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

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EXECUTIVE SUMMARY

This document serves as a U.S. Department of Energy (DOE) post-project assessment of a project in its Clean Coal Technology (CCT) Program, Round 3, "Evaluation of Gas Reburning and Low-NO_x Burners on a Wall-Fired Boiler," conducted by Energy and Environmental Research Corporation (EER). In October 1990, EER entered into a cooperative agreement with DOE to conduct this study, with the Gas Research Institute (GRI), the Electric Power Research Institute, Public Service Company of Colorado (PSCo), and Colorado Interstate Gas Company as the other project participants. The demonstration was conducted between October 1992 and January 1995 on PSCo's 158-MWe (net) wall-fired Cherokee Station Unit 3 located in Denver, Colorado. Unit 3 is a 172-MWe wall-fired boiler that uses Colorado bituminous, low-sulfur coal. Over 4,000 hours of operation were achieved. Low-NO_x burners achieved a NO_x reduction of 65% at an average gas heat input of 18% compared to the performance goal of 70%. The performance goal of 70% reduction was met on many runs, but at higher gas heat inputs. DOE provided 50% of the total project funding of $17.8 million.

Gas reburning (GR) involves firing natural gas (up to 25% of total heat input) above the primary combustion zone in utility boilers and industrial furnaces. This upper-level firing creates a slightly fuel-rich zone. NO_x produced in the primary zone of the boiler is "reburned" in this zone and converted to molecular nitrogen and other reduced nitrogenous species. Overfire air is injected downstream of the reburn zone to burn out the remaining combustibles and convert the reduced nitrogenous species to molecular nitrogen. Low-NO_x burners (LNBs) positioned in the coal combustion zone retard the production of NO_x by staging the burning process so that the coal-air mixture can be carefully controlled at each stage. The combination of these two technologies is referred to as GR-LNB. The combined effect of adding a reburning stage to wall-fired boilers equipped with LNBs was intended to lower NO_x emissions by up to 70%. In this project, GR was operated with and without the use of flue gas recirculation.

The objectives for this project were:

- To attain up to 70% reduction in NO_x emissions from an existing wall-fired utility boiler firing low-sulfur coal
- To assess the impact of GR-LNB on boiler performance

The project could not meet these objectives except for short-term tests, in which very high reburn gas heat input was used. Boiler operability was found acceptable in long-term testing. No significant adverse boiler impacts were observed, such as large decreases in thermal performance or electrostatic precipitator collection efficiency. Other emissions impacts on air, water, and land remained within acceptable limits.

Economics of the GR-LNB process have been estimated for a hypothetical 300-MWe cyclone boiler fired with 3% sulfur coal, and assuming a $\$1/10^6$ Btu price differential between gas and coal fuels. The capital cost is estimated at \$26/kWe and the 15-year levelized cost is estimated at \$1,027/ton of NO_x removed (current dollar basis).

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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 is a DOE post-project assessment of a project selected in CCT Round 3, "Evaluation of Gas Reburning and Low-NO_x Burners on a Wall-Fired Boiler," as described in a Report to Congress [1] dated September 1990. In October 1990, Energy and Environmental Research Corporation (EER) entered into a cooperative agreement to conduct this study. Other project participants were the Gas Research Institute (GRI), the Electric Power Research Institute (EPRI), Public Service Company of Colorado (PSCo), and Colorado Interstate Gas Company. The host site was PSCo's 158-MWe (net) wall-fired Cherokee Station Unit 3, located in Denver, Colorado. DOE provided 50% of the total project cost of $17.8 million. Baseline testing was started in October 1992, and field testing was completed in January 1995.

Gas reburning (GR) involves firing natural gas (up to 25% of the total heat input) above the primary combustion zone in a coal-fired boiler. This upper-level firing creates a slightly fuel-rich zone. NO_x produced in the lower region of the boiler is reduced in this "reburn" zone and converted to molecular nitrogen (N_2). Low-NO_x burners (LNBs) positioned in the primary combustion zone reduce the production of NO_x by staging the burning process to lower the temperature and oxygen/fuel ratio during primary combustion. The combination of these two technologies is referred to as GR-LNB. The expected effect of adding a reburning stage to a wall-fired boiler equipped with LNBs was to lower NO_x emissions by up to 70%. In this project, GR was demonstrated with and without the use of flue gas recirculation (FGR).

