DOE/FE-0442

ENERGY AND ENVIRONMENTAL RESEARCH CORPORATION

EVALUATION OF GAS REBURNING AND LOW-NO_x BURNERS ON A WALL-FIRED BOILER

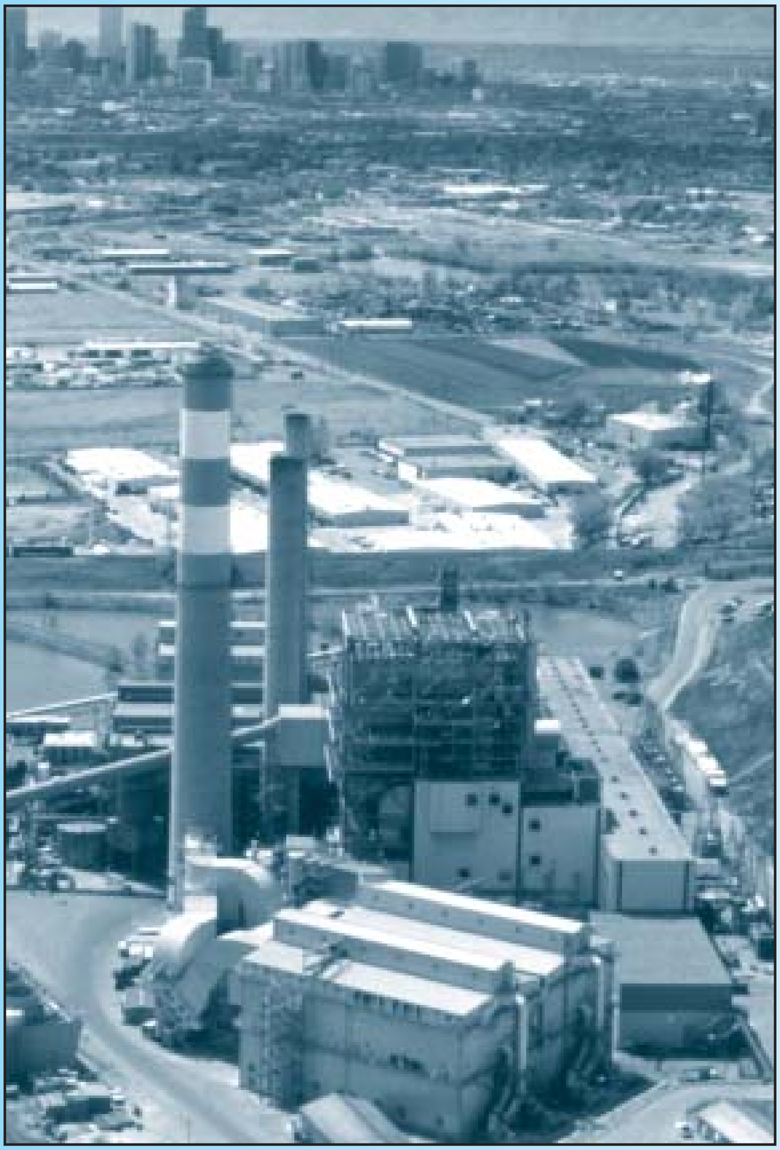
PROJECT PERFORMANCE SUMMARY

CLEAN COAL TECHNOLOGY DEMONSTRATION PROGRAM

OCTOBER 2001

Energy and Environmental Research Corporation

Evaluation of Gas Reburning and Low-NO_x Burners on a Wall-Fired Boiler



Project Performance Summary
Clean Coal Technology Demonstration Program

Environmental Control Devices

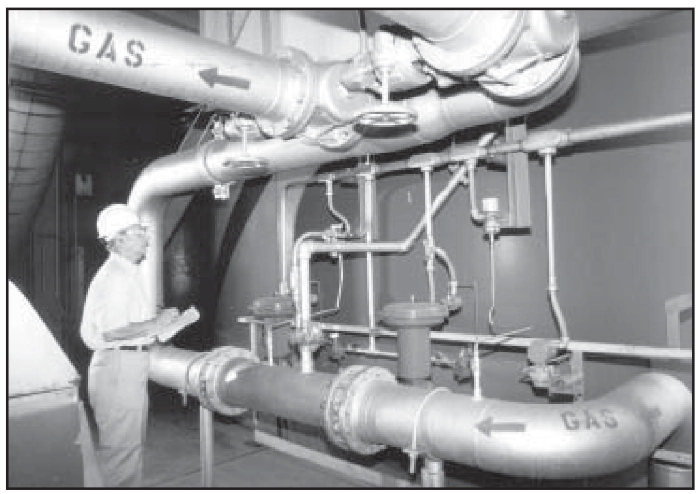
Evaluation of Gas Reburning and Low-NO_x Burners on a Wall-Fired Boiler

- Gas reburning (GR) enables optimum low-NO_x burner (LNB) performance and significantly increases overall NO_x reduction.
- Together GR and LNB offer a low-cost alternative to selective catalytic reduction (SCR) for deep NO_x reduction.

