Appendix 5.0-6

MICRONIZED COAL REBURN DEMONSTRATION PROJECT FOR NO_X CONTROL AT THE EASTMAN KODAK CYCLONE-FIRED BOILER 15

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EVALUATION TEST PROGRAM RESULTS

Final Report

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Micronized Coal Reburn Demonstration Project for NO_x Control at the Eastman Kodak Cyclone-Fired Boiler 15

Abstract

The Micronized Coal Reburn Demonstration Project for NO_x Control at the Eastman Kodak Cyclone-Fired Boiler 15 is part of the DOE Clean Coal Technology Program. The objective is to demonstrate the effectiveness of micronized coal reburning in reducing NO_x emissions to meet the compliance limit of 0.6 lb/MM Btu in the Eastman Kodak cyclone-fired Boiler 15.

A reburn system utilizing micronized coal with a fineness exceeding 90% passing 325 mesh was installed on the boiler. The evaluation test program was conducted by CONSOL and consisted of a sequence of four test sets: 1) Diagnostic, 2) Performance, 3) Long-Term, and 4) Validation. The diagnostic test program was based on the analysis of results of short-term (1-3 hours) optimization tests conducted by Babcock & Wilcox to obtain parametric data. The performance test program assessed a detailed set of operating variables. The long-term test program evaluated the long-term (two months) NO_x emissions performance of the reburn system. The validation test program included short-term (1-3 hours) parametric testing to re-evaluate the performance of the reburn system following long-term testing.

The focus of the evaluation was on micronized coal reburning, but also included baseline (no reburn) testing for comparison. A primary consideration was given to maintaining reliable boiler operation for power generation. High-volatile bituminous Pittsburgh seam coal was burned during the evaluation, using the same coal as both the primary and the reburn fuels.

At full boiler load (400 kpph steam), the micronized coal reburn system (at reburn stoichiometry of 0.89) reduced NO_x emissions from a baseline (no reburn) of 1.36 to 0.59 lb/MM Btu (57% reduction), increased the fly ash carbon content from 11% to 37%, and reduced the boiler efficiency from 87.8% to 87.3%. Long-term operation, which included boiler load fluctuation and variable utilization of the micronized coal reburn system, achieved NO_x emissions of 0.69 ± 0.03 lb/MM Btu (95% confidence), and a fly ash carbon content of 38% ± 2%. The increase in the fly ash carbon content relative to baseline was partially due to a lower cyclone heat input and partially due to the staged combustion. The contribution of reburning alone (assuming no change in the cyclone heat input) to the increase in the fly ash carbon content was estimated at less than 12% (absolute).

The effects of the reburn stoichiometry, the cyclone heat input, the cyclone (primary) stoichiometry and the final stoichiometry on NO_x emissions and the fly ash carbon content were assessed. The reburn stoichiometry had a dominant effect on NO_x emissions and a significant effect on the fly ash carbon content, with lower reburn stoichiometries reducing NO_x emissions and increasing the fly ash carbon content. Lower cyclone heat inputs reduced NO_x emissions and increased the fly ash carbon content, attributed to lower temperatures in the cyclone zone. The effect on NO_x was of minor significance with typical reburn applications (reburn stoichiometries below 0.9). At the same cyclone firing rate, the fly ash carbon content

was not significantly different with or without reburning, suggesting that in reburn applications, the fly ash carbon content could be maintained at levels similar to baseline by maintaining a high cyclone firing rate. Variations in the primary stoichiometry between 1.02 and 1.14 had minor effects on NO_x emissions (less than 0.03 lb/MM Btu) and the fly ash carbon content (less than 5%). Variations in the final stoichiometry between 1.05 and 1.16 had no significant effects on NO_x emissions or the fly ash carbon content.

The optimization and the validation test results were compared. Both test programs produced consistent results with respect to the effects of the operating variables on NO_x emissions and the fly ash carbon content. However, the validation tests generated 0.05 lb/MM Btu lower NO_x emissions and 4% higher fly ash carbon contents than the optimization tests, attributed partially to differences in coal properties, and partially to experimental variability.

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List of Abbreviations

ASME	American Society of Mechanical Engineers
Btu	British Thermal Units
C	Carbon, Elemental
EC	Degrees Celsius
CCT	Clean Coal Technology
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CONSOL	CONSOL Inc.
Cyc	Cyclone
Det	As Determined
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ESP	Electrostatic Precipitator
EF	Degrees Fahrenheit
H	Hydrogen, Elemental
H_2O	Water
HGI	Hardgrove Grindability Index
kpph	Kilo (Thousand) Pounds Per Hour
lb	Pounds
MCR	Micronized Coal Reburn
MM	Million
MW	Mega (Million) Watts
N	Nitrogen, Elemental
N_2	Nitrogen Gas
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides, NO and NO_2
NYSEG	New York State Electric & Gas Corporation
O	Oxygen, Elemental
O_2	Oxygen Gas
ppm	Parts Per Million
psig	Pounds Per Square Inch, Gauge
rpm	Revolutions Per Minute
S	Sulfur, Elemental
SO_2	Sulfur Dioxide
SR1	Stoichiometric Ratio in the Primary Combustion Zone of Reburning
SR2	Stoichiometric Ratio in the Reburn Combustion Zone of Reburning
SR1	Stoichiometric Ratio in the Final Combustion Zone of Reburning
Temp	Temperature
UARG	Utility Air Regulatory Group

Objective

The objective of the evaluation test program conducted by CONSOL was to demonstrate the effectiveness of micronized coal reburning in reducing NO_x emissions to meet the compliance limit of 0.6 lb/MM Btu in the Eastman Kodak cyclone-fired Boiler 15. The evaluation included an assessment of the effects of the operating variables on NO_x emissions and unburned carbon losses (measured as fly ash carbon content).

Conclusions

An evaluation test program was conducted by CONSOL to assess micronized coal reburning at the Eastman Kodak cyclone-fired Boiler 15 burning high-volatile bituminous Pittsburgh seam coal and using the same coal as the primary and the reburn fuels. The evaluation test program consisted of four sequential test programs (Diagnostic, Performance, Long-Term and Validation) assessing the effects of several operating variables on NO_x emissions and the fly ash carbon content. The diagnostic test program was based on the analysis of results of short-term (1-3 hours) optimization tests conducted by Babcock & Wilcox to obtain parametric data. The performance test program assessed a detailed set of operating variables. The long-term test program evaluated the long-term (two months) NO_x emissions performance of the reburn system. The validation test program included short-term (1-3 hours) parametric testing to re-evaluate the performance of the reburn system following long-term testing. The following conclusions were derived.

- **Micronized Coal Reburn Performance:** Based on performance testing, using 17.3% micronized coal reburn (reburn stoichiometry of 0.89) reduced NO_x emissions from a baseline (no reburn) of 1.36 to 0.59 lb/MM Btu (57% reduction), increased the fly ash carbon content from 11% to 37%, and reduced the boiler efficiency from 87.8% to 87.3%.

- **Long-Term NO_x Performance:** Based on long-term testing, the achievable annual NO_x emissions (at 15.6% reburn or stoichiometry of 0.90) were 0.69 ± 0.03 lb/MM Btu (95% confidence), corresponding to a fly ash carbon content of 38% ± 2%. Higher reburn feeds (estimated at 18.4% reburn or stoichiometry of 0.87) would be required for long-term compliance with the 0.6 lb/MM Btu NO_x emissions limit.

- **Overall Effect of Reburn Application:** The application of micronized coal reburning reduced NO_x emissions and increased the fly ash carbon content. The final NO_x emissions mainly depended on the reburn stoichiometry, typically dropping below 0.6 lb/MM Btu at reburn stoichiometries below 0.9 and corresponding to 40-45% carbon in the fly ash, compared to typical baseline (no reburn) NO_x emissions of 1.2-1.4 lb/MM Btu and 10-15% carbon in the fly ash. The increase in the fly ash carbon content relative to baseline was partially due to a lower cyclone heat input resulting in lower temperatures and partially due to the staged combustion resulting in shorter residence times under oxidizing conditions. The contribution of reburning alone (assuming no change in the cyclone heat input) to the increase in the fly ash carbon content was estimated at less than 12% (absolute).

- **Effect of Reburn Stoichiometry:** The reburn stoichiometry had a dominant effect on NO_x emissions and a significant effect on the fly ash carbon content. Lower reburn stoichiometries reduced NO_x emissions and increased the fly ash carbon content. Based on validation testing, NO_x emissions as low as 0.41 lb/MM Btu were achievable at maximum reburn utilization (reburn stoichiometry of 0.81), corresponding to 48% carbon in the fly ash.

- **Effect of Cyclone Heat Input:** Based on short-term optimization and validation testing, lower cyclone heat inputs reduced NO_x emissions and increased the fly ash carbon content. That was attributed to lower temperatures in the primary (cyclone) combustion zone, which reduced thermal NO_x formation and resulted in less efficient char burnout. The effect on NO_x was of minor significance with typical reburn applications (reburn stoichiometries below 0.9). At the same cyclone heat input, the fly ash carbon content was not significantly different with or without reburning, suggesting that in reburn applications, the fly ash carbon content could be maintained at levels similar to baseline by maintaining a high cyclone heat input.

- **Effect of Cyclone Stoichiometry:** Based on short-term validation testing, variations in the primary stoichiometry between 1.02 and 1.14 had minor effects on NO_x emissions (less than 0.03 lb/MM Btu) and the fly ash carbon content (less than 5%).

- **Effect of Final Stoichiometry:** Based on short-term optimization and validation testing, variations in the final stoichiometry between 1.05 and 1.16 had no significant effects on NO_x emissions or the fly ash carbon content.

- **Reproducibility:** The optimization and the validation test programs produced consistent results with respect to the effects of the operating variables on NO_x emissions and the fly ash carbon content. However, the validation tests generated 0.05 lb/MM Btu lower NO_x emissions and 4% higher fly ash carbon contents than the optimization tests, attributed partially to differences in coal properties, and partially to experimental variability.

Recommendations

The following recommendations are made based on the results of the micronized coal reburn evaluation test program at the Eastman Kodak cyclone-fired Boiler 15.

