DOE/FE-0471

NEW YORK STATE ELECTRIC & GAS CORPORATION

MICRONIZED COAL REBURNING DEMONSTRATION FOR NO_x CONTROL

PROJECT PERFORMANCE SUMMARY
CLEAN COAL TECHNOLOGY DEMONSTRATION PROGRAM

JULY 2004

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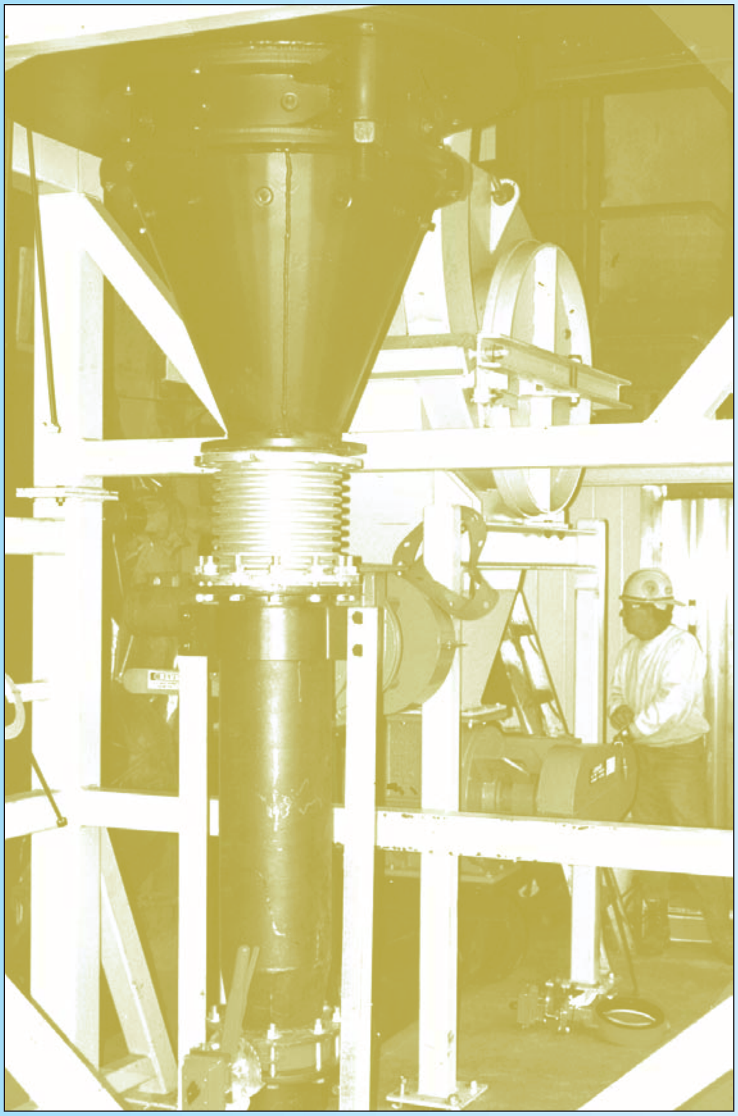


PROJECT PERFORMANCE SUMMARY
CLEAN COAL TECHNOLOGY DEMONSTRATION PROGRAM

ENVIRONMENTAL CONTROL DEVICES

Micronized Coal Reburning Demonstration for NO_x Control

MCR proved to be a combustion modification option for NO_x reduction in cyclone-fired boilers and as a NO_x control supplement to low-NO_x burners in tangentially-fired boilers.

Overview

This project is part of the U.S. Department of Energy's Clean Coal Technology Demonstration Program (CCTDP), which was established to address energy and environmental concerns related to coal use. The project presented here was one of nine selected from 33 proposals submitted in response to the CCTDP's fourth solicitation in 1991.

The New York State Electric & Gas Corporation (NYSEG) sponsored a demonstration of micronized coal reburning (MCR) for NO_x control on both a tangentially-fired boiler and a cyclone-fired boiler at two separate sites. Cofunders of the project included the New York State Energy Research and Development Authority, the Empire State Electric Energy Research Corporation, and Eastman Kodak Company, which also hosted the cyclone-fired boiler project. The participation reflected the priority New York placed on reducing NO_x emissions and the potential for MCR.

Reburning reduces NO_x emissions by staging combustion in the boiler through injecting reburning fuel and air to complete combustion of the fuel above the primary combustion zone. Reburning with natural gas or oil is an established NO_x control technique that is effective but expensive because of the use of premium fuels. Natural gas and oil owe their effectiveness to mixing well with flue gas streams (because of their common fluid state) and to relatively high reactivity. Micronizing coal — grinding it to a nominal 20 micron size — makes the coal act much like a fluid and enhances reactivity as a result of increased surface area, which is nine times that of typical pulverized coal at a nominal 60 micron size.

The finer size also addresses a concern regarding loss on ignition (LOI) in applying coal reburning, which means energy loss through unburned carbon. The staging inherent in reburning makes coal reburning vulnerable to increased LOI due to the relatively short oxidation residence times for the reburning fuel. Micronizing the coal makes it less susceptible to increased LOI because complete combustion is achieved more rapidly than with pulverized coal.

MCR achieved a 59% NO_x reduction on the cyclone-fired boiler, exceeding the NO_x reduction objective of 50%; and achieved a 28% further NO_x reduction on the tangentially-fired boiler previously retrofitted with low-NO_x burners, meeting the NO_x reduction objective of 25–35%.

The Project

The search continued throughout the 1990s for combustion modification alternatives to expensive post-combustion selective catalytic reduction (SCR) technologies for greater (deeper) NO_x reduction. This activity prompted further investigation of coal reburning beyond an earlier promising CCTDP project at Wisconsin Power and Light Company's Nelson Dewey Station. MCR showed the potential to overcome issues limiting coal reburning performance. Pulverizing coal to the point where it is micronized — 80% less than 325 mesh (nominally 20 microns in size) — results in coal properties similar to natural gas and petroleum, without the high cost, limited availability, and dual fuel handling.

