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INNOVATIVE CLEAN COAL TECHNOLOGY (ICCT)

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

Final Report and
Key Project Findings

December 1993
REPRINTED FEBRUARY 1994

DOE Contract Number
DE-FC22-90PC89653

SCS Contract Number
C-91-000028

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Cleared by DOE Patent Counsel on September 30, 1993

Legal Notice

Acknowledgments

The authors wish to gratefully acknowledge the support and contribution of the following personnel: Mr. J.D. McDonald of Gulf Power; Messrs. James Gibson and Jose Perez, Instrumentation Specialists of Spectrum Systems Inc.; and Messrs. Robert Collette and Angelos Kokkinos of ABB/CE.

We like to thank Mr. Steve Wilson, Southern Company Services and Dr. Gerald Elia, Project Manager of the US Department of Energy for their guidance and support.

The following companies are also recognized for their outstanding efforts in planning and implementing the test program, and analyzing the data:

- Flame Refractories, Inc.
- W.S. Pitts Consulting
- Radian Corp., and
- Southern Research Institute.

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Abbreviations

ABB/CE	Asea Brown Boveri/Combustion Engineering, Inc.
CAAA	Clean Air Act Amendment of 1990
CCOFA	Closed-Coupled Overfire Air
CEM	Continuous Emission Monitor
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DAS	Data Acquisition System
DOE	Department of Energy
EPRI	Electric Power Research Institute
ESP	Electrostatic Participator
FC/VM	Fixed Carbon/Volatile Matter
HHV	High Heating Value
ICCT	Innovative Clean Coal Technology
LNBFS	Low NOx Bulk Furnace Staging
LNCFS	Low NOx Concentric Firing System
LOI	Loss-on-Ignition
NHI/PA	Net Heat Input/Plan Area
NHR	Net Heat Rate
NSPS	New Source Performance Standards
O&M	Operating and Maintenance
O_2	Oxygen
ppm	Parts per Million
SOFA	Separated Overfired Air
UARG	Utility Air Regulatory Group
UBC	Unburned Carbon

Abstract

This report provides the key findings of the Innovative Clean Coal Technology (ICCT) demonstration project at Gulf Power's Lansing Smith Unit #2 and the implications for other tangentially-fired boilers. L. Smith Unit #2 is a 180 MW tangentially-fired boiler burning Eastern Bituminous coal, which was retrofitted with Asea Brown Boveri/Combustion Engineering Services' (ABB/CE) LNCFS I, II and III technologies. An extensive test program was carried-out with US Department of Energy, Southern Company and Electric Power Research Institute (EPRI) funding.

The LNCFS I, II, and III achieved 37 percent, 37 percent, and 45 percent average long-term NOx emission reduction at full load, respectively (see following table). Similar NOx reduction was achieved within the control range (100-200 MW). However, below the control point (100 MW), NOx emissions with the LNCFS technologies increased significantly, reaching pre-retrofit levels at 70 MW. Short-term testing proved that low load NOx emissions could be reduced further by using lower excess O_2 and burner tilt, but with adverse impacts on unit performance, such as lower steam outlet temperatures and, potentially, higher CO emissions and LOI.

Table - Full Load NOx Emissions

Technology	NOx (lbs/MBtu)	% NOx Reduction
Baseline	0.63	—
LNCFS I	0.39	37
LNCFS II	0.39	37
LNCFS III	0.34	45

These NOx reduction levels were achieved with some impacts on unit performance:

- Increased average long-term, full load CO emissions for LNCFS III from 10 ppm to 33 ppm.
- Change in the required excess O_2; 0.5 percent lower excess O_2 was required at full load for LNCFS I, while 0.8 percent and 0.6 percent higher excess O_2 was required for LNCFS II and III, respectively.
- LOI did not change with the LNCFS retrofits, but it showed significant sensitivity to changes in coal fineness.
- Furnace slagging was reduced, but backpass fouling was increased.
- Steam outlet temperatures were reduced by up to 35°F at low loads with LNCFS I and III. Steam temperatures could be maintained at pre-retrofit levels by increasing the excess O_2 and burner tilt, but NOx emissions will increase above the reported levels.
- Unit operation was not affected significantly, but the operating flexibility of the unit was reduced at low loads with LNCFS II and III.

As a result of the above changes, the unit net heat rate at full load increased by:

- 0.1 percent for LNCFS I
- 0.36 percent for LNCFS II, and
- 0.18 percent for LNCFS III.

Considering the capital costs, heat rate changes and NOx emission reduction achieved, the average cost-effectiveness of the technologies tested relative to baseline is:

- LNCFS I: $103/ton of NOx removed
- LNCFS II: $444/ton, and
- LNCFS III: $400 /ton.

The incremental costs of LNCFS III as compared to LNCFS I are estimated to be 1546 $/ton.

Implications for Other Tangentially-fired Units

Implications Regarding NOx Emissions: The Smith ICCT project, along with other industry retrofits, showed that:

- The LNCFS technologies are expected to achieve long-term NOx reduction within the control range (50-100 percent load) in the following range:
  - 25-37 percent for LNCFS I
  - 30-40 percent for LNCFS II, and
  - 40-50 percent for LNCFS III.

- NOx emissions below the control point (100 MW) may increase for all LNCFS technologies. This is particularly true when the primary objective of unit operation at low loads is to control steam outlet temperatures and maintain unit response rate, rather than minimize NOx emissions.

O&M Impacts of Tangentially-fired Units Adverse O&M impacts can occur even where steps are taken to carefully integrate retrofit NOx control technologies with existing plant generation requirements. In general, the higher the NOx reduction sought the greater the potential for O&M impacts. The most common O&M impacts observed to date, including the Smith ICCT project, has been reduced boiler efficiency due to increased excess O_2 requirements, especially for low NOx technologies with separated overfire air systems. Other potential impacts include: increased CO emissions, reduced steam outlet temperatures and changes in furnace slagging and backpass fouling patterns.

Capital Costs: Based on the recent experience from Smith Unit 2 and other LNCFS retrofits (Ref. 10), the capital costs for LNCFS retrofits are expected to be in the following range:

- LNCFS I: $ 5 - 15 per kW,
- LNCFS II: $15 - 25 per kW, and
- LNCFS III: $15 - 25 per kW.

Low NOx Retrofit Outage: A four- to six-week outage should be planned for LNCFS I retrofits and a six- to eight-week outage for LNCFS II and III retrofits. At Smith, the LNCFS II required a 3-week unit outage, because significant percentage of the work was completed before the unit came off-line and around-the-clock (3-shift) construction.

Start-up and Optimization: Two to three weeks are adequate for LNCFS optimization (tuning). At Smith Unit 2, two-week optimization was needed initially for each system. In addition, a three-day re-optimization of LNCFS II was performed to reduce NOx emissions at low loads.

Overview

This Innovative Clean Coal Technology (ICCT) project was funded jointly by the U.S. Department of Energy, The Southern Company, and the Electric Power Research Institute (EPRI). Under this project, a range of Asea Brown Boveri/Combustion Engineering Services' (ABB/CE) low NOx combustion technologies were installed and tested at Gulf Power Company's Plant Lansing Smith Unit 2; a 180 MW tangentially-fired unit burning eastern bituminous coal. The technologies tested were the Low NOx Concentric Firing System (LNCFS) Levels I, II, and III, and the Low NOx Bulk Furnace Staging (LNBFS).

The primary objective of this project was to determine the NOx emission reduction and boiler performance impacts for ABB/CE's range of low NOx technologies under normal dispatched operating conditions. Long-term test data were collected and analyzed with the baseline configuration of the boiler and LNCFS I, II, and III. Short-term tests (under controlled conditions) were also performed to assess the impact of key design and operating variables on NOx and unit performance. A limited number of tests were performed with the LNBFS under controlled (short-term) conditions.

The purpose of this report is to document the key findings of the project and identify their implications for other tangentially-fired boilers. The LNBFS results are presented only in the body of this report (Section 6.1.4), because the scope of the LNBFS testing was limited and the results were inconclusive. Therefore, the Executive Summary focuses on the LNCFS technologies.

NOx emissions reported in this document are presented in the following formats:

- Average long-term at each load;
- Short-term; and
- Annual achievable NOx emissions.

However, more emphasis is placed on the average long-term NOx emissions because they reflect normal unit operating practices. As such, the term "*NOx emissions*" is used throughout the report instead of the "average long-term NOx emissions" at the specified unit load unless otherwise indicated. The short-term NOx emissions are included in the report when they differ from the long-term NOx emissions or when they provide additional insight into NOx emission trends. The annual achievable NOx emissions, which provides the basis for regulatory compliance, are reported in Section 6.3.

Unit Description

Plant Lansing Smith Unit 2 is a tangentially-fired boiler, commissioned in 1967, which is burning eastern bituminous coal (nitrogen: 1.4%, sulfur 2.8%, fixed carbon/volatile matter: 1.3, and higher heating value: 12,000 Btu/lb). The unit is rated at 180 MW but is capable of producing 200 MW. The boiler has five elevations of coal nozzles fed by five ABB/CE RPS 623 mills. The unit was originally designed to burn more than one type of coal and, as such, has a relatively low heat release rate (net heat input/plan area (NHI/PA): 1.65 MBtu/hr-sqft, while ABB/CE pre-NSPS boilers range from 1.6 to 2.2). The unit is also equipped with hot- and cold-side electrostatic precipitators (ESP) with adequate design redundancy to accommodate small changes in the dust loading and gas flow rate.

Project Activity Sequence

In order to test the LNBFS and all three LNCFS technologies, the following chronological sequence of testing and retrofit activities was followed:

1. Installation of the continuous emission monitor (CEM) and data acquisition system (DAS) followed by baseline testing;

2. LNCFS II retrofit and testing;

3. LNBFS testing by setting the offset air nozzles to be in-line with the coal nozzles;

4. Conversion of LNCFS II to LNCFS III by exchanging the top coal nozzle with the air nozzle below and installation of two close-coupled overfire air (CCOFA) nozzles;

5. LNCFS III testing;

6. Testing of "simulated" LNCFS I by closing the separated overfire air (SOFA) ports of the LNCFS III.

Baseline Performance

In order to assess the impact of the low NOx technologies on NOx emissions and performance, the unit was tested before the retrofit (baseline testing). The baseline testing reflected normal operating conditions. The results of the tests were as follows:

- Average long-term NOx emissions at full load (180 MW) were 0.63 lbs/MBtu. NOx emissions were fairly constant within the control range (100-200 MW) and decreased below 100 MW.

- The average excess O_2 at full load was 3.7 percent. However, the baseline configuration was not tuned because the project objective was to characterize unit performance based on existing operating conditions. Also, there was no CO emission monitor available in the control room to assist operators in reducing O_2 while keeping CO within acceptable operating limits.

- The LOI[1] was 4.8 percent at full load and 4.5 percent at low loads; and

- The boiler experienced medium furnace slagging.

NOx Emissions and Unit Performance Impacts Due to the Low NOx Technologies

The project improved the knowledge base of the utility industry regarding low NOx retrofit technologies by demonstrating the following:

[1] The LOI (loss-on-ignition) accounts for all the unburned combustibles (including carbon) in the flyash. For the coal burned at Smith, the unburned carbon comprised more than 95% of the LOI.

- In boilers such as Smith Unit 2 (with relatively large furnace), the LNCFS I may achieve 30-40 percent NOx reduction which is higher than the 25-30 percent predicted prior to this project (Ref. 9);

- The LNCFS II and III achieved the expected level of NOx reduction within the control range (100-200 MW); 30-40 percent for LNCFS II and 40-50 percent for LNCFS III;

- NOx emissions increased significantly below the control point (100 MW) for all LNCFS technologies;

- The only significant performance impact due to the LNCFS retrofits was a change in the excess O_2. Compared to be baseline results, the average excess O_2 at full load for the LNCFS I was reduced by 0.5 percent while average excess O_2 for LNCFS II and III increased by 0.8 and 0.6 percent, respectively. Similar O_2 changes were observed throughout the load range.

This demonstration was the first project which provided information on the NOx and the boiler performance impacts of LNCFS I and III firing eastern bituminous coal.

NOx Emissions Within the Control Range (100 - 200 MW)

The LNCFS I, II, and III achieved 37 percent, 37 percent, and 45 percent average long-term NOx emission reductions at full load, respectively. As shown in Table S.1, full load NOx emissions were reduced from 0.63 lbs/MBtu during baseline testing to 0.39, 0.39 and 0.34 lbs/MBtu, respectively. Figure S.1 also shows that the NOx emission profiles were relatively flat within the control range (100-200 MW).

Table S.1 - Full Load NOx Emissions

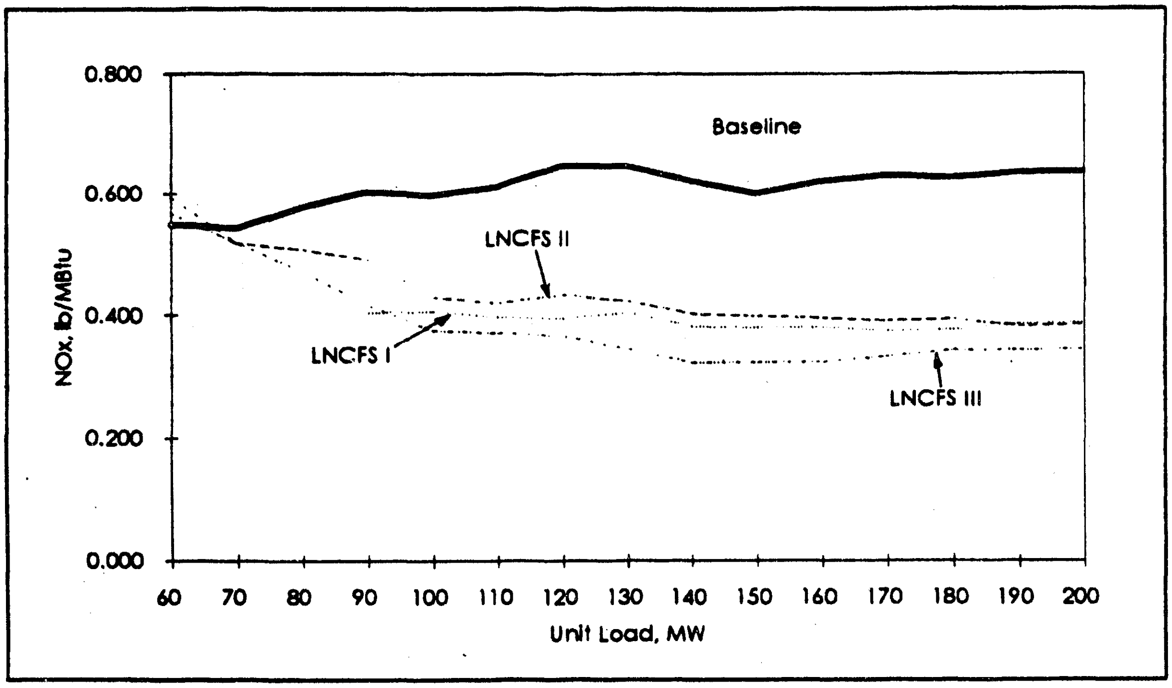
Technology	NOx (lbs/MBtu)	% NOx Reduction
Baseline	0.63	—
LNCFS I	0.39	37
LNCFS II	0.39	37
LNCFS III	0.34	45

The NOx emission reduction (37 percent) achieved by LNCFS I is higher than the 20-30 percent previously predicted for most tangentially-fired units by ABB/CE (see Ref. 9). The higher NOx reduction is attributed to:

1. The stability of the LNCFS I allowed operation with lower excess O_2 than the LNCFS II and III; average long-term O_2 of 3.2 percent compared to 4.5 percent for LNCFS II, and 4.3 percent for LNCFS III.

2. The CCOFA system which was designed with approximately 20 percent larger cross-sectional area than the average tangentially-fired systems because of the availability of space.

Figure S.1 - Comparison of Baseline, LNCFS Levels I, II, and III Long-term NOx Emissions



Low Load NOx Emissions

Below the control point (100 MW), NOx emissions with the LNCFS technologies increased significantly, reaching pre-retrofit levels at 70 MW. As shown in Figure S.1, LNCFS II NOx emissions increased from 0.39 lbs/MBtu at full load to 0.52 at 80 MWs, and 0.58 lbs/MBtu at 70 MWs. Similarly, LNCFS III NOx emissions increased from 0.34 lbs/MBtu at full load to 0.48 at 80 MWs and 0.60 lbs/MBtu at 70 MWs. The unit did not operate long enough at low loads with LNCFS I to characterize the NOx emissions adequately. However, it is expected that the LNCFS I impact on low load NOx emissions would be similar to LNCFS III because of the similarities of the two systems at low loads (when the SOFA dampers of the LNCFS III are closed).

The NOx emission increase at low loads for LNCFS II and III is attributed to the following factors:

- Higher O_2 than baseline (0.6-0.8 percent);
- Use of tilt (+6° with LNCFS III and +8° with LNCFS II compared to horizontal tilt during baseline and +3° during LNCFS I testing);
- Lower SOFA flow rates than recommended by ABB/CE were required at low loads to maintain acceptable windbox pressures;
- Higher fuel air flow rate than recommended by ABB/CE at low loads was required to maintain acceptable unit response rate.

Short-term testing indicated that NOx emissions can be reduced below the long-term NOx levels by using lower excess O_2 and burner tilt, but they will reduce the steam outlet temperatures and, potentially, increase CO emissions and LOI.

Unit Performance Impacts

Several potential unit performance impacts were assessed including CO emissions, required excess O_2, LOI, furnace slagging, backpass fouling, steam outlet conditions, performance of the particulate removal equipment, and unit operation. The impacts of the LNCFS technologies on unit performance are summarized in Table S.2.

All the impacts shown in Table S.2 are based on long-term data except the LOI which was measured during short-term testing. Because the average long-term O_2 and the O_2 during the LOI testing differ, the latter is shown in parenthesis next to the LOI results.

Table S.2 - Unit Performance Impacts Based on Long-term Testing

	Baseline	LNCFS I	LNCFS II	LNCFS III
Avg. CO at Full Load (ppm)	10	12	22	33
Avg. O_2 at Full Load (%)	3.7	3.2	4.5	4.3
% Full Load LOI (% O_2)	4.8 (4.0)	4.6 (3.9)	4.2 (5.3)	5.9 (4.7)
Steam Outlet Conditions (see Figures 6.19 and 6.20)	OK at full load: low temps at low loads[2]	Full load: 5-10°F lower than baseline; Low loads: 10-30°F lower than baseline	Same as Baseline	160-200 MWs: OK; 80 MW: 15-35°F lower than baseline
Furnace Slagging & Backpass Fouling	Medium	Medium	Reduced Slagging, but increased Fouling	Reduced Slagging, but increased Fouling
Operating Flexibility	Normal	As easy as Baseline	More care required at low loads (watch: windbox pressure drop and flame stability)	More difficult to operate than the other systems (sensitive to operating changes)

CO Emissions and Excess O_2

CO emissions were maintained within acceptable limits (below 100 ppm), but CO increased from 10 ppm to 22 ppm for LNCFS II and 33 ppm for LNCFS III. Also, the excess air needed to maintain CO emissions low for LNCFS II and III was higher than baseline and LNCFS I. Short-term tests indicated (see Figure S.2) that the minimum O_2 required to maintain CO below 100 ppm was impacted by the LNCFS technologies. The average excess O_2 at full load changed for all LNCFS technologies compared to the baseline. As shown in Table S.2 and Figure S.3, LNCFS I operated at full load with 3.2 percent O_2 (0.5 percentage points lower than

[2] Steam outlet temperatures are well below design levels at low loads due to removal of reheat surface area in the 1970s.

baseline), while the LNCFS II and III operated with an average 4.5 and 4.3 percent O_2, respectively.

Figure S.2 - Full Load CO Emissions as a Function of Excess Oxygen

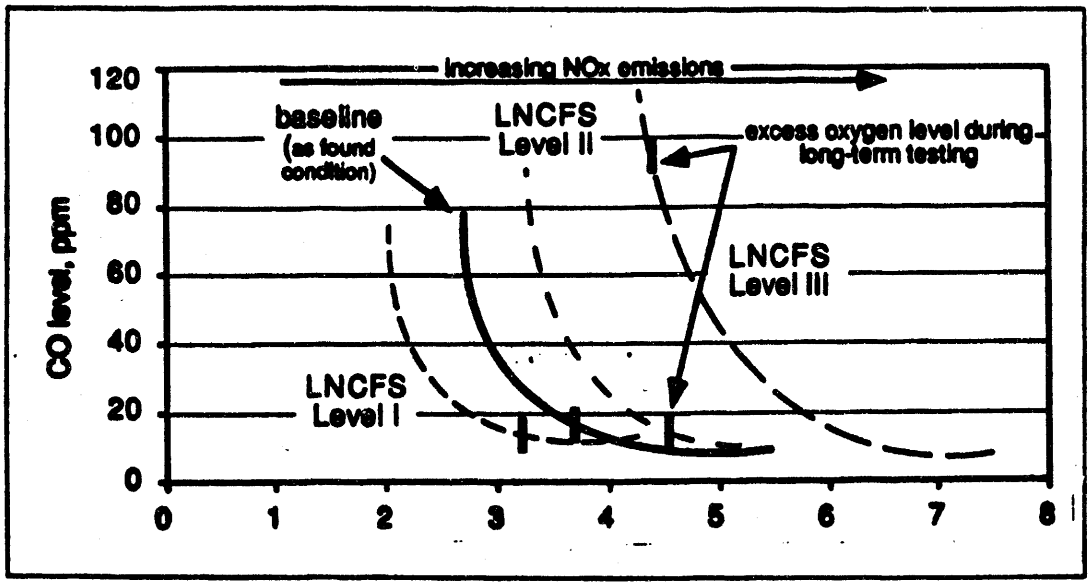
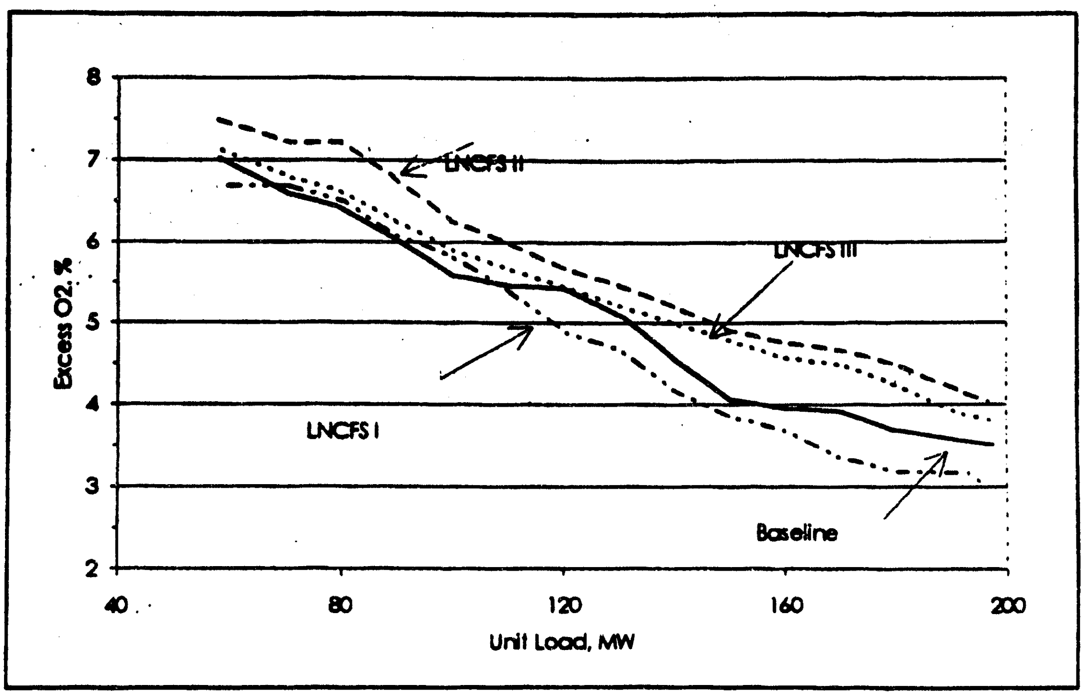


Figure S.3 - Comparison of Baseline, LNCFS Level I, II and III Long-term Excess Oxygen Levels



As Figure S.3 shows, similar O_2 trends were experienced throughout the load range for all LNCFS technologies tested. The LNCFS I operated at O_2 below baseline levels throughout the control range (above 100 MW), while the LNCFS II and III required up to one percent higher O_2 at certain loads.

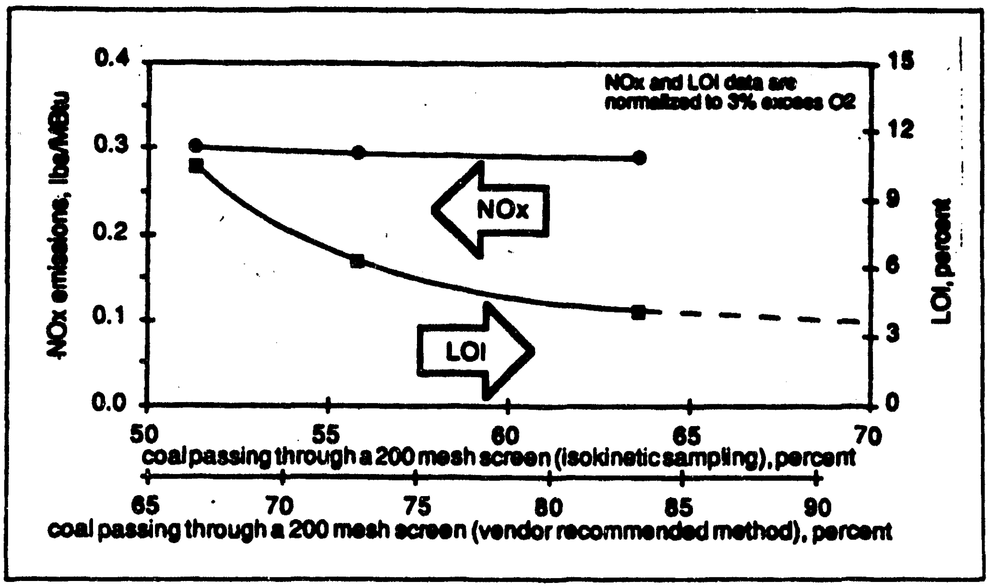
For LNCFS II and III, the available O_2 operating range was reduced because the minimum O_2 increased, while the maximum O_2 (defined by maximum fan capacity) remained the same. A wide O_2 range allows the operators to increase O_2 temporarily during load transients and avoid spikes in CO and NOx emissions. As such, narrowing of the available O_2 range reduces the operating flexibility of the unit.

Carbon in the Flyash/LOI:

As Table S.2 shows, the LOI for all of the LNCFS technologies did not change significantly from the baseline level of 4.8 percent; 4.6 percent for LNCFS I, 4.2 percent for LNCFS II, and 5.9 percent for LNCFS III. If the difference in coal fineness between the tests and the level of measurement accuracy are taken into account, it is concluded that the LOI was not impacted by the LNCFS technologies.

The LOI with LNCFS III was particularly sensitive to changes in the coal fineness, especially in the range of 52 to 60 percent through 200 mesh (*note:* coal fineness measured isokinetically in the coal pipe). As Figure S.4 shows, coal fineness of 62 percent through 200 mesh resulted in four percent LOI, while coal fineness of 52 percent through 200 mesh increased LOI to 10 percent. Similar trends of coal fineness on LOI are expected for the LNCFS I and II.

Figure S.4 - LNCFS III: Impacts of Coal Fineness on LOI and NOx Emissions



Furnace Slagging and Backpass Fouling:

Furnace slagging with LNCFS I was medium; similar to baseline. The LNCFS II and III technologies reduced slagging significantly, but increased backpass fouling. As a result, the furnace wallblower operating frequency was reduced relative to baseline, but the retractable sootblowers were used more frequently to clean the backpass. Although the benefits from reduced furnace cleaning were counterbalanced by the increased backpass cleaning, the slagging reduction was an overall improvement, because it is more difficult to clean the furnace slagging deposits than the backpass. In addition, slagging usually increases boiler tube failures, which cause forced outages.

The furnace slagging reduction is attributed mainly to the impact of the SOFA system and the offset air on the heat release and heat absorption profile. Due to the staged combustion, the same heat is released over a larger furnace height which results in lower furnace gas temperatures, heat absorption rates, and slagging tendency.

Steam Outlet Temperatures:

The steam outlet conditions, both reheat and superheat, were not affected significantly by the LNCFS retrofits at full load, but they were affected by LNCFS I and III at low loads; steam outlet temperatures with LNCFS I and III were 10 - 35°F lower than baseline at low loads. In addition to the close-coupled OFA (CCOFA), lower excess O_2 than baseline with LNCFS I, and furnace slagging reduction with LNCFS III were the main reasons for the steam temperature reduction.

Short-term testing showed that the steam outlet temperatures could be increased for both LNCFS I and III to pre-retrofit levels by increasing the excess O_2 and/or the burner tilt, but NOx emissions will increase as well. The selection of the optimum operating conditions (e.g., O_2 and tilt) requires a trade-off between NOx and unit heat rate. For example, at 75 MW, a two percent O_2 reduction from normal operating levels reduced NOx emissions by approximately 0.075 lbs/MBtu (18 percent reduction), but reduced the superheat and reheat outlet temperatures by 40-50°F. Considering that this steam temperature reduction increases the unit net heat rate by approximately one percent, the plant operators need to trade-off 0.075 lbs/MBtu with one percent unit heat rate and decide which one is preferable.

ESP Performance:

The higher O_2 and the furnace slagging reduction with LNCFS II and III increased the volumetric flow rate and dust loading through the ESPs by up to five percent, but did not impact the unit's ability to maintain opacity within acceptable limits. This was due to the excess capacity (design redundancy) of the existing ESPs.