The Clean Air Act, initially promulgated in 1970 and amended in 1977, established New Source Performance Standards (NSPS) for emissions of SO_2, NO_x, and particulates, among other pollutants, from stationary coal-fired power plants. These regulations were made more stringent in the Clean Air Act Amendments (CAAA) of 1990. The GR-LNB process offers a potential means of meeting NO_x emissions requirements of the CAAA as administered by the U.S. Environmental Protection Agency (EPA).

The objectives for this project were:

- To attain up to 70% reduction in NO_x emissions from an existing wall-fired utility boiler firing low-sulfur coal

- To assess the impact of GR-LNB on boiler performance

The independent evaluation contained herein is based primarily on information from EER's Final Report dated July 1998 [11], as well as the other sources cited. In fulfillment of the cooperative agreement, EER also prepared a Guideline Manual [12] which provides an overview of the technology requirements for GR-LNB.

II. TECHNICAL AND ENVIRONMENTAL ASSESSMENT

This project evaluates the technical and economic feasibility of controlling NO_x emissions from a wall-fired utility boiler by using GR in combination with LNBs. LNBs usually achieve 30-50% NO_x reduction, while GR usually achieves 50-60% NO_x reduction. Adding GR to a wall-fired boiler equipped with LNBs was expected to lower NO_x emissions by up to 70%. The benefits anticipated from the combined GR-LNB technology were low capital costs relative to other NO_x-reduction processes coupled with no adverse effects on boiler thermal performance. Although there have been several demonstrations of the separate GR and LNB technologies prior to this project, this CCT project was the first full-scale demonstration of the combined technologies.

A. Process Description

A schematic flow diagram of the GR-LNB process is shown in Figure 1. GR is a combustion modification process that reduces the amount of NO_x formed in the boiler by creating a reducing zone (the reburn zone) above the primary combustion zone. LNBs are air-staged burners that reduce temperature and oxygen concentration during the combustion process and, thus, reduce the amount of NO_x produced in the primary combustion zone. LNBs have become the technology of choice for meeting the mandates of the CAAA for Phase I, Group 1 boilers, i.e., dry-bottom wall-fired boilers and tangentially fired (T-fired) boilers.

Gas Reburning (GR)

For coal-fired boilers, GR involves injecting natural gas downstream of the existing burners to create a reducing or reburn zone to destroy NO_x. High furnace temperatures (2,600°F) and adequate residence times are needed for efficient NO_x reduction. Reburning is followed by the injection of burnout or overfire air (OFA) to complete the combustion of the reducing gases, mainly carbon monoxide (CO). The process is shown schematically in Figure 2.

Reburn technology involves three zones in the furnace: (1) a *primary combustion zone* where coal is fired; (2) a *reburn zone* where additional fuel is added to create reducing conditions to convert the NO_x produced in the primary zone to molecular nitrogen (N_2) and other reduced nitrogen species; and (3) a *burnout zone* to complete the combustion of the reducing gases produced in the reburn zone.

Each zone has a unique stoichiometric air ratio (ratio of air used to that theoretically required for complete combustion) as determined by the flow of primary fuel, burner air, natural gas, and OFA. FGR can be used to increase the momentum of the injected natural gas to improve furnace penetration and mixing; but because recirculated flue gas has a low oxygen content, FGR has only a minor impact on the reburn zone fuel requirement and the burnout zone air rate.

- **Primary Combustion Zone**--Coal is fired at a rate corresponding to 75-90% of the total heat input, under normal to low excess air conditions. The rate of NO_x formation in this zone is reduced by about 10% because less fuel is fired (lower production of fuel NO_x), the heat release rate is lower (lower production of thermal NO_x), and, generally, the excess air level to the burners is reduced to lower the oxygen concentration (lower fuel and thermal NO_x production).