The Eastman Kodak Park Power Plant's 60-MWe Unit 15 represented a good demonstration opportunity because cyclone-fired boilers emit high levels of NO_x and reburning is the only combustion modification NO_x control technique applicable to cyclone-fired boilers. Cyclone burners are massive and operate on principles that do not lend themselves to staged combustion as used in low-NO_x burners. For this project, two Fuller Micromill™ pulverizers, specifically designed for producing micronized coal, were dedicated to providing reburning fuel to the cyclone boiler.

NYSEG's 148-MWe tangentially-fired Milliken Station Unit 1 provided an opportunity to leverage an ongoing CCTDP project. The ABB Low NO_x Concentric Firing System III™ (LNCFS III™) low-NO_x burners installed at Milliken as part of a previous CCTDP project and the use of new D.B. Riley MPS 150 coal pulverizer mills enabled MCR demonstration without additional capital expenditure. The LNCFS III™ low-NO_x burners, which use separated overfire air ports and four widely spaced coal injection ports, allow setup in a reburning configuration, and the D.B. Riley MPS 150 mills can deliver micronized coal.

Both sites carried out MCR testing to assess the effects of a range of operating parameters, identified optimum operating conditions, and conducted long-term tests to assess MCR performance and the impact on plant performance.

Project objectives were to (1) demonstrate 50% NO_x reduction on cyclone boilers and an additional 25–35% NO_x reduction on tangentially-fired boilers fitted with low-NO_x burners; (2) evaluate the impact of MCR on plant performance; and (3) demonstrate the long-term reliability of MCR equipment. All objectives were successfully achieved.

Project Sponsor
New York State Electric & Gas Corporation (NYSEG)

Additional Team Members
Eastman Kodak Company–host and cofunder
CONSOL (formerly Consolidation Coal Company)–coal sample tester
DB Riley–technology supplier
Fuller Company–technology supplier
Energy and Environmental Research Corporation (EER)–reburning system designer
New York State Energy Research and Development Authority–cofunder
Empire State Electric Energy Research Corporation–cofunder

Location
Lansing, Tompkins County, NY (NYSEG's Milliken Station, Unit No. 1. This station is currently owned by AES Corporation and is designated AES Cayuga).
Rochester, Monroe County, NY (Eastman Kodak Company's Kodak Park Power Plant, Unit No. 15)

Technology
Micronized coal reburning using DB Riley's MPS mill (at Milliken Station) and Fuller's Micromill™ (at Eastman Kodak) technologies for producing micronized coal

Plant Capacity/Production
Milliken Station: 148-MWe tangentially-fired boiler
Kodak Park: 60-MWe cyclone-fired boiler

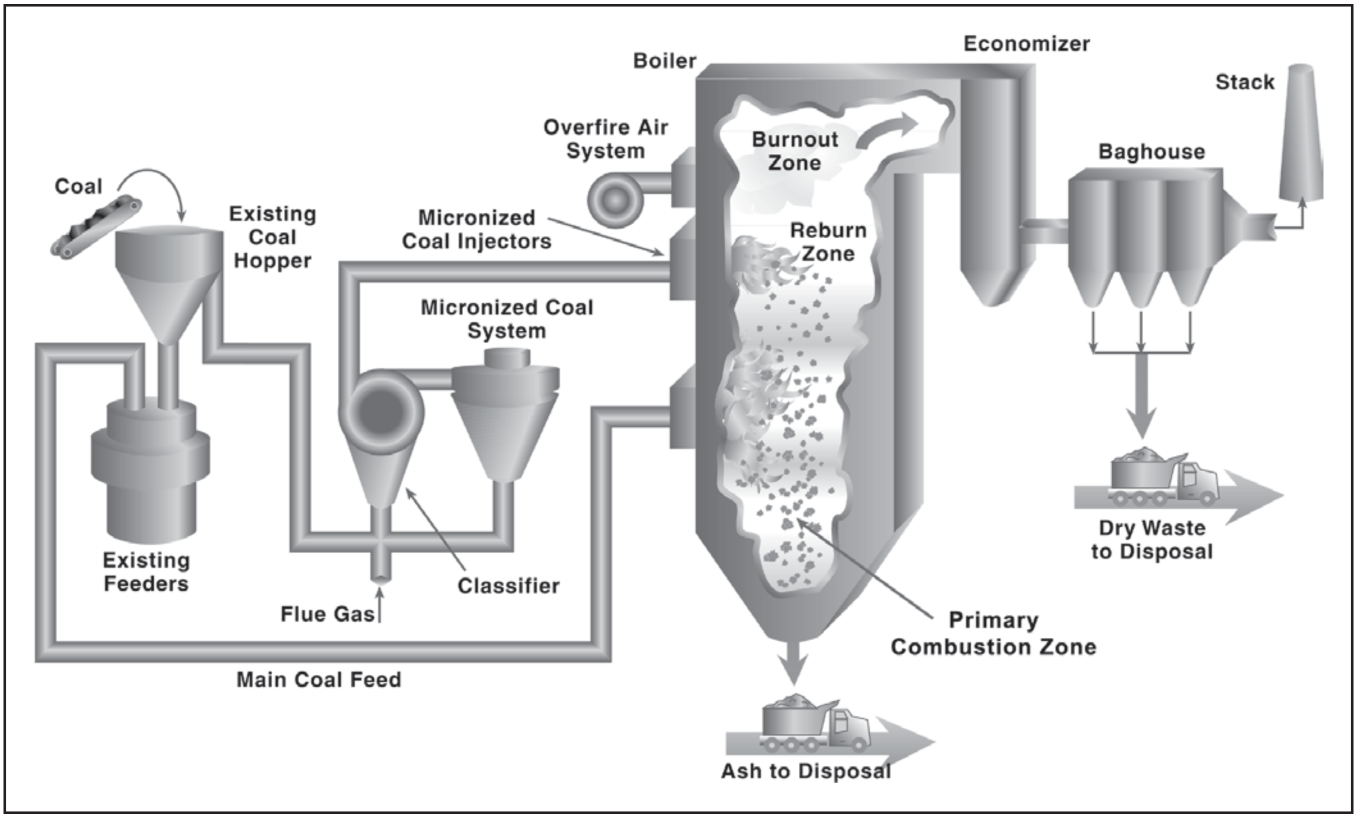
Coal
Pittsburgh seam bituminous, medium- to high-sulfur and nitrogen (3.2% sulfur and 1.5% nitrogen at Milliken and 2.2% sulfur and 1.6% nitrogen at Kodak Park)

Demonstration Duration
March 1997–April 1999

Project Funding

Total	$9,096,486	100%
DOE	2,701,011	30%
Participant	6,395,475	70%

The Technology



Reburning Process

Reburning reduces NO_x emissions by staging combustion in a boiler through creation of three zones—primary combustion zone, reburn zone, and burnout zone. The primary zone, which is comprised of the boiler's existing burners, receives 70–90% of the coal. The balance is injected into a reburn zone above the primary zone, and excess air is injected into a burnout zone above the reburn zone to complete combustion of the reburn coal.