Unit Operation:

There was, generally, no significant impact on unit operation. Operation of the LNCFS I was very similar to the baseline system. The operating flexibility of the unit with LNCFS II and III was reduced due to the reduction of the available O_2 range. This was particularly noticeable with the LNCFS III, for which the available O_2 range was limited to 4.2 - 5.0 percent (due to CO emissions and fan capacity, respectively) and the operators did not have much flexibility to temporarily increase the excess O_2 during load transitions (e.g., when bringing mills into or out of service) to avoid spikes of CO and NOx emission.

Impacts on Boiler Efficiency and Unit Heat Rate

The effects of the above unit performance impacts (e.g., O_2 and LOI) on boiler efficiency, turbine heat rate, and unit net heat rate are assessed in this section. First, the effect of each performance parameter, which changed due to the LNCFS technologies, on boiler efficiency and turbine heat rate was estimated. Parameters which changed due to factors other than the LNCFS (e.g., air heater leakage) were normalized to be the same as baseline. Then, the net heat rate was calculated: Unit Net Rate = Turbine Heat Rate/Boiler Efficiency.

The main performance parameters which were considered in the calculation of the boiler efficiency and were affected by the LNCFS technologies were:

- CO emissions;
- Excess O_2;
- LOI; and
- Air heater outlet (indicative of the stack) temperature.

Similarly, the impacts on turbine heat rate impact were estimated based on the changes in superheat and reheat outlet temperatures. The reheat spray was not a factor in the calculation of the turbine heat rate, because it was not used in both pre- and post-retrofit operation.

The effects of the LNCFS technologies on full load (180 MW) boiler efficiency, turbine heat rate, and unit net heat rate are shown in Table S.3.

Table S.3 - LNCFS Impacts on Boiler Efficiency and Unit Heat Rate (180 MW)

	Baseline	LNCFS I	LNCFS II	LNCFS III
Boiler Efficiency	Base: 90.0%	90.2%	89.7%	89.85%
Effic. Change		0.2	(0.3)	(0.15)
Turbine Heat Rate	Base: 9,000[3]	9,011	9,000	9,000
Unit Net Heat Rate	Base: 9,995	9,986	10,031	10,013
% NHR Change	-----	(0.1)	(0.36)	(0.18)

Table S.3 shows that the LNCFS I retrofit increased the boiler efficiency at full load by 0.192 percent, while it increased the turbine heat rate from 9,000 to 9,011 Btu/kWh due to a 5-10°F steam temperature reduction. These changes in boiler efficiency and turbine heat rate resulted in 0.1 percent decrease of the unit net heat rate. Similarly, the LNCFS II decreased boiler efficiency by 0.322 percent (mainly due to the higher O_2) and increased the net heat rate by the same percentage (0.36 percent). The impact of the LNCFS III was a 0.157 percent decrease in boiler efficiency and a 0.18 percent increase in net heat rate.

The impact on boiler efficiency and heat rate was estimated only at full load because of the higher uncertainty of some measurements at low loads (especially LOI) and the fact that Smith Unit 2 is a baseloaded unit. However, for cycling units which may experience steam outlet temperature reductions similar to Smith Unit 2, the impact of the LNCFS on low load heat rates is expected to be more significant.

Costs and Cost-Effectiveness

The economic impacts of low NOx technology retrofits consist of capital costs required for the retrofit and changes in O&M costs due to performance impacts, such as LOI, excess O_2 and steam outlet temperature changes, additional auxiliary power requirements and increased non-fuel operating and maintenance costs. The average cost-effectiveness of each low NOx technology (expressed in $/ton of NOx removed) was estimated by taking into account the capital costs, O&M costs, and the NOx emission reduction on an annual basis. For the purposes of this report, it was assumed that the unit is base-loaded with a capacity factor of 65 percent.

[3] Assumed turbine heat rate.

Capital Costs:

Considering that only the LNCFS II was a complete retrofit (the other technologies were modifications of LNCFS II), capital costs for LNCFS I and III can not be estimated based on the Smith Unit 2 project costs. However, the Smith Unit 2 retrofit, as well as other tangentially-fired LNCFS retrofits, indicate (Ref. 10) that the capital cost requirements fall within the following ranges:

- LNCFS I: $5-15 per kW
- LNCFS II: $15-25 per kW
- LNCFS III: $15-25 per kW.

Although site-specific considerations affect significantly the capital cost requirements, the above ranges reflect the recent experience and are widely accepted as a good first estimate for planning purposes.

The capital costs of the LNCFS II at Smith, estimated to be approximately $3 million or $17 per kW, fall within the projected range. For the purposes of this report, the LNCFS I and III costs are estimated to be:

- $ 8 per kW for LNCFS I; and
- $ 20 per kW for LNCFS III.

O&M Costs:

As has been shown in Table S.3, the performance changes due to the LNCFS retrofits have an impact on boiler efficiency and unit heat rate. As a result, the fuel requirements and the O&M costs are also affected. Considering the net heat rate impacts presented in Table S.3, 65 percent capacity factor and 2 $/MBtu coal cost, the following annual O&M changes are estimated due to the LNCFS technologies:

- LNCFS I: $ 18,450 per year reduction;
- LNCFS II: $ 73,800 per year increase;
- LNCFS III: $ 36,900 per year increase.

Cost-effectiveness of LNCFS Technologies:

Table S.4 summarizes the impact of the above O&M cost increases, capital cost requirements and NOx emission reduction, and estimates their cost-effectiveness[4] relative to baseline. The resulting cost-effectiveness is:

- LNCFS I: $103/ton;
- LNCFS II: $444/ton;
- LNCFS III: $400 /ton.

In a similar manner, the incremental costs of LNCFS III as compared to LNCFS I are estimated to be 1546 $/ton. This is because the capital costs of LNCFS III are double, while the NOx reduction improvement is only 8 percent.

[4] Levelization factor: 0.144

Table S.4 - Cost-Effectiveness of the LNCFS Technologies Tested at Smith Unit 2

	Baseline	LNCFS I	LNCFS II	LNCFS III
Average NOx (lbs/MBtu)	0.63	0.39	0.39	0.34
% NOx Reduction	-	37	37	45
Annual NOx Reduction (tons/yr)	-	1,159	1,159	1,396
Net Heat Rate (Btu/kWh)	9,995	9,986	10,031	10,013
Changes in O&M Costs ($/yr)	-	(18,450)	73,800	36,900
Capital Costs ($ millions)	-	1.44	3.06	3.6
Cost-Effectiveness ($/ton of NOx removed)	-	103	444	400

Considering the sensitivity of the above estimates to the assumptions made, the following conclusions can be drawn:

- The LNCFS I technology is more cost-effective than LNCFS II and III;
- The cost-effectiveness of LNCFS II and III technologies is approximately the same. However, LNCFS III has higher NOx reduction capability; 40-50 percent instead of 30-40 percent for LNCFS II.

Implications for Other Tangentially-fired Units

This section provides key conclusions which are applicable to other tangentially-fired units. As a general guide, the results from this project with other low NOx retrofit projects (shown in Table S.5) can be used to project NOx emissions, performance impacts, and costs at future sites considering retrofits with LNCFS technologies.

Table S.5 - Selected LNCFS Retrofit Projects

LNCFS Type	Utility	Unit Name & Number	Size (MW)
LNCFS I	TVA	Gallatin #4	288
	Illinois Power	Joppa #3	150
LNCFS II	Public Service of Colorado	Cherokee #4	370
	Public Service of Colorado	Valmont #5	165
	Indianapolis P&L	Stout #5	100
	Centerior G&E	Eastlake #2	132
	Virginia Power	Yorktown #2	175
LNCFS III	Union Electric	Labadie #4	600

The closer a unit is to the Smith Unit 2, in terms of boiler design and coal characteristics, the higher the confidence in terms of predicting the NOx reduction and performance impacts based on the results of this project. Of particular importance are the following boiler design and fuel characteristics of Smith Unit 2:

- Its furnace size is above average relative to other pre-NSPS units; NHI/PA: 1.65 MBtu/hr-sqft as compared to 1.6 to 2.2 for most pre-NSPS ABB/CE boilers.

- The existing windbox is taller than the average tangentially-fired unit of similar rating and allowed for a larger CCOFA system (approximately 20 percent larger cross-sectional area).

- The reactivity of the coal is higher than most eastern bituminous coals and, as such, would be expected to have less impact on LOI than other lower reactivity eastern bituminous coals. More specifically, the reactivity of the coal burned at Smith as measured by the Fixed Carbon/Volatile Matter (FC/VM) is 1.30 (lower FC/VM means higher reactivity) which is at the low end of the High Volatile Eastern Bituminous coals (FC/VM: 1.4 - 1.7) and more typical of the SubBituminous coals (FC/VM: 1.1 - 1.4).

Implications Regarding NOx Emissions

The Smith ICCT project, along with other retrofits, showed that:

- The LNCFS I can achieve 25-37 percent NOx emission reduction within the control range (100 - 200 MW) in boilers with design characteristics similar to Smith Unit 2. This NOx reduction is above the 25-30 percent level which has been observed in other tangentially-fired units (e.g., TVA's Gallatin #4) and was expected for most tangentially-fired units by ABB/CE (Ref. 9).

- The LNCFS II and III can achieve the expected level of NOx reduction (Ref. 9) within the control range; 30-40 percent for LNCFS II and 40-50 percent for LNCFS III.

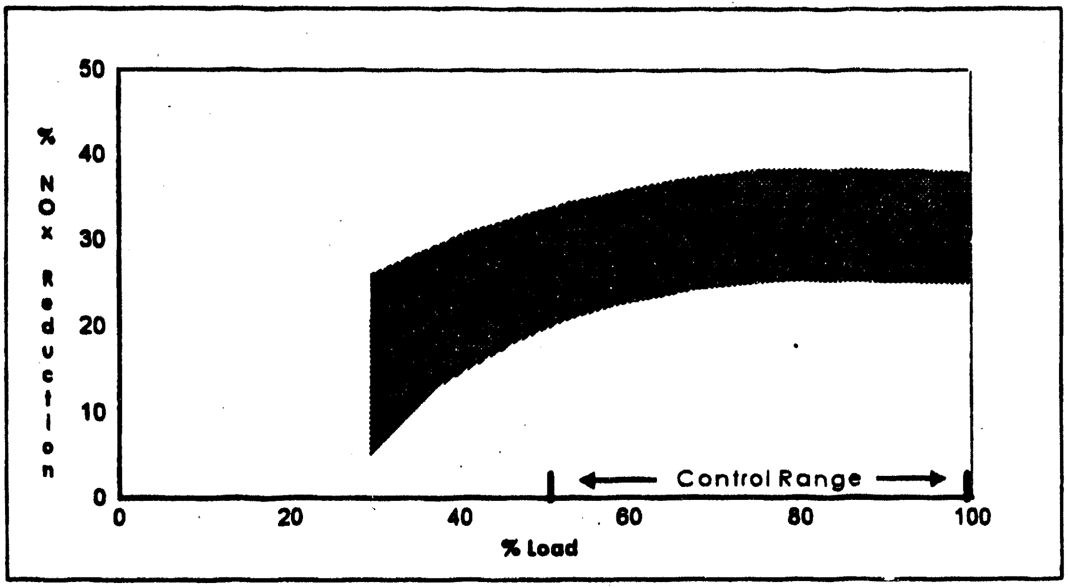
- NOx emissions below the control point (100 MW) may increase for all LNCFS technologies. This is particularly true when the primary objective of unit operation at low loads is to control steam outlet temperatures and maintain unit response rate rather than minimize NOx emissions.

Figures S.5, S.6, and S.7 and the following paragraphs provide the NOx reduction projections across the load range for tangentially-fired units utilizing the LNCFS I, II, and III, respectively.

LNCFS I:

Figure S.5 shows the NOx reduction potential of LNCFS I. Based on the experience of Smith Unit 2 and other LNCFS retrofits, it is expected that NOx reduction of 25 to 37 percent within the control range may be achieved by LNCFS I. The NOx reduction projections below 50 percent load (see Figure S.5) are based on the LNCFS III testing at Smith. (Note that when the SOFA dampers of the LNCFS III are closed at low loads, the LNCFS III and I are identical).

Figure S.5 - Expected NOx Emissions Reduction for Tangentially-fired Units with LNCFS I



Smith Unit 2 achieved 37 percent long-term NOx reduction within the control range (50-100 percent load). Other units retrofitted with the LNCFS I have achieved NOx reduction in the 20 to 32 percent range.

LNCFS II:

The LNCFS II is expected to achieve 30-40 percent long-term NOx reduction within the control range (50-100 percent load). This projection is based on the Smith Unit 2 experience, as well as results from LNCFS II retrofits such as Public Services of Colorado's Cherokee #4 and 5 (Ref. 11) and Indianapolis P&L's Stout #5 (Ref. 12).

LNCFS III:

Forty to 50 percent NOx reduction is expected within the control range (50-100 percent load) with LNCFS III. This is based on the operating experience from Smith Unit 2 and Union Electric's Labadie #4 (Ref. 13) retrofits.

Low Load NOx Emissions:

The NOx reduction below the control point (50 percent load) may decline depending on the unit design characteristics and the operating objectives. If the primary operating objective at low loads is to maintain steam outlet temperatures and/or unit response rate, the NOx emission reduction may decrease significantly, as shown in Figures S.5, S.6, and S.7 for LNCFS I, II and III, respectively. The resulting NOx reduction due to the different operating objectives is shown in Figures S.6 and S.7:

- The shaded area marked "*No Operating Adjustments*" shows the NOx reduction if the boiler is operated as before the low NOx retrofit, when the primary operating objective was to maintain steam outlet temperatures.

- The area marked "*With Performance Trade-offs*" indicates the potential for additional NOx reduction through operating adjustments; however, these adjustments may have adverse impacts on boiler efficiency, turbine heat rate and unit net heat rate.

Figure S.6 - Expected NOx Emission Reduction for Tangentially-fired Units with LNCFS II

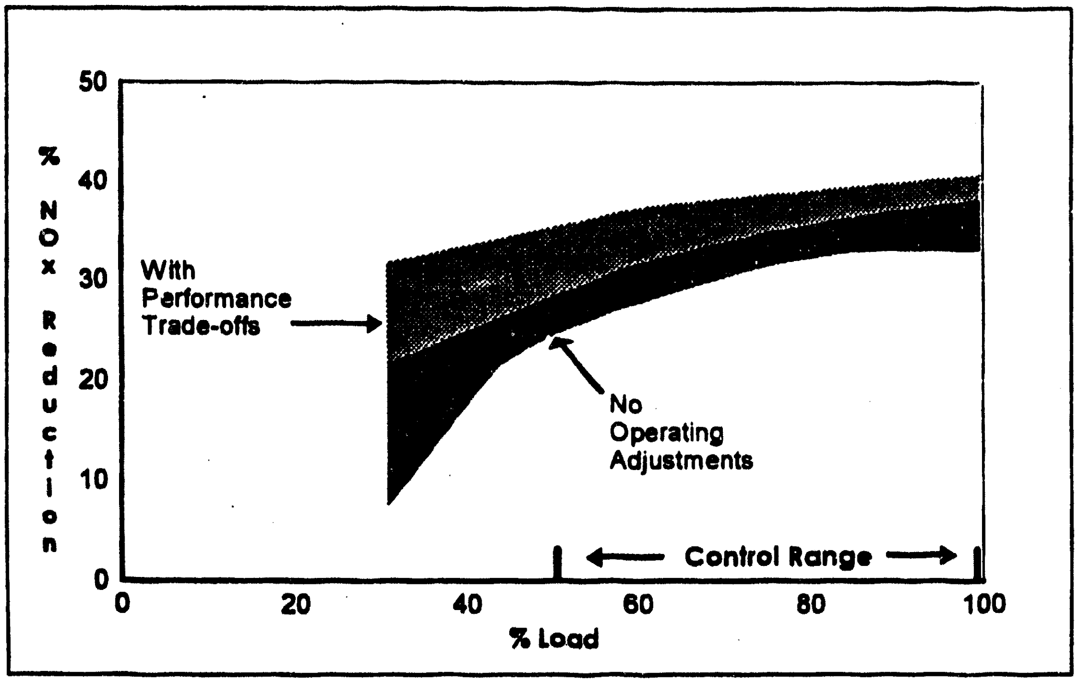
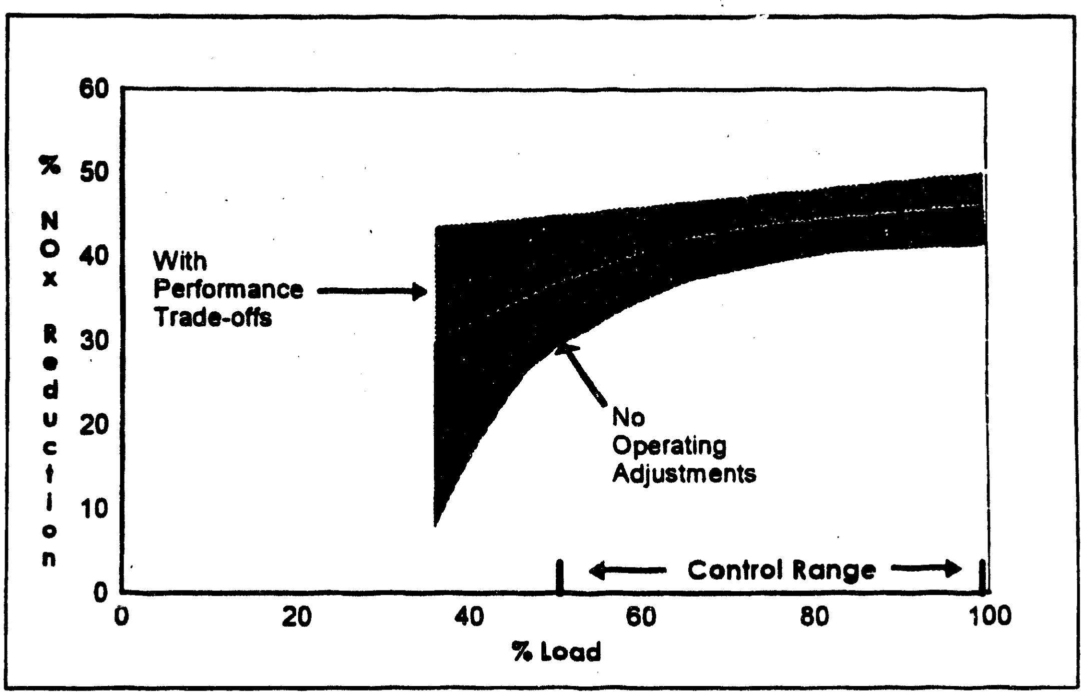


Figure S. 7 - Expected NOx Emission Reduction for Tangentially-fired Units with LNCFS III



If such NOx reduction decline needs to be avoided, a number of actions can be taken before and after the LNCFS retrofit has been completed:

During design specification, the utility may elect to specify the NOx emission levels required throughout the load range, including low loads. In response, the low NOx technology vendors may design the system to reduce NOx at low loads.

After the LNCFS Retrofit, NOx emissions at low loads can be reduced through operating adjustments, such as reduction of excess O_2 and burner tilt and/or increase of overfire air flow rate. However, these adjustments may impact adversely the steam outlet temperatures and the unit heat rate. In this case, an optimum operating point should be determined through trade-off of NOx reduction and heat rate (production costs).

O&M Impacts of Tangentially-fired Units

Adverse O&M impacts can occur even where steps are taken to carefully integrate retrofit NOx control technologies with existing plant generation requirements. In general, the higher the NOx reduction sought the greater the potential for O&M impacts.

The most common of the O&M impacts observed to date, including the Smith ICCT project, has been reduced boiler efficiency due to increased excess O_2 requirements, especially for low NOx technologies with separated overfire air systems. Although not necessarily witnessed at Smith Unit 2, other potential impacts may include:

- Increased CO emissions;
- Increased LOI, especially with low reactivity coals;
- Changes in furnace slagging and backpass fouling patterns;
- Increased waterwall corrosion;
- Reduced steam outlet temperatures;
- More difficult boiler operation; and
- Reduced equipment reliability.

Increased CO Emissions and Excess O_2: The potential exists for increased CO emissions. If the baseline CO is below 20 ppm, CO compliance is not expected to be a problem. However, in marginal CO cases, CO may need to be controlled by increasing the excess air. Increases up to 1.5 percentage points in excess O_2 have been observed in LNCFS retrofits. Where retrofits have resulted in replacement of worn or damaged equipment, decreases in excess O_2 of up to 0.5 percentage points have been documented.

Increased LOI: No significant impacts on LOI have been observed and are expected with higher reactivity coals. However, less reactive eastern bituminous coals may result in increased LOI (3 to 5 percentage points).

Changes in Furnace Slagging and Backpass Fouling: Low NOx retrofits affect the heat release and heat absorption profiles. As a result, furnace slagging and backpass fouling may be affected depending on the degree of change of these profiles.

Most retrofits, including Smith Unit 2, have experienced decreased furnace slagging. However, furnace slagging reduction, very often, is accompanied by increased dust loading of the flue gas and increased backpass fouling. The net result may be reduced waterwall sootblowing, but increased backpass sootblowing frequency and potential particulate compliance problems.

Reduced Steam Outlet Temperatures: Changes in steam outlet temperatures, especially reheat temperature at low loads, may be observed in units experiencing changes in furnace slagging patterns. Such changes can be controlled with excess O_2 or burner tilt increases, but NOx emissions may increase. Specific recommendations on how to avoid such steam temperature changes though appropriate design specifications, unit operating adjustments and hardware modifications are provided in Section 8.

Increased Waterwall Corrosion: To date, there have been no reports of increased corrosion due to low NOx operation, which increases the potential for local reducing environments. However, because of the long-term nature of corrosion impacts and the relatively few projects where corrosion rates have been rigorously determined, it cannot be assumed that these results apply to the general boiler population.

Unit Operation Impacts: Impacts have varied. Increased attention to monitoring and adjustments of existing boiler control parameters (e.g., primary air flow) have been reported in several instances. Where retrofitted equipment has replaced worn or damaged components, improved operation has resulted. Reduced load ramp rate was observed for one tangentially-fired application. Generally, no impact on boiler turndown has been reported, except in one instance where it improved.

Equipment Reliability: Generally, NOx control equipment reliability has been favorable. Some early design enhancements, especially when replacing worn or damaged equipment, have led to improved reliability. However, long-term operating experiences remain limited and some reliability problems continue to be reported. These include plugging of coal/air nozzles some of which have led to forced outages.

Some of the above impacts can be reduced or eliminated through systematic testing before and after the retrofit, as well as design and operating adjustments of the combustion system, boiler and auxiliary equipment. However, such adjustments may reduce one O&M impact, but may have other adverse impacts on boiler performance and the level of NOx reduction potential.

Implications for Planning Future Tangentially-fired Low NOx Retrofit Projects

Pre- and Post-Retrofit Testing:

- To avoid or reduce potential adverse impacts and achieve the optimum level of NOx reduction and unit performance, systematic testing before and after the retrofit is advised. Pre-retrofit testing should establish clearly the baseline conditions throughout the load range, identify high incidence of prior O&M problems and provide all the information needed for designing the low NOx system and integrating it into the boiler in an optimum manner.

- The pre-retrofit testing should provide information which will be included in the low NOx design specifications, such as:
  - operating condition of key components (e.g., mills and fans);
  - primary air flow rates over the load range;
  - air and coal flow imbalances;

- prior problem areas, such as excessive waterwall corrosion, high attemperation rates and low reheat temperatures.

Low NOx System Design Specifications:

- The design specifications should communicate clearly the project objectives, the existing condition of the equipment and other related operating and hardware changes being planned. Careful integration of the low NOx system with other modifications being planned independently of the low NOx retrofit is essential for minimizing adverse impacts and achieving satisfactory NOx reduction. Modifications which are planned sometimes in parallel with or after the low NOx retrofit are:
  - mill upgrading or operating changes;
  - reheat resurfacing;
  - replacement of unit controls with digital control system;
  - addition of gas conditioning equipment or ESP upgrading;

Capital Costs:

- Based on the recent experience from Smith Unit 2 and other LNCFS retrofits (Ref. 10), the capital costs for LNCFS retrofits are expected to be in the following range:
  - LNCFS I: $ 5 - 15 per kW;
  - LNCFS II: $15 - 25 per kW;
  - LNCFS III: $15 - 25 per kW.

Low NOx Retrofit Outage:

- A four- to six-week outage should be planned for LNCFS I retrofits and a six- to eight-week outage for LNCFS II and III retrofits. At Smith, the LNCFS II was the only complete retrofit (the others were modifications of the LNCFS II) and required a 3-week unit outage. This was accomplished because:

  i. There were no interferences with the installation of the windbox and the SOFA ducts;

  ii. Extensive preparation preceded the retrofit, including installation of SOFA ducts; and

  iii. "Around-the-clock" work schedule during the three-week retrofit.

The fact that the LNCFS II retrofit was accomplished in such a short period of time suggests that a three- to four-week outage is feasible for an LNCFS retrofit in cases where there are no interferences; however, a more typical schedule requires six to eight weeks.

Start-up and Optimization:

- Two to three weeks are adequate for LNCFS optimization (tuning). In cases of marginal NOx compliance (after the retrofit has been completed), re-optimization of the combustion system may be beneficial in further reducing

NOx emission. Such re-optimization should be scheduled three to six months after the original optimization, depending on the operating experience of the unit and the need for additional NOx emission reduction.

At Smith Unit 2, two-week optimization was needed initially for each system. In addition, a three-day re-optimization of LNCFS II was performed to reduce NOx emissions at low loads.

SECTION ONE
INTRODUCTION

This Innovative Clean Coal Technology (ICCT) Project included installation and testing of Asea Brown Boveri/Combustion Engineering Services' (ABB/CE) Low NOx Concentric Firing Systems (LNCFS) at Gulf Power's Plant Lansing Smith Unit 2. The LNCFS I, II, and III technologies, as well as the LNBFS, were tested.

The project was funded jointly by The Southern Company, the U.S. Department of Energy (DOE), and the Electric Power Research Institute (EPRI). Also, ABB/CE shared in the cost of the LNCFS retrofits. The purpose of the project was to assess the effectiveness of the low NOx technologies in reducing NOx and to identify their limitations, potential adverse impacts on unit performance, and implications for other tangentially-fired units.

The purpose of this report is to summarize the key findings of the project with particular emphasis on the comparison of the systems tested and the implications for other tangentially-fired units. The previous section provided an overview of the key findings of the project in terms of NOx reduction and O&M impacts observed at Smith Unit 2, as well as their implications for other tangentially-fired units.

Section 2 identifies the project objectives and the test program approach. Section 3 provides the key design characteristics of the boiler and auxiliary equipment and the results of the baseline (pre-retrofit) testing, which establishes a reference point against which the LNCFS technologies will be compared.

Section 4 describes the low NOx technologies with particular emphasis on the differences between the systems tested at Smith Unit 2 and low NOx systems offered commercially by ABB/CE. These design differences provide the basis for extrapolating the results of the Smith test program to other tangentially-fired boilers.

Section 5 provides a brief description of the unit retrofit and start-up activities including:

- Unit retrofit activities;
- Burner optimization; and
- Operator training programs.

The evaluation of the low NOx technologies is presented in Section 6. The NOx emission reduction and the unit performance impacts relative to baseline testing are provided first for each technology tested at Smith Unit 2. Then, all the low NOx technologies are compared in terms of NOx emission, adverse impacts on boiler performance and unit heat rate. Also the impact of dispatch profile on the unit's annual achievable NOx emissions and its ability to comply with the Clean Air Act Amendment NOx regulations is assessed.

Section 7 assesses the impact of the LNCFS technologies on operating and maintenance (O&M) costs, as well as the impact of retrofit costs and O&M costs on the cost-effectiveness of each technology ($/ton of NOx removed).

Finally, Section 8 provides the implications drawn from the Smith ICCT project for other tangentially-fired units considering similar low NOx burner retrofits. The implications include NOx emission reduction projections, unit performance impacts, and lessons learned for planning and implementing future low NOx retrofit projects.

Some the results included in this report have been presented in various conferences (see References # 2, 6, 7 and 13). For more detailed information on the project, the reader is referred to the Project Quarterly Reports, as well as the following reports:

Measurement of Chemical Emissions Under the Influence of Low NOx Combustion Modifications, (Ref. 14). In response to Title III of the 1990 Amendments to the Clean Air Act, Southern Research Institute was contracted to perform chemical emissions testing at Plant Smith Unit 2. The goals of the testing were (1) to evaluate the emissions levels of certain chemicals designated as Air Toxics under Title III, (2) to determine the effects of low NOx firing on the levels of chemical emissions, and (3) through material balance determinations, to evaluate the efficiency of a hotside electrostatic precipitator at controlling chemical emissions. Pre-low NOx burner retrofit "baseline" testing was conducted in September 1991, and post-low NOx burner retrofit testing was conducted in January 1992. The Final Report was issued in October 1993.

ESP Performance During the 180 MW Demonstration of Advanced Tangentially-fired Company Techniques for the Reduction of Nitrogen Oxides from Coal-Fired Boilers, (Ref. 15). This report summarizes the gaseous and particulate emissions from the boiler during performance testing of each technology. The data collected includes unburned carbon levels, particle size distribution, particle mass loading, gas volume flow and temperature, and vapor phase SO_2 and SO_3 concentrations were measured. In addition, a computer model of ESP performance was used to assess the effects that low NOx combustion would have on ESP operation.

Test Program Topical Reports, (Refs. 3,4, and 16). For each phase of testing, a topical report was prepared that provides analysis of the data collected during that phase. In the Phase I report, the baseline emissions data are presented. In addition, the design of the continuous emissions monitors, data acquisition system, and other analysis and test equipment are described. In the Phase II report, the LNCFS II emissions and performance data are presented. In the Phase III report, the LNCFS III and LNCFS I emissions and performance data are presented.