- **Reburn Zone**--Reburn fuel (natural gas in this case, but coal and oil can also be used) injection creates a reducing (fuel-rich) region within which natural gas (mostly methane, CH_4) breaks down to form 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 around 0.90. This is achieved by injecting natural gas at a rate corresponding to 10-25% of the total heat input, depending on the primary combustion zone excess air level. The lower this excess air, the lower the reburn fuel requirement. FGR is sometimes used as a carrier for the reburn fuel and/or to increase momentum and penetration into the furnace.

- **Burnout Zone**--OFA is injected downstream of the reburn zone to complete combustion of the reburn zone fuel gases. OFA is typically 20% of the total air flow. An overall excess air level of 15-25%, depending on the primary fuel type, is normally maintained. The OFA injection rate is optimized for each specific application to minimize CO emissions and unburned carbon in the fly ash.

Low-NO_x Burners (LNBs)

LNBs reduce emissions of NO_x by staging the mixing of coal and air. This results in a fuel-rich region for char combustion, longer flames, and lower peak flame temperatures. LNBs generally use dual air registers in parallel to delay the mixing of air with coal injected through a coal nozzle in the center of the burner. While LNBs reduce NO_x, they may result in higher levels of unburned carbon and higher emissions of CO. These result from incomplete combustion which may occur from the staging of coal/air mixing. OFA is sometimes used to decrease unburned carbon and CO. LNBs do not affect the emissions of other species such as CO_2, SO_2, or particulates.

B. Project Description

The demonstration site was PSCo's Cherokee Station, located in Denver, CO. The Cherokee Station is PSCo's largest electric power generating station, comprised of four boilers that generate a total of about 775 MWe. GR-LNB was installed on Cherokee Unit 3, which was built by Babcock and Wilcox (B&W) in 1962 and, therefore, did not have to meet NSPS as required under the CAAA for units constructed after 1971. Unit 3 is a 172-MWe gross (158 MWe net) balanced-draft, wall-fired boiler, originally equipped with conventional B&W flare-type pulverized coal (PC) burners. The unit has 16 burners (four rows of four burners) located on the front wall of the furnace.

Coal is pulverized with four Riley Stoker No. 556 duplex drum pulverizers to a specified fineness of 70% passing 200 mesh and 50% passing 50 mesh. Pulverized coal is conveyed by 160^{o}F primary air to the burners and combusted with 600^{o}F secondary air. After leaving the main furnace, flue gas passes over a secondary superheater, reheat superheater, primary superheater, economizer, and two rotary air preheaters. Particulate collection is achieved via a baghouse using fabric filters.

The CCT demonstration project included replacing the existing burners with Foster Wheeler Controlled Flow/Split Flame LNBs and installing injection ports to accommodate GR. Natural gas reburn fuel was injected through a total of 16 injectors, eight on the front wall and eight on the rear wall. Ambient air was used to cool the gas injection nozzles when the GR system was not in operation. OFA at a temperature of approximately 600^{o}F was withdrawn from two secondary air ducts and boosted from 2 in. of water to 12 in. of water by an OFA booster fan. The OFA was routed to six ports located on the front wall of the furnace. The OFA injectors were tilted down at an angle of 10^o to provide better penetration of the air into the furnace combustion gases and to increase residence time in the burnout zone to lower CO emissions.

For this project, the GR-LNB equipment was controlled by a Westinghouse Distributed Process Family system (WDPF). The WDPF provided integrated modulating control, sequential control, and data acquisition for a wide variety of system applications.

FGR was used initially to increase the momentum of the natural gas in an effort to achieve optimum penetration into the furnace cross section. However, during the course of the project (see Figure 3), it was found that FGR had a minimal effect on NO_x emissions. Cherokee Unit 3 has a reburn zone residence time of half a second, which is sufficient to achieve NO_x reduction without the need for FGR. Therefore, part way through the project the unit was modified as follows:

- The FGR system was removed.

- The natural gas injectors were redesigned to operate at higher pressures. This took advantage of the higher pressure at which the natural gas was available and increased the velocity of gas injection.

- The OFA ports were modified to provide higher jet momentum, air swirl, and velocity control. These modifications were designed to improve furnace lateral coverage and turbulence for air mixing with unburned fuel in the upper furnace.

