DOE/PC89659-TI

U.S. Department of Energy

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PITTSBURGH ENERGY TECHNOLOGY CENTER

THE COAL REBURNING FOR CYCLONE BOILER NO_X CONTROL DEMONSTRATION PROJECT

A DOE ASSESSMENT

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September 1995

EXECUTIVE SUMMARY

This document serves as a U.S. Department of Energy post-project assessment of a project in the Clean Coal Technology Round 2, "Demonstration of Coal Reburning for Cyclone Boiler NO_X Control." In early 1990, The Babcock & Wilcox (B&W) Company entered into an agreement to conduct the study, with Wisconsin Power & Light (WP&L) as the host and co-sponsor. The plant scale demonstration was conducted from February 1992 to December 1992.

This project was undertaken to evaluate the technical, operational, and economic feasibility of using coal reburning for cyclone boiler NO_X emissions control in electric power plant service. Cyclone boilers use cylindrical burners in which the bulk of the coarsely crushed coal particles are captured and burned in a layer of molten slag. The mineral matter melts, exits the furnace from the tap at the cyclone throat, and is dropped into a water-filled slag tank. Cyclone boilers inherently produce high levels of NO_X emissions because of the high intensity of combustion.

The performance objectives of this project were as follows:

1. To provide a technically and economically feasible means for cyclone boilers to achieve 50% or greater NO_X reduction at full load, using the existing boiler fuel (coal) for reburning.

2. To achieve this NO_X reduction goal with no substantial adverse impact on other boiler emissions.

3. To provide a system that maintains boiler reliability, operability, and steam production performance after retrofit.

All three goals were met or exceeded in the demonstration project, which was conducted at WP&L's Nelson Dewey Station (Cassville, WI), Unit 2 (rated at 110 MW.). NO_X emissions reductions of 50 - 55% were achieved on a commercial scale at full load, burning both bituminous and subbituminous coals. No significant adverse effects on boiler operation or other emissions were experienced. WP&L has accepted the coal reburning system and continues to run it on a routine basis. The demonstration project produced valuable data for future design improvements.

Reburning with gas, oil, or coal is the only available combustion control technology applicable to cyclone boilers, which currently provide about 8% of U.S. coal-fired generating capacity. Of these reburning options, coal reburning generally offers the most favorable economics because the lower price of coal relative to the other fuels more than offsets the higher capital cost for coal reburning. More detailed analysis would be required for specific situations, taking into account the availability of natural gas and the cost of constructing a pipeline to bring it to the power plant if needed.

Since utilities plan to operate these cyclone boilers for at least an additional 10 to 20 years, the achievement of these performance objectives represents a significant advance in utilizing coal in an environmentally acceptable way.

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I. Introduction

The goal of the U.S. Department of Energy (DOE) Clean Coal Technology (CCT) program is to furnish the energy marketplace with a number of advanced, more efficient, and environmentally responsive 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 in CCT Round 2, "Demonstration of Coal Reburning for Cyclone Boiler NO_X Control." In early 1990, The Babcock & Wilcox (B&W) Company entered into a cooperative agreement to conduct the study. Wisconsin Power & Light (WP&L) was the site host and co-sponsor. Other cofunders were the Electric Power Research Institute (EPRI), and the state of Illinois. Acurex and Sargent & Lundy functioned as the testing and architect engineer subcontractors, respectively. Additionally, there were a number of utility cosponsors. The demonstration- was started up in February 1992 and completed in December 1992. The independent evaluation contained herein is based primarily on information from the Final Project Report prepared by B&W, dated February 1994 [1], and other references as cited.

Cyclone furnaces use cylindrical burners in which the bulk of the coarsely crushed coal particles are captured and burned in a layer of molten slag. The mineral matter melts, exits the furnace from the tap at the cyclone throat, and is dropped into a water-filled slag tank. Because of intense combustion, cyclone boilers produce high levels of NO_X emissions.

An earlier feasibility study conducted by B&W [2] had determined that coal reburning technology could potentially be applied to a majority of the more than 100 cyclone boilers in the United States, with a potential of achieving NO_X emission reductions of 50 to 70%. The purpose of this project was to demonstrate coal reburning for cyclone boilers on a commercial scale.

The host site chosen for this CCT demonstration project was WP&L's Nelson Dewey Station, Unit 2, located in Cassville, WI. The unit is a drum-type radiant boiler equipped with three B&W cyclone burners. At 110 MW, rated capacity, this unit is large enough to demonstrate commercial scale operation while minimizing the cost of the test program. Two types of coal were tested, a bituminous coal and a subbituminous coal, with long-term testing being done when firing the bituminous coal.

The project was carried out by both B&W and Acurex, an independent testing organization. As part of the project, B&W's Small Boiler Simulator (SBS) pilot facility was used to simulate the operation of Nelson Dewey Unit 2. Data obtained in the SBS were used to develop mathematical models, which in general proved accurate in predicting the full-scale combustion and heat transfer performance of coal reburning.

The reburning process employs multiple combustion zones: the primary combustion zone, the reburn zone, and the burnout zone. The reburn and burnout zones operate under conditions appropriate to achieving maximum overall reduction of NO_X to molecular nitrogen.

The performance objectives of this project were as follows:

1. To provide a technically and economically feasible means for cyclone boilers to achieve 50% or greater NO_X emissions reduction at full load, using the existing boiler fuel (coal) without supplemental fuels (oil or gas).

2. To achieve this NO_X emissions reduction goal with no serious impact on other boiler emissions (i.e., gaseous species such as CO, N_2O, SO_3, total unburned hydrocarbon combustibles/organics or particulates) or on carbon carryover.

3. To provide a system that maintains boiler reliability, operability and steam production performance after retrofit.

II. Technical and Environmental Assessment

A. Promise of the Technology

This project was undertaken to evaluate the technical, operational, and economic feasibility of using coal reburning for cyclone boiler NO_X, emissions control in electric power plant service. It consisted of a commercial scale demonstration of the technology, which was supported by two previous B&W projects:

> 1) An engineering feasibility study sponsored by the Electric Power Research Institute (EPRI) [21 analyzed the population of cyclone boilers to determine candidates for coal reburning. A major criterion was to ensure that sufficient residence time existed in the reburn zone for NO_X reduction to take place. On this basis, it was determined that the technology could potentially be applied to a majority of the cyclone boilers in the U.S., with NO_X emission reductions of.50 to 70%. This conclusion was based on the assumption that no site specific factors other than residence time existed which would preclude installation of a coal reburning system.
>
> 2) A pilot scale evaluation of reburn technology was performed under joint sponsorship of EPRI and the Gas Research Institute (GRI) [3]. This work evaluated the use of natural gas, oil, and coal as reburn fuels. All three fuels were found to perform well in achieving NO_X, reductions without deleterious effects on combustion efficiency.