Final Public Design Report, (Ref. 17). Design information utilized by the project participants is provided in this report. The report includes the introduction to the instruction manual provided by ABB/CE, the specification developed by The Southern Company, and the proposal prepared by ABB/CE. The specification includes the scope of work, a listing of the applicable codes and standards to be applied to the design process, the design, fabrication, and erection requirements for the low NOx combustion technology, and the criteria by which the equipment will be judged once installed. The proposal from ABB/CE includes a general discussion of tangentially-fired boilers, a description of the low NOx combustion technologies including a list of major equipment, and a discussion of NOx control.

All of the above reports are available through the U.S. Department of Energy or The Southern Company.

SECTION TWO

PROJECT OBJECTIVES AND TEST PROGRAM APPROACH

The primary objective of this project was to determine the long-term effects of commercially available low NOx combustion technologies on NOx emissions and unit performance. Additional project objectives were to evaluate the relationship between NOx and key operating parameters (through parametric short-term testing) and extrapolate the results to other tangentially-fired units. Four low NOx technologies were tested in a stepwise fashion: LNCFS II, LNBFS, LNCFS III and LNCFS I.

To accomplish these objectives, the project team collected and analyzed long-term data under normal load-dispatched operating conditions for the LNCFS technologies, as well as the baseline system. The reasons for focusing on long-term data are:

- They reflect typical plant operation; and
- They allow for estimating annual achievable NOx which provides the basis for compliance with CAAA Title IV.

However, it was recognized that the long-term data may also reflect unique site-specific operating procedures and requirements, and may not be easy to extrapolate the results to other units. For this reason, the long-term testing was supplemented with short-term testing to assess the impact of key operating parameters on NOx emissions and unit performance. Detailed monitoring of unit performance, during short-term testing, allowed more in-depth cause-and-effect type analyses to explain certain performance trends.

Based on the long-term NOx data gathered, the following NOx emissions were determined:

1. Average long-term NOx emissions at a certain load;
2. Average long-term NOx emissions over the testing period;
3. Thirty-day achievable NOx emissions; and
4. Annual achievable NOx emissions.[1]

Even though the basis for regulatory compliance is the annual achievable NOx emissions (item #4), this report focuses on the average long-term NOx emissions at a certain load (item #1), because:

- It is not affected by the unit dispatch profile (which is unit specific and affects the annual achievable NOx emissions);

[1] The analysis methods for these regulatory determinations have been developed by the Control Technology Committee of the Utility Air Regulatory Group (UARG) (Ref. 5).

- It reflects normal operation of the unit; and
- It can be compared to short-term NOx emissions for further data analysis.

The term "NOx emissions" is used in this report for the average long-term NOx emissions at a specific load, unless otherwise indicated. The annual achievable NOx emissions are provided in Section 6.3. Short-term NOx emissions are reported only when they differ from long-term NOx or when they are used for analyzing specific NOx trends.

For the test program, Smith Unit 2 was equipped with a continuous emission monitoring system (CEM), a data acquisition system (DAS), gas sampling ports, coal and ash sampling devices, heat flux measurements and an acoustic gas temperature monitoring system at the furnace outlet plane.

The coal fineness was measured at two locations; the coal pipe and the mill outlet. The former was used by the test program team and is based on mill coal flow weighted average (isokinetic sampling). The latter is recommended by ABB/CE and is not isokinetic. Because of the significant difference in the measurements in these two locations, both measurements are reported in this document.

SECTION THREE

Unit Description and Pre-Retrofit (Baseline) Testing

This section provides the key design features of the Smith Unit 2 and the baseline NOx emissions and boiler performance. The design features are useful in assessing the applicability of the results to other tangentially-fired units. The baseline NOx and boiler performance provide the basis against which the LNCFS technologies will be compared.

3.1 Unit Description

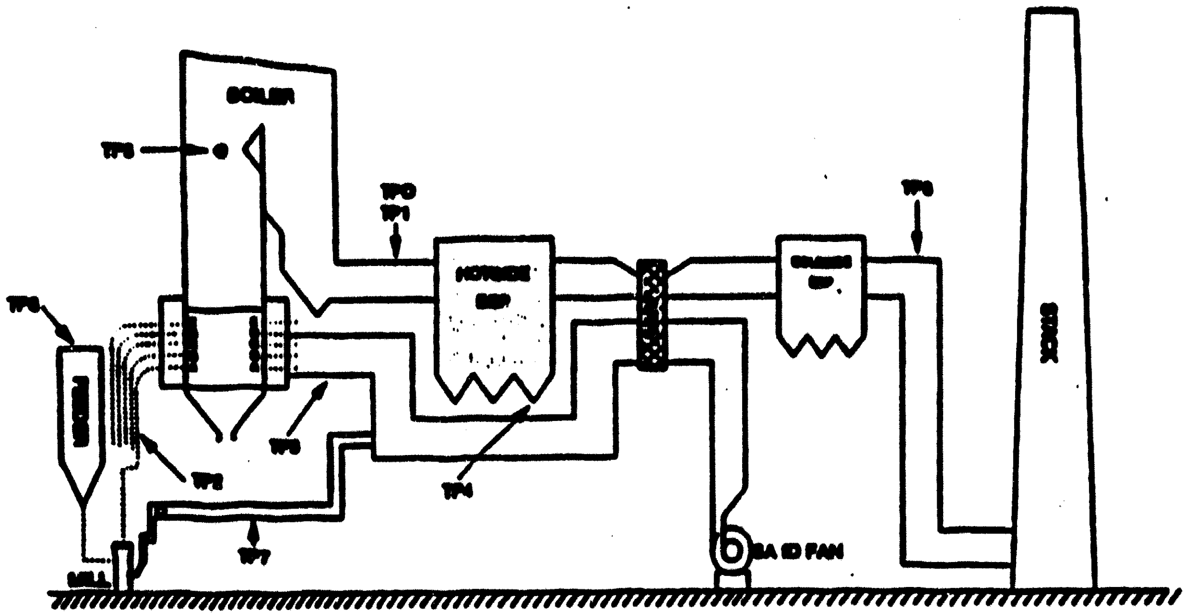
Plant Lansing Smith, owned and operated by Gulf Power Company, includes Unit 2 which is a tangentially-fired boiler (aspect ratio (width/depth) = 1.5) rated at 180 MW with the capability to provide up to 200 MWs. The boiler is an ABB/CE radiant reheat, natural circulation steam generator, which came on line in 1967. Although originally designed for pressurized furnace operation, the unit was converted to balanced-draft operation in 1976. It is designed for continuous indoor service to deliver steam at 1,306,000 lbs/hr at full load (180 MW), a pressure of 1,800 psig, and a temperature of 1000°F at the superheater and the reheater outlets.

As shown in Figure 3.1, exhaust gases are treated with hot-and cold-side electrostatic precipitators in series. The ESPs have adequate design redundancy (283 SCA for the hot side and 126 SCA for the cold side) to accommodate small changes in gas flow rate and dust loading which may result from the LNCFS retrofits. The unit is equipped also with Ljungstrom air preheaters, two forced-draft fans, and induced draft fans. The key characteristics of the unit are summarized in Table 3.1.

Key features of the Smith Unit 2, which may impact NOx emission reduction and the applicability of the results to other tangentially-fired boilers, are:

- The unit was originally designed for more than one coal and has a relatively large furnace in terms of plan area, windbox height, and furnace height; more specifically:
  - The furnace heat release rate (Net Heat Input/Plan Area: NHI/PA) of Smith Unit 2 is 1.65 MBtu/hr-sqft, which is in the low end of tangentially-fired units (typically range from 1.6 to 2.2 MBtu/hr-sqft). This suggests that the plan area of Smith Unit 2 is in the high end of tangentially-fired units.
  - The existing windbox is taller than the average tangentially-fired unit and accommodated a CCOFA system with an approximately 20 percent larger cross-sectional area than the typical ABB/CE system;
  - There is adequate distance (40' 4") between the top coal burner and furnace outlet to fit the separated overfire air (SOFA) system.
- Five mills (RPS 623) provide coal with fineness ranging from 55 to 65 percent through 200 mesh measured isokinetically in the coal pipe (average coal fineness at the mill outlet was: 68.6 percent through 200 mesh and 2.4 percent remaining on 50 mesh).

Figure 3.1 - Smith Unit 2 Layout and Test Site Locations



Test Point Description

Site No.	Location	Tests Performed
TP0	Flue Gas Before APH	- Gas Species - Temperature
TP1	Flue Gas Before APH	- Resistivity - SO_3, TPM, Particle Size
TP2	Pulverizer	- Dirty Air Velocity - Particle Size - Coal Flow Distribution
TP3	Secondary Air Venturi	- Velocity
TP4	ESP Hopper	- Resistivity - LOI
TP5	Furnace Nose	- Gas Species - HVT
TP6	Coal Feeder Inlet	- Coal Samples
TP7	Primary Air	- Air Flow Duct
TP8	Stack	- Gas Species

Table 3.1 - Lansing Smith Unit 2 Description

Unit Size (MWe)	180 (Max. 200 MW)
Commissioning Year	1967
Firing System/Number of burners	T-fired/20 coal nozzles
Vendor	ABB/CE
Furnace - Configuration - Width X Depth (ft X ft) - NHI/PA (MBtu/hr-sqft)	 Single Furnace 40' X 25.93' 1.65
Windbox Design - Cast/Std - Coal Elevation Spacing - Top coal elevation-to-furn. outlet	 Std Windbox 51" 40 ft. 4 in.
Number of Mills/Mill Type Air/Fuel Ratio	5 RPS623 2.3-3.0
Mill Transition Points	130-140 MW: A to AB-MOOS 110-120 MW:AB to ABE-MOOS 65-75 MW: ABC to ABE-MOOS
Coal Type (see Table 3.2 for coal analysis)	Eastern Bituminous
FC/VM	1.3
N_2 (%)	1.4
ESP (Design SCA)	Hot ESP: 283 Cold ESP: 126

The coal being burned at Smith Unit 2 is eastern bituminous. The analyses of the coal as fired and the design coal are provided in Table 3.2. As shown in Figure 3.2, this is a medium-to-high reactivity coal with a Fixed Carbon/Volatile Matter ratio similar to Wyoming sub bituminous B coals.

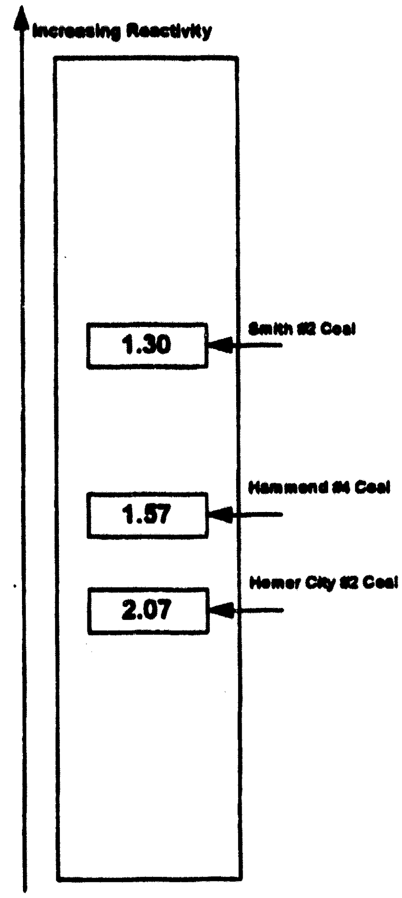
Table 3.2 - Coal Analysis

Ultimate Analysis:	Coal As Fired:	Design Coal:
- Carbon %	67.4	66.6
- H_2O %	9.0	8.5
- Hydrogen %	4.6	4.7
- Nitrogen %	1.4	1.2
- Sulfur %	2.8	3.7
- Oxygen %	6.0	6.8
- Ash %	8.7	6.8
- Chlorine %	0.1	
Proximate Analysis:		
- Volatile Matter	35.79	---
- Fixed Carbon	46.30	---
HHV Btu/lb	12,050	12,000

Figure 3.2

Comparison of Smith Coal Reactivity to Other U.S. Coals

Coal Type	FC/VM*
Peat	0.34
Lignite (ND)	0.77
Lignite (TX)	1.0
Sub Bituminous C (WY)	1.11
SubBituminous B (WY)	1.35
High Vol. Bituminous C (CO)	1.39
SubBituminous A (WY)	1.42
High Vol. Bituminous B (IL)	1.59
High Vol. Bituminous A (PA)	1.73
Medium. Vol. Bituminous (WV)	3.37
Low Vol. Bituminous (WV)	4.94
Semi-Anthracite (Ark)	6.75
Anthracite (PA)	10.26



* Fixed Carbon/Volatile Matter (FC/VM) ratio is used as a measure of the coal reactivity. Lower FC/VM means higher reactivity.

3.2 Baseline NOx Emissions and Unit Performance

3.2.1 *NOx Emissions*

The average long-term NO_X emissions at full-load (180 MW) were 0.63 lbs/MBtu with an average O_2 of 3.7 percent. This emission level does not reflect a well-tuned burner system and optimized boiler performance, but rather normal operation. Also, there was no attempt to reduce the excess O_2 because of the lack of a CO emission monitor reading in the control room. Also, burner tilts were not operational; they were set at horizontal position.

As shown in Figure 3.3, NOx emissions decreased slightly with load, especially below 100 MWs. At 75 MWs, NOx emissions were approximately at 0.56 lbs/MBtu. NOx varied by as much as 0.2 lbs/MBtu at each load. The lower 5 percent, upper 5 percent, and average values of the load, excess O_2, and NOx emissions are also provided for various load segments in Table 3.3.

Figure 3.3 - Long-term Baseline NOx Emissions

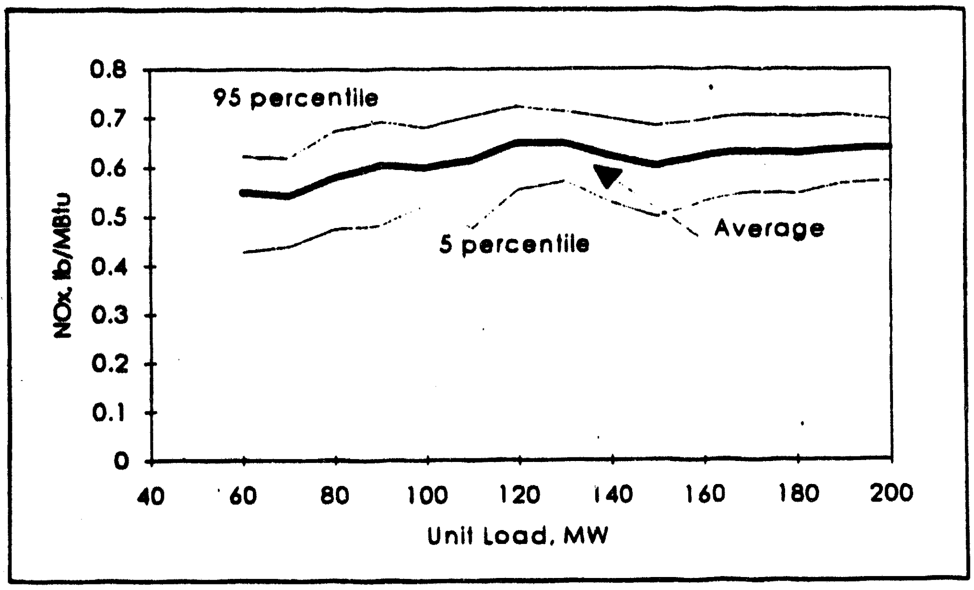


Table 3.3 - Baseline Long-term Data

Load		Load, MW			Excess Oxygen, %			NOx, lb/MBtu		
Segment	N	Lower	Average	Upper	Lower	Average	Upper	Lower	Average	Upper
55-65	1892	55.50	58.04	61.50	6.24	7.03	7.81	0.427	0.549	0.621
65-75	892	66.50	70.45	74.50	5.87	6.60	7.32	0.439	0.542	0.619
75-85	763	75.50	79.44	84.50	5.52	6.44	7.27	0.474	0.577	0.672
85-95	609	85.50	89.79	94.50	5.00	6.05	6.97	0.482	0.604	0.691
95-105	696	95.50	100.29	104.50	4.71	5.59	6.47	0.524	0.598	0.679
105-115	772	105.50	110.41	114.50	4.09	5.47	6.44	0.475	0.612	0.703
115-125	611	115.50	119.96	124.50	4.52	5.44	6.33	0.553	0.648	0.722
125-135	721	125.50	130.07	134.50	3.48	5.08	6.20	0.570	0.647	0.712
135-145	771	135.50	140.21	144.50	3.63	4.55	5.45	0.529	0.622	0.698
145-155	812	145.50	150.06	154.50	3.07	4.07	5.15	0.498	0.601	0.682
155-165	840	155.50	160.08	164.49	3.05	3.95	4.85	0.530	0.621	0.696
165-175	987	165.49	169.84	174.49	3.08	3.92	4.89	0.547	0.631	0.705
175-185	1085	175.49	179.99	184.49	2.79	3.69	4.69	0.546	0.627	0.701
185-195	1762	185.49	191.20	194.49	2.72	3.57	4.70	0.567	0.636	0.705
195-200	9179	195.49	197.55	199.49	2.69	3.51	4.98	0.571	0.639	0.696

Parametric (short-term) testing showed that the impact of O_2 on NOx emissions decreases with decreasing load. As Table 3.4 shows, the impact of O_2 on NOx changed from 50 ppm/% O_2 at full load to 33 ppm/% O_2 at 70 MW.

Table 3.4

Baseline System/Effect of Excess O_2 on NOx Emissions

Load (MW)	NOx/O_2 (ppm/%O_2)
180	50
115	40
70	33

3.2.2 *Baseline Unit Performance*

The main parameters characterizing the unit performance which may be affected by or affect the LNCFS retrofits are: CO emissions, O_2 required for complete combustion and safe operations, LOI, coal fineness, coal distribution, furnace slagging, steam outlet temperatures and the operating condition of key components such as burner tilts, dampers, and mills.

The following summarizes the measurements of these parameters during baseline testing:

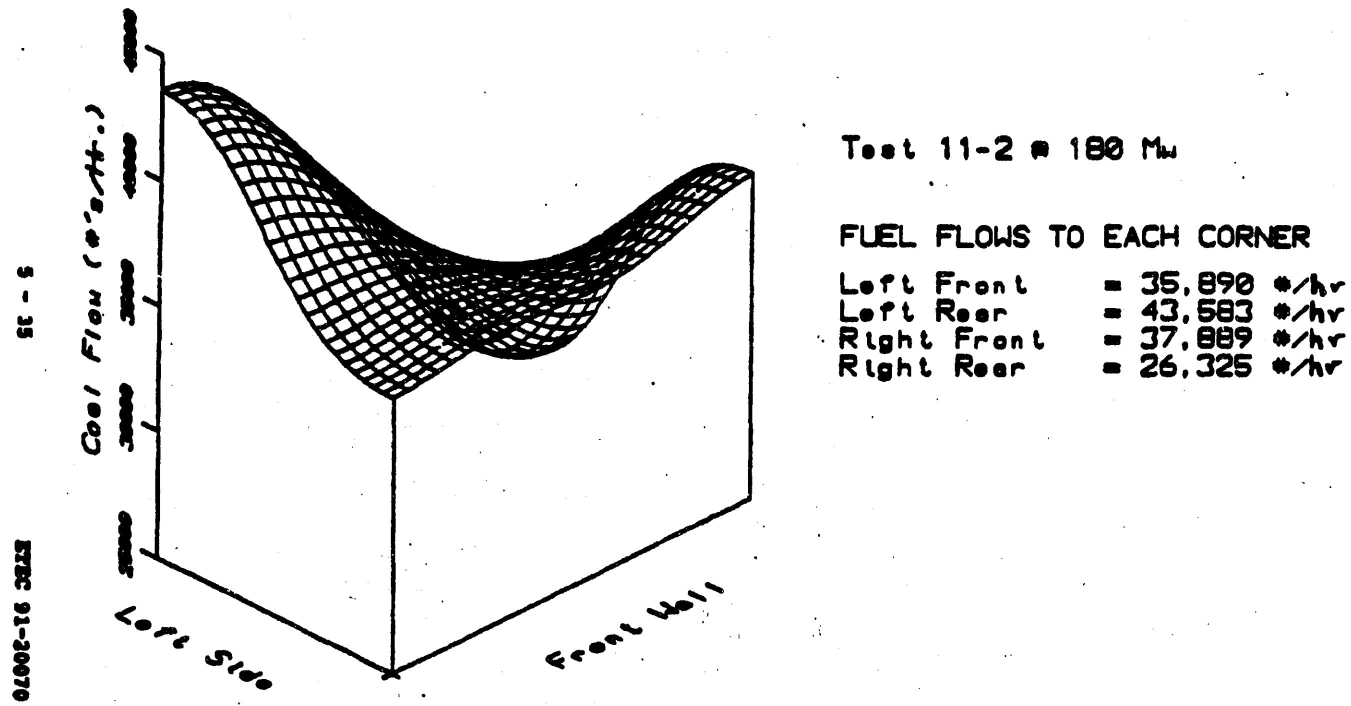
- Average CO emissions were kept below 20 ppm throughout the long-term baseline testing.

- The O_2 at full load ranged from 2.7 to 5.0 percent with an average of 3.7 percent. The lower limit was established to keep CO low, while the upper limit was due to forced draft fan capacity limitation. Because of the lack of CO monitor readings in the control room and the emphasis of the baseline testing on "normal unit operation", no attempt was made to tune the burners and reduce O_2.

- The LOI ranged from 4 to 4.8 percent; 4.8 percent at full load with 4 percent O_2. This LOI was achieved with an average coal fineness (in the coal pipe) of 58.9 percent through 200 mesh and 2.65 percent left on 50 mesh. Coal fineness at the mill outlet was 68.6 percent through 200 mesh and 2.4 percent left on 50 mesh.

- Coal distribution among the four corners of the unit was not uniform. For example, during test 11-2 (180 MW) the coal flow ranged from 18 to 30 percent to each of the four corners (see Figure 3.4) instead of ranging from 22.5 to 27.5 percent which is the recommended range (uniform distribution).

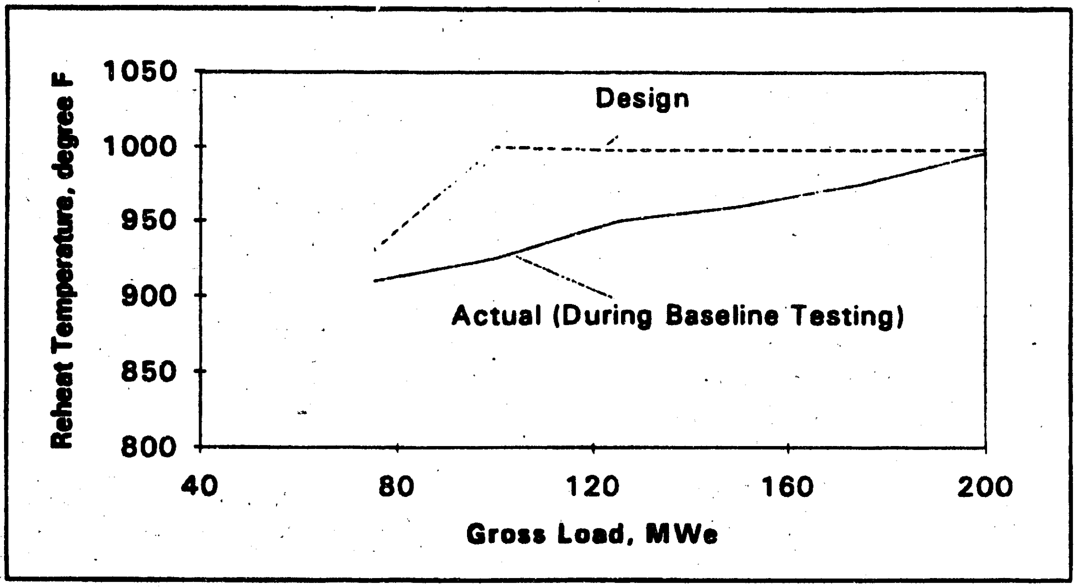
Figure 3.4 - Coal Flow Distribution (180 MW)



- Furnace slagging was characterized as "medium".

- The superheat outlet temperature was maintained at 1000° F throughout the load range. However, the reheat outlet temperature was below design levels by as much as 60-70° F at control load (100 MW). Figure 3.5 shows the actual reheat temperatures during baseline testing and compares them to the design temperatures. The difference is mainly due to removal of the reheat surface in the 1970s when the unit switched coals. To separate the impact of reheat surface removal from the impact of the LNCFS retrofit on steam temperatures, the post-retrofit temperatures will be compared with the baseline rather than "design" steam temperatures.

Figure 3.5 - Baseline Reheat Temperature Over the Load Range



The ESPs did not impose any constraints on the operation of the boiler. The ESP inlet conditions during baseline short-term testing were:

- Excess O_2: 6.1 percent
- LOI: 5.0 percent
- Dust Loading: 2.69 gr/scf
- Gas Flow Rate: 390,600 dscfm

No measurements were made in the ESP outlet.

- Key boiler components which may have an impact on NOx emissions and unit performance were in good operating condition except that the burner tilts were not operational; they were set at horizontal position.

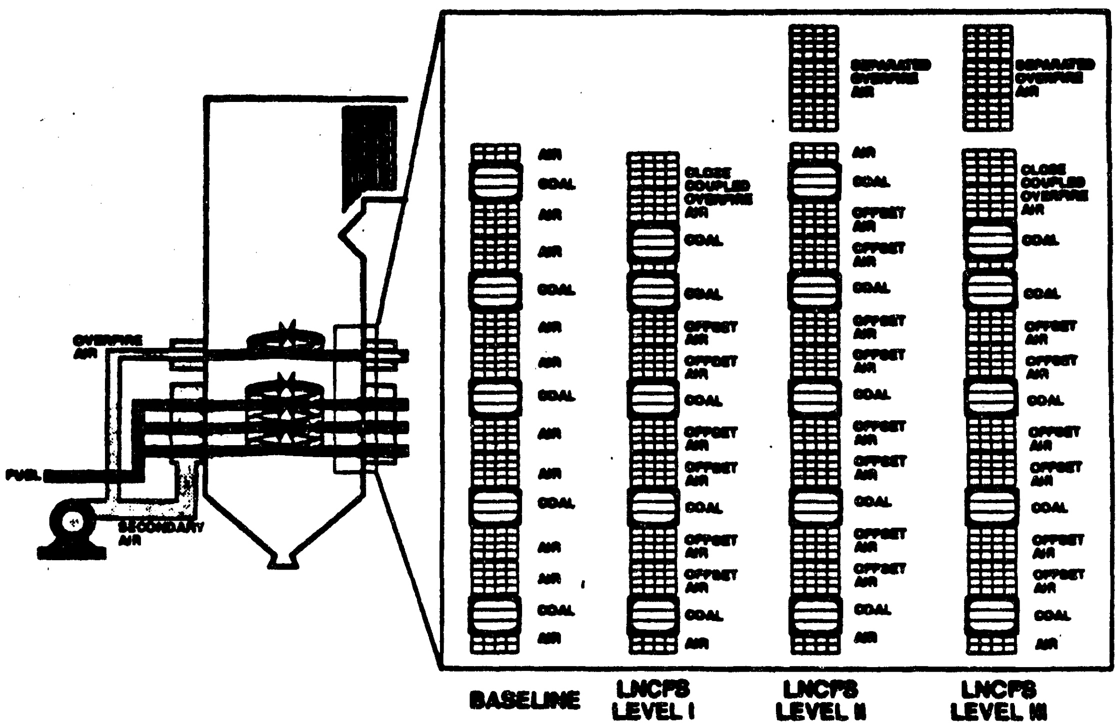
SECTION FOUR

LOW NOx TECHNOLOGIES RETROFITTED AT SMITH UNIT 2

As has been mentioned previously in this report, the original combustion system was initially retrofitted with the LNCFS II and then modified to LNCFS III. LNCFS I operation was simulated by closing the SOFA dampers. As a result of the need to test all LNCFS technologies on one unit, some compromises were made in the design of LNCFS I and III. The main differences between the standard LNCFS designs offered commercially by ABB/CE and the systems tested at Smith Unit 2 are highlighted in this section. More detailed descriptions of the LNCFS technologies offered commercially by ABB/CE are provided in the literature (see References 9 and 10).

The LNCFS technologies, along with LNBFS and the baseline system, are shown in Figure 4.1. The LNCFS I includes a Close-Coupled Overfire Air (CCOFA) system in the upper part of the main windbox. Compared to the baseline configuration, LNCFS Level I is arranged by exchanging the highest coal nozzle with the air nozzle immediately below it. This configuration provides the NOx reducing advantages of an overfire air system without pressure part modifications to the boiler. Also, the LNCFS I includes a concentric firing system (offset air nozzles) and new flame attachment tips on the coal nozzles.

Figure 4.1 - Tangentially-Fired Combustion Systems



A Separated Overfire Air (SOFA) system is used in the remaining three systems, LNCFS II, III, and LNBFS. 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. These dampers were not used at Smith because there was adequate pressure. However, in general, the intent of operating at a higher pressure is to increase the quantity and injection velocity of the overfire air into the furnace.

An automatically controlled damper controls the air flow rate to each overfire air nozzle. 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 main nozzles in the secondary windbox. The SOFA system was designed for approximately 20-25 percent of the total air flow rate which is typical of ABB/CE designs. Smith Unit 2 had enough space (40' 4") between the top burner and the furnace outlet to fit the SOFA system and locate it in such a way that adequate residence time is provided for complete combustion. For LNCFS III, the SOFA and CCOFA system together accounted for 30 - 40 percent of the total air flow to the boiler which is at the upper end of the overfire air flow rate of ABB/CE low NOx systems.

The LNBFS utilizes the existing windbox with a SOFA system. The LNCFS II includes a SOFA and the offset air feature of the LNCFS I — it does not include the CCOFA system and offset air nozzles. The LNCFS III combines all the low NOx features of the other systems, namely, CCOFA, offset air, flame attachment coal nozzle tips, and SOFA.

