases of retrofit may indicate whether any beneficial or undesirable effects on the furnace wall tubing is associated with the low NOx technologies.

The Fluxdome sensors consist of small metal cylinders welded to the fire side surface of a boiler tube. The shape, size, and weld specifications of the cylinder are carefully controlled to assure exact dimensions in order to provide a specific heat path from the furnace/tube interface into the boiler tube. Two type K thermocouples are embedded in each cylinder at prescribed depths. The temperature gradient (typically 0-70 °C) detected by the thermocouples is proportional to the heat flux at the point of measurement. A total of eighteen Fluxdomes are installed at Plant Lansing Smith Unit 2. There are four elevations with four Fluxdomes and one elevation with two Fluxdomes. The Fluxdomes are located on the centerline of the four walls.

Low NOx Combustion Technologies

Four different low NOx combustion technologies (Figure 2) offered by ABB CE for tangentially-fired boilers are planned for demonstration during this project. The testing of these technologies progresses in the most logical manner from an engineering and construction viewpoint. During Phase I of the project, the baseline conditions of the unit were studied. During Phase II, the LNBFS system and the LNCFS Level II are being demonstrated. Finally, LNCFS Levels I and III will be demonstrated during Phase III.

The concept of overfire air is demonstrated in all of these systems. In LNCFS Level I, a Close-Coupled Overfire Air (CCOFA) system is integrated directly into the windbox. Compared to the baseline configuration, LNCFS Level I is arranged by exchanging the highest coal nozzle with the air nozzle

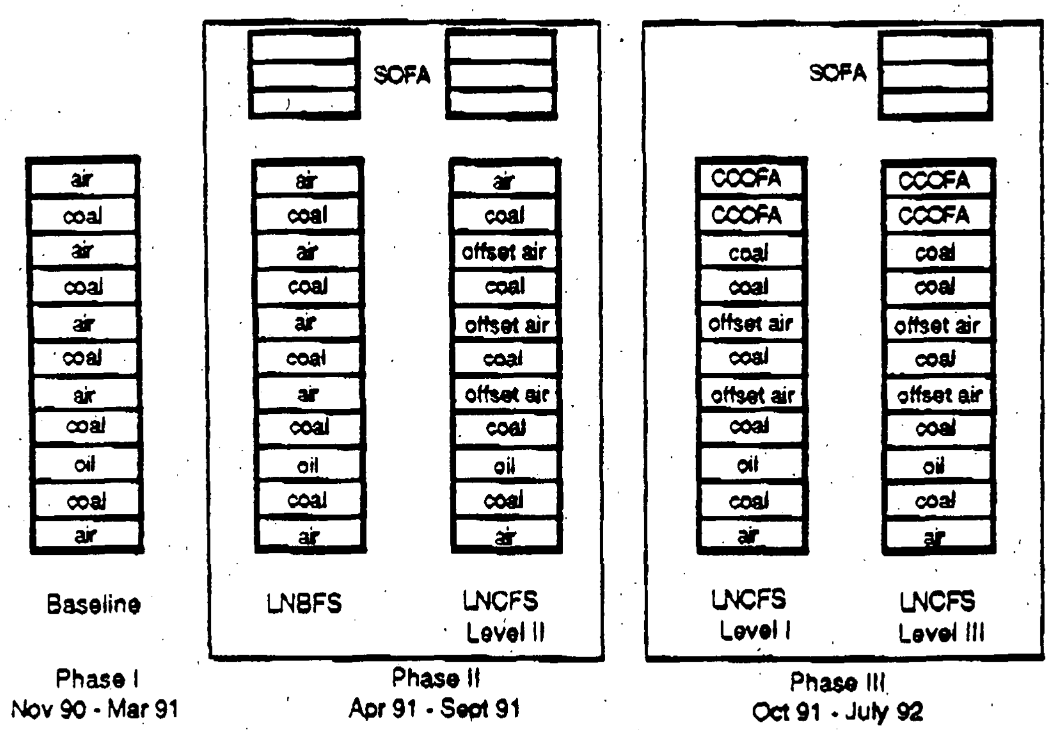

Figure 2. Low NOx Concentric Firing Systems

immediately below it. This configuration provides the NOx reducing advantages of an overfire air system without major pressure part modifications to the boiler.