The primary zone operates as close to stoichiometric conditions as possible, *i.e.*, the theoretical ratio of fuel to air needed for complete combustion, or a stoichiometric ratio of 1.0. However, combustion stability and low LOI typically require excess air levels of 10%, or a stoichiometric ratio of 1.10. NO_x emission reductions of 10% in this zone can be expected as a result of injecting less coal, reducing the heat release rate, and lowering the stoichiometry.

The reburn zone is established as close as possible above the primary zone, but far enough away to allow for complete combustion of the coal injected in the primary zone. This location is driven by the need for high temperatures to support breakdown of the reburn fuel into hydrocarbon fragments and their reactions with the NO_x in the flue gas. The extent of the reburn zone is determined by the need for a residence time of 300 to 500 milliseconds. The exact reburn fuel injection rate is determined by the desired reburn zone stoichiometric ratio, typically in the range of 0.85 to 0.95. This optimum range of stoichiometric ratios reflects the need to have a reducing environment to strip oxygen from the NO_x, avoid significant fuel-bound NO_x release, and facilitate subsequent burnout of the reburn fuel. Lower primary combustion zone excess air equates to a lower reburn fuel requirement. The reburn fuel injection medium is often recirculated flue gas in lieu of air to reduce reburn fuel requirements.

In the burnout zone, overfire air (OFA) is added to bring the overall boiler combustion system to its normal (no reburn) operating stoichiometry. OFA is typically 20% of the total air flow. The challenge is to effect complete combustion of the reburn fuel to minimize LOI and carbon monoxide (CO) emissions using as little excess air as possible to avoid boiler efficiency losses.

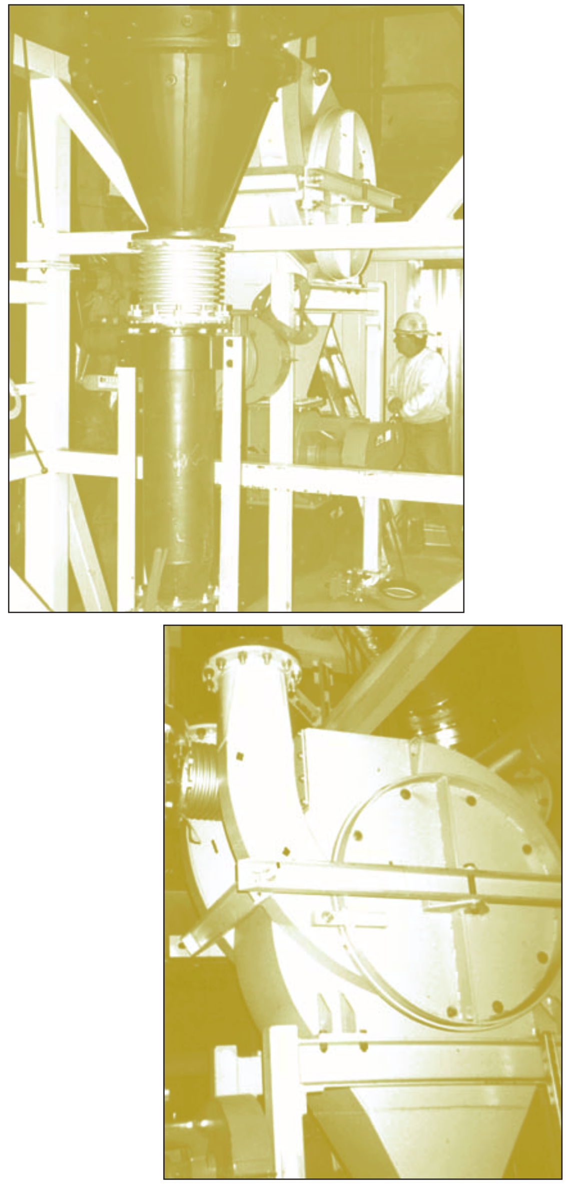
Kodak Park Installation

The schematic reflects the Kodak Park MCR installation. Existing mills provide coal to the two existing 8-foot diameter cyclone-fired burners. Two Fuller Micromill™ units are dedicated to injecting micronized coal into the reburn zone, the second serving as a spare at typical reburn fuel injection rates.

In the Fuller Micromill™, primary air and coal enter the lower portion of the 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 fuel move up the cone, the cross-sectional area increases and the velocity drops until the mass of the particles prevents further movement up the cone. That results in bands of particles that become denser and finer traveling up the cone. The smaller particles, which possess higher velocities, travel up through the cone, pass through the bands of the larger and slower moving particles, and pulverize them as the particles collide. The vortex of entrained particles also causes breakdown of particles through attrition. Particles which are small enough to be drawn out of the centrifugal bands pass through the impeller and into a classifier. A static classifier subjects incoming coal to a set air velocity, causing oversized material to fall through a rotary air lock and back into the feed air stream. The classifier air velocity can be adjusted to achieve the desired coal fineness. The fineness used for the Kodak project was 90% passing 325 mesh.

Micronized coal is transported from the classifier to eight reburn fuel injectors by recirculated flue gas transported by a fan from the flue gas stream leaving the electrostatic precipitator. Six of the injectors are on the boiler wall opposite the cyclone burners and one each on the side walls. The eight injectors are on an elevation just above the cyclone burners. The injectors provide control over both swirl and velocity.