Other design features of the LNCFS technologies tested at Smith Unit 2 which usually are not included in ABB/CE's standard design are the SOFA flow measuring devices, adjustable yaw of the offset air nozzles and backpressuring dampers.

SECTION FIVE

UNIT RETROFIT AND START-UP ACTIVITIES

This section provides a summary of the key activities during the low NOx burner retrofits and start-up. Particular emphasis is placed on the duration of the retrofits, the burner optimization, and the operators' training program.

5.1 Unit Retrofit

The low NOx technologies were tested in the following order: LNCFS II, LNBFS, LNCFS III and LNCFS I. To accomplish this, the boiler was retrofitted first with the LNCFS II (Spring '91). Then, the LNBFS was tested by setting the offset air nozzles to be in-line with the coal nozzles. Retrofit of the LNCFS III (Fall '91) required installation of two close-coupled OFA compartments at the top of each windbox by switching the top coal nozzle with the air nozzle below. LNCFS I system operation was simulated (Summer '92) by closing the SOFA dampers of the LNCFS III system; it did not require any equipment additions or modifications. The LNCFS II and III retrofits are described in the following paragraphs because they were the only ones requiring hardware modifications.

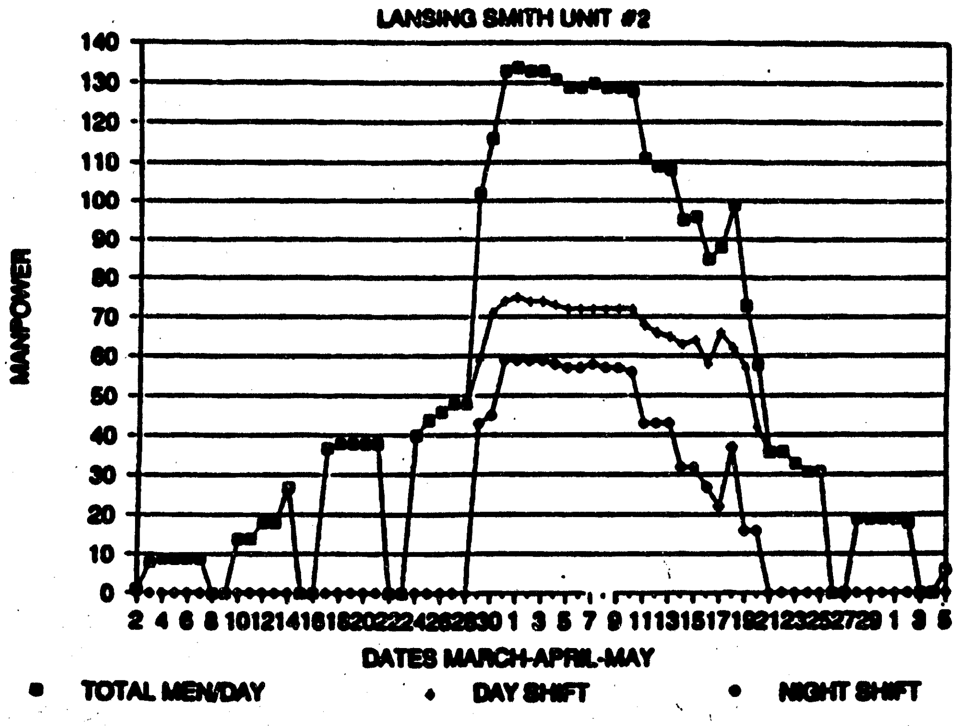
5.1.1 LNCFS II Retrofit

The LNCFS II retrofit required complete replacement of the existing coal and air nozzles and installation of separated overfire air (SOFA) ports in the four corners of the furnace. The LNCFS II was installed during a three week outage which began on March 29, 1991. During that outage, craft labor worked seven days a 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. As is shown in Figure 5.1, as many as 70 craft laborers per shift and 134 men per day were involved during the peak work of the retrofit. A full furnace scaffold was installed to expedite the job.

Extensive pre-retrofit work (4 weeks working 5 days/week, 8 hrs/day) contributed also to the short unit outage. Time-consuming activities, such as installation of the SOFA ducts, were completed before the unit came 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 then inserted into the 5-feet high by 2-feet wide openings in the waterwall.

The critical path for this outage was the modification to the main windboxes. After the boiler came off line, the windboxes were completely stripped of coal nozzles, auxiliary air nozzles, tilt linkages, and all bearings and bushings. After removing this equipment, 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, 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 replaced.

Figure 5.1 - Manpower During LNCFS II Retrofit



During the outage, two unexpected events occurred which could have impacted unit start-up following the outage. First, asbestos insulation was inadvertently uncovered and removed from a section of the secondary air ductwork by craft laborers. Upon identification of the asbestos, the building was cleared of all personnel and the area was properly cleaned. Four working shifts were lost as a result of this incident. Second, the main boiler feedwater line required relocation. These unexpected complications required higher than planned manpower for the remaining outage activities. However, the retrofit was completed within the projected 21-day outage.

In retrospect, this outage is considered too short; a 6-8 week outage is recommended for similar projects. However, this retrofit indicates that if the unit outage has to be reduced to the minimum, a 3-4 week outage is feasible provided that the burner retrofit is the only activity during the outage and a significant amount of preparation is done before the unit comes off-line.

5.1.2 LNCFS III Retrofit

The conversion of the LNCFS II to LNCFS III required reconfiguration of the top three windbox nozzles in each corner of the boiler (see Figure 4.1). The existing top coal nozzles and the two auxiliary air nozzles were replaced with one stationary auxiliary air, one coal and two CCOFA nozzles. Along with the coal nozzle, the corresponding piping, ignitors, and flame scanners were relocated.

The unit outage for the LNCFS III retrofit required minimal work, because the majority of equipment were installed as part of the LNCFS II retrofit. Two weeks were required for the LNCFS III retrofit working 10 hrs/shift, 2 shifts/day, 5 days/week. The average manpower loading was 36 men/day.

5.2 Unit Optimization

The objective of the system optimization was to determine the best settings for the combustion system and boiler control variables, (e.g., secondary air (SA) dampers, SOFA dampers, SOFA and main windbox auxiliary air yaw position, and SOFA tilt position) over the load range and provide the plant operators with operating procedures, which will result in optimum unit performance.

5.2.1 General Optimization Approach

The approach followed by ABB/CE was to start at full load with the control variables set at a nominal operating position and then adjust one variable at the time to assess its impact on NOx, CO and LOI. The following adjustments are then made sequentially:

1. Open OFA dampers (one at a time starting from the bottom damper) and monitor NOx, CO, and LOI;

2. Adjust SA dampers to maintain pressure drop and ignition point;

3. Vary O_2 to determine limitations (at full load, too low O_2 results in high CO, while an upper limit may exist due to fan and ESP capacity limitations or steam temperature control constraints; at low loads, O_2 is limited by the need to maintain windbox pressure drop and steam outlet temperatures);

4. Vary burner tilt position (+/- 30°);

5. Adjust main windbox and SOFA yaws (SOFA yaws correct for coal distribution imbalances);

6. Vary OFA tilt (+/- 7°) and eventually tie it to burner tilt for automatic operation.

5.2.2 Optimization of LNCFS I, II and III

A two-week optimization was required for each of the LNCFS technologies. The recommended settings at the end of the optimization are shown in Tables 5.1 and 5.2. Table 5.1 shows the burner variables which are set during the optimization and are not adjusted during normal unit operation. Table 5.2 includes the control variables which change either from the control room or manually during normal unit operation.

Table 5.1 - Yaw Settings for All Loads

	LNCFS I	LNCFS II	LNCFS III
SOFA yaws (Right Front, Left Front & Left Rear)			
-Upper	NA	+ 15°	+ 12°
-Middle	NA	Zero	Zero
-Lower	NA	- 15°	- 12°
SOFA yaws (Right Rear)			
-Upper	NA	- 15°	- 12°
-Middle	NA	- 15°	- 12°
-Lower	NA	- 15°	- 12°
Main Windbox Yaws	+16°	+ 22°	+ 16°

Note: 1. Yaw angle is measured from the direction of the coal injection.
2. Positive angle indicates rotation towards the fireball.
3. NA = Not Applicable

Table 5.2 - Recommended Control Variable Settings

Control Variable	Control (Auto/Manual)	LNCFS I	LNCFS II	LNCFS III
Average Full Load O_2 % (O_2 Range)	Auto	3.0	4	3.8
SOFA Dampers	Auto	Not Applicable	Figure 5.4	Figure 5.6
CCOFA Dampers	Auto	Figure 5.2	NA	Figure 5.7
Auxiliary Air (Windbox Pressure Drop)	Auto (except at low loads)	Figure 5.3	Figure 5.5	Figure 5.8
Fuel Air Dampers	Auto (except at low loads)	Not Available	Not Available	• 20% open between 115 & 200 MW • 10% open below 115 MW
Burner Tilt at Full Load	Auto to control reheat outlet temp	Horizontal	Horizontal	Horizontal

SOFA tilt was set to follow a linear relationship with the burner tilt; SOFA tilt set to +7° when the burner tilt is at +30° (approximately 1° SOFA tilt for every 4° of burner tilt). ABB/CE also provided recommended O_2 levels over the load range.

Following the original LNCFS II optimization (see Figure 5.4, "Original"), ABB/CE visited the site again to re-optimize the system. The main reason for this was to improve the NOx emission reduction at low loads. The re-optimization lasted 3 days and resulted in new recommendations for the SOFA dampers over the load range (see Figure 5.4, "Revised"). The "revised" settings are not reflected in the test data of LNCFS II because the LNCFS II testing was completed shortly after the re-optimization. However, they were taken into account in the LNCFS III testing. Similar re-optimization may not be required by all tangentially-fired units.

Figure 5.2 - LNCFS Level I Upper and Lower CCOFA Damper Settings

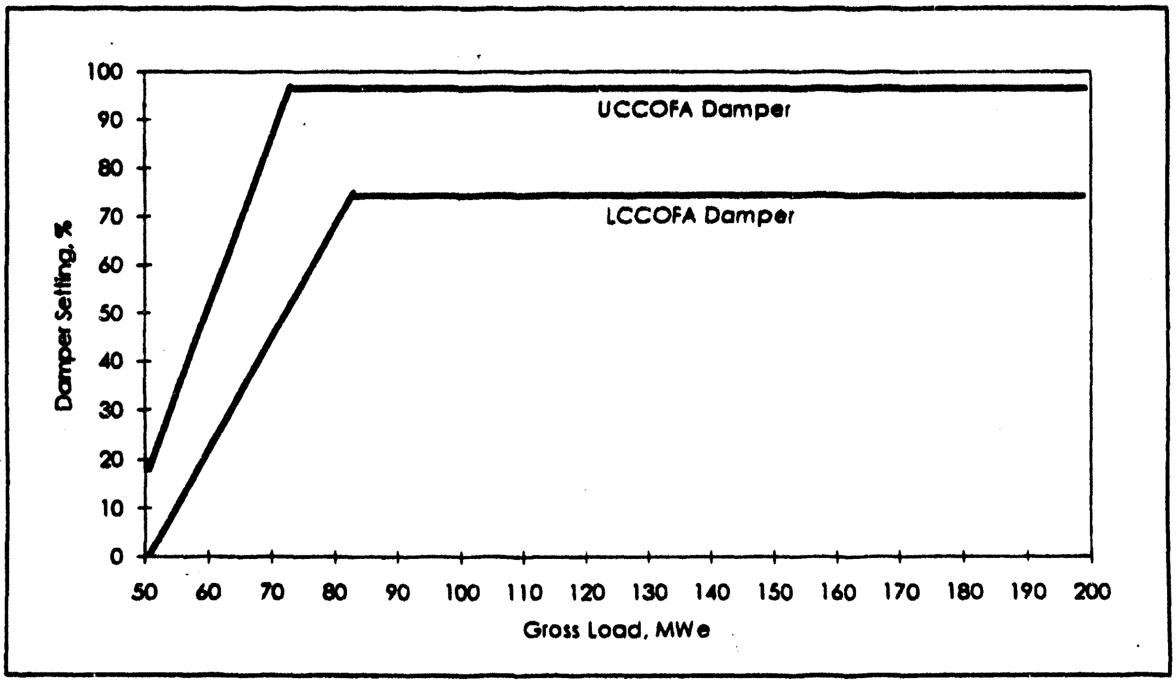


Figure 5.3 - LNCFS I Windbox Pressure at Normal Oxygen

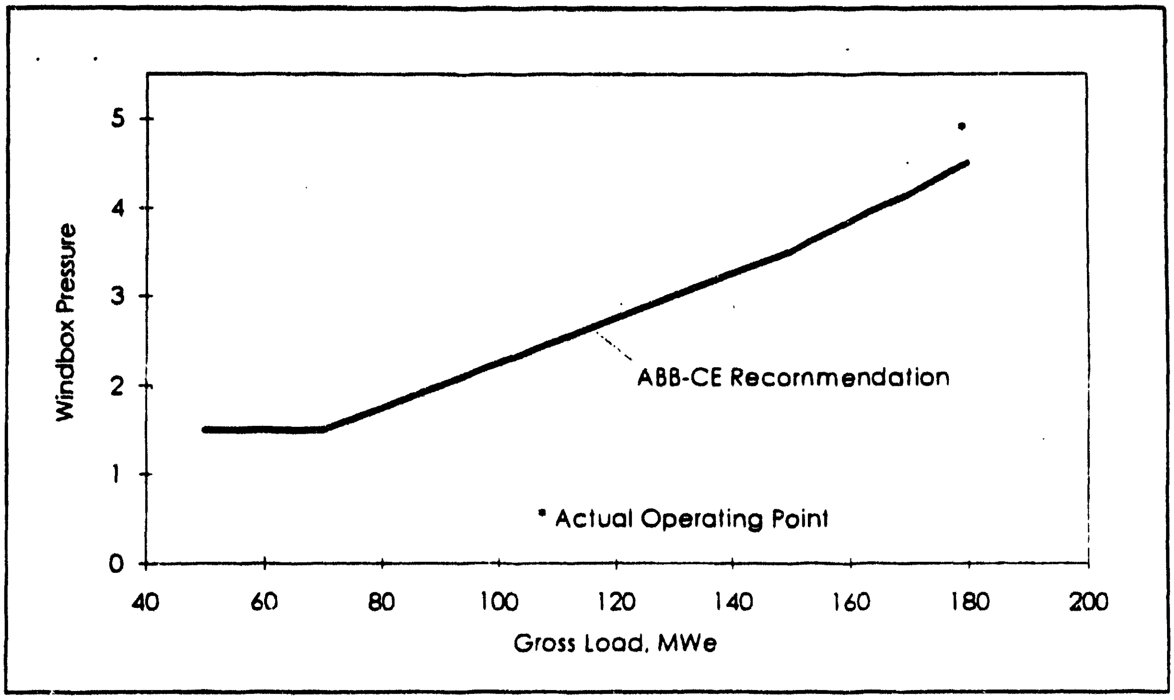


Figure 5.4 - LNCFS II SOFA Damper Setting

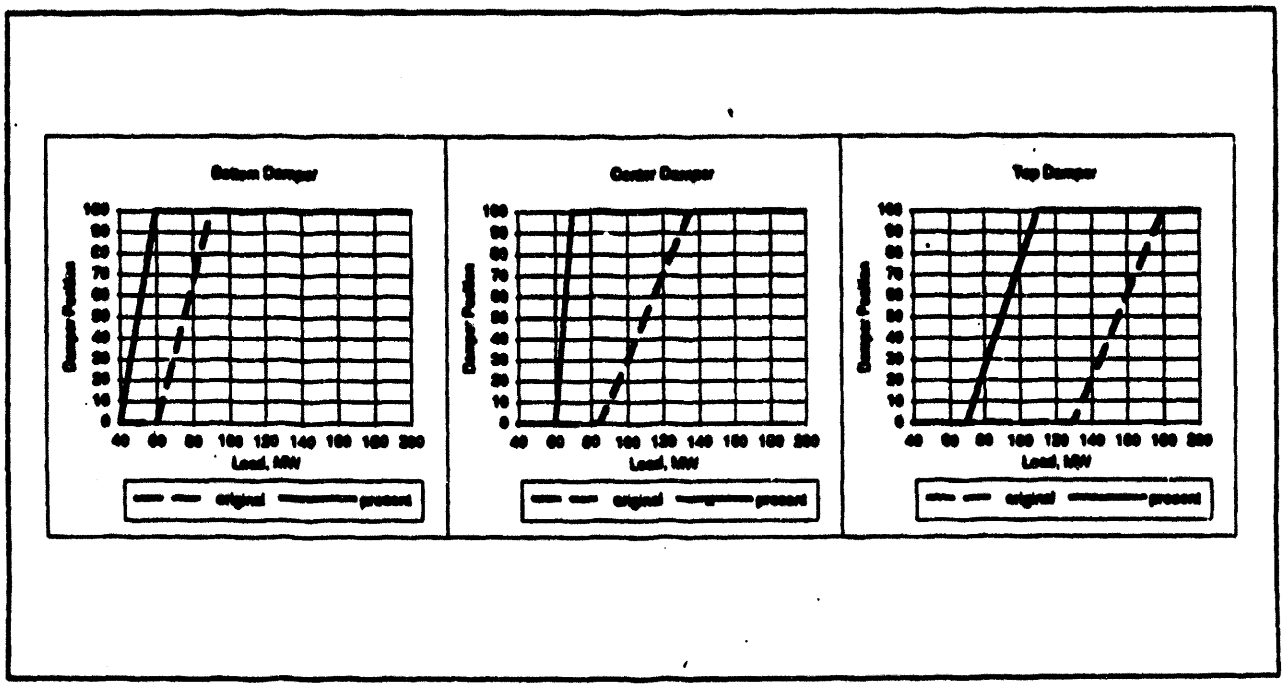


Figure 5.5 - LNCFS II Windbox Pressure Drop vs. Load

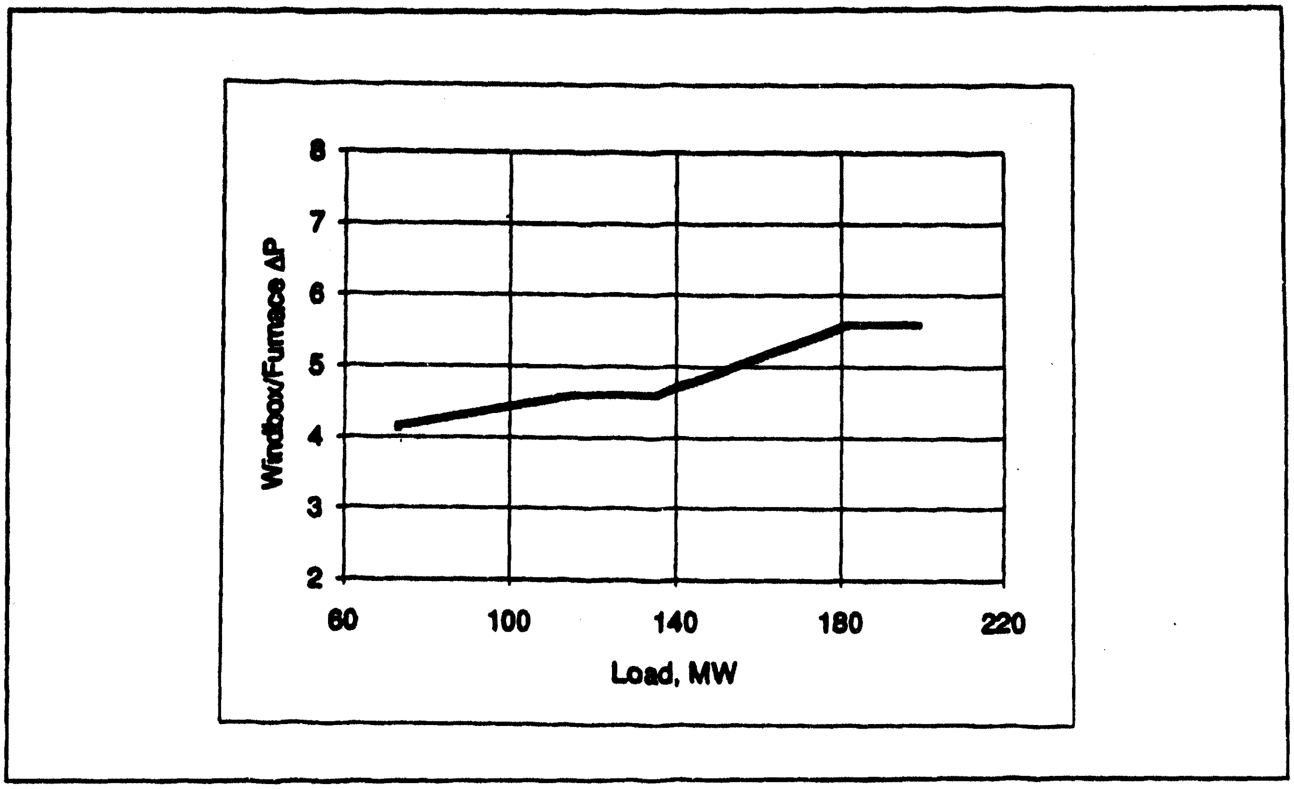


Figure 5.6 - LNCFS III: Upper, Center, and Lower SOFA vs. Load

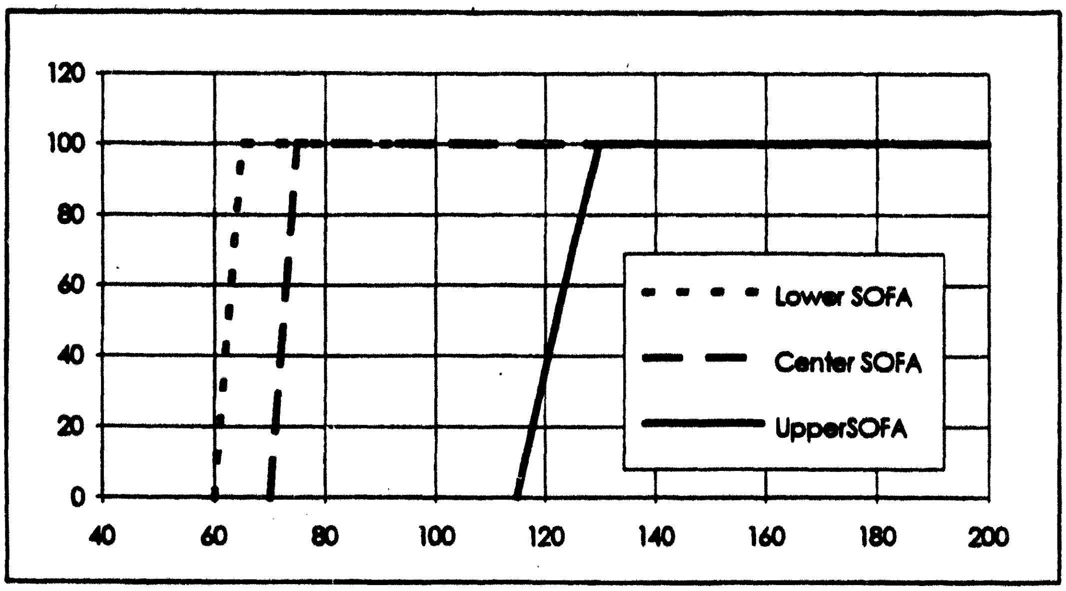


Figure 5.7 - LNCFS III: Upper and Lower CCOFA vs. Load

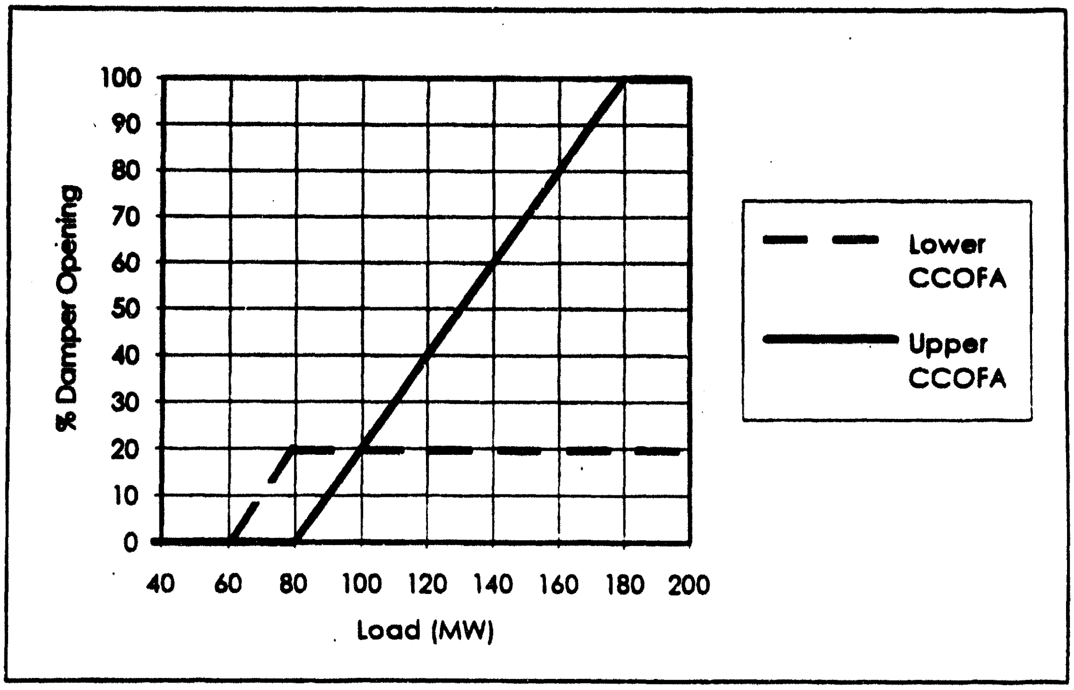
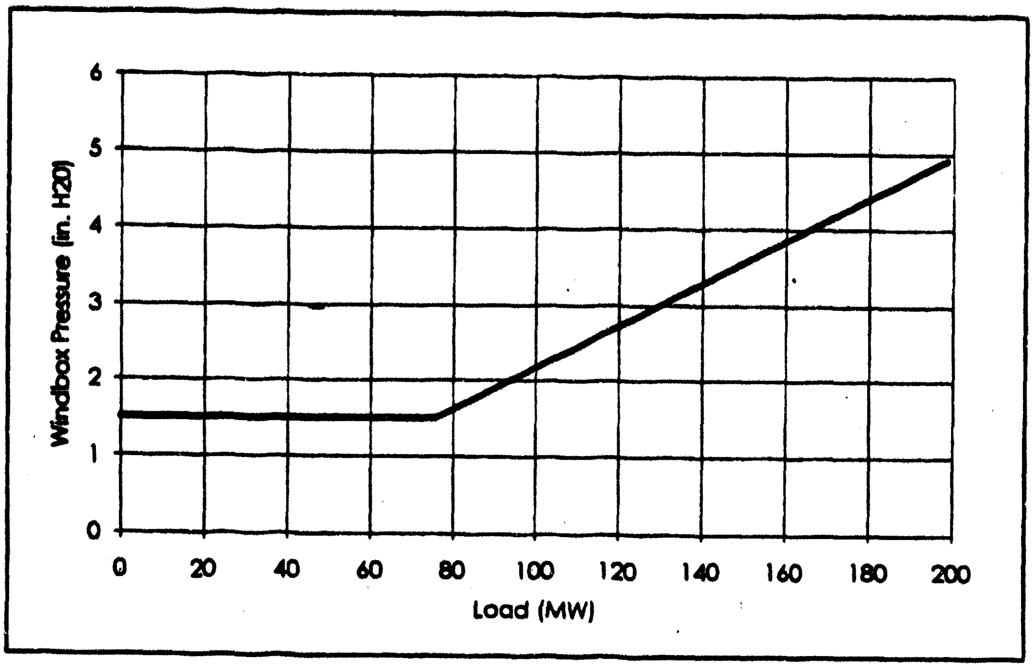


Figure 5.8 - LNCFS III: Windbox Pressure vs. Load (MW)



5.3 Operator Training

ABB/CE typically recommends the following training program in addition to the on-the-job training provided during LNCFS start-up (Ref. 18):

- A one-day classroom training program on LNCFS operation immediately followed by a one-day repeat presentation.
- A one-day classroom training program on LNCFS maintenance immediately followed by a one-day repeat presentation.
- A five-day classroom training program on LNCFS operation to be conducted six months following unit start-up.

At Smith, a one-day classroom-type course on LNCFS II was offered. This course covered NOx generation principles and LNCFS operation. Nearly all of the plant operators participated in the training program for LNCFS II. No additional training was provided for LNCFS III and I.

SECTION SIX

LOW NOx TECHNOLOGY EVALUATION

This section is divided into three parts: (i) the NOx emissions and performance impacts of each technology relative to baseline (Section 6.1); (ii) the comparison of the technologies (Section 6.2); and (iii) assessment of the unit dispatch profile on the annual NOx emissions and its ability to comply with CAAA Title IV NOx regulations.

6.1 Performance of LNCFS Technologies Relative to Baseline

6.1.1 *"Simulated" LNCFS I*

LNCFS I operation was "simulated" by closing the SOFA dampers of LNCFS III. The term "simulated" LNCFS I is used to indicate the difference between the system tested at Smith Unit 2 and a more typical LNCFS I. The main difference was the air leakage through the SOFA ports (average 4.4 percent of the total air flow at full load) , which was required to keep the SOFA nozzles from overheating during boiler boiler operation. Air leakage was reduced significantly below 140 MWs. Also, the air velocities through the various compartments of the windbox (auxiliary, secondary and CCOFA) may not be exactly what they would have been for a typical LNCFS I system. NOx emissions presented in this report were corrected for the air leakage based on SOFA air flow rate measurements. As such, the NOx emissions reported in this document provide an accurate indication of NOx emissions with LNCFS I.

