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Micronized Coal Reburning Demonstration for NO_X Control: A DOE Assessment

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Disclaimer

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Executive Summary

This document is a U.S. Department of Energy (DOE) post-project assessment of a project in Round IV of the Clean Coal Technology (CCT) Demonstration program: *Micronized Coal Reburning (MCR) Demonstration for NO_X Control.* In 1995, the New York State Electric & Gas Corporation (NYSEG) and Eastman Kodak Company agreed to fulfill the project requirements by installing MCR on two boilers. DOE provided 30 percent of the total project funding of $9.1 million. The New York State Energy Research and Development Authority and the Empire State Electric Energy Research Corporation were cofunders. Also participating were technology suppliers, DB Riley, Fuller Company, and Energy and Environmental Research Corporation (EER), as well as technical consultation from Consolidation Coal Company (CONSOL). ABB Combustion Engineering conducted a test program at Milliken Station, and Babcock & Wilcox conducted a test program at Kodak.

The project involved the application of MCR to a 150-MWe tangentially fired (T-fired) boiler at NYSEG's Milliken Station in Lansing, NY, and to a 50-MWe equivalent cyclone boiler at the Kodak Power Plant in Rochester, NY. At the Milliken site, new DB Riley MPS coal mills with dynamic classifiers had been installed as part of a prior DOE project; therefore, construction was not required. Operations at Milliken covered the period from March 1997 to April 1999. At Kodak, construction and operations covered the period from September 1996 to October 1998.

Micronized coal reburning involves the staged addition of fuel into two zones: (1) the primary combustion zone where coal is fired, and (2) the reburn zone where micronized coal is added to create a reducing (oxygen-deficient) condition. This reducing condition converts the nitrogen oxides (NO_X) produced in the primary zone to nitrogen (N_2) and water. The standard for micronized coal is that 80 wt% of the particles have a diameter less than 43 µm (that is, pass through a 325 mesh screen). The DB Riley mills at Milliken came very close to that standard. Development of the centrifugal-pneumatic mill, used to produce micronized coal at the Kodak site, was carried out by MicroFuel Corporation (MFC), which is now owned by Fuller Power Corporation.

The purpose of this CCT project was to demonstrate not only the advantage of coal over natural gas or oil for use as a reburn fuel, but also the improvement in reburning performance resulting from using micronized coal as the reburn fuel. Micronized coal is produced from the same coal routinely fired in the boiler, so no additional fuel source is necessary. The fuel used in this project was Pittsburgh seam, medium- to high-sulfur coal. Novel project features were the MCR configuration and the Fuller MicroMill™.

The primary objectives of the MCR project were to

- Establish the operating performance of boilers using MCR for NO_X control;
- Demonstrate the long term reliability of the equipment used to implement MCR;
- Compare the performance of the Fuller MicroMill™ to the DB Riley MPS-150 (with dynamic classifier) micronizing system;

- Confirm that, on full-scale boilers, MCR can achieve its objective of at least 50-percent NO_X reduction on cyclone boilers and an additional 25- to 35-percent NO_X reduction on T-fired boilers fitted with LNBs; and
- Identify steady-state NO_X levels using MCR.

Demonstrations of MCR at Milliken and Kodak, on units typical of a large portion of the nation's utility and industrial boilers, were successful and show that the technology is widely applicable. Although the demonstrations were on T-fired and cyclone boilers, the technology should be equally applicable to wall-fired boilers.

Major conclusions from the MCR Clean Coal Technology project follow.

- Coal reburning was successfully demonstrated on both a T-fired (Milliken) and a cyclone (Kodak) boiler. On the T-fired boiler, existing mills were used to produce near micronized coal (70 to 72 percent through 325 mesh). On the cyclone boiler, a MicroMill™ was used to produce micronized coal (80 percent or greater through 325 mesh). The objective of at least 50-percent NO_X reduction on the cyclone boiler was met with a demonstrated 57-percent reduction. The NO_X level for the T-fired boiler was reduced from 0.39 to 0.25 lb/1x10^6Btu with MCR, a 36-percent reduction. This met the project objective of at least 25- to 35-percent reduction on a T-fired boiler already equipped with low-NO_x burners (LNBs).

- At Milliken, several variables were found to have an important effect on the level of NO_x reduction. At Kodak, reburn stoichiometry, cyclone heat input, and cyclone stoichiometry all affected both NO_X and loss on ignition (LOI).

- This project demonstrated the long-term reliability of the MCR systems. At Milliken, existing equipment was utilized, and no operational problems were encountered that were caused by MCR operations. At Kodak, some system components experienced wear, including rotary valves and mill components. Wear-resistant coatings should overcome this problem.

Although NO_X reductions as high as 57 percent were demonstrated in this program, this will not be enough for many units to meet the EPA standard to be implemented in 2003, which calls for reducing NO_X emissions to 0.15 lb/1x10^6Btu MCR may be limited in commercial application to units that are part of an emissions averaging plan under which the total of reductions required can be met by inclusion of MCR with other technologies.

Commercialization will be a joint effort of Fuller, covering coal preparation and delivery, and EER, handling reburn and furnace technology. As the market expands, a separate group will be formed to have sole responsibility for marketing the technology. Other plans include marketing the micronized coal reburn technology to the industrial market sector for NO_X control on smaller coal-fired units, both pulverized and stoker-fired.

I Introduction

The goal of the U.S. Department of Energy's (DOE) Clean Coal Technology (CCT) program is to furnish the energy marketplace with a number of advanced, more efficient, and environmentally responsible coal utilization technologies through demonstration projects. These projects seek to establish the commercial feasibility of the most promising advanced coal technologies that have developed beyond the proof-of-concept stage.

This document serves as a DOE post-project assessment of a project selected in CCT Round IV, the Micronized Coal Reburning (MCR) Demonstration for NO_X Control, as described in a report to Congress (U.S. Department of Energy 1999). The need to meet strict emissions requirements at a minimum cost prompted the Tennessee Valley Authority (TVA), in conjunction with Fuller Company, Energy and Environmental Research Corporation (EER), and Fluor Daniel, to submit the proposal for this project to be sited at TVA's Shawnee Fossil Plant. In July 1992, TVA entered into a cooperative agreement with DOE to conduct the study. However, because of operational and environmental compliance strategy changes, the Shawnee site became unavailable.

In 1995, the New York State Electric & Gas Corporation (NYSEG) and Eastman Kodak Company agreed to fulfill the project requirements. The reconfigured project involved applying MCR on Unit No. 1, a 150-MWe (net), tangentially fired (T-fired) boiler, at NYSEG's Milliken Station in Lansing, NY, and Eastman Kodak's Unit No. 15, a 50-MWe equivalent cyclone boiler, at the Kodak Power Plant in Rochester, NY. This arrangement had two advantages. First, it made use of the project team already in place for the Milliken Clean Coal Technology Demonstration (MCCTD) Project (New York State Electric & Gas Corporation 1999) and the investment that DOE had made at Milliken for that project. Second, it provided MCR demonstration on two types of boilers, rather than just one as originally proposed.

In addition to NYSEG and Kodak, the New York State Energy Research and Development Authority and the Empire State Electric Energy Research Corporation were cofunders. Others participating in the project were technology suppliers DB Riley, Fuller Company, and Energy and Environmental Research Corporation, and Consolidation Coal Company, which supplied technical consulting. ABB Combustion Engineering conducted a test program at Milliken Station, and Babcock & Wilcox conducted a test program at Kodak. DOE provided 30 percent of the total project funding of $9.1 million (which includes funds expended before the project was transferred to NYSEG).

This independent evaluation is based primarily on information from the project final report (Consolidated Coal Company 1999), as well as other references cited.

II Project/Process Description

II.A Purpose

The purpose of this CCT project was to demonstrate not only the advantage of coal over natural gas or oil for use as a reburn fuel for nitrogen oxides (NO_X) reduction, but also to show the improvement in reburning performance resulting from using micronized coal (80 percent through 325 mesh) as the reburn fuel.

This project had a number of objectives, including

- Confirming on full-scale boilers that MCR can achieve at least 50 percent NO_X reduction on cyclone boilers and an additional 25 to 35 percent NO_X reduction on T-fired boilers fitted with low- NO_X burners (LNBs);
- Showing that these NO_X reductions can be achieved with little or no effect on boiler performance and efficiency;
- Demonstrating the long term reliability of the equipment used to implement MCR;
- Comparing the performance of the Fuller MicroMill™ with that of the DB Riley MPS-150 mill (with dynamic classifier);
- Identifying steady-state emissions levels; and
- Determining the effect of MCR on electrostatic precipitator (ESP) performance.

Specifically, the impact of MCR on the following was assessed:

- Nitrogen oxide (NO), nitrogen dioxide (NO_2), NO_X, oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), and particulate matter (PM) emissions as a function of load;
- Fly ash loss on ignition (LOI), which is essentially the same as unburned carbon on ash;
- Performance of various systems (pulverizer/mill, air preheater);
- Coal flow rate and particle size distribution;
- Boiler slagging and fouling;
- Waterwall and convection section corrosion;
- Furnace temperature profile;
- Boiler efficiency;
- Combustion system reliability; and
- Boiler load response.