The OFA system receives about 20% of the secondary air provided to the boiler and injects it into the burnout zone through four injectors on the front boiler wall (same wall as cyclone burners) at an elevation just below the nose of the boiler. The OFA injectors use EER's second generation, dual-concentric design, which provides for variable injection velocity and swirl.



Fuller Micromill™ (top) and classifier (bottom)

Milliken Installation

At Milliken, the previously installed burner system and DB Riley MPS 150 mills with dynamic classifiers enabled demonstration of MCR without additional capital investment in equipment. The top coal burner in the LNCFS III™ four-burner-level configuration was used as the reburn burner, and three separated overfire air (SOFA) ports provided air to the burnout zone. The lower three coal burner elevations were biased to carry approximately 80% of the fuel required for full load. The DB Riley MPS 150 mill dedicated to the level four burners (one MPS 150 mill used per level) was operated at higher than normal dynamic classifier speeds to provide coal fineness approaching that of micronized coal (70–72% through 325 mesh).

Results Summary

Environmental Performance

- Short-term parametric tests on the Kodak Park cyclone boiler at full load showed that a reburn fuel heat input of 17.3% and reburn stoichiometry of 0.89 reduced NO_x emissions from 1.36 to 0.59 lb/10^6 Btu, or 57%, increased fly ash carbon content (LOI) from 11% to 37%, and decreased boiler efficiency from 87.8% to 87.3%.

- Short-term parametric tests on the Milliken tangentially-fired boiler at full load showed that a reburn fuel heat input of 14.4% reduced NO_x emissions from 0.39 to 0.25 lb/10^6 Btu, or 36%, while maintaining LOI below 5% and boiler efficiency in the range of 88.4% to 88.8%.

- Long-term tests on the Kodak Park cyclone boiler under load-following conditions (near full load average) showed that a reburn fuel heat input of 15.6% and reburn stoichiometry of 0.90 reduced NO_x emissions to 0.69 lb/10^6 Btu, or 49%, with a corresponding average LOI of 38%; and that higher reburn fuel heat input and reduced reburn stoichiometry would enable further NO_x emission reductions.

- Long-term tests on the Milliken tangentially-fired boiler under load-following conditions (near full load average) showed that a reburn fuel heat input of 15.1% reduced NO_x emissions to 0.25 lb/10^6 Btu, or 36%, with a corresponding average LOI of 4.4%.

- At Kodak Park, reburn stoichiometry was the dominant parameter in controlling NO_x emissions and LOI at a given boiler oxygen level. Varying cyclone burner stoichiometries from 1.02 to 1.14 showed little effect on NO_x emissions and LOI; and varying final stoichiometries from 1.05 to 1.16 also showed little effect on NO_x emissions and LOI.

- At Milliken, no single operating variable had a dominant effect on reburning performance at a given economizer oxygen level. However, both NO_x emissions and LOI were reduced by significantly increasing the fineness (reducing particle size) of reburn and primary combustion coal and by concentrating OFA to fewer ports and reducing top level auxiliary air; lowering the main burner tilt angle to 5 degrees below the horizontal lowered LOI without increasing NO_x emissions by increasing residence times.

- At Kodak Park, increased LOI was attributed to lower than baseline temperatures in the primary combustion zone due to lower cyclone heat input and to short oxidation residence times for the reburn fuel in the burnout zone. The contribution of reburning alone to the increase in LOI (assuming no change in cyclone heat input) was estimated at less than 12% (absolute), suggesting that in reburn applications, LOI could be maintained at baseline levels by maintaining a high cyclone heat input.

Operational Performance

- At Kodak Park, the final steam temperature with MCR in service remained within 10 °F of the desired 900 °F throughout the load range of 300,000–400,000 lb/hr of steam; and the drop in boiler efficiency from 87.8% to 87.3% with MCR in service was attributed primarily to increased LOI.

- At Kodak Park, MCR increased electrostatic precipitator (ESP) efficiency from 95.5% to 97.1%, but also increased particulate loading to the ESP to 2.8 times the baseline, which resulted in an increased stack emissions of particulate to 1.8 times the baseline. These results stem from the fact that cyclone burners convert 70–90% of the ash to slag, leaving the balance as fine particle ash (5–8 microns), while all MCR ash, which has a larger average particle size (23–25 microns), goes to the ESP.

- At Milliken, MCR did not impact ESP efficiency, but the short oxidation residence time for the reburn fuel increased LOI from 2.4% to 3.7% and increased fly ash loading to the ESP, resulting in a 30% increase in particulate stack emissions.

Economic Performance

- The estimated capital cost for MCR applied to a generic 300-MWe cyclone boiler is \$56/kW (1999\$); estimated operating costs are \$0.80 million per year (1999\$); and 15-year levelized costs are \$741/ton of NO_x removed (current 1999\$) or \$571/ton of NO_x removed (constant 1999\$).

- The estimated capital cost for MCR applied to a generic 300-MWe tangentially-fired boiler with low-NO_x burners is \$14/kW (1999\$); estimated operating costs are \$0.30 million per year (1999\$); and 15-year levelized costs are \$1,329/ton of NO_x removed (current 1999\$) or \$1,023/ton of NO_x removed (constant 1999\$).