This modified configuration is referred to by EER as Second-Generation GR, and it provided CO control within acceptable limits at a lower natural gas usage level. Elimination of FGR benefitted the process by (1) reducing natural gas usage and (2) reducing capital cost. The reduction in natural gas usage reduced operating costs because of the natural gas/coal price differential. The reduced gas usage also reduced superheater attemperation water spray rates due to the decreased heat release in the upper part of the furnace.

The coal burned during this project was a low-sulfur (0.45 wt%) Colorado bituminous coal. Properties of this coal are given in Table 1.

C. Project Results

Field testing included parametric optimization studies, followed by one year of long-term testing. Baseline, uncontrolled NO_x emissions at Cherokee Unit 3 were 0.73 lb/10^6 Btu. Replacement of the original burners with low-NO_x burners reduced NO_x emissions to 0.46 lb/10^6 Btu, a 37% reduction. While significant, this performance fell short of the target value of 45% reduction. The use of GR in combination with LNBs resulted in a further lowering of NO_x emissions to an average of 0.25 lb/10^6 Btu, an overall reduction of 66%. This level of reduction was achieved at a natural gas usage of 18% of the total heat input. At these conditions, GR achieved only a 45% reduction of the NO_x reaching the reburn zone, which is on the low side of what is normally achieved with GR.

Following installation of the Second-Generation GR equipment and tune-up of the LNBs, the system achieved a NO_x emissions rate of 0.26 lb/10^6 Btu, a 64% overall reduction from baseline, at a natural gas reburn heat input of only 12.5%. This version of GR-LNB offers improved economics, since the same degree of NO_x emissions reduction is achieved with a significantly smaller consumption of natural gas, which is more expensive than coal on a Btu basis.

Figure 4 shows NO_x emissions reduction during the test period. In both the first- and second-generation tests, the target level of 70% overall NO_x reduction was reached, but only for short periods and with significantly higher gas heat inputs than required for the results discussed above.

Thus, it is somewhat questionable to say that the performance objectives of the CCT project were achieved, as claimed in the EER Final Report and its companion Guideline Manual.

The variables studied in the demonstration of GR-LNB were: (a) primary combustion zone excess air level; (b) natural gas heat input as a fraction of the total heat input; (c) reburn zone air/fuel stoichiometric ratio; (d) FGR rate; (e) and OFA rate.

The importance of the primary zone stoichiometric ratio (SR) is shown by Figure 5. As the primary zone SR increases, so do NO_x emissions. Another effect of higher primary zone SR is to increase the reburn fuel requirement. Since the reburn zone needs to be in a fuel rich situation, the more oxygen reaching the reburn zone, the more fuel that needs to be added to achieve fuel rich conditions. On the other hand if the primary SR is too low, the loss on injection (LOI) can be high and reduced sulfur compounds produced at these conditions can cause erosion of the boiler tubes. For this work, a SR in the range of 1.08-1.10 gave satisfactory results.

Figure 6 (First Generation GR) and Figure 7 (Second Generation GR) show the effect on NO_x emissions of the percentage of the total heat input provided by natural gas. Better results were obtained as the natural gas rate increased, but benefits appear to level out somewhere in the range of 10-15% natural gas heat input. Figure 8 shows that good NO_x-reduction results can be achieved over a load factor range of 70-100%.

Figure 9 (First Generation GR) and Figure 10 (Second Generation GR) show that the effect of total excess air, as indicated by the oxygen in the flue gas, is relatively small. This is not unexpected because total excess air tends to be set by the amount of overfire air, which should have relatively little effect on NO_x emissions. The slight increase in NO_x levels with increased excess air is probably attributed to some secondary NO_x formation in the burnout zone. An important function of the burnout zone is to decrease CO concentration, so OFA rate needs to be high enough to achieve an acceptable CO emissions level. The effect of excess air on NO_x reduction, unburned carbon, and CO emissions is shown in Table 2. As this table shows, both CO emissions and carbon-in-ash values are acceptable with furnace exit O_2 levels of 4% or higher.