Reburning with oil and gas can be used effectively for reducing NO_X emissions from cyclone boilers-, however, research has shown that coal is also suitable, with no detrimental effects on boiler performance. Thus, boilers using reburning for NO_X control can maintain 100% coal usage instead of switching to more expensive oil or gas and adding the requisite transportation, handling, and storage equipment. The fuel based cost savings for coal are somewhat offset by the necessity to Install new pulverizer capacity to produce fine coal for the reburning burners, since the coarse coal fired in the primary combustion zone is not suitable as a reburn fuel.

B. - Process Description

Cyclone Boilers

As illustrated in Figure 1, a cyclone furnace contains one or more cyclone burners, each connected to a horizontal water-cooled cylinder, which is commonly referred to as the cyclone barrel. Air and crushed coal are introduced through the cyclone burner into the cyclone barrel. Injecting the air tangentially creates a swirling motion which throws the larger coal particles against the barrel walls, where they are captured and burned in the molten slag layer which forms there. The smaller coal particles are burned in suspension. The flue gases and fly ash leave the cyclone and enter the main furnace chamber. The mineral matter melts, exits the cyclone furnace from the tap at the cyclone throat, and is dropped into a water-filled slag tank.

The cyclone furnace design has proved effective in accommodating a range of low-grade coals. The high intensity combustion, however, also promotes thermal NO_X production as well as conversion of fuel nitrogen to NO_X. Effective NO_X control for cyclone boilers is complicated because changes to reducing conditions in the high temperature turbulent mixing zone to suppress NO_X may very likely degrade the performance of the slag tap or create materials problems. Staged combustion within the cyclone barrel (which would be analogous to low-NO_X combustion modifications systems for pulverized coal-fired boilers) is not feasible; accordingly, technologies developed for NO_X reduction in other types of boilers are not applicable to cyclones.

NO_X emissions from cyclone boilers generally are in the range of 0.8 to 1.8 lb/106 Btu. Although cyclone boilers are exempt from Phase I NO_X emission control requirements under Title IV of the Federal Clean Air Act Amendments of 1990, the specified limits for Group I (dry bottom) boilers, controlled under Phase 1, are 0.45 to 0.50 lb/106 Btu. Emission standards for Group 2 (wet bottom) boilers, which include cyclone boilers, have not yet been established by the Environmental Protection Agency (EPA).

All of the cyclone boilers in the U.S. were designed or installed prior to 1971, that is, before New Source Performance Standard (NSPS) for boilers were established. The total generating capacity of the cyclone boilers in the U.S. is about 26,000 MWe, which represents about 8% of total U S capacity. Although this is equivalent to only 15% of pre-NSPS capacity, cyclone boilers are responsible for 21% of the NO_X emissions from all pre-NSPS coal-fired utility boilers. Although many cyclone boilers are 20 to 30 years old, utilities plan to operate these units for at least an additional 10 to 20 years.

Fundamentals of Reburning

Reburning employs multiple combustion zones in the furnace. These are defined as the primary (or main) combustion zone, the reburn zone, and the burnout zone, as illustrated in Figure 2. One of the most important variables in combustion is the ratio of air to fuel, and a major difference between the different combustion zones is the air/fuel ratio. The theoretical air requirement, also known as the stoichiometric requirement, can be calculated from the composition of the fuel. Actual combustion conditions are defined in terms of the stoichiometric ratio (SR), which is the actual air/ fuel ratio divided by the theoretical air/fuel ratio.

An SR greater than 1.0 represents oxidizing conditions, whereas an SR less than 1.0 represents reducing conditions. While oxidizing conditions favor NO_X formation, a reducing (oxygen deficient) atmosphere provides the conditions for NO_X reduction. In the reburn zone, the fuel breaks down to form hydrocarbon radicals, which react with the NO_X to form nitrogen gas, as illustrated in the following simplified equations:

$$\text{Fuel} + O_2 \text{ --- > } CH + \text{other species}$$

$$NO_X + CH \text{ --- > } N_2 + CO_2 + H_20$$

Although reburning takes place in a reducing atmosphere, it is conducted while the cyclone operates under normal oxidizing conditions, thereby minimizing any effect on cyclone performance. Thus reburning offers an especially promising method for NO_X control in cyclone boilers.

Reburning can use gas, oil, or coal as the reburn fuel. A separate technology development under the CCT program involves gas reburning for boilers whose primary fuel is coal. The Japanese have successfully used reburning, mostly on oil-fired units and on some gas-fired units. The Japanese reburning experience does not include cyclone burners.

Coal Reburning in Cyclone Boilers

In coal reburning, the majority of the fuel (70 to 80%) is burned in the main combustion zone. This zone should be operated at an SR greater than 1.0. Because many cyclones bum high sulfur, high iron content bituminous coals, the molten slag resulting from combustion at an SR of less than 1.0 would contain iron sulfide, which is highly corrosive. In this demonstration project, the cyclone burners were operated at an SR of 1.1 to 1.2, which represents 10 to 20% excess air.

The balance of the fuel (20 to 30%) is introduced in the reburn zone, above the cyclones, through separate burners. Air is also introduced through these burners. The reburning burners are similar to standard B&W wall-fired burners except that they are fired at an extremely low SR (less than 0 6). The SR in the reburn zone is in the range of 0.85 to 0.95, which was found to be the optimum SR for NO_X reduction.

The remaining combustion air (totaling 15 to 20%) is introduced through overtire air (OFA) ports. Sufficient residence time within this burnout zone is required for complete combustion. The OFA ports were designed with adjustable air velocity controls to enable optimization of mixing for complete fuel burnout prior to exiting the furnace. The SR in the burnout zone was about 1.15 to 1.20 in the demonstration runs. The coal reburning installation at Nelson Dewey Unit 2 is shown in Figure 3.

The demonstration project included the use of flue gas recirculation (FGR) to the reburn zone coal burners to impart higher momentum to the flames. This results in increased penetration, spreading, and mixing of the reducing reburn products with the main combustion gases, thereby maximizing NO_X reduction. The existing FGR system at Nelson Dewey Unit 2, used for steam temperature control, was modified for this purpose.

Reburning is the only in-furnace NO_X, control technology potentially- applicable to cyclone boilers. Other approaches such as staged air combustion are not appropriate because they rely on a heavily oxygen deficient atmosphere in the primary combustor. In a cyclone, this would increase the potential for tube corrosion, which is highly undesirable from a maintenance standpoint.