<u>NOx Emissions</u>

The average long-term NOx emissions at full-load (180 MW) were 0.39 lbs/MBtu with 3.2 percent O_2 corresponding to a 37 percent NOx emission reduction relative to baseline. As Figure 6.1 shows, NOx emissions were almost constant within the control range (100-200 MW). NOx emissions below 100 MWs (approximately 50 percent load) are not provided because of lack of adequate test data. However, it is expected that NOx emissions below 100 MWs will increase with decreasing load (see dotted line of Figure 6.1). This conclusion is based on LNCFS III low load NOx emissions and the similarities between LNCFS III and I at low loads (when the SOFA dampers of the LNCFS III are closed).

The long-term NOx emissions are also shown in Table 6.1.

Figure 6.1 - Long-term LNCFS I NOx Emissions

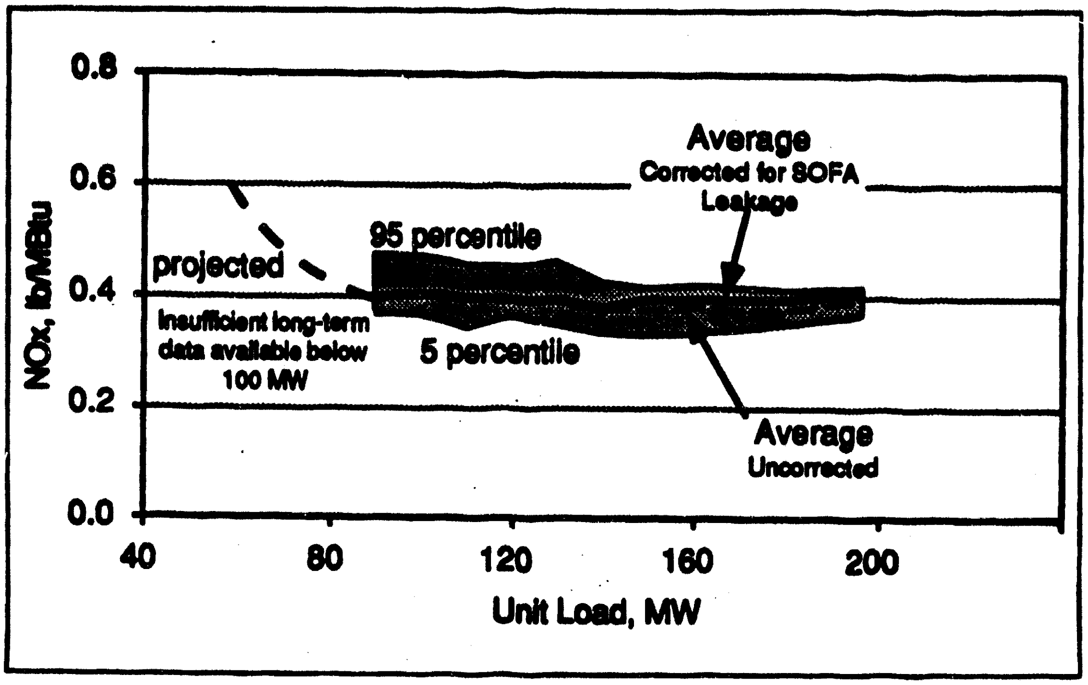


Table 6.1 - LNCFS Level I, Long-term Data

Load Segment	# of Data Points	Average Load	Average O_2 at Stack	Average O_2 at Econ Outlet	Average NOx Uncorrected	Average NOx Corrected
55 - 65	30	59.60	9.73	6.69	0.373	0.37
65 - 75	16	70.81	9.81	6.68	0.323	0.32
75 - 85	45	81.01	9.60	6.49	0.397	0.40
85 - 95	234	89.43	9.00	6.10	0.399	0.40
95 - 105	172	99.77	8.85	5.83	0.405	0.40
105 - 115	199	109.64	8.44	5.43	0.397	0.40
115 - 125	307	120.50	7.93	4.88	0.394	0.39
125 - 135	558	130.31	7.76	4.67	0.393	0.39
135 - 145	643	140.07	7.32	4.18	0.381	0.38
145 - 155	527	149.98	7.01	3.86	0.375	0.39
155 - 165	701	160.16	6.75	3.68	0.378	0.40
165 - 175	570	169.61	6.52	3.37	0.275	0.39
175 - 185	616	180.42	6.32	3.18	0.376	0.39
185 - 195	3632	193.23	6.25	3.17	0.388	0.41
195 - 200	13608	196.08	6.20	3.01	0.390	0.41

Short-term average NOx emissions at full load were 0.39 lbs/MBtu, which is similar to the average long-term NOx emissions at the same load.

Performance Impacts

The LNCFS I did not impact significantly boiler performance. The only changes observed were in:

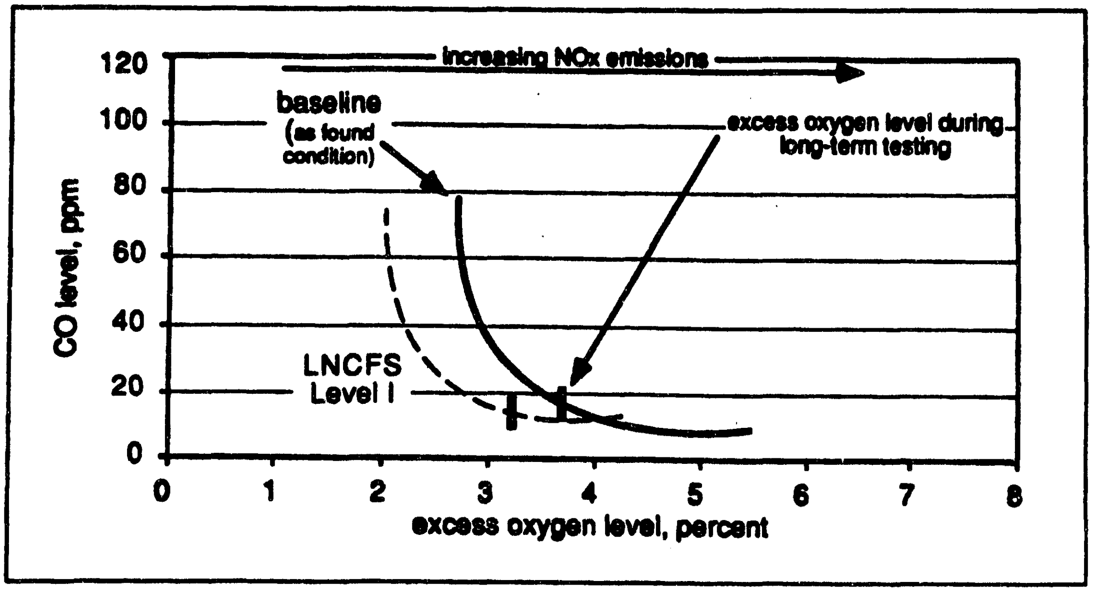
- excess O_2, and
- steam outlet temperatures, especially at low loads.

The average O_2 at full load was 3.2 percent (0.5 percentage point lower than the baseline). As Figure 6.2 shows, the boiler operated as low as 2.5 percent O_2 without any increase in CO emissions, while the baseline system had to operate above 3.2 percent O_2 to maintain CO below 100 ppm. This difference may be attributed to the fact that the baseline system was not tuned.

LOI was similar to baseline; 4.6 percent LOI with an average coal fineness of 55.4 percent through 200 mesh and 2.9 percent left on 50 mesh measured in the coal pipe (or 71.6 percent through 200 mesh and 1.1 percent left on 50 mesh as measured at the mill outlet).

At full load, a small superheat outlet temperature decrease was experienced (5-10°F) relative to baseline. However, at reduced loads, both superheat outlet and reheat outlet temperatures were significantly lower than baseline; at 90 MWs, they decreased by as much as 30°F below baseline levels. Steam outlet temperatures below 90 MWs are not reported, because of lack of adequate data in this load range. Based on short-term tests performed with LNCFS II and III at low loads, it is concluded that the steam outlet temperatures with LNCFS I can be increased above the reported levels by increasing the excess O_2 and/or burner tilt, but this will result in higher NOx emissions.

Figure 6.2 - CO Emissions vs. Oxygen for Baseline and LNCFS I (Full Load)



The ESP performance was not affected adversely by the LNCFS I. As the following table shows the dust loading and gas flow rate into the ESP with LNCFS I were lower than the baseline testing. Also, the flyash resistivity was not affected by the LNCFS I.

Comparison of ESP Inlet Conditions between Baseline and LNCFS I

	O_2	LOI	Dust Loading (gr/dscf)	Gas Flow Rate (dscfm)
Baseline	4.0	5.0	2.69	390,600
LNCFS I	3.9	4.6	2.64	346,000

The operation of LNCFS I was very similar to the baseline system; fireball rotation, furnace visibility (clarity), flame brightness and flexibility in unit operation (changing of load and control variable settings) did not change from baseline operation. Furnace slagging was similar to baseline (medium slagging).

6.1.2 LNCFS II

NOx Emissions at Full Load

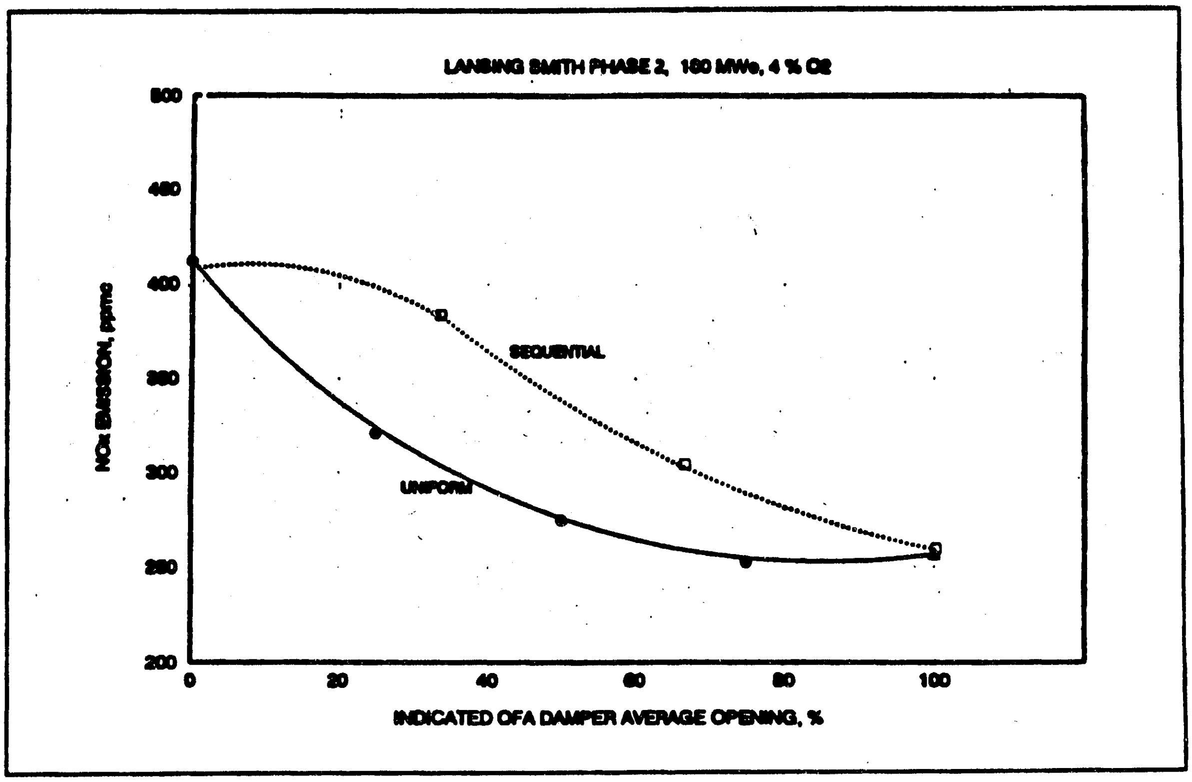
The average full-load NOx emissions were 0.39 lbs/MBtu corresponding to 37 percent NOx reduction. The average long-term excess O_2 at full load for LNCFS II was 4.5 percent, which is 0.5 percentage point higher than the baseline and 1 percentage point higher than the LNCFS I excess O_2. The long-term NOx emissions for various load segments are also presented in Table 6.2.

Table 6.2 - LNCFS II, Long-term Data

Load		Load, MW			Excess Oxygen, %			NOx, lb/MBtu		
Segment	N	Lower	Average	Upper	Lower	Average	Upper	Lower	Average	Upper
55-65	245	55.50	57.86	61.50	6.828	7.50	9.478	0.286	0.567	0.671
65-75	566	68.50	71.12	74.50	6.215	7.21	8.585	0.384	0.518	0.608
75-85	412	75.50	80.10	84.50	8.058	7.22	8.400	0.396	0.508	0.598
85-95	419	85.50	89.66	94.50	5.595	6.79	7.953	0.411	0.492	0.575
95-105	389	95.50	100.00	104.50	5.068	6.27	7.650	0.313	0.429	0.503
105-115	330	105.50	110.08	114.50	4.585	5.99	7.208	0.350	0.420	0.487
115-125	391	115.50	120.32	124.50	4.390	5.67	6.883	0.372	0.433	0.493
125-135	392	125.50	129.90	134.50	4.255	5.48	6.653	0.362	0.424	0.487
135-145	465	135.50	140.20	144.50	4.123	5.20	6.425	0.335	0.403	0.470
145-155	429	145.50	149.85	154.50	3.913	4.92	6.033	0.348	0.399	0.476
155-165	484	155.50	159.45	164.49	3.835	4.77	5.608	0.346	0.395	0.448
165-175	600	165.49	170.48	174.49	3.858	4.66	5.483	0.337	0.391	0.446
175-185	624	175.49	180.19	184.49	3.763	4.49	5.178	0.339	0.394	0.436
185-195	1150	185.49	192.17	194.49	3.565	4.15	4.708	0.339	0.383	0.430
195-200	10221	195.49	196.91	198.49	3.433	4.03	4.580	0.341	0.386	0.430

Short-term NOx emissions at full-load with the O_2 recommended by ABB/CE (3.9 percent O_2) were 0.39 lbs/MBtu; the same with long-term NOx emissions. Short-term tests were used for investigating the effect of the SOFA flow rate and the excess O_2 on NOx emissions. As Figure 6.3 ("uniform" curve) shows, the NOx emission reduction at full load was particularly sensitive to changes in the SOFA damper position. Closed SOFA dampers resulted in NOx emissions around 400 ppm, while 100 percent open reduced NOx to 250 ppm; a 37 percent reduction. This result suggests that almost all the NOx reduction of LNCFS II comes from the utilization of the SOFA system. Figure 6.3 also shows the potential impact of the SOFA compartment operation on NOx. The "uniform" curve shows the NOx emissions when all three SOFA compartments (bottom, middle, and top) open uniformly. The "sequential" curve shows the NOx when the bottom SOFA compartment opens first, then followed by the middle, and finally, the top. Figure 6.3 shows that the sequential opening of the SOFA dampers (from the bottom to the top) results in higher emissions. Figure 6.4 shows the effectiveness of the SOFA dampers on NOx decreases with decreasing load.

Figure 6.3 - LNCFS II: Effect of SOFA Damper Opening at Full Load

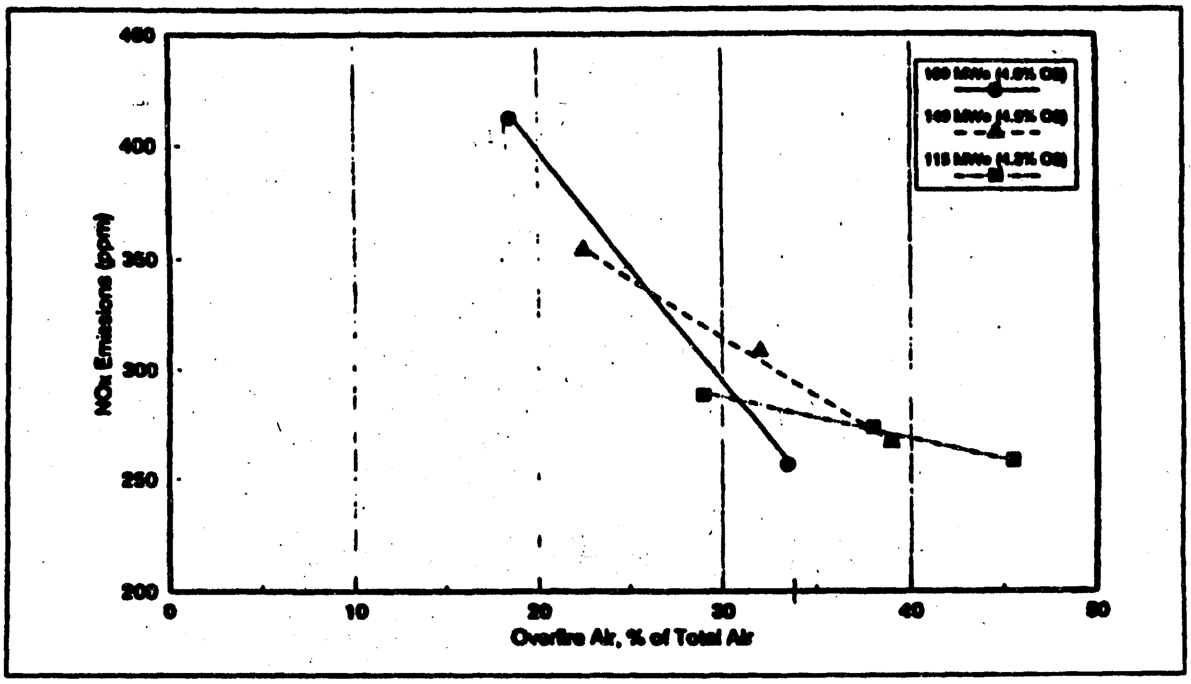


The impact of excess O_2 on NOx was also assessed through short-term testing. As the following table shows, O_2 has a decreasing impact on NOx emissions with declining load. This impact ranges from 18 to 35 ppm/%O_2, as compared to 33-50 ppm/%O_2 for the baseline system.

Impact of O_2 on NOx for Various Loads and Typical Mills Out of Service Patterns

Load (MW)	Mills Out of Service (MOOS)	NOx/%O_2 (ppm/%O_2)
180	All mills in service or A-MOOS	35
140	A-MOOS or AB-MOOS	25
115	AB-MOOS	18
70	ABC-MOOS	24

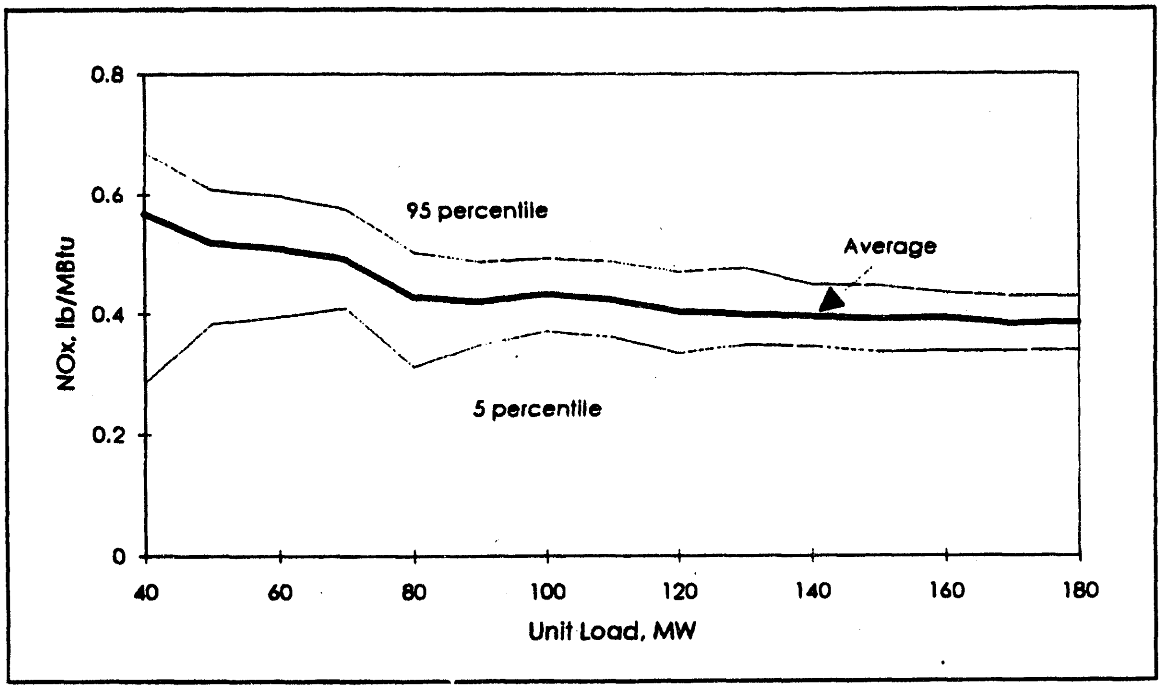
Figure 6.4 - LNCFS II: Effect of SOFA Damper Opening on NOx at Various Loads



NOx Emissions at Low Load

As shown in Figure 6.5, long-term NOx emissions within the control range (100-200 MWs) did not change significantly from full load levels; NOx reduction in this load range varied from 32 to 37 percent. However, NOx emissions increase significantly outside the control range (below 100 MWs) reaching pre-retrofit levels below 70 MWs; NOx reduction at 100 MW is 32 percent diminishing to 0 percent at 50 MWs.

Figure 6.5 - Long-term LNCFS II NOx Emissions



Short-term testing was particularly useful in analyzing the causes of increasing NOx at low loads. Short-term data analysis shows that higher O_2 than during baseline testing, positive burner tilt, lower SOFA flow rate and higher fuel air flow rate than recommended by ABB/CE contributed to the higher NOx at low loads. Examples from short-term testing indicating the impact of these variables on NOx emissions at low loads are:

- 0.5-1.0 percent O_2 increase contributes to a 18-24 ppm (6-8 percent) NOx increase at 70 MWs;
- A change of tilt from zero to +15° at 115 MWs increases NOx emissions by 50-60 ppm (18-21 percent) and the reheat outlet temperature by 25°F;
- Opening of the lower OFA damper to the 50 percent open position (while the other two OFA dampers are closed) at 75 MWs reduces NOx by 50 ppm (16 percent NOx reduction).

Comparison of the long-term and the short-term NOx emissions at low loads (see Figure 6.6) indicates that short-term NOx emissions are significantly lower than long-term NOx emissions. Further data analysis indicates the following differences between long- and short-term testing:

- 0.5-1 percent higher O_2 during long-term testing (see Figure 6.7);
- Tilt mostly in horizontal position during short-term testing as compared to an average of +8° during long-term LNCFS II;

- SOFA and CCOFA damper settings resulted in lower SOFA/CCOFA air flow rates during long- than short-term testing; during normal operation (long-term testing), the operators started opening the SOFA dampers at a higher load than recommended by ABB/CE, because of the low pressure drop across the windbox;

- Also, the fuel air flow rate during long-term testing was higher than short-term testing to improve unit response in load transients.

The difference between short- and long-term NOx emissions suggests that the long-term NOx emissions at low loads can be reduced through operating adjustments (boiler operation closer to short-term, "controlled" conditions). However, these operating adjustments may have adverse impacts on the performance of L. Smith Unit 2, such as, reduction of steam temperatures and increase of LOI and heat rate, and may be limited by operating constraints such as the minimum pressure drop across the windbox.

Considering that the unit does not operate often below 100 MWs, the increasing NOx emissions at low loads should not be viewed as a failure of the LNCFS II system to meet expected performance. However, low load NOx may be important for other tangential-fired units which operate more often at low loads (peaking and intermediate load units).

Figure 6.6 - Comparison of Long- and Short-term Emission Characteristics

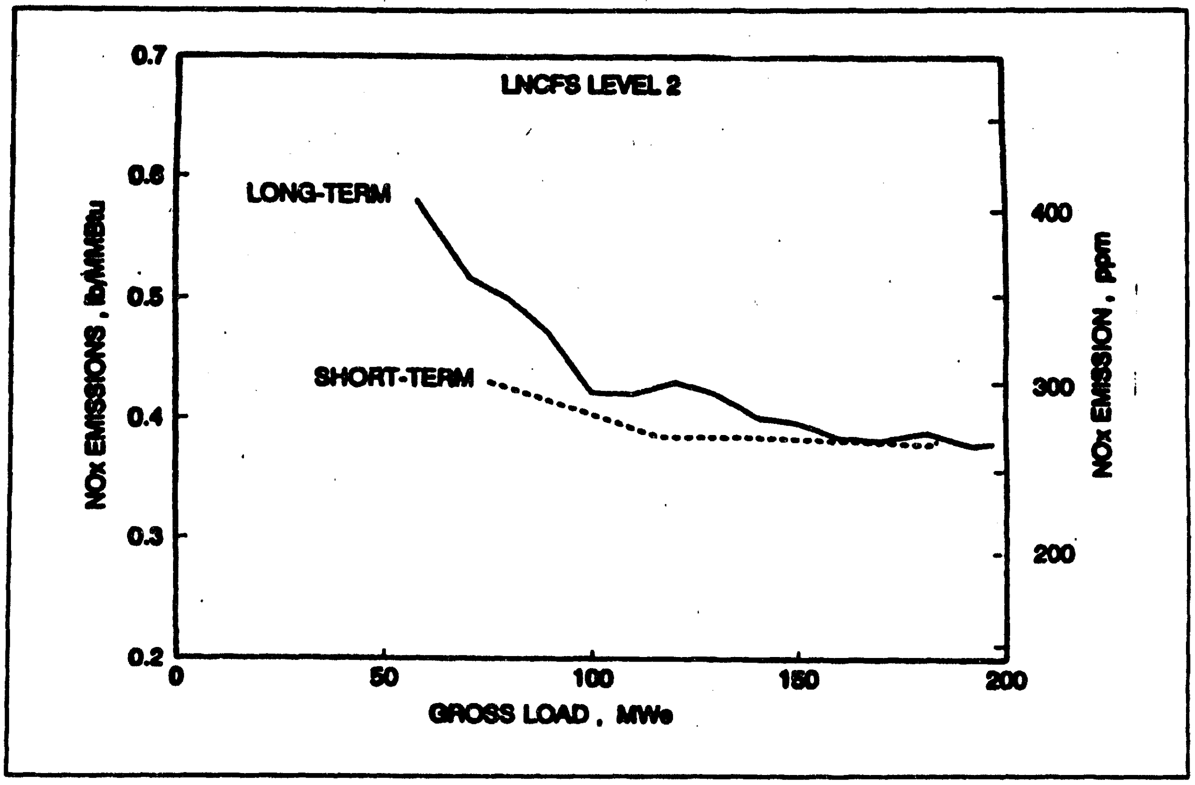
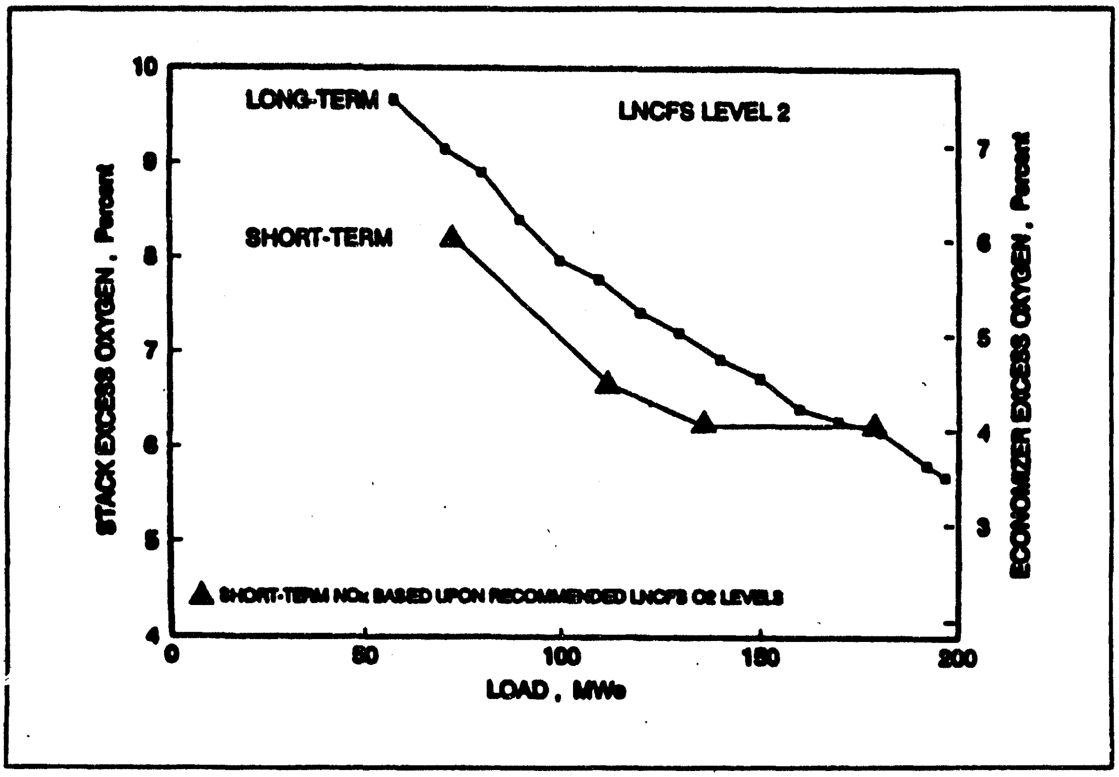


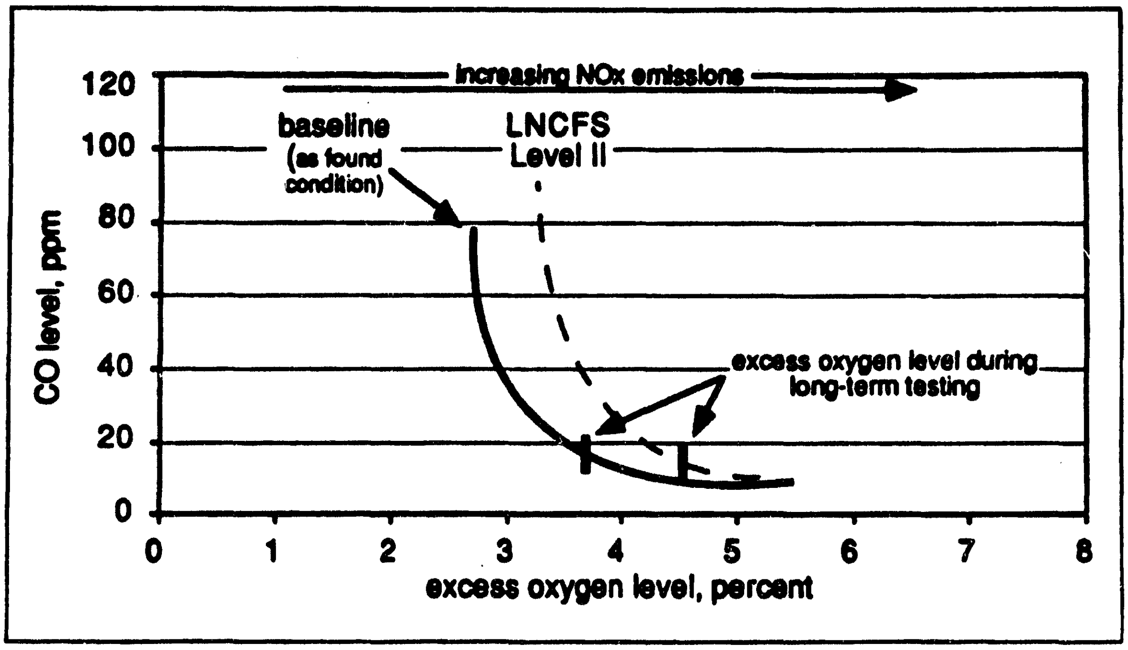
Figure 6.7 - Comparison of Long- and Short-term Oxygen Levels



Performance Impacts

As Figure 6.8 shows, CO emissions remained at baseline levels (20 ppm) when the excess O_2 was above 4.0 percent. However, below 4 percent O_2, CO was very sensitive to O_2 variations and CO exceeded 100 ppm below 3.2 percent O_2.