Environmental Performance

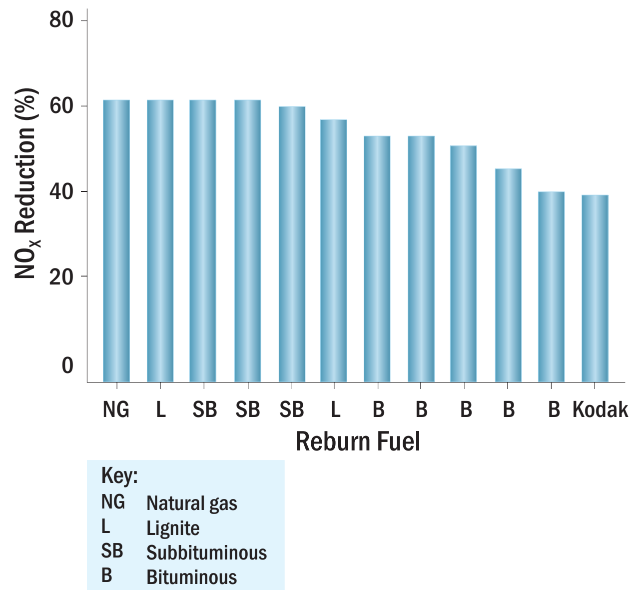
Kodak Park

In examining the environmental performance of MCR, it is informative to note the specific reburn fuel used, the operating characteristics of the cyclone boiler, and ramifications of incorporating MCR. The reburn fuel was a low-volatile Pittsburgh seam bituminous coal, which proved to be only a moderate reburning performer in comparative tests with other coals (lignite, subbituminous, and bituminous) and natural gas (see Figure 1). A proximate fuel analysis for the Kodak coal is shown in Table 1.

As to boiler characteristics, cyclone boilers rely on slagging the ash in the coal for primary particulate emission control. This means that 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 a slag tank. The heat input requirement to affect slag formation and movement is roughly 80% of full load, or 320,000 pounds per hour (pph) of steam. Thus, boiler output at 80% full load was generated solely through the cyclone burners (zero MCR), and output above that load was controlled by increasing the reburn fuel heat input. That meant that NO_x emissions increased as boiler load decreased, which is counter intuitive. Also, cyclone boilers have relatively small volumes above the burners because the cyclone burners concentrate the heat output. The small volumes equate to high velocities and short residence times for the flue gas, which limits reburn zone and burnout zone residence times.

Parametric testing at Kodak Park established the impacts of a range of NO_x control variables on NO_x emissions and performance of the boiler and balance of plant equipment. Variables included primary combustion zone stoichiometry, reburn zone stoichiometry, burnout zone stoichiometry, boiler load, cyclone burner heat input, reburn fuel heat input, and reburn fuel and OFA mixing settings. The results showed that reburn zone stoichiometry was by far the dominant parameter in controlling NO_x emissions and LOI over the range of reburn application. Varying cyclone burner stoichiometries from 1.02 to 1.14 showed little effect on NO_x emissions and LOI over the range of reburn application. However, under conditions where reburning is not actuated, cyclone burner stoichiometry does impact NO_x emissions and LOI because it is essentially the reburn stoichiometry as well. Varying final stoichiometries from 1.05 to 1.16 also showed little effect on NO_x emissions and LOI.

Figure 1. Comparison of NO_x Control Performance of Kodak Coal to Other Coals and Natural Gas



Note: All reburn tests run under same conditions – 400 ppm initial NO_x, 0.4 second residence time, and stoichiometric ratio of 0.90.

Table 1. Coal Analysis for Kodak MCR Design

Proximate Analysis:		
Carbon	(wt%)	73.38
Hydrogen	(wt%)	4.94
Nitrogen	(wt%)	1.33
Sulfur	(wt%)	2.25
Oxygen	(wt%)	4.84
Chlorine	(wt%)	0.11
Ash	(wt%)	7.15
Moisture	(wt%)	6.00
Total		**100.00**
Higher Heating Value	(Btu/lb)	13,192

A set of parameters was chosen for short-term testing that optimized NO_x emission control within acceptable plant operation limits regarding emissions and potential damage to equipment. The short-term tests were then run under tightly controlled conditions relative to the chosen set of parameters for a period of 1–3 hours. Short-term tests showed that with the Kodak Park cyclone boiler at full load, a reburn fuel heat input of 17.3%, and a reburn stoichiometry of 0.89, reduced NO_x emissions from 1.36 to 0.59 lb/10^6 Btu, or 57%. On the other hand, at these conditions fly ash carbon content (LOI) increased from 11% to 37%, and boiler efficiency decreased from 87.8% to 87.3%. (The 37% LOI value represents a high carbon content for a relatively small amount of fly ash because cyclone boilers remove 70–90% of what would have been fly ash as slag.) The boiler oxygen (O_2) level measured in the economizer was 2.5% versus a baseline of 3.2%, which contributed to lower NO_x emissions.

Long-term testing of MCR followed short-term testing. The MCR system was set to achieve NO_x emissions below the compliance limit of 0.6 lb/10^6 Btu while maintaining the required steam conditions and reliable boiler operation. The test duration was 63 days, exceeding the 51-day minimum time requirement recommended by industry (Control Technology Committee of the Utility Regulatory Group) to adequately describe the time dependence of the data. 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 days and then rolling the average from day to day. On this basis, the achievable annual NO_x emissions were estimated at 0.69 lb/10^6 Btu with an uncertainty of plus or minus 0.03 lb/10^6 Btu at a 95% confidence level. The corresponding LOI was estimated at 38% with an uncertainty of plus or minus 2% at a 95% confidence level. The daily averaged values for boiler load was 392,000 pph of steam (maximum 406,000 and minimum 348,000), MCR reburn was 15.6%, reburn stoichiometry was 0.9, and boiler O_2 level was 2.9%.

Established performance curves and calculations showed that to achieve long-term compliance with 0.60 lb/10^6 Btu NO_x emission limits would require a reburn stoichiometry of 0.87, which based on an average cyclone stoichiometry of 1.066 (from long-term tests) equates to a reburn heat input of 18.4%.

Tests were conducted to assess the various contributors to high LOI values under MCR operation. The increased LOI was attributed to lower than baseline temperatures in the primary combustion zone due to lower cyclone heat input and to short oxidation residence times for the reburn fuel in the reburn zone. The contribution of reburning alone to the increase in LOI (assuming no change in cyclone heat input) was estimated at less than 12% (absolute), suggesting that in reburn applications, LOI could be maintained at baseline levels by maintaining a high cyclone heat input.

Kodak Park

Milliken Station

A low-volatile Pittsburgh seam coal was also used in the MCR demonstration at Milliken. In the Milliken testing, the primary objective was to determine the lowest possible NO_x emission level at full boiler load while maintaining required steam conditions, reliable boiler operation, and marketable fly ash production — a fly ash carbon content (LOI) below 5%.

