Appendix 5.0-2

MICRONIZED COAL REBURN DEMONSTRATION PROJECT FOR NO_X CONTROL AT THE NEW YORK STATE ELECTRIC & GAS TANGENTIALLY-FIRED MILLIKEN UNIT 1

MICRONIZED COAL REBURN
DEMONSTRATION PROJECT FOR NO_x CONTROL AT THE
NEW YORK STATE ELECTRIC & GAS TANGENTIALLY-FIRED MILLIKEN UNIT 1

EVALUATION TEST PROGRAM RESULTS

Prepared by

Jamal B. Mereb

CONSOL Inc.
Research & Development
4000 Brownsville Road
Library, PA 15129-9566

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Organization(s) that Co-funded this Report:

New York State Electric & Gas Corporation
Corporate Drive, Kirkwood Industrial Park
P.O. Box 5224
Binghamton, NY 13902-5224
Attn: James J. Harvilla

U.S. Department of Energy
FETC
P.O. Box 10940
Pittsburgh, PA 15236-0940
Attn: James Watts

Electric Power Research Institute
3412 Hillview Avenue
P.O. Box 10412
Palo Alto, CA 94303
Attn: Richard Rhudy

CONSOL Inc.
Research & Development
4000 Brownsville Road
Library, PA 15129-9566
Attn: Robert M. Statnick

Empire State Electric Energy
Research Corporation
1515 Broadway, 43rd Floor
New York, NY 10036-5701
Attn: Debra Dimeo

New York State Energy
Research & Development Authority
Two Rockefeller Plaza
Albany, NY 12223
Attn: Joseph Sawyer

Ordering Information: For information about ordering this report, contact James J. Harvilla, Project Manager, New York State Electric & Gas Corporation, Corporate Drive, Kirkwood Industrial Park, P.O. Box 5224, Binghamton, NY 13902-5224, (607) 762-8630.

Micronized Coal Reburn Demonstration Project for NO_x Control at the New York State Electric & Gas Tangentially-Fired Milliken Unit 1

Abstract

The Micronized Coal Reburn Demonstration Project for NO_x Control at the New York State Electric & Gas tangentially-fired Milliken Unit 1 is part of the DOE Clean Coal Technology Program. The objective is to demonstrate the effectiveness of coal reburning in reducing NO_x emissions utilizing the existing Low-NO_x Concentric Firing System Level 3 (LNCFS-3) burner configuration.

Reburning was applied utilizing the existing LNCFS-3 configuration by introducing the top coal feed as the reburn fuel, and reducing the top burner level air flows (less coal air and auxiliary air) relative to the LNCFS-3 setting. Furthermore, reburning was enhanced by concentrating the over fire air through fewer and higher ports and using finer grind reburn coal (exceeding 70% passing 325 mesh) to maintain less than 5% fly ash LOI.

The evaluation test program was conducted by CONSOL and consisted of an evaluation of a sequence of three test sets: 1) Diagnostic, 2) Performance, and 3) Long-Term. The diagnostic test program consisted of short-term (1-3 hours) optimization tests conducted to obtain parametric data, and to select settings for long-term operation. The selected settings were utilized during performance and long-term testing to achieve the lowest NO_x emissions at full boiler load (140-150 MW) while maintaining the required steam conditions, reliable boiler operation and fly ash LOI below 5%. The performance test program assessed a detailed set of operating variables for the reburn configuration. The long-term test program evaluated the long-term (23 days) NO_x emissions performance of the reburn configuration, and estimated the annual emissions.

The evaluation test program focused on coal reburning, and utilized, as baseline, the LNCFS-3 configuration which generated the lowest NO_x emissions (0.35 lb/MM Btu), while maintaining the fly ash loss on ignition (LOI) below 5%. A primary consideration was given to maintaining reliable boiler operation for power generation. High-volatile bituminous Pittsburgh seam coal was used as both the primary and the reburn fuels during the evaluation.

Reburning was successfully applied using the existing LNCFS-3 configuration and without installing a separate reburn system. At the same economizer O_2 level, no single operating variable had a dominant effect on reburning performance. A combination of operating settings (utilized during performance and long-term testing) achieved the final results (lowest NO_x and reliable operation). The selected operating settings for long-term operation were 14-16% reburn coal, 105 rpm top mill classifier speed (corresponds to 70-72% -325 mesh), -5 degrees main burner tilt and 2.8% economizer O_2.

At full boiler load (140-150 MW) and 14.4% reburn heat input, the coal reburn configuration reduced NO_x emissions from a baseline (LNCFS-3) of 0.35 to 0.25 lb/MM Btu (28% reduction), while maintaining the fly ash LOI below 5% and the boiler efficiency at 88.4-88.8%. The achievable annual NO_x emissions using 15.1% coal reburn were estimated at 0.245 ± 0.011 lb/MM Btu (95% confidence), and the estimated average fly ash LOI was 4.4 ± 0.4%.

Based on replicated performance tests and a 95% confidence level, variations in NO_x emissions less than 0.006 lb/MM Btu and in fly ash LOI less than 1.5% were assumed not to be statistically significant by this analysis. There were large uncertainties with respect to the effects on LOI, possibly because LOI generally varied within a relatively narrow range (between 3% and 5%), in response to the operating variables.

The optimization tests assessed the effects of SOFA tilt, reburn coal transport air, top level auxiliary air, excess air, reburn coal fineness, overall coal fineness, main burner tilt, reburn coal fraction, boiler load, and mill pattern on NO_x emissions and the fly ash LOI. Variations in the SOFA tilt between 0 and 15 degrees (above horizontal) had minor effects on both NO_x emissions and LOI. An increase in the reburn coal transport air (top burner primary air), corresponding to an increase in the air-to-fuel ratio between 2.0 to 2.5, increased NO_x emissions. Increasing the top level auxiliary air flow increased both NO_x emissions and LOI. Increasing the economizer O_2 generated the classical response of higher NO_x emissions and lower or stable LOI. The sensitivity was estimated at 0.1 lb NO_x/MM Btu per 1% change in O_2, and was relatively independent of the reburn coal fineness. Using finer grind coal (reburn or overall) reduced both NO_x emissions and LOI. The effect of reburn coal fineness on NO_x was significant (relative to uncertainty level of 0.006 lb/MM Btu) only for relatively large variations in the top mill classier speed (e.g. change of 30 rpm). Operating the main burner tilt slightly below the horizontal (about -5 degrees) improved the reburning performance (lower LOI without increasing NO_x), relative to the horizontal setting. Increasing the reburn coal fraction between 14% and 25% increased NO_x emissions and had a minor effect on LOI (generally less than 1.5% absolute). Reducing the boiler load reduced NO_x emissions, and the effect was greater when the second mill was taken out of service. Thus, reducing the boiler load by taking the second mill out of service is a recommended option. Furthermore, taking the second mill out of service, while maintaining the same boiler load, reduced NO_x emissions at both high (140 MW) and low (110 MW) boiler loads, possibly due to longer residence times in the primary combustion zone.

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List of Abbreviations

Auxiliary Air	Secondary Air Portion Between Top and Bottom Concentric Air
ABB C-E	Asea Brown Boveri Combustion Engineering
A/F	Air-to-Fuel Ratio (Pounds Air Per Pounds Coal)
Btu	British Thermal Unit
C	Carbon, Elemental
EC	Degrees Celsius
CCOFA	Close-Coupled Over Fire Air
CO	Carbon Monoxide
CO_2	Carbon Dioxide
Coal Air	Fuel Air, Secondary Air Portion on Top and Bottom of Primary Air
Concentric Air	Offset Secondary Air Portion on Top and Bottom of Auxiliary Air
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ESP	Electrostatic Precipitator
EF	Degrees Fahrenheit
H	Hydrogen, Elemental
H_2O	Water
kpph	Kilo (Thousand) Pounds Per Hour
lb	Pound
LNCFS^{TM}	Low-NO_x Concentric Firing System
LNCFS-3	LNCFS Level 3 (Equipped with SOFA and CCOFA)
LOI	Loss on Ignition, 100 - % Ash$_{\text{fly ash}}$
MCR	Micronized Coal Reburn
MM	Million
MW	Mega (Million) Watts
N	Nitrogen, Elemental
N_2	Nitrogen Gas
NO_x	Nitrogen Oxides, Nitric Oxide (NO) and Nitrogen Dioxide (NO_2)
NYSEG	New York State Electric & Gas Corporation
O	Oxygen, Elemental
O_2	Oxygen Gas
Primary Air	Air Transporting Coal Feed
ppm	Parts Per Million
psig	Pounds Per Square Inch, Gauge
Reb	Reburn
rpm	Revolutions Per Minute
S	Sulfur, Elemental
SO_2	Sulfur Dioxide
SOFA	Separated Over Fire Air
Temp	Temperature

Objective

The objective of the evaluation test program conducted by CONSOL was to demonstrate the effectiveness of coal reburning in reducing NO_x emissions at the New York State Electric & Gas tangentially-fired Milliken Unit 1 utilizing the existing Low-NO_x Concentric Firing System Level 3 (LNCFS-3) burner configuration. The evaluation included an assessment of the effects of the operating variables on NO_x emissions and unburned fuel losses measured as the fly ash loss on ignition (LOI).

Conclusions

An evaluation test program was conducted by CONSOL to assess coal reburning at the New York State Electric & Gas tangentially-fired Milliken Unit 1 using high-volatile bituminous Pittsburgh seam coal as both the primary and the reburn fuels. The evaluation consisted of three sequential test programs (Diagnostic, Performance and Long-Term) assessing the effects of the reburn configuration on NO_x emissions and the fly ash loss on ignition (LOI). The diagnostic test program was based on short-term (1-3 hours) optimization tests conducted to obtain parametric data, and to identify settings for long-term operation, which achieved the lowest NO_x emissions at full boiler load (140-150 MW) while maintaining the required steam conditions, reliable boiler operation and LOI below 5%. The performance test program assessed a detailed set of operating variables. The long-term test program evaluated the long-term (23 days) NO_x emissions performance of the reburn configuration and estimated the annual emissions. The following conclusions were reached.

- **Applying Coal Reburning Using LNCFS-3:** Reburning was successfully applied using the existing LNCFS-3 configuration and without installing a separate reburn system. This was accomplished by introducing the top coal feed as the reburn fuel, and reducing the top burner level air flows by introducing less coal air and auxiliary air flows relative to the LNCFS-3 setting. Furthermore, the impact of reburning was increased by concentrating the over fire air through fewer and higher ports and using finer grind reburn coal (exceeding 70% passing 325 mesh) to maintain LOI below 5%.

- **Overall Effect of Operating Variables:** At the same economizer O_2 level, no single operating variable had a dominant effect on reburning performance. A combination of operating settings (selected for long-term operation) achieved the final results (lowest NO_x and reliable operation). Appropriate operating settings for long-term operation were 14-16% reburn coal, 105 rpm top mill classifier speed (corresponds to 70-72% -325 mesh), -5 degrees main burner tilt and 2.8% economizer O_2. No additional improvement in LOI was observed using higher top mill classifier speeds (relative to the long-term setting of 105 rpm).

- **Coal Reburn Configuration Performance:** Based on performance testing, using 14.4% coal reburn at full boiler load (140-150 MW) reduced NO_x emissions from a baseline (LNCFS-3) of 0.35 to 0.25 lb/MM Btu (28% reduction), while maintaining the fly ash LOI below 5% and the boiler efficiency at 88.4-88.8%.

- **Long-Term NO_x Performance:** Based on long-term testing consisting of 23 days of continuous measurements, the achievable annual NO_x emissions using 15.1% coal reburn were estimated at 0.245 ± 0.011 lb/MM Btu (95% confidence), and the estimated average fly ash LOI was 4.4 ± 0.4%.

- **Experimental Uncertainty:** Based on replicated performance tests and a 95% confidence level, variations in NO_x emissions less than 0.006 lb/MM Btu and in fly ash LOI less than 1.5% were assumed to be of no statistical significance. There were large uncertainties with respect to the effects on LOI, possibly because LOI generally varied within a relatively narrow range (between 3% and 5%), in response to the operating variables.

- **Effect of SOFA Tilt:** Variations in the SOFA tilt between 0 and 15 degrees (above horizontal) had minor effects on both NO_x emissions and LOI in both LNCFS-3 and reburn configurations.

- **Effect of Reburn Coal Transport Air:** An increase in the reburn coal transport air (top burner primary air), corresponding to a 20% increase in the air-to-fuel ratio from 2.05 to 2.45 (lb/lb), increased NO_x emissions from 0.28 to 0.31 lb/MM Btu. The increase in NO_x was attributed to less reducing reburn zones with the additional introduction of an oxidant with the reburn fuel.

- **Effect of Top Level Auxiliary Air:** Increasing the top level auxiliary air flow increased both NO_x emissions and LOI. The increase in NO_x was attributed to less reducing reburn zones as more oxidant was introduced through the auxiliary air nozzle situated directly below the reburn coal nozzle. The increase in LOI was attributed to lower excess air levels in the primary combustion zone as more air was diverted away from the lower burners.

- **Effect of Overall Excess Air:** Increasing the economizer O_2 generated the classical response of higher NO_x emissions and lower or stable LOI. The sensitivity was estimated at 0.1 lb NO_x/MM Btu per 1% change in O_2 and was relatively independent of the reburn coal fineness.

- **Effect of Reburn Coal Fineness:** Using finer grind reburn coal (top mill) reduced both NO_x emissions and LOI. The effect on NO_x was significant (relative to the uncertainty level of 0.006 lb/MM Btu) only for relatively large variations in the top mill classier speed (e.g. change of 30 rpm).

- **Effect of Overall Coal Fineness:** Using finer grind coal (all mills) reduced both NO_x emissions and LOI.

- **Effect of Main Burner Tilt:** Operating the main burner tilt slightly below the horizontal (about -5 degrees) improved the reburning performance (lower LOI without increasing NO_x), relative to the horizontal setting. That was attributed to longer residence times in the furnace prior to over fire air introduction. Overall, the effect was difficult to quantify due to a limited number of tests.