C. Project ObiectiveslResults

The primary objective of this demonstration project was to evaluate coal reburning technology for reducing NO_X emissions from power plants using cyclone burners at a commercial scale. This demonstration project was designed to confirm pilot scale results, as well as to resolve those technical, economic, and operational issues that are not adequately addressed in an engineering study or in pilot scale tests.

Two coals were used in the test program: Lamar, a medium sulfur Indiana bituminous coal, having a rank of high volatile A; and Decker, a low sulfur subbituminous coal from the Powder River Basin. Coal properties are given in Table 1.

The performance goals and results were as follows:

1. **Provide a technically and economically feasible means to achieve at lent 50% reduction of NO_X emissions.**

NO_X emissions reductions of 50 - 55% were achieved at full load, using both bituminous and subbituminous coals.

2. Achieve the desired NO_X emissions reduction with no substantial impact on other boiler emissions.

The targeted reduction in NO_X emissions was achieved with no significant adverse effects on other emissions, namely carbon monoxide (CO), unburned carbon (UBC), particulates, and hazardous air pollutants (HAPs).

3. Provide a system that maintains boiler reliability, operability, and steam production performance after retrofit.

There were no operational problems during the demonstration program at WP&L's Nelson Dewey Station. Slagging and fouling effects were minimal, and no tube wall corrosion was detected. This plant scale test of coal reburning was conducted successfully over a period of about one year. The utility has accepted the coal reburning system and continues to run it on Unit 2.

D. Environmental Performance

The demonstration program on coal reburning achieved the desired degree of NO_X, removal, while showing no adverse environmental impacts in terms of increased CO emissions, UBC, particulate emissions, stack plume opacity, or HAPs. Emission measurements were made by both B&W and Acurex, an independent testing organization, with generally good agreement between the results. The results are discussed in the following sections:

1. NO_X Emissions

The most critical factor in reducing NO_X emissions was found to be the reburn zone SR; the lower the SR, the greater the NO_X reduction. As shown in Figure 4, baseline operation when burning bituminous coal at full load with 10% excess air (SR of 1.10) corresponds to a NO_X, emissions level of about 600 ppm (at 3% 02). The desired 50% reduction to about 300 ppm NO_X was achieved at a reburn SR in the range of 0.85 to 0.90. A reburn SR of between 0.80 and 0.95 gives an even greater reduction in NO_X, but operating at such low levels of SR is undesirable because of excessive production of CO and unburned carbon. Similar performance was experienced when firing subbituminous coal. At full load and an SR of 0.85 to 0.90 NO_X emissions were reduced from a baseline level of about 560 ppm (at 3% 0.) to 250 ppm with reburning, representing a reduction of about 55%.

2. CO Emissions

For the bituminous coal, baseline emissions of CO were 50 to 60 ppm, increasing to 90 to 100 ppm during reburn operation. Likewise for the subbituminous coal, baseline CO emissions ranged from 28 to 48 ppm, increasing to 45 to 84 ppm under reburning conditions. These higher CO levels me not considered significant in the power generating industry, where CO emissions as high as about 100 ppm are acceptable.

3. Particulates

Coal reburning in cyclone furnaces results in increased quantities of fly ash leaving the boiler since a smaller proportion of the ash is removed as slag. This results in a greater particulate load on the electrostatic precipitator (ESP) or baghouse. The precipitator at Nelson Dewey Unit 2 has a specific collection area (SCA) of 272 fi'/1000 actual ft3/min. The SCA is a parameter of interest because a given facility might overtax its existing unit due to a change in the proportion of fly ash and bottom ash. In the demonstration project, minimal increases were experienced in precipitator outlet particulate loading, and there was no change in opacity levels between baseline conditions and optimized reburning operation. This was the result of several factors, including: a) no change in fly ash resistivity, b) slightly larger fly ash mean particle size distribution with reburning, and c) improved ESP efficiency. (The efficiency improved when burning bituminous coal, but there was no change in the case of subbituminous coal).

4. Hazardous Air Pollutants

The demonstration project results indicate that coal reburning has no significant effect on emissions of trace metals, sulfates, or hydrocarbons. There is also no effect on leachate toxicity.

E. Post Demonstration Achievements

WP&L continues to operate the Nelson Dewey unit with coal reburning. As a precaution, fireside corrosion is being monitored by annual tubewall thickness measurements to confirm the favorable results found in the one-year demonstration program.

The long term testing with bituminous coal in the demonstration project showed no adverse effects on boiler performance. This will continue to be verified by WP&L through annual heat rate determinations on Nelson Dewey Unit 2.

An operating database is being established which will provide useful information for additional process improvements. B&W has done a number of engineering feasibility studies on coal reburning at the request of various electric utilities. No installations have been ordered as yet.

III. Operating Capabilities Demonstrated

A. Size *of Unit Demonstrated*

Host Site

The demonstration project was conducted at WP&L's Nelson Dewey Station, Unit 2. The unit is a nominal 100 MWe radiant-type boiler, manufactured by B&W, with three cyclone furnaces. Actual plant capacity is about 110 MWe. At this capacity, the results are considered representative of commercial scale operation.

Background Studies

As a follow-up to the previous engineering feasibility study (21, the cyclone boiler population was surveyed to assess the suitability. of these units for retrofitting coal reburning technology. The population was first categorized according to furnace arrangements (single and opposed burners) and generating capacities (40 to 1150 MWe). Specific representative units from each category were then selected for a more detailed evaluation.

Based on the earlier modeling efforts, it was determined that the major criterion to predict whether coal reburning could be successfully applied is gas residence time in the furnace. In addition, space availability at the locations for installation of reburn burners and OFA ports was examined. It was found that most of the existing cyclone boilers in the U.S. would be candidates for coal reburning. Only the smallest (<80 MW.) single burner units appear to be unsuitable, because of insufficient reburn zone residence time.

Before embarking on the plant scale tests, B&W's 6 million Btu/hr Small Boiler Simulator (SBS) was utilized to examine the feasibility of coal reburning for NO_X control and to identify any side effects. The SBS was run at conditions simulating those at Nelson Dewey Unit 2. This pilot plant program investigated NO_X reduction performance as a function of several operating variables, including reburn coal fineness, reburn zone SR, and FGR rate. Also studied were the effects of coal reburning on unburned carbon losses (UBCL), furnace exit gas temperature, fireside tubewall corrosion, fireside deposition, and ESP performance. Since no major operating problems were encountered, these pilot scale investigations provided assurance of the success of the plant scale demonstration.