Figure 6.8 - LNCFS II: CO Emissions vs. Excess Oxygen (Full Load)



The average O_2 at full load was 4.5 percent which is 0.8 percentage points higher than the baseline. Considering the increasing CO emissions at lower O_2 levels and fan limitations at higher O_2, the O_2 operating range with LNCFS II was limited to 4.0-5.0 percent.

The LOI varied from 3.8 to 5.4 percent in the 115 to 200 MW load range; approximately the same with baseline LOI. However, the average coal fineness during LNCFS II testing was better (higher) than the baseline case. Coal fineness in the pipe (measured isokinetically) was 62.9 percent through 200 mesh with 2 percent remaining on 50 mesh compared to 58.9 percent through 200 mesh and 2.65 percent remaining on 50 the mesh during baseline testing.

Furnace slagging was reduced from medium during baseline to low during LNCFS II testing. However, the convection pass fouling increased. These changes reduced the wallblower operating frequency and increased the backpass sootblower operation. The net result was no significant change in overall surface cleaning requirements, but improved boiler operation because slagging is more difficult to remove and often causes boiler tube failures. The steam outlet temperatures during LNCFS II testing were similar to baseline throughout the load range.

As the following table indicates, the ESP inlet conditions did not change significantly from baseline. Also, the flyash resistivity was not affected by the LNCFS II retrofit.

Comparison of ESP Inlet Conditions Between Baseline and LNCFS II

	% O_2	LOI (%)	Dust Loading (gr/dscf)	Gas Flow Rate (dscfm)
Baseline	4.0	5.0	2.69	390,600
LNCFS II	5.3	4.2	2.61	395,200

Boiler operation was similar to the baseline system, but the fireball rotation rate was slower and the furnace brightness was reduced. The latter is typical of low NOx combustion systems with overfire air and is not a cause for concern. The reduced furnace slagging improved the overall boiler operation.

A small reduction in operating flexibility of the system was observed. The main reasons were:

- The windbox pressure drop required more careful monitoring of the unit operation at low loads. When the OFA dampers were operated per ABB/CE's recommended operating procedures, the pressure drop across the windbox was reduced to 1.0-1.5 in wg which is considered low by the plant operators.

- In order to increase windbox pressure drop and improve the unit readiness to respond to load changes, the operators had to:

  - Close the SOFA dampers more than recommended by ABB/CE; and

  - Increase the fuel air flow rate at low loads.

6.1.3 LNCFS III

NOx Emissions

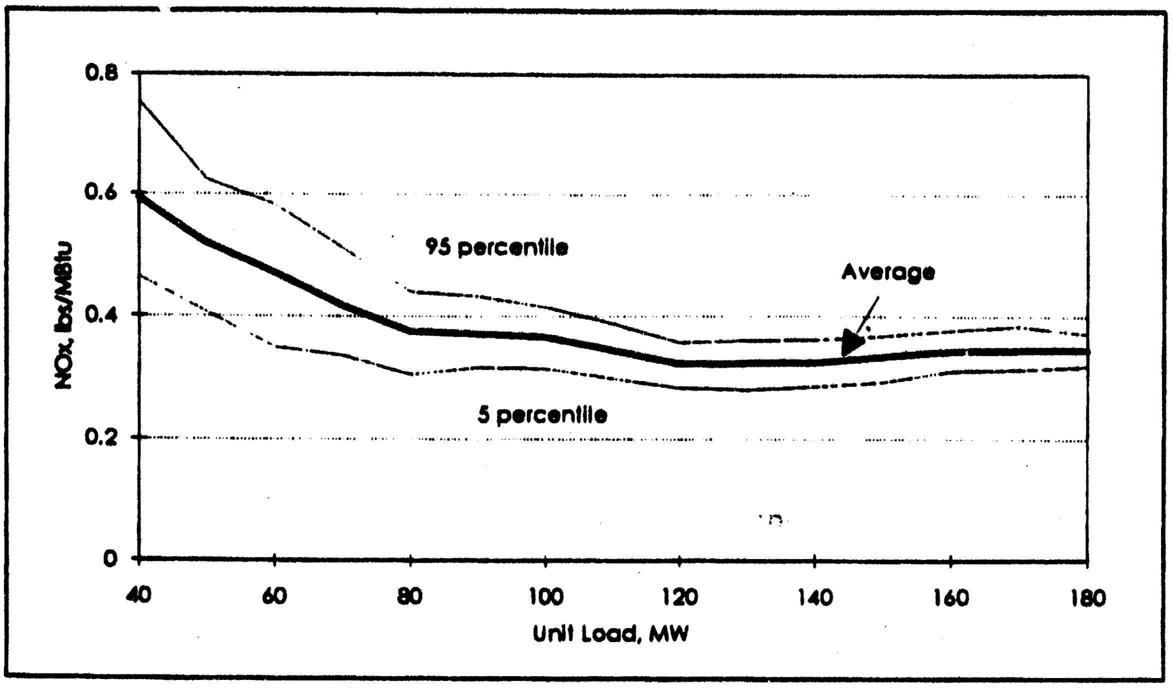
The LNCFS III achieved a 45 percent long-term NOx emission reduction at full load, which is within the expected range (40-50 percent). This NOx reduction corresponds to 0.34 lbs/MBtu and was achieved with an average 4.3 percent O_2. The long-term NOx emissions are also shown in Table 6.3.

Table 6.3 - LNCFS III, Long-term Data

		Load, MW			Excess Oxygen %			NOx lb/MBtu		
Load Segment	N	Lower	Average	Upper	Lower	Average	Upper	Lower	Average	Upper
55-65	1225	55.50	58.59	62.50	5.615	7.13	8.263	0.464	0.593	0.755
65-75	1726	67.50	71.22	74.50	5.580	6.78	7.895	0.407	0.519	0.623
75-85	799	75.50	79.45	84.50	5.363	6.63	7.818	0.350	0.471	0.583
85-95	662	85.50	89.90	94.50	5.025	6.27	8.180	0.337	0.418	0.512
95-105	662	95.50	100.27	104.50	4.705	5.90	7.433	0.306	0.376	0.441
105-115	649	105.50	110.33	114.50	4.673	5.67	6.780	0.317	0.372	0.433
115-125	615	115.50	120.13	124.50	4.533	5.45	6.350	0.315	0.366	0.414
125-135	782	125.50	129.96	134.50	4.360	5.22	6.113	0.299	0.345	0.389
135-145	801	135.50	139.88	144.50	4.035	5.00	5.950	0.283	0.322	0.357
145-155	730	145.50	150.10	154.50	3.770	4.78	5.858	0.280	0.323	0.361
155-165	754	155.50	160.02	164.49	3.580	4.57	5.553	0.285	0.323	0.362
165-175	766	165.49	170.41	174.49	3.515	4.48	5.278	0.293	0.333	0.368
175-185	935	175.49	178.94	184.49	3.308	4.28	5.070	0.311	0.343	0.378
185-195	841	185.49	191.19	194.49	2.945	3.90	4.848	0.313	0.345	0.385
195-200	5114	195.49	197.24	198.49	2.970	3.80	4.358	0.319	0.345	0.372

As Figures 6.9 indicates, long-term NOx emissions at low loads exhibited the same behavior with LNCFS II; they were almost constant within the control range, but they increased significantly outside the control range (below 100 MWs). NOx in the 100-120 MW range increased to 0.38 lbs/MBtu and below 70 MWs increased to pre-retrofit levels (0.6 lbs/MBtu)

Figure 6.9 - Long-term LNCFS III NOx Emissions



The same observations made on LNCFS II NOx emissions at low loads apply to LNCFS III. The main reasons for the increased NOx at low loads are:

- Utilization of positive tilt (average tilt during long-term testing: +6°; as compared to tilt in horizontal position during baseline testing);
- Closing of the SOFA dampers more than recommended by ABB/CE to maintain windbox pressure drop; and
- Increased fuel air flow rate for quick unit load response..

Similarly to LNCFS II, the short-term NOx emissions at low load did not increase as much as the long-term NOx emissions; short-term NOx at 70 MW increased to 0.4 lbs/MBtu from 0.34 lbs/MBtu at full load, while the long-term NOx emissions at the same load were close to pre-retrofit levels (0.60 lbs/MBtu). The lowest NOx emission level during short-term testing, 0.29 lbs/MBtu, was achieved at 135 MW with 4.5 percent O_2.

Short-term testing indicates that NOx emissions at low loads could be reduced below the levels measured at Smith Unit 2 through operating adjustments in O_2, tilt, SOFA dampers and fuel air dampers. However, such improvement in NOx emissions may have adverse impacts on steam outlet temperatures and unit heat rate.

Performance Impacts

During LNCFS III long-term testing, CO ranged from 20 to 100 ppm (higher than baseline: 10 ppm). As Figure 6.10 shows, a higher excess O_2 level was needed for LNCFS III to maintain CO emission within acceptable limits. A minimum O_2 of 4.2 percent is needed to keep CO below 100 ppm.

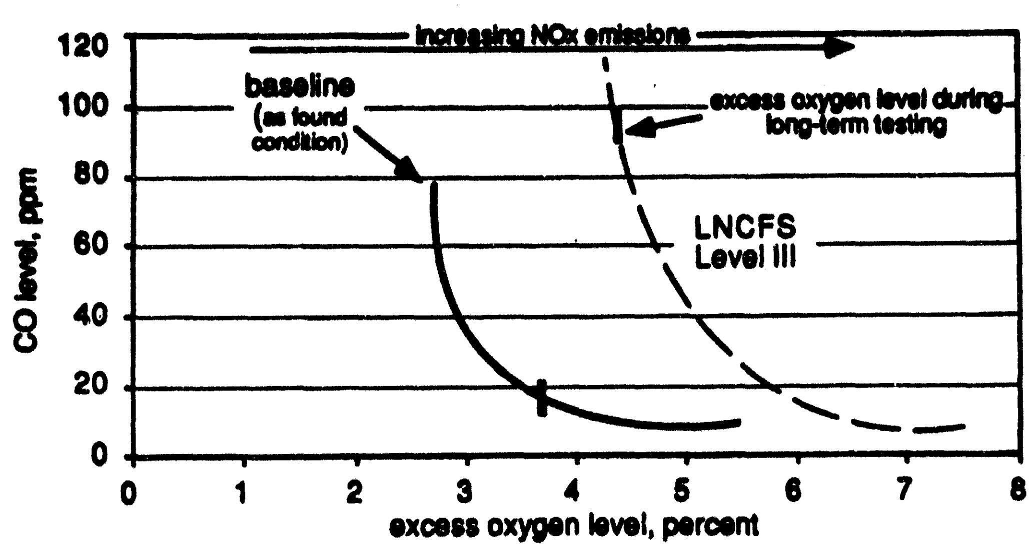
The average long-term O_2 at full load was 4.3 percent, which is 0.6 percentage points higher than the baseline system. Similarly to full load, the O_2 within the control range (100-200 MW) was 0.3-0.8 percent higher than baseline.

The LOI at full load was 5.9 percent; approximately 1 percent higher than LNCFS II and baseline. One contributing factor for the LOI increase is the lower coal fineness. As Table 6.4 shows, the average coal fineness, 55.8 percent through 200 mesh is 3 percent below baseline and 7 percent below LNCFS II, while the percentage left on 50 mesh (2.1 percent) is significantly above the maximum 1-1.5 percent recommended by ABB/CE.

Table 6.4 - Coal Fineness during LNCFS III Testing

Nominal classifier setting	Size designation in figures	Weight through 200 mesh, %		Weight through 50 mesh, %	
		Vendor recommended method	Isokinetic method	Vendor recommended method	Isokinetic method
1	low finess	66.0	51.3	97.0	95.4
3	med. fineness	72.3	55.8	99.0	97.9
6	high fineness	83.3	63.6	99.8	98.8

Table 6.10 - LNCFS III: CO Emissions vs. Excess Oxygen (Full Load)



To investigate further the impact of coal fineness on LOI and NOx, additional tests were carried out. The coal fineness was varied by changing the classifier settings on each mill. The results shown in Figure 6.11, indicate that there is a strong relationship between coal fineness and LOI (especially below 63 percent through 200 mesh). For example, LOI is approximately 10 percent with coal fineness at 52 percent through 200 mesh, but it is reduced to 4 percent when the coal fineness improves to 62 percent through 200 mesh. During this coal fineness change, NOx emissions are not affected, as shown in Figure 6.11.

Similar impacts were observed due to changes in the percentage remaining on 50 mesh screen. As Figure 6.12 shows, for 4 percent remaining on 50 mesh, the LOI was approximately 9 percent, while reduction to 1.2 percent remaining on 50 mesh also reduced the LOI to approximately 4 percent.

The above results suggest also that if the coal fineness during LNCFS III testing was the same with baseline, the LOI would have been 4 to 5 percent. Therefore, for the same coal fineness, the LNCFS III did not impact the LOI.

Similarly to LNCFS II, furnace slagging was reduced and backpass fouling was increased relative to baseline conditions. This resulted in reduced wallblower and increased the backpass sootblower operating frequency. Although the overall surface cleaning activities were not reduced substantially, the furnace slagging reduction was perceived by the operators as an improvement.

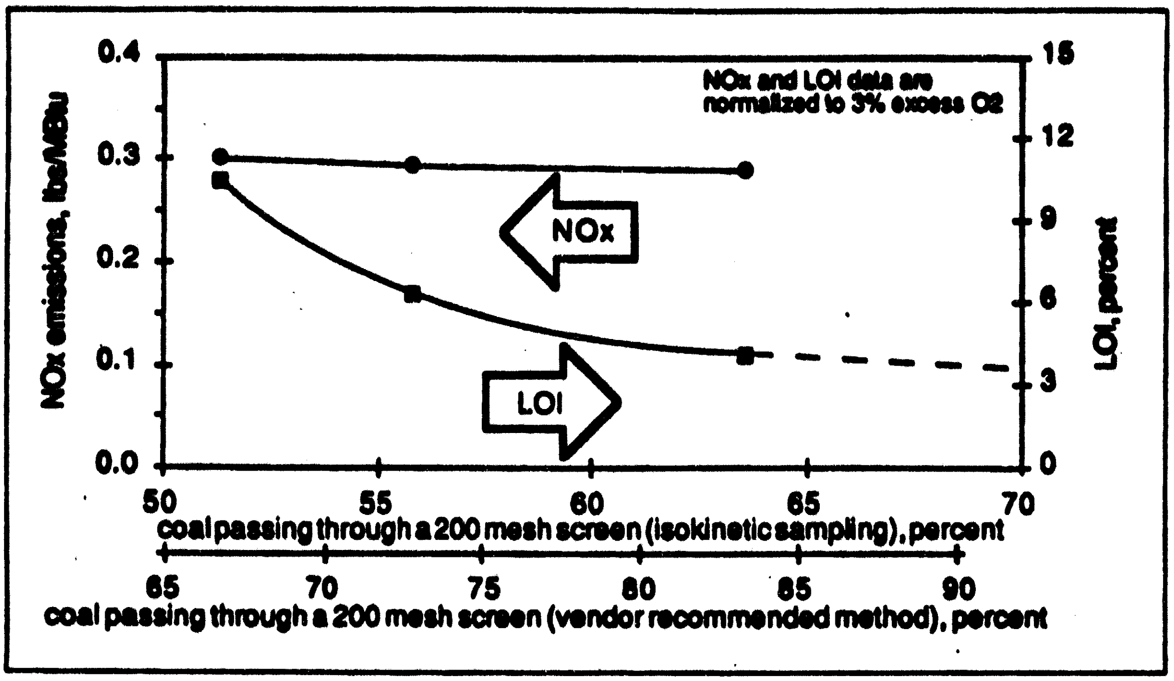
Steam outlet temperatures at full load were maintained at the baseline level. However, at reduced loads both the superheat and reheat outlet temperatures were lower than baseline. More specifically, the superheat outlet temperature was maintained at pre-retrofit levels in the 140 - 200 MWs load range. Below 140 MWs, the superheat outlet temperature declined; at 80 MWs it was approximately 20°F below pre-retrofit superheat outlet temperature. Even more significant was the decline of the reheat outlet temperature; at 115 MWs it was 25°F and at 80 MW 35°F less than the baseline superheat outlet temperature at the same load.

The ESP performance was not impacted significantly by the LNCFS III. As is shown in the following table, the dust loading increased slightly relative to the baseline (from 2.69 to 2.80 gr/dscf), but did not impact the unit opacity. The flyash resistivity was also not affected by the LNCFS III.

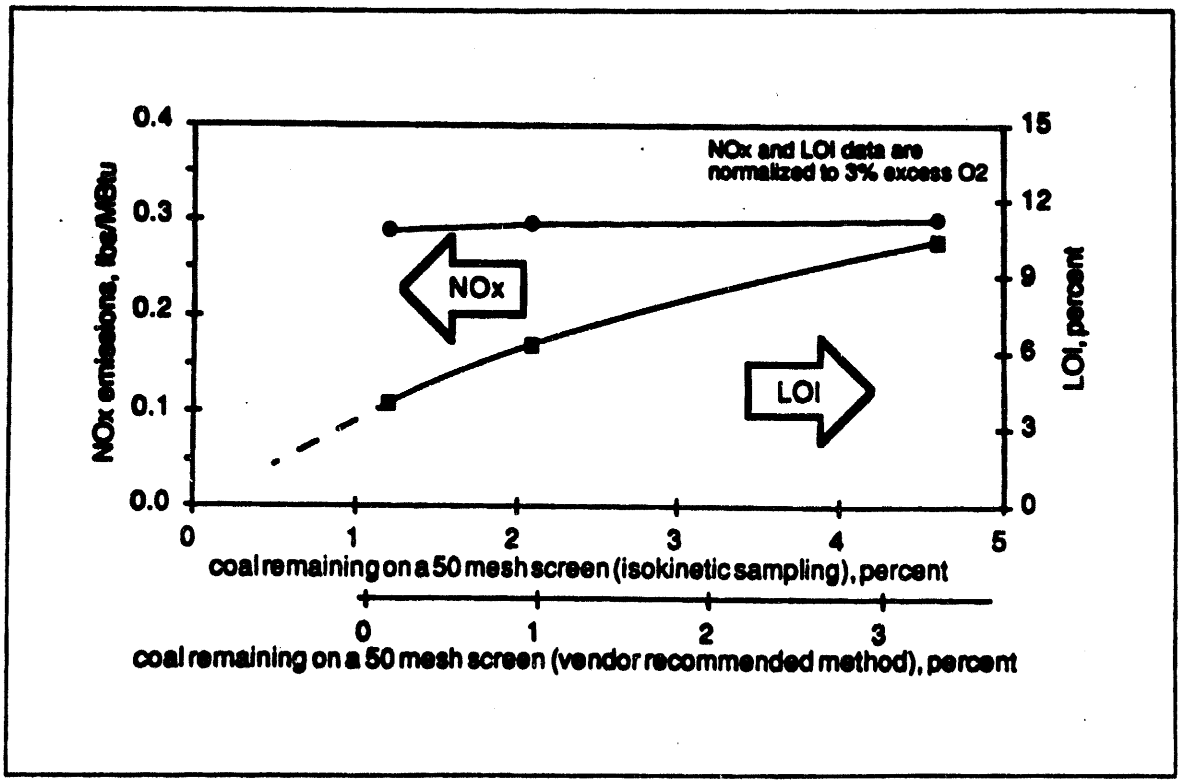
Comparison of ESP Inlet Conditions Between Baseline and LNCFS III

	% O_2	LOI (%)	Dust Loading (gr/dscf)	Gas Flow Rate (dscfm)
Baseline	4.0	5.0	2.69	390,600
LNCFS III	4.7	5.9	2.80	385,500

Figure 6.11 - LNCFS III: NOx and LOI vs. Percentage through 200 Mesh



6.12 - LNCFS III: NOx and LOI vs. Percentage Left on 50 Mesh



LNCFS III system operation was more sensitive to changes in operating parameters (e.g., excess O_2) than the original burners. Load transitions which required bringing mills in and out of service resulted in spikes of CO and NOx emissions. Also, the O_2 range restriction at full load (minimum O_2 4.0 percent instead of 3.2 percent for the baseline system and 2.3 percent for LNCFS I) limited the flexibility of the operators to increase the O_2 before load transitions to avoid CO and NOx increases.

6.1.4 LNBFS

A limited number of short-term tests with the LNBFS system indicated 30-32 percent NOx reduction, which is significantly higher than expected by ABB/CE (15-25 percent). Because of the perceived limited market potential of this system (due to the marginal cost difference between LNBFS and LNCFS II and the potential for increased waterwall corrosion), it was decided that detailed characterization of the LNBFS was not cost effective. Instead, the test program focused on more detailed characterization of the other three LNCFS technologies.

6.2 Comparison of the LNCFS Technologies Tested at Smith Unit 2

The previous section (6.1) provided the NOx emission reductions achieved and the performance impacts for each of the LNCFS technologies tested at Smith Unit 2 relative to baseline. This section (6.2) compares the LNCFS technologies tested relative to each other in terms of:

- NOx reduction;
- Unit performance impacts; and
- Boiler efficiency and unit heat rate.

6.2.1 Comparison of NOx Reduction and Performance Impacts

NOx Emission Reduction at Full Load

The NOx emissions and NOx emission reduction relative to baseline for the LNCFS technologies tested at Smith Unit 2 are shown in Table 6.5. The LNCFS I, II, and III, achieved 37, 37, and 45 percent average long-term NOx emission reduction at full load, respectively; NOx emissions were reduced from 0.63 lbs/MBtu during baseline testing to 0.39, 0.39 and 0.34 lbs/MBtu, respectively. This NOx reduction was achieved with the following adverse performance impacts:

- 0.6-0.8 percent higher O_2 for LNCFS II and III relative to baseline ; and
- Up to 30-40^{o} F steam outlet temperature reduction at low loads with LNCFS I and III.

All LNCFS options tested achieved NOx below the CAAA presumptive limit of 0.45 lbs/MBtu.

Table 6.5 - Long-Term NOx Emissions at Full Load (180 MW)

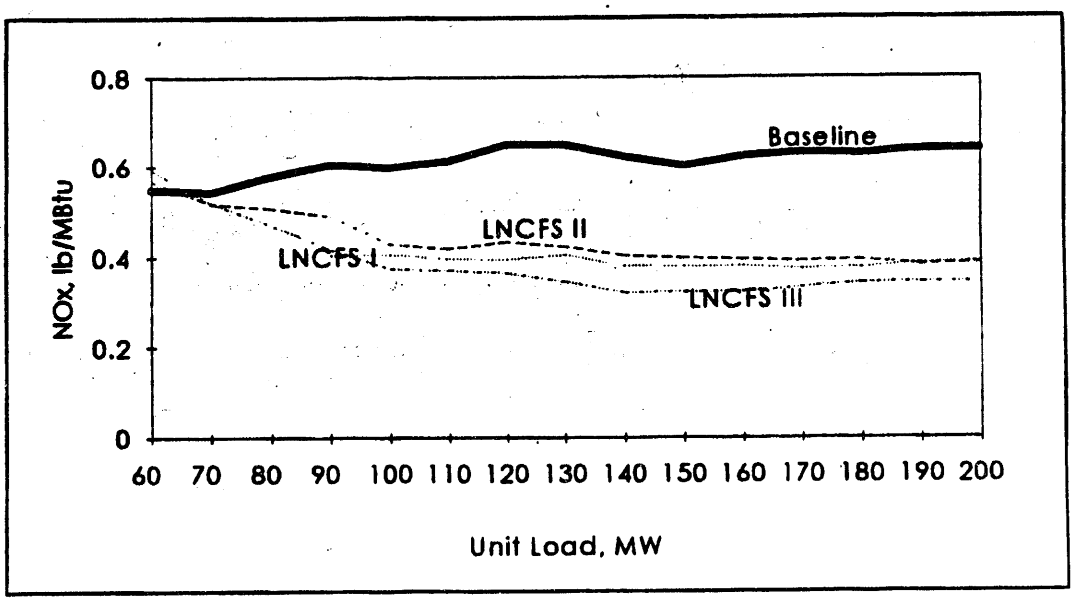
	Baseline	LNCFS I	LNCFS II	LNCFS III
NOx (lbs/MBtu)	0.63	0.39	0.39	0.34
% NOx Reduction	-	37	37	45

NOx Emission Reduction at Low Loads

The low load NOx emission reduction of all three LNCFS technologies exhibits similar behavior. The NOx emissions within the control range (100-200 MWs) did not change significantly from the full load NOx level. However, NOx emissions below the control point (100 MWs) increased significantly, reaching pre-retrofit levels at 50-70 MW (see Figure 6.14). LNCFS II NOx increased from 0.39 lbs/MBtu at full load to 0.40 at 140 MWs, 0.52 at 80 MWs and 0.58 lbs/MBtu at 70 MWs. Similarly, LNCFS III NOx emissions increased from 0.34 lbs/MBtu at full load to 0.48 at 80 MWs and 0.60 lbs/MBtu at 70 MWs.

The unit did not operate long enough at low loads with LNCFS I to draw any conclusions about its impact on NOx emissions. However, it is expected that NOx emissions with the LNCFS I at low loads would be similar to LNCFS III, because of the similarities of the two systems when the SOFA dampers of the LNCFS III are closed.

Figure 6.13 - Comparison of Baseline, LNCFS Levels, I, II, and III Average NOx Emissions



Impacts on Unit Performance

Several potential performance impacts were assessed at Smith Unit 2 including CO emissions, required excess O_2, LOI, furnace slagging, backpass fouling, steam outlet temperatures, ESP performance, and unit operation. Table 6.2 shows the main impacts of the LNCFS systems on boiler performance during long-term testing.

As shown in Table 6.6:

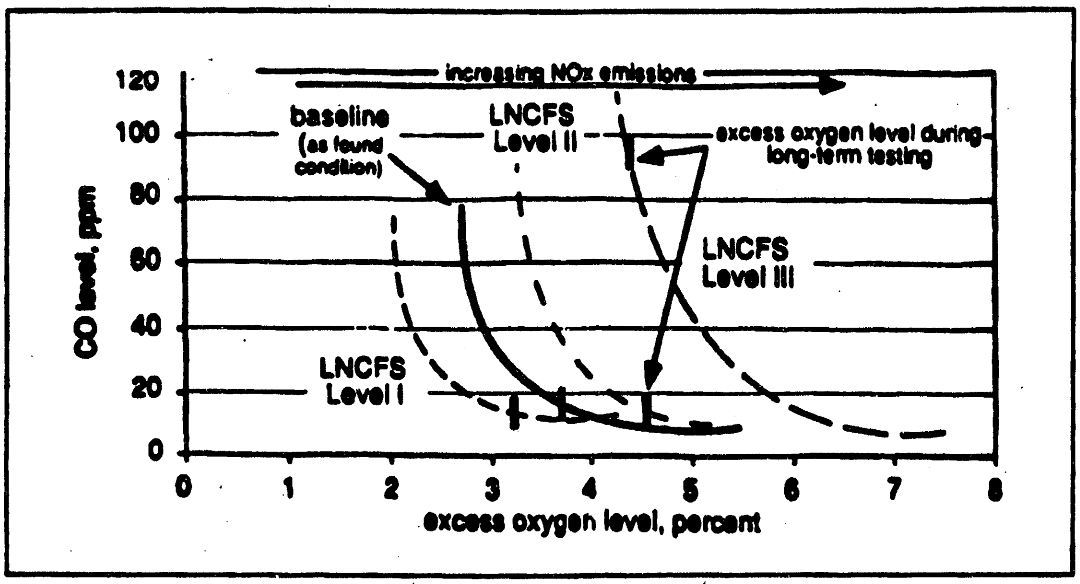
- CO emissions with the baseline and the LNCFS technologies were maintained below 100 ppm. However, this was accomplished with different level of excess O_2; LNCFS II and III required higher O_2 to keep CO below 100 ppm;
- Both the minimum O_2 required to maintain low CO and the average long-term O_2 were affected by the LNCFS technologies.