In LNBFS and LNCFS Level II, a Separated Overfire Air (SOFA) system is used. This is an advanced overfire air system having backpressuring and flow measurement capabilities. The air supply ductwork for the SOFA is taken off from the secondary air duct and routed to the corners of the furnace above the existing windbox. The inlet pressure to the SOFA system can be increased above windbox pressure using dampers downstream of the takeoff in the secondary air duct. The intent of operating at a higher pressure is to increase the quantity and injection velocity of the overfire air into the furnace. A multi-cell venturi is used to measure the amount of air flow through the SOFA system. LNCFS Level III utilizes both CCOFA and SOFA.

In addition to overfire air, the LNCFS installed at Plant Smith incorporates other techniques affecting the combustion process: (1) horizontally adjustable offset air nozzle tips in the main auxiliary compartments; (2) the reduction of the free area available in the coal compartments through which the fuel-air mixture can pass; (3) the addition of divergent coal-nozzle tips, and (4) refurbished tilting mechanisms for the main windbox. Using the offset air nozzle tips, two concentric circular combustion regions are formed (Figure 3). The inner region contains the majority of the coal thereby being fuel rich. This region is surrounded by a fuel lean zone containing the offset combustion air. For this demonstration, the size of this outer circle of combustion air can be varied using the adjustable offset air nozzles.

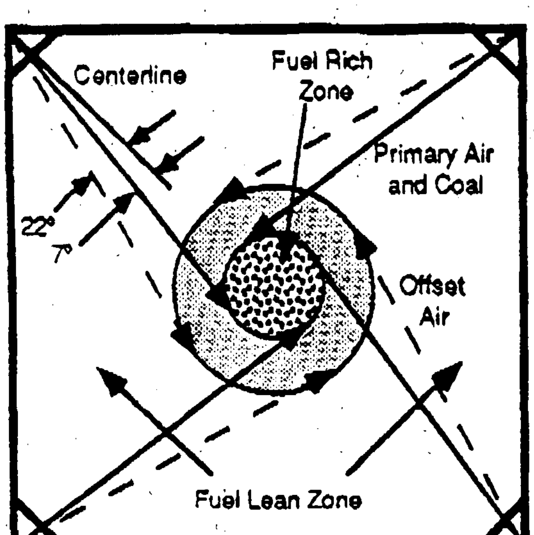

Figure 3. Concentric Firing System

The LNBFS consists of a standard T-fired windbox with a SOFA system. This technology will be demonstrated by repositioning the offset air nozzles in the main windbox to be in line with the fuel nozzles. No other modifications to the windbox will be required. Due to the limits of the project schedule, LNBFS will be demonstrated using short-term diagnostic tests only.

RESULTS DISCUSSION

Baseline Testing. In November 1990, baseline testing began with a series of forty-one diagnostic tests conducted at four load conditions (75, 115, 135, and 180 megawatts). The matrix for these tests focused on the parameters that most directly affect NOx production. Excess oxygen levels were exercised well above and below the normal operating range for the unit and, when possible, multiple mill patterns were tested. During these one- to three-hour tests, manual data were collected from the control room, automated boiler operational data were recorded on the DAS, furnace backpass ash samples were collected from the automatic samplers, coal samples were collected from the individual feeders, and economizer exit and air preheater exit species and temperatures were recorded utilizing the sample distribution manifold.

Figure 4 presents the baseline emissions characteristics of the unit as a function of load. Each marker represents NOx emissions data collected during the diagnostic or performance tests. The major difference between data points at each load level is the furnace excess oxygen level. At full load, excess oxygen levels ranged from two to five percent. At minimum load, excess oxygen levels ranged from four to eight percent. In general, NOx emissions increased with increases in the excess oxygen level.

Following completion of the diagnostic tests, seven performance tests were conducted at nominal loads of 115, 135, and 180 megawatts with the boiler in the as-found condition. For these tests, additional subcontractors were retained to conduct fuel/air and exit gas particulate characteristics tests. Boiler efficiency testing consistent with the ASME PTC 4.1 Heat-Loss Method was also conducted. Each test covered a period lasting ten to twelve hours during which the manual and automated boiler operation data were recorded, the fuel-ash samples acquired, gaseous and solid emissions measurements made, and the engineering performance tests conducted.