The most important findings were:

- Increasing the fractional heat input in the reburn zone up to about 20% and decreasing the reburn zone stoichiometric ratio to about 0.9 have the strongest impact on NO_x emissions.

- The NO_x emissions reduction target level can be approached by operating with reburn gas heat input levels of only 10-13%, using the Second Generation GR system (elimination of FGR and redesigned OFA injection).

D. Boiler Impacts

In the test program, GR-LNB operation was shown to have only minor impacts on boiler performance. The thermal performance parameters monitored were the flow rate, temperature and pressure of the steam, steam attemperation flow rate, total heat transferred to water/steam, gas side temperatures, thermal efficiency, and heat rate. The most significant impacts were observed in the boiler temperature profile, which changed because of the increased heat release in the upper furnace. Operational changes, such as increasing the steam attemperation flow rate, were required to maintain the thermal performance of the unit. Thermal efficiency was reduced slightly; thus heat rate was increased to a minor extent (about 0.8%), as a result of two factors: (a) increased dry gas heat loss caused by higher economizer inlet temperatures, and (b) increased moisture in the flue gas caused by combusting natural gas, which has a higher hydrogen content than coal. Another boiler impact was a small amount of furnace slagging.

Regarding parasitic power requirements, there are offsetting effects. Increased power is required for the OFA fans. On the other hand, because of the decreased coal consumption, pulverizer power is reduced. The result is a slight decrease in auxiliary power requirements for GR-LNB. There was no measurable tube wear or reduction of baghouse efficiency.

The GR-LNB project also produced some environmental effects. The use of lower carbon content natural gas to replace part of the coal feed provided a modest reduction (about 5% at 13% gas input) in emissions of CO_2, a major greenhouse gas. As anticipated, SO_2 and particulate emissions were reduced in proportion to the amount of coal feed replaced with natural gas.

Award

EPA, GRI, and DOE were the recipients of the Air & Waste Management Association's 1997 J. Dean Sensenbaugh Award for their collaborative work in developing GR into a viable and commercial emissions-control option for utility and industrial power-generation boilers.

E. Commercialization of the Technology

Although this CCT project included both LNBs and GR, GR is the more novel of the two technologies because LNBs have been used extensively to meet CAAA NO_x emissions limits. Therefore, the following discussion primarily concerns the commercialization of gas reburning. The progress in commercializing GR is evidenced by the installations discussed below.

In a separate Round 1 CCT project, GR was successfully demonstrated, along with sorbent injection (SI) for SO_2 control, at City Water, Light and Power's (CWLP) Lakeside Unit 7 located at Springfield, Illinois, a 33-MWe (net) cyclone boiler, and at Illinois Power's Hennepin Unit 7 located at Hennepin, Illinois, a 71 MWe (net) T-fired boiler [8]. These demonstrations achieved about 60% NO_x reduction with 18-23% gas heat input. Thus, the GR-SI CCT project successfully demonstrated NO_x reduction on two types of boilers other than the wall-fired boiler tested at Cherokee. Hennepin Unit 1 is typical of T-fired boilers, which are also fired with PC but produce relatively low levels of NO_x (on the order of 0.6-0.7 lb/10^6 Btu). Lakeside Unit 7 is typical of cyclone firing systems, which burn crushed coal and generate high levels of NO_x (typically 1.0-2.0 lb/10^6 Btu). The success of controlling NO_x emissions on three different boiler firing systems is a promising indication of the broad applicability of GR, although site-specific conditions must be taken into account when considering the applicability of GR-LNB.

In addition, GR has been successfully applied on a 300-MWe T-fired boiler in Ukraine [6]. Reburning has also been used on a number of utility boilers ranging up to 800 MWe in Italy [9], and testing a GR installation on a 700-MWe wall-fired boiler of Scottish Power [7] is in progress. Japan had the earliest installations, but these are now idle because the stringent Japanese NO_x emissions regulations can be satisfied only by post-combustion processes such as selective catalytic reduction (SCR).