The SBS tests also served to elucidate the mixing requirements for the reburn and burnout zone gases, and provided data for the mathematical and physical flow models used for predicting the combustion and heat transfer performance of the commercial scale unit. This modeling capability is one of the major accomplishments of the CCT demonstration program.

B. *Performance Level Demonstrated*

Overall Accomplishments

Reductions of 50% or more in NO_X emissions were achieved, using both Lamar bituminous coal and Powder River Basin subbituminous coal as fuels. The results are discussed in greater detail in subsequent sections.

In the case of the subbituminous coal, reburning eliminated the need for derating the unit. Usually, when switching from a higher heat content eastern coal to a lower heat content western coal, the boiler must be derated because of coal handling and furnace heat release limitations. However, by supplying about 25 to 30% of the boiler heat input to the reburn zone, the total heat input can be maintained or even increased. If this performance feature prevails generally, it would constitute a significant advantage for coal reburning in cyclone boiler NO_X control applications.

Successful reburn operation was achieved at a turndown ratio of 66% when burning bituminous coal and 63% for subbituminous coal. These turndown ratios exceeded expectations, and indicate excellent process flexibility.

It was found that coal reburning requires accurate and responsive control of both air and fuel flow rates to various regions of the boiler. A distributed control system (DCS) is essential for air/ fuel ratio control. Accurate measurement and control of both fuel and air are critical to maintaining an acceptable SR in both the cyclone burner and the reburn zone. This is especially important for large, open windbox cyclone boilers, for which it may not be feasible to accurately measure the air flows to individual cyclones.

It was also found that effective in-furnace mixing between the gases from the cyclone and reburning burners is a key factor in obtaining optimum results. Mathematical modeling is an extremely useful tool to help in this determination, and the actual results proved to be consistent with predicted performance.

NO_X Emissions Reduction

The NO_X emissions reduction results with bituminous coal are summarized in Table 2. At full load, uncontrolled NO_X emissions averaged 609 ppm (0 82 lb/1 06 Btu). With coal reburning NO_X emissions decreased to 290 ppm (0.39 lb/106 Btu). This represents a 52.4% reduction. The percentage reduction in emissions is less at reduced boiler loads. The results for the subbituminous coal are also included in Table 2. Reburning resulted in a 55.4% reduction in NO_X emissions at full load, with only a minor percentage reduction at lower loads.

Based on the results of this demonstration project, coal reburning should provide 50 to 60% reduction in NO_X emissions from cyclone boilers. Applying this technology to the majority of the existing cyclone boilers in the U.S. would achieve a significant reduction in total NO_X, emissions.

C. Major Operating Variables Studied

Effect of Rue Gas Recirculation

As mentioned previously, the demonstration project design provided for FGR to the reburn zone coal burners. It was found at Nelson Dewey Unit 2 that operating with FGR is essential for preventing air infiltration into the flue gas duct. Without FGR to the reburn burners it was not possible to achieve the SR required for optimum NO_X reduction, due to higher O_2 levels in the reburn zone. Whether or not this effect is site specific remains to be determined.

In the plant scale coal reburning tests an interesting observation was that, above a minimum FGR rate, further increases had no effect on the degree of NO_X reduction. This is in contrast to SBS pilot scale results, where NO_X emissions reduction was enhanced with increasing FGR rate, presumably due to better penetration and mixing in the SBS unit. This issue requires further study.

Effect of Stoichiometric Ratio

Both short term and long term field testing results using coal reburning verified the predictions based on SBS testing: a reburn zone SR of 0.85 to 0.95 is optimum for effective NO_X, reduction over the range of boiler loads tested. At higher values of reburn zone SR, the NO_X, reduction performance drops off rapidly.

It should be noted that about 25 to 30% of the total heat input was required in the reburn zone to achieve the NO_X reduction goal. This contrasts with gas reburning, where only 15 to 23% of the total heat input is required as reburn fuel for effective NO_X, emissions reduction from coal fired boilers. This difference may be attributed to (1) the fact that gas injectors, rather than burners, have been used in field demonstrations of gas reburning and (2) the faster rate of combustion of natural gas compared to coal.

D. Boiler Impacts

Effect on Boiler Capacity

Boiler capacity was not compromised by coal reburning Because of problems with flame stability at lower capacity, the lowest operable load when burning bituminous coal was 37 MWe with reburning compared with 30 MWe under baseline conditions. When burning subbituminous coal under reburning conditions, the minimum load was 41 MWe. As stated previously, these figures correspond to an average turndown ratio of about 65%, which represents excellent process flexibility.

At intermediate and full load operation, coal reburning had no effect on boiler output when using bituminous coal. In contrast, with the western low sulfur subbituminous coal, it was possible to increase the maximum load from 110 MWe to I 18 MWe. Operation at even higher loads might have been possible but was not achieved due to feedwater pump capacity limitations.

Effect on Boiler Efficiency

Coal reburning resulted in a minor loss in boiler efficiency due to unburned carbon loss (UBCL), but this had no major effect on overall power plant efficiency. This effect was different for the bituminous and subbituminous coals. For the bituminous coal, with 30% of the heat input in the form of pulverized coal, fly ash was found to be as much as 40% of the total ash, compared to about 25% under baseline conditions. As shown in Table 3, the reduction in boiler efficiency attributed to UBCL ranges from 0 to 1.5%.

There were some additional efficiency losses with the subbituminous coal under coal reburning conditions. These are attributable to increased dry gas losses resulting from higher flue gas temperatures caused by some fouling in the economizer. Dry gas losses, which represent heat not recovered in the air heater, are smaller than those experienced with gas reburning for NO_X control (1.0-1.5%), but with coal reburning there is a small additional efficiency loss due to power consumption by the reburn coal mill pulverizer.

Effect on Furnace Exit Gas Temperature

There was concern, based on the modeling predictions, that the furnace exit gas temperature would increase with reburn operation, which could result in potential problems with steam temperature control in the convective pass. However, it was found that exit gas temperature actually decreased with coal reburning, thereby eliminating these concerns. B&W hypothesizes that this unexpected result may be due to changes in char emissivity with reburn operation. The effect is not fully understood, and will require further study before extrapolation to other units.

Effect on Tube Wall Slagging and Fouling

Under long term testing conditions, there was little or no effect of coal reburning on slagging and fouling, which are essentially fuel dependent. Additionally. detailed ultrasonic tube wall thickness measurements made before and after one year of reburn operation did not reveal any increase in tube wall corrosion rate.

Other boiler operating characteristics were not significantly affected. These included surface cleanliness, which determines the frequency of sootblowing, and spray flow requirements for superheat and reheat steam temperature control.