- **Effect of Reburn Coal Fraction:** Decreasing the reburn coal fraction from 25% to 14% decreased NO_x emissions from 0.25 to 0.23 lb/MM Btu and had a minor effect on LOI (generally less than 1.5% absolute). The decrease in NO_x was attributed to lower excess air levels in the primary combustion zone as more coal was diverted to the lower burners.

- **Effect of Boiler Load:** Reducing the boiler load reduced NO_x emissions, and the effect was greater when the second mill was taken out of service. Thus, reducing the boiler load by taking the second mill out of service is a recommended option.

- **Effect of Mill Pattern:** Taking the second mill out of service while maintaining the same boiler load reduced NO_x emissions at both high (140 MW) and low (110 MW) boiler loads, possibly due to longer residence times in the primary combustion zone.

Introduction

The Micronized Coal Reburn Demonstration Project for NO_x Control at the New York State Electric & Gas tangentially-fired Milliken Unit 1 is part of the DOE Clean Coal Technology Program. The goal is to demonstrate the effectiveness of coal reburning in reducing NO_x emissions utilizing the existing Low-NO_x Concentric Firing System Level 3 (LNCFS-3) burner configuration, thus eliminating the need to install a separate reburn system.

High-volatile bituminous Pittsburgh seam coals were burned during the demonstration testing; the same coal was used as both the primary fuel and the reburn fuel. The evaluation test program consisted of three sequential test programs (Diagnostic, Performance and Long-Term) assessing the effects of the reburn configuration on NO_x emissions and the fly ash loss on ignition (LOI).

The discussion that follows includes: 1) a general review of NO_x control by reburning, with emphasis on coal reburning; 2) a description of the Milliken Unit 1 boiler and the reburn configuration; 3) a description of the overall evaluation test program; 4) a discussion of the Diagnostic test program; 5) a discussion of the Performance test program; and 6) a discussion of the Long-Term test program. The discussion for each test program includes a description of the experimental design and the results.

NO_x Control by Reburning

Reburning is a three-stage combustion modification process for NO_x control. A primary fuel is burned in the main (primary) combustion zone under excess air conditions. Then, a secondary fuel, which can be the same or different from the primary fuel, is introduced downstream of the primary flame at 10%-30% of the total thermal input. Adding the reburn fuel typically creates a fuel rich reburn zone where the nitrogen oxides (NO_x) that are formed in the primary zone react with hydrocarbons to initiate a reaction path favoring N_2 formation. Finally, over fire air is added further downstream to complete the combustion.

The reburning process reduces NO_x emissions due to 1) reactions between NO_x and hydrocarbon radicals in the reburn zone, 2) less thermal NO_x formation, as part of the heat input is diverted from the primary zone to the reburn zone, and 3) less thermal and fuel NO_x formation, as the primary zone is operated at lower excess air levels than those possible without reburning. Generally, reburning can achieve NO_x reductions above 50% relative to uncontrolled levels (without combustion modification).

The variables which effect NO_x reduction by reburning include the operating variables associated with the three combustion stages created by the reburning process: primary, reburn and final. The following is a brief review of the effects of these variables on NO_x emissions.

The primary zone is the main combustion zone prior to reburn fuel introduction. The primary flame is operated fuel-lean (excess air conditions), which is essential to burn the primary fuel and to generate the primary combustion products including NO_x. However, a low excess air level is desired in the primary zone to inhibit primary NO_x generation, to generate a more fuel rich reburn zone using the same amount of reburn fuel, and to lower the oxygen carried over into the reburn zone. Primary zone residence times exceeding 0.3 seconds are desired to achieve sufficient primary fuel burnout and to reduce the oxygen carryover into the reburn zone which might reduce the reburning effectiveness in reducing NO_x emissions (Antifora et al., 1997; Chen et al., 1986). Generally, reburning is less effective at lower primary NO_x concentrations (Chen et al., 1986; Liu et al, 1997; Maly et al., 1997; Yang et al., 1997).

The reburn zone is created by introducing a reburn fuel downstream of the primary flame and is typically operated fuel rich to promote NO_x destruction and N_2 formation. An optimum contribution of reburn fuel for low NO_x emissions is encountered with the introduction of increasing amounts of reburn fuel (Chen et al., 1986; Kolb et al., 1988; Hesselmann, 1997). The optimum is the result of a trade off under fuel-rich conditions between the enhanced destruction of NO_x and the enhanced formation of nitrogenous species (HCN and NH_3) which oxidize as over fire air is added and contribute to the final NO_x emissions. The optimum reburn fuel contribution, typically occurring between 15% and 25% of the total thermal input, depends on the excess air level in the primary zone, the amount of oxidant introduced with the reburn fuel in the transport stream, and the mixing level between the reburn fuel and the primary combustion products. Specifically, higher excess air levels in the primary zone and greater amounts of oxidant introduced with the reburn fuel generate less reducing reburn zones using the same amount of reburn fuel. Better mixing conditions in the reburn zone enhance the NO_x response to the application of reburning, create a less reducing optimum and enhance the reburning performance (Chen et al., 1986; Kolb et al., 1988). Longer reburn zone residence times enhance NO_x destruction, reaching an asymptotic level at 0.5-0.8 seconds (Antifora et al., 1997; Yang et al., 1997).

The final combustion zone of reburning is created by adding over fire air downstream of the reburn fuel introduction location to complete the combustion under overall excess air conditions. The properties of the final zone typically have a minor effect on the final NO_x emissions, but may affect the overall fuel burnout and CO emissions. Specifically, high unburned fuel losses and high CO emissions may occur if insufficient residence time and poor mixing conditions are allowed in the final stage of reburning.

Reburning can utilize any hydrocarbon reburn fuel, including coal, oil or natural gas, with varying NO_x reduction results. In a coal-fired boiler, coal reburning has an advantage over natural gas reburning, since using the same fuel as the primary fuel and the reburn fuel eliminates the need for multiple fuel utilization. Nevertheless, there is a general perception that coal as a reburn fuel may not be as effective as natural gas, possibly generating higher NO_x

emissions and higher unburned fuel losses, as suggested in earlier studies (Chen et al., 1986). That is not necessarily the case, as evident in several recent pilot-scale and full-scale studies demonstrating that coal reburning is capable of generating low NO_x emissions that are competitive with those achievable with natural gas reburning (Hesselmann, 1997; Maly et al., 1997; Mereb and Abbott, 1998; Rhee, 1995). The potential increase in unburned fuel losses due to the application of coal reburning can be mitigated using finer grind reburn fuel, which is the logic leading to the evolution of the concept of micronized coal reburning. Micronized coal is typically defined as coal pulverized to a size consistency of at least 80% passing 325 mesh (44 microns), corresponding to an overall average particle diameter of 15-30 microns.

The DOE Clean Coal Technology Demonstration Program included three commercial-scale demonstrations of coal reburning. The first pulverized coal reburn demonstration was conducted at the Wisconsin Power and Light 110 MW cyclone-fired Nelson Dewey Unit 2 boiler (Babcock & Wilcox, 1994). At full boiler load and 18% reburn, the reburn system reduced NO_x emissions from 0.83 to 0.39 lb/MM Btu (52% reduction) burning an Illinois Basin high-volatile bituminous coal, and from 0.76 to 0.34 lb/MM Btu (55% reduction) burning a Powder River Basin subbituminous coal. Firing bituminous coal, the fly ash loss on ignition was maintained close to baseline levels (9-18%) by increasing the reburn coal fineness level from 80% to 95% passing 200 mesh. The second demonstration utilizing micronized coal reburning (fineness exceeding 90% passing 200 mesh) was conducted at the Eastman Kodak cyclone-fired Boiler 15 (CONSOL, 1999). At full boiler load (400 kpph steam) and 17.3% reburn heat input, NO_x emissions dropped from a baseline (no reburn) of 1.36 to 0.59 lb/MM Btu (57% reduction), the fly ash carbon content increased from 11% to 37%, and the boiler efficiency dropped from 87.8% to 87.3%. The third demonstration utilizing coal reburning was conducted at the New York State Electric & Gas 150 MW tangentially-fired Milliken Unit 1 boiler equipped with Low-NO_x Concentric Firing System Level 3 (LNCFS-3) burners; that is the subject of this study.

Milliken Unit 1 and the Coal Reburn Configuration

The New York State Electric & Gas tangentially-fired Milliken Unit 1 is one of two twin tangentially-fired boilers at the station located in Lansing, New York, on the eastern shore of Cayuga Lake. It is a natural circulation, balanced draft unit, built in 1955 and designed to burn high-volatile bituminous coal. The boiler is designed to generate steam at 1900 psig and 1005 EF at the superheater outlet, with a maximum continuous rating of 900 kpph of superheat steam and 811 kpph of reheat steam, with a maximum load of 150 MW net (160 MW gross).

The boiler was retrofitted with ABB C-E Low-NO_x Concentric Firing System Level 3 (LNCFS-3) burners during the summer of 1993. A detailed description of this low-NO_x burner technology can be found elsewhere (Grusha and Hart, 1993). The LNCFS-3 technology combines the NO_x reducing capabilities of air-staged combustion with early volatile release from the coal. Part of the secondary air, referred to as concentric air, is offset relative to the coal jet and is directed towards the furnace wall. The concentric air is designed to provide a protective air layer against wall slagging and corrosion. Thus, a fuel rich flame can be generated in the lower part of the firebox without creating a reducing environment next to the furnace walls. Another part of the combustion air (up to 40%) is diverted from the main firing zone and introduced downstream as close-coupled and separated over fire air (CCOFA and SOFA).

The Milliken Unit 1 LNCFS-3 configuration consists of four elevations of burners and five over fire air ports (two CCOFA and three SOFA) which provide the operational flexibility in NO_x emissions control. Each burner elevation consists of a coal and primary air nozzle with two coal air nozzles on both sides (up and down), and an auxiliary air nozzle below with two concentric air nozzles on both sides (up and down).

The Milliken Unit 1 coal milling system consists of four DB Riley Stoker MPS 150 mills equipped with dynamic classifiers. Each mill has a design capacity of 36.8 kpph coal (Hardgrove Grindability Index of 57) and supplies coal to one elevation of burners (four corners). The dynamic classifiers provide the flexibility in adjusting the coal fineness to produce fly ash with low loss on ignition (LOI) levels, preferably below 5%. Maintenance and testing of all the mills were performed by DB Riley in early 1997. The top mill was fine tuned to enhance its milling capacity, which allowed pulverization of the top level coal feed to a fineness level of 75% passing 325 mesh.

Reburning was applied at Milliken Unit 1 utilizing the existing LNCFS-3 burner configuration by decoupling the top coal feed from the other three, and utilizing it as reburn fuel in conjunction with reduced air flows through the top burner elevation. The goal was to apply reburning without the installation of a separate reburn system. Specifically, the top burner level air flows were reduced while maintaining reliable burner operation by decreasing the coal air damper position from a typical setting of 85% to 60% open and decreasing the auxiliary air damper position from a typical setting of 25% to less than 10% open. In addition to reduced top burner level air flows, reburning was promoted by diverting portions of the over fire air to higher ports to prolong reburn zone residence times under fuel-rich conditions, and using finer grind reburn fuel (coal fed through top burners) to maintain the fly ash LOI below 5%.

The reliable operation of the coal reburn configuration was established through optimization testing, which was subsequently used to identify the operating limits of the reburn configuration and appropriate settings for long-term operation. The results of the optimization tests were also utilized to evaluate the effectiveness of the reburn configuration in reducing NO_x emissions.

Evaluation Test Program

The objective of the evaluation test program was to demonstrate the effectiveness of coal reburning in reducing NO_x emissions at the New York State Electric & Gas tangentially-fired Milliken Unit 1 utilizing the existing LNCFS-3 burner configuration. The evaluation consisted of three sequential test programs: 1) Diagnostic, 2) Performance, and 3) Long-Term. The diagnostic test program consisted of three phases of short-term (1-3 hours) optimization tests, which were used to obtain parametric data and to identify appropriate operating settings to achieve low NO_x emissions at acceptable fly ash LOI (less than 5%). These operating settings were utilized in subsequent performance and long-term testing. The performance test program consisted of characterization tests, which assessed a detailed set of operating variables. The long-term test program assessed the long-term NO_x emissions performance of the reburn configuration and estimated the annual emissions based on 23 days of continuous measurements.

The evaluation test program focused on coal reburning, and utilized, as baseline, the LNCFS-3 configuration which generated the lowest achievable NO_x emissions, namely, 0.35 lb/MM Btu, while maintaining the fly ash LOI below 5%. The reburn and the baseline test results were compared to assess the impact of the reburn configuration on NO_x emissions and the fly ash LOI. Throughout the test program, a primary consideration was given to maintaining reliable boiler operation for power generation. Consequently, when a set of test conditions could not maintain the required steam conditions, the operating variables were adjusted accordingly or the test was terminated as soon as sufficient data were collected.

The operating data and gas emissions measurements, including NO_x emissions in lb/MM Btu, were obtained from the plant data acquisition system. The operating variables were evaluated with respect to their impact on NO_x emissions and the fly ash LOI. For most tests, the fly ash was sampled during unloading of the first ESP hopper, since that allowed for quick sample extraction (grab sample). However, during the first phase of diagnostic testing, the fly ash was sampled iso-kinetically at the air heater outlet. During performance testing, the fly ash was sampled using both methods (during unloading of the first ESP hopper and iso-kinetically using EPA Method 17 at the ESP inlet as part of the ESP performance evaluation). The fly ash samples were subsequently analyzed for LOI. Where applicable, the LOI results from the two fly ash sampling methods were compared.

High-volatile bituminous Pittsburgh seam coal was burned during the evaluation test program; the same coal was used as both the primary fuel and the reburn fuel. The coal proximate and ultimate analyses and the pulverized coal fineness data, corresponding to the different phases of testing, are presented in Table 1.

Diagnostic Test Program

The goals of the diagnostic test program were: 1) to provide short-term (1-3 hours) parametric data with respect to the effects of the operating variables of the coal reburn configuration on NO_x emissions and the fly ash LOI; and 2) to identify appropriate operating settings for long-term operation that would achieve the lowest NO_x emissions at full boiler load (140-150 MW) while maintaining the required steam conditions, reliable boiler operation and the fly ash LOI below 5%. The diagnostic test program consisted of three phases of optimization testing which were conducted during three time periods spanning 18 months (between March 1997 and September 1998). The top coal mill (mill feeding the reburn fuel) was serviced prior to each phase of optimization testing to assure its milling performance and to allow pulverization to the micronized coal classification (greater than 80% passing 325 mesh).