At the start of the baseline long-term testing in December 1990, drift and relative accuracy certifications of the Continuous Emissions Monitoring (CEM) system were performed. The

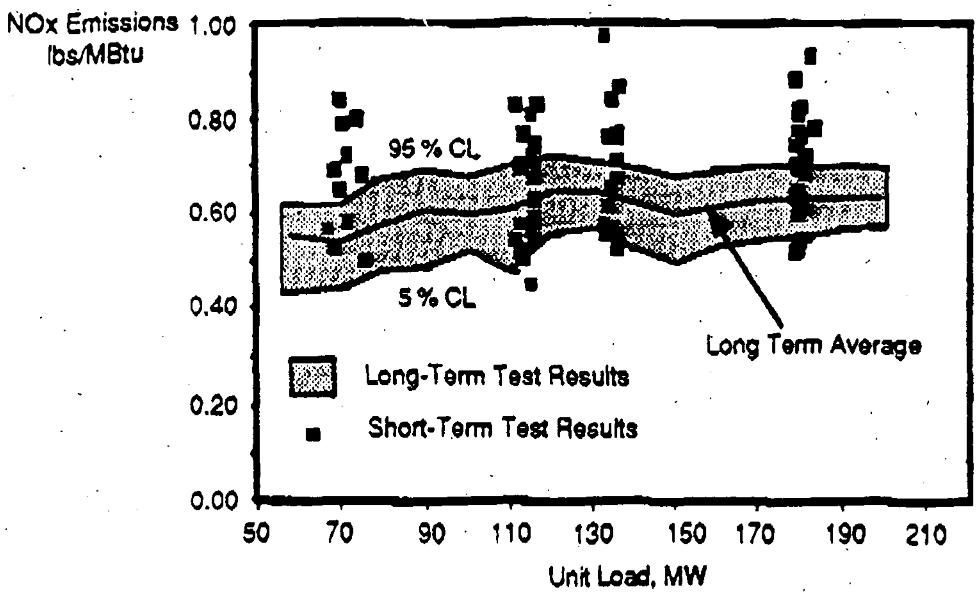

Figure 4. Baseline Long- and Short-Term NOx Emissions, CL = Confidence Limit

benchmarks for these tests are set by the Environmental Protection Agency (EPA). The KVB Continuous Emission Monitoring System failed initial certification. Following repair by KVB personnel. the system passed certification. Long-term testing of the unit began in December 1990. and ended in March 1991. During that time period seventy-five days of long-term data were collected and recorded at five minute intervals. A day of data is considered valid when at least eighteen hours of data are collected. These data are presented with the short-term data in Figure 4. The upper and lower borders of the data set represent the upper 95 percent and the lower 5 percent confidence levels for the long-term data. The long-term average shows the average operating condition for the unit under normal dispatch operations. This average resides in the lower band of the short-term test range due to efforts to maximize unit performance by maintaining low furnace excess oxygen levels.

A brief summary of the statistical analysis results of the baseline long-term data are shown in Table 3. The average load during the long-term testing was 156 MW with a relative standard deviation (RSD) of 14.8 percent. The average emission level was 0.62 lb NOx/MBtu with a RSD of 5.8 percent. Using the long-term data, an achievable emission limit can be calculated. This limit is derived from a statistical analysis of the test data and assumes that the operating conditions during which the data were collected are representative of future operating conditions and the statistical properties of the twenty-four hour averages are true population values. Based on the load scenario followed at Plant Smith between December 1990 and March 1991, the baseline achievable emission limit for a thirty day rolling average was 0.68 lb NOx/MBtu.

Following the completion of the long-term testing, baseline verification tests were conducted. These short-term tests were designed to identify any changes in boiler operating trends which might have occurred during the long-term test phase. An analysis of the tests results indicated no significant changes in boiler operating conditions over the long-term test period.