II.B Need for the Technology Demonstration

Reburning for NO_X control has been commercially practiced, mainly using natural gas or oil as the reburn fuel. Although successful, use of these fuels for reburning suffers from one or more of the following disadvantages: unreliable supply, especially in winter; high fuel costs; problems with firing dual fuels; and reduced efficiency because the higher hydrogen content increases the moisture in the flue gas. This project was designed to demonstrate that micronized coal would have advantages over natural gas or oil for use as a reburn fuel.

Although the components of the technology have been demonstrated elsewhere, this is the first demonstration in this configuration. Thus, until this project, there was no demonstration of the exact combination of technologies utilized here. The novel features were the MCR configuration and the Fuller MicroMill™. The successful demonstrations at Milliken and Kodak on units typical of a large portion of the nation's utility and industrial boilers shows that MCR is widely applicable. Although the demonstrations were on T-fired and cyclone boilers, the technology should be equally applicable to wall-fired boilers.

II.C Promise of the Technology

The major promise of MCR was to achieve 25- to 60-percent NO_X reduction from coal fired boilers while firing only the original coal and while maintaining unit efficiency and fly ash LOI. Potential benefits include

Use of the same coal routinely fired in the boiler to produce micronized coal, so no additional fuel source is necessary;

- Increased boiler capacity on mill-limited units, because addition of the micronized coal mill provides additional coal grinding capabilities;
- Use of the micronizing mill to provide backup for the existing pulverizers;
- Competitive capital and operating costs;
- Ease of retrofit because the reburn burners and overfire air (OFA) ports are the only furnace wall penetrations required. The Fuller MicroMill™ is compact and requires only a small floor area, and other required changes can be made at minimum expense;
- Ability to fire low-sulfur, subbituminous coal as the reburn fuel;
- Up to 30-percent reduction in existing pulverizer throughput, thus permitting classifiers to be adjusted to achieve a significant improvement in coal fineness;
- Improved steam and superheat temperatures at low load caused by firing micronized coal in the upper furnace and rapid devolatilization and char burnout of the reburn fuel;
- NO_X reductions on coal-fired units of as much as 60 percent, depending on furnace type and configuration;
- Small impact on boiler performance;
- No measurable emissions of new species, such as ammonia (NH_3), which could combine with sulfur oxides to form deposits, or nitrous oxide (N_2O), which is a greenhouse gas; and
- Applicability to most types of coal-fired boilers.

II.D Technology Description

Most of the NO_X formed from burning coal is the result of two oxidation mechanisms: (1) reaction of nitrogen in the combustion air with excess O_2 at elevated temperatures, referred to as thermal NO_X; and (2) oxidation of nitrogen that is chemically bound in the coal, referred to as fuel NO_X. For most coal-fired units, thermal NO_X typically represents about 25 percent and fuel NO_X about 75 percent of the total NO_X formed. However, for cyclones and other boilers that operate at very high temperatures, the ratio of thermal to fuel NO_X is different, and thermal NO_X can be considerably higher than fuel NO_X. In addition to the above mechanisms, minor amounts of NO_X are formed early in the combustion process through complex interactions of molecular nitrogen with hydrocarbon free radicals to form reduced nitrogen species that are later oxidized to NO_X, referred to as prompt NO_X.

MCR involves two technologies, coal micronization and coal reburning. These are separate technologies because coal reburning can be carried out using coal that is not micronized, and micronized coal, which requires special techniques for its preparation, can be used for purposes other than reburning.

II.D.1 The Reburning Process

Reburning, or the staged introduction of fuel into a combustion device, is based on laboratory-scale studies in the early 1970s by Wendt and Sternling of Shell Development Company (Wendt, Sternling, and Matovich 1973). The first commercial-scale application of this technology to control NO_X emissions was installed in Japan during the same decade. Subsequently, commercial-scale testing was conducted in the U.S. and Europe, mainly on electric utility boilers, but also to some extent on municipal waste incinerators. At present, natural gas, coal, and fuel oil (in Italy) reburning applications are in operation. The majority of the commercial installations in the U.S. use natural gas as the reburn fuel, but either natural gas or coal can achieve about 50- to 60-percent NO_X reduction without adversely affecting boiler operations.

Reburning involves the staged addition of fuel into two combustion zones. (See Figure 1.) Coal is fired in the primary combustion zone. In the reburn zone, additional fuel, such as natural gas or micronized coal, is added to create a reducing (oxygen-deficient) condition that converts the NO_X produced in the primary zone to nitrogen (N_2) and water. Above the reburn zone is a burnout zone in which OFA is added to complete the combustion. Each zone has a unique stoichiometric air ratio (the ratio of the air used to that theoretically required for complete combustion) as determined by the flows of primary fuel, burner air, reburn fuel, and OFA.

In the primary combustion zone, coal is fired under normal to low excess air conditions, at a rate corresponding to 70 to 90 percent of the total heat input. The amount of NO_X created in this zone is reduced by about 10 percent This is because less coal is fired in this zone (lower production of fuel NO_X), the heat release rate is lower (lower production of thermal NO_X) and, generally, the excess air level in the burners is reduced (a lower O_2 concentration results in lower fuel and thermal NO_X).

In the reburn zone, reburn fuel injection creates a reducing region within which the reburn fuel molecules break down to hydrocarbon fragments (CH, CH_2, etc.) that react with NO_X, producing reduced nitrogen species (mainly N_2). The optimum reburn zone stoichiometric ratio is 0.85 to 0.95. This is achieved by injecting reburn fuel at a rate corresponding to 10 to 30 percent of the total heat input. The exact rate depends on the primary zone excess air level; the lower the primary combustion zone excess air, the lower the reburn fuel requirement. Flue gas may be withdrawn downstream of the electrostatic precipitators (ESPs) and recirculated through the reburn fuel injectors. This will increase the momentum of the injected reburn fuel and improve furnace penetration and mixing. Because flue gas has a low O_2 content, its use for this purpose has only a minor impact on the reburn zone stoichiometry.

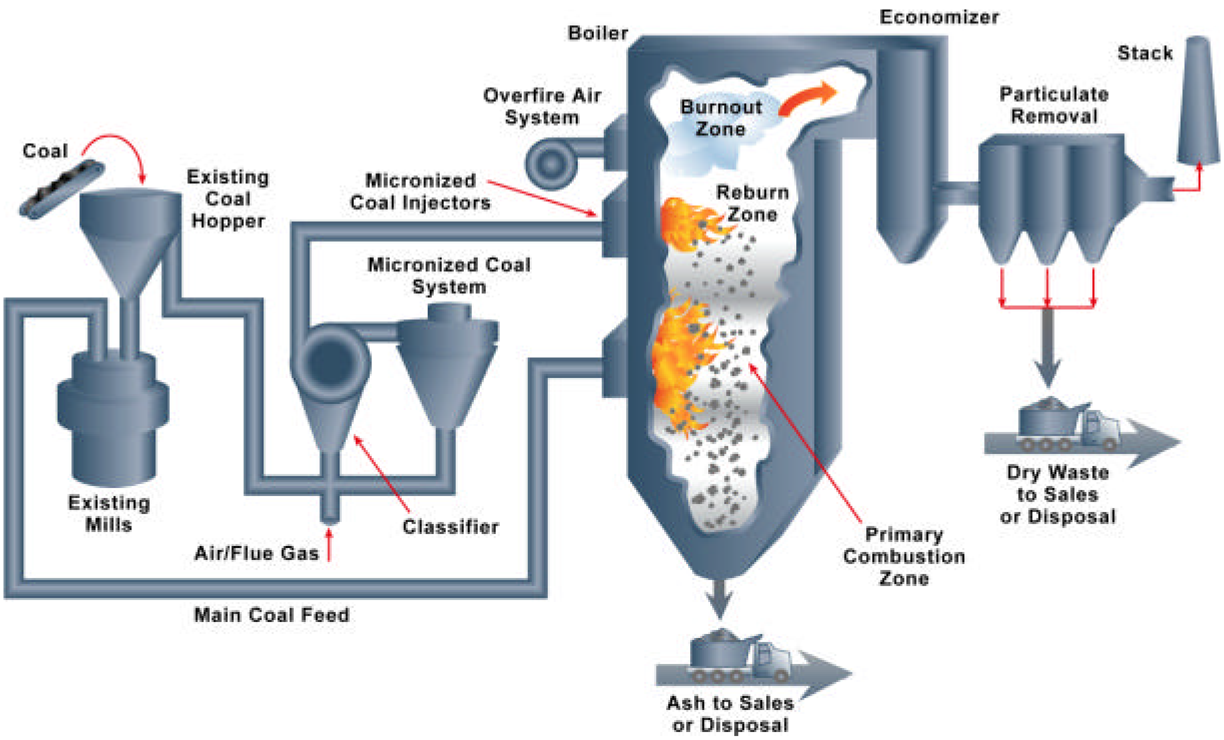

Figure 1. Schematic of Micronized Coal Reburn System

In the burnout zone, downstream of the reburn zone, OFA is injected to complete combustion. OFA is typically 20 percent of the total air flow with an overall excess air level of 15 to 25 percent being usual. The OFA injection rate is optimized for each specific application to minimize CO emissions and LOI. Thermal NO_X formation in the burnout zone is small because of the relatively low temperature. It is important to keep LOI low, because unburned carbon represents a loss of efficiency. Also, a high LOI may prevent fly ash sales.