- Operating at a reburn stoichiometry of 0.87, which can be accomplished using a cyclone stoichiometry of 1.05 and 17% micronized coal reburn, is recommended for long-term compliance with the 0.6 lb/MM Btu NO_x emissions limit.

- Exploring operation at cyclone stoichiometries below the current setting of 1.07-1.08 for more efficient utilization of the reburn system is recommended. A lower cyclone stoichiometry inhibits primary NO_x generation, reduces the amount of reburn fuel required to create the desired reburn stoichiometry and permits operation at higher cyclone heat inputs. That may allow the boiler to operate at lower NO_x emissions and lower fly ash carbon content. Short-term operation at cyclone stoichiometries as low as 1.02 was tested with no adverse effects.

- Using coarser micronized coal reburn fuel should be investigated. The current micronizer setting produces a fineness level exceeding 90% passing 325 mesh. Coarser coal may generate similar results at a reduced cost.

Introduction

The Micronized Coal Reburn Demonstration Project for NO_x Control at the Eastman Kodak Cyclone-Fired Boiler 15 is part of the DOE Clean Coal Technology Program. The goal is to demonstrate compliance with the 0.6 lb/MM Btu NO_x emission limit for coal-fired cyclone boilers under Title 1 of the Clean Air Act Amendments of 1990 using combustion modification NO_x control techniques, specifically, micronized coal reburning.

A reburn system was installed on Kodak Boiler 15 to achieve the desired NO_x reduction level utilizing micronized coal with a fineness exceeding 90% passing 325 mesh. Pittsburgh seam coals (high-volatile bituminous) were burned during the demonstration testing, with the same coal used as both the primary fuel and the reburn fuel. Testing by CONSOL was conducted following the completion of optimization testing conducted by Babcock & Wilcox to identify the operating limits of the reburn system and to define automatic control parameters. The boiler and the operating settings utilized as a result of optimization testing were used as a reference in conducting additional tests.

The micronized coal reburn evaluation test program consists of sequential test programs conducted to assess the effects of several operating variables on NO_x emissions. The test programs are discussed following a general review of NO_x control by reburning with emphasis on coal reburning, and descriptions of the Kodak boiler and the reburn system.

NO_x Control by Reburning

Reburning is a three-stage combustion modification process for NO_x control. A primary fuel is burned under excess air conditions. Then, a secondary fuel is added downstream of the primary flame at 10%-30% of the thermal input to create a fuel-rich reburn zone where the NO_x formed in the primary zone reacts with hydrocarbons to initiate a 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%.

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), including the three stoichiometries. The stoichiometry is the ratio of the actual air feed to the theoretical air requirement for complete combustion of the fuel. The following is a brief review of the variables which affect NO_x emissions in reburning.

The primary zone is the main combustion zone prior to reburn fuel introduction. A fuel-lean (excess air) primary stoichiometry is essential to combust the primary fuel resulting in the formation of combustion products including NO_x. However, a low primary stoichiometry is desired to inhibit primary NO_x generation, to reduce the amount of reburn fuel required to create the desired reburn stoichiometry, 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 oxygen carryover into the reburn zone which would reduce the reburning effectiveness in reducing NO_x. Generally, reburning is less effective at lower primary NO_x concentrations.

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 reburn stoichiometry for low NO_x emissions typically occurs between 0.8 and 0.9. The optimum results from 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 effect of the reburn stoichiometry depends on the level of mixing between the reburn fuel and the primary combustion products, with better mixing conditions creating a sharper dependence on the stoichiometry, a less fuel-rich optimum and an enhanced reburning performance. Longer reburn zone residence times enhance NO_x destruction, reaching an asymptotic level above 0.5-0.8 seconds.

The final combustion zone of reburning is created by adding over fire air to complete the combustion under overall excess air conditions. The properties of this zone are expected to have a minor effect on the final NO_x emissions, but may affect fuel burnout and CO emissions. Specifically, high unburned fuel losses and high CO emissions may result 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 generally 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. That is not necessarily the case, as evident in 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. The potential increase in unburned fuel losses due to the application of coal reburning can be controlled using finer grind reburn fuel, which is the motivation behind the evolution 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 Program included three commercial 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 ("Demonstration of Coal Reburning for Cyclone Boiler NO_x Control," Report DOE/PC/89659-T16, DE94013052, Babcock & Wilcox, Alliance, Ohio, 1994). The reburn system reduced NO_x emissions from 0.83 to 0.39 lb/MM Btu using 18% reburn fuel. Fly ash loss on ignition was maintained close to baseline levels by increasing the reburn coal fineness from 80% to 95% passing 200 mesh. A second demonstration utilizing micronized coal reburning is in progress at the New York State Electric & Gas 150 MW tangentially-fired Milliken Unit 1 boiler equipped with low-NO_x burners (DeAngelo, J. G., and Chang, S. S., "Meeting the Title I NO_x Requirements: A Comprehensive Approach," Proceedings of the 1997 International Joint Power Generation Conference, ASME, New York, New York, Vol. 1, pp. 125-145, 1997). NO_x emissions dropped from 0.35 to 0.26 lb/MM Btu using 15% reburn fuel. A third demonstration utilizing micronized coal reburning was completed at the Eastman Kodak Cyclone-Fired Boiler 15, and is the study reported here.

Kodak Boiler 15 and the Micronized Coal Reburn System

The Kodak Boiler 15 is a Babcock & Wilcox cyclone-fired boiler built in 1956. It is equipped with two cyclones, eight feet in diameter each. The boiler was designed to produce steam at 1425 psi and 900EF at the superheater outlet, with a maximum continuous rating of 400 kpph of steam and a peak capacity of 440 kpph. The boiler was retrofitted with a micronized coal reburn system consisting of two mills, reburn fuel injectors, a flue gas recirculation system to transport the reburn fuel, and over fire air injectors. The reburn system was designed to provide up to 30% of the boiler peak load heat input.

A Fuller MicroMill™, with a product capacity of 8 kpph, is utilized to pulverize the reburn coal to a micronized size consistency exceeding 90% passing 325 mesh. The mill is a centrifugal-pneumatic pulverizer which reduces the coal size by particle-to-particle attrition. The raw fuel is fed from the main bunker though a variable speed screw feeder and is pneumatically conveyed into a hot primary air stream transporting a recycled coal stream for size reduction in the mill. The primary air and the coal enter the lower portion of a cone where the surface moisture evaporates, and the fuel is picked up in a swirling air flow created by the rotation of an impeller and is pushed towards the wall of the cone by centrifugal forces. As the air and the fuel move up in the cone, the cross-sectional area increases and the velocity drops until the mass of the coal particles prevents further movement up in the cone. That results in bands of particles that become denser and finer travelling up the cone. The smaller particles which possess higher velocities travel up through the cone, pass though the bands of the larger and slower-moving particles, and break them up as the particles collide. The particles which are small enough to be drawn out of the centrifugal bands pass through the impeller and into a classifier, where the small particles pass though orifices into a collection system, and the oversized particles return to the mill feed system in a recycle stream.

The micronized reburn fuel exits the pulverizer and is distributed among eight coal injectors located just downstream of the slag screen, including six equally spaced across the rear wall and one in each side wall. The micronized reburn fuel is transported from the micronizer to the boiler by hot recirculated flue gas (350 ± 20EF) taken from the electrostatic precipitator outlet duct. An over fire air stream of up to 140 kpph is extracted from the secondary air ducts and distributed among four injectors equally spaced across the furnace front wall above the reburn zone.

In a cyclone-fired boiler, the heat generated from the cyclone burners must be sufficient for the ash to remain in a molten state until it drains from the furnace into the slag tank. For Kodak Boiler 15, the minimum boiler load required to maintain satisfactory operation is 320 kpph of steam or 80% of full load. Consequently, at full boiler load and 20% reburn heat input, the cyclones operate near their minimum load, and further turn down in load cannot be achieved without reducing the reburn fuel feed at the expense of less NO_x reduction by reburning. Thus, typical boiler load variations are accomplished by maintaining the cyclone heat input at the minimum level (315-320 kpph) and adding micronized coal reburn fuel to achieve the desired boiler load. That results in higher NO_x emissions at reduced boiler loads when the reburn system is in use.

The micronized coal reburn system was started in January 1997. Several operational problems were resolved prior to the optimization testing. Several examples are listed below.

1) Micronized coal feed pluggage resulting in reburn feed interruption was mitigated using air lances.

2) Reburn fuel injector slagging was mitigated by improving the distribution of the reburn fuel and the transport gas among the injectors.

3) Leakage problems in the flue gas recirculation system used to transport the reburn fuel were corrected.

4) Inaccurate boiler O_2 measurements were corrected utilizing a six-point monitoring system in which three meters on each half of the boiler (east and west) would be averaged to control the operation of the respective cyclone burner.

5) The original process control system controlled the cyclone coal feeds according to the boiler O_2. This created reducing conditions in the cyclones in cases of reburn feed interruption (e.g. coal pluggage in wet periods). A reducing environment is destructive to the cyclone tubing and makes slag tapping more difficult due to the formation of pig iron in the slag. The control system was subsequently modified for better control of the stoichiometries. Specifically, the air-to-fuel ratio delivered to each cyclone burner was controlled independently of the boiler O_2, and the over fire air flow was controlled based on the boiler O_2 while maintaining it above a minimum level (theoretical requirement).

After establishing reliable operation of the micronized coal reburn system, optimization testing by Babcock & Wilcox followed to identify the operating limits of the reburn system, to optimize NO_x reduction, and to obtain the information necessary for automatic control of the system. The results of the optimization tests and additional tests conducted by CONSOL were utilized in evaluating the effectiveness of the reburn system in reducing NO_x emissions.

Evaluation Test Program

The objective of the evaluation test program was to demonstrate the effectiveness of micronized coal reburning in reducing NO_x emissions below the compliance limit of 0.6 lb/MM Btu in the Eastman Kodak cyclone-fired Boiler 15. The evaluation consisted of sequential test programs conducted to assess the effects of several operating variables on NO_x emissions and unburned carbon losses (measured as fly ash carbon content). The test programs included the optimization testing conducted by Babcock & Wilcox, and additional testing conducted by CONSOL to further evaluate the effectiveness of the micronized coal reburn system in reducing NO_x emissions. Although the optimization tests were not specifically designed to provide parametric information, the results were analyzed to assess the effects of the operating variables on NO_x emissions and the fly ash carbon content. The boiler and the operating settings obtained from the optimization test results were used as a reference in conducting additional tests.