LNCFS Level II Retrofit. The following discussion is included to provide insight into the retrofit requirements for a low NOx combustion system on a tangentially-fired boiler. Level II of ABB CE's Low NOx Concentric Firing System was installed during a three week outage that began on March 29, 1991. During that outage, craft labor worked seven days a

Table 3. Baseline and LNCFS Level II Long-Term Test Results

Unit Configuration	Baseline		LNCFS Level II	
	Mean	RSD, %	Mean	RSD, %
Number of Daily Averaged Values	75	-	43	-
Average Load (MW)	156	14.8	174	6.2
Average Emissions (lb NOx/MBtu)	0.62	5.8	0.40	5.5
Average O2 Level (at stack)	6.56	11.2	6.25	6.4
Achievable Emission Limit (lb NOx/MBtu)	0.68	-	0.42	-

* RSD = Relative Standard Deviation = 100 * Standard Deviation / Mean

week with two ten-hour shifts per day. The remaining four hours of the day were reserved for x-raying welds in the furnace walls. During peak work loads, as many as seventy craft laborers per shift were involved in the retrofit. A full furnace scaffold was installed to expedite the job.

Due to the scope of the work required to be performed during the outage, the SOFA ductwork was hung in place prior to the unit coming off line. The installation of the SOFA windboxes required significant pressure part modifications to each corner of the boiler above the main windbox. Preassembled bent tube panels were welded into the four 10 feet high by 4 feet wide holes cut in the boiler. The overfire air windboxes with three sets of air nozzles were inserted into the 5 feet high by 2 feet wide openings in the tube panels. Each nozzle has its own automatically controlled damper to provide regulation of the flow to the overfire air ports. The yaw adjustment on each SOFA nozzle is manually adjustable. The three nozzles tilt in unison via automatic controls tied to the tilting of the nozzles in the secondary air windbox.

The critical path for this outage was the modification to the main windboxes. The windboxes were completely stripped of coal nozzles, auxiliary air nozzles, tilt linkages, and all bearings and bushings. After removing this equipment, the partition plates and windbox turning vanes were inspected for warpage and general wear. When necessary, these parts were replaced or refurbished. Additional partition plates were installed in the top and bottom auxiliary air compartments. All of the partition plates were cut back approximately three inches to allow greater tilting mobility of the new coal and air nozzles. All coal nozzles and tips were replaced. Rockwell couplings were installed in the fuel lines to relieve fuel pipe loadings on the windbox, and four elevations of flame scanners were installed including a cooling air system with a dedicated fan. The windbox tilting mechanism was completely replaced. The offset air nozzles in the main windbox have the capability to move in the horizontal direction by a manual adjustment. The air nozzles and coal nozzles tilt in unison via automatic controls.

LNCFS Level II Testing. After the retrofit to install LNCFS Level II, the fine tuning and initial adjustments were completed. Following these tests by ABB CE, Phase II short-term testing was accomplished. To date, over 50 diagnostic and 7 performance tests have been completed. These tests were carried out in a manner similar to those conducted during the baseline tests. The results of these tests are presented in comparison to the baseline test results in Figure 5 which shows the LNCFS Level II and baseline NOx emissions as a function of load. These data show that, unlike the baseline results, unit NOx emissions increase as unit load decreases. This can be partly attributed to the operation of the SOFA system. At full load, the dampers in the SOFA are open 100 percent. However, as unit load is decreased, these are closed until there is no overfire air flow at minimum load.

A pre- and post-retrofit comparison of combustibles loss-on-ignition values collected during short-term performance tests is presented in Table 4.