Depending on the nature of the reburn fuel, various boiler retrofits are required. In all cases, the boiler needs to be equipped with fuel injection in the reburn zone and OFA ports in the burnout zone; flue gas recirculation (FGR) may also be added. If the reburn fuel is coal, additional coal handling and pulverizing equipment may have to be installed. For example, cyclone boilers are fired with coarse crushed coal, which needs to be reduced to smaller particle sizes to be an effective reburn fuel.

Studies have shown that the most critical parameters which impact reburning performance are (1) NO_X level entering the reburn zone, (2) reburn zone stoichiometry, (3) reburn zone temperature and residence time, and (4) mixing of the reburn fuel and OFA with the bulk furnace gas. These parameters are discussed further in the following sections.

Reburn Zone Stoichiometry. Reburn zone stoichiometry is defined as the ratio of the total air supplied to the primary and reburn zones to the total theoretical air requirement of the primary and reburn fuels. NO_X reduction is highest when the reburn zone stoichiometry is in the vicinity of 0.90. To minimize the amount of reburn fuel needed to reach the optimum stoichiometry, the primary combustion zone should be operated as close to stoichiometric conditions as possible. For coal-fired boilers, operation of the primary combustion zone with an excess air level of 10 percent or less is preferred to bring the reburn fuel requirement to 18 to 20 percent of the heat input to the furnace and to maintain coal flame combustion characteristics. Lower stoichiometries can be used in the primary combustion zone provided that combustion stability and LOI are not sacrificed and corrosion is not increased.

In the burnout zone, OFA is added to bring the overall furnace combustion system to its normal (no reburn) operating stoichiometry. When applying reburning, it is desirable to use the minimum overall excess air level consistent with good combustion in order to improve the thermal efficiency of the unit. This reduction can be accomplished if the reburning system is designed to provide effective mixing of the OFA and if it does not cause problems with operation of the boiler's thermal cycle.

Furnace Temperature. The temperature of the gas in the furnace at the point where the reburn fuel is injected has an impact on the process efficiency, with higher temperatures being preferred. This suggests that the reburn fuel should be injected as close to the primary zone as possible. However, the reburn fuel must be injected at a sufficient distance above the primary zone to allow burnout of the volatile hydrocarbons in the primary flame and reduction of the O_2 concentration entering the reburning zone. The temperature at which the burnout air is injected does not directly influence the efficiency of the reburning process for most gas and liquid reburn fuels, but it is important that the temperature be high enough to allow oxidation of CO and hydrocarbon fragments from the reburning zone to occur readily.

Zone Residence Time. Sufficient residence time must be available in the primary combustion zone to allow combustion of the primary fuel to proceed to near completion. However, residence time in the reburning zone is the most critical to the process. Sufficient residence time in the reburning zone must be available to allow mixing and reaction of the reburn fuel with the residual O_2 and the products from the primary combustion zone. Studies have shown that the reburn zone residence time should be 0.3 to 0.5 s. Finally, sufficient residence time must be provided in the burnout zone to permit oxidation of the CO and hydrocarbon fragments from the reburning zone. Because of reduced furnace volume, providing sufficient residence time in the various zones can be a problem when installing MCR on small units.

Mixing. Effective mixing of the reburn fuel optimizes the process by making the most efficient use of the available furnace residence time, while effective mixing of the OFA reduces CO emissions and LOI. In order to ensure that the reburn fuel is mixed effectively in the furnace, FGR has been used to boost the nozzle velocity. In any case, the use of coal as a reburn fuel requires the use of a transport medium for the coal.

II.D.2 Chemistry of the Reburning Process

The following equations are approximate representations of the complex, free-radical reactions that occur during reburning. They are not elementally balanced.

The major reactions occurring in the primary combustion zone (low to normal excess air; stoichiometric ratio of 1.1 to 1.2) are fuel combustion and NO_X formation.

$$\text{Main Fuel} + O_2 \rightarrow CO_2 + CO + H_2O + \text{Other Species} \quad (1)$$
$$N(\text{fuel}) + O_2 \rightarrow NO_X \text{ (fuel } NO_X \text{ formation)} \quad (2)$$
$$N_2(\text{air}) + O_2 \rightarrow NO_X \text{ (thermal } NO_X \text{ formation)} \quad (3)$$

The chemistry in the reburn zone (fuel rich; stoichiometric ratio of 0.85 to 0.95) is very complex. NO_x reacts with hydrocarbon free radicals to form reduced nitrogen species, which in turn react with additional NO_x to form nitrogen gas.

$$\text{Reburn Fuel} \rightarrow CH_x + \text{Other Species} \quad (4)$$
$$CH_x + NO_X \rightarrow \bullet CN + \bullet NH_2 + H_2O \quad (5)$$
$$NO_X + \bullet NH_2 \rightarrow N_2 + H_2O \quad (6)$$
$$NO_X + \bullet CN \rightarrow N_2 + CO \quad (7)$$
$$NO_X + CO \rightarrow N_2 + CO_2 \quad (8)$$

The main function of the burnout zone (normal excess air; stoichiometric ratio of 1.20 to 1.25) is to complete combustion of the fuel. However, any unreacted reduced nitrogen compounds may be reoxidized to NO_x. This latter effect is normally small, and the overall result of reburning is a reduction in NO_x emissions.

$$\text{Air} + CH_x + CO \rightarrow CO_2 + H_2O + \text{Other Species} \quad (9)$$
$$\bullet CN + \bullet NH_2 + O_2 \rightarrow NO_X + CO_2 + H_2O \quad (10)$$

Kinetic studies of reburning chemistry have shown that a peak concentration of hydrocarbon radicals is generated at a stoichiometric ratio near 0.9. Increasing the amount of reburn fuel beyond this point does not improve NO_X reduction. In fact, for fuels containing nitrogen, such as coal, increasing the quantity of reburn fuel above the optimum level can have a negative effect on reburn performance.

II.D.3 Coal Micronization

The development of micronized coal technology has been advanced primarily in the U.S., where the standard for micronized coal is that 80 wt% of the particles have a diameter less than 43 µm (that is, pass through a 325 mesh screen). Most of the operating history of micronized-coal-fired combustion systems is on industrial-sized process furnaces, rather than on utility boilers. Development of the centrifugal-pneumatic mill, used to produce micronized coal, began in the fall of 1983; and, during an 18-month development period, several prototype mills were designed, built, and tested. MicroFuel Corporation (MFC) is the developer of this technology, which is now owned by Fuller Power Corporation.

In 1984, significant interest developed in firing micronized coal as a replacement fuel for gas or oil for industrial applications, including aggregate dryers, cement plants, packaged boilers, and other process furnaces. Since a 5 ton/hr mill was required to meet the firing rates of most furnace applications, a 30-in. mill was developed with a classifier, based upon a horizontal cyclone design and a solid steel cast impeller. Several 30-in. mill systems were built in the mid-to-late 1980s, most of which were installed on aggregate dryers. However, by 1988 the focus was on utility applications, and a more reliable impeller was required. Therefore, a replaceable-blade impeller was designed, and a unit incorporating this technology was thoroughly tested at full scale.

MFC installed micronizing mills in 1988 at Duke Power's Cliffside Power Station on a 600-MWe Combustion Engineering T-fired furnace. The main oil guns were removed from corners 2 and 4, and micronized coal-fired burners were installed for startup ignition. The MCR project at Kodak used the same type of system as Cliffside, except that it was designed to be run continuously. Figure 2 shows a schematic drawing of the Fuller MicroMill™.

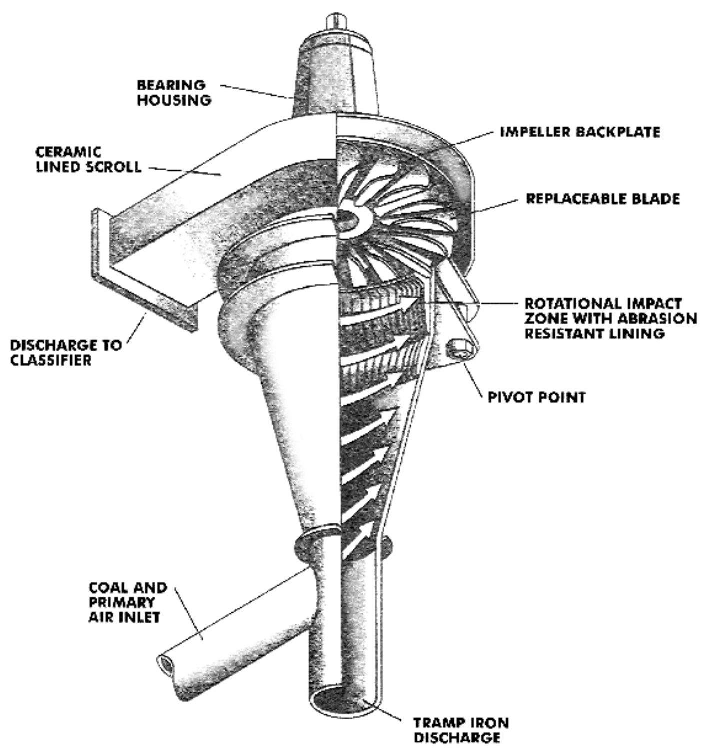

Figure 2. Schematic View of Fuller MicroMill™

II.E Project Implementation

This project was implemented at two sites: NYSEG's Milliken Station and Eastman Kodak's Kodak Park. The fuel fired at both sites was Pittsburgh seam, medium- to high-sulfur coal with a Hardgrove Grindability Index (HGI) of approximately 55 and a higher heating value (HHV) of about 13,300 Btu/lb.