Overview

The project is part of the U.S. Department of Energy's (DOE) Clean Coal Technology Demonstration Program (CCTDP) established to address energy and environmental concerns related to coal use. DOE sought cost-shared partnerships with industry through five nationally competed solicitations to accelerate commercialization of the most advanced coal-based power generation and pollution control technologies. The CCTDP, valued at over $5 billion, has leveraged federal funding twofold through the resultant partnerships encompassing utilities, technology developers, state governments, and research organizations. This project was one of 13 selected in December 1989 in response to the Program's third solicitation.

The Energy and Environmental Research Corporation (EER), with the Public Service Company of Colorado (PSCo) as the host utility, demonstrated a co-application of two NO_x control technologies—low-NO_x burners (LNB) and gas reburning (GR). The need to bring much of the nation into compliance with National Ambient Air Quality Standards for ozone provided the impetus for the demonstration. NO_x is a precursor to the formation of ground level ozone in the presence of sunlight and summer temperatures. Bringing ozone "non-attainment" areas into compliance was projected to require NO_x emission reductions far below the levels established under Title IV of the Clean Air Act Amendments of 1990, which dealt with acid rain. The only available technology at the time of the demonstration capable of achieving the needed deeper NO_x reductions was selective catalytic reduction (SCR)—an expensive post-combustion technology.



In-plant natural gas distribution lines for gas reburning

The thrust of the demonstration was integration of EER's GR technology with a relatively established LNB—Foster Wheeler Energy Corporation's (FWEC) Controlled Flow/Split Flame (CF/SF) burner. The project largely achieved its performance goals. Targets of 70% NO_x reduction without adverse effects on boiler or plant performance were met, but optimum long-term operational set points for the GR-LNB technology resulted in 64% NO_x reduction. GR complemented LNB performance, bringing carbon monoxide and unburned carbon emissions down to acceptable levels at LNB settings designed for maximum NO_x reduction without compromising boiler performance. GR also reduced sulfur dioxide (SO_2) and carbon dioxide (CO_2) emissions and the dust loading to the particulate removal system.

GR-LNB achieved 64% NO_x reduction at natural gas heat inputs of only 12.5%. Capital costs for a commercial application at 300-MWe scale are estimated to be as low as $26/kW ($1996) for plants with immediate access to a gas pipeline. Because of the successful performance demonstrated by the technology, PSCo retained the GR-LNB system for commercial service.

The Project

The objective of the project was to demonstrate the commercial readiness of the GR-LNB technology for application to pre-NSPS (New Source Performance Standards) utility boilers. These older boilers have one of several common firing configurations with the wall-fired type being the most common. The specific goal was to demonstrate that high levels of NO_x reduction (70%) could be achieved with minimal impacts to other areas of unit operation including carbon burnout, furnace slagging or corrosion, convective pass fouling, steam capacity and steam conditions.

LNBs are designed to create less NO_x than conventional burners. However, the NO_x control achieved is limited to 30-50%. Also, typically, when LNBs are operated at set points that achieve maximum NO_x reduction, carbon monoxide (CO) emissions and unburned carbon (UBC) levels are above acceptable standards. This occurrence prompts readjustment and lower NO_x reduction. Gas reburning enables LNB operation at optimum NO_x reduction set points, as well as further reducing NO_x emissions through staged fuel combustion. When combined, GR and LNB work in harmony to both minimize NO_x emissions and maintain acceptable levels of CO and UBC.

The GR-LNB project test program was developed to first optimize the system through short parametric tests and then operate it for an extended period in a normal dispatch mode. Optimum conditions are defined as those providing the maximum benefit (reduction of NO_x emissions) for the minimum cost (natural gas usage) when operating within established boiler constraints. Over 4,000 hours of operation were achieved, providing substantial data.

Following long-term testing, it was determined that the system could operate effectively without a flue gas recirculation (FGR) system, and the GR system was modified. The modified configuration, referred to as Second Generation Gas Reburning, was tested in conjunction with an extension to the program granted by DOE. Specific modifications included the removal of the FGR system, installation of high-velocity natural gas jets, and installation of double concentric overfire air ports for enhanced CO burnout.

Project Sponsor
Energy and Environmental Research Corporation

Additional Team Members
Public Service Company of Colorado – cofunder and host
Gas Research Institute – cofunder
Colorado Interstate Gas Company – cofunder
Electric Power Research Institute – cofunder
Foster Wheeler Energy Corporation – technology supplier (LNBs)

Location
Denver, Adams County, CO
(Public Service Company of Colorado's Cherokee Station, Unit No. 3)

Technology
Energy and Environmental Research Corporation's Gas-Reburning (GR) system
Foster Wheeler Energy Corporation's Low-NO_x Burners (LNB)

Plant Capacity
172 MWe (gross), 158 MWe (net)