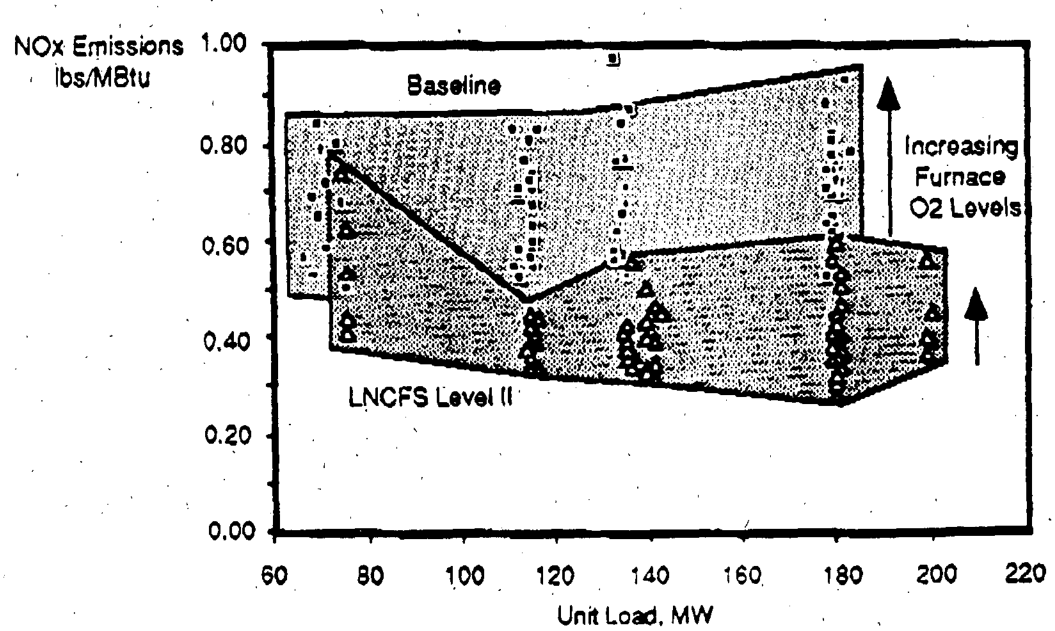

Figure 5. Comparison of Baseline and LNCFS Level II NOx Emissions

Table 4. Comparison of Short-Term Baseline and LNCFS Level II LOI Values		
Boiler Load MW	Baseline LOI Results %	LNCFS Level II LOI Results %
200	*	5.4
180	5.0	4.2
135	4.2	3.9
115	4.0	3.8

* No baseline tests were conducted at 200 MW.

During short-term tests, baseline CO emission maintained a band in the 5 to 20 ppm range over the entire load range. Post-retrofit CO emissions were not as predictable. CO emissions with LNCFS Level II are highly dependant upon unit excess oxygen levels. As the excess oxygen level decreases, unit CO emissions increase. During some tests, reductions of only 0.50 percent in excess oxygen levels have caused CO emissions to increase over 60 ppm. CO levels as high as 148 ppm were witnessed during short-term tests of the LNCFS Level II system. Figure 6 shows the average long-term baseline and LNCFS Level II CO emissions. These data show that there has been a 5 to 15 ppm increase in CO emissions over the entire load range of the unit.

As stated previously, the primary objective of this project is to determine the long-term NOx emissions for a T-fired boiler retrofit with low NOx combustion equipment. Long-term data collection is the definitive method to determine the actual NOx reduction characteristics of a low NOx combustion system. Although the entire long-term data set for LNCFS Level II has not yet been collected, Figure 7 presents the long-term NOx emissions collected in June, July and August 1991. These data show that at full load (200 MW), the unit is able to meet a 0.45 lb/MBtu standard for NOx emissions with an average emission level of 0.38 lb NOx/MBtu. Compared to the baseline full load emission of 0.64 lb NOx/MBtu, LNCFS Level II provides a full load NOx reduction of 40 percent. However, this is not the case for low load operation. NOx emissions during off peak hours when the unit is at minimum load are well above the 0.45 lb/MBtu limit. At minimum load, NOx emissions average 0.58 lb/MBtu which translates to a 5.5 percent increase in NOx emissions over baseline levels.

A brief summary of the statistical analysis results of the LNCFS Level II long-term data are shown in Table 3 with the baseline long-term data. The average load during the LNCFS Level II long-term testing was 174 MW with an RSD of 6.2 percent. The average emission level was 0.40 lb NOx/MBtu with an RSD of 5.8 percent. Using this long-term data collected from June to August 1991, an achievable emission limit was calculated in a manner similar to the method for the baseline data. The thirty day rolling average achievable emission limit when operating with LNCFS Level II was 0.42 lb NOx/MBtu.

There is a difference in the characteristics of the baseline and LNCFS Level II long-term data sets. The LNCFS Level II long-term data were collected during the hot summer months when system demands are the greatest. Plant Smith operates around the clock at or near full load during the summer months. As a result, the average unit load was 174 MW and