The first phase of optimization testing was conducted by ABB C-E during March 12-26, 1997 and consisted of 36 tests. The purpose of these tests was to explore the concept of utilizing the existing LNCFS-3 burner configuration to simulate reburning and to assess the operating boundaries of the coal reburn configuration. The results of these tests were subsequently analyzed by CONSOL to assess the effects of several operating variables on NO_x emissions and the fly ash LOI, and to establish guidelines for further optimization testing. A diagnostic matrix consisting of 25 tests was subsequently constructed based on the results of the first phase of optimization testing, as shown in Table 2. Specifically, Table 2 presents the NO_x and LOI results for tests in which several operating variables of interest were varied. The matrix did not include tests which could not be utilized as part of a set to assess the effect of a particular operating variable, or tests which explored specific options to reduce NO_x emissions but were inconclusive.

The matrix in Table 2 included four data sets which were used to assess the coal reburn configuration. Set 1 consisted of two LNCFS-3 tests at two SOFA tilt settings (0 and 15 degrees) which were utilized as baseline in evaluating the reburn performance with respect to NO_x emissions and the fly ash LOI. The other three sets consisted of reburn tests in which the top coal feed was utilized as the reburn fuel and the air flows through the top burner elevations were reduced. Specifically, the top burner air flows were reduced by decreasing the coal air flow from the LNCFS-3 setting (Tests 1 and 2) of about 85% damper opening to the reburn setting of about 60% opening and decreasing the auxiliary air flow from the LNCFS-3 setting (Tests 1 and 2) of about 20% damper opening to the typical reburn setting of less than 10% opening. In addition, reburning was promoted by diverting part of the over fire air to higher ports (from OFA Configuration 0 for LNCFS-3 to OFA Configuration 1 and 2 for reburn, as shown in Table 2), and using finer grind reburn fuel (top coal feed) to maintain low fly ash LOI (goal of less than 5%).

Set 2 in Table 2 consisted of 16 reburn tests corresponding to an over fire air configuration which utilized four ports (OFA Configuration 1 in Table 2) and assessing the effects of the following variables: 1) overall excess air (or economizer O_2 level), 2) reburn coal fineness, 3) top level auxiliary air, 4) SOFA tilt, and 5) reburn coal fraction. Set 3 consisted of six reburn tests corresponding to another over fire air configuration which utilized three ports (OFA Configuration 2 in Table 2). The over fire air configuration for Set 3 (OFA Configuration 2) achieved better reburning performance (lower NO_x emissions and lower LOI) than that for Set 2 (OFA Configuration 1), and was adopted in subsequent reburn testing. Set 3 assessed the effects of the following variables: 1) overall coal fineness, and 2) reburn coal transport air (or top level primary air). Set 4 included a reburn test at reduced boiler load (110 MW), which in combination with the full boiler load (140 MW) Test 18A (in Set 3) assessed the effect of boiler load.

The second phase of optimization testing was conducted by CONSOL/NYSEG during October 7-8, 1997 and consisted of six tests, as shown in Table 3. The over fire air configuration which achieved the best reburning results (lower NO_x emissions and lower LOI), namely, OFA Configuration 2 in Table 2, was utilized in these tests. The tests assessed the effects of the following variables: 1) boiler load, 2) mill pattern (or number of mills in service), and 3) main burner tilt.

The third and final phase of optimization testing was conducted by CONSOL/NYSEG between August 31 and September 2, 1998 and consisted of 11 tests, as shown in Table 4. The effects of the main burner tilt, reburn coal fraction, reburn coal fineness, and over fire distribution were further assessed. Test 8 examined the possibility of improving reburning performance (lower NO_x emissions) by concentrating the over fire air through the highest two SOFA ports, thus prolonging the reburn zone residence time under fuel-rich conditions. However, this configuration (Test 8) did not achieve lower NO_x emissions relative to the one previously tested (OFA Configuration 2, see Test 6) and generated higher fly ash LOI. Two tests compared reburning and LNCFS-3 (Tests 10 and 11, respectively) at reduced boiler load (120 MW) and under conditions that favored low NO_x emissions for each configuration. Specifically, the residence times in the fuel-rich stage of combustion were prolonged by taking out of service the second highest mill for the reburn test (Test 10) and the top mill for the LNCFS-3 test (Test 11). The two tests achieved similar NO_x emissions (0.24-0.25 lb/MM Btu) and similar fly ash LOI (2.0-2.7%) levels. However, the reburning test favored lower LOI; this was attributed to the use of fine grind reburn fuel (top mill classifier speed of 129 rpm).

The results of the three phases of optimization testing (Tables 2, 3 and 4) were further analyzed. The following discussion of the results uses graphical representations of the effects of the operating variables of interest on NO_x emissions and the fly ash LOI. Based on replicated performance tests (discussed in a later section) and a 95% confidence level, variations in NO_x emissions less than 0.006 lb/MM Btu and in fly ash LOI less than 1.5% were assumed to be of no statistical significance.

Figure 1 shows the NO_x emissions and the fly ash LOI results for a LNCFS-3 configuration and a coal reburn configuration, based on the Phase 1 optimization test results (Table 2). Also shown are the effects of varying the SOFA tilt between 0 and 15 degrees above the horizontal.

Variations in the SOFA tilt had minor effects (no trends) on both NO_x emissions and LOI in both LNCFS-3 and reburn configurations. The reburn configuration produced lower NO_x emissions (0.31 lb/MM Btu) than the LNCFS-3 configuration (0.35 lb/MM Btu), and no significant differences in LOI (less than 1.5% absolute), which generally varied between 4.5% and 5.5%.

The variations in the reburn coal transport air (or the top burner primary air) were assessed with respect to the effects on NO_x emissions and the fly ash LOI, based on the Phase 1 optimization test results (Table 2), as shown in Figure 2. The NO_x and LOI results in Figure 2 are presented as functions of the top burner air-to-fuel ratio (lb air per lb coal), which varied between 2.0 and 2.5. A 20% increase in the reburn stream air-to-fuel ratio (from 2.05 to 2.45) increased NO_x emissions from 0.28 to 0.31 lb/MM Btu and had an inconclusive effect on LOI. Lower top burner primary air flows favor lower NO_x emissions, since introducing an oxidant with the reburn fuel consumes part of it, results in a less reducing reburn zone, and reduces the reburning effectiveness in destroying NO_x. The transport air flow is estimated at 20% of the total air flow through a single burner elevation (including primary, coal, concentric and auxiliary).

The effects of varying the top burner level auxiliary air between 0% (closed damper) and 38% open damper position on NO_x emissions and the fly ash LOI were assessed based on the Phase 1 optimization test results (Table 2), as shown in Figure 3. Increasing the top level auxiliary air flow increased both NO_x emissions and LOI. Specifically, an increase from 0 to 20% damper opening increased NO_x emissions from 0.32 to 0.36 lb/MM Btu. The corresponding effect on LOI was less conclusive, with a possible increase between 4% and 5.5%, but not exceeding the uncertainty measurement level (1.5% absolute). The top level auxiliary air nozzle is situated directly below the top level coal and primary air (reburn fuel and transport air) nozzle, and introduces air just upstream of the reburn fuel. This air enters the reburn zone, consumes part of the reburn fuel, creates a less reducing reburn zone, and decreases the reburning effectiveness in destroying NO_x. Furthermore, increasing the top level auxiliary air flow diverts part of the air flow from the primary combustion zone (lower three burner elevations), reducing the excess air level, which may increase LOI. The auxiliary air flow corresponding to a damper position of 20% open is estimated at 10% of the total air flow through a single burner elevation (including primary, coal, concentric and auxiliary).

Figure 4 shows the effects of varying the overall excess air level on NO_x emissions and the fly ash LOI at four reburn coal fineness levels resulting from mill classifier speed settings of 85, 98, 115 and 120 rpm, based on the Phase 1 optimization test results (Table 2). The excess O_2 concentration in the flue gas at the economizer outlet on a wet basis was used as a measure of the overall excess air level. The top mill classifier speed correlated with the reburn coal fineness level, as shown in Table 1. Increasing the excess O_2 generated the classical response of higher NO_x emissions and lower or stable LOI. Differences in the reburn coal fineness produced a small effect on NO_x emissions (generally less than 0.01 lb/MM Btu). Using finer grind reburn coal generally reduced LOI. For example, increasing the top mill classifier speed from a typical LNCFS-3 operating setting of 98 rpm, which corresponded to a fineness of 64% -325 mesh and 87% -200 mesh, to a reburn setting of 115 rpm, which corresponded to a fineness of 72% -325 mesh and 95% -200 mesh, reduced LOI 1.0-1.7% absolute. The sensitivity of NO_x emissions to variations in the excess O_2 was relatively independent of the reburn coal fineness and was estimated at 0.1 lb NO_x/MM Btu per 1% change in O_2 (slope of regression line in Figure 4).

The NO_x emissions and the fly ash LOI results of Figure 4 are presented again in Figure 5, as a function of the top mill classifier speed at two excess O_2 levels (at economizer outlet) of 2.5% and 3.3% (nominal). Also shown in Figure 5 are additional reburn test results at 2.8% excess O_2, based on the Phase 3 optimization test results (Table 4). The Phase 1 tests utilized over fire Configuration 1, whereas the Phase 3 tests utilized over fire Configuration 2 (see Tables 2 and 4). For the three cases shown in Figure 5, using finer reburn coal reduced both NO_x emissions and LOI. The effect on NO_x was significant (relative to the uncertainty level of 0.006 lb/MM Btu) only for relatively large variations in the top mill classier speed. For example, for the Phase 1 test at 3.3% O_2, increasing the top mill classifier speed from 85 to 115 rpm, corresponding to an increase in the fineness level from 54% to 72% passing 325 mesh and from 77% to 95% passing 200 mesh, reduced NO_x emissions from 0.344 to 0.336 lb/MM Btu and reduced LOI from 6.5% to less than 4%. There was an improvement in the reburning performance (lower NO_x emissions and lower LOI) in Phase 3 relative to Phase 1; this was attributed mainly to differences in the over fire air configuration. Phase 3 achieved NO_x emissions below 0.25 lb/MM Btu and LOI below 3.5%.

Figure 6 shows the effects of varying the classifier speed for all mills between 95 and 118 rpm on NO_x emissions and the fly ash LOI, based on the Phase 1 optimization test results (Table 2). In these tests, the four mills were generally operated at the same mill classifier speed. The relationship between the mill classifier speed and the coal fineness is described in Table 1. Also shown in Figure 6 is a comparison between the two over fire configurations previously discussed (OFA Configurations 1 and 2 in Table 2). For both over fire air configurations, using finer coal (higher mill classifier speed) reduced both NO_x emissions and LOI. For example, for Configuration 2, increasing the mill classifier speed from 98 rpm, which corresponded to a fineness of 56% -325 mesh and 81% -200 mesh (average of four mills), to 115 rpm, which corresponded to a fineness of 65% -325 mesh and 91% -200 mesh, reduced NO_x emissions from 0.30 to 0.28 lb/MM Btu and reduced LOI from 5% to 2.5% (estimated from the regression line). Configuration 2, which utilized three over fire air ports, achieved better reburning performance (lower NO_x emissions and lower LOI) than Configuration 1, which utilized four over fire air ports.

The effects of varying the main burner tilt between -10 degrees (below horizontal) and 0 degrees (horizontal) on NO_x emissions and the fly ash LOI were assessed, as shown in Figure 7. Two cases are presented, one based on the Phase 2 optimization test results (Table 3), and another based on the Phase 3 optimization test results (Table 4). In both cases, the results suggest a possible advantage in operating the main burner tilt slightly below the horizontal (e.g. at -5 degrees), with respect to potentially generating lower LOI without an increase in NO_x emissions, relative to the horizontal setting. Lowering the burner tilt allows longer residence times in the furnace prior to over fire air introduction. A burner tilt setting of -5 degrees was selected for long-term operation. Limited tests were available to adequately evaluate the difference in reburning performance between Phases 2 and 3.

The effects of varying the reburn coal fraction between 14% and 25% on NO_x emissions and the fly ash LOI were assessed, as shown in Figure 8. Two cases are presented, one based on the Phase 1 optimization test results (Table 2), and another based on the Phase 3 optimization test results (Table 4). In both cases, higher reburn coal fractions generated higher NO_x emissions and higher or stable LOI. Specifically, increasing the reburn coal contribution from 14% to 25% increased NO_x emissions from 0.30 to 0.33 lb/MM Btu for the Phase 1 test and from 0.23 to 0.25 lb/MM Btu for the Phase 3 test. There was a large uncertainty with respect to the effect on LOI, as indicated by the scatter of the data. Increasing the contribution of the reburn coal (greater top coal feed) creates a more fuel rich reburn zone which favors lower NO_x emissions, but is typically accompanied by greater transport air flow (top burner primary air), shorter reburn zone residence times, reduced coal feeds to the lower burners and higher excess air levels in the primary zone, which promote higher NO_x emissions. Maintaining a low reburn coal fraction (14-16%) achieved lower NO_x emissions and was adopted for long-term operation.

The effects of changing the boiler load between 110 MW and 140 MW on NO_x emissions and the fly ash LOI were assessed, as shown in Figure 9. Two cases are presented, one based on the Phase 1 optimization test results (Table 2) in which the drop in boiler load was accomplished with all the mills in service, and another based on the Phase 2 optimization test results (Table 3) in which the drop in boiler load was accomplished by removing the second highest mill out of service. In both cases, a lower boiler load generated lower NO_x emissions, and the effect was greater in taking the second mill out of service. The lower boiler load generated higher fly ash LOI with all the mills in service and no change in LOI when taking the second mill out of service. It should be noted that a large uncertainty is suspected with respect to the effect on LOI, possibly due to variations within only a relatively narrow range of 3-5% (typical), as observed in the LOI responses to the different variables. Overall, in going from a full boiler load to a reduced boiler load, taking the second mill out of service would be a desired option, as it reduces NO_x emissions, possibly without increasing LOI.