The evaluation test program consisted of a sequence of four series of tests: 1) Diagnostic, 2) Performance, 3) Long-Term, and 4) Validation. The diagnostic tests consisted entirely of the short-term (1-3 hours) optimization tests conducted by Babcock & Wilcox, and the results (including coal and fly ash analyses) were utilized as reported to obtain parametric data. The performance tests were characterization tests assessing a detailed set of boiler variables. The long-term (two months) test assessed the long-term NO_x emissions performance of the reburn system. The validation tests were short-term (1-3 hours) parametric tests re-evaluating the NO_x performance of the reburn system following long-term testing.

The evaluation test program focused on micronized coal reburning, but also included baseline (no reburn) testing. The reburn and the baseline test results were compared to assess the impact of the reburn system on NO_x emissions and the fly ash carbon content. 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.

Operating data and gas emissions measurements, including NO_x emissions in lb/MM Btu, were obtained from the plant data acquisition system, collected as 15-minute averages. The operating variables which were evaluated in this study, with respect to their impact on NO_x emissions and the fly ash carbon content, included the cyclone heat input, and the three process stoichiometries corresponding to the three combustion stages of reburning (primary, reburn and final). The stoichiometry, defined as the ratio of the actual air feed to the theoretical air requirement for complete combustion of the fuel, was calculated from the plant measurements of coal and air flows. The cyclone heat input was utilized as a boiler load parameter, calculated by multiplying the total boiler load by the fraction of the total coal fed through the cyclone burners.

Fly ash samples were collected from the ESP hoppers and analyzed for unburned carbon and ash contents. The samples collected during the optimization and the validation tests were obtained from the first hopper at the ESP inlet, since that allowed for sample extraction within a few minutes. The samples collected during the long-term test were composite samples from all the ESP hoppers using a fly ash sampler operated for 30-60 minutes. During performance testing, samples were collected using both sampling methods in addition to iso-kinetic sampling using EPA Method 17 at the ESP inlet (part of ESP performance evaluation). The results from the three methods were subsequently compared.

High-volatile bituminous Pittsburgh seam coal was burned during the evaluation test program, using the same coal as both the primary fuel and the reburn fuel. Coal proximate and ultimate analyses and micronized coal fineness data (for the reburn fuel), corresponding to different phases of testing, are presented in Table 1. The coal burned during the validation test program was received from a different coal supplier and differed slightly in the analyses from those of the coal burned during the optimization, performance and long-term test programs.

Diagnostic Test Program

The goal of the diagnostic test program was to provide short-term (1-3 hours) parametric data with respect to the effects of the boiler and the operating variables on NO_x emissions and the fly ash carbon content. Constraints of time and resources necessitated using the optimization tests conducted by Babcock & Wilcox as diagnostic tests rather than performing additional testing. The optimization tests were conducted during April 13-29, 1998, to identify the operating boundaries of the micronized coal reburn system, to optimize the NO_x reduction performance, and to obtain the information necessary for automatic control of the system. The results of these tests were analyzed by CONSOL to assess the effects of several operating variables on NO_x emissions and the fly ash carbon content. The operating variables included the cyclone heat input, and the two stoichiometries corresponding to the reburn and the final combustion stages of reburning.

A diagnostic matrix corresponding to 22 tests was obtained from the optimization test results, as presented in Table 2. The matrix excluded tests in which the air flows were unbalanced and included five data sets. Set 1 consisted of four baseline (no reburn) tests at various boiler loads (313-400 kpph). Set 2 consisted of four reburn tests representing normal operation in which the variation in the total boiler load was accomplished by maintaining the cyclone heat input near the minimum level (315-320 kpph) and adding micronized coal reburn fuel to achieve the desired boiler load. Set 3 consisted of four reburn tests in which the total boiler load was maintained near the full level (400 kpph nominal), and the micronized coal reburn feed was varied (up to 23% of the total heat input). Set 4 consisted of seven tests in which the cyclone and the reburn heat inputs were unchanged, and the mode of over fire air introduction was varied to create various mixing patterns in the final stage of reburning. Set 5 consisted of two tests in which the over fire air flow was varied to assess variations in the final stoichiometry.

The diagnostic matrix (Table 2) was analyzed to assess the effects of the cyclone heat input, the reburn stoichiometry and the final stoichiometry on NO_x emissions and the fly ash carbon content. The available information was insufficient to assess the effect of the primary stoichiometry. The effect of mixing in the final stage of reburning (Set 4) was assumed to be of minor significance relative to the effects of the other assessed variables.

The following observations were derived based on the results presented in Table 2. Under baseline (no reburn) conditions (Set 1), reducing the boiler load generated lower NO_x emissions and higher fly ash carbon content. With reburning, increasing the contribution of the reburn fuel (Sets 2 and 3) reduced NO_x emissions and increased the fly ash carbon content. The effect of reburning on the fly ash carbon content was more dramatic when higher reburn fuel feeds accompanied a decrease in the cyclone heat input (Set 3), compared to no change in the cyclone heat input (Set 2). Furthermore, in all three cases (Sets 1, 2 and 3), the increase in the fly ash carbon content was accompanied by a drop in the primary (cyclone) stoichiometry. Therefore, with the application of micronized coal reburning, three factors might have contributed to the increase in the fly ash carbon content relative to the baseline level: 1) lower cyclone heat inputs resulting in lower temperatures in the primary (cyclone) combustion zone, 2) lower primary stoichiometries resulting in lower excess O_2 levels, and 3) fuel-staged combustion (reburning) resulting in shorter residence times under oxidizing conditions. In the reburn tests of Table 2, the cyclone stoichiometry generally varied in a range between 1.05 and 1.09, which was not sufficiently large to assess the effect of this variable. The relative significance of the other two factors, namely, the cyclone heat input and the reburn level (measured as the reburn stoichiometry), was further investigated.

The effects of varying the cyclone heat input on NO_x emissions and the fly ash carbon content were assessed for baseline (no reburn) and reburn applications (reburn stoichiometries between 0.85 and 1.03) based on the optimization test results (Table 2). A graphical presentation of the results is shown in Figure 1. Lower cyclone heat inputs reduced NO_x emissions and increased the fly ash carbon content, attributed to lower temperatures in the primary (cyclone) combustion zone resulting in less thermal NO_x formation and less efficient char burnout. The effect on NO_x emissions was less significant with greater applications of reburning corresponding to lower reburn stoichiometries. At the same cyclone heat input, the fly ash carbon content was not very different with or without reburning, as suggested by the close proximity of the curves. Consequently, with reburning it may be possible to maintain the fly ash carbon content close to baseline levels by maintaining a high cyclone heat input. This concept was tested during the validation test program.

The effects of varying the reburn stoichiometry between 0.82 and 1.03 on NO_x emissions and the fly ash carbon content were assessed based on the optimization test results (Table 2), as shown in Figure 2. The reburn stoichiometry had a dominant effect on NO_x emissions, with no significant dependence on the cyclone heat input. NO_x emissions dropped below 0.6 lb/MM Btu at reburn stoichiometries below 0.88. Furthermore, the reburn stoichiometry had a significant effect on the fly ash carbon content and the effect strongly depended on the cyclone heat input. Within a narrow range of cyclone heat inputs (315-325 kpph), the sensitivity of the fly ash carbon content to variations in the reburn stoichiometry (slope of linear fit) was estimated at -59. For example, a drop in the stoichiometry from 1.08 (no reburn) to 0.88 (typical reburn) would increase the fly ash carbon content by 12% (absolute), which was the estimated increase attributed to staged combustion in reburning.

The effects of varying the final stoichiometry between 1.11 and 1.22 on NO_x emissions and the fly ash carbon content were assessed based on the optimization test results (Table 2), as shown in Figure 3. The reburn stoichiometry varied within a relatively narrow range between 0.84 and 0.86. The final stoichiometry had minor effects on both NO_x emissions and the fly ash carbon content. The weak trends observed in Figure 3 were attributed to the uncontrolled variations of other operating variables, such as the reburn stoichiometry.

Performance Test Program

The performance test program consisted of characterization tests assessing a detailed set of boiler and combustion parameters. The goal was to evaluate the impact of the micronized coal reburn system on boiler performance, including NO_x emissions, the fly ash carbon content and the boiler efficiency. The operating conditions for the performance tests were normal operating conditions at full boiler load (400 kpph) based on the optimization test results and the plant operating experience using the reburn system. Specifically, the reburn performance test conditions were set to achieve NO_x emissions below the compliance limit of 0.6 lb/MM Btu while maintaining the required steam conditions and reliable boiler operation. The baseline performance test conditions were set by turning off the micronized coal reburn feed and increasing the cyclone coal feed to achieve full boiler load.

The performance tests were conducted during June 2-4, 1998, and included four micronized coal reburn and four baseline (no reburn) tests conducted over a three-day period. Daily crushed coal samples were collected and analyzed for heating value, moisture, and proximate and ultimate compositions (Table 1). The daily coal samples were combined into a composite sample and detailed analyses were performed, including ash elemental composition and ash fusion temperatures, as presented in Table 3. Micronized coal samples were also collected for each reburn test and analyzed for heating value, moisture, proximate and ultimate compositions, and fineness (wet screen) sizing (Table 1). Each performance test was 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, three fly ash samples were collected: 1) a grab sample from the first hopper at the ESP inlet, 2) a composite sample from all ESP hoppers using a fly ash sampler operated for 30-60 minutes, and 3) an iso-kinetic sample collected using EPA Method 17 at the ESP inlet. The fly ash samples were analyzed for unburned carbon and ash contents.

The operating parameters, and the flue gas and fly ash results for the eight performance tests (four reburn and four baseline) are presented in Tables 4 and 5, respectively. The carbon contents of fly ash samples collected from the first ESP hopper (38-44% for reburn and 12-17% for baseline) were not significantly different from those collected from all ESP hoppers (37-42% for reburn and 13-18% for baseline excluding Test 1), but were higher than those collected iso-kinetically (34-39% for reburn and 7-15% for baseline). There was insufficient information to further assess these differences.