E. Commercialization of the Technology

Modeling Capabilities

An important aspect of the demonstration project was the development of significant capabilities in mathematical and physical flow modeling. Simultaneous modeling of the cyclones, reburn burners, and OFA ports within a single boiler was a considerable technical challenge. B&W met this challenge and provided the means to extrapolate coal reburning results to other boilers. The modeling effort had two objectives:

- To characterize the flow patterns for the baseline boiler configuration and establish mathematical and physical flow models as benchmarks based on measured gas velocities in Nelson Dewey Unit 2.
- To simulate reburning conditions and to assist in the design of the reburning system.

B&W developed the appropriate models and correctly predicted that Nelson Dewey Unit 2 would have sufficient residence times in the reburn and burnout zones for successful reburning using coal. This provides confidence in the models. However, since jet penetration and mixing may be more of an issue with larger boilers, scale-up needs to be demonstrated.

The size, number, and location of reburning burners and OFA ports required to control mixing in the reburn and burnout zones of the boiler were based on model predictions. The furnace flow patterns, mixing, and residence times obtained at B&W's SBS pilot scale unit were evaluated using B&W's FORCE and CYCLONE models for both baseline and reburning conditions tested in the SBS. These mixing simulations provided the criteria for the design of the full-scale coal reburning system. Combustion and heat transfer predictions were made using B&W's FORCE and FURMO computer models. The results obtained in the full-scale tests were generally in good agreement with the performance predicted on the basis of the models.

One outcome of this project was demonstration of the validity of B&W's design methodology for coal reburning. These database and modeling capabilities should readily allow extrapolation to other commercial applications of this technology.

The success of the coal reburning test program at WP&L's Nelson Dewey Unit 2 represents a significant accomplishment in NO_X control. B&W now offers coal reburning technology applied to cyclone boilers on a commercial scale, with guarantees determined on a site-specific basis

Application to Future Projects

Coal reburning will likely be deployed to other cyclone boilers and, possibly, to other coal fired boilers in the near future. Once the technology is applied to other sites, further investigation in the following areas would provide additional understanding of the process:

- Effect of uncontrolled NO_X level. The demonstration project at Nelson Dewey Unit 2 was highly successful in reducing NO_X, emissions from 0.82 lb/1 06 Btu to 0.39 lb/106 Btu at full load, a reduction of over 50%. Presumably a similar or possibly even higher degree of NO_X reduction can be achieved when applying coal reburning to other cyclone boilers having higher levels of uncontrolled NO_X, emissions, which, as indicated previously, can range as high as 1.8 lb/106 Btu. Additional commercial scale testing would be required to confirm this projection.

- Effect of coal reburning on furnace exit gas temperature. It is uncertain whether the favorable results of a decrease in exit gas temperature with coal reburning found in this test program are generally applicable to other cyclone boilers. Future commercial applications of this technology would provide opportunities to better define this relationship.

- Tubewall corrosion. Although no measurable tubewall corrosion was observed during the demonstration, fireside tubewall corrosion is being monitored by WP&L in their ongoing operation to confirm this favorable result.

- Effect of FGR on NO_X reduction. Contrary to expectations, increasing the rate of FGR in the reburn zone did not enhance NO_X reduction. This may be due to the high degree of penetration, coverage, and mixing of the reburn flames with the main gas flow at the standard FGR rate. The need for FGR in the reburn burners to seal the main FGR ports at Nelson Dewey Unit 2 may be site specific and would require testing on other units before a general recommendation can be made.

- Modeling. Although B&W achieved success in process modeling as part of this project. it is recognized that the predictive capability of the models is limited. At present, since the models do not incorporate chemical kinetics of NO_X formation or reduction, NO_X emissions cannot be predicted directly for future commercial applications of coal reburning.

IV. Market Analysis

A. *Potential Markets*

Coal reburning technology is applicable to most of the cyclone boilers in the U.S., except for smaller units (<80 MWe). Typical NO_X, emissions from uncontrolled cyclone boilers range from 0.8 to 1.8 lb/l0^6 Btu. As indicated previously, the total power generating capacity of cyclone boilers in the U.S. is about 26,000 MWe. As shown below, coal reburning appears to be a cost effective approach to NO_X control in cyclone boilers. Assuming that 1) 90% of the U.S. cyclone capacity is retrofitted with coal reburning, 2) the average uncontrolled NO_X emissions rate is 1.3 lb/106 Btu, 3) power plant capacity factor is 65%, and 4) 50% NO_X removal is achieved via coal reburning, the reduction in NO_X emissions achieved by this technology would be in excess of 400,000 tons/yr.

B. *Economic Assessment for Utility Boiler Applications*

Coal Reburning Costs

Based upon data returned from the demonstration, the cost of coal reburning technology appears to be in a range, which is acceptable in the current marketplace. B&W has prepared economic estimates for commercial utility applications of coal reburning at two plant sizes, assuming 50% NO_X, emissions reduction. For a 110 MWe. power plant, the same size as Nelson Dewey Unit 2, total capital cost for coal reburning is estimated at $66/kW. This figure decreases to $43/kW at a capacity of 605 MWe. Ten-year levelized costs are 2.4 mills/kWh at 110 MWe. and 1.6 mills/kWh at 605 MWe. These levelized costs correspond to $1075/ton of NO_X, removed at I 10 MWe. and $408/ton of NO_X removed at 605 MWe.

Site-specific factors will impact the economics of coal reburning retrofits on existing cyclone boilers. These factors include:

- The state of existing controls.
- The availability of FGR. In this demonstration project, it was necessary to use FGR to prevent air leakage into the reburn zone, thereby maintaining reducing conditions in that zone. A number of operating utilities have removed FGR fans. For efficient NO_X, control with coal reburning, new FGR fans may be required.
- The availability of space to locate the pulverizers, reburn burners, and OFA ports within the existing structure.
- The scope of coal handling equipment modifications or additions required to supply fuel to the reburn burners.

- Sootblowing capacity and coverage.
- Boiler tube corrosion potential.
- ESP or other flue gas cleanup equipment capacity.
- Boiler circulation considerations.
- Steam temperature control capabilities.

Additional investment and operating costs could be incurred in conjunction with any of the above factors.

Comparison with Gas Reburning

As mentioned previously, reburning with gas or oil is an alternative to coal reburning for NO_X, reduction in cyclone boilers. Economic comparison of gas reburning versus coal reburning involves a) the cost differential between gas and coal, b) the capital and operating costs of pulverizers required for the coal reburning fuel for cyclone boilers and other coal handling and storage equipment, and c) the relative impacts on boiler efficiency.