As presented in the *The Technology* section, the installed LNCF-III™ low-NO_x burner system and DB Riley MPS 150 mills with dynamic classifiers enabled demonstration of MCR without additional capital investment in equipment. The top coal burner delivered reburn fuel to the reburn zone and the SOFA provided air to the burnout zone. The MPS 150 mills delivered a coal fineness near that of micronized coal (70–72% passing through 325 mesh) which was considered to be the economic limit.

Variables studied at Milliken included boiler load, reburn coal fineness, O_2 level at the economizer, percent reburn fuel, main burner tilt, and SOFA tilt. At the same economizer O_2 level, no single operating variable had a dominant effect on reburning performance. However, the economizer O_2 levels significantly impacted both NO_x emissions and LOI. Increased O_2 levels increased NO_x emissions and lowered LOI and vice versa — a classic response. The effect on NO_x emissions was about 0.1 lb/10^6 Btu increase for each 1.0% increase in O_2 level and was relatively independent of reburn coal fineness.

Concentration of the burnout air through injection at fewer SOFA ports improved NO_x emission control. Variation in the SOFA injector tilt angle between 0º and 15º above horizontal had only a minor effect on NO_x emissions and LOI. Increasing the top level air flow in the main burner section just beneath the designated reburn burner increased both NO_x emissions and LOI. The increased auxiliary air flow raised the reburn zone stoichiometry, which resulted in the higher NO_x emissions. The increased LOI was the result of lowering excess air levels in the primary combustion zone by diverting air to the top port. Increasing air used to transport reburn coal from an air-to-fuel ratio of 2.05 lb/lb to 2.45 lb/lb increased NO_x emissions from 0.28 lb/10^6 Btu to 0.31 lb/10^6 Btu by lowering reburn zone stoichiometry.

Using finer grind reburn coal had little effect on NO_x emissions but a significant effect upon LOI. At classifier speeds of 150 rpm, coal fineness is 70–72% passing through 325 mesh, which reduces LOI to below 5% as targeted. Feeding finer grind coal to the primary combustion zone reduced both NO_x emissions and LOI.

Milliken Station

Decreasing the reburn coal fuel fraction from 25% to 14% decreased NO_x emissions from 0.25 lb/10^6 Btu to 0.23 lb/10^6 Btu, with only a minor effect on LOI. This result was due to diverting coal from the reburn burners to the main burners, reducing the excess air levels in the primary combustion zone. Setting the main burner tilt 5° below the horizontal lowered LOI without increasing NO_x emissions by increasing the primary combustion zone residence time. Taking the MPS mill delivering coal to the second main burner (just above the bottom burner) out of service at a given boiler load in the range of 110–140 MWe reduced NO_x emissions, probably due to longer coal residence times in the primary combustion zone. NO_x emissions decreased as the boiler load decreased in the classic fashion because MCR was functional throughout the load range.

A set of parameters was chosen to achieve the primary objective for the Milliken demonstration. These parameters included 14–16% reburn fuel, 105 rpm reburn mill classifier speed, -5° main burner tilt, and 2.8% economizer O_2.

Short-term tests were run under tightly controlled conditions relative to the chosen set of parameters for a period of 1–3 hours. Short-term tests showed that the Milliken tangentially-fired boiler at full load and 14.4% reburn fuel reduced NO_x emissions from 0.39 lb/10^6 Btu to 0.25 lb/10^6 Btu, or 36%, while maintaining fly ash LOI below 5% and the boiler efficiency at 88.4–88.8%.

Long-term testing indicated that the achievable annual NO_x emissions level on Milliken Unit 1 was 0.25 lb/10^6 Btu using 15.1% reburn fuel, with an average fly ash LOI of 4.4%.

Operational Performance

Kodak Park

Several operational issues were resolved prior to initiating testing. The coal feed to the Fuller Micromill™ experienced frequent plugging, requiring the addition of air lances. Slagging of coal ash at the reburn fuel injectors occurred, requiring adjustments to the distribution of reburn fuel and transport gas among the injectors. Leakage in the flue gas recirculation systems required improved sealing. Installation of a six-point O_2 monitoring system in the boiler (three East and three West) corrected inaccurate O_2 measurements used for cyclone boiler control. Boiler controls were modified to prevent damaging reducing conditions in the cyclone burners in the event of reburn fuel feed interruption, which was possible using boiler O_2 as the sole control parameter. Modifications included independent control of the cyclone burner stoichiometries and controlling OFA by maintaining boiler O_2 above an established minimum level.

The Fuller Micromill™ experienced excessive wear on the impeller blades. This prompted application of a new wear-resistant coating during the test period, which showed promise for resolving the problem. Evaluation of coating effectiveness was continuing at the close of the project.

Testing at Kodak Park assessed the impact of MCR on ESP performance. This test program involved simultaneous sampling of fly ash at the ESP inlet and outlet. Four sets of paired samples were collected for the baseline and MCR test conditions. Daily composite samples of as-fired coal were collected. The results showed that under MCR operation, ESP efficiency actually increased slightly from a baseline of 95.5% to 97.1%. However, ESP emissions to the stack increased to 1.8 times the baseline as particulate loading at the ESP inlet increased to 2.8 times the baseline. These results stem from the fact that cyclone boilers convert 70–90% of coal ash to slag, leaving the balance as fine (5–8 microns) fly ash, which is relatively difficult for ESPs to remove. All MCR ash goes to the ESP, but has a larger average particle size (23–25 microns), which is readily captured by the ESP. As in the case at Kodak Park, cyclone boiler plant ESPs are not typically sized to handle the significant increase in fly ash that MCR produces, and may require an ESP upgrade.