Figure 10 shows the effects of removing the second highest mill out of service on NO_x emissions and the fly ash LOI at two boiler loads (140 MW and 110 MW), based on the Phase 2 optimization test results (Table 3). Taking the second mill out of service reduced NO_x emissions for both boiler loads, increased LOI at the high boiler load (140 MW) and decreased LOI at the low boiler load (110 MW). Again, a large uncertainty is suspected with respect to the effect on LOI. Removing the second mill out of service generates longer residence times in the primary combustion zone (lower three burner elevations) resulting in better primary fuel burnout, less oxygen carryover into the reburn zone, and thus a more fuel rich reburn zone, which may improve reburning performance in reducing NO_x emissions.

The optimization test results were used to identify appropriate operating settings for long-term operation of the coal reburn configuration. These settings achieved the lowest NO_x emissions at full boiler load (140-150 MW) while maintaining the required steam conditions, reliable boiler operation and the fly ash LOI below 5%. These operating conditions were the same as those for Test 9 in Table 4, and those utilized in the performance and the long-term test programs. Specifically, these settings were 14-16% reburn coal, 105 rpm top mill classifier speed, -5 degrees burner tilt and 2.8% economizer O_2.

Performance Test Program

The performance test program consisted of characterization tests assessing a detailed set of boiler and combustion parameters. The goal of this test program was to evaluate the impact of the coal reburn configuration on boiler performance, including NO_x emissions, fly ash LOI, and the boiler efficiency. The operating settings selected for the reburn performance tests were based on the optimization test results, and were those achieving the lowest NO_x emissions at full boiler load (140-150 MW) while maintaining the required steam conditions, reliable boiler operation and the fly ash LOI below 5% (see Phase 3 Optimization Test 9 in Table 4). Similar performance tests conducted in October 1995 to evaluate the LNCFS-3 burner configuration were utilized as baseline tests (Baseline A) in comparing the operating parameters and the boiler efficiency calculations of the reburn and the LNCFS-3 configurations. However, in comparing the performances with respect to NO_x emissions and the fly ash LOI, another LNCFS-3 test conducted in October 1997 (Test 2 in Table 2) was a more suitable choice for use as baseline (Baseline B), as is later discussed.

The reburn performance tests were conducted during September 9, 1998, and included three replicates. A raw coal sample (before milling) was collected and analyzed for heating value, moisture, and proximate and ultimate compositions (Table 1). Each performance test was approximately two hours in duration (data collection period) and was coupled with an ESP performance evaluation test which included EPA Method 17 sampling at the ESP inlet. During each performance test, two fly ash samples were collected: 1) a grab sample during unloading of the first ESP hopper, and 2) an iso-kinetic sample using EPA Method 17 at the ESP inlet. The fly ash samples were analyzed for unburned carbon and ash contents.

The operating parameters for all the performance tests, including the three reburn tests and the two LNCFS-3 (baseline) tests, are presented in Table 5. The flue gas and the fly ash results for the same tests are presented in Table 6.

The replicated performance tests, including three reburn and two LNCFS-3 tests, were used to estimate the measurement uncertainty for both NO_x and LOI. At the 95% confidence level, the uncertainty was estimated at ± 0.003 lb/MM Btu for NO_x, and ± 0.76% for LOI (fly ash sampled during unloading of the first ESP hopper). These uncertainty levels were used in this study to assess the significance of the measured responses. Specifically, differences that were less than twice the uncertainty level were assumed not to be statistically significant in this analysis.

The LOI values of the fly ash samples collected iso-kinetically were 4.6%-4.9% for reburn and 3.5%-3.7% for LNCFS-3. The LOI values of the fly ash samples collected during unloading of the first ESP hopper were 4.7%-5.8% for reburn and 3.0%-3.3% for LNCFS-3. The average difference in LOI values between the two sampling methods was less than 0.4% absolute for both reburn and LNCFS-3 configurations. The difference was of no statistical significance.

The boiler efficiency calculations, presented in Table 7, were based on the American Society of Mechanical Engineers (ASME) Abbreviated Efficiency Test and were conducted as part of the performance test program. Unburned carbon heat losses were calculated based on the assumption that for both reburn and LNCFS-3 (baseline) configurations, 90% of the inlet ash (introduced with the coal feed) escaped the furnace as fly ash and 10% remained as bottom ash. The bottom ash was assumed to contain 1% unburned carbon (no data were available). Differences in the boiler efficiency values between the reburn (88.7%-88.8%) and the LNCFS-3 (88.4%-88.5%) configurations were relatively minor (less than 0.4% absolute) and were mainly due to differences in the flue gas excess O_2 level (differences of up to 2% absolute).

The results of the three reburn performance tests and the two LNCFS-3 performance tests were averaged, as shown in Table 8 (identified as Reburn and Baseline A, respectively). Also shown in Table 8 are the results of a LNCFS-3 test (Phase 1 Optimization Test 2 in Table 2), which was utilized as baseline (identified as Baseline B in Table 8) in comparing the reburn and the LNCFS-3 configurations with respect to NO_x emissions and the fly ash LOI. There were two reasons for selecting this test as baseline instead of the LNCFS-3 performance tests conducted in 1995. First, the LNCFS-3 performance tests were conducted with only three mills in service, which was atypical and made it difficult to compare to the reburn configuration, which utilized all four mills. Second, the LNCFS-3 performance tests did not achieve the lowest NO_x emissions possible within the specified constraint of fly ash LOI less than 5%. Specifically, the NO_x emissions for the LNCFS-3 configuration could be reduced from 0.38 lb/MM Btu (Baseline A) to 0.35 lb/MM Btu (Baseline B), corresponding to an increase in the fly ash LOI from 3.6% to 4.6% (iso-kinetic fly ash samples).

The NO_x emissions and the fly ash LOI results of the reburn configuration (Reburn in Table 8) and the LNCFS-3 configuration (Baseline B in Table 8) were compared. At full boiler load (140-150 MW) and using 14.4% reburn heat input, the coal reburn configuration reduced NO_x emissions from a baseline (LNCFS-3) of 0.35 to 0.25 lb/MM Btu, corresponding to a reduction of 28%, while maintaining the fly ash LOI below 5%.

Long-Term Test Program

The purpose of the long-term test program was to estimate the achievable annual NO_x emissions, and to determine the long-term NO_x reduction effectiveness of the coal reburn configuration. In conducting long-term testing, a time requirement consisting of at least 51 days is recommended to adequately account for the time dependence of the data. The time dependence of long-term gas emissions data was demonstrated in a statistical evaluation conducted by the Control Technology Committee of the Utility Air Regulatory Group (UARG). In this test program, a scheduled annual boiler outage limited the long-term test to only 23 days of continuous measurements. The operating settings for the long-term test were based on the optimization test results, and were the same as those utilized in performance testing. Specifically, the operating settings were those achieving the lowest NO_x emissions at full boiler load (140-150 MW) while maintaining the required steam conditions, reliable boiler operation and the fly ash LOI below 5%.

The long-term test program was conducted following the completion of the last phase (Phase 3) of optimization testing and overlapped with performance testing. The long-term test consisted of 23 days of continuous measurements, starting September 7, 1998, and ending September 29, 1998. The measurements included the operating and gas emissions data (including NO_x emissions in lb/MM Btu) collected as hourly averages, and LOI analyses corresponding to fly ash samples collected 3-5 times daily (typical). A graphical presentation of the hourly averaged NO_x emissions data is shown in Figure 11. Normal boiler load fluctuations and variable contribution of the coal reburn (fluctuating fraction but unchanged reburn coal feed) were represented in the measurements. A representative operating data set for the long-term test is the reburn performance test average, shown in Table 8 (identified as Reburn).

The long-term test hourly averaged data were subsequently combined into daily averages, which were further analyzed to estimate the achievable annual NO_x emissions and the corresponding fly ash LOI. In addition, the hourly averages were further analyzed to assess the effects of two operating variables, the boiler load and the top level auxiliary air flow, on NO_x emissions. The variations of the other operating variables were not sufficiently large to adequately assess their effects.

The achievable annual NO_x emissions were estimated using 10-day rolling averages obtained from the long-term test daily averages. A 10-day rolling average is calculated by averaging 10 continuous daily averages following the initial 10-day lapse and rolling the average from day to day. The daily averages, the 10-day rolling averages and a statistical summary of NO_x emissions, fly ash LOI and selected key operating variables, are presented in Table 9. The achievable annual NO_x emissions were estimated at 0.245 lb/MM Btu with an uncertainty of ± 0.011 lb/MM Btu at the 95% confidence level. The fly ash LOI was estimated at 4.4% with an uncertainty of ± 0.4% at the 95% confidence level. The averaged values (using daily averages) for the operating variables (also shown in Table 9) were 142 MW for the total boiler load, 15.1% for the coal reburn and 2.9% for the boiler O_2 at the economizer outlet. The mill classifier speeds were typically 105-110 rpm for the coal reburn mill and 94-101 rpm for the other three mills. The main burner tilt was mostly unchanged at -5 degrees.

The hourly averages obtained from the long-term measurements were further analyzed to assess the effects of the boiler load and the top level auxiliary air flow on NO_x emissions. Increasing the boiler load from 120-130 MW to 140-150 MW increased NO_x emissions from 0.239 to 0.250 lb/MM Btu. Increasing the top level auxiliary air flow from 0% (closed damper position) to 20% open damper position increased NO_x emissions from 0.235 to 0.266 lb/MM Btu.

A second long-term test will be initiated during summer 1999, and is expected to continue for at least 51 days. The results of this test will be subsequently analyzed and documented in an addendum to the final report.

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Table 1. Test Program Coal Analyses and Fineness Data.

Coal Analyses:

Date	Test	Total H_2O %	Dry VM %	Dry Btu/lb	Dry C %	Dry H %	Dry N %	Dry S %	Dry Ash %
Baseline Performance Testing									
10/21/95	Overall[+]	7.80	38.49	13970	78.78	4.98	1.57	1.92	7.39
Reburn Optimization Testing, Phase 1									
03/07/97	Overall[+]	5.5	37.0	13800	77.5	5.1	1.2	2.2	8.0
Reburn Optimization Testing, Phase 2									
10/07/97	01	5.42	40.11	13910	76.87	4.93	1.51	3.14	7.94
10/07/97	03	5.42	40.88	14190	78.35	4.99	1.55	2.52	6.67
Reburn Optimization Testing, Phase 3									
08/31/98	01	--	38.42	13861	76.80	4.91	1.49	2.92	8.21
09/01/98	04	--	38.85	13967	76.21	4.77	1.51	2.88	7.77
09/01/98	05	--	39.15	13969	76.59	4.87	1.46	2.85	7.76
09/02/98	06	--	39.17	13948	76.56	4.95	1.45	2.84	7.79
Reburn Performance Testing									
09/09/98	Overall[+]	6.09	39.15	13944	77.63	5.12	1.45	2.98	7.80

Pulverized Coal Fineness Data (Sieve Mesh Size):

Date	Test	Classifier Speed rpm	Reburn Mill -325 %	Reburn Mill -200 %	Other Mills -325 %	Other Mills -200 %
Reburn Optimization Testing, Phase 1						
March 97	Overall[*]	85	54	77	33	59
March 97	Overall[*]	98	64	87	53	79
March 97	Overall[*]	115	72	95	63	89
March 97	Overall[*]	130	74	97	--	--
Reburn Optimization Testing, Phase 2						
10/07/97	01	96	68	90		
10/07/97	03	131	80	99		
Reburn Optimization Testing, Phase 3						
08/31/98	01	98	63	87		
09/01/98	04	116	75	97		
09/01/98	05	133	83	100		
09/02/98	06	98	68	92		

[+] Sampled Before Milling

[*] Correlated Data:

Reburn Mill: $\% -325 = -95 + 2.6*rpm - 0.01*rpm^2$; $\% -200 = \% -325 + 23$

Other Mill: $\% -325 = -345 + 7.0*rpm - 0.03*rpm^2$; $\% -200 = \% -325 + 26$

Table 2. Optimization Test Matrix, Phase 1 (Conducted by ABB C-E).