Coal
Colorado bituminous, 0.40% sulfur, 1.51% nitrogen

Demonstration Duration
October 1992 – January 1995

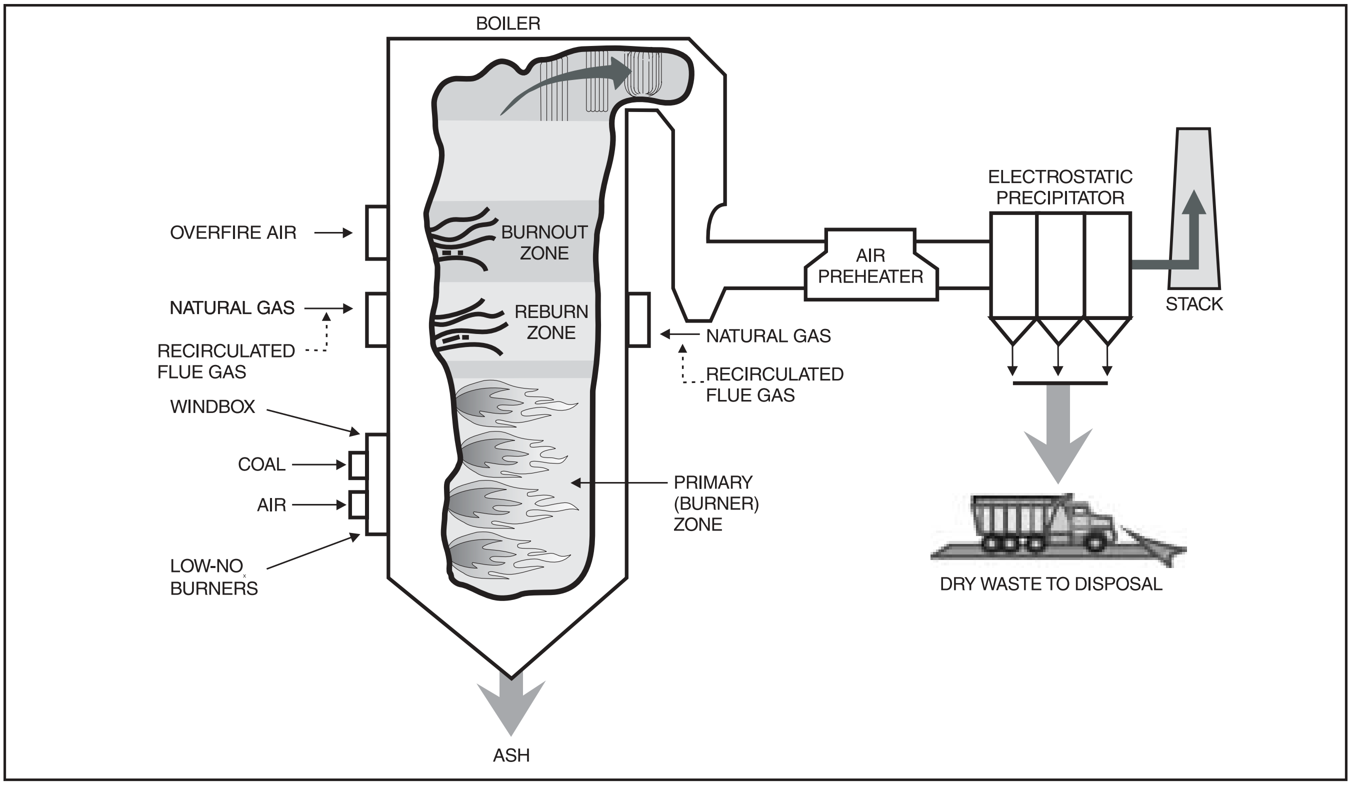
Project Funding

Total Project Cost	$17,807,258	100%
DOE	$8,895,790	50%
Participant	$8,911,468	50%

Main natural gas shut-off valve for the plant

The Technology

Figure 1. GR-LNB Configuration



The technology is a co-application of two previously demonstrated technologies, GR and LNBs. GR complements LNB by allowing it to operate at low stoichiometric ratios, enabling low NO_x emissions without exceeding acceptable CO and UBC levels — under 200 ppm for CO and 4.5% for UBC. A stoichiometric ratio (SR) of 1.0 is the theoretical value at which there is just enough oxygen in relation to fuel to complete combustion.

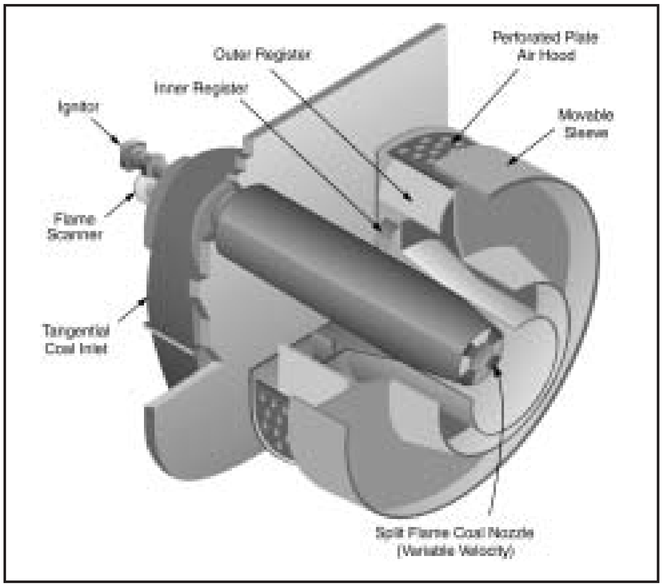
Gas reburning uses a three-zone process. The process reduces the levels of coal and combustion air in the burner area, injects natural gas above the burners, and follows by injecting overfire air (OFA) above the reburn zone as shown in Figure 1. This three-zone process creates a reducing or reburn zone in the furnace wherein NO_x created in the primary zone (from nitrogen in the coal) is reduced to elemental nitrogen and other less harmful nitrogen species. The description of the zones follows:

Primary (burner) Zone: Coal is fired at a rate corresponding to 75 to 90% of the total heat input, under low excess air. NO_x created in this zone is limited by the lower heat release and the reduced excess air level. The burner zone is nominally operated at a stoichiometric ratio of 1.10 (10% excess air), forming a balance between NO_x formation and carbon conversion. The flow of combustion air to the 16 burners (four burners in each of four rows) is reduced to create this condition.

Reburn Zone: Natural gas (methane) injection creates a fuel-rich region within which CO and hydrogen are formed and methane breaks down to hydrocarbon fragments (CH, CH_2, etc.), all three of which react with NO_x, reducing it to atmospheric nitrogen. The optimum reburn zone SR is 0.90, achieved by injecting natural gas at a rate corresponding to 10 - 25% of the total heat input. At this condition, insufficient amounts of oxygen exist to complete the combustion of the fuel in the zone. The injection of natural gas must be optimized with respect to rapid dispersion and mixing with the furnace flue gas, since the residence time in the upper furnace is limited. Analyses of these conditions are used to select the number and size of injectors, their placement, and the quantity of carrier gas (FGR) used. In this case, the configuration used was 16 injectors, eight each on opposing boiler walls.

Burnout (exit) Zone: Overfire air is injected higher up in the furnace to complete the combustion at cooler tem-

FIGURE 2. FWEC CONTROLLED FLOW/SPLIT FLAME (CFSF)



peratures to reduce thermal NO_x formation. OFA is typically 20% of the total air flow. The burnout zone SR is determined by the minimum amount of excess air needed to meet acceptable CO emissions and UBC. OFA in this application was provided by six ports equally spaced across the front (burner side) wall of the boiler.

Each zone has a unique SR as determined by the flow of coal, burner air, natural gas, and OFA. In general, the SRs in all three zones should be at the lowest acceptable values to maintain the highest possible boiler efficiency consistent with gas reburning technology. FGR was initially used for natural gas injection because theory suggested that the mass flow was needed to provide momentum to and mixing of the injected natural gas (FGR is essentially devoid of oxygen and does not affect SRs).

LNBs reduce emissions of NO_x by staging the mixing of coal and air, resulting in a fuel-rich region for char combustion, longer flames, and lower peak flame temperatures. The FWEC Controlled Flow/Split Flame (CF/SF) burner, shown in Figure 2, divides secondary air between inner and outer flow cylinders and splits the coal/primary air mixture into four concentrated streams. The inner secondary air register apportions the flow between inner and outer paths and controls the degree of additional coal/air mixture swirl. An axially movable inner sleeve tip provides a means for varying primary air velocity while maintaining constant flow. The outer flow cylinder injects air axially into the furnace to provide excess air for complete combustion. The segregation of coal/air mixture into four streams minimizes coal and air mixing, which assists combustion staging.

RESULTS SUMMARY

ENVIRONMENTAL

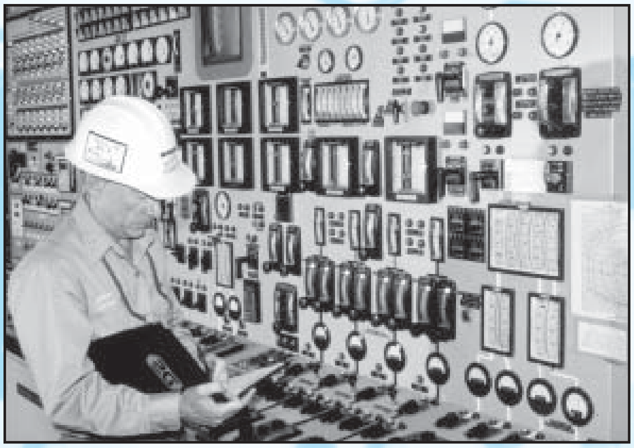
- GR-LNB operated successfully on the wall-fired boiler and achieved the targeted 70% NO_x reduction at full load, but only at higher than accepted reburn gas heat inputs.
- LNB alone, as initially set up to operate with first-generation GR, reduced NO_x emissions at full load from a pre-construction baseline of 0.73 lb/10^6 Btu to 0.46 lb/10^6 Btu, a 37% NO_x reduction.
- LNB alone, as set up for second-generation GR, reduced NO_x emissions at full load by 44%.
- First-generation GR, which incorporated flue gas recirculation, in combination with LNB, reduced NO_x emissions at full load to 0.25 lb/10^6 Btu, a 66% NO_x reduction at an 18% gas heat input.
- Second-generation GR, without flue gas recirculation, in combination with LNB, reduced NO_x emissions at full load to 0.26 lb/10^6 Btu, a 64% NO_x reduction with only 12.5% gas heat input.
- The average NO_x emissions reduction achieved in a dispatch mode over the longer term was approximately 64% for both first- and second-generation GR.
- SO_2 emissions were reduced in direct proportion to GR gas heat input and CO_2 emissions were reduced by 44% of the GR gas heat input.
- After modifying the OFA system to enhance penetration and turbulence (as part of second-generation GR), CO emissions were controlled to acceptable levels at low gas heat inputs (5-10%).