Milliken Station

The MPS 150 mill dedicated to providing reburn fuel, mill 1A1, was tested to ensure that the mill could deliver the amount of coal needed at the higher classifier speeds required for the finer grind, without causing potentially damaging conditions for the mill. Mill 1A1 was equipped with a special back pressure roller loading control valve to provide higher and more stable cap-end loading cylinder pressure for better system cushioning. Previous MPS 150 mill testing showed that the system exceeded guarantees for Eastern bituminous coals (grindability index 57, moisture 5.6%), producing a mill product fineness capability of 94% (87% guaranteed) through 200 mesh and 100% (98% guaranteed) through 100 mesh at 18.4 tons/hour. Mill 1A1 tests at elevated classifier cage speeds demonstrated stable operation over the load range of 8–12 tons/hour, which was sufficient to support reburn fuel requirements. These tests also showed that the higher classifier speeds produced much sharper particle size distributions, and that mill product fineness values were predictable over the load range of 8–12 tons/hour. Although performing adequately, the special back pressure control valve provided no noticeable improvement in back-pressure cushioning.

Testing at Milliken assessed the impact of MCR on the performance of their recently rebuilt ESP. The ESP rebuild included new internals, new computer-controlled transformer-rectifier sets, an additional third field, and increased plate spacing to 16 inches. MCR had no noticeable effect on ESP efficiency, but short oxidation residence times for the reburn fuel in the burnout zone increased LOI from 2.4% to 3.7% and increased fly ash loading to the ESP, resulting in a 30% increase in particulate stack emissions.

Milliken Station

Economic Performance

Cost analyses for generic 300-MWe commercial applications of MCR technology were performed for both cyclone-fired and tangentially-fired boilers. The design basis for the economics is shown in Table 2, and the values of the economic parameters are shown in Table 3.

Table 2. Design Basis Used in MCR Economic Evaluations

Boiler Type	T-Fired	Cyclone
Plant Capacity, MWe	300	300
Coal Higher Heating Value, Btu/lb	12,900	12,900
Plant Capacity Factor, percent	65	65
Annual Coal Consumption, tons	629,000	629,000
Plant Heat Rate, Btu/kWh	9,500	9,500
Coal Through Reburn Burners, %	15	20
Initial NO_x Level, lb/10^6 Btu	0.4	1.25
NO_x Reduction, %	25	50
Micronized Coal Conveying Fluid	Air	Flue Gas
No. of MCR Burner Rows	1	1
No. of Coal Mills/Row	1	1
Increase in Fly Ash LOI, %	5	510
Increase in Fly Ash Rate, %	10	20
Prior Retrofit of LNBs	Yes	--
Prior Retrofit of Overfire Air	Yes	No
Ash in Coal, %	10	10
Boiler Efficiency, %	–	87

Table 3. Economic Parameters Used in MCR Economics Evaluations

Cost of Debt, %		8.5
Dividend Rate for Preferred Stock, %		7.0
Dividend Rate for Common Stock, %		7.5
Debt/Total Capital, %		50.0
Preferred Stock/Total Capital, %		15.0
Common Stock/Total Capital, %		35.0
Income Tax Rate, %		38.0
Investment Tax Credit, %		0.0
Property Tax & Insurance, %		3.0
Inflation Rate, %		4.0
Discount Rate (with inflation), %		7.93
Discount Rate (without inflation), %		3.744
Escalation of Raw Materials Above Inflation, %		0.0
Construction Period, days		90
Remaining Life of Power Plant, Years		15
Year for Costs Presented in This Report		1999
Construction Downtime, Days		0
Royalty Allowance, % of Total Capital		0.00
Capital Charge Factor	Current Dollars	0.160
	Constant Dollars	0.124
O&M Levelization Factor	Current Dollars	1.314
	Constant Dollars	1.000
Sales Tax Rate, %		5.0
Cost of Freight for Process Equipment, %		2.0
General Facilities, % of Total Process Capital		10.0
Engineering & Home Office, % of Total Process Capital		10.0

Table 4 shows the capital cost (1999$) to install MCR on existing cyclone- and tangentially-fired boilers, including a retrofit adjustment. No allowance was included for funds used during construction. The assumption was that a new coal pulverizer would be installed while the power plant was in operation and that final ductwork modifications and connections would be installed during a planned plant outage. A project contingency of 15% was applied, but no process contingency was used, as the required equipment is commercially available and successfully demonstrated.

For the cyclone-fired boiler, the total capital requirement is $16.9 million, or approximately $56/kW. These costs assume the following:

- Space is present on the cyclone boiler for installation of both MCR and OFA ports at locations allowing sufficient residence time for completion of the combustion reactions;
- A single new pulverizer and dynamic classifier is dedicated to suppling micronized coal to the MCR injectors;
- Sufficient plot area is available for installation of the new coal pulverizer and associated equipment; and
- Additional instrumentation and controls are required, including upgrade of the digital control system.

For the tangentially-fired boiler, the total capital requirement is $4.3 million, or approximately $14/kW. The underlying assumptions are the same as for the cyclone boiler retrofit, except in the area specific to boiler type. For the tangentially-fired boiler, the assumption is that the existing top row of burners can be used without modification for MCR injection.

Table 4. Total MCR Capital Requirement for 300-MWe Boilers

Area		Cyclone Boiler		T-Fired Boiler	
		$\$10^6$	$/kW	$\$10^6$	$/kW
A	Total Process Capital	12.2	40.5	3.1	10.3
B	General Facilities, 10% of A	1.2	4.05	0.3	1.0
C	Engineering & Home Office, 10% of A	1.2	4.05	0.3	1.0
D	Project Contingency, 15% of A+B+C	2.2	7.3	0.6	1.9
E	**Total Plant Cost**	**16.8**	**55.9**	**4.3**	**14.2**
F	Allowance for Funds During Construction	0.0	0.0	0.0	0.0
G	**Total Plant Investment**	**16.8**	**55.9**	**4.3**	**14.2**
H	Royalty Allowance	0.0	0.0	0.0	0.0
I	Preproduction Costs (1 month of startup)	0.13	0.4	0.02	0.08
J	Inventory Capital	0.0	0.0	0.0	0.0
K	Initial Catalyst & Chemicals	0.0	0.0	0.0	0.0
L	**Subtotal Capital**	**16.9**	**56.3**	**4.3**	**14.3**
M	Cost of Construction Downtime	0.0	0.0	0.0	0.0
	Total Capital Requirement	**16.9**	**56.3**	**4.3**	**14.3**

Table 5 shows the projected incremental operating and maintenance (O&M) costs for installing MCR on 300-MWe cyclone- and tangentially-fired boilers. Higher LOI increases coal cost, higher power requirements for the pulverizer increase electric power needs, and finer grind requirements inherently increase pulverizer maintenance. Fixed O&M costs are higher for the cyclone boiler because the extent of modifications for MCR installation is greater.