Since conclusion of the Cherokee demonstration project, the GR-LNB system has been retained and operated by the host site. During the course of this project, a database was developed for future application of GR-LNB technology to control NO_x emissions from wall-fired boilers. The technology is being commercialized by EER. EER has installed and started up GR systems on a glass furnace at an Anchor Glass factory, and on a 100-MWe (net) T-fired utility boiler at the Greenidge Station of New York State Electric and Gas (NYSEG). In addition, EER has recently been awarded contracts for GR retrofit installations on up to five large coal-fired cyclone boilers. These include the 330-MWe Unit 1 (startup in progress) of the Allen Fossil Station of TVA with options for Units 2 and 3 (330 MWe each), and the 200-MWe Unit 2 of the C.P. Crane Station of Baltimore Gas and Electric with an option for Unit 1 (also 200 MWe). These new projects would increase EER's U.S. reburning installations to 11 with a total capacity of 1700 MWe. Ultimately, NO_x emissions regulations will be the driving force for GR commercialization.

B&W has installed GR for NO_x control on an electric utility-size coal-fired industrial cyclone boiler (40 MWe equivalent) at Kodak Park, Rochester NY. This commercial installation was also supported by GRI as part of its "Validation and Deployment of Gas Injection Technologies" project. Fifty percent NO_x reduction was achieved.

ABB Combustion Engineering has installed and tested a commercial "close-coupled" gas reburn retrofit on a 200-MWe gas- and oil-fired boiler at Long Island Electric Company's E.G. Barrett Station. This work was also supported by Empire State Electric Energy Research Corporation

(ESEERCO), EPRI, and GRI. A reduction in NO_x emissions of 50% was achieved with either gas reburning or staged air combustion.

Size Considerations

Since GR is an injection technology, the issue of scale-up for adequate gas jet penetration, coverage, and mixing with the bulk flue gases still needs to be evaluated on larger-scale applications. Based on experience in other countries and ongoing U.S. projects using GR for NO_x-emissions control, the feasibility of applying GR technology to larger units appears to be promising, and, so far, no upper size limitations for GR applications have been encountered. The minimum size is probably close to that of CWLP's Lakeside Unit 7, based on requirements of sufficient residence time at the appropriate temperatures in the reburn zone. There are no minimum or maximum capacity limitations on LNB installations.

III. MARKET ANALYSIS

A. Potential Markets

The driving force for the use of GR-LNB to control NO_x emissions from coal-fired utility boilers stems from Titles I and IV of the CAAA. Title IV (acid rain) regulations for Phase I, Group 1 boilers (dry-bottom wall-fired and T-fired) became effective January 1, 1996, followed by regulations for Phase II, Group 1 and Phase II, Group 2 boilers (cyclone, cell burner, wet bottom, dry bottom vertical, stoker, and fluidized bed firing systems), which will become effective January 1, 2000. The Title IV regulations for utility boiler NO_x emissions are shown in Table 3.

Title I ozone nonattainment regulations are also expected to become a significant driving force for utility boiler NO_x control. EPA has recently promulgated a rule that would apply stringent NO_x controls to 22 states and the District of Columbia. This could result in a large number of coal-fired utility boilers having to meet NO_x emissions limits as low as 0.15 lb/10^6 Btu.

From the perspective of the potential market for GR applications, the cyclone boilers in Group 2 represent the best opportunity (in addition to the existing potential for Group 1 boilers), because the less expensive LNB and staged fuel-firing options seem to provide an appropriate solution for cell burner and other wet-bottom boilers, respectively. There are about 75 cyclone boilers in the United States, having a total capacity of about 20,000 MWe; these boilers exceed the NO_x emissions standard of 0.86 lb/10^6 Btu under Title IV, Phase II. It should be noted that virtually any fossil fuel can be used for reburning, so GR would not have all of the reburning market to itself. For example, coal reburning, which is a demonstrated technology, has higher capital and lower operating costs than GR, so the choice is site-specific.

The most significant market factors affecting the application of GR are the availability and price of natural gas. Availability impacts the capital cost, while the price of natural gas (or the gas/coal price differential) is of critical importance to the operating cost.