Test	Date	Time	Boiler		Reb	Top	Other	Burner Tilt		Reb		Damper, % Open		Boiler	NO_x	
No.	in 1997	Period	Load MW	Coal %	Mill rpm	Mill rpm	Main Deg.	SOFA Deg.	A/F lb/lb	Aux Air Top	Aux Air Low	Coal Air Top	Coal Air Low	O_2 %	lb/ MMBtu	LOI %
Set 1: LNCFS-3 and OFA Configuration[*] 0 [0, 50, 100, 50, 0]																
- SOFA Tilt Variation																
01	03/12	09:05-10:05	139	25.0	97	96	-2.5	15.1	2.13	20	19	86	69	3.12	0.356	4.69
02	03/12	11:00-12:00	142	25.0	97	96	-3.4	0.1	2.13	19	18	85	69	3.15	0.352	4.60
Set 2: Reburn with OFA Configuration[*] 1 [100, 50, 10, 35, 0]																
- Boiler O_2 and Reburn Coal Fineness Variation																
03B	03/12	16:00-17:00	142	25.1	98	96	-0.3	0.2	2.20	1	25	59	99	3.28	0.340	5.14
04	03/13	08:15-09:15	140	25.0	98	97	0.1	0.0	2.23	0	7	60	100	2.59	0.281	6.16
05	03/13	10:30-11:30	140	25.1	97	97	0.1	0.1	2.22	1	29	60	100	3.80	0.416	3.88
07	03/13	14:30-15:30	140	25.2	115	97	0.1	0.1	2.23	1	16	60	99	3.30	0.337	3.97
08	03/17	08:15-09:15	141	24.7	115	96	0.1	0.5	2.21	24	24	60	100	3.42	0.389	4.86
09	03/13	16:45-17:45	140	25.3	115	97	-0.1	0.1	2.23	1	5	60	99	2.48	0.275	4.59
10	03/17	10:10-11:10	140	24.7	115	96	0.1	0.6	2.21	19	19	60	100	3.07	0.347	4.40
26	03/25	16:40-17:40	139	22.6	85	96	-0.3	1.0	2.43	1	22	60	100	3.23	0.345	6.67
- Top Level Auxiliary Air Variation																
12	03/19	16:05-17:05	142	22.3	119	98	-0.4	-0.4	2.42	8	16	60	99	3.00	0.332	4.39
28	03/14	10:45-11:45	146	24.0	115	105	-0.1	0.2	2.24	38	38	60	100	3.30	0.408	5.77
- SOFA Tilt Variation																
13A	03/19	13:30-14:30	141	22.8	106	117	-0.4	15.2	2.35	9	14	60	99	3.01	0.307	5.06
13B	03/20	17:30-18:30	140	21.8	119	110	-0.2	0.6	2.42	12	12	60	99	2.87	0.294	2.86

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[*] OFA configuration: OFA port % damper open, [top SOFA, mid SOFA, low SOFA, top CCOFA, low CCOFA]

Table 2. (Continued)

Test No.	Date in 1997	Time Period	Boiler Load MW	Coal %	Reb Mill rpm	Top Mill rpm	Other Main Deg.	Burner Tilt SOFA Deg.	A/F lb/lb	Reb Aux Air Top	Reb Aux Air Low	Damper, % Open Coal Air Top	Damper, % Open Coal Air Low	O_2 %	Boiler lb/ MMBtu	NO_x LOI %
Set 2 (Continued): Reburn with OFA Configuration* 1 [100, 50, 10, 35, 0]																
- Reburn Coal Fraction Variation																
19	03/18	08:30-09:30	139	22.4	120	98	-0.4	4.7	2.37	1	15	59	99	3.05	0.309	5.38
20	03/18	10:30-11:30	139	19.1	115	99	-0.4	4.7	2.69	1	14	59	99	2.99	0.309	4.54
21	03/18	16:15-17:15	139	15.6	127	99	-0.4	4.7	3.11	1	16	59	99	3.04	0.312	4.00
23	03/24	15:35-16:35	140	14.4	133	107	-0.5	1.1	3.32	3	13	60	100	2.98	0.295	4.30
Set 3: Reburn with OFA Configuration* 2 [100, 0, 100, 100, 0]																
- Overall Coal Fineness Variation																
16	03/20	11:05-12:05	141	25.1	97	97	-0.2	0.5	2.23	5	5	60	80	2.83	0.298	4.08
18A	03/20	13:55-14:55	141	22.6	125	116	-0.2	0.6	2.36	3	3	60	80	2.78	0.282	2.31
18B	03/24	13:05-14:05	140	24.9	105	104	-0.5	1.1	2.23	6	5	60	80	3.01	0.290	2.01
- Reburn Coal Transport Air Variation																
24	03/25	08:35-09:35	140	24.9	104	104	-0.3	0.9	2.45	1	0	60	81	3.00	0.305	4.20
25	03/25	10:55-11:55	139	25.0	104	104	-0.2	1.0	2.07	5	5	60	81	3.07	0.285	4.37
27	03/25	14:10-15:10	140	24.9	95	95	-0.3	1.0	2.28	4	4	60	81	3.09	0.299	5.43
Set 4: Reburn with OFA Configuration* 2 [75, 0, 75, 75, 0]																
- Reduced Boiler Load Test																
29	03/25	22:05-23:05	111	18.4	131	118	-0.2	0.3	3.30	1	2	59	80	2.41	0.253	4.28

* OFA configuration: OFA port % damper open, [top SOFA, mid SOFA, low SOFA, top CCOFA, low CCOFA]

Table 3. Optimization Test Matrix, Phase 2 (Conducted by CONSOL/NYSEG).

Test	Date	Time	Boiler		Reb	Top	Other	Burner Tilt	Reb		Damper, % Open			Boiler	NO_x
No.	in	Period	Load	Coal	Mill	Mill	Main	SOFA	A/F	Aux Air		Coal Air		O_2	lb/	LOI
	1997		MW	%	rpm	rpm	Deg.	Deg.	lb/lb	Top	Low	Top	Low	%	MMBtu	%
Reburn with OFA Configuration[*] 2, [100, 0, 100, 100, 0] at 140 MW, [75, 0, 75, 75, 0] at 110 MW																
- Boiler Load and Main Burner Tilt Variations, Four Mills on																
01A	10/07	08:45-09:45	140	25.0	96	98	0.1	-0.3	2.12	11	11	60	87	2.84	0.301	3.55
01B	10/07	10:30-11:00	147	25.0	97	97	-10.3	-0.3	2.05	6	6	60	87	2.85	0.266	3.06
02	10/07	12:30-13:30	111	17.9	132	117	-0.2	-0.3	2.98	17	17	60	87	2.62	0.272	3.94
- Boiler Load and Main Burner Tilt Variation, Second Highest Mill out of Service																
03	10/07	15:00-16:00	110	19.1	131	103	-0.1	-0.3	2.98	10	17	60	100	2.69	0.240	1.41
04	10/08	12:00-13:00	142	31.0	127	98	-8.2	0.4	1.89	8	29	60	100	2.81	0.252	4.09
05	10/08	14:00-15:00	110	33.3	97	98	-1.6	0.4	2.11	10	8	60	100	2.86	0.229	3.60

[*] OFA configuration: OFA port % damper open, [top SOFA, mid SOFA, low SOFA, top CCOFA, low CCOFA]

Table 4. Optimization Test Matrix, Phase 3 (Conducted by CONSOL/NYSEG).

Test	Date	Time	Boiler		Reb	Top	Other	Burner Tilt		Reb		Damper, % Open			Boiler	NO_x
No.	in 1998	Period	Load MW	Coal %	Mill rpm	Mill rpm	Main Deg.	SOFA Deg.	A/F lb/lb	Aux Air Top	Aux Air Low	Coal Air Top	Coal Air Low	O_2 %	lb/ MMBtu	LOI %
Reburn with OFA Configuration[*] 2 [100, 0, 100, 100, 0]																
- Main Burner Tilt Variation																
01	08/31	10:00-12:00	140	24.9	98	98	-0.0	1.0	2.21	6	12	59	80	2.80	0.253	2.79
02	08/31	12:30-14:30	140	25.0	98	98	-5.5	1.0	2.20	5	11	59	80	2.78	0.256	2.16
03	08/31	15:00-17:00	140	25.1	98	98	-10.0	1.0	2.20	7	10	59	80	2.84	0.250	3.43
- Reburn Coal Fraction and Fineness Variations																
04	09/01	08:30-10:30	140	19.4	116	99	-0.2	0.1	2.51	2	6	60	80	2.81	0.232	3.09
05	09/01	11:00-13:00	140	15.5	133	100	-0.2	0.1	2.95	7	4	60	80	2.81	0.236	1.86
06	09/02	09:00-10:15	139	15.6	98	99	-0.2	0.1	2.95	8	0	61	83	2.81	0.241	2.14
07	09/01	15:00-17:00	140	19.4	98	99	-0.2	0.1	2.51	10	6	60	80	2.81	0.238	3.31
Reburn with Maximum Air Staging, OFA Configuration[*] [100, 100, 0, 0, 0]																
08	09/02	10:30-12:00	139	15.5	98	99	-0.2	0.1	2.95	7	17	60	83	2.83	0.235	4.13
Comparing Reburning (Second Mill Out) and Air Staging (Top Mill Out), OFA Configuration[*] 2 [75, 0, 75, 75, 0]																
10	09/01	18:30-20:00	122	18.6	129	104	-0.2	0.1	2.85	6	27	60	80	2.83	0.247	2.02
11	09/01	21:15-23:15	124	0.0	0	101	-0.2	0.1	0.00	19	39	1	80	2.76	0.240	2.71
Reburn Operating Conditions for Long-Term Operation, OFA Configuration[*] [100, 0, 100, 100, 0]																
09	09/02	13:30-14:30	147	14.7	105	100	-4.7	0.1	2.94	14	10	60	83	2.79	0.247	2.58

[*] OFA configuration: OFA port % damper open, [top SOFA, mid SOFA, low SOFA, top CCOFA, low CCOFA]

Table 5. Performance Test Operating Parameters.

		Micronized Coal Reburn				**Baseline A**	
Performance Test		1	2	3		1	2
Test Year		1998	1998	1998		1995	1995
Test Date		09/09	09/09	09/09		10/21	10/21
Test Start Time	11:00	14:00	16:30		09:00		12:00
Test End Time		13:00	16:00	18:30		10:00	13:00
Gross Boiler Load, MW		155	152	156		154	150
Net Boiler Load, MW		146	143	148		145	141
Total Coal Feed, tph		55.8	54.9	56.4		54.6	54.6
Reburn Coal, %	14.4	14.6	14.2		33.3		33.3
Reburn Mill Classifier Speed, rpm	108	108	108		102		102
Other Mill Classifier Speed, rpm	99	98	99		100		100
Primary Air Flow, kpph		224	223	225		192	192
Primary Air Temperature, EF		150	150	150		174	173
Reburn Coal Transport Air, kpph	48	48	48		65	65	
Other Primary Air, kpph	59	59	59		64	64	
Secondary Air Flow, kpph		881	857	870		952	930
Top Auxiliary Air, % Damper Open		13	10	10		80	80
Other Auxiliary Air, % Damper Open		11	10	10		80	80
Top Coal Air, % Damper Open		60	60	60		100	100
Other Coal Air, % Damper Open	83	83	83		100		100
Top SOFA, % Damper Open		100	100	100		2	2
Mid SOFA, % Damper Open		1	1	1		1	1
Low SOFA, % Damper Open		101	101	101		90	90
Top CCOFA, % Damper Open		100	100	100		100	100
Low CCOFA, % Damper Open		1	1	1		100	100
Main Burner Tilt, Degrees		-5.3	-5.3	-5.4		-5.4	-5.4
SOFA Tilt, Degrees		0.2	0.2	0.2		-0.3	-0.3
Economizer Outlet Gas Temperature EF		681	680	681		--	--
Air Heater Outlet Gas Temperature, EF		314	313	315		304	298
Main Steam Flow, kpph	1094	1070	1102		1046		1012
Main Steam Temperature, EF		997	994	998		1004	1005
Main Steam Pressure, psig		1846	1846	1848		1839	1837
Reheater Steam Temperature, EF	1003	1001	1005		1004		1007
Reheater Steam Pressure, psig		462	452	466		441	427
Feed Water Flow, kpph		1081	1057	1091		1030	994
Feed Water Temperature, EF		474	472	475		469	466
Feed Water Pressure, psig		1964	1960	1967		1948	1942

Table 6. Performance Test Flue Gas and Fly Ash Results.

	Micronized Coal Reburn			**Baseline A**	
Performance Test	1	2	3	1	2
Flue Gas Emissions					
Boiler O_2 Wet, %	2.65	2.72	2.65	3.55	3.49
ESP Inlet O_2 Dry, %	6.3	6.2	6.0	7.6	8.0
ESP Inlet H_2O Wet, %	7.36	6.85	7.28	6.66	6.26
NO_x, lb/MM Btu	0.256	0.253	0.251	0.381	0.380
SO_2, lb/MM Btu	4.17	4.22	4.14	2.53	2.64
Fly Ash Emissions					
Opacity, %	3	2	2	4	4
ESP Inlet Temperature, EF	296	297	300	289	287
ESP Inlet Particulate Loading, lb/h	9879	8620	9160	7974	6396
ESP Outlet Particulate Loading, lb/h	31	15	6	--	--
ESP Collection Efficiency, %	99.7	99.8	99.9	--	--
Fly Ash Analysis: Iso-Kinetic Sampling					
C, %	3.51	3.79	3.78	2.99	3.01
S, %	0.63	0.54	0.53	0.43	0.33
Ash, %	95.41	95.37	95.10	96.29	96.51
LOI, %	4.59	4.63	4.90	3.71	3.49
Fly Ash Analysis: Sampling the First ESP Hopper					
C, %	3.93	3.27	3.43	2.65	2.98
Ash, %	94.19	95.35	95.25	96.98	96.71
LOI, %	5.81	4.65	4.75	3.02	3.29

Table 7. Performance Test Boiler Efficiency Calculations.

		Micronized Coal Reburn					**Baseline A**
Performance Test		1	2	3		1	2
ESP Inlet Temp EF		296	297	300		289	287
Flue Gas Composition by Volume:							
CO_2, %	12.7	12.8	13.0		11.7	11.4	
O_2, %		6.3	6.2	6.0		7.6	8.0
CO, ppm		0	0	0		0	0
N_2, %		81.0	81.0	81.0		80.7	80.6
Coal Analysis, Dry Basis:							
% C		77.63	77.63	77.63		78.78	78.78
% H		5.12	5.12	5.12		4.98	4.98
% N		1.45	1.45	1.45		1.57	1.57
% S		2.98	2.98	2.98		1.92	1.92
% O		5.02	5.02	5.02		5.36	5.36
% Ash		7.80	7.80	7.80		7.39	7.39
Btu/lb		13944	13944	13944		13970	13970
H_2O (Wet Basis)	6.09	6.09	6.09		7.80	7.80	
Ash Analysis, Dry Basis:							
% Ash		95.41	95.37	95.10		96.29	96.51
% C		3.51	3.79	3.78		2.99	3.01
% S		0.63	0.54	0.53		0.43	0.33
Calculations, Based on 1 lb of As-Fired Fuel, Dry Basis:							
Fly Ash, % Inlet (estimate)		90	90	90		90	90
Fly Ash, lb		0.069	0.069	0.069		0.064	0.064
Bottom Ash, lb		0.007	0.007	0.007		0.007	0.007
C Burnout, lb		0.727	0.726	0.726		0.724	0.724
Gas, lb		14.64	14.54	14.35		15.71	16.17
Heat Losses, %:							
1. Dry Gas		5.80	5.78	5.79		6.12	6.24
2. H_2O in Fuel		0.53	0.53	0.53		0.69	0.69
3. H in Fuel		3.79	3.79	3.79		3.67	3.66
4. Flue Gas CO		0.00	0.00	0.00		0.00	0.00
5. Unburned C		0.28	0.30	0.30		0.22	0.22
6. Radiation		0.21	0.21	0.21		0.21	0.21
7. H_2O in Air		0.12	0.12	0.12		0.12	0.12
8. Unmeasured		0.50	0.50	0.50		0.50	0.50
Efficiency, %		88.78	88.77	88.76		88.47	88.35

Table 8. Performance Test Summary.