Although comparison between these technologies is highly site specific, in general, the capital cost of coal reburning is higher than that of gas reburning, primarily because of the cost of the coal pulverizers and ancillary equipment when using coal reburning. On the other hand, if natural gas is not available, the cost of installing a supply line from the nearest pipeline to the power plant must be taken into account in any economic comparison. Of the 26,000 MWe capacity represented by coal-fired cyclone boilers, only about 8% of this capacity had natural gas available at these power generation facilities in 1997. Therefore, natural gas availability will likely constrain rapid deployment of gas reburning for cyclone boilers.

Comparison of levelized costs for coal reburning and gas reburning is sensitive to the price differential between coal and gas. At present, coal is significantly cheaper than gas on a heat content basis. This price differential is a significant factor in the selection of reburning fuel, and is expected to widen over the next 15 years in favor of coal [10].

Alternative NO_X Control Technologies

Reburning with coal, gas, or oil involves combustion modification. Other competing technologies for cyclone boiler NO_X control are flue gas treatment processes such as selective catalytic reduction (SCR) or selective noncatalytic reduction (SNCR). SCR has the capability of a larger percentage of NO_X reduction than coal reburning. but is more expensive. Long term U.S. experience with SCR is being gained which should demonstrate its applicability to cyclones and other coal fired boilers. Issues being addressed include catalyst deactivation, plugging, and increased pressure drop.

SNCR appears to be more of a "niche" technology. Because of its low capital and high operating costs, it is particularly applicable to smaller, non-baseloaded units. Also involved in selection of SNCR are residence time and furnace temperature profile considerations. Further work is needed to establish the performance of SNCR in terms of acceptable NO_X reduction with low levels of ammonia slip under the typical load cycle of cyclone fired utility boilers.

V. Conclusions .

A successful field demonstration of coal reburning for NO_X control on a representative commercial cyclone boiler has been performed. All project goals were achieved, namely 50% or higher NO_X reduction at full load without significant adverse effects on boiler operation or other emissions. The demonstration project produced valuable data for future design improvements. Specific findings include the following:

- The optimum stoichiometric ratio in the reburn zone is 0.85 to 0.95.
- Successful operation of coal reburning requires flue gas recirculation; however, more data are needed to define the rate required.
- Coal reburning requires accurate and responsive control of both air and fuel flow rates to various regions of the boiler. A distributed control system is essential for air/fuel ratio control.
- Effective in-furnace mixing between the gases from the cyclone and reburning burners is a key factor in obtaining optimum results.
- Mathematical modeling of the reburning process has proven valuable for predicting mixing, combustion, and heat transfer for design purposes.
- A turndown ratio of about 65% was achieved, which is acceptable for power plant operation.
- ESP performance is not affected by coal reburning; opacity and particulate emissions are essentially unchanged.
- When firing subbituminous coal at the test facility, coal reburning eliminated the need for boiler derating.
- Coal reburning results in enhanced flame stability when firing subbituminous coal.
- Operational flexibility is improved through use of coal reburning.
- Coal reburning results in a slight, but acceptable, reduction in boiler efficiency.
- Coal reburning has no impact on boiler cleanliness.
- The cost of coal reburning technology is acceptable in the current marketplace and is expected to remain competitive in the future.

In summary, coal reburning is an economically competitive technology for controlling NO_X in cyclone boilers. An effective and apparently robust technology for cyclone boiler NO_X control has been demonstrated in this project. Reburning, which is the sole combustion control technology applicable to cyclone boilers, is also possible with natural gas as an alternative to coal. The relative economics are site specific and depend heavily on the price differential between coal and natural gas. With an expected increased price differential between natural gas and coal in future years, coal reburning is expected to remain a viable option for controlling NO_X in cyclone boilers.

Ownership of this coal reburning retrofit emission control installation has been transferred to the host, WP&L, who will continue operating the technology on a routine basis. Information gathered in this ongoing operation will benefit future commercial. applications.

VI References

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[5] Technical Report TR-91-101, "Nelson Dewey Cyclone Reburn -- Baseline Environmental Tests," Acurex Corporation, March 27, 1991.

[6] Environmental Monitoring Plan, "Babcock & Wilcox Demonstration of Coal Reburning for Cyclone Boiler NO_X Control," Acurex Corporation, Project 8408, November 18, 1991.

[7] Technical Report 8408-92-01, "Quality Assurance Project Phase III Testing for Cyclone Boiler NO_X Control," Acurex Corporation, January 1992.

[8] Test Report, "Hazardous Air Pollution Monitoring: Demonstration of Coal Reburning for Cyclone Boiler NO_X Control," Acurex Corporation, June 1993.

[9] Technical Report TR-93-101, "Nelson Dewey Cyclone Reburn -- Optimization and Performance Environmental Tests," Acurex Corporation, June 1993.

[10] "Coal Data: A Reference," Energy Information Administration, November 1991.

TABLES

TABLE I

COAL PROPERTIES

	Bituminous Coal	**Subbituminous Coal**
Source	Indiana	Powder River Basin
Name	Lamar	Decker
***Proximate Analysis,** %*		
Moisture	14.6	24.7
Volatile Matter	37.9	33.7
Fixed Carbon	43.7	38.0
Ash	-3.8	3.6
Total	100.0	100.0
Gross Heating Value, *Btu/lb*	11811	9384
Ultimate Analysis, %		
Carbon	66.0	54.6
Hydrogen	4.6	3.8
Sulfur	1.7	0.3
Oxygen	7.9	12.3
Nitrogen	1.3	0.7
Moisture	14.7	24.7
Ash	-3.8	3.6
Total	100.0	100.0

TABLE 2

AVERAGE NO$_X$ EMISSIONS REDUCTION ACHIEVED BY COAL REBURNING

Bituminous Coal
Reburn Zone Stoichiometric Ratio 0.85 - 0.90

Load, MWe	NO$_X$ Emissions, ppm (lb/10^6 Btu)		Reduction from Baseline, %
	Uncontrolled	Controlled	
110	609(0.82)	290(0.39)	52.4
82	531 (0.72)	265(0.36)	50.1
60	506(0.69)	325(0.44)	35.8
37	600(0.81)	400(0.54)	33.3

Subbituminous Coal
Reburn Stoichiometric Ratio 0.86 - 0.90

Load, MWe	NO$_X$ Emissions, ppm (lb/10^6 Btu)		Reduction from Baseline, %
	Uncontrolled	Controlled	
110	561 (0.76)	250(0.34)	55.4
82	480(0.65)	230(0.31)	52.1
60	464(0.63)	220(0.30)	52.6
41	-- (--)	210(0.28)	--