OPERATIONAL

- Slag formed around the OFA injectors due to the OFA creating a cool surface adjacent to the high flue gas temperatures produced in the burnout zone. However, the build-up was slow enough to be controlled during regularly scheduled outages.
- There was a reduction in thermal efficiency of less than 1% largely due to increased moisture from the combustion of natural gas.
- UBC and CO levels were acceptable for first- and second-generation GR with LNB, but not LNB alone.

ECONOMIC

- Capital cost for GR-LNB retrofit is $26/kW ($1996) plus the gas pipeline cost, if not in place, for a 300-MWe plant ($12/kW for GR only, and $14/kW for LNB only).



APPROACH

From October 1992 to April 1993, project activities focused on carrying out a parametric/optimization test program. Each key parameter was varied one at a time while holding all others constant to quantify the selected parameter's impact on and relationship to the other system parameters. These data provided the information needed to approximate the boiler set points. Fine tuning followed to establish settings for optimum performance over the full range of operation. Criteria for the settings were to achieve the maximum NO_x reduction with the least possible natural gas heat input, while maintaining operation within established boiler operating constraints. The following summarizes the parameters examined, the range of variation, and the specific relationships of interest:

Load. Load was varied from 60 MWe to 150 MWe to establish the relationship between load and boiler emissions and performance with the gas reburning system in operation.

Boiler Excess O_2. Excess oxygen (O_2) was varied from 2.5% to 4.0% (14% to 24% excess air) at full load and higher levels at reduced loads (at lower loads excess air is increased to increase the mass flow needed for effective heat transfer). The objective was to determine the minimum amount of excess air needed to ensure flame stability, combustion completion, and acceptable levels of slagging and corrosion potential in the boiler.

Gas Reburn Heat Input. Natural gas heat input was varied from 5% to 25% with the primary combustion zone SR fixed at 1.10 to establish the relationship between the natural gas fuel rate and the boiler NO_x emissions.

FGR Flow Rate. FGR carrier flue gas was varied from 4,000 standard cubic feet per minute (scfm) to 14,000 scfm to determine the impact on GR process efficiency.

OFA Flow Rate. OFA flow rate was varied from zero to 75,000 scfm to establish the minimum excess air in the burnout zone needed to maintain CO and UBC levels within acceptable limits (under 200 ppm for CO and 4.5% for UBC) and also to evaluate the effect on NO_x emissions.

OFA Vane Position. OFA vane position was varied from 10 degrees below horizontal (-10 degrees) to 10 degrees above horizontal (+10 degrees) to assess the impact on CO emissions and UBC levels.

Table 1 summarizes the optimal settings established for full load operation as a result of the parametric tests.

In April 1993, after establishing optimum operating conditions as a guide, PSCo returned the GR-LNB-equipped boiler to normal load dispatch to assess GR-LNB impacts on boiler performance and economics over the long term. Beyond assessing the effects of GR-LNB on emissions, testing included impacts on furnace conditions such as slagging and waterwall corrosion rates, bottom ash characteristics and sluicing requirements, convective pass fouling, steam temperatures and pressures, process auxiliary power requirements, and impacts on the fabric filter dust collector.

Long-term testing ceased in January 1994 to transform the first-generation GR into a second-generation GR. Testing of the second-generation GR with modified LNBs began in March 1994 with a brief optimization test followed by normal load dispatch operation for a period of 95 hours. Testing concluded in January 1995.

The coal used throughout the demonstration was a high-volatile C bituminous coal provided by Empire Energy. The coal had an average higher heating value of 11,268 Btu/lb, a nitrogen content of 1.51%, and sulfur content of 0.4% (equating to a theoretical SO_2 emission rate of 0.8 lb/10^6 Btu). Moisture (10.19%) and ash (9.62%) were relatively low, and the ash had a medium slagging propensity. Coal composition remained fairly uniform over the course of testing.

TABLE 1: OPTIMUM FIRST-GENERATION FULL-LOAD OPERATING CONDITIONS

Variable	Optimal Operating Condition
SR_1	1.08
SR_2	0.90
SR_3	1.15
Gas Heat Input	18%
FGR Flow Rate	4,000–10,000 scfm
OFA Flow Rate	68,000 scfm
OFA Vane Position	-10 degrees
O_2	3.25%
NO_x Emissions	0.25 lb/10^6 Btu
CO	43 ppm
UBC	4.5%