II.E.1 Milliken Station

The Milliken site consists of two balanced draft mode units with a rated capacity of 150 MWe (net) each, for a total station capacity of 300 MWe (net). The units are T-fired with four levels of burners in each of the four corners. Unit 1 was completed in 1955 and Unit 2 in 1958. Just prior to initiation of the MCR Project, Milliken Unit No. 1 had undergone a general upgrade as part of the MCCTD Project. This upgrade included retrofitting ABB combustion air heaters, an upgraded Westinghouse WDPF control system, and S-H-U flue gas desulfurization.

MCR was demonstrated on Milliken Unit No. 1 using the equipment installed for the MCCTD project. The Riley MPS-150 mills with dynamic classifiers operated with fineness approaching 75 percent through 325 mesh, and the mills were tested at higher classifier speed to demonstrate the required 80 percent through 325 mesh. Because the MPS-150 mills could approach micronized coal fineness, new mills were not installed. The upper burner compartment of the low- NO_X concentric firing system level III (LNCFS-III™) was used to inject the reburn fuel. Figure 3 shows a schematic representation of the MCR installation at Milliken.

Since existing equipment was used, essentially no construction time was required at the Milliken site. Operations for the demonstration project covered the period from March 1997 to April 1999. The Milliken units are typical of many power plants in the United States, and demonstration of MCR at this scale is sufficient to establish its commercial viability.

II.E.2 Kodak Park

The No. 15 boiler at Kodak Park is a Babcock & Wilcox Model RB-230 cyclone boiler commissioned in 1956. This industrial boiler, designed to generate 400,000 lb/hr of 1,400 psig, 900 ^oF steam, has a rated heat input of $478x10^6$Btu/hr (50-MWe equivalent) at maximum continuous rating.

Before implementing MCR technology at Kodak, pilot-scale combustion studies were performed at EER's test site in El Toro, CA, to evaluate the suitability of the Pittsburgh Seam bituminous coal fired by Kodak as a reburning fuel. This testing was necessary, since it is not possible to predict the NO_X control performance achievable with a specific coal based upon simple coal analysis. The results of these tests indicated that the coal fired by Kodak could be used as an effective reburning fuel at the conditions typical of Boiler No. 15 and that NO_X reductions of 50 to 60 percent might be expected.

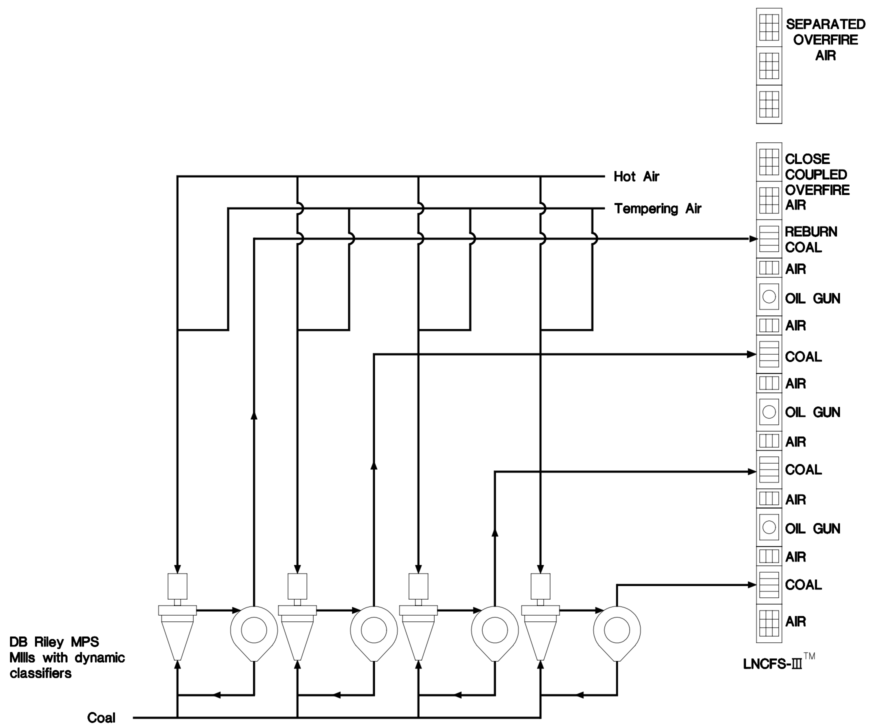

Figure 3. Schematic of MCR System at Milliken

To implement this project at Kodak Park, Kodak installed a Fuller MicroMill™ coal micronizing system plus new micronized coal and gas reburn injectors/burners and OFA ports downstream of the cyclone burners. The existing air and gas handling systems were modified to reroute the air and gas to the new burners and ports. Figure 4 shows a schematic of the MCR installation at Kodak Park. Construction covered the period from September 1996 to January 1997. Operations were initiated in April 1997 and completed in October 1998.

The Fuller MicroMill™ uses a tornado-like column of air to create a rotational impact zone where the coal particles strike against each other and crush themselves. Typical particles generated by the Fuller MicroMill™ are approximately 20 µm in diameter compared to normal pulverized coal, which has a particle diameter of about 60 µm. The resulting tripling in surface area allows for improved combustion in a shorter time period. This was critical to the success of the project, since the Kodak boiler is small and has a low residence time. A new distributed control system was installed in a new control room.

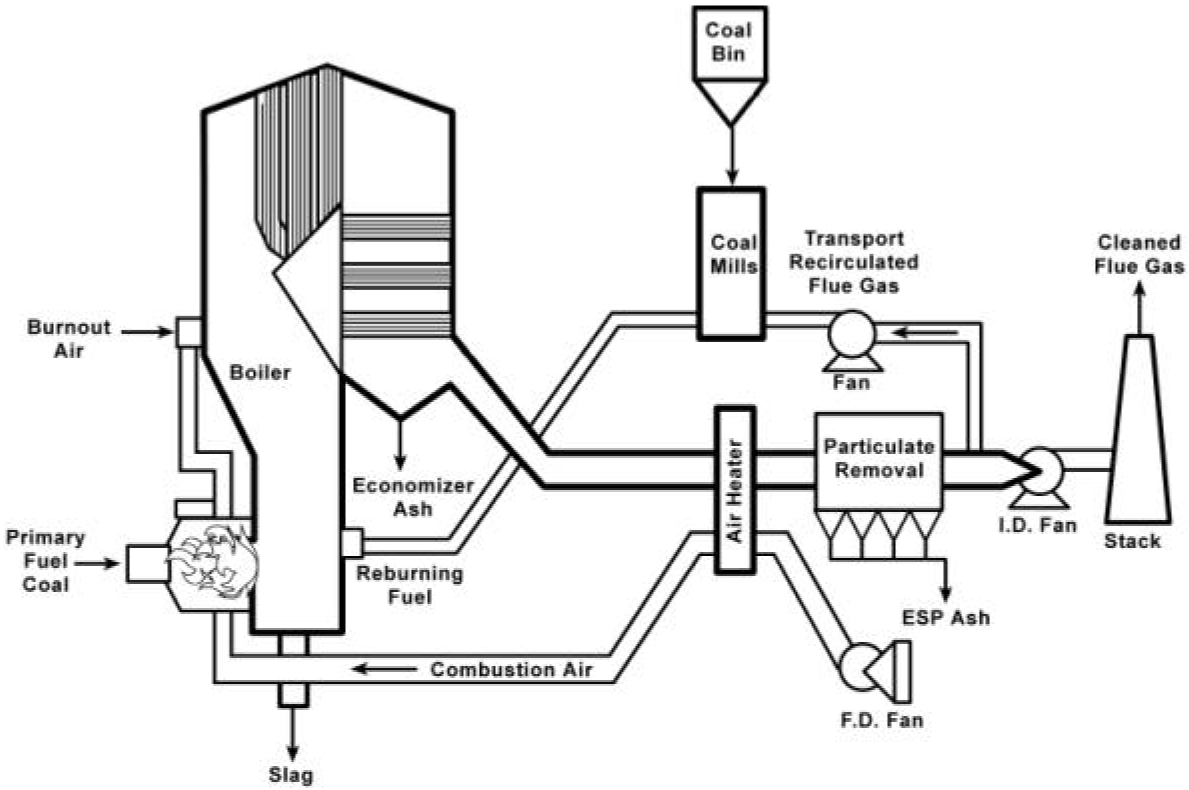

Figure 4. Coal Reburning Process Flow Diagram for Kodak Unit 15

III Technical and Environmental Performance

A summary of short- and long-term test results and the effects of operating variables is provided below.

III.A Results at Milliken Station

In 1996, NYSEG Corporation contracted DB Riley, Inc. to provide mill-system technical support in conjunction with the MCR project at Milliken Station. On January 28 and 29, 1997, reduced load, maximum mill capability, and fineness tests were conducted on Mill 1A1, which was providing pulverized coal to the boiler's top row of burners. The MPS-150 mills installed at Milliken Station are equipped with planetary gear reducers, hydro-pneumatic roller loading, and hydraulically-driven dynamic classifiers (type SLS). The mills were guaranteed to deliver 18.4 tons/hr of pulverized coal at a minimum fineness of 87 percent through 200 mesh and 98 percent through 100 mesh, when grinding an Eastern bituminous coal having a moisture content of 5.6 percent and an HGI of 57.