	Reburn	Baseline A	Baseline B
Date	09/98	10/95	10/97
Mills Out of Service	None	No. 2	None
Gross Boiler Load, MW	154	152	152
Net Boiler Load, MW	146	143	142
Total Coal Feed, tph	55.7	54.6	53.7
Reburn Coal, %	14.4	33.3	25.0
Reburn Mill Classifier Speed, rpm	108	102	97
Other Mill Classifier Speed, rpm	99	100	96
Primary Air Flow, kpph	224	192	233
Primary Air Temperature, EF	150	173	171
Reburn Coal Transport Air, kpph	48	65	57
Other Primary Air, kpph	59	64	59
Secondary Air Flow, kpph	869	941	851
Top Auxiliary Air, % Damper Open	11	80	19
Other Auxiliary Air, % Damper Open	10	80	18
Top Coal Air, % Damper Open	60	100	85
Other Coal Air, % Damper Open	83	100	69
Top SOFA, % Damper Open	100	2	1
Mid SOFA, % Damper Open	1	1	50
Low SOFA, % Damper Open	101	90	100
Top CCOFA, % Damper Open	100	100	50
Low CCOFA, % Damper Open	1	100	1
Main Burner Tilt, Degrees	-5.3	-5.4	-3.4
SOFA Tilt, Degrees	0.2	-0.3	0.1
Economizer Outlet Gas Temperature EF	681	--	687
Air Heater Outlet Gas Temperature, EF	314	301	308
Main Steam Flow, kpph	1088	1029	1026
Main Steam Temperature, EF	996	1005	998
Main Steam Pressure, psig	1847	1838	1841
Reheater Steam Temperature, EF	1003	1006	1002
Reheater Steam Pressure, psig	460	434	--
Feed Water Flow, kpph	1076	1012	1020
Feed Water Temperature, EF	474	468	--
Feed Water Pressure, psig	1964	1945	1944
Boiler O_2 Wet, %	2.68	3.52	3.15
ESP Inlet O_2 Dry, %	6.2	7.8	--
ESP Inlet H_2O Wet, %	7.16	6.46	--
NO_x, lb/MM Btu	0.253	0.381	0.352
SO_2, lb/MM Btu	4.18	2.59	--
Opacity, %	2	4	13
ESP Inlet Temperature, EF	298	288	--
Fly Ash LOI, Iso-Kinetic, %	4.71	3.60	4.60
Fly Ash LOI, First ESP Hopper, %	5.07	3.16	--
Boiler Efficiency, %	88.77	88.41	--

Table 9. Long-Term Test Daily and 10-Day Rolling Averages.

	Daily Averages				10-Day Rolling			
Day in 1998	**Boiler Load MW**	**Reburn Coal %**	**O_2 %**	**Boiler lb/ MMBtu**	**NO_x Ash % LOI**	**Fly lb/ MMBtu**	**NO_x Ash % LOI**	**Fly**
07-September	139	15.4	3.0	0.26	4.13			
08-September	136	15.7	2.9	0.26	3.82			
09-September	137	15.5	2.8	0.25	3.93			
10-September	136	15.5	2.9	0.24	3.73			
11-September	138	15.3	2.8	0.23	3.64			
12-September	141	15.1	2.8	0.23	4.10			
13-September	138	15.4	2.8	0.22	4.47			
14-September	139	15.4	2.8	0.23	4.28			
15-September	145	15.0	2.9	0.25	4.26			
16-September	142	15.2	2.9	0.23	4.10	0.24	4.0	
17-September	145	14.8	2.8	0.24	4.31	0.24	4.1	
18-September	139	15.2	2.9	0.24	5.30	0.24	4.2	
19-September	144	14.8	2.8	0.25	4.63	0.24	4.3	
20-September	144	14.9	2.8	0.26	4.55	0.24	4.4	
21-September	144	14.9	2.8	0.26	4.49	0.24	4.4	
22-September	145	14.8	2.8	0.25	5.09	0.24	4.5	
23-September	142	15.1	2.9	0.23	4.32	0.24	4.5	
24-September	146	14.9	2.8	0.24	4.26	0.25	4.5	
25-September	141	15.2	2.9	0.25	4.65	0.25	4.6	
26-September	148	14.5	2.8	0.27	4.54	0.25	4.6	
27-September	148	14.6	2.8	0.26	4.87	0.25	4.7	
28-September	144	15.0	2.9	0.27	4.36	0.25	4.6	
29-September	141	15.3	2.9	0.25	4.85	0.25	4.6	
Statistical Summary								
Count	23	23	23	23	23	14	14	
Minimum	136	14.5	2.8	0.22	3.6	0.238	4.05	
Maximum	148	15.7	3.0	0.27	5.3	0.254	4.67	
Average	142	15.1	2.9	0.25	4.4	0.245	4.43	
Standard Deviation						0.005	0.20	
95% Confidence Level						0.011	0.43	

Figure 1. Comparing LNCFS-3 and Reburning at Various SOFA Tilt, Phase 1 Optimization Tests.

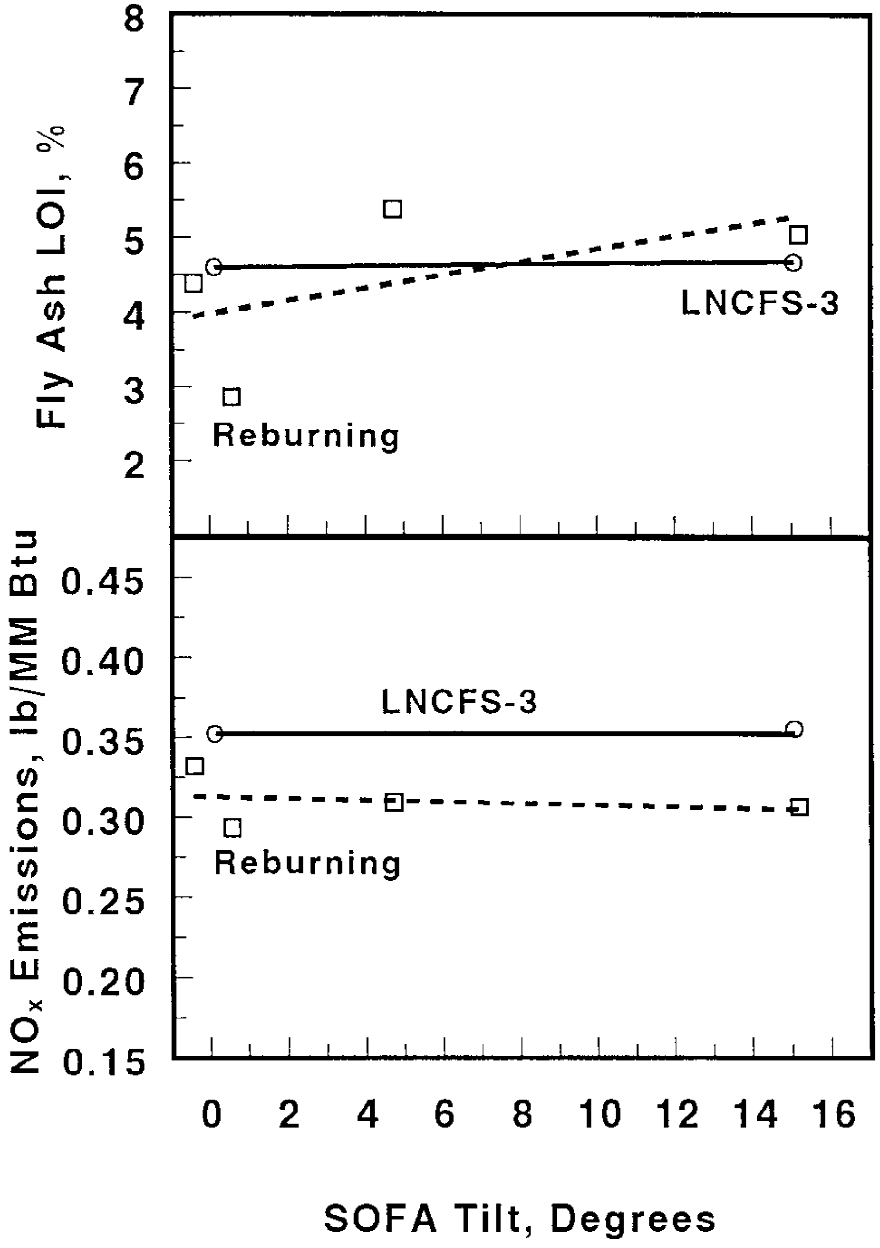

Figure 2. Effect of Reburn Coal Transport Air, Phase 1 Optimization Tests.

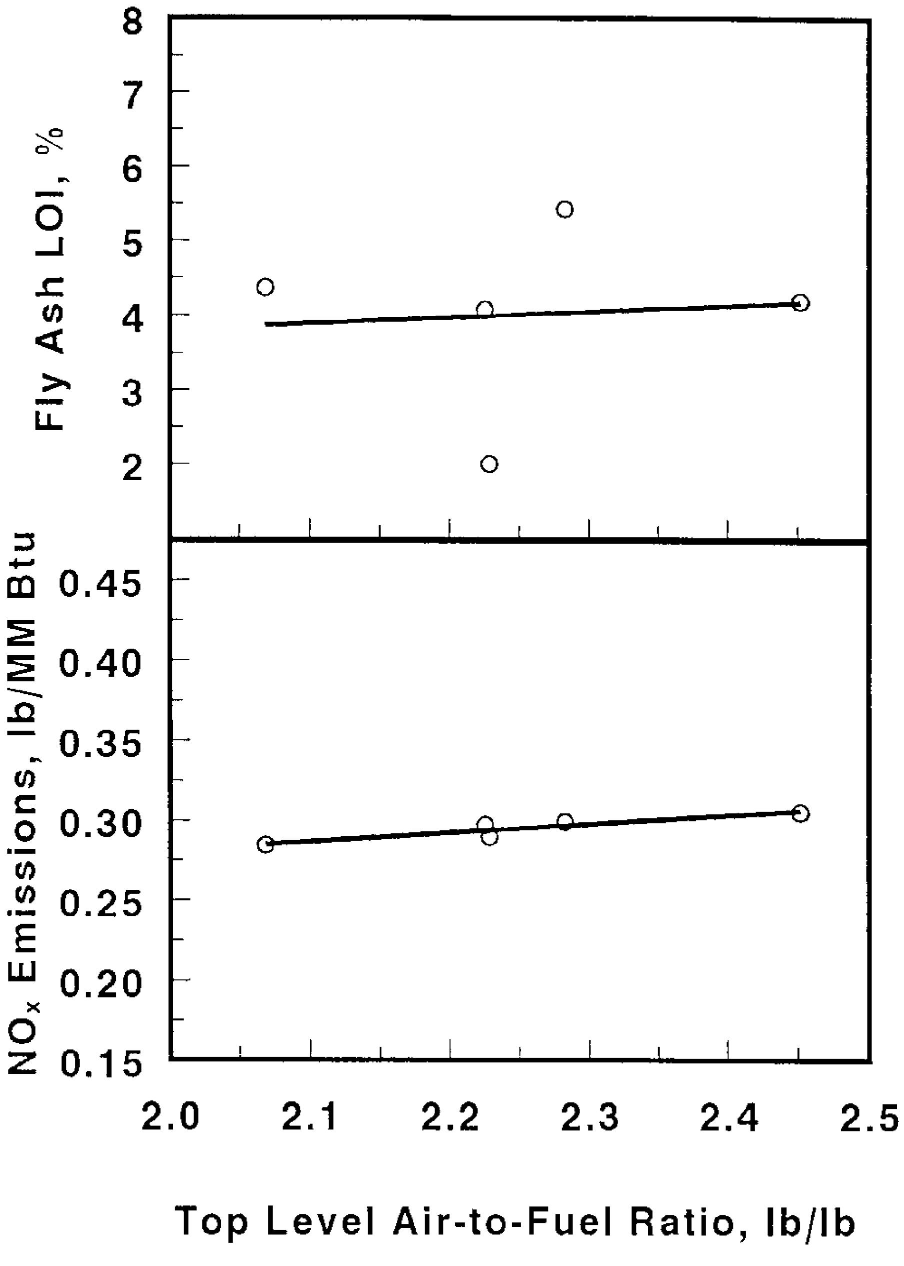

Figure 3. Effect of Top Level Auxiliary Air, Phase 1 Optimization Tests.