The boiler efficiency calculations, presented in Table 6, were based on the ASME Abbreviated Efficiency Test and were conducted as part of the performance test program. Unburned carbon losses were calculated based on the assumption that under baseline (no reburn) conditions, 20% of the ash entering the cyclone escaped the furnace as fly ash and 80% was tapped as bottom ash slag, whereas under reburning conditions, the split was 40% as fly ash and 60% as bottom ash. These assumptions match the average values calculated in Table 5. The bottom ash slag was assumed to contain 1% unburned carbon. Micronized coal reburning reduced the boiler efficiency from a baseline of 87.7-88.0% to 86.9-87.5% (less than 1.3% drop).

The results of the four reburn and the four baseline performance tests were averaged and compared, as shown in Table 7. Using 17.3% micronized coal reburn (reburn stoichiometry of 0.89) reduced NO_x emissions from a baseline (no reburn) of 1.36 to 0.59 lb/MM Btu, corresponding to a reduction of 57%, and increased the fly ash carbon content from 11% to 37%. The reburn system reduced the boiler efficiency from a baseline of 87.8% to 87.3%, mainly due to the increase in the fly ash carbon content.

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 NO_x reduction effectiveness of the micronized coal reburn system based on long-term measurements. For long-term testing, a minimum time requirement of 51 days is recommended to adequately describe the time dependence of the data, as demonstrated in a statistical evaluation of long-term gas emissions data conducted by the Control Technology Committee of the Utility Air Regulatory Group (UARG). Following the UARG recommendation, the long-term test consisted of two months of continuous measurements. The test conditions were the normal plant operating conditions (typically in automatic control) based on the optimization test results and the plant operational experience using the reburn system. The micronized coal reburn system was set to achieve NO_x emissions below the compliance limit of 0.6 lb/MM Btu while maintaining the required steam conditions and reliable boiler operation.

The long-term test program was conducted following the completion of the performance test program and consisted of 63 days of measurements, starting June 5, 1998, and ending August 6, 1998. The measurements included operating and gas emissions data (including NO_x emissions in lb/MM Btu) collected as 15-minute averages, and fly ash carbon content analyses corresponding to fly ash samples collected daily. Normal boiler load fluctuations and variable utilization of the micronized coal reburn system were represented in the measurements. The 15-minute averaged data were subsequently combined into hourly averages and then into daily averages. The daily averages were further analyzed to estimate the achievable annual NO_x emissions and the corresponding fly ash carbon content. The hourly averages were further analyzed to assess the effects of the cyclone heat input and the reburn stoichiometry on NO_x emissions, and to assess differences between long-term and short-term results.

The achievable annual NO_x emissions were estimated using 30-day rolling averages obtained from the long-term test daily averages. A 30-day rolling average is calculated by averaging 30 continuous daily averages following the initial 30-day lapse and rolling the average from day to day. The daily averages, the 30-day rolling averages and a statistical summary are presented in Table 8. The achievable annual NO_x emissions were estimated at 0.69 lb/MM Btu with an uncertainty of ± 0.03 lb/MM Btu at the 95% confidence level. The corresponding fly ash carbon content level was estimated at 38% with an uncertainty of ± 2% at the 95% confidence level. The averaged values (using daily averages) for selected operating variables (also shown in Table 8) were 392 kpph for the total boiler load, 15.6% for the micronized coal reburn, 0.90 for the reburn stoichiometry, and 2.9% for the boiler O_2 at the economizer outlet.

The effects of the cyclone heat input and the reburn stoichiometry on NO_x emissions were assessed using hourly averages obtained from the long-term measurements. A statistical evaluation of the data showed that the cyclone heat input had a significant effect on NO_x emissions for baseline (no reburn) but not for reburn applications. In both cases (baseline and reburn), the reburn stoichiometry had a significant effect on NO_x emissions. It should be noted that for baseline, the reburn stoichiometry is also the cyclone (primary) stoichiometry, and the cyclone heat input is also the total boiler load. The data were grouped into three data sets for further evaluation, including 25 baseline cases at 320-340 kpph cyclone heat input, 41 baseline cases at 390-410 kpph cyclone heat input and 1175 reburn cases at 310-410 kpph cyclone heat input. A graphical presentation of the results showing variations of NO_x emissions as a function of the reburn stoichiometry for the three data sets (shown as curve fit lines) is presented in Figure 4. Also shown in Figure 4 are the short-term optimization test results (shown as data points). A good agreement between the long-term and the short-term results was obtained.

Long-term compliance with the 0.6 lb/MM Btu NO_x emissions limit requires a target of 0.57 lb/MM Btu (accounting for 95% confidence level of 0.03 lb/MM Btu), which can be achieved at reburn stoichiometries below 0.87 (Figure 4). The required fraction of the total coal feed as micronized coal reburn can be calculated by taking the ratio of reburn to cyclone stoichiometries and subtracting from one. For example, with a cyclone stoichiometry of 1.066 (average from long-term test), reburn feeds above 18.4% would be expected to achieve the desired goal.

Validation Test Program

The goal of the validation test program was to validate the previous results by re-assessing the effects of selected process variables on NO_x emissions and the fly ash carbon content, and to characterize any changes that might have occurred during the long-term test. The validation test program was conducted following the completion of the long-term test to provide short-term (1-3 hours) parametric data with respect to the effects of the variables of interest.

The validation test program was conducted during September 21-23, 1998, and consisted of 18 tests, as shown in Table 9. The duplicate fly ash analyses (for carbon content) shown in Table 9 corresponded to single samples, and averaged values were used in subsequent evaluations. The validation test matrix included a reference test, six test sets (Sets 1-6) assessing the effects of the variables of interest, and five miscellaneous reburn tests. The reference test was conducted under typical operating conditions using the micronized coal reburn system, and the test conditions were similar to those utilized during the reburn performance test program. The six test sets assessed the effects of the cyclone heat input with and without reburn (Sets 1 and 2, respectively), the cyclone (primary) stoichiometry with and without co-variation of the cyclone heat input (Sets 3 and 4, respectively), the reburn stoichiometry (Set 5) and the final stoichiometry (Set 6). Each set consisted of two tests corresponding to low and high levels of the variable of interest, relative to the reference test. Overall, the effects of the cyclone heat input, and the three process stoichiometries corresponding to the three combustion stages of reburning (primary, reburn and final) on NO_x emissions and the fly ash carbon content were assessed.

The effects of varying the cyclone heat input on NO_x emissions and the fly ash carbon content were assessed for baseline (no reburn) and reburn applications at two reburn stoichiometry levels (0.88-0.89 and 0.90) based on the validation test results (Table 9). A graphical presentation of the results is shown in Figure 5. The two reburn stoichiometry levels (0.88-0.89 and 0.90) produced different NO_x emissions, but no obvious differences in the fly ash carbon content. Without reburning, lower cyclone heat inputs reduced NO_x emissions and increased the fly ash carbon content, in agreement with the optimization test results. With reburning, the cyclone heat input had no significant effect on NO_x emissions and a possible effect on the fly ash carbon content. At the same cyclone heat input of about 330 kpph, the fly ash carbon content with and without reburning was not significantly different, with values at 41-47% and 41%, respectively. The increase in the fly ash carbon content due to micronized coal reburning was estimated at less than 6% (absolute) relative to the baseline level, as compared to an estimate of less than 12% obtained from the optimization test results. A reburn test in which the cyclone heat input was maintained relatively high at 360 kpph (Set 1 in Table 9, also shown in Figure 5) generated a fly ash carbon content of 32%, which was similar to the baseline levels of 32-41%. The results suggested that in applying the reburn system, it might be possible to maintain the fly ash carbon content low relative to baseline by maintaining high cyclone coal feeds.

The effects of varying the cyclone (primary) stoichiometry between 1.02 and 1.14 on NO_x emissions and the fly ash carbon content were assessed at two reburn stoichiometry levels (0.88-0.89 and 0.90) based on the validation test results (Table 9), as shown in Figure 6. Again, the two reburn stoichiometry levels (0.88-0.89 and 0.90) produced different NO_x emissions, but no obvious differences in the fly ash carbon content. Within the tested range, the cyclone stoichiometry had no significant effect on NO_x emissions (less than 0.03 lb/MM Btu) and a minor effect on the fly ash carbon content. Specifically, lower stoichiometries generated higher fly ash carbon contents. The sensitivity of the fly ash carbon content to variations in the cyclone stoichiometry (slope of linear fit) was estimated at -44. For example, reducing the stoichiometry from 1.08 (typical setting) to 1.02 (low setting) increased the fly ash carbon content less than 3% (absolute).

The effects of varying the reburn stoichiometry on NO_x emissions and the fly ash carbon content were assessed based on the validation test results (Table 9), as shown in Figure 7. Also shown in Figure 7 are some of the optimization test results. The reburn stoichiometry had a dominant effect on NO_x emissions, in agreement with the optimization test results. However, the validation tests generated about 0.05 lb/MM Btu lower NO_x emissions than the optimization tests. The range of tested reburn stoichiometries (generally 0.87-0.90) was not sufficiently large to assess the effect on the fly ash carbon content (between 39% and 48%). Within a narrow range of cyclone heat inputs (315-325 kpph) and at the average reburn stoichiometry of 0.88, the average fly ash carbon content was 44% for the validation tests and 40% (estimated from line fit in Figure 2) for the optimization tests. Therefore, the validation tests generated 4% higher fly ash carbon contents than the optimization tests. The differences in the results (NO_x emissions and the fly ash carbon content) between the validation and the optimization test programs were partially due to differences in the coal properties and partially due to experimental variability between the two test periods. Specifically, the coal burned during the two test periods differed slightly in the analyses (Table 1), and the two test programs were conducted differently as previously discussed.

The NO_x reduction limit of the micronized coal reburn system was explored by utilizing a low cyclone stoichiometry of 1.03 and a maximum reburn coal feed (8 kpph) to achieve a reburn stoichiometry of 0.81. NO_x emissions dropped to 0.41 lb/MM Btu, corresponding to a fly ash carbon content of 48%, which was not significantly higher than the typical level of 41-48% achieved at moderate reburn applications and corresponding to a reburn stoichiometry of 0.88.