Some conclusions drawn from these tests are

- Mill 1A1 operated stably over a load range of 8 to 12 tons/hr at elevated classifier speeds;
- The higher classifier speeds produced much sharper particle size distributions; and
- Mill product fineness values over a load range of 8 to 12 tons/hr can be predicted.

An evaluation program was conducted consisting of a sequence of three test sets: diagnostic, performance, and long-term. The diagnostic program consisted of short-term (1 to 3 hours) optimization tests conducted to obtain parametric data and to select settings for long-term operations. The selected settings were utilized during performance and long-term testing to achieve the lowest NO_X emissions at full boiler load (140 to 150 MWe) while maintaining the required steam conditions, reliable boiler operation, and fly ash LOI below 5 percent. The performance program assessed the effect of operating variables on reburning. The long-term program evaluated long-term (23 days) NO_X emissions performance to permit estimation of annual emissions.

The baseline for the evaluation tests was the LNCFS-III™ configuration, which generated the lowest NO_X emissions (0.39 lb/1x10^6Btu) while maintaining the fly ash LOI below 5 percent. Primary consideration was given to maintaining reliable boiler operation.

These tests produced the following results.

- Reburning was successfully applied to the existing LNCFS-III™ configuration without installing a separate reburn system, by using the top coal feed level to supply the reburn fuel and reducing the top burner level air flow relative to the LNCFS-III™ setting. Reburning results were improved by concentrating the OFA through fewer, higher ports and using a finer grind reburn coal (more than 70 percent passing 325 mesh) to maintain LOI below 5 percent.

- At the same economizer O_2 level, no single operating variable had a dominant effect on reburning performance. Appropriate operating settings for lowest NO_X and reliable long-term operation were 14- to 16-percent reburn coal, 105 rpm top mill classifier speed (corresponding to 70 to 72 percent through 325 mesh), -5^o main burner tilt, and 2.8-percent economizer O_2. No additional improvement in LOI was observed using top mill classifier speeds higher than 105 rpm.

- During performance testing, NO_X emissions were reduced from a baseline of 0.39 to 0.25 lb/1x10^{6}Btu (36-percent reduction) using 14.4 percent reburn fuel at full boiler load (140 to 150 MWe), while maintaining fly ash LOI below 5 percent and the boiler efficiency at 88.4 to 88.8 percent.

- Long-term testing indicated that the achievable annual NO_X emissions level on Unit 1 using 15.1 percent coal reburn fuel is 0.25 lb/1x10^{6}Btu with an average fly ash LOI of 4.4 percent.

- LOI generally varied only within a relatively narrow range (3 to 5 percent).

- Variation in the OFA injector tilt between 0° and 15° above horizontal had only a minor effect on NO_X emissions and LOI.

- Increasing the air used to transport the reburn coal from 2.05 lb/lb to 2.45 lb/lb increased NO_X emissions from 0.28 to 0.31 lb/1x10^{6}Btu, because of a lower reducing reburn-zone stoichiometry.

- Increasing the top level auxiliary air flow increased both NO_X and LOI. The increased NO_X was caused by a lower reducing reburn-zone stoichiometry because more air was introduced through the auxiliary air nozzle directly below the reburn coal nozzle. The increased LOI was caused by lower excess air levels in the primary combustion zone as air was diverted away from the lower burners.

- Increasing the economizer O_2 generated the classical response of higher NO_X emissions and lower or unchanged LOI. The effect was about a 0.1 lb NO_X/1x10^{6}Btu increase for each 1-percent increase in O_2 and was relatively independent of reburn coal fineness.

- Using a finer grind reburn coal reduced both NO_X and LOI, but the effect on NO_X was significant only for relatively large variations in the top mill classifier speed (a change of 30 rpm).

- Feeding a finer grind coal to the primary combustion zone reduced both NO_X and LOI.

- Setting the main burner tilt 5° below the horizontal lowered LOI without increasing NO_X, because of the longer residence time in the furnace prior to OFA introduction.

- Decreasing the reburn coal fraction from 25 to 14 percent decreased NO_X emissions from 0.25 to 0.23 lb/1x10^6Btu with only a minor effect on LOI, because of lower excess air levels in the primary combustion zone as more coal was diverted to the lower burners.

- NO_X emissions decreased as the boiler load decreased.

- Taking the second mill out of service at a given boiler load in the range 110 to 140 MWe reduced NO_X emissions, probably because of a longer residence time in the primary combustion zone.

Just prior to the MCR Project, NYSEG had rebuilt the Milliken ESP, including new internals, new computer controlled transformer-rectifier sets, and an additional third field; also, plate spacing was increased to 16 in. Performance of the ESP was evaluated in September 1998 while injecting micronized coal, and no significant effect of MCR, as measured by removal efficiency, was observed. However, fly ash LOI increased from 2.4 to 3.7 percent, and particulate stack emissions increased approximately 30 percent. Micronized coal injection high in a boiler with a short residence time caused an increased loading of fly ash with a higher LOI to reach the ESP inlet. Results could differ for ESPs with a different configuration.

III.B Results at Kodak Boiler No. 15

An optimization study of the MCR system retrofit to Eastman Kodak's No. 15 boiler was carried out between April 13 and April 29, 1997, to evaluate pre- and post-reburn performance relative to NO_X emissions, boiler efficiency, and superheater performance. Various OFA port settings were evaluated to determine optimum combustion efficiency for the reburn system. The combustion stoichiometries in the cyclone, reburn, and burnout zones were optimized to produce the air and fuel flow data necessary to operate the system in automatic control. The study determined the load range over which the reburn system could be operated while not adversely affecting boiler performance. (See Figure 5.) The test data were used to identify the maximum NO_X reduction capability of the system and to create a NO_X vs. boiler load profile. The combustion control system was configured to match the emission versus load profile, and the boiler was successfully put into automatic operation.

A system evaluation was conducted, consisting of four test programs: diagnostic, performance, long term, and validation. The diagnostic test program consisted of short-term (1 to 3 hours) optimization tests conducted by Babcock & Wilcox in order to obtain parametric data. The performance test program consisted of assessing the effect of operating variables. The long-term test program assessed NO_X emissions performance of the reburn system for 2 months. The validation test program used short-term parametric tests to reevaluate the performance of the reburn system following long-term testing. The evaluation included baseline (no reburn) testing for comparison. The following conclusions were reached.

- Performance tests indicated that using 17.3-percent reburn fuel (reburn stoichiometry of 0.89) reduced NO_X from a baseline level of 1.36 to 0.59 lb/1x10^6Btu, a 57-percent reduction.

Fly ash LOI increased from 11 to 37 percent, and boiler efficiency decreased from 87.8 to 87.3 percent.

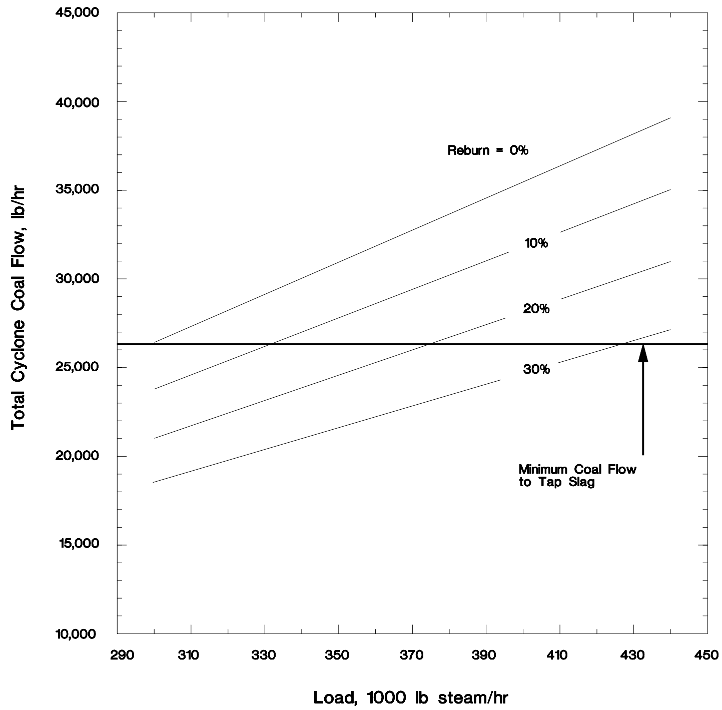

Figure 5. Total Coal Flow Rate vs. Load for Kodak Boiler No. 15

- Achievable NO_X emissions at 15.6-percent reburn (stoichiometry of 0.90) were estimated, based on long-term tests, to be 0.69 lb/1x10^6Btu, with a corresponding fly ash LOI of 38 percent. A higher reburn feed level, estimated at 18.4 percent (stoichiometry of 0.87), would be required to achieve a NO_X level of 0.6 lb/1x10^6Btu.

- MCR reduced NO_X emissions and increased the fly ash LOI with the final NO_X level depending primarily on the reburn stoichiometry. The increase in fly ash LOI relative to baseline is partially caused by a lower cyclone heat input, resulting in a lower temperature in the primary combustion zone, and partially caused by staged combustion, resulting in a shorter residence time under oxidizing conditions.