Environmental Performance

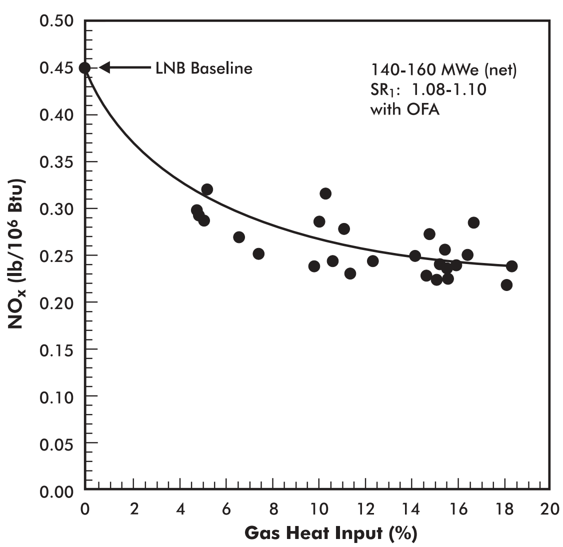
Table 2 summarizes the results of emissions testing at full load and 3.5% excess O_2 for the boiler in the baseline "as found" condition and conditions following installation of LNBs alone, LNBs with OFA, and first generation GR-LNB under optimum settings (see Table 1).

Table 2: Results of Parametric Tests

Test Condition	NO_x lb/10^6 Btu (% reduction)	CO ppm	UBC wt%	SO_2 ppm (% reduction)
Baseline	0.73	67	4.4	355
LNB	0.46 (37%)	<500	6-10	NA
LNB-OFA	0.39* (47%)	<150	7.0	NA
GR-LNB	0.25 (66%)	43	4.5	291 (18%)

*Achieved with an SR_1 of 1.10 in the primary combustion zone

Figure 3. NO_x Versus Natural Gas Heat Input



The initial LNB setup failed to meet a target of 45% NO_x emissions reduction in a stand-alone mode and also failed to maintain CO and UBC levels within acceptable limits—under 200 ppm for CO and 4.5% for UBC. Applying OFA enabled the LNBs to operate at lower combustion zone SRs (SR_1), enhanced NO_x reduction, and maintained CO levels below 150 ppm. The minimum SR_1 for stand-alone LNB operation was 1.23. OFA allowed the boiler to operate with an SR_1 below 1.10, but the degree of NO_x reduction tapered off below that point. OFA did not bring UBC levels under control. At optimum settings, first-generation GR-LNB reduced NO_x by 66%, achieved acceptable levels of CO and UBC, and reduced SO_2 emissions in direct proportion to natural gas heat input.

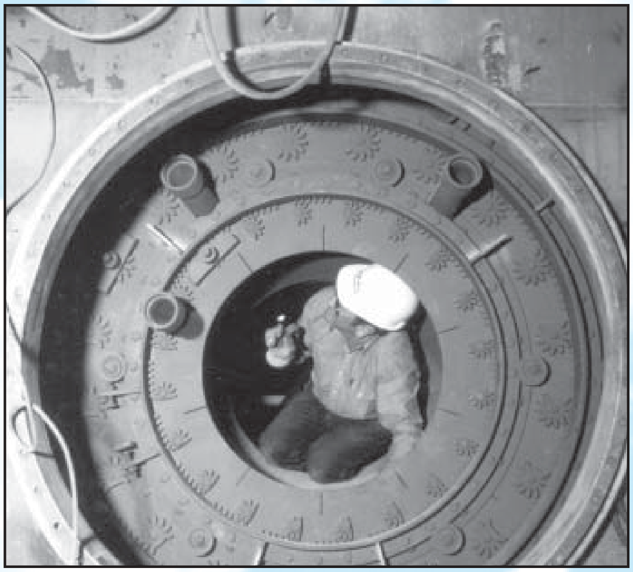
As shown in Figure 3, under constant load and SR_1, increasing natural gas heat input has a significant impact on NO_x emission reduction up to about 10%, at which point it begins to taper off. This parametric test data are consistent with prior research suggesting that dropping the reburn zone SRs (SR_2) below 0.90 has diminishing returns. The natural gas heat input needed to achieve a 0.90 SR_2 is determined by the SR_1 level and the boiler load.

Parametric testing indicated a potential problem in maintaining acceptable CO and UBC levels at low natural gas heat inputs because the air available to the OFA is reduced (primary combustion zone air requirements increase). This was largely responsible for the relatively high natural gas heat input setting of 18%. Also, FGR flow rates beyond 4,000 scfm seemed to have little impact on NO_x reduction, and use of FGR required higher than baseline steam attemperation water flows for temperature control due to release of heat higher in the furnace.

First-generation GR-LNB underwent long-term load dispatch testing for a period of 2,913 hours. Table 3 shows the averages for key data over this period. Long-term testing verified that FGR was both unnecessary and a problem and that OFA did indeed have a problem maintaining acceptable CO and UBC at low gas heat inputs. As a result, the GR system was modified and, during GR modification, the LNBs were reworked to improve performance.

The GR modifications: (1) eliminated the FGR system; (2) incorporated high-velocity natural gas jet injectors leveraging available pipeline pressure; and (3) provided OFA ports with higher momentum at low OFA flow rates. The resultant second-generation GR-LNB demonstrated enhanced performance and reduced capital, operating, and maintenance costs. Table 3 summarizes performance over a 95-hour load dispatch test period.