The effects of varying the final stoichiometry between 1.05 and 1.16 on NO_x emissions and the fly ash carbon content were assessed at a reburn stoichiometry level of 0.88-0.89 based on the validation test results (Table 9), as shown in Figure 8. Variations in the final stoichiometry had no significant effects on either NO_x emissions or the fly ash carbon content, in agreement with the optimization test results.

TABLES AND FIGURES

Table 1. Test Program Coal Analyses.

Date	Coal	Total H_2O %	As Det H_2O %	Dry VM %	Dry Btu/lb	Dry C %	Dry H %	Dry N %	Dry S %	Dry Ash %	Sieve Mesh Size, % -400 %	-325 %	-200 %
Optimization Testing													
4/20/97	6.20		39.30	14184	78.80	5.20	1.50	2.40	6.90		91.7	99.0	
Performance and Long-Term Testing													
6/2/98	Raw	5.89	1.74	39.87	14227	77.96	5.25	1.59	2.19	6.67			
6/3/98	Raw	5.67	1.58	39.65	14206	78.71	5.25	1.58	2.19	6.66			
6/4/98	Raw	7.62	1.53	39.96	14202	78.63	5.12	1.58	2.22	6.68			
6/2/98	MCR 1		0.54	39.16	14116	78.13	5.13	1.57	2.21	6.79	87.7	94.1	98.9
6/2/98	MCR 2		0.62	39.12	14149	78.52	5.09	1.52	2.24	6.83	88.0	94.0	98.9
6/3/98	MCR 3		0.63	39.39	14150	78.33	4.81	1.49	2.27	6.72	86.8	94.1	98.8
6/3/98	MCR 4		0.58	39.52	14112	78.57	4.90	1.51	2.29	6.88	87.6	93.1	98.8
Validation Testing													
9/98	Raw		1.15	38.52	14015	78.51	4.99	1.53	2.02	7.60			

Table 2. Optimization Test Matrix (Tests Conducted by Babcock & Wilcox).

	Boiler Load kpph	MCR %	Cyc Input kpph	O_2 %	SR1	SR2	SR3	NO_x lb/ MMBtu	Fly Ash % C
Set 1: Baseline (No Reburn) Tests, Variable Boiler Load									
	400	0.0	400	3.25	1.12	1.12	1.19	1.38	12.4
	373	0.0	373	3.35	1.09	1.09	1.16	1.23	16.5
	342	0.0	342	3.10	1.05	1.05	1.13	1.16	22.3
	313	0.0	313	3.60	1.05	1.05	1.13	1.06	38.6
Set 2: Reburning Tests, Variable Boiler Load and Constant Cyclone Heat Input									
	398	20.0	319	3.85	1.07	0.86	1.18	0.56	41.6
	375	15.0	319	3.35	1.06	0.90	1.12	0.68	38.4
	357	10.9	318	3.12	1.06	0.95	1.11	0.84	35.4
	338	6.7	315	3.50	1.05	0.98	1.12	1.00	33.3
Set 3: Reburning Tests, Constant Boiler Load and Variable Cyclone Heat Input									
	399	5.7	376	2.75	1.09	1.03	1.13	1.19	20.6
	398	11.5	352	2.70	1.08	0.96	1.12	0.87	28.1
	403	16.7	336	2.75	1.06	0.89	1.11	0.62	38.7
	414	22.6	320	2.65	1.06	0.82	1.10	0.50	41.9
Set 4: Reburning Tests, Variable Over Fire Air Mixing Parameters									
	400	19.4	323	3.55	1.07	0.86	1.13	0.57	41.5
	399	19.5	321	3.80	1.05	0.85	1.16	0.54	44.2
	400	19.4	322	3.90	1.05	0.85	1.16	0.55	47.5
	401	19.4	323	3.50	1.03	0.83	1.14	0.52	37.5
	402	19.5	323	3.75	1.05	0.84	1.16	0.52	43.2
	399	19.7	321	3.75	1.05	0.85	1.16	0.55	44.2
	398	20.0	319	3.85	1.07	0.86	1.18	0.56	36.7
Set 5: Reburning Tests, Variable Over Fire Air Flow									
	399	19.9	320	4.40	1.05	0.84	1.22	0.57	42.8
	402	19.9	322	2.70	1.07	0.86	1.11	0.54	40.3
Micronized Coal Reburn Recommended Setting									
	398	19.8	319	3.25	1.05	0.85	1.11	0.51	37.9

Table 3. Performance Test Coal Analysis.

Total Moisture, %		6.38
As Determined Moisture, %		1.60
Grindability HGI (at Det Moisture)	53	
Free Swelling Index		8
Btu/lb, Dry		14209
Volatile Matter		39.54
<u>Ultimate, Dry %</u>		
C		78.50
H		5.04
N		1.58
Chlorine		0.134
S, Total	2.21	
Ash		6.64
O (Difference)		5.90
<u>Sulfur Forms, Dry %</u>		
Pyritic		0.75
Sulfate		0.01
Organic	1.45	
<u>Reducing Ash Fusion Temperature, EF</u>		
I.D.		2179
H=W		2226
H=W/2	2273	
Fluid		2362
<u>Oxidizing Ash Fusion Temperature, EF</u>		
I.D.		2476
H=W		2540
H=W/2	2575	
Fluid		2602
<u>Major Ash Elements, % (Ignited at 750 EC)</u>		
SiO2		45.34
Al2O3		22.90
TiO2		1.08
Fe2O3		17.45
CaO		5.51
MgO		0.99
Na2O		1.33
K2O		1.13
P2O5		0.36
SO3		4.05

Table 4. Performance Test Operating Parameters.

		Micronized Coal Reburn Test					Baseline (No Reburn) Test			
Performance Test		1	2	3	4		1	2	3	4
Test Date		6/2/98	6/2/98	6/3/98	6/3/98		6/3/98	6/4/98	6/4/98	6/4/98
Test Start Time	10:30	13:30	08:30	11:45		17:00	08:15	10:30	15:00	
Test End time		12:30	15:30	10:30	13:45		19:00	10:15	12:30	17:00
Boiler Load, kpph Steam	400	400	398	402		400	403	404	402	
Cyclone Coal Flow, kpph		30.5	30.5	29.7	29.9		36.8	37.4	37.6	36.8
MCR Flow, kpph		6.1	6.1	6.5	6.7		0.0	0.0	0.0	0.0
Micronized Coal Reburn, %		16.7	16.6	17.9	18.2		0.0	0.0	0.0	0.0
Cyclone Heat Input, kpph Steam	333	334	327	329		400	403	404	402	
Cyclone Air Flow, kpph	328	328	321	324		402	409	410	403	
Over Fire Air Flow, kpph	72	68	69	67		22	22	22	21	
Calculated East Air-to-Fuel Ratio	--	11.0	11.0	11.0		11.0	11.0	11.0	10.9	
Calculated West Air-to-Fuel Ratio		--	10.7	10.7	10.7		10.8	11.0	10.8	10.7
Cyclone Stoichiometry		1.08	1.08	1.08	1.08		1.09	1.09	1.09	1.09
Reburn Stoichiometry		0.90	0.90	0.89	0.89		1.09	1.09	1.09	1.09
Final Stoichiometry		1.10	1.08	1.08	1.07		1.15	1.15	1.15	1.15
MCR Transport Gas Flow, kpph	16.3	16.2	16.5	16.5		17.2	17.9	17.9	17.9	
MCR Mill Current, Ampere		186	186	190	193		--	--	--	--
MCR Feeder Motor Speed, rpm		--	646	690	709		--	--	--	--
MCR Classifier Outlet Duct Temp, EF		300	302	289	285		330	324	329	330
Feed Water Temperature, EF		407	406	407	407		406	409	409	408
Back-Up Attemperator Water, kpph		0.0	0.0	0.0	0.0		23.6	25.8	26.9	22.1
Secondary Superheater Press, psig		1425	1429	1427	1430		1422	1426	1426	1426
Primary Super Heater Outlet Temp, EF		742	736	732	730		770	789	790	770
Gas Temp at Economizer Outlet, EF		701	680	693	681		738	760	779	718
Gas Temp at Air Heater Outlet, EF		342	341	335	335		354	358	368	355
Opacity, %		10.0	10.4	7.5	9.0		8.3	11.4	14.4	4.2

Table 5. Performance Test Flue Gas and Fly Ash Results.

		Micronized Coal Reburn Test					Baseline (No Reburn) Test			
Performance Test		1	2	3	4		1	2	3	4
Flue Gas Emissions										
Boiler O_2, %		2.5	2.5	2.5	2.5		3.2	3.2	3.0	3.4
Plant CO_2, %		13.3	13.2	13.6	13.5		13.0	13.2	13.4	13.2
CO, ppm		30	42	39	41		2	4	0	1
Gas H_2O, %		7.5	8.8	8.1	8		8.1	7.2	7.7	7.7
Plant NO_x, ppm		354	351	382	382		821	870	877	777
NO_x, lb/MM Btu	0.57	0.57	0.61	0.61		1.35	1.42	1.41	1.27	
SO_2, lb/MM Btu	2.72	2.88	2.97	2.97		2.95	2.91	2.92	2.92	
Fly Ash Emissions										
ESP Inlet Particulate Loading, lb/h		1493	1756	1361	1400		526	468	520	611
Fly Ash, % Inlet Ash		38.8	45.6	38.3	37.8		18.8	17.7	19.3	22.3
Fly Ash Analysis: Iso-Kinetic Sampling at the ESP Inlet										
%C		38.95	37.49	34.12	36.51		14.68	7.08	9.11	14.36
%S		0.91	1.17	0.96	0.95		1.18	1.25	1.31	1.23
%Ash		59.68	59.58	63.91	62.07		82.65	87.51	86.13	82.95
Fly Ash Analysis: Sampling the First ESP Hopper										
%C		40.03	43.75	38.16	41.05		17.35	12.06	12.48	15.06
%Ash		59.51	54.74	60.47	58.45		81.39	86.72	85.41	83.37
Fly Ash Analysis: Sampling the ESP Silo (Composite)										
%C		42.41	38.14	36.78	39.19		23.88	14.50	17.64	13.04
%Ash		55.04	61.36	60.26	59.65		73.80	83.45	80.83	84.64

Table 6. Performance Test Boiler Efficiency Calculations.