- Reburn stoichiometry has a dominant effect on NO_X emissions. Based on validation testing, NO_X emissions as low as 0.41 lb/1x10^6Btu were achievable at a reburn stoichiometry of 0.81, but this resulted in increasing the LOI to 48 percent, which might not be acceptable in some cases.

- Based on short-term testing (validation), variations in the primary stoichiometry between 1.02 and 1.14 had only a small effect on the NO_X level (less than 0.03 lb/1x10^6Btu) and LOI (less than 5 percent).

- Based on short-term testing (optimization and validation), variations in the final stoichiometry between 1.05 and 1.16 had no significant effects on NO_X emissions or fly ash LOI.

- The optimization and the validation test programs produced consistent results with respect to the effects of the operating variables on NO_X emissions and LOI. However, the validation tests generated 0.05 lb/1x10^6Btu lower NO_X emissions and 4 to 7 percent higher fly ash LOI than the optimization tests, attributed partially to differences in coal properties and partially to experimental variability.

- NO_X emissions could be maintained below 0.60 lb/1x10^6Btu when operating at full boiler load with a reburn fuel input of 20 percent of the total heat input to the boiler. As load is reduced, the reburn NO_X emission rate increases until it equals the baseline NO_X at a steam flow of 320,000 lb/hr.

- The final steam temperature with MCR in service remained within 10 °F of the desired 900 °F throughout the load range of 300,000 to 400,000 lb/hr.

Testing was conducted during the week of June 2, 1998, on Kodak Boiler No. 15 ESP at full load to assess the impact of MCR on ESP performance. This test program involved the simultaneous sampling of 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 following conclusions were reached.

- ESP removal efficiency did not decline for the reburn tests, but actually increased slightly. Average efficiency for the MCR tests was 97.1 percent vs. 95.5 percent for the baseline tests.

- MCR operations increased particulate loading to the ESP to 2.8 times the baseline, and the loading to the stack increased to 1.8 times the baseline.

- ESP particulate removal exceeded the design removal of 94.4 wt% for all the MCR tests and for three of the four baseline tests. Therefore, MCR operations do not appear to be detrimental to ESP performance.

- MCR flue-gas particulate was significantly coarser than the baseline particulate. Average particle diameters were 23 to 25 μm for MCR and 5 to 8 μm for the baseline.

- With MCR in operation, fly ash LOI increased from 11.3 percent for the baseline operations to 36.8 percent, indicating lower carbon burnout for the micronized coal.

- There are significant differences between the ESP energization levels for MCR and baseline operations. Under MCR conditions, field energizations were significantly higher than under baseline conditions. This helps to explain why removal efficiency remained high for MCR, even though the particulate loading was several times the baseline value.

Adding MCR to a cyclone boiler has more of an impact on ESP performance than adding MCR to a T-fired boiler. This is because in a T-fired boiler, most of the coal ash (approximately 80 percent) is removed as fly ash by the ESP, and adding MCR does not significantly change this situation. However, in a cyclone boiler, most of the coal ash is removed as slag, with only a relatively small part (15 to 30 percent) being captured as fly ash by the ESP. When MCR is added to a cyclone boiler, the micronized coal is burned in a region of the furnace where only a small amount of coal combustion normally occurs. Combustion of the micronized coal produces a significant increase in fly ash production and greatly increases the load on the ESP. Even if ESP efficiency does not decrease, the quantity of particulates going to the stack will increase.

Cyclone boilers are designed so that most of the coal combustion occurs in the cyclone and only the very fine particles escape to the rest of the furnace. Therefore, the volume of the rest of the furnace is relatively smaller than for a pulverized coal-fired boiler. This reduced residence time for coal combustion can significantly increase the LOI of the fly ash produced from the micronized coal. It may also explain why the fly ash from the micronized coal is coarser than the baseline fly ash.

IV Market Analysis

IV.A Economics

Cost analyses for generic 300 MWe commercial applications of MCR technology were performed for both T-fired and cyclone boilers. The design basis for these economics is shown in Table 1, and the values of the economic parameters are shown in Table 2. Alternative values were used where appropriate to be consistent with the design and operation of the MCR process. However, when estimating costs for a particular installation, scope adjustments and site specific factors, (e.g., unit size, sparing philosophy, design coal properties, space availability, and necessary furnace penetrations) need to be taken into account. The most likely initial application of this technology will be retrofit of existing power stations.

Table 1. Design Basis Used in MCR Economic Evaluations

Boiler Type	T-Fired	Cyclone
Plant Capacity, MWe	300	300
Coal 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/1x10^6Btu	0.4	1.25
NO_X Reduction, %	25	50
Micronized Coal Conveying Fluid	Air	Recirculated Flue Gas
No. of MCR Burner Rows	1	1
No. of Coal Mills/Row	1	11
Increase in Fly Ash LOI because of MCR, % (absolute)	5	510
Increase in Fly Ash Rate because of MCR, % (absolute)	10	20
Prior Retrofit of LNBs	Yes	--
Prior Retrofit of overfire air	Yes	No
Ash in Coal, %	10	10
Boiler Efficiency, %		87

Table 2. 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		0.0
Capital Charge Factor	Current Dollars	0.160
	Constant Dollars	0.124
O&M[a] 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

a operation and maintenance

IV.A.1 T-Fired Boiler

Estimated Capital Costs. Since existing T-fired boilers vary over a wide range of configurations, manufacturers, and age, the following assumptions were used in calculating costs to retrofit MCR to a generic 300-MWe boiler:

- The existing top row of burners can be used without modification for MCR injection;
- One coal pulverizer supplies pulverized coal to the reburn burners;
- An existing coal pulverizer is replaced with a new pulverizer and dynamic classifier to achieve the required coal fineness (70 percent <325 mesh); and
- Sufficient plot area is available for installation of the new coal pulverizer and associated equipment.

Additional instrumentation and controls are required, including upgrade of the distributed control system (DCS). The capital cost (1999 dollars) to install MCR on a 300-MWe T-fired boiler is shown in Table 3. Since these costs are for a retrofit application, the retrofit adjustment is already included. No allowance was included for funds used during construction. It was assumed that the new coal pulverizer could be installed while the power plant was in operation and that final ductwork modifications and connections could be installed during a planned plant outage. A project contingency of 15 percent was applied, but no process contingency was used, since the required equipment is commercially available and successfully demonstrated at Milliken Station.

The total capital requirement is \$4.3 million, or approximately \$14/kW. This low investment is because existing burners are used for MCR injection. If space is unavailable for installation of a new pulverizer or if the existing burners cannot be used for MCR injection, costs will be higher, the amount depending on site specific factors. On the other hand, some existing installations already include pulverizers that can produce coal of the required fineness. Little capital would be needed in such instances.

Table 3. Total MCR Capital Requirement for 300-MWe Boilers

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

Projected Operating Costs. Operating and maintenance costs are shown in Table 4. The costs shown are only the incremental costs resulting from installating MCR. The increased coal cost is caused by the need to compensate for carbon loss from the increased LOI of the fly ash, and the power requirement is caused by increased energy usage by the micronized coal pulverizer and dynamic classifier. Maintenance costs will be higher for the coal pulverizer mill and classifier compared to standard equipment. Overall, these costs are small in comparison to the total O&M costs of the power plant.

Because of the reducing atmosphere produced by MCR, the potential exists for boiler tube corrosion between the MCR injection ports and the OFA ports. This reducing environment could increase forced outages and maintenance costs substantially. No change in plant availability was assumed in the economics presented here.

Table 4. Projected Incremental Operating and Maintenance Costs for 300-MWe T-Fired Boiler
(thousands of dollars per year)

Fixed O& M Costs	
Operating Labor	20
Maintenance Labor	50
Maintenance Material	70
Administration/Support Labor	40
Total Fixed Costs	**180**
Variable Operating Costs	
Coal	110
Electric Power	10
Total Variable Costs	**120**
Total O&M Cost	**300**

Discussion of Economics for a T-Fired Boiler. The impact of MCR on power costs is shown in Table 5. Costs are levelized both on current dollar and constant dollar bases. Levelized costs for a 300-MWe unit are $1,329/ton of NO_X removed on a current dollar basis and $1,023/ton on a constant dollar basis. Busbar costs are 0.63 mills/kWh on a current dollar basis and 0.49 mills/kWh on a constant dollar basis. These costs assume year-round operation.

Table 5. Effect of MCR on Cost of Power for 300-MWe T-Fired Boiler

	Current Dollars		**Constant Dollars**	
Levelized Cost of Power	**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	0.16	846.22	0.124	655.98
Fixed O&M Cost	1.314	291.40	1.00	221.77
Variable Operating Cost	1.314	191.41	1.00	145.67
Total Cost		**1329**		**1023**

The analysis was conducted for a 300-MWe power plant operating at a 65-percent capacity factor with an initial NO_X level (before MCR) of 0.4 lb/$1x10^6$Btu. Additional economic analyses were performed to determine the impact of variations in these parameters. These analyses were performed on a constant dollar basis.