As shown in Table 6.6 and Figure 6.14, the minimum excess O_2 required to keep CO emissions below 100 ppm was different for each technology. Table 6.2 provides the minimum O_2 (5 percentile) based on long-term full load operation. Figure 6.14 is based on short-term data and shows the impact of excess O_2 on CO emissions for all the systems tested.

Table 6.6 - Unit Performance Impacts

	Baseline	LNCFS I	LNCFS II	LNCFS III
Avg. CO at Full Load (ppm)	10	12	22	33
Min. O_2 at Full Load (%)	2.8	2.7	3.8	3.3
Avg. O_2 at Full Load (%)	3.7	3.2	4.5	4.3
% Full Load LOI (%O_2)	4.8 (4.0)	4.6 (3.9)	4.2 (5.3)	5.9 (4.7)
Steam Outlet Conditions	OK at full load; low temps at low loads	Full load: 5-10°F lower than baseline; Low loads: 10-30°F lower than baseline	Same as Baseline	160-200 MWs: OK; 80 MW: 15-35°F lower than baseline
Furnace Slagging & Backpass Fouling	Medium	Medium	Reduced Slagging, but Increased Fouling	Reduced Slagging, but increased Fouling
Operating Flexibility	Normal	As easy as Baseline	More care required at low loads (watch: windbox pressure drop and flame stability)	More difficult to operate than the other systems (sensitive to operating changes)

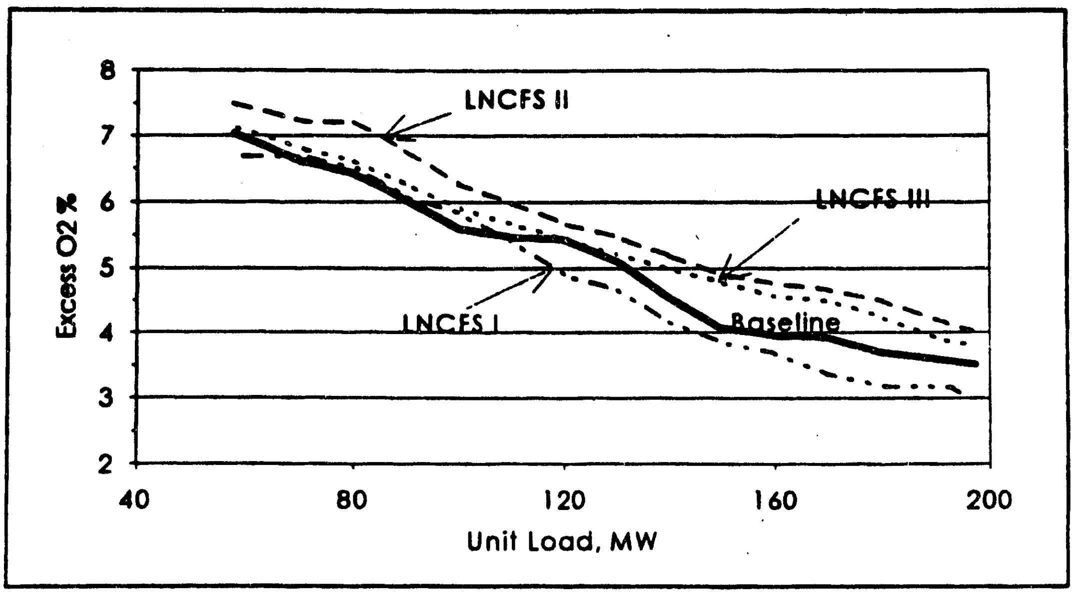
Figure 6.14 - CO Emissions as a Function of Excess Oxygen (Full Load)



As shown in Figure 6.15, similar changes in average long-term O_2 were observed throughout the operating load range:

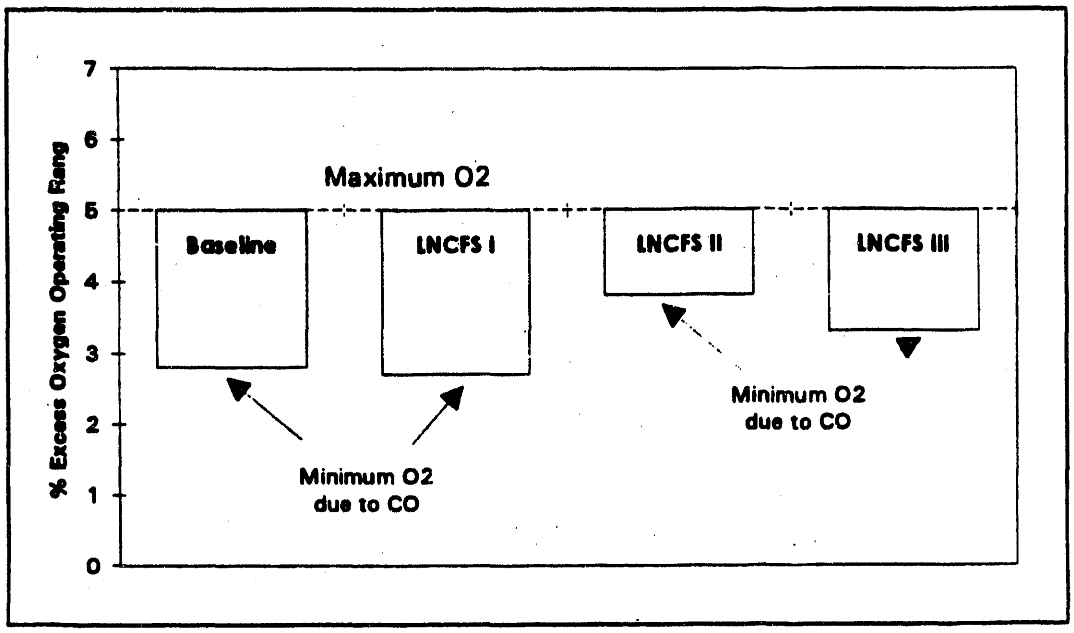
- LNCFS II and III averaged up to one percentage point higher than baseline O_2;
- LNCFS I required approximately 0.5 percentage point lower O_2 than baseline.

Figure 6.15 - Comparison of Average Long-term Excess Oxygen Levels



The change in minimum required O_2 to maintain low CO emissions also impacted the available O_2 operating range which provides plant operators the flexibility to temporarily increase O_2 during load transients to avoid CO and NOx spikes. As is shown in Figure 6.16, the available O_2 operating range increase for LNCFS I, relative to baseline, but decreased significantly for LNCFS II and III.

Figure 6.16 - Full Load Oxygen Operating Ranges



Also, the distribution of the air into hot and cold primary air, secondary and separated overfire air change for each of the LNCFS technologies tested. Figure 6.17 and Table 6.7 shows the air flow distribution for the baseline and the LNCFS technologies at full load. The LNCFS I shows 5 percent separated overfire air because of the air leakage even though the SOFA dampers were closed.

Figure 6.17 - Air Flow Distribution to the Boiler at 180 MW

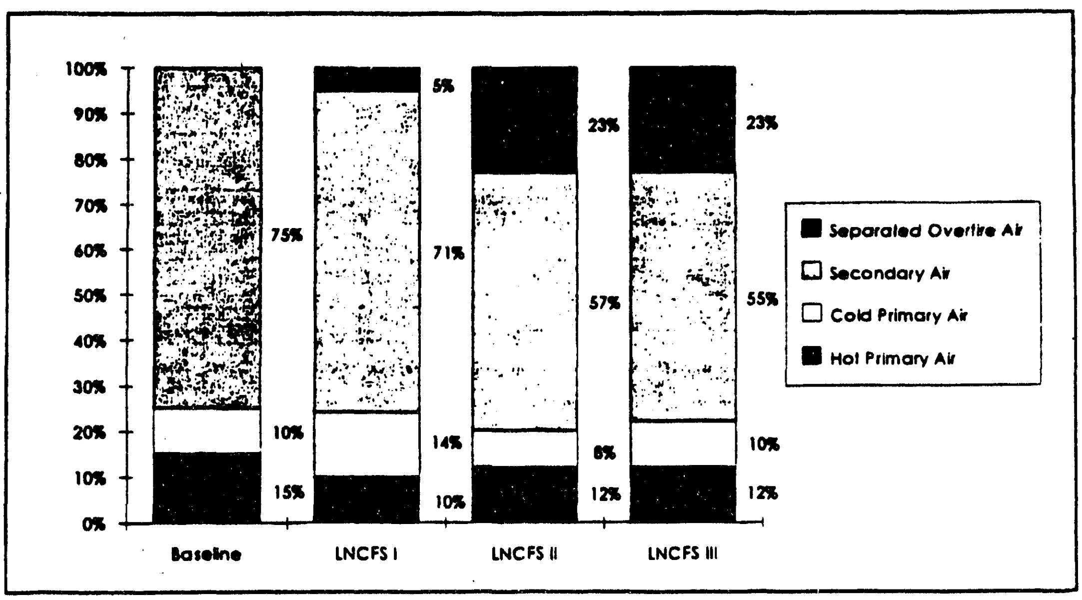


Table 6.7 - Smith Unit 2: Air Flow Distribution at Full Load (180 MW)

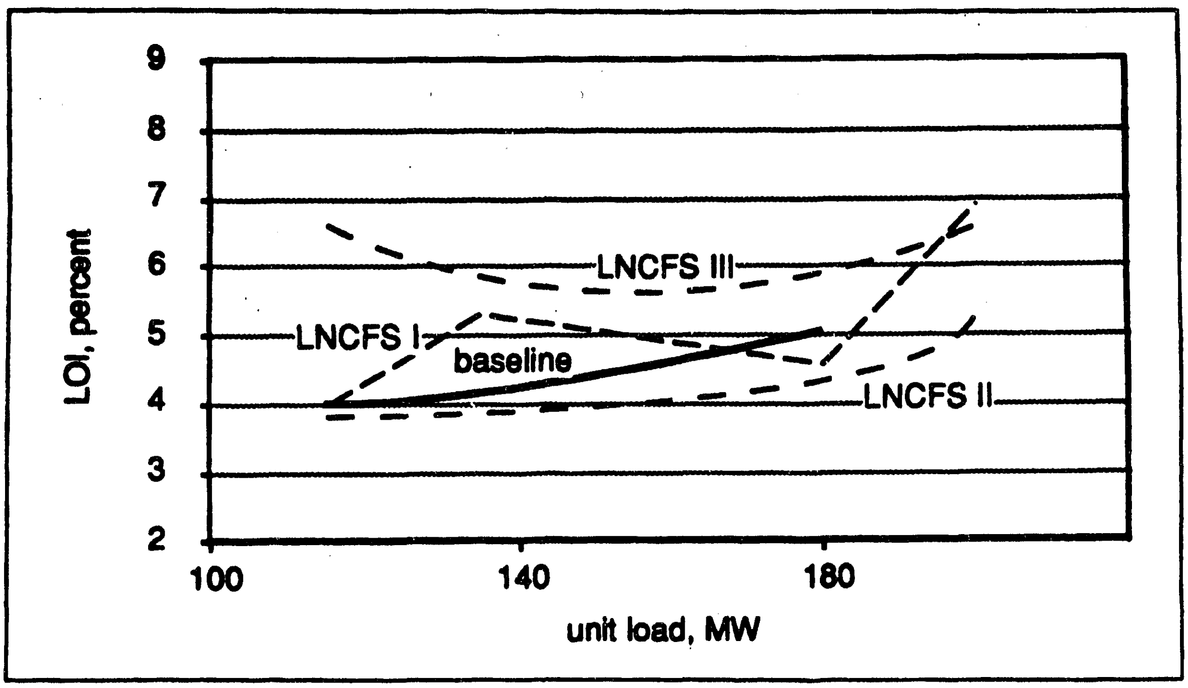
	Baseline	LNCFS I	LNCFS II	LNCFS III
Hot Primary	26,000	158,000	202,000	188,000
Cold Primary	153,000	200,000	139,000	145,000
Secondary Air	1,117,000	1,037,000	926,000	832,000
SOFA	0	71,000	370,000	342,000
TOTAL	1,296,000	1,466,000	1,637,000	1,507,000

LOI for the same coal fineness was similar for the baseline and the LNCFS technologies. The small LOI changes measured are due to changes in coal fineness and are within the LOI measurement accuracy. Figure 6.18 shows these changes in LOI throughout the load range.

Significant furnace slagging reduction was experienced with LNCFS II and III. The baseline system and LNCFS I experienced medium slagging, while LNCFS II and III experienced very low furnace slagging. However, slagging reductions were accompanied by backpass fouling increases. As a result, less frequent furnace waterwall sootblowing was required, but more frequent backpass cleaning. The net result was no significant change in sootblowing requirements, but easier boiler operation and potential boiler tube failure reduction with LNCFS II and III due to decreased furnace slagging.

As it is indicated in Figures 6.19 and 6.20, as well as in Table 6.6, the superheat and reheat outlet temperatures were not affected by the LNCFS II operation. However, the burner tilts were set higher during LNCFS II testing compared to all other systems (LNCFS I, LNCFS III, and baseline) as shown in Figure 6.21.

Figure 6.18 - Comparison of Baseline, LNCFS I, II, and III LOI Results



6.19 - Superheat Temperature Characteristics

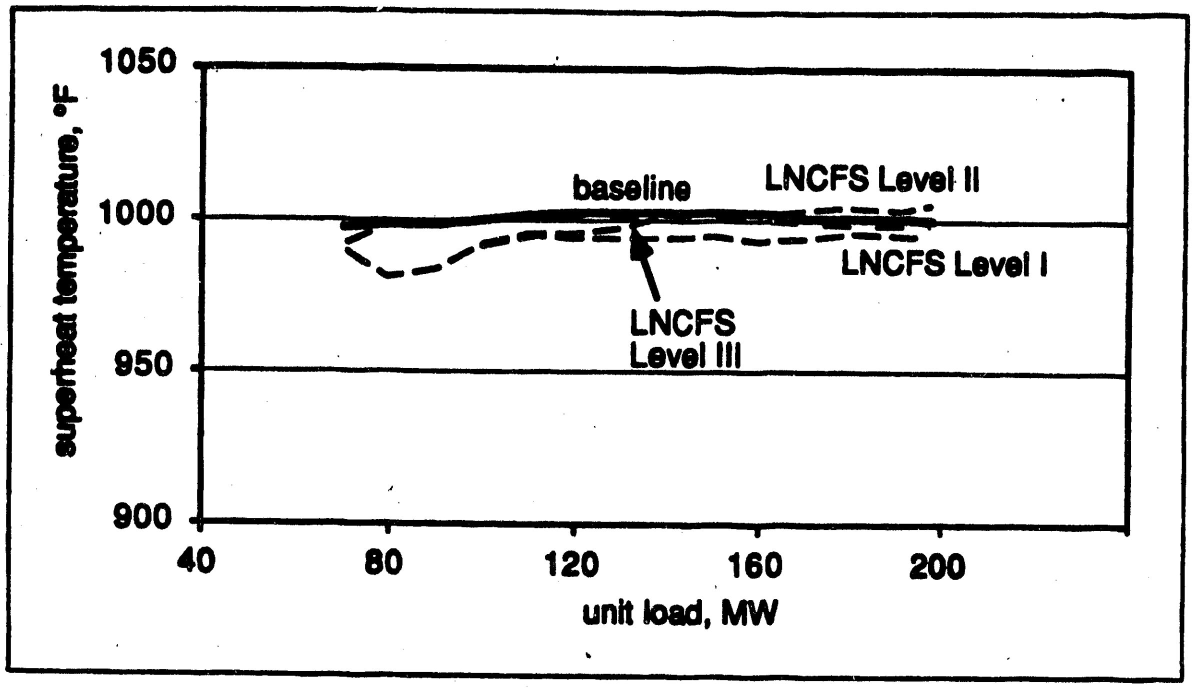


Figure 6.20 - Reheat Temperature Characteristics

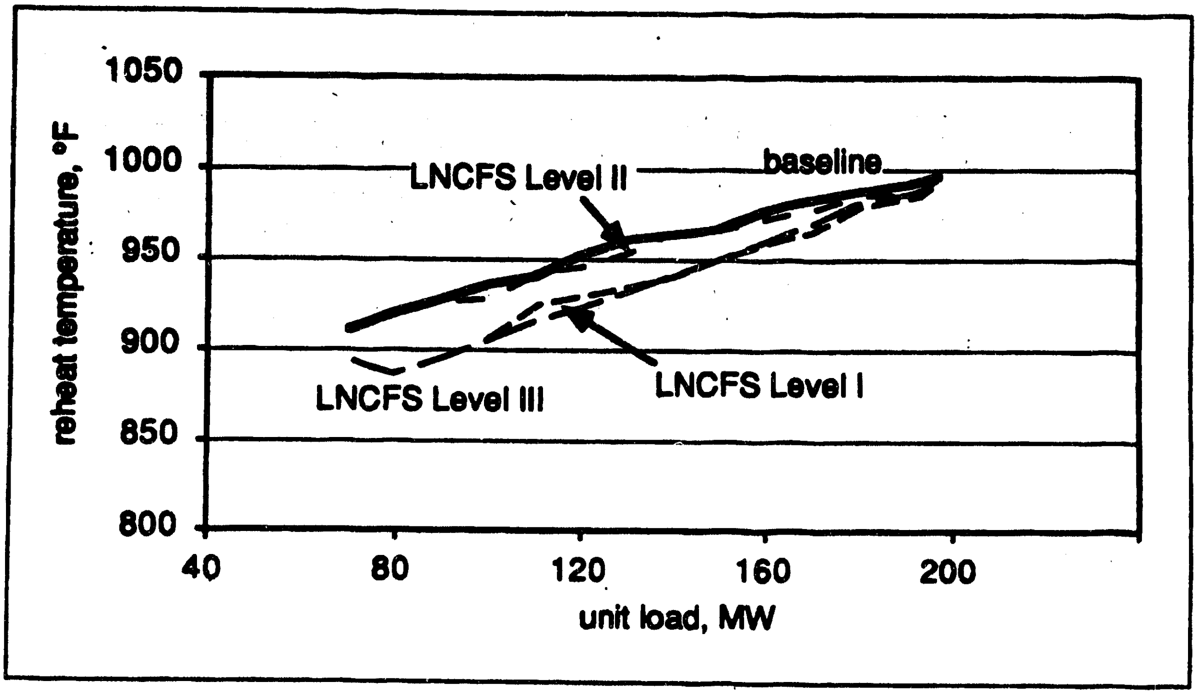
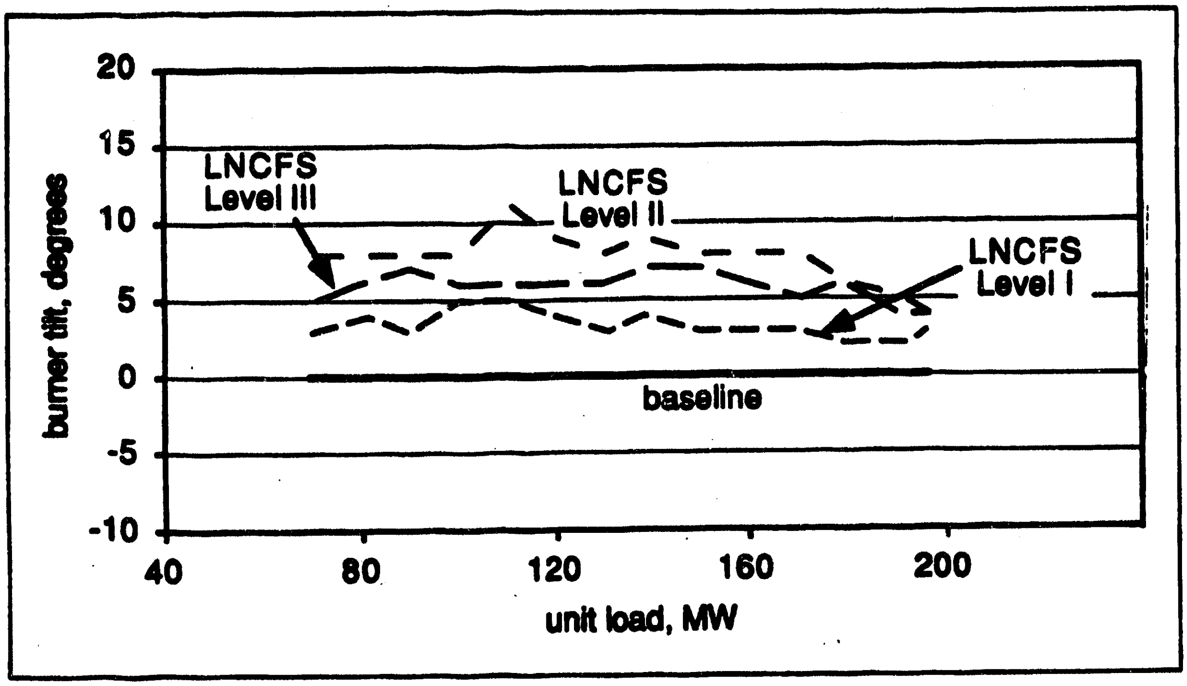


Figure 6.21 - Average Long-term Tilt Position vs. Load



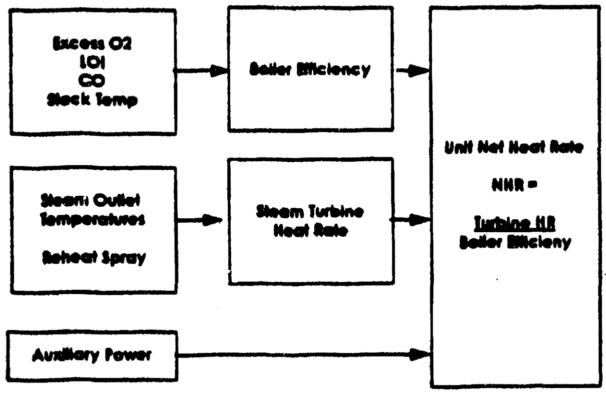
LNCFS I and III reduced both superheat and reheat outlet temperatures at low loads by up to 35°F relative to baseline. Short-term testing indicated that the steam outlet temperatures can be restored to baseline levels through operating changes such as O_2 and burner tilt adjustments, but NOx emissions will be increased.

The operating flexibility of the boiler was affected by LNCFS II and III, but the plant operators were able to handle the operating changes. Especially, LNCFS III required careful monitoring of windbox pressure drop and flame stability at low loads, and making operating adjustments (e.g., closing of SOFA dampers and increasing fuel air flow rate).

As is shown in Figure 6.16, the available O_2 range for LNCFS II and III was reduced significantly. This reduction limited the operators ability to increase O_2 to avoid CO and NOx emission increases during boiler transients. In addition, the LNCFS III was particularly sensitive to operating changes (e.g., bringing mills into operation or changing load) resulting in CO and NOx emission spikes. A positive change in boiler operation was the furnace slagging reduction.

Impacts on Boiler Efficiency and Unit Heat Rate

The performance impacts described in the previous paragraphs (CO, O_2, LOI, and steam temperatures) affect the boiler efficiency, turbine heat rate, and auxiliary power (see Box 1), which, in turn, affect the unit net heat rate. The contribution of each performance impact as well as their cumulative effect on boiler efficiency, turbine heat rate, and net heat rate at full load are shown in Table 6.8.



Parameters such as excess O_2, LOI, CO emissions, and stack temperature impact the boiler efficiency. Similarly, changes in the superheat and reheat outlet temperatures and reheat spray affect the turbine heat rate. The auxiliary power requirements of the pulverizers and fans may also be affected by the low NOx technology. The boiler efficiency, turbine heat rate, and auxiliary power are then used for estimating the unit net heat rate.

Box 1 - Evaluation of Low Technology Impacts on Unit Performance

Table 6.8 - LNCFS Impacts on Boiler Efficiency and Unit Heat Rate (180 MW)

	Baseline	LNCFS I	LNCFS II	LNCFS III
Boiler Efficiency	Base: 90.0%	90.2%	89.7%	89.85%
Effic. Change		0.2	(0.3)	(0.15)
Turbine Heat Rate	Base: 9,000[1]	9,011	9,000	9,000
Unit Net Heat Rate	Base: 9,995	9,986	10,031	10,013
% NHR Change	——	(0.1)	(0.36)	(0.18)

The LNCFS I retrofit increased the boiler efficiency at full load by 0.2 percentage points, while it increased the turbine heat rate from 9,000 to 9,011 Btu/kWh due to a 5-10°F steam outlet temperature reduction. These changes in boiler efficiency and turbine heat rate result in a 0.1 percentage point decrease of the unit net heat rate. Similarly, the LNCFS II decreased boiler efficiency by 0.3 percentage points (mainly due to the higher O_2) and increased the net heat rate by approximately the same percentage (0.36 percent). The impact of the LNCFS III was: 0.15 percentage points decrease in boiler efficiency and 0.18 percentage points increase in net heat rate.

The impact on boiler efficiency and heat rate was estimated only at full load, because of the higher uncertainty of some measurements at low loads (especially LOI). Considering that Smith Unit 2 is a baseloaded unit, the assessment of full load impacts only is adequate.

[1] Assumed turbine heat rate.

However, for cycling units which may experience steam outlet temperature reductions similar to Smith Unit 2, the impact of the LNCFS on low load heat rates is expected to be more significant.

6.3 Effect of Unit Dispatch on Annual NOx Emissions and the Ability to Comply with CAAA Title IV NOx Regulations

The previous section focused on the impact of the LNCFS technologies on full load unit performance and heat rate. However, in reality, the unit is dispatched based on the system load demand and operates throughout the load range. Because (i) the annual achievable NOx emission level (which is the basis for environmental compliance) depends on the unit dispatch profile; and (ii) the LNCFS technologies exhibited increasing NOx emissions at low loads, it is important to assess the impact of the alternative unit dispatch profiles on its ability to comply with environmental regulations such as CAAA Title IV.

The impact of load scenario on the average NOx emission level can be demonstrated through the use of three different types of scenarios - base load (Smith baseline scenario), intermediate load, and peaking load (Figure 6.22). The intermediate and peaking scenarios are simulated load profiles depicting times spent at various loads. An intermediate scenario might be typical of small units in a large system which are utilized to trim system daily peak demand. The peaking unit scenario might be an older unit nearing retirement which is used for utility system reliability purposes to respond to periodic peak demand situations. The base scenario is the actual load profile for Smith Unit 2 that was recorded during the collection of the baseline data.

Assuming that these three scenarios represent the time spent at specific loads for an annual period, the annual average NOx emissions for each scenario and each technology can be calculated (Ref. 7). Table 6.8 shows the resulting annual average NOx emissions for the three scenarios and the three LNCFS technologies. Clearly the unit load dispatch profile has an impact on the annual achievable NOx emission. More specifically, the peaking load scenario with LNCFS II, results in annual NOx emission which exceed the 0.45 lb/MBtu CAAA presumptive limit. Also, based only upon the average emission characteristics for Level III, the unit would only marginally comply for this same scenario. If the statistical characteristics of the long-term data rather than only the long-term average NOx emissions were factored into the determination, the Level III peaking scenario NOx emissions would have also likely exceeded the limitation.

Figure 6.22 - Peaking, Cycling, and Baseload Scenarios

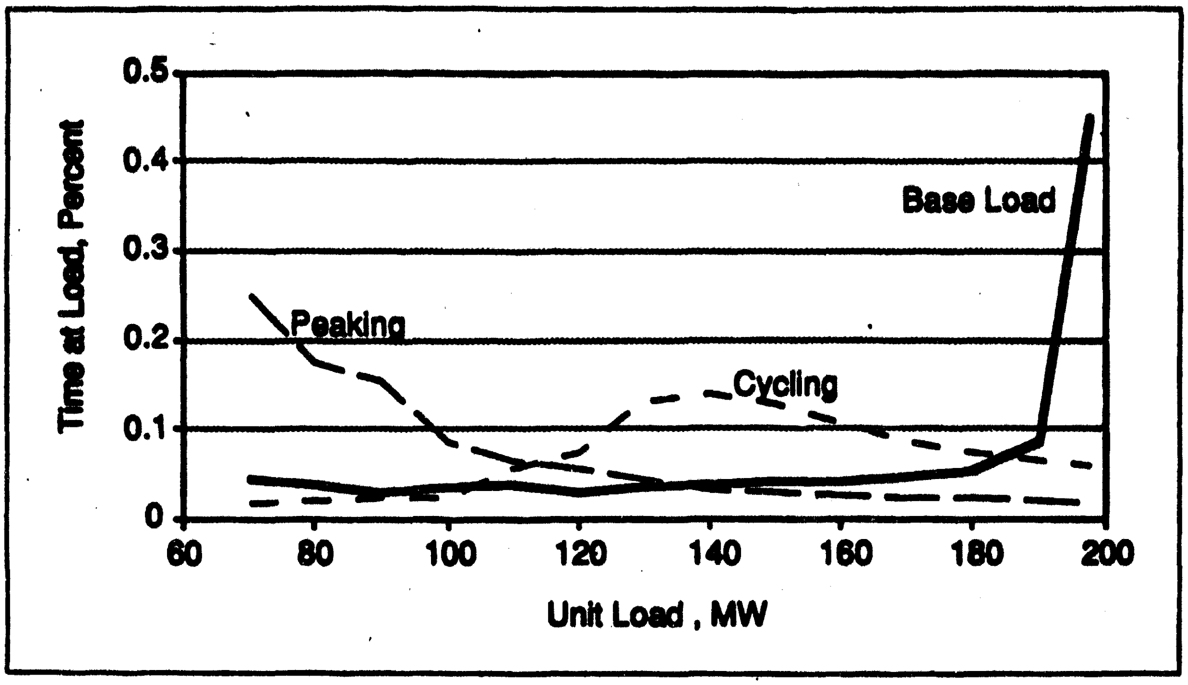


Table 6.9 - Annual NOx Emissions for Peaking, Cycling, and Base Load Scenarios

Boiler Duty Cycle		Technology			
		Baseline	*Level I*	*Level II*	*Level III*
BASE Avg. Load:=161.8 MW	Average NOx, lb/MBtu Average NOx Reductions, %	0.62 —	0.41 38.7	0.41 38.7	0.36 42.2
INTERMEDIATE Avg. Load=146.6 MW	Average NOx, lb/MBtu Average NOx Reductions, %	0.62 —	0.40 39.2	0.41 35.9	0.34 45.3
PEAKING Avg. Load=101.8 MW	Average NOx, lb/MBtu Average NOx Reductions, %	0.59 - —	0.45 36.1	0.47 20.3	0.43 28.0

The above estimates indicate that the unit dispatch may have an impact on the unit's ability to comply with environmental regulations, especially if the unit is close to the compliance limit. For example, the baseloaded scenario with LNCFS II results in 0.41 lbs/MBtu annual NOx emissions, but the peaking scenario results in 0.47 lbs/MBtu. Low NOx burners for peaking units may need to be designed in such a way that low load NOx emissions are kept low (at the same level with full load NOx emissions) either by appropriate burner/windbox design or by operating adjustments.