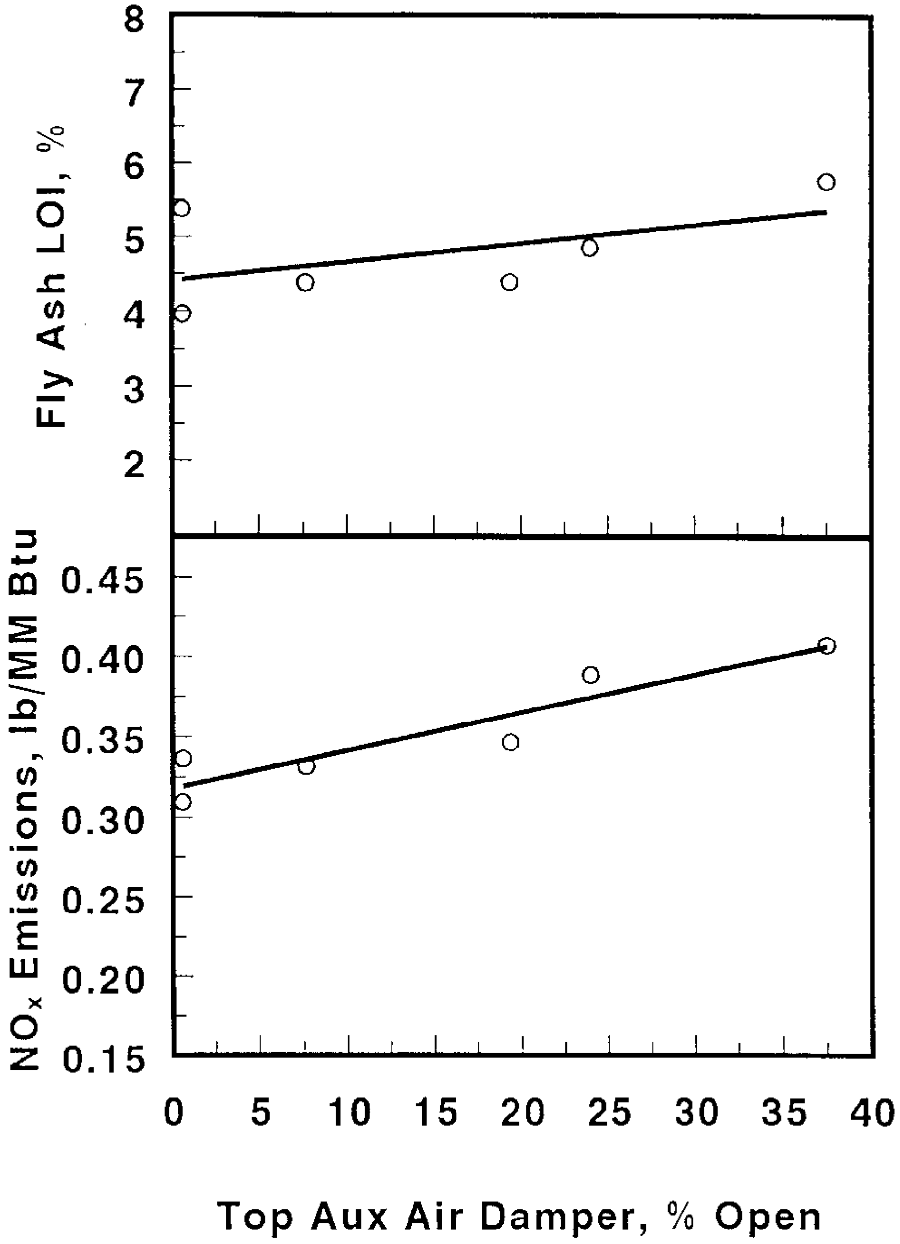

Figure 4. Effect of Overall Excess Air, Phase 1 Optimization Tests.

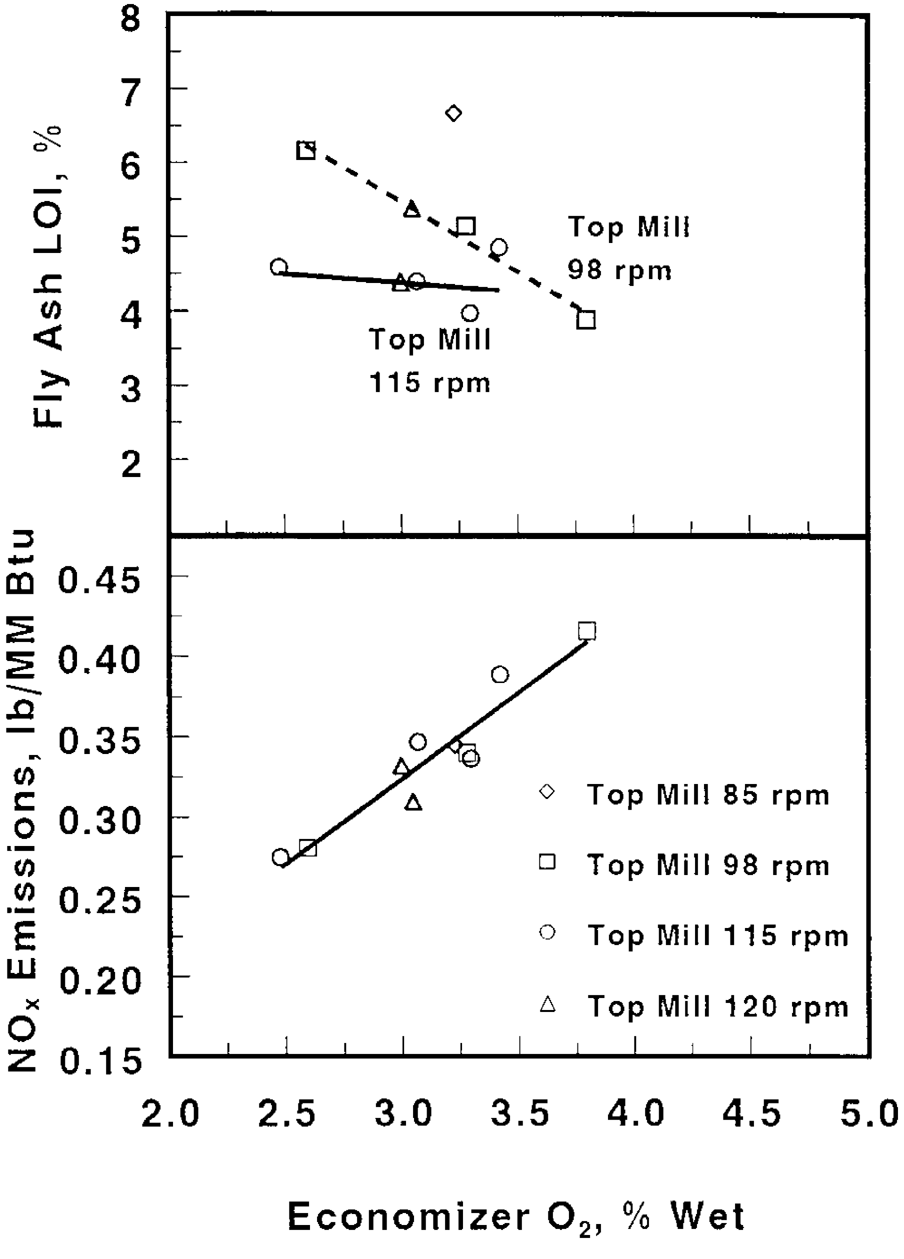

Figure 5. Effect of Reburn Coal Fineness, Phases 1 and 3 Optimization Tests.

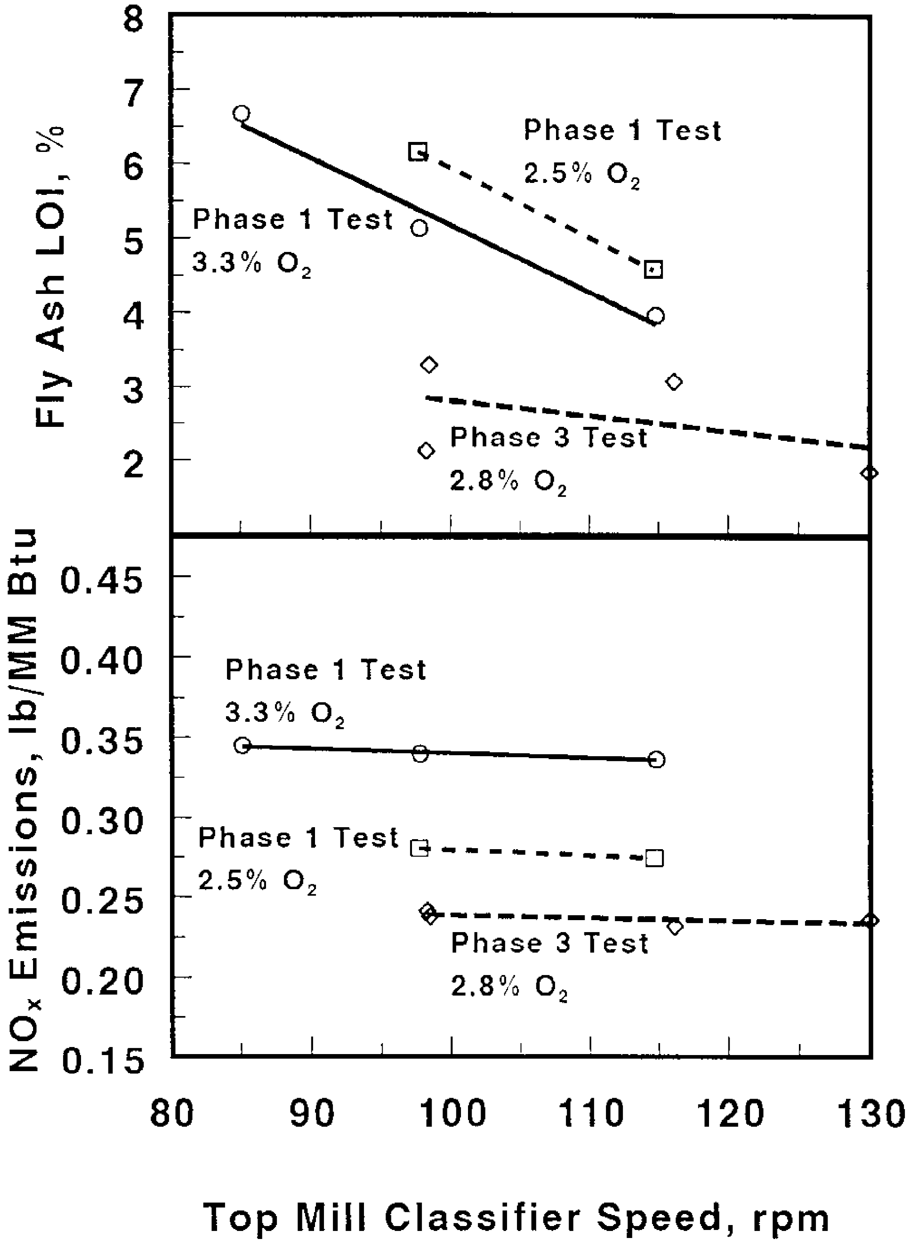

Figure 6. Effect of Overall Coal Fineness and Over Fire Air Configuration, Phase 1 Optimization Tests.

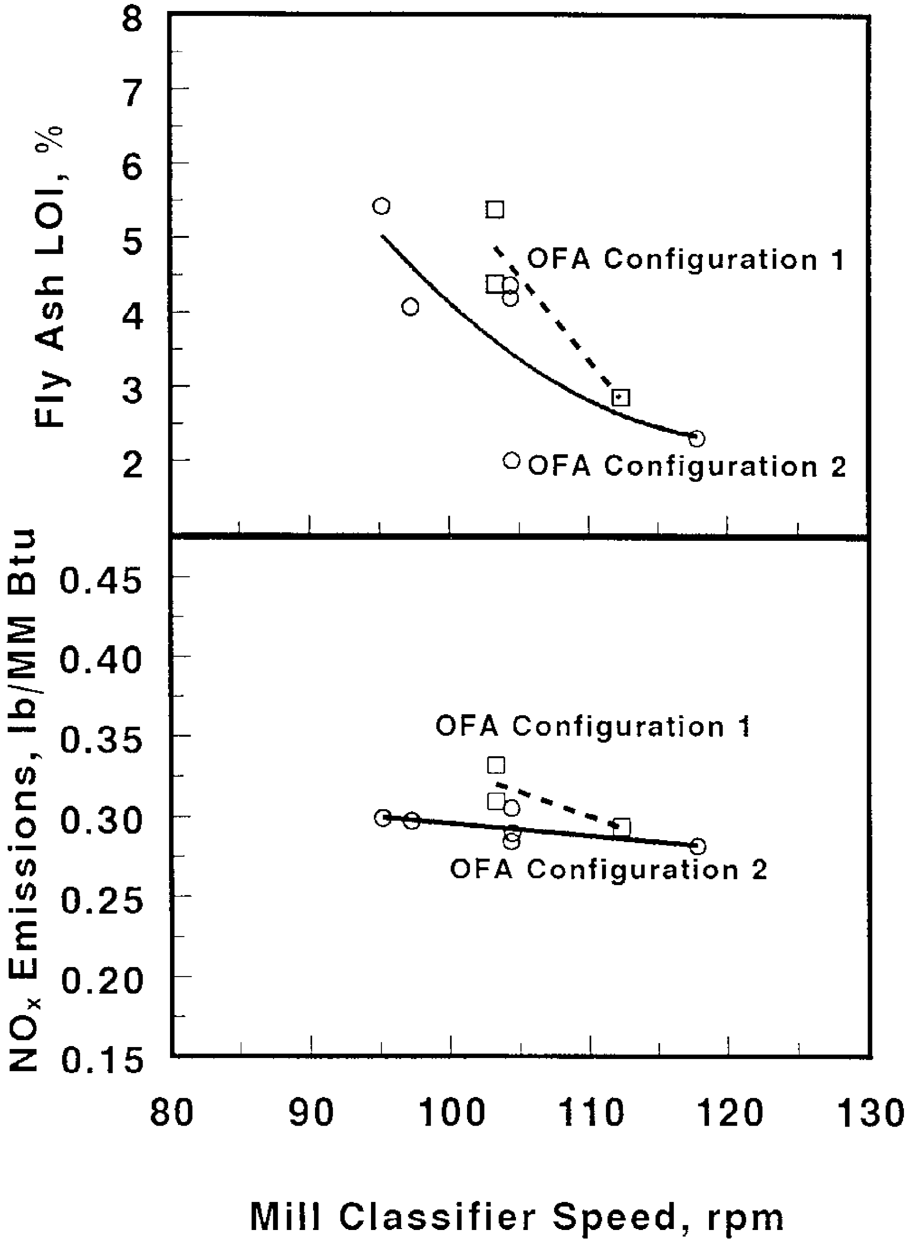

Figure 7. Effect of Main Burner Tilt, Phases 2 and 3 Optimization Tests.