As plant size increases, capital and fixed costs per MWe decrease, while variable costs stay about the same on a per MWe basis. The overall effect is a decrease in the dollars/ton of NO_X removed as the plant size increases as shown in Figure 6. Sensitivity to plant capacity factor is shown in Figure 7. Since the capital costs are fixed, increasing the capacity factor increases the quantity of NO_X removed for a given capital investment. Figure 8 shows the sensitivity to initial NO_X level. A fixed percentage level of reduction is assumed for all cases. Therefore, as the initial level decreases, the absolute quantity of NO_X removed also decreases, and the dollars/ton of NO_X removed increases.

Within the accuracy of these estimates, costs for a wall-fired boiler using MCR technology would be approximately the same as for a T-fired boiler.

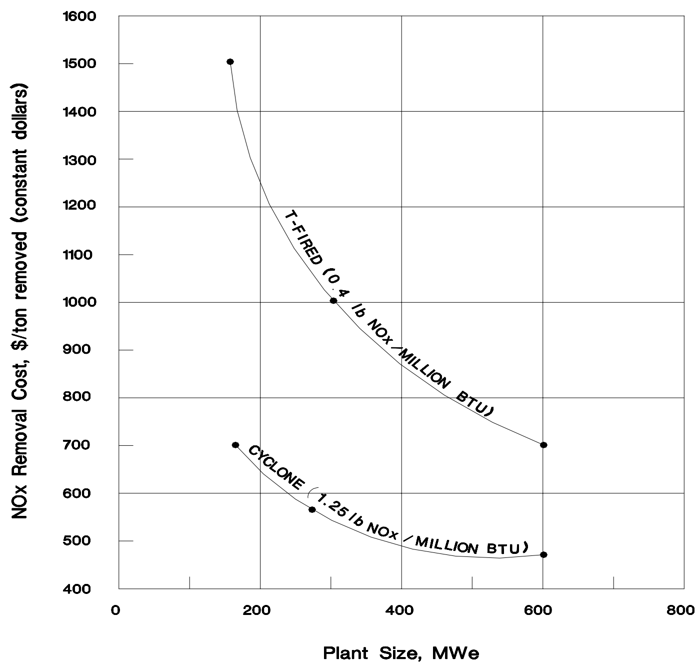

Figure 6. NO_X Removal Cost vs. Plant Size
(65-percent capacity factor)

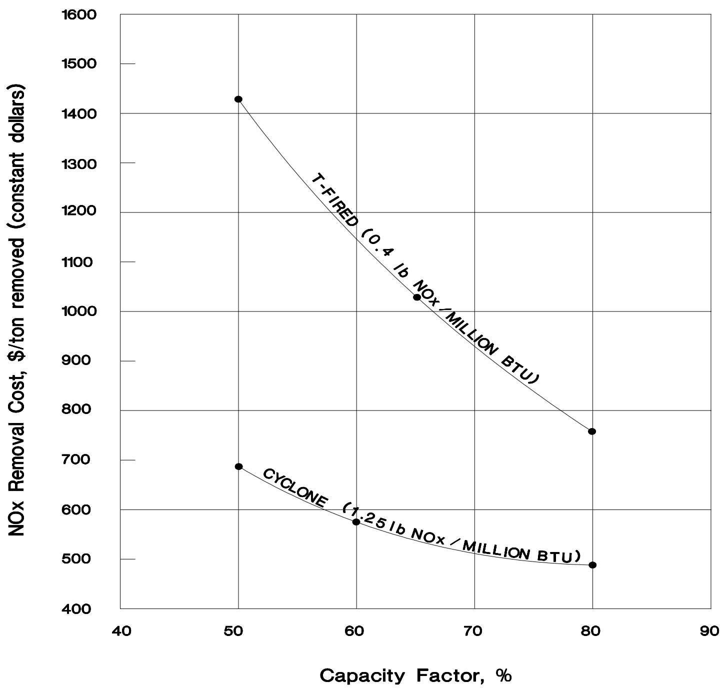

Figure 7. NO_x Removal Cost vs. Capacity Factor
(300-MWe plant)

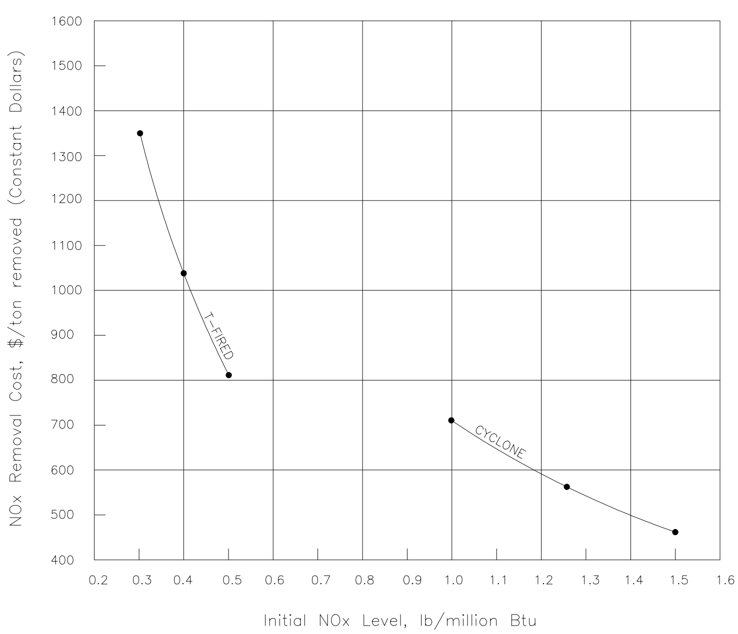

Figure 8. NO_X Removal Cost vs. Initial NO_X Level

IV.A.2 Cyclone Boiler

Estimated Capital Costs. The assumptions made in the economic analysis for a cyclone boiler are as follows:

- Space is present on the boiler for installation of both MCR injectors and OFA ports at locations allowing sufficient residence time for completion of the combustion reactions;
- A single, dedicated coal pulverizer supplies micronized coal to the MCR injectors;
- A new pulverizer and dynamic classifier is installed to achieve the required coal fineness;
- 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 DCS.

The capital cost (1999 dollars) to install MCR on a 300-MWe cyclone boiler is shown in Table 3. Since these costs are for a retrofit application, no additional retrofit adjustment is required. No allowance was included for funds used during construction. It was assumed that a new pulverizer could be installed with the power plant in operation,and final ductwork modifications and connections could be installed during a normal plant outage. A project contingency of 15 percent was applied, but no process contingency was used, since the successful demonstration of the technology at Kodak Park obviates the need for such a contingency and since the equipment is commercially available.

The total capital requirement is $16.9 million, or approximately $56/kW. These costs are consistent with projections made by Babcock & Wilcox, based on MCR testing performed at Wisconsin Power & Light's Nelson Dewey Station (Bradshaw et al. 1991). If space is not available for installation of a new pulverizer or MCR injectors or OFA ports, the costs will be higher. Costs are higher in comparison to a T-fired boiler because existing burners in the T-fired unit could be used for MCR injection and OFA ports were assumed to be available as a consequence of prior retrofit of LNBs.

Projected Operating and Maintenance Costs. Operating and maintenance costs are shown in Table 6. The costs shown are only the incremental costs resulting from installation of MCR. The only material required is coal. Coal consumption has to increase slightly to make up for the higher loss of carbon on the fly ash, which has both an increased rate and LOI. Parasitic power consumption increases because of the power required by the coal pulverizer and dynamic classifier. Maintenance will be somewhat greater for the pulverizer mill and classifier in comparison to standard equipment.

Discussion of Economics for a Cyclone Boiler. The impact of MCR on power costs is shown in Table 7. Costs were levelized both on a current dollar and constant dollar basis. Levelized costs for the 300-MWe unit are $741/ton of NO_X removed on a current dollar basis, and $571/ton on a constant dollar basis. Even though the capital required is greater, these costs are lower on a dollars/ton removed basis compared to the T-fired boiler because of the much higher NO_X removal on the cyclone boiler (50 percent NO_X reduction compared to 25 percent for the T-fired boiler). Also, because of the much higher initial NO_X level, the absolute NO_X reduction with the cyclone boiler is six times greater than for the T-fired boiler. Busbar costs are 2.2 mills/kWh on a current dollar basis and 1.7 mills/kWh on a constant dollar basis. These costs assume year-round operation.

Table 6. Projected Incremental Operating and Maintenance Costs for 300-MWe Cyclone Boiler
(thousands of dollars per year)

Fixed O&M Costs Operating Labor	50
Maintenance Labor	185
Maintenance Material	275
Administration/Support Labor	140
Total Fixed Costs	**650**
Variable Operating Costs Coal	100
Electric Power	50
Total Variable Costs	**150**
Total O&M Cost	**800**

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

	Current Dollars		Constant Dollars	
Levelized Cost of Power	**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**

This analysis was conducted for a 300-MWe power plant operating at a 65-percent capacity factor with an initial NO_X level (before MCR) of 1.25 lb/1x10^6Btu. An analysis was performed to determine the impact of various parameters on economics. As plant size increases, capital and fixed costs per MWe decrease, while variable costs remain relatively constant. The overall effect is a decrease in the cost of NO_X removed on a dollars/ton basis, as the plant size increases as shown in Figure 6.