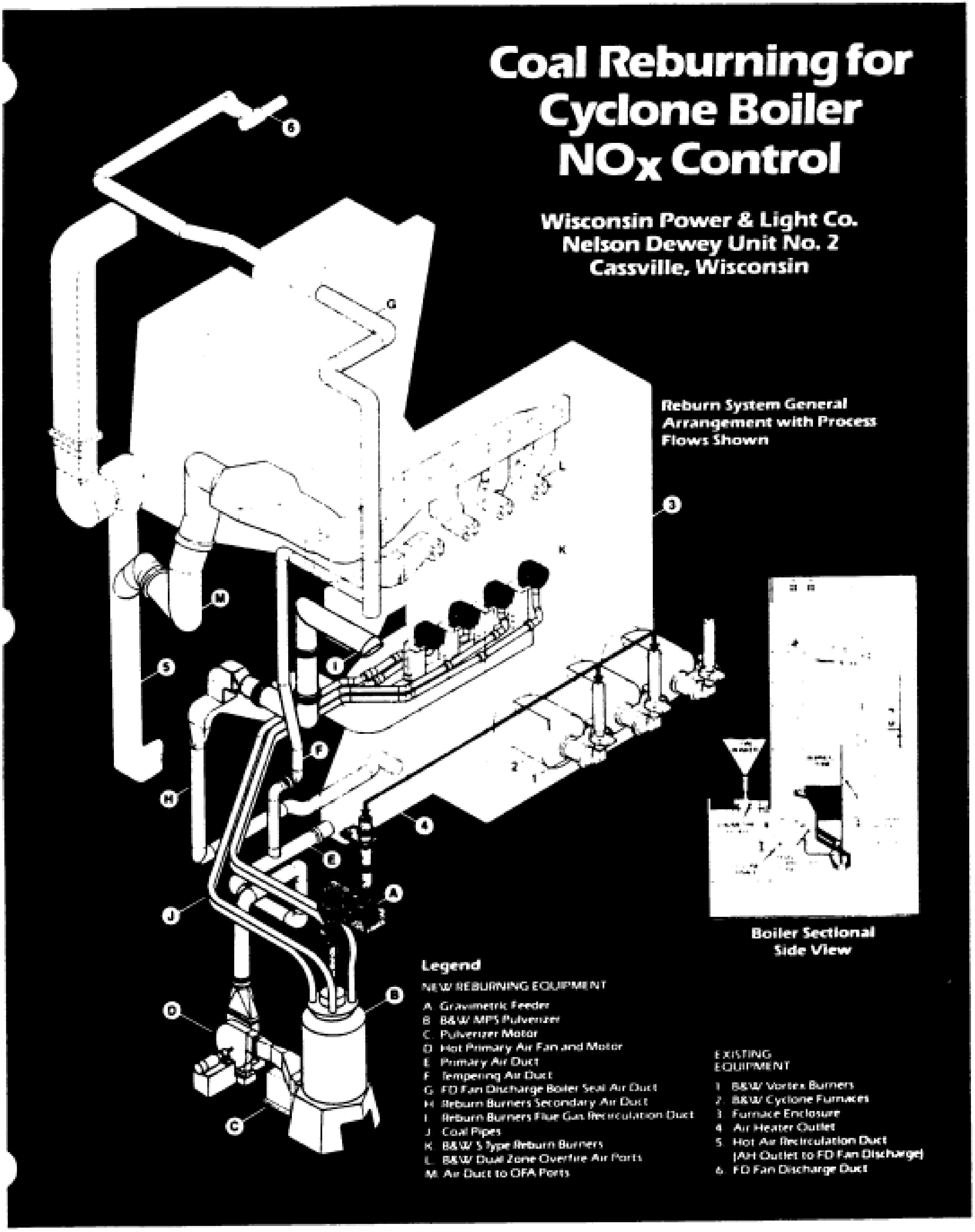
TABLE 3

UNBURNED CARBON LOSSES

% of Full Load	Reduction in Boiler Efficiency Due to Unburned Carbon, %	
	Bituminous Coal	**Subbituminous Coal**
100	0.10	0
75	0.25	0.20
50	1.50	0.30

FIGURES

Figure 1



Coal Reburning for Cyclone Boiler NO_x Control

Wisconsin Power & Light Co.
Nelson Dewey Unit No. 2
Cassville, Wisconsin

Reburn System General Arrangement with Process Flows Shown

Boiler Sectional Side View

Legend

NEW REBURNING EQUIPMENT

- A. Gravimetric Feeder
- B. B&W MPS Pulverizer
- C. Pulverizer Motor
- D. Hot Primary Air Fan and Motor
- E. Primary Air Duct
- F. Tempering Air Duct
- G. FD Fan Discharge Boiler Seal Air Duct
- H. Reburn Burners Secondary Air Duct
- I. Reburn Burners Flue Gas Recirculation Duct
- J. Coal Pipes
- K. B&W S Type Reburn Burners
- L. B&W Dual Zone Overfire Air Ports
- M. Air Duct to OFA Ports

EXISTING EQUIPMENT

1. B&W Vortex Burners
2. B&W Cyclone Furnaces
3. Furnace Enclosure
4. Air Heater Outlet
5. Hot Air Recirculation Duct (AH Outlet to FD Fan Discharge)
6. FD Fan Discharge Duct