	Micronized Coal Reburn				Baseline (No Reburn)			
Performance Test	1	2	3	4	1	2	3	4
ESP Inlet Temp EF	351	345	346	340	366	365	376	364
Flue Gas Composition by Volume:								
CO_2, %	15.0	15.7	15.6	15.8	15.1	15.2	15.3	15.1
O_2, %	3.7	3.0	3.0	2.8	3.6	3.6	3.4	3.7
CO, ppm	30	42	39	41	2	4	0	1
N_2, %	81.3	81.3	81.4	81.4	81.3	81.2	81.3	81.2
Coal Analysis, Dry Basis:								
% C	77.96	77.96	78.71	78.71	78.71	78.63	78.63	78.63
% H	5.25	5.25	5.25	5.25	5.25	5.12	5.12	5.12
% N	1.59	1.59	1.58	1.58	1.58	1.58	1.58	1.58
% S	2.19	2.19	2.19	2.19	2.19	2.22	2.22	2.22
% O	6.34	6.34	5.61	5.61	5.61	5.77	5.77	5.77
% Ash	6.67	6.67	6.66	6.66	6.66	6.68	6.68	6.68
Btu/lb	14227	14227	14206	14206	14206	14202	14202	14202
H_2O (Wet)	5.89	5.89	5.67	5.67	5.67	7.62	7.62	7.62
Ash Analysis, Dry Basis:								
% Ash	59.68	59.58	63.91	62.07	82.65	87.51	86.13	82.95
% C	38.95	37.49	34.12	36.51	14.68	7.08	9.11	14.36
% S	0.91	1.17	0.96	0.95	1.18	1.25	1.31	1.23
Calculations, Based on 1 lb of As-Fired Fuel, Dry Basis:								
Fly Ash, % Inlet 40	40	40	40	20	20	20	20	
Fly Ash, lb	0.042	0.042	0.039	0.040	0.015	0.014	0.014	0.015
Bottom Ash, lb	0.038	0.038	0.038	0.038	0.051	0.050	0.050	0.050
C Burnout, lb	0.717	0.718	0.729	0.727	0.740	0.725	0.725	0.724
Gas, lb	12.27	11.82	12.02	11.87	12.60	12.31	12.17	12.35
Heat Losses, %:								
1. Dry Gas	5.96	5.62	5.73	5.53	6.45	6.42	6.59	6.42
2. H_2O in Fuel	0.52	0.51	0.49	0.49	0.50	0.68	0.69	0.68
3. H in Fuel	3.89	3.88	3.89	3.88	3.92	3.82	3.84	3.82
4. Flue Gas CO	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
5. Unburned C	1.82	1.75	1.49	1.64	0.30	0.17	0.20	0.29
6. Radiation	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
7. H_2O in Air	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
8. Unmeasured	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Efficiency, %	86.85	87.26	87.43	87.49	87.87	87.95	87.73	87.83

Table 7. Performance Test Summary.

		MCR	Baseline
Boiler Load, kpph Steam	400	402	
Cyclone Coal Flow, kpph	30.1	37.1	
MCR Flow, kpph	6.3	0.0	
Micronized Coal Reburn, %		17.3	0.0
Cyclone Heat Input, kpph Steam	331	402	
Cyclone Air Flow, kpph	325	406	
Over Fire Air Flow, kpph	69	22	
Calculated East Air-to-Fuel Ratio	11.0	11.0	
Calculated West Air-to-Fuel Ratio	10.7	10.8	
Cyclone Stoichiometry		1.08	1.09
Reburn Stoichiometry		0.89	1.09
Final Stoichiometry		1.08	1.15
MCR Transport Gas Flow, kpph	16.4	17.7	
MCR Mill Current, Ampere		189	--
MCR Feeder Motor Speed, rpm		682	--
MCR Classifier Outlet Duct Temp, EF		294	328
Feed Water Temperature, EF		407	408
Back-Up Attemperator Water, kpph		0.0	24.6
Secondary Super Heater Press, psig		1428	1425
Primary Super Heater Outlet Temp, EF		735	780
Gas Temp at Economizer Outlet, EF		689	748
Gas Temp at Air Heater Outlet, EF	338	359	
Opacity, %		9.2	9.6
Boiler O_2, %		2.5	3.2
Plant CO_2, %		13.4	13.2
CO, ppm		38	2
Gas H_2O, % Vol	8.1	7.7	
Plant NO_x, ppm		367	837
NO_x, lb/MM Btu	0.59	1.36	
SO_2, lb/MM Btu	2.89	2.93	
ESP Inlet Particulate Loading, lb/h	1503	531	
Fly Ash, % Inlet Ash		40.1	19.5
C in Fly Ash, Iso-Kinetic, %		36.8	11.3
C in Fly Ash, First ESP Hopper, %		40.7	14.2
C in Fly Ash, ESP Silo, %		39.1	15.1
Boiler Efficiency, %		87.3	87.8

Table 8. Long-Term test Daily and 30-Day Rolling Averages.

		-------------		Daily Averages	------------			30-Day Rolling	
Day in 1998		**Boiler Load kpph**	**MCR %**	**SR2**	**Boiler O_2 %**	**NO_x lb/ MMBtu**	**Fly Ash % C**	**NO_x lb/ MMBtu**	**Fly Ash % C**
05-June		392	16.3	0.90	2.7	0.66	20.5		
06-June		400	17.9	0.88	2.8	0.59	37.8		
07-June		389	16.4	0.89	2.8	0.63	37.0		
08-June		398	18.0	0.87	2.8	0.58	40.4		
09-June		401	18.5	0.87	2.8	0.58	44.2		
10-June		399	17.7	0.88	2.9	0.58	56.1		
11-June		402	17.3	0.89	2.8	0.57	52.7		
12-June		402	17.2	0.89	2.8	0.57	36.1		
13-June		399	17.0	0.89	2.8	0.58	67.8		
14-June		389	15.7	0.91	2.9	0.65	33.5		
15-June		402	17.9	0.89	2.8	0.59	40.0		
16-June						0.58	27.6		
17-June		400	17.9	0.88	2.8	0.63	38.1		
18-June		399	17.9	0.89	2.8	0.58	59.9		
19-June		397	15.7	0.91	2.9	0.65	43.8		
20-June		356	11.2	0.95	2.9	0.81	41.5		
21-June		368	14.0	0.93	2.9	0.72	24.5		
22-June		395	17.1	0.90	2.8	0.60	33.8		
23-June		405	17.7	0.89	2.8	0.57	25.3		
24-June		406	17.5	0.89	2.8	0.55	52.3		
25-June		404	13.9	0.93	2.9	0.69	33.4		
26-June		399	17.4	0.89	2.8	0.60	33.4		
27-June		364	12.6	0.94	3.0	0.77	37.2		
28-June		380	14.6	0.93	2.9	0.68	31.5		
29-June		405	13.2	0.92	3.1	0.78	27.5		
30-June		398	7.3	0.99	2.9	0.97			
01-July	374	12.0	0.94	2.9	0.83	32.6			
02-July	376	14.6	0.91	2.9	0.77	49.9			
03-July	388	16.6	0.89	2.9	0.69	47.7			
04-July	380	17.1	0.89	2.9	0.66	39.5	0.66	39.5	
05-July	385	16.5	0.91	3.0	0.65	29.4	0.66	39.8	
06-July	394	17.2	0.90	3.0	0.69	34.1	0.66	39.7	
07-July	364	9.9	0.96	3.3	0.86	30.0	0.67	39.4	
08-July	390	12.7	0.93	3.0	0.78	27.3	0.67	39.0	
09-July	398	17.3	0.88	3.1	0.61	26.5	0.68	38.4	

Table 8 (Continued).

		-------------		Daily Averages	------------			30-Day Rolling	
Day in 1998		**Boiler Load kpph**	**MCR %**	**SR2**	**Boiler O_2 %**	**NO_x lb/ MMBtu**	**Fly Ash % C**	**NO_x lb/ MMBtu**	**Fly Ash % C**
10-July	392	16.0	0.89	2.9	0.68	40.0	0.68	37.8	
11-July	388	17.7	0.88	2.7	0.61	50.9	0.68	37.8	
12-July	392	16.2	0.91	2.8	0.64	31.5	0.68	37.6	
13-July	377	15.5	0.90	2.7	0.66	41.9	0.68	36.7	
14-July	387	14.2	0.92	2.8	0.71	48.4	0.69	37.2	
15-July	395	17.4	0.89	2.7	0.60	43.1	0.69	37.3	
16-July	404	18.9	0.87	2.9	0.57	35.9	0.69	37.6	
17-July	403	16.9	0.89	2.8	0.63	32.5	0.69	37.4	
18-July	401	15.8	0.90	2.9	0.68	39.7	0.69	36.7	
19-July	390	15.4	0.90	2.9	0.67	47.6	0.69	36.9	
20-July	400	17.9	0.88	2.9	0.60	47.5	0.68	37.1	
21-July	403	18.6	0.88	2.8	0.59	55.2	0.68	38.1	
22-July	399	3.7	1.00	2.9	1.01	40.5	0.69	38.4	
23-July	401	16.6	0.90	2.8	0.68	38.0	0.70	38.8	
24-July	398	19.0	0.87	2.8	0.56		0.70	38.3	
25-July							0.70	38.5	
26-July							0.70	38.7	
27-July	380	10.4	0.95	2.8	0.85	36.4	0.70	38.7	
28-July	396	16.0	0.90	2.8	0.76		0.71	38.9	
29-July					0.86		0.71	39.4	
30-July							0.70	39.4	
31-July							0.69	39.7	
01-August								0.69	39.3
02-August								0.69	38.9
03-August		348	5.9	1.00	3.4	0.96	39.1	0.70	38.8
04-August		399	18.9	0.87	2.9	0.58	22.9	0.70	38.5
05-August		399	18.2	0.88	2.8	0.58		0.70	38.7
06-August		395	17.6	0.89	2.9	0.60		0.69	39.2
Statistical Summary									
Count		55	55	55	55	57	51	34	34
Minimum		348	3.7	0.87	2.7	0.55	20.5	0.66	36.7
Maximum		406	19.0	1.00	3.4	1.01	67.8	0.71	39.8
Average		392	15.6	0.90	2.9	0.67	38.9	0.69	38.4
Standard Deviation								0.014	0.92
95% Confidence Level								0.027	1.8

Table 9. Validation Test Matrix.