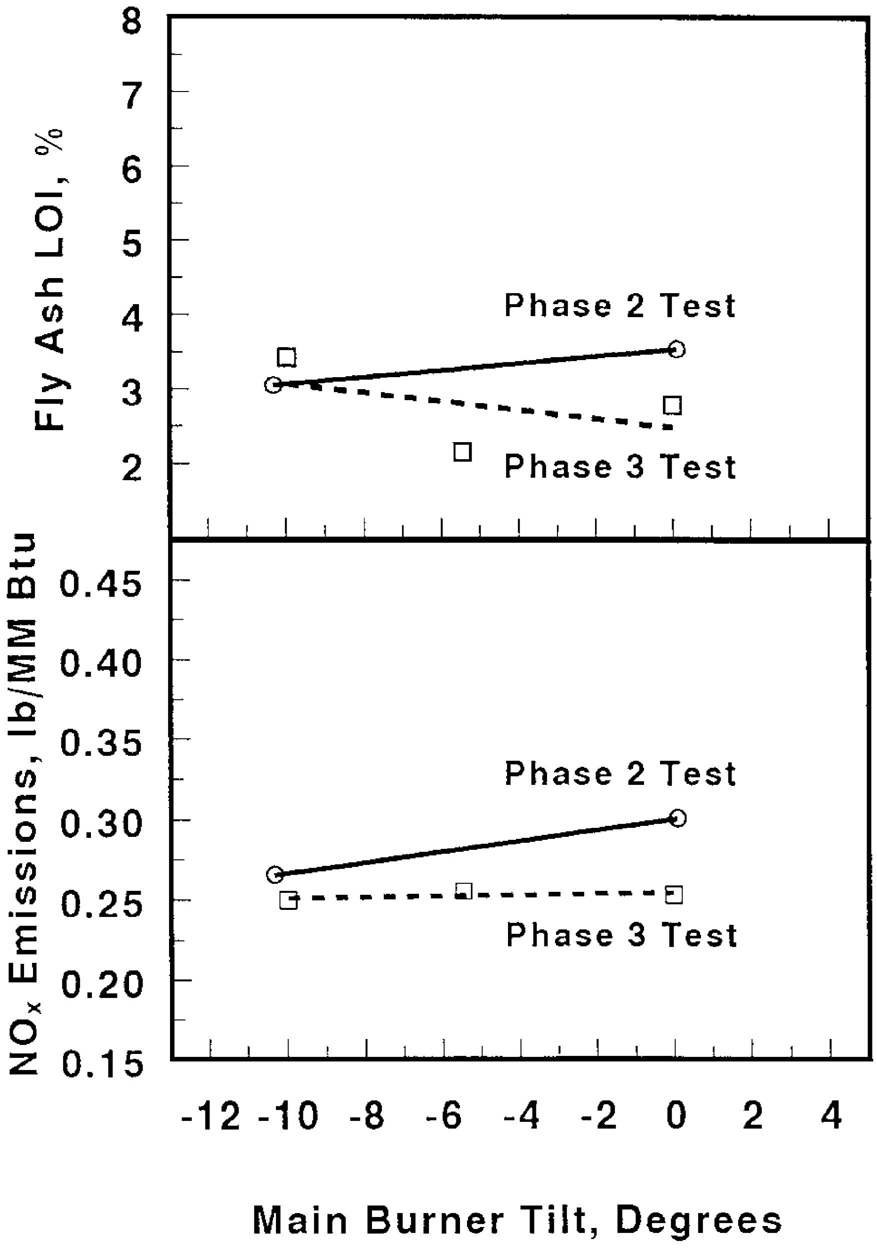

Figure 8. Effect of Reburn Coal Fraction, Phases 1 and 3 Optimization Tests.

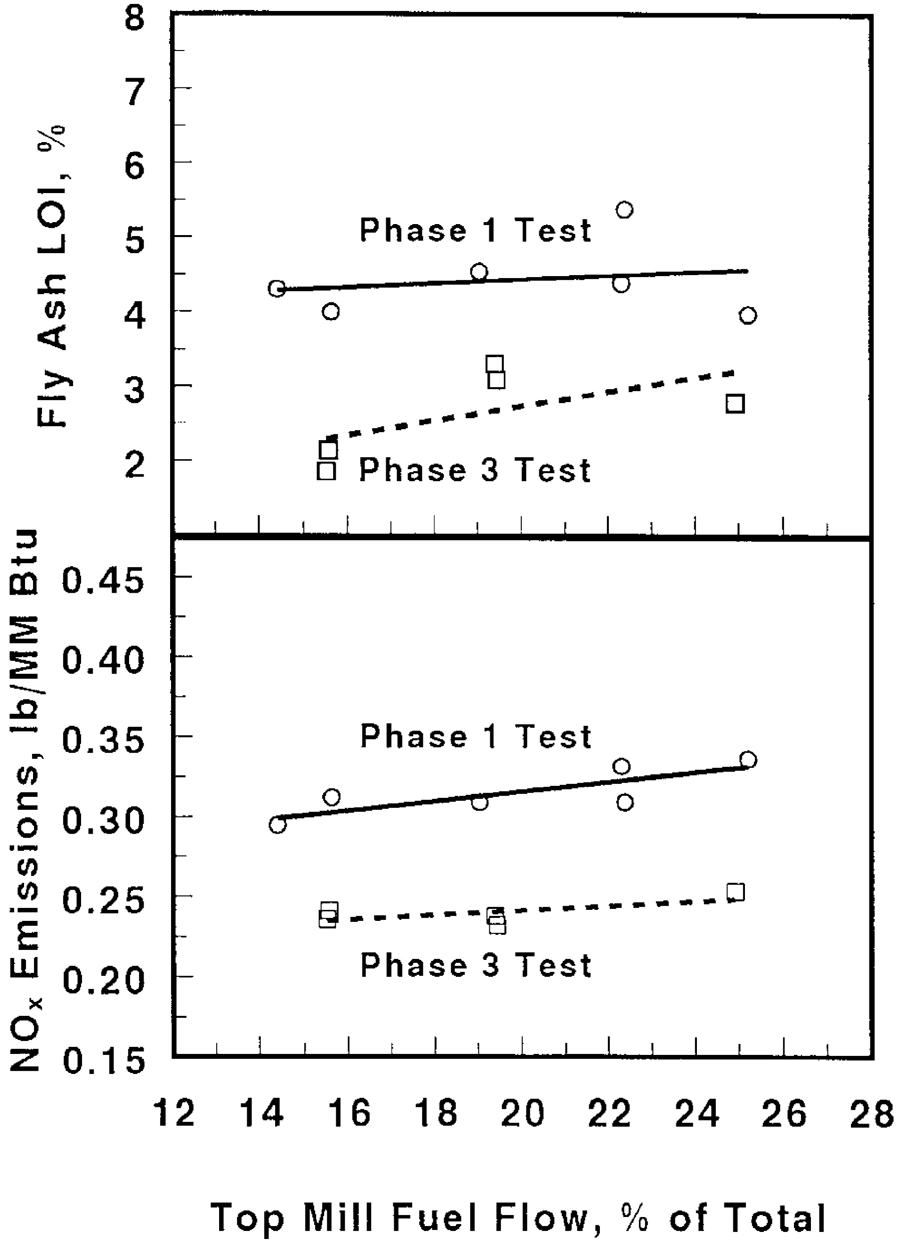

Figure 9. Effect of Boiler Load, Phases 1 and 2 Optimization Tests.

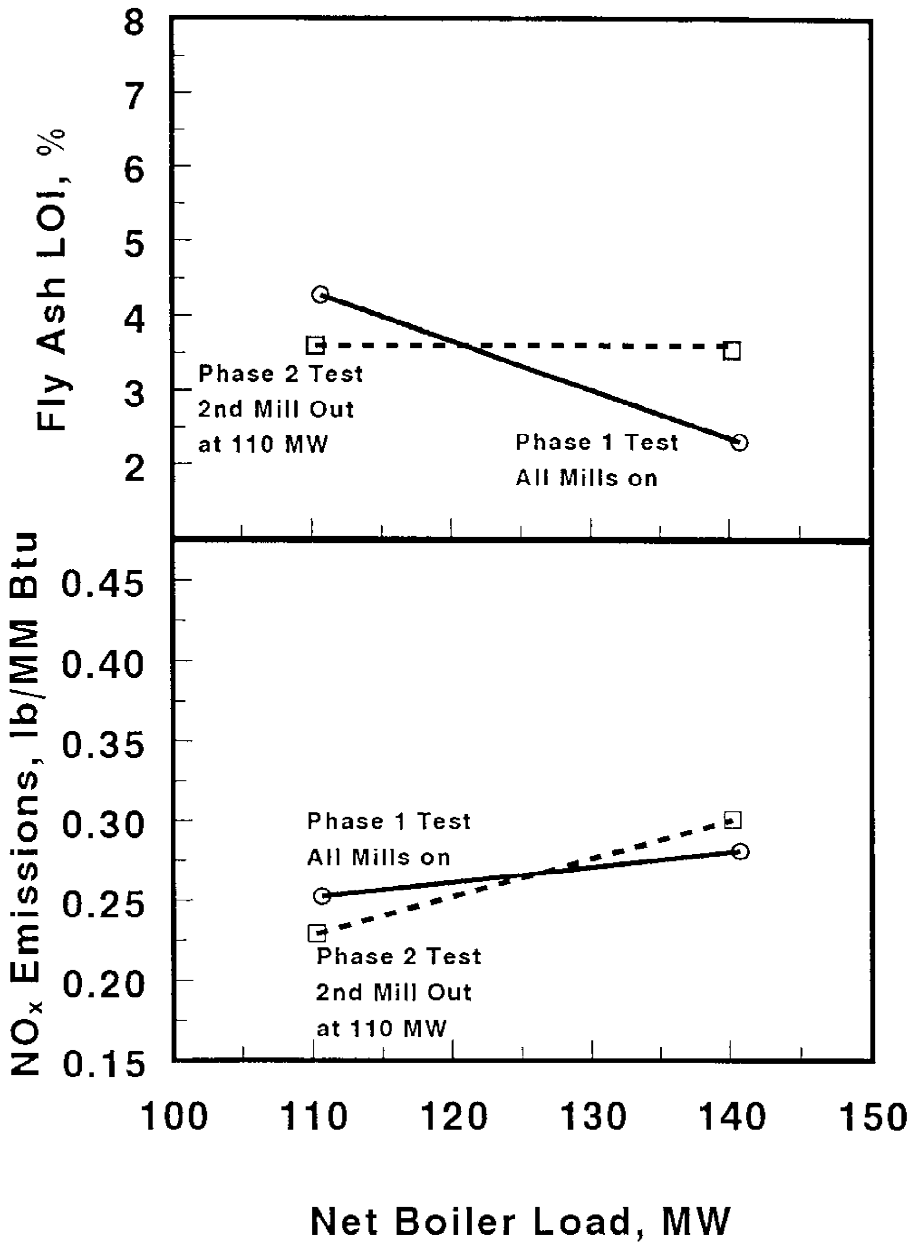

Figure 10. Effect of Mill Pattern, Phase 2 Optimization Tests.

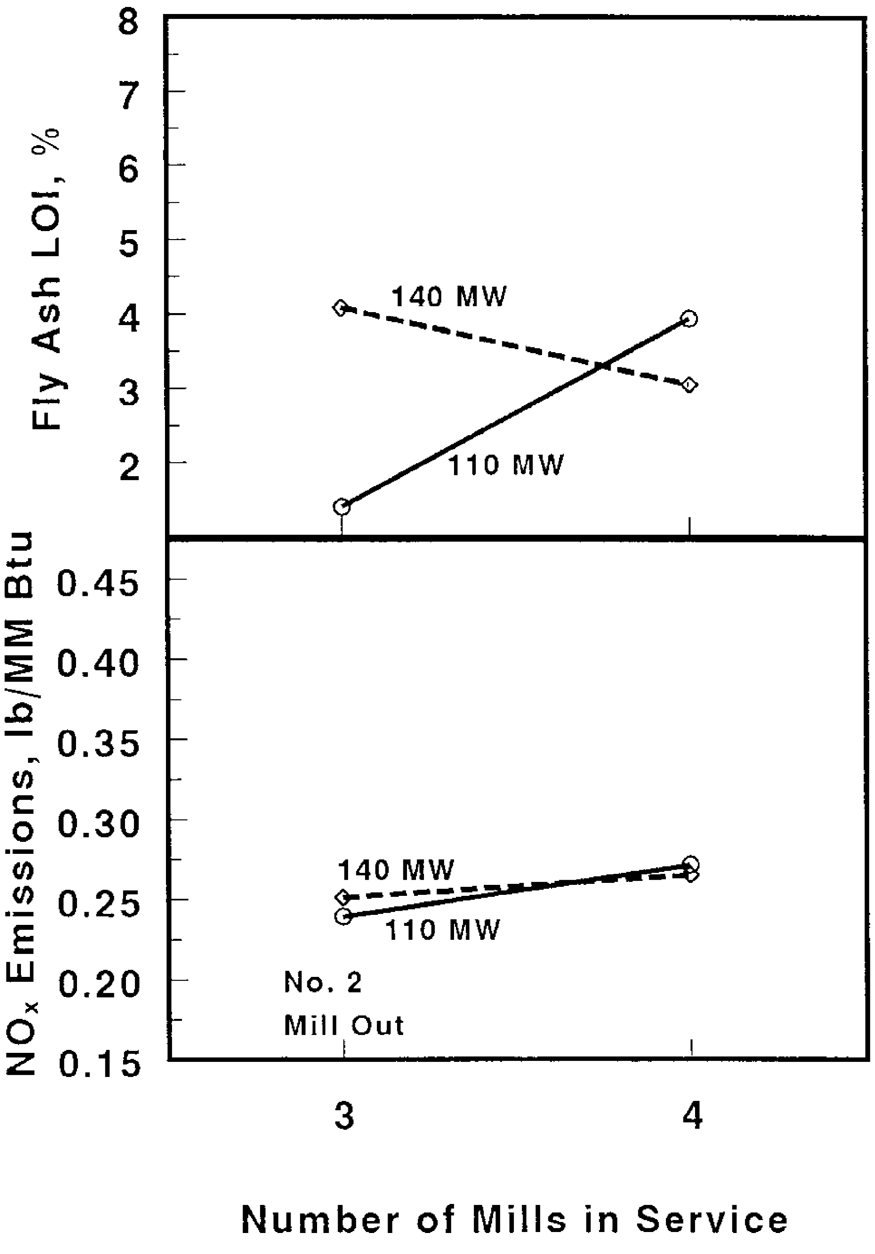

Figure 11. Long-Term NO_x Emissions.