Sensitivity to plant capacity factor is shown in Figure 7. Here, the capital costs are fixed. Therefore, increasing the capacity factor increases the quantity of NO_X removed for a given capital investment and thus lowers the cost per ton of NO_X removed. Figure 8 shows the sensitivity to initial NO_X level. Since a fixed fractional reduction is assumed for all cases, as the initial NO_X level decreases, the absolute quantity of NO_X removed also decreases. Therefore, the dollars/ton of NO_X removed increases as the initial NO_X level decreases.

IV.B Marketing

IV.B.1 Applicability of the Technology

The test boilers used for this demonstration were a 50-MWe equivalent cyclone boiler and a 150-MWe T-fired boiler, but the technology should be equally applicable to wall-fired units. The units used in this program are typical of a large portion of the nation's utility and industrial operating boilers. Thus, there is a potential for wide application of the technology. The successful demonstration of the DB Riley MPS mills with dynamic classifiers indicates that the technology should be applicable to large power plants. Tests have indicated that the technology can use virtually any coal that can be micronized.

Although primarily developed as a means for decreasing NO_X emissions from coal-fired furnaces, the MCR technology has several other potential benefits (see Section II.C.) that will make it attractive for many operators of coal-fired units. The combination of micronized coal and reburning for NO_X control is a natural fit for existing older fossil units.

IV.B.2 Market Size

The primary competing technology for MCR is LNBs, since NO_X reduction potential and costs for these two technologies are comparable; but because over 75 percent of utility boilers have now been retrofitted with LNBs, there is little opportunity for direct competition. However, there is potential for use on units where MCR can be cheaply installed to enhance NO_X removal (such as those applying LNCFS-III™) or where installation of MCR would permit a smaller and therefore cheaper selective catalytic reduction (SCR) unit to meet NO_X emissions standards. There may be some units that have installed LNBs where adding MCR would help meet NO_X emission standards, but this generally will not be the case. Small, uncontrolled boilers, particularly industrial boilers, may offer some potential, but there may not be sufficient space in these units to complete burnout. This was somewhat of a problem at Kodak. Also, it is unlikely that MCR alone on such units can reach future stringent emissions limitations (0.15 lb $NO_x/1x10^6$Btu).

It is relatively difficult to determine the potential market for MCR. At the time this project was selected in 1991 as part of the CCT program, market opportunities looked attractive, but now almost 10 years later with lower NO_X emissions limits, the potential market appears to be smaller. The overseas market may hold more potential.

IV.B.3 Market Barriers

Although NO_X reductions as high as 57 percent were demonstrated in this program, for many units this will still not meet the U.S. Environmental Protection Agency (EPA) standard to be implemented by May 2003, which calls for reducing NO_X emissions to 0.15 lb/1x10^6Btu. In order to meet the EPA regulation, MCR will have to be augmented with other technologies (for example selective non-catalytic reduction [SCNR]) or replaced all together (by SCR, for example). Therefore, MCR will be limited in application for commercialization to units that are part of an emissions averaging plan under which the total of reductions required can be met by inclusion of MCR with other technologies, or where NO_X reduction achievable with MCR alone is sufficient to meet the emissions limit.

IV.B.4 Economic Comparison With Competing Technologies

Some of the NO_X reduction technologies that compete with MCR are gas reburning, SCNR, and SCR. Table 8 shows levelized costs (in constant dollars) recently reported in the literature for these technologies compared to MCR.

Table 8. Comparison of Costs of NO_X Reduction Technologies

NO_X Reduction Technology	GasReburn	MCR	SNCR	SRC
T-Fired				
Initial NO_X Level, lb/1x10^6Btu	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/1x10^6Btu	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.

Gas costs were assumed to be $3/1x$10^6$Btu. Costs shown in Table 8 assume year-round operation of each technology. However, in some geographical regions, NO_X reduction may only be required during the summer ozone season (May to September). In this case, because fixed costs are spread over a smaller number of tons of NO_X removed, levelized costs on a dollars/ton of NO_X removed basis will increase for each technology. The smallest increase will be for those technologies with the least capital investment. This could favor MCR, which has a relatively low capital investment. MCR NO_X reduction economics will be particularly attractive in those cases where a 25 percent NO_X reduction is acceptable. Ultimately, the technology selected must not only be economical but also be able to achieve the NO_X reduction necessary to meet environmental limits.

On a levelized cost per ton of NO_X removed, gas reburn for T-fired units is the most expensive option, while MCR and SCR costs are comparable. Although SCR capital costs are much higher, because SCR removes much more NO_X, costs on a dollars/ton of NO_x removed basis are comparable.

For cyclone units, on a levelized cost per ton of NO_X removed, SNCR is the most expensive while MCR is the least expensive. However, MCR alone may not be able to achieve anticipated future NO_X emission limits. The high level of NO_X reduction with SCR may make it the technology of choice.

IV.B.5 Commercialization Plans

NYSEG and Kodak sponsored the MCR demonstration as end-users and have no responsibility for the commercialization of this technology. This responsibility lies with Fuller, DB Riley, and EER. MCR can be applied to most coal-fired units, including wall-fired, T-fired, cyclone, and large stoker units. There is also no upper limit on the size of the units to which this technology can be applied.

The three major subcontractors responsible for the commercialization of their technologies plan to support the electric utility industry in the area of micronized coal for displacement of liquid and gaseous fuels in the utility market sector. Development of MCR technology is only an extension of the current market plans, and the corporate management of all three companies is committed to this market sector.

Commercialization will be through a joint effort of two major subcontractors, Fuller and EER. Both companies maintain test facilities for combustion tests, coal preparation and classification, and both companies have the resources and facilities for engineering, manufacturing, and marketing of their individual products. The team will jointly market the technology, while each will retain responsibility for its area of expertise—Fuller for coal preparation and delivery, and EER for reburn and furnace technology. As the market expands, a separate group will be formed that will have sole responsibility for marketing the technology. Other plans include marketing the micronized coal reburn technology to the industrial market sector for NO_X control on smaller coal-fired units, both pulverized and stoker-fired.

Development of this technology will be accomplished in the normal course of business of both companies. The major area of development will be the design of a larger Fuller MicroMill™ to serve reburning applications on large central station units.

V Conclusions

- Coal reburning was successfully demonstrated on both a T-fired (Milliken) and a cyclone (Kodak) boiler. On the T-fired boiler, existing mills were used to produce near micronized coal (70 to 72 percent through 325 mesh). On the cyclone boiler, a Fuller MicroMill™ was used to produce micronized coal (80 percent or more through 325 mesh). The objective of at least 50-percent NO_X reduction on the cyclone boiler was met with a demonstrated 57-percent reduction. The low NO_X baseline (0.39 lb/1x10^6Btu) from the T-fired boiler was reduced to 0.25 lb/1x10^6Btu (a 36-percent reduction) with MCR, meeting the project objective of at least 25- to 35-percent reduction on a T-fired boiler already equipped with LNBs.

- At Milliken, it was found that no single operating variable had a dominant effect on reburning performance. Rather, several variables were found to have an important effect on the level of NO_X reduction.

- At Kodak, reburn stoichiometry, cyclone heat input, and cyclone stoichiometry all affected both NO_X and LOI.

- At Milliken, adding MCR had little or no effect on ESP collection efficiency. At Kodak, ESP removal efficiency during MCR operation actually increased; however, since the particulate loading entering the ESP increased significantly, particulate loading in the stack gas increased over the baseline.

- There are significant differences between the ESP energization levels for MCR and baseline operations. Under MCR conditions, field energizations were significantly higher than under baseline conditions. This helps to explain why removal efficiency remained high for MCR, even though the particulate loading was several times the baseline value.

- This project demonstrated the long-term reliability of the systems and materials utilized in MCR. At Milliken, existing equipment was utilized, and no operational problems were encountered that were caused by MCR operations. At Kodak, certain components of the system experienced wear, including rotary valves and mill components. Wear-resistant coatings should overcome this problem.

- The DB Riley MPS-150 mill (with dynamic classifier) used at Milliken was not originally designed to produce micronized coal. Therefore, comparing its performance to that of the Fuller MicroMill™ used at Kodak is not appropriate.

- Although boiler operations were followed over a sufficiently long period to determine boiler performance under MCR, additional testing to ensure that there are no adverse long-term effects would be desirable.

Abbreviations

CCT	Clean Coal Technology
CO	carbon monoxide
CO_2	carbon dioxide
CONSOL	Consolidation Coal Company
DCS	distributed control system
DOE	U.S. Department of Energy
EER	Energy and Environmental Research Corporation
EPA	U.S. Environmental Protection Agency
ESP	electrostatic precipitators
FGR	flue gas recirculation
HGI	Hardgrove Grindability Index
HHV	higher heating value
LNBs	low-NO_X burners
LNCFS-III™	low-NO_X Concentric Firing System Level III
LOI	loss on ignition
MCCTD	Milliken Clean Coal Technology Demonstration
MCR	micronized coal reburning
MFC	MicroFuel Corporation
MWe	megawatts (electric)
N_2	nitrogen
N_2O	nitrous oxide
NO	nitrogen oxide
NO_2	nitrogen dioxide
NO_X	nitrogen oxides
NYSEG	New York State Electric & Gas Corporation
O_2	oxygen
O&M	operation and maintenance
OFA	overfire air
PM	particulate matter
SCR	selective catalytic reduction
SNCR	selective non-catalytic reduction
SO_2	sulfur dioxide
T-fired	tangentially fired
TVA	Tennessee Valley Authority

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