Date	Time Period	Boiler Load kpph	MCR %	Cyc Input kpph	O_2 %	SR1	SR2	SR3	NO_x lb/ MMBtu	Fly Ash 1 % C	2 % C
Reference Test: Typical Operating Conditions											
09/21	13:45-14:45	405	17.7	333	3.0	1.07	0.88	1.12	0.55	46.0	48.0
Set 1: Cyclone Heat Input Variation (Reburn)											
09/22	14:00-15:00	371	17.3	307	3.0	1.07	0.89	1.09	0.57	42.8	43.5
09/22	12:15-12:45	437	17.7	360	3.0	1.10	0.90	1.14	0.61	27.4	36.6
Set 2: Cyclone Heat Input Variation (No Reburn)											
09/23	10:00-11:00	332	0.0	332	3.8	1.06	1.06	1.13	1.06	39.7	41.6
09/23	11:45-12:45	407	0.0	407	3.8	1.08	1.08	1.19	1.24	36.9	27.9
Set 3: Cyclone Stoichiometry Variation, Variable Cyclone Heat Input											
09/21	15:30-16:30	399	13.8	344	2.9	1.02	0.88	1.11	0.57	46.9	49.4
09/21	18:00-19:00	401	21.4	316	3.0	1.14	0.89	1.14	0.54	42.3	43.6
Set 4: Cyclone Stoichiometry Variation, Constant Cyclone Heat Input											
09/21	19:45-20:45	383	13.6	331	3.0	1.04	0.90	1.11	0.61	46.1	43.1
09/22	09:15-10:15	416	20.6	331	3.0	1.13	0.90	1.11	0.62	40.6	42.1
Set 5: Reburn Stoichiometry Variation											
09/22	17:30-18:00	399	21.1	315	3.0	1.03	0.81	1.11	0.41	47.1	47.6
09/22	15:30-16:30	404	19.9	323	3.0	1.08	0.87	1.12	0.50	44.3	46.2
Set 6: Final Stoichiometry Variation											
09/22	20:30-21:30	402	17.6	331	2.5	1.06	0.88	1.05	0.55	44.8	45.5
09/22	19:00-20:00	398	17.6	328	3.6	1.08	0.89	1.16	0.57	41.4	44.0
Miscellaneous Reburn Tests											
09/23	07:30-08:30	403	19.6	324	3.0	1.08	0.87	1.08	0.59	42.2	44.9
09/22	22:45-23:45	399	15.6	337	2.5	1.07	0.90	1.06	0.62	39.1	39.2
09/21	16:45-17:15	401	13.9	345	3.0	1.05	0.90	1.12	0.63		
09/22	16:30-17:00	399	21.5	313	3.1	1.08	0.85	1.11	0.48		
09/22	11:00-11:30	440	17.6	362	3.1	1.14	0.94	1.13	0.69		

Figure 1. **Effect of Cyclone Heat Input, Optimization Testing.**

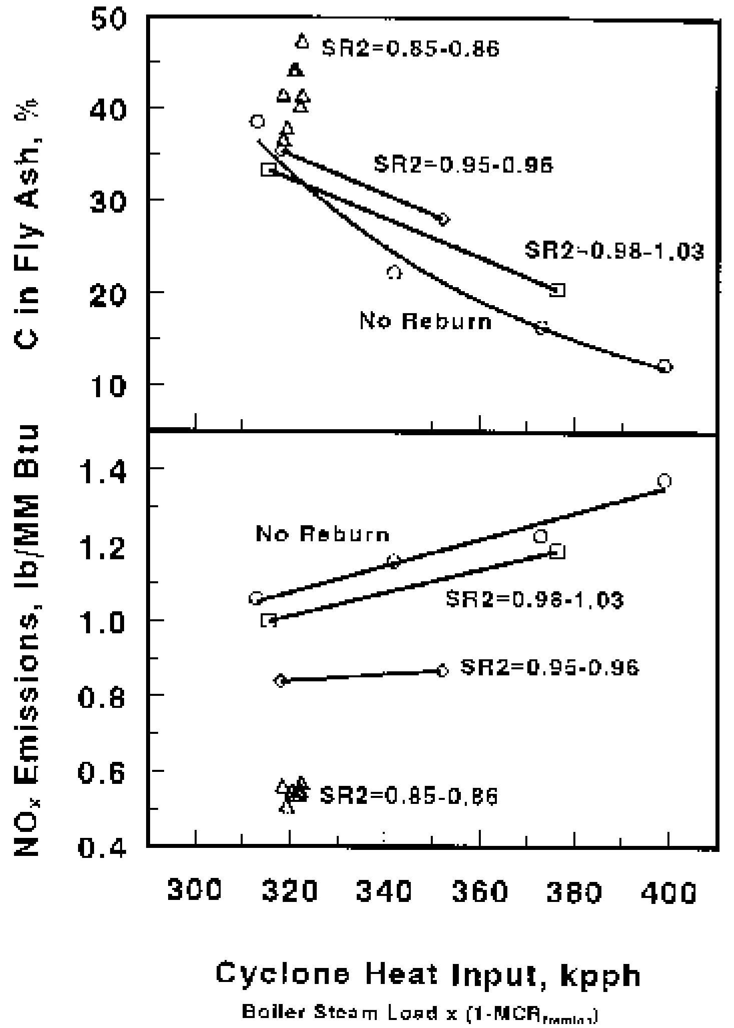

Figure 2. Effect of Reburn Stoichiometry, Optimization Testing.

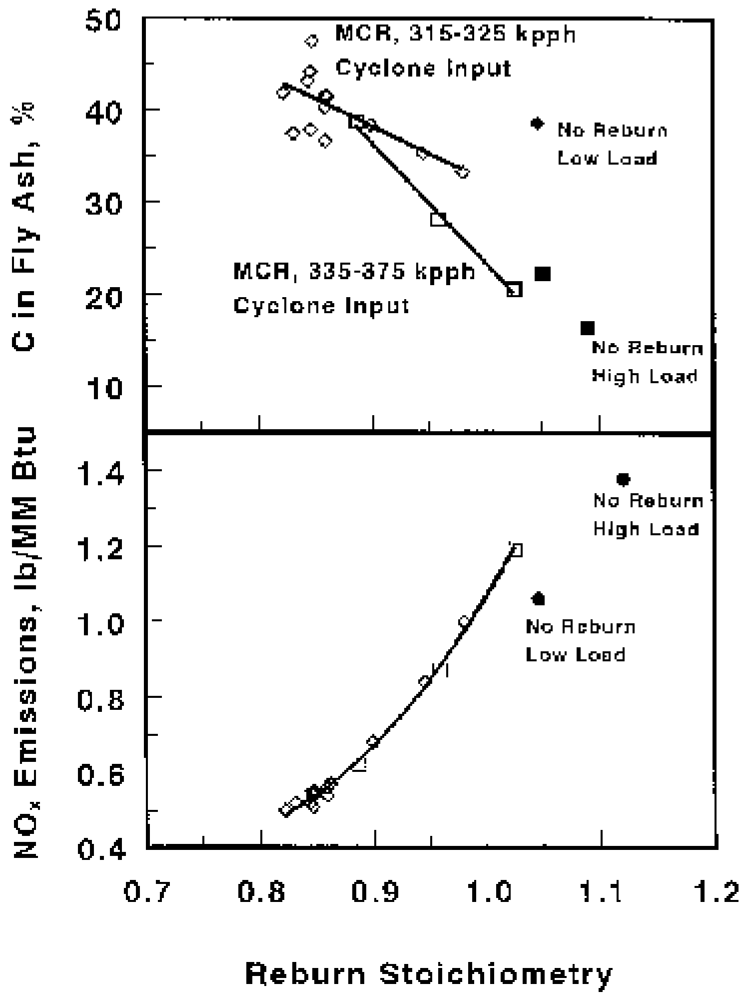

Figure 3. Effect of Final Stoichiometry, Optimization Testing.

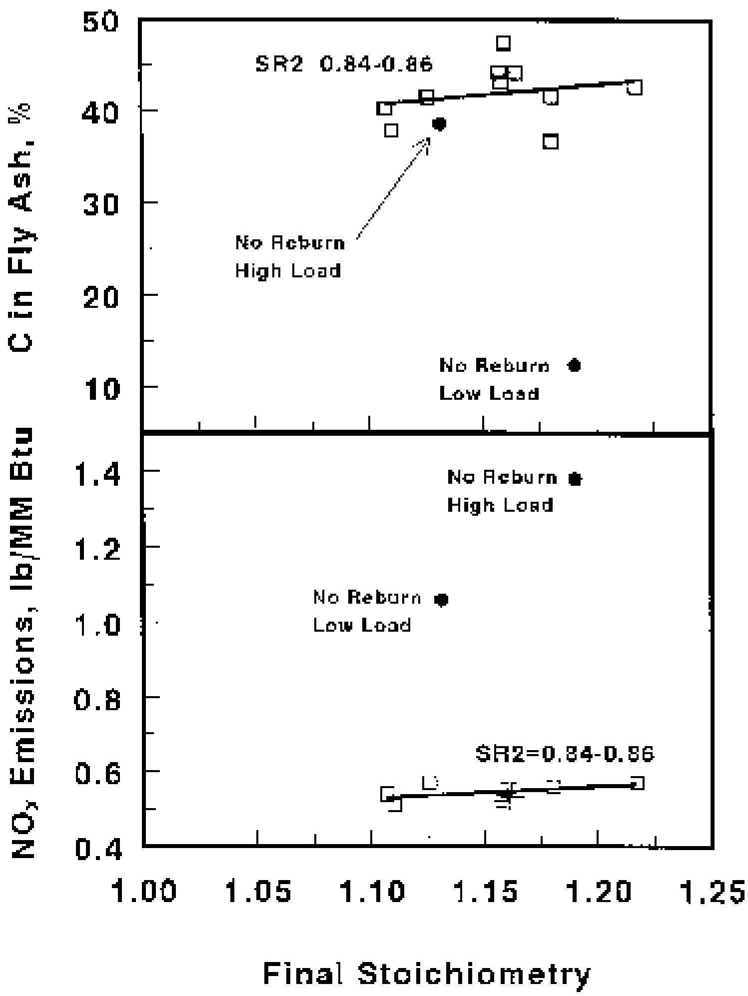

Figure 4. Comparing Long and Short Term NO_x Reduction.