Table 5. Projected Incremental Operating and Maintenance Costs for 300-MWe Boiler

Fixed O&M Costs	Cyclone Boiler	T-Fired Boiler
Operating Labor	50	20
Maintenance Labor	185	50
Maintenance Material	275	70
Administration/Support Labor	140	40
Total Fixed Costs	**650**	**180**
Variable Operating Costs		
Coal	100	110
Electric Power	50	10
Total Variable Costs	**150**	**120**
Total O&M Cost	**800**	**300**

Tables 6 and 7 provide estimates of the effect of MCR on the cost of power for 300-MWe cyclone- and tangentially-fired boilers operating at a 65% capacity factor. The cyclone-fired boiler is assumed to have a baseline NO_x emission rate of 1.25 lb/10^6 Btu, and the tangentially-fired boiler a baseline NO_x emission rate of 0.4 lb/10^6 Btu.

The levelized cost of MCR on a $/ton of NO_x removed basis decreases as power plant size and capacity factor increases. Also, for a fixed percentage level of NO_x reduction, the levelized cost of MCR decreases as the baseline NO_x emission rate increases.

Table 6. Effect of MCR on Cost of Power for 300-MWe Cyclone Boiler

Levelized Cost of Power	Current Dollars		Constant Dollars	
	Factor	Mills/kWh	Factor	Mills/kWh
Capital Charge	0.16	1.58	0.124	1.23
Fixed O&M Cost	1.314	0.50	1.00	0.38
Variable Operating Cost	1.314	0.11	1.00	0.09
Total Cost		**2.19**		**1.70**
Levelized Cost – NO_x Basis	**Factor**	**$/Ton Removed**	**Factor**	**$/Ton Removed**
Capital Charge	0.16	533.30	0.124	413.3
Fixed O&M Cost	1.314	169.00	1.00	128.60
Variable Operating Cost	1.314	38.71	1.00	29.46
Total Cost		**741**		**571**

Table 7. Effect of MCR on Cost of Power for 300-MWe T-Fired Boiler

Levelized Cost of Power	Current Dollars		Constant Dollars	
	Factor	Mills/kWh	Factor	Mills/kWh
Capital Charge	0.16	0.04	0.124	0.31
Fixed O&M Cost	1.314	0.14	1.00	0.11
Variable Operating Cost	1.314	0.09	1.00	0.07
Total Cost		**0.63**		**0.49**
Levelized Cost – NO_x Basis	**Factor**	**$/Ton Removed**	**Factor**	**$/Ton Removed**
Capital Charge		846.22		655.98
Fixed O&M Cost	0.16	291.40	0.124	221.77
Variable Operating Cost	1.314	191.41	1.00	145.67
Total Cost	1.314	**1329**	1.00	**1023**

Table 8 shows comparative levelized costs (in constant dollars) for technologies competing with MCR that were reported in the literature in the same time frame as the MCR costs were developed. The competing technologies are Gas Reburning, selective non-catalytic reduction (SNCR), and selective catalytic reduction (SCR).

Natural gas costs were assumed to be $3/10^6 Btu. Table 8 costs assume year-round operation of each technology. For regions where NO_x controls may be applied only in summer months, the lower capital cost options gain a levelized cost advantage.

Table 8. Comparison of Costs of NO_x Reduction Technologies

NO_x Reduction Technology	Gas Reburn	MCR	SNCR	SRC
T-Fired				
Initial NO_x Level, lb/10^6 Btu	0.4	0.4	0.4	0.4
NO_x Reduction, %	50	25	25	80
Capital Cost, $/kW	15[a]	14	15[b]	59[b]
Levelized Cost, $/ton of NO_x Removed	2,805[c]	1,023	1,506[b]	2,060[b]
Cyclone				
Initial NO_x Level, lb/10^6 Btu	1.25	1.25	1.25	1.25
NO_x Reduction, %	60	50	25	80
Capital Cost, $/kW	15[a]	56	15[b]	73[d]
Levelized Cost, $/ton of NO_x Removed	748	571	1,506[b]	984[d]

[a] Fulson and Tyson 1998

[b] Interpolated from Burns and Roe 1998

[c] Calculated by CONSOL Inc.

[d] Staudt 1998

Commercial Applications

MCR can be applied to most coal-fired units, including wall-fired, tangentially-fired, cyclone-fired, and large stoker units. There is no upper limit on the size of the units to which MCR technology can be applied. MCR technology offers considerable flexibility as a retrofit NO_x control measure for all types of power plants, large or small.

Although tested on bituminous coals, MCR may have even greater potential when using subbituminous coals. This is suggested by test data from the CCTDP coal reburning project at Nelson Dewey Station. Subbituminous coals are more reactive, and in cyclone-fired boiler applications, the reburn burners provide the extra capacity to avoid derating the boiler in cases where subbituminous coals displace bituminous coals as a sulfur emissions control measure.

MCR offers a flexible option for tangentially-fired boilers to lower NO_x emissions in the summer season to address ozone formation concerns; and relatively low capital costs make MCR an attractive NO_x emissions control option for older coal-fired units relegated to less than baseload capacity. Also, MCR may provide the added control to ensure next generation low-NO_x burners can meet projected NO_x emissions without assistance from expensive post combustion control measures.

Contacts

Jim Harvilla
New York State Electric & Gas Corporation
Corporate Drive—Kirkwood Industrial Park
P.O. Box 5224
Binghamton, NY 13902-5224
(607) 762-8630
(607) 762-4002 (fax)
jjharvilla@nyseg.com

Victor K. Der, DOE/HQ
(301) 903-2700
victor.der@hq.doe.gov

Thomas A. Sarkus, NETL
(412) 386-5981
thomas.sarkus@netl.doe.gov

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