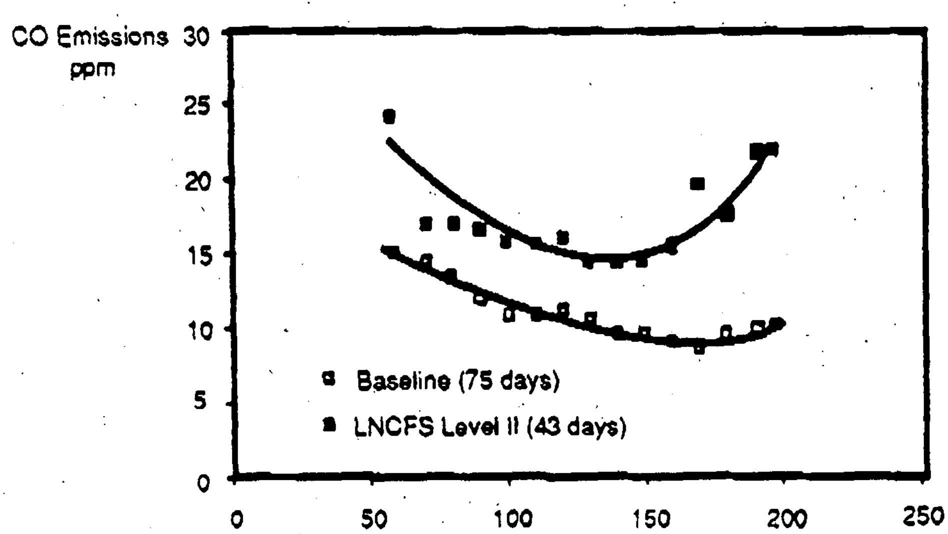

Figure 6. Comparison of Long-Term Baseline and LNCFS Level II CO Emissions

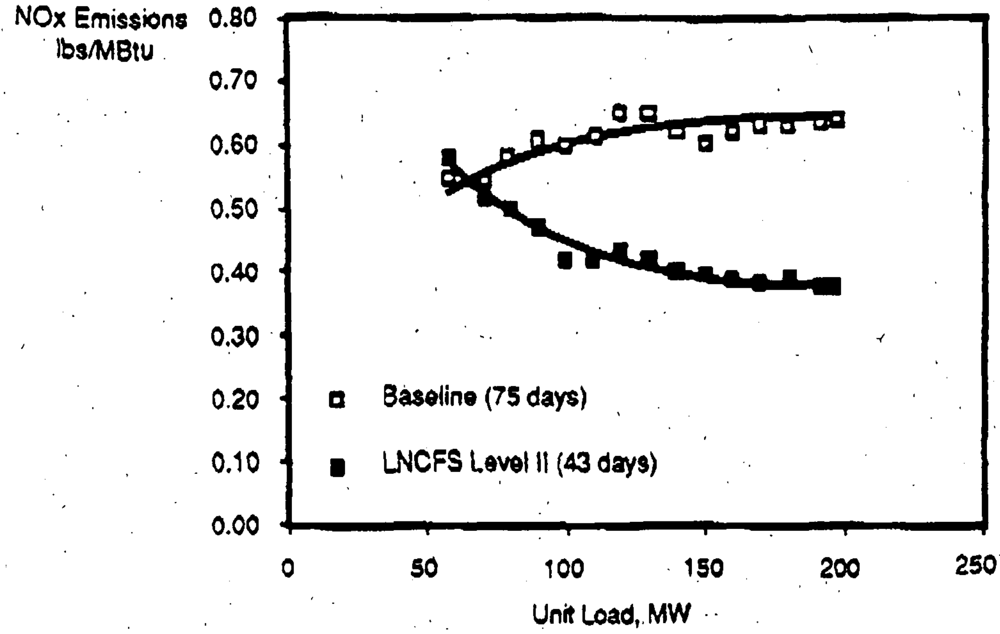

Figure 7. Comparison of Average Baseline and LNCFS Level II Long-Term Data

the RSD was 6.2 percent. In contrast, the baseline data were collected during the winter months when system load profiles in the Southeastern United States are more variable. During this time period, the average unit load was lower at 156 MW with a higher RSD of 14.8 percent. By applying the baseline load information to the LNCFS Level II data, Figure 7 shows that a reduction in average load will increase the average NOx emissions of the unit. As a result, unit emissions may or may not be within the proposed 0.45 NOx standard when operating under an off-peak load scenario.

FUTURE ACTIVITIES

Post retrofit evaluation of the LNCFS Level II data is continuing. During an outage in late October 1991, LNCFS Level III will be retrofitted. Evaluation of that technology and a simulated LNCFS Level I will follow.

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