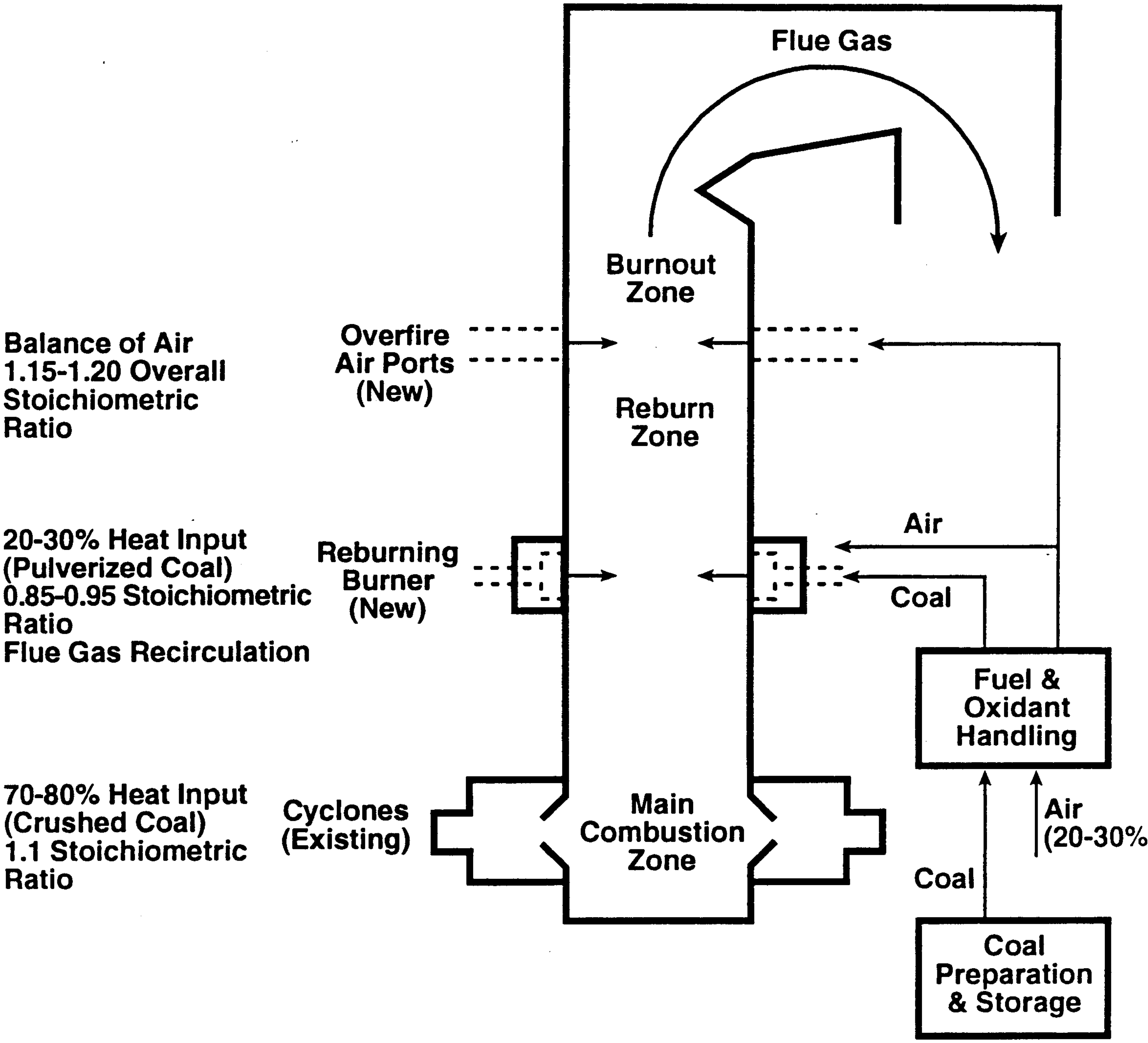


Figure 2. Schematic of Coal Reburning Process

Figure 3

Cyclone Furnace

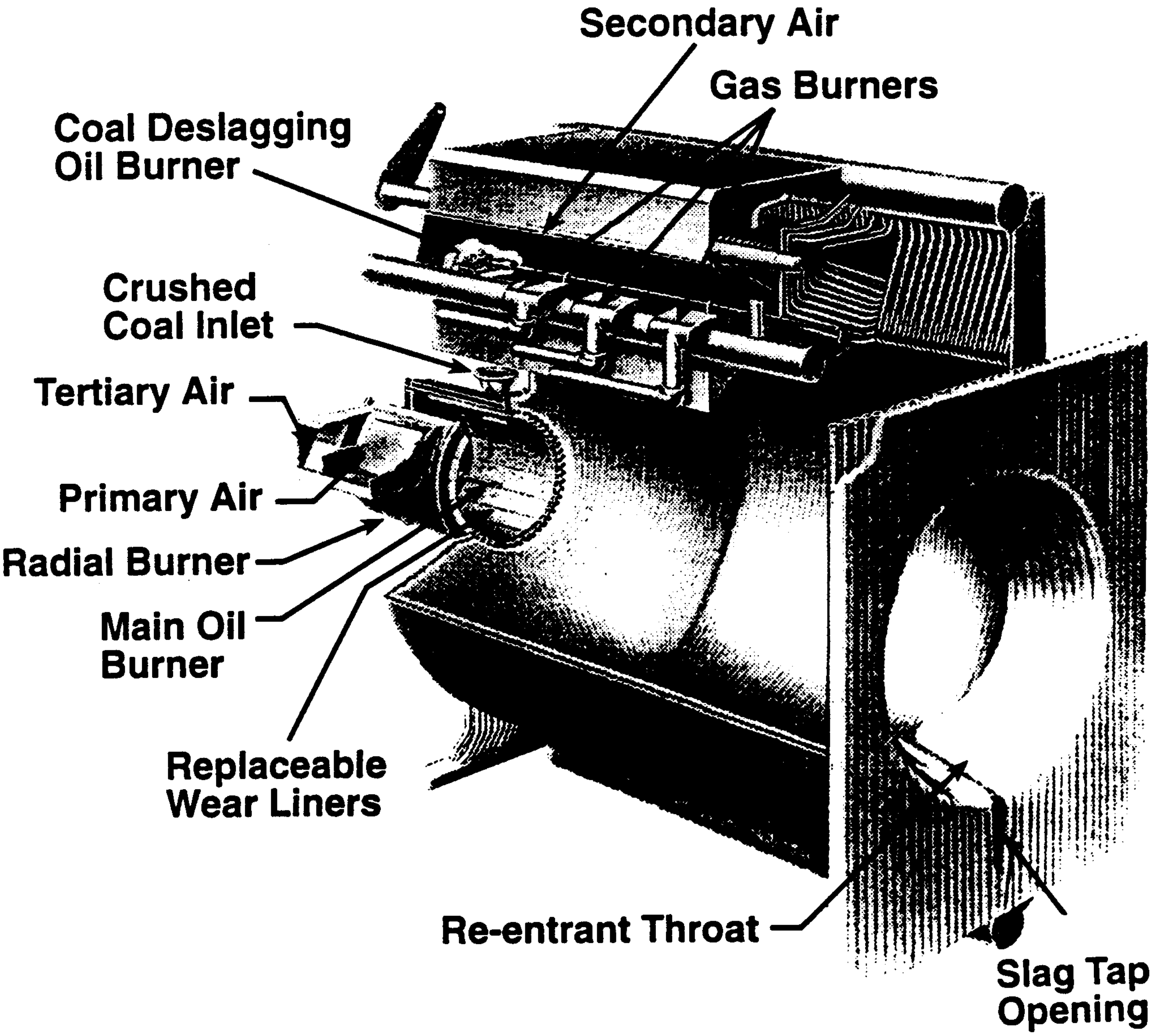


Figure 4

Coal Reburning Plant Scale Results
Lamar Bituminous Coal
Full Load Operation - 110 MW