SECTION SEVEN

COST AND COST-EFFECTIVENESS OF LNCFS TECHNOLOGIES

The economic impacts of low NOx technology retrofits consist of capital costs required for the retrofit, changes in O&M costs, both fuel- and non-fuel-related, and lost revenue due to the unit outage for the retrofit. For the purposes of this report, it is assumed that the non-fuel O&M costs and the lost revenue were not significant. Therefore, the main economic impacts were due to the capital costs and the fuel-related (heat rate-related) O&M costs.

7.1 Capital Costs

Considering that only the LNCFS II was a complete retrofit, the capital costs of the Smith ICCT project for LNCFS I and III do not reflect complete retrofit project costs. Even the costs for LNCFS II were impacted by design features (e.g., SOFA air flow metering devices and offset air yaw adjustment capability), which were included because of the demonstration nature of the project. For these reasons, a capital cost range was established based on the most recent industry experience (Ref. 10) and a rough cost estimate was developed for assessing the cost-effectiveness of the LNCFS technologies. The project costs, both ranges and specific estimates for Smith Unit 2, are shown in Table 7.1.

Table 7.1 - LNCFS Retrofit Costs

	Expected Range ($/kW)	Estimated for Smith Unit 2	
		$/kW	$ Million
LNCFS I	5-15	8	1.44
LNCFS II	15-25	17	3.06
LNCFS III	15-25	20	3.60

7.2 O&M Cost Impacts

The annual fuel-related O&M cost changes relative to baseline were estimated based on the changes in unit net heat rate (see Table 6.8) and the following assumptions:

- Baseloaded unit;
- 65 percent capacity factor; and
- $2 per MBtu coal cost.

As a result, the following annual O&M cost changes were estimated for:

- LNCFS I: $ 18,450 reduction;
- LNCFS II: $ 73,800 increase; and
- LNCFS III: $ 36,900 increase.

7.3 Cost Effectiveness

The capital and O&M cost impacts, along with the annual NOx emission reduction (based on average long-term testing) were used for estimating the average cost-effectiveness of the LNCFS technologies. The results are shown in Table 7.2.

Table 7.2 - Cost-Effectiveness of the LNCFS Technologies Tested at Smith Unit 2

	Baseline	LNCFS I	LNCFS II	LNCFS III
Average NOx (lbs/MBtu)	0.63	0.39	0.39	0.34
% NOx Reduction	-	37	37	45
Annual NOx Reduction (tons/yr)	-	1,159	1,159	1,396
Net Heat Rate (Btu/kWh)	9,995	9,986	10,031	10,013
Changes in O&M Costs ($/yr)	-	(18,450)	73,800	36,900
Capital Costs ($ millions)	-	1.44	3.06	3.6
Cost-Effectiveness [1] ($/ton of NOx removed)	-	103	444	400

Considering the level of accuracy of the testing and the assumptions made, the following conclusions are drawn:

- LNCFS I is more cost-effective than LNCFS II and III.
- LNCFS II and III are equally cost-effective. However, LNCFS III has the additional advantage of higher NOx reduction potential; 40-50 percent instead of 30-40 percent for LNCFS II.

The cost-effectiveness estimated in Table 7.2 is an annual average and is useful in comparing the various low NOx burners to select the most cost-effective technology. After the installation of the burners, it is particularly useful to know the marginal NOx reduction cost (cost of removing an additional ton of NOx). Such information could be used for making operating decisions relating to unit dispatch and system performance optimization (identify the settings of the control variables which satisfy the NOx emission requirements in the most cost-effective way).

[1] Levelization factor: 0.144

SECTION EIGHT

IMPLICATIONS FOR OTHER TANGENTIALLY-FIRED UNITS

Although each unit has its own unique features which affect NOx emissions (e.g., windbox size, availability of space to fit the SOFA system, and coal characteristics), the results from the Smith ICCT project, as well as other low NOx burner demonstration projects (see Table 8.1), provide a good basis for planning future tangentially-fired low NOx retrofit projects. Based on a comparison between the unit being considered for low NOx retrofit and Smith Unit 2, a first estimate of the NOx emission reduction and performance impacts could be made for planning purposes. More accurate estimates may require pilot plant testing and/or more detailed analyses. The latter may be needed especially when the boiler design and the coal characteristics differ significantly from Smith Unit 2 or other units already retrofitted with the LNCFS technologies.

Table 8.1 - Selected LNCFS Retrofit Projects

LNCFS Type	Utility	Unit Name & Number	Size (MW)
LNCFS I	TVA	Gallatin #4	288
	Illinois Power	Joppa #3	150
LNCFS II	Public Service of Colorado	Cherokee #4	370
	Public Service of Colorado	Valmont #5	165
	Indianapolis P&L	Stout #5	100
	Centerior G&E	Eastlake #2	132
	Virginia Power	Yorktown #2	175
LNCFS III	Union Electric	Labadie #4	600

When using the results of the Smith ICCT test program to estimate the NOx reduction potential and the performance impacts of other tangentially-fired units, it should be kept in mind that:

- Smith Unit 2 is at the upper end of the range of tangentially-fired units relative to furnace size; NHI/PA: 1.65 MBtu/hr-sqft compared to 1.6 - 2.2 for most pre-NSPS tangentially-fired boilers.

- The existing windbox is taller than average and allowed for a 20 percent larger CCOFA system.

- The reactivity of the coal utilized at Plant Smith is high relative to other eastern bituminous coals and, as such, it would be expected to have less impact on LOI than other low reactivity eastern bituminous coals. More specifically, the reactivity of the coal burned at Smith Unit 2 as measured by the Fixed Carbon/Volatile Matter (FC/VM) is 1.30 (lower FC/VM means higher reactivity) which is at the low end of the high volatile Eastern Bituminous coals (FC/VM: 1.4 -1.7) and more typical of the SubBituminous coals (FC/VM: 1.1 - 1.4)

Implications Regarding NOx Emissions

The Smith ICCT project, along with other retrofits, showed that:

- The LNCFS I can achieve 25 to 37 percent NOx emission reduction within the control range (100 - 200 MW). Boilers such as Smith Unit 2 may achieve NOx reduction at the upper end of the range, while boilers with a short windbox and small furnace may achieve NOx reduction in the lower end of the range (25-30 percent).

- The LNCFS II and III can achieve the expected level of NOx reduction (Ref. 9) within the control range: 30-40 percent for LNCFS II and 40-50 percent for LNCFS III.

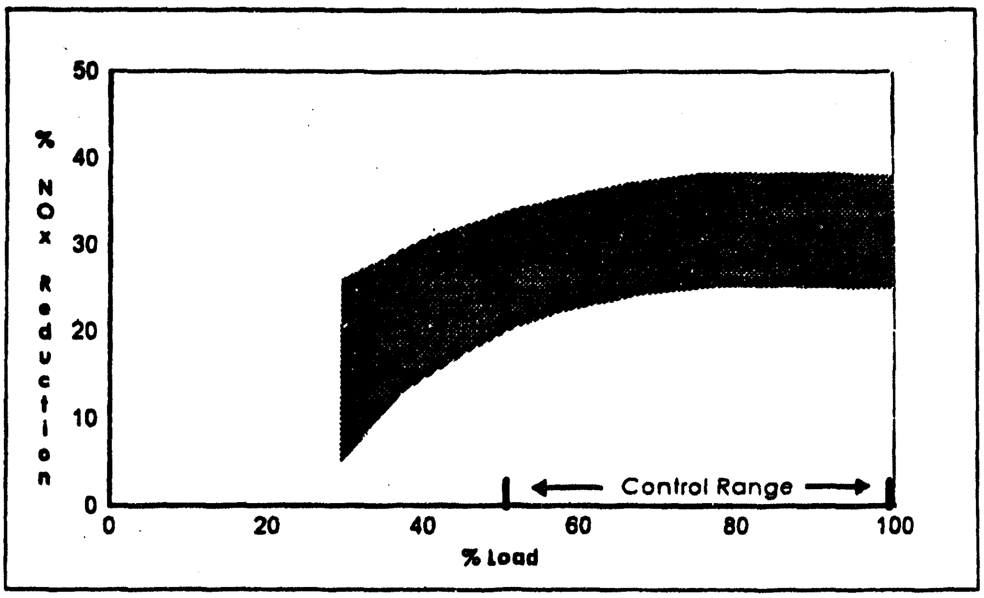
- NOx emissions below the control point (100 MW) may increase for all LNCFS technologies. This is particularly true when the primary objective of unit operation at low loads is to control steam outlet temperatures and maintain unit response rate rather than minimize NOx emissions.

Figures 8.1, 8.2, and 8.3, and the following paragraphs, provide the NOx reduction projections across the load range for tangentially-fired units utilizing the LNCFS I, II, and III, respectively.

Full Load NOx Emissions

LNCFS I: Figure 8.1 shows the NOx reduction potential of LNCFS I. Before the Smith ICCT project, the expected NOx reduction was 25-30 percent across the load range. Based on the experience of Smith Unit 2 and other LNCFS I retrofits, it is expected that NOx reduction of 25 to 37 percent within the control range may be achieved by LNCFS I.

Figure 8.1 - Expected NOx Emissions Reduction for Tangentially-Fired Units with LNCFS I



Smith Unit 2 achieved 37 percent long-term NOx reduction within the control range (50-100 percent load). Other units retrofitted with the LNCFS I have achieved NOx reduction in the 20 to 32 percent range.

Units with windbox similar to Smith Unit 2, which may accommodate a "larger-than-average" CCOFA system may achieve NOx reduction at the upper end of this range (30-37 percent). Units which impose limitations on the size of the CCOFA system (short existing windbox) may achieve NOx reduction in the lower end of the range (25-30 percent).

As Figure 8.1 shows (heavy line), the NOx reduction below 50 percent load is expected to decrease with decreasing load. This expectation is based on the similarities of the LNCFS I and III systems at low loads when the SOFA dampers of the latter are closed. The NOx reduction at low loads can be improved by reducing excess O_2 and burner tilt, but the steam outlet temperature will be reduced and the unit heat rate will increase.

LNCFS II: As shown in Figure 8.2, the LNCFS II is expected to achieve 30-40 percent long-term NOx emissions within the control range (50-100 percent load). This projection is based on the results from the Smith Unit 2 project, as well as other LNCFS II retrofits (Public Service of Colorado's Cherokee #4 and 5 (Ref. 11), and Indianapolis Power & Light's Stout #5 (Ref. 12)).

LNCFS III: Similarly, LNCFS III is expected to achieve 40-50 percent NOx reduction within the control range (see Figure 8.3). This is based on the operating experience from Smith Unit 2 and Union Electric's Labadie #4 (Ref. 13) retrofits.

Low Load NOx Emissions

The NOx reduction below the control point (50 percent load) may decline depending on the unit design characteristics and the operating objectives. If the primary operating objective is to maintain steam outlet temperatures and/or unit response rate at low loads, the NOx emission reduction may decrease significantly, as is shown in Figure 8.1, 8.2, and 8.3 for LNCFS I, II, and III, respectively. The resulting NOx reduction due to the different operating objectives is shown in Figures 8.2 and 8.3:

- The shaded area marked "*No Operating Adjustments*" shows the NOx reduction if the boiler is operated as before the low NOx retrofit, when the primary operating objective was to maintain steam outlet temperatures.

- The area marked "*With Performance Trade-offs*" indicates the potential for additional NOx reduction through operating adjustments; however, these adjustments may have adverse impacts on boiler efficiency, turbine heat rate, and unit heat rate.

Figure 8.2 - Expected NOx Emissions Reduction for Tangentially-fired Units with LNCFS II

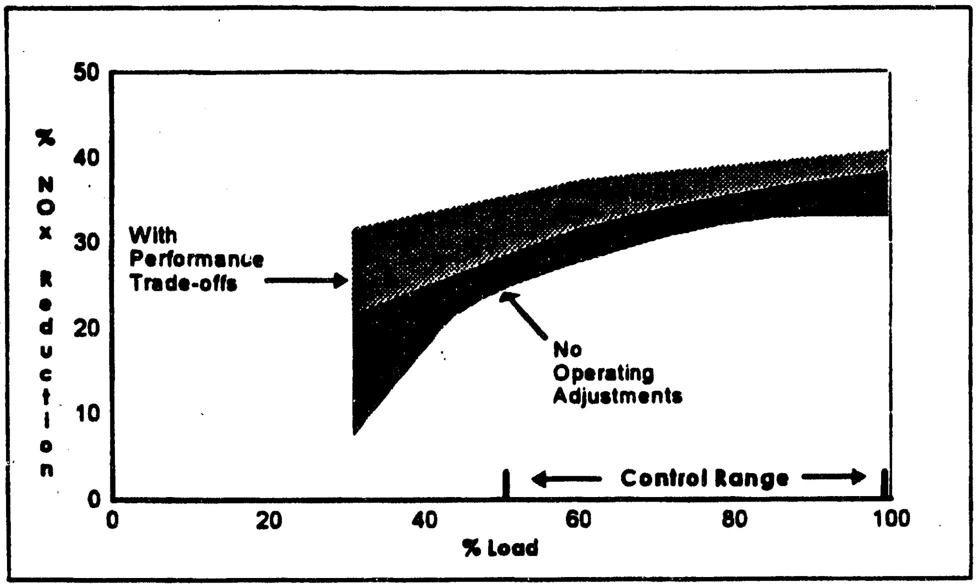
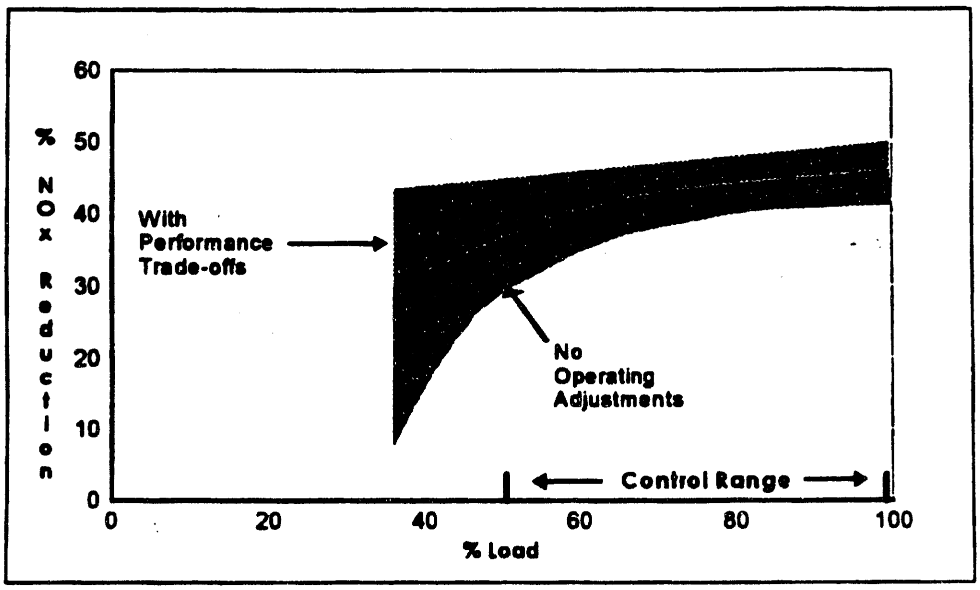


Figure 8.3 - Expected NOx Emissions Reduction for Tangentially-fired Units with LNCFS III



If such NOx reduction decline needs to be avoided, a number of actions can be taken before and after the LNCFS retrofit has been completed.

During design specification, the utility may elect to specify the NOx emission levels required throughout the load range, including low load. In response, the low NOx technology vendors may design the system to reduce NOx at low loads. In this case, the benefits (increased NOx reduction at low load) should be evaluated against potential penalties (e.g., increased windbox pressure drop throughout the operating range, higher auxiliary power, and higher capital costs).

After the LNCFS Retrofit, NOx emissions at low loads can be reduced throughout operating adjustments such as reduction of excess O_2 and burner tilt and/or increase of overfire air flow rate. However, these adjustments may impact adversely the steam outlet temperatures and the unit heat rate. In this case, an optimum operating point should be determined through trade-off of NOx reduction and heat rate (production costs).

LNBFS

Limited short-term testing at Smith Unit 2 showed that the LNBFS system is capable of reducing NOx emissions by up to 32 percent. However, it is uncertain whether other tangentially-fired units will experience similar NOx reduction. In addition, there are a number of questions remaining about LNBFS' potentially adverse impact on waterwall corrosion and its cost-effectiveness compared to LNCFS I and II. The industry perception regarding the LNBFS is:

- The LNBFS is more expensive than LNCFS I and has similar NOx emission reduction potential. In addition, the LNBFS does not provide the high turndown capability of LNCFS I, and may increase the waterwall corrosion.

- The LNBFS is only marginally less expensive than LNCFS II, but has the disadvantages of potential waterwall corrosion, low turndown, and lower NOx reduction potential (6 - 10 percent less NOx reduction than the LNCFS II).

Until recently, the LNBFS was thought to be particularly suitable for retrofitting cast windbox boilers, which are difficult to retrofit with the LNCFS I. However, this may change when Duke Power's River Bend #4 is retrofitted with LNCFS I later during this year (1993). If this demonstration is successful, the only applications for LNBFS will be oil and natural gas boilers.

Implications Regarding Unit Performance Impacts of Tangentially-fired Units

More information on the potential impacts is provided in the following paragraphs. Adverse O&M impacts can occur even where steps are taken to carefully integrate retrofit NOx control technologies with existing plant generation requirements. In general, the higher the NOx reduction sought the greater the potential for negative impacts on unit performance.

The most common of the impacts observed to date, including the Smith ICCT project, has been reduced boiler efficiency due to increased excess O_2 requirements, especially for low NOx technologies with separated overfire air systems. Other potential impacts may include:

- Increased CO emissions and excess O_2;
- Increased LOI, especially with low reactivity coals;
- Changes in furnace slagging and backpass fouling patterns;
- Reduced steam outlet temperatures;

- Increased waterwall corrosion;
- More difficult boiler operation; and
- Reduced equipment reliability.

Impact on CO Emissions and Excess O_2

CO may increase to or above the 100 ppm level, but it can be controlled through increased O_2 and burner optimization. Therefore, the excess O_2 required for complete combustion and stable flame is expected to increase by up to 0.5-1.5 percent for systems with overfire air such as LNCFS II and III. The LNCFS I is not expected to require higher O_2.

Impact on LOI

Most tangentially-fired units retrofitted with LNCFS technologies have experienced minimal LOI increases. However, future LNCFS retrofits may experience higher LOI depending on site-specific factors such as:

- Low reactivity coal;
- Low coal fineness or non-uniform coal fineness between the different mills;
- Significant coal and/or air imbalance (more than 5 percent from the uniform flow distribution flow rate); and
- Short furnace or SOFA ports located too close to the furnace outlet plane; both of these factors reduce the residence time of the coal particles in the furnace and may increase the LOI.

In the case of LOI increase due to the LNCFS retrofit, it may be possible to control it to pre-retrofit levels by:

- Adjusting the coal fineness (coal classifier adjustment);
- Increasing excess O_2; and
- Mill biasing.

Impact on Furnace Slagging and Backpass Fouling

The impact of the LNCFS on furnace slagging is unit-specific and requires a detailed analysis of the boiler performance, which is usually performed by the boiler vendor. However, the Smith ICCT project, as well as other retrofits, have shown that LNCFS retrofits usually reduce the slagging tendency of the unit. LNCFS II and III are expected to reduce slagging more than LNCFS I because they "spread" the firing zone, reduce the peak furnace temperature, and make the gas temperature profile more uniform along the height of the furnace. However, slagging reduction is usually accompanied by increased dust loading at the furnace outlet which may increase the backpass fouling.

Impact on Steam Outlet Conditions

The steam outlet conditions are usually affected by the LNCFS retrofits. The specific impact depends on the LNCFS, the boiler design (reheat surface amount and location, initial slagging behavior, NHI/PA, etc.) and the unit operating approach. The impact of the retrofit on the steam temperatures is expected to be higher at low loads; up to 20°F SHO and 30-50°F RHO temperature reduction at 50 percent load. Units experiencing significant slagging reduction due to LNCFS retrofit (most likely units with high heat release and high slagging tendency) will also experience a high steam temperature reduction. The operating approach of the unit will impact also the steam outlet temperatures:

- If NOx emission reduction is the primary operating objective, the boiler may be operated with minimum O_2 and tilt even though the steam outlet temperatures are reduced relative to pre-retrofit conditions;

- If steam temperature control is a higher priority objective than NOx emission reduction (which is case when the unit satisfies the NOx emission regulatory requirements), O_2 will be set in such a way that steam outlet temperatures are maintained.

The NOx emission increase at low loads may not be of particular concern to baseloaded units such as Smith Unit 2, but it may be critical for other units, especially cycling units in ozone non-attainment areas. For the latter category of units, NOx reduction decrease at low loads can be avoided through design and operating adjustments:

- The design specifications of the low NOx retrofit should provide the NOx reduction requirements at low loads or the marginal value of NOx emissions in $/ton and the steam temperature profile over the load range, as well as the fuel cost ($/ton) and the baseline unit heat rate (Btu/kWh); this information will allow the low NOx supplier to optimize the design relative to the NOx steam temperature trade-off.

- If the lower steam temperatures are identified after the low NOx retrofit, they can be restored to pre-retrofit levels through operating or boiler modifications:
  - Increase excess O_2, burner tilt, and SOFA flow rate;
  - Resurfacing of the reheat section of the unit; and potentially
  - Addition of a flue gas recirculation (FGR) system.

Considering that higher O_2 and burner tilt will increase NOx emissions, the optimum operating point should be identified based on NOx — steam temperature (unit heat rate) trade-off. Reheat resurfacing should consider the following:

- In addition to restoring reheat temperatures to pre-retrofit levels, resurfacing (if designed properly) can further reduce the required excess O_2 at low loads, which results in further NOx emission reduction;

- However, too much reheat surface may convert the unit into "reheat lead" (uncontrolled reheat outlet temperature higher than superheat outlet temperature), To control reheat temperature in this case, reheat spray will be required which adversely affects the unit heat rate.

Increased Waterwall Corrosion

To date, there have been no reports of increased corrosion due to low NOx operation. However, because of the long-term nature of corrosion impacts and the relatively few projects where corrosion rates have been rigorously determined, it cannot be assumed that these results apply to the general boiler population.

Unit Operation Impacts

Impacts have varied. Increased attention to monitoring and adjustments of existing boiler control parameters (e.g., primary air flow) have been reported in several instances. Where retrofitted equipment has replaced worn or damaged components, improved operation has resulted. Reduced load ramp rate was observed for one tangentially-fired application. Generally, no impact on boiler turndown has been reported, except in one instance where it improved.

Equipment Reliability

Generally, NOx control equipment reliability has been favorable. Some early design enhancements, especially when replacing worn or damaged equipment, have led to improved reliability. However, long-term operating experiences remain limited and some reliability problems continue to be reported. These include plugging of coal/air nozzles some of which have led to forced outages.

Some of the above aspects can be reduced or eliminated through systematic testing before and after the retrofit, as well as design and operating adjustments of the combustion system, boiler, and auxiliary equipment. However, such adjustments may reduce one O&M impact but may have other adverse impacts on boiler performance and the level of NOx reduction potential.

Additional Implications for Planning Future T-fired Low NOx Retrofit Projects

Pre- and Post-retrofit Testing:

- To avoid or reduce potential adverse impacts and achieve the optimum level of NOx reduction and unit performance, systematic testing before and after the retrofit is advised. Pre-retrofit testing should establish clearly the baseline conditions throughout the load range under normal unit operation, identify high incidence of prior O&M problems and provide all the information needed for designing the low NOx system and integrating it into the boiler in an optimum manner.

- The pre-retrofit testing should provide information which will be included in the low NOx design specifications, such as:
  - baseline NOx emissions;
  - operating condition of key components (e.g., mills and fans);
  - primary air flow rates over the load range;
  - air and coal flow imbalances;
  - prior problem areas, such as excessive waterwall corrosion, high attemperation rates and low reheat temperatures.

Low NOx System Design Specifications:

- The design specifications should communicate clearly the project objectives, the existing condition of the equipment and other related operating and hardware changes being planned. Careful integration of the low NOx system with other modifications being planned independently is essential for minimizing adverse impacts and achieving satisfactory NOx reduction. Modifications which are planned sometimes in parallel with or after the low NOx retrofit are:
  - mill upgrading or operating changes;
  - reheat resurfacing;
  - replacement of unit controls with digital control system;
  - addition of gas conditioning equipment or ESP upgrading;

- The design specifications for low NOx retrofit projects of cycling units which require high NOx emission reduction at low loads should provide adequate information so that the burner supplier can optimize the design of the system across the operating load range. The following information should be added to the design specifications:
  - The expected unit dispatch profile;
  - The marginal value of NOx emissions across the load range;
  - Present steam (superheat and reheat) outlet temperature profile over the load range;
  - Net heat rate and variable O&M costs of the unit as a function of load; and
  - The key assumptions to be used for evaluating the low NOx retrofit proposals.

If NOx emission requirements over the load range are specified, the financial penalties for exceeding these requirements and the benefits from over-complying should be also provided.

- Candidate retrofit units which:
  - Do not "make" steam outlet temperatures (temperatures are lower than design levels) over the operating load range;
  - Operate frequently at low loads (cycling or intermediate units);
  - Require low load NOx emission reduction similar to full load;

  should consider reheat section re-surfacing combined with the low NOx burner retrofit. Such re-surfacing will increase the reheat outlet temperatures at low loads without the need for higher excess O_2, which increases NOx emissions. The economic attractiveness of reheat resurfacing will depend on site-specific considerations.

- Candidate retrofit units with non-operational burner tilts and high NOx emission reduction requirements at low loads should evaluate the impact of tilt on NOx emissions at low loads before they decide to refurbish the tilting mechanisms. If high NOx emission reduction is required at low loads, it may be more cost-effective to avoid refurbishment of the burner tilting mechanisms. The final decision regarding refurbishment of the tilts will depend on site-specific considerations, including the NOx emission requirements at low loads.

Capital Costs:

- Based on the recent experience from Smith Unit 2 and other projects, the costs for LNCFS retrofits are expected to be in the following range:
  - LNCFS I: $5 - 15 per kW;
  - LNCFS II: $15 - 25 per kW;
  - LNCFS III: $15 - 25 per kW.

Low NOx Retrofit Outage:

- A four- to six-week outage should be planned for LNCFS I retrofits and a six- to eight-week outage for LNCFS II and III retrofits. At Smith, the LNCFS II was the only complete retrofit (the others were modifications of the LNCFS II) and required a 3-week unit outage. This was accomplished because:

  (i.) There were no interferences with the installation of the windbox and the SOFA ducts;

  (ii.) Extensive preparation preceded the retrofit, including installation of SOFA ducts; and

  (iii.) "Around-the-clock" work schedule during the three-week retrofit.

  The fact that the LNCFS II retrofit was accomplished in such a short period of time suggests that a three- to four-week outage is feasible for an LNCFS retrofit in cases there are no interferences; however, a more orderly schedule requires six to eight weeks.

Optimization and Training:

- Two to three weeks are adequate for LNCFS optimization (tuning). In cases of marginal NOx complianc (after the retrofit), re-optimization of the combustion system may be beneficial in reducing further NOx emissions. Such re-optimization should be scheduled 3 to 6 months after the original optimization, depending on the operating experience of the unit and the need for additional NOx emission reduction. At Smith Unit 2, a 2-week optimization was needed for each system. In addition, a 3-day re-optimization of LNCFS II was considered necessary to reduce NOx emissions at low loads;

- One to two day classroom training course on NOx generation principles and operational strategies should be offered by the low NOx burner vendor and attended by all plant operators. In case of marginal NOx compliance, it is suggested that NOx emission trade-off with LOI and/or steam outlet conditions (heat-rate) should be included in the training. The classroom training course should be followed by control room training, which focuses on the operational strategies discussed during the classroom training more suitable to the retrofitted unit.

- An on-line performance monitoring and optimization system is needed to advise the plant operators as to the operating conditions (settings of boiler and burner control variables) which optimize the NOx emissions and unit heat rate. Such optimization should take into account:

  - The marginal value of NOx emissions;

  - The heat rate and variable O&M costs over the load range;

  - The impact of each burner and boiler control variable on O&M costs and NOx emissions; and

  - Regulatory, equipment design and operating constraints, etc.

  Initially, the optimization system should be an advisor to the plant operators, but eventually it should be integrated into the control system. Also, it should be capable of performing trade-off analyses (e.g., reheat temperature vs. NOx emissions or LOI vs. NOx emissions).

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DATE
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6/22/94

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