Second-generation GR-LNB performance gains and operating cost reductions are due primarily to a modified OFA system. The modified OFA system incorporates a double concentric port design capable of on-line cross-sectional area variation to provide optimum velocity, and swirl vanes to assist penetration. This modification enables effective operation at a far lower full load natural gas heat input of 12.5% for optimum performance, significantly reduces the major operating cost (natural gas), and significantly reduces CO emissions. FGR elimination represents a significant capital cost reduction and reductions in operating and maintenance costs as well. The FGR system was expensive, the fan was difficult to maintain, and the multiclone dust removal system was a source of recurrent maintenance problems. The reworked LNBs achieved a 44% stand-alone NO_x reduction, but again at unacceptable CO and UBC levels.



FWEC LNB mounting shroud

Table 3: Averages for Load Dispatch Testing

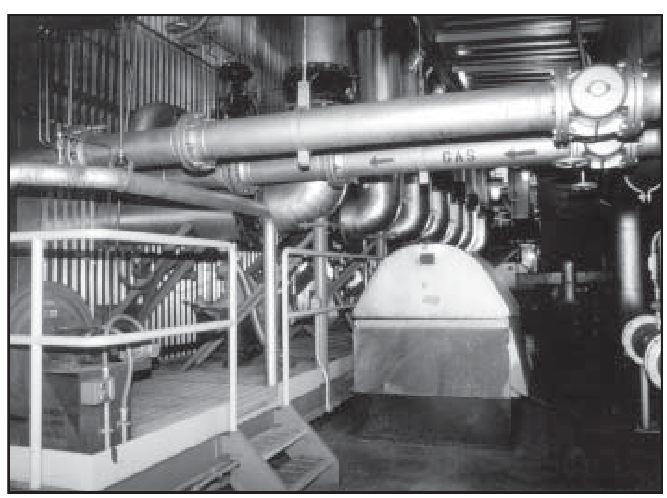
Factor	Long-Term GR-LNB Test 2,913 Hours	2nd-Generation GR-LNB Test 95 Hours
Net Power Output	133 MWe	134 MWe
NG Heat Input	13.9%	10.5%
O_2 Level	3.57%	3.16%
NO_x emissions	0.260 lb/10^6 Btu	0.264 lb/10^6 Btu
CO emissions	160 ppm	68 ppm
SO_2 emissions	304 ppm	330 ppm

Operational Performance

Boiler Impacts. The application of LNBs increased slagging in the primary combustion zone somewhat. Also, periodic episodes of LNB flames extending into the arch region of the boiler caused bridging of slag deposits in the secondary superheater section. Heavy slag deposits formed around three of the six OFA ports after about three months of operation. Higher flue gas temperatures in the OFA area with GR operation prompted precipitation of slag where air from the OFA ports chilled the adjacent surface. In the absence of sootblowers in the OFA area, the slag accumulated until a significant "eyebrow" formed over the port, which was removed during regularly scheduled maintenance. Slag formed around some of the gas injection nozzles on a random basis, but posed no problem—access ports enabled rapid cleaning by "rodding out" the injectors.

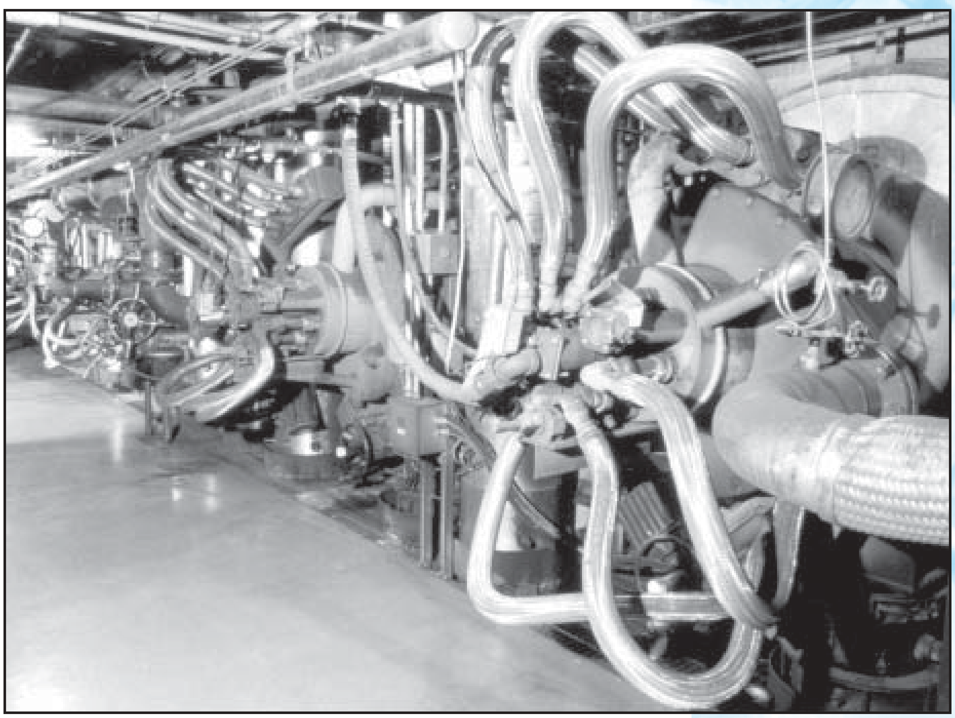
The potential for accelerated boiler tube wear caused by reducing atmospheres stripping off protective oxide coatings prompted non-destructive testing of the boiler tubes. However, ultrasonic tube thickness measurements at strategic locations in the boiler showed no significant tube wastage over a three-year test period.