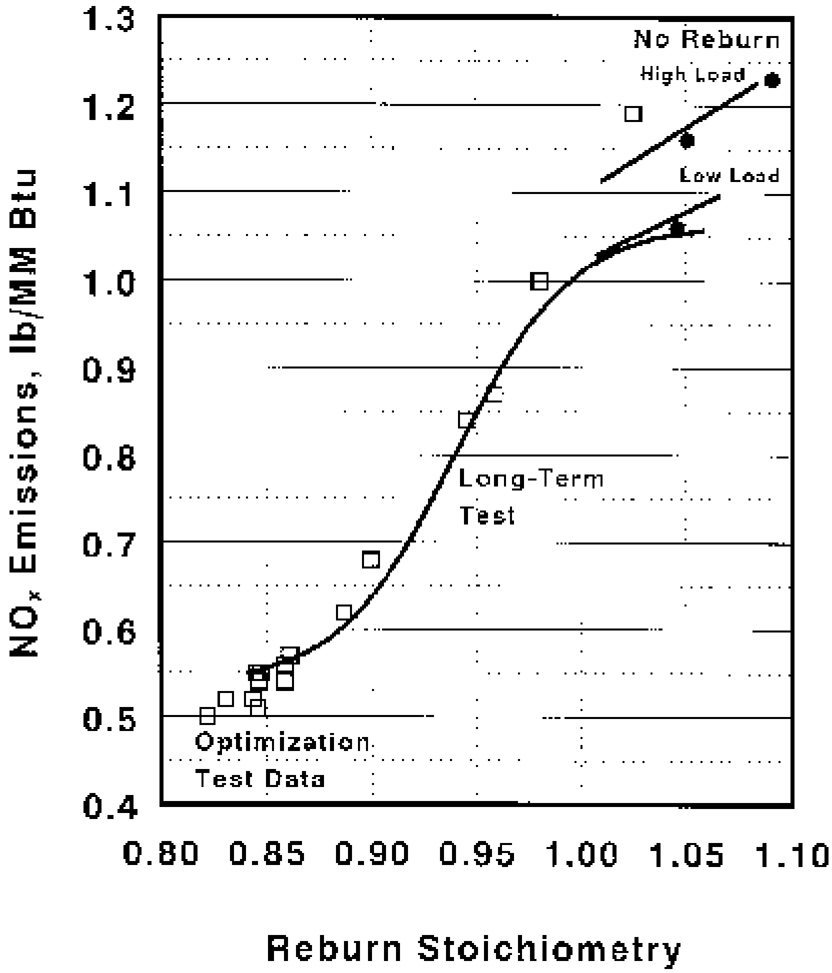

Figure 5. Effect of Cyclone Heat Input, Validation Testing.

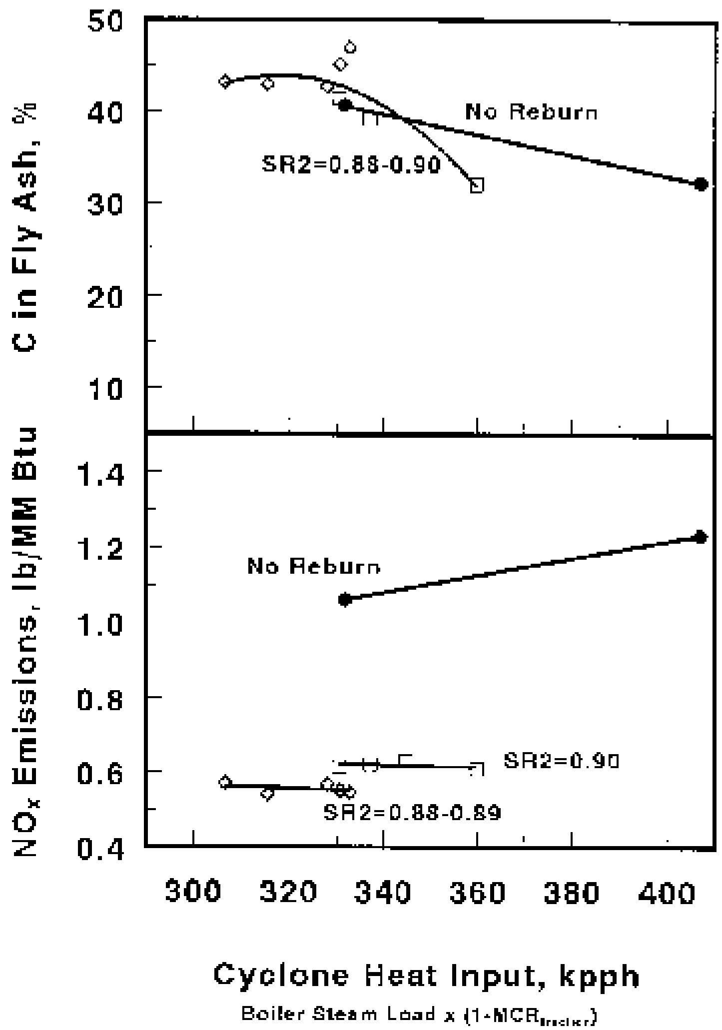

Figure 6. Effect of Cyclone Stoichiometry, Validation Testing.

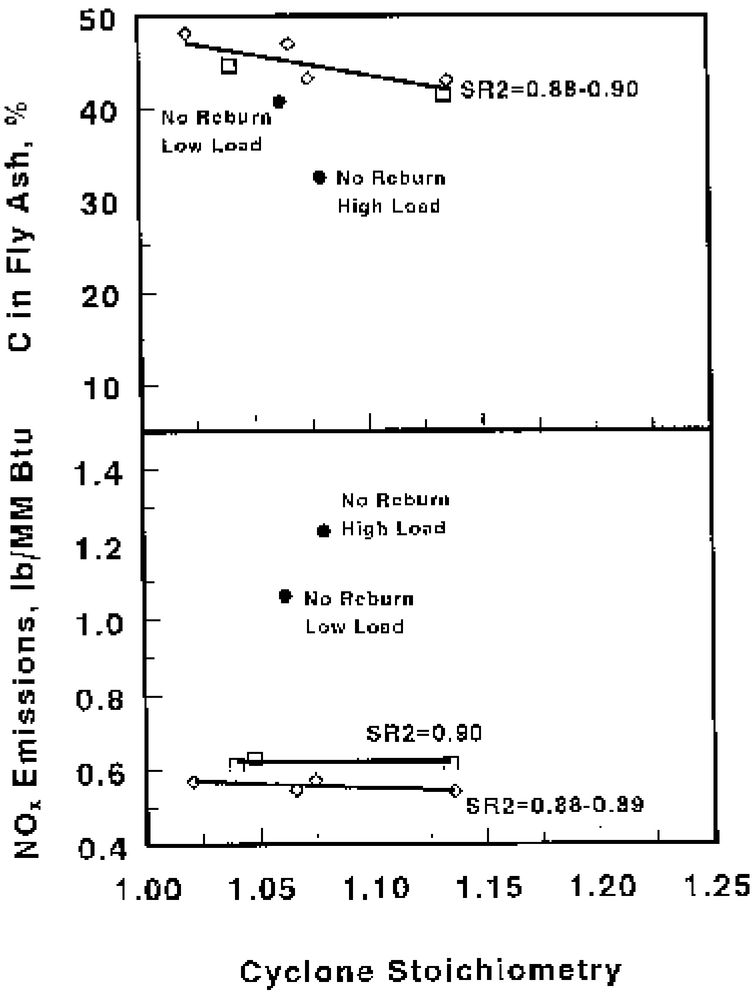

Figure 7. Effect of Reburn Stoichiometry, Validation Testing.

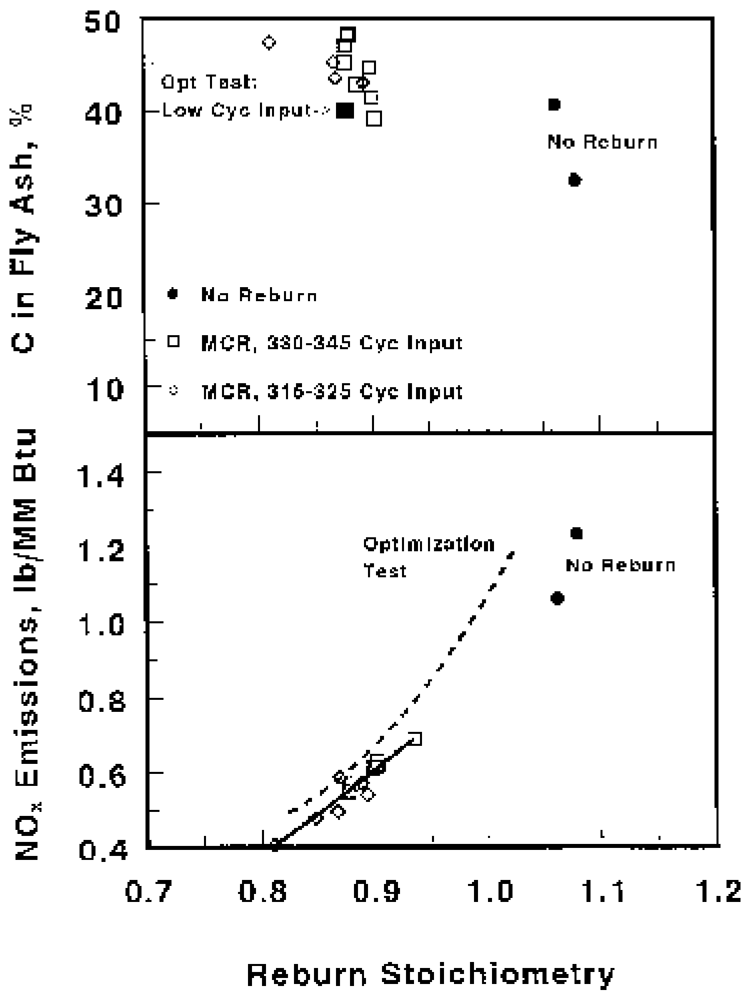

Figure 8. Effect of Final Stoichiometry, Validation Testing.