Natural gas injection system with eight injectors each on both the front and rear walls



Thermal Performance/Efficiency. With GR-LNB, the furnace exit O_2 level was reduced from the baseline value of 3.2% to 2.6%, which contributed to decreased boiler efficiency and NO_x reduction and proved sufficient for CO control. GR-LNB increased both main and reheat steam temperatures due to more heat release in the upper convection pass section of the boiler relative to baseline. Attemperation sprays adequately controlled the increase in steam temperature, but represented an efficiency loss. This loss was lessened with second-generation GR-LNB because the natural gas heat input was reduced.

GR-LNB reduces heat transfer in the primary combustion zone, increases heat transfer in the convection section, and results in an overall dry gas heat loss. With first generation GR-LNB (18% gas heat input), the primary zone temperature dropped 150 ^{o}F while the reburn and burnout zones increased in temperature by about 70 ^{o}F and 60 ^{o}F, respectively. But, the greater heat loss is due to the increased moisture from combustion associated with natural gas—the higher hydrogen content produces more water than does coal. Second-generation GR-LNB reduces efficiency losses from both mechanisms by reducing natural gas heat input from 18% to 12.5%. The total reduction in efficiency was less than 1% for all conditions.



FWEC LNBs installed on front boiler wall.

Economic Performance

GR-LNB is a retrofit technology in which the economic benefits are dependent on the following site-specific factors:

- Gas availability at the site
- Gas/coal cost differential
- Boiler efficiency
- SO_2 removal requirements
- Value of SO_2 emission credits

Based on the demonstration, GR-LNB is expected to achieve at least 64% NO_x control with a gas heat input of 12.5%. The capital cost estimate for a 300-MWe wall-fired installation is $26/kW ($1996) plus gas pipeline costs, if required. This cost includes both equipment and installation costs and a 15% project contingency. The GR and LNB system capital costs can be easily separated from one another because they are independent systems. The capital cost for the GR system only is estimated at $12/kW. The LNB system capital cost is $14/kW.

Operating costs are almost entirely dependent on the cost differential between natural gas and coal reduced by the value of the SO_2 emissions credits received due to the absence of sulfur in natural gas. Gas costs more than coal on a $/Btu basis, so a differential cost of $1.00/$10^6$ Btu was used. Boiler efficiency was estimated to decline by 0.80%; the cost of this decline was calculated using a composite fuel cost of $1.67/$10^6$ Btu. Auxiliary loads for overfire air booster and cooling fans will be partially offset by lower loads on the pulverizers. No additional operating labor is required, but there is an increase in maintenance costs. Allowances were also made for overhead, taxes, and insurance. Based on these assumptions and assuming an SO_2 credit allowance of $95/ton (February 1996), the net operating cost is $2.14 million per year.

The levelized cost of power for a 300-MWe plant, with a 65% capacity factor, 15-year life, and using 3.0% sulfur coal is 2.40 mills/kWh in current dollars (0.160 capital charge factor; 1.314 O&M factor), and is 1.84 mills/kWh in constant 1996 dollars (0.124 capital charge factor; 1.000 O&M factor). The levelized cost on a NO_x removal basis is $1,027/ton (current dollars) and $786/ton (constant 1996 dollars).

Commercial Applications

GR-LNB technology can be used in retrofit, repowering, or greenfield installations of nearly all wall-fired boilers. However, there are a couple of site-specific factors, beyond those already presented, that affect commercial applications. A minimum combustion air windbox pressure of 4–6 inches of water column is needed to avoid installation of a booster fan for the OFA system. Also, GR is most effective where furnace temperatures exceed 2,600 ^{o}F and the residence time in the reburning zone is 0.5 seconds or more.

GR-LNB is expected to be less capital intensive, or less costly, than a scrubber, selective catalytic reduction, or other technologies. GR-LNB functions equally well with any kind of coal and is applicable to any type of boiler.

Public Service Company of Colorado, the host utility, decided to retain the low-NO_x burners and the gas-reburning system for immediate use; however, a restoration was required to remove the flue gas recirculation systems.

As of August 2001, Energy and Environmental Research Corporation has been awarded two contracts to provide gas-reburning systems for five cyclone coal-fired boilers: TVA's Allen Unit No. 1, with options for Unit Nos. 2 and 3, (identical 330-MWe units); Baltimore Gas and Electric's C.P. Crane, Unit No. 2, with an option for Unit No. 1, (similar 200-MWe units). Use of the technology also extends to overseas markets. One of the first installations of the technology took place at the Ladyzkin State Power Station in Ladyzkin, Ukraine.

This project was one of two that received the Air and Waste Management Association's 1997 J. Dean Sensenbaugh Award.

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** All references available on CCT Compendium at http://www.lanl.gov/projects/cctc/index.html*

U.S. Department of Energy

Assistant Secretary for Fossil Energy

Washington, DC 20585