B. Economic Assessment of Utility Boiler Applications

GR-LNB Costs

The EER Final Report [11] includes preliminary economics (-10%/ +15% accuracy) for the GR-LNB technology. The economics assume a hypothetical 300-MWe (net) wall-fired boiler retrofit burning 3 wt% sulfur coal, with a 10,000 Btu/kWh heat rate, a capacity factor of 65%, and 12.5% gas heat input. It is assumed that access to a natural gas pipeline is available onsite, thereby eliminating the need to bring gas to the power plant. Providing a pipeline could add significantly to the cost of a GR project, depending on the distance involved.

The economics for GR-LNB are presented in Table 4. The estimated capital cost is $26/kWe, of which GR contributes $12/kWe and LNB contributes $14/kWe. Natural gas is priced at $\$2.47/10^6$ Btu and coal at $\$1.47/10^6$ Btu, i.e., a cost differential between gas and coal of $\$1.00/10^6$ Btu. To account for the slight loss in overall boiler efficiency, the amount of fuel fired is increased by 0.8% compared with baseline operation. This incremental fuel is priced at $\$1.60/10^6$ Btu, which is the weighted price of coal and gas in the proportions used. The economics include an allowance for reduced SO_2 emissions resulting from the substitution of natural gas (containing no sulfur) for a portion of the coal feed. EER credits this reduction in SO_2 at $95/ton in the emissions trading market. Based on these assumptions, the levelized cost of the GR-LNB process is $1,027/ton NO_x removed (current dollar basis) or $786/ton (constant dollar basis). Figure 11 shows the effect of several operating variables on the cost of NO_x reduction.

Comparison with Other Technologies

The EER Final Report includes an economic comparison of GR-LNB with other technologies, using information from a separate study supported by the EPA. Table 5 compares capital and levelized costs for GR-LNB with those for coal reburning, selective noncatalytic reduction (SNCR) and SCR at a power plant capacity of 400 MWe, again assuming a $\$1/10^6$ Btu gas/coal price differential. GR-LNB appears to be the most expensive of the technologies considered, but the comparison is limited to processes offering modest levels of NO_x removal, i.e., 35-65%. The economics of SCR would be significantly different at its maximum NO_x-reduction capability of 80-90%.

IV. CONCLUSIONS

The results from the GR-LNB technology demonstrated by EER at Cherokee Station approached, but did not meet, the CCT project's performance objectives. Acceptable unit operability was achieved with both the GR and the LNB components.

The gas reburning component of the process appears to be broadly applicable for retrofit NO_x control to most utility boilers and, in particular, to wet-bottom cyclone boilers, which are high NO_x emitters and are difficult to control (LNB technology is not applicable to cyclone boilers). GR-LNB can reduce NO_x to mandated emissions levels under Title IV of the CAAA without significant, adverse boiler impacts. The GR-LNB process may be applicable to boilers significantly larger than the demonstration unit, provided there is adequate dispersion and mixing of injected natural gas.

Major results of the demonstration project are summarized as follows:

- NO_x-emissions reductions averaging 64% were achieved with 12.5% gas heat input in long-term tests on a 158-MWe (net) wall-fired unit. The target reduction level of 70% was achieved only on a short-term basis with higher gas consumption.

- The thermal performance of coal-fired boilers is not significantly affected by GR-LNB. Convective section steam temperatures can be controlled within acceptable limits. Thermal efficiency is decreased by a small amount (about 0.8%), because of increased dry gas loss and higher moisture in the flue gas as a result of the GR process.

- Furnace slagging and convective section fouling can be adequately controlled.

- Because of the higher hydrogen/carbon (H/C) ratio of natural gas compared with coal, use of the GR process results in a modest reduction in CO_2 emissions. SO_2 and particulate emissions are reduced in direct proportion to the fraction of heat supplied by natural gas.

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11. Energy and Environmental Research Corporation, "Evaluation of Gas Reburning and Low-NO_x Burners on a Wall-Fired Boiler," Final Report, July 1998.

12. Energy and Environmental Research Corporation, "Evaluation of Gas Reburning and Low-NO_x Burners on a Wall-Fired Boiler," Guideline Manual, July 1998.

Table 1. Properties of Coal Used in GR-LNB Tests

Coal Source: Colorado Bituminous

Proximate Analysis, wt%	
Fixed Carbon	45.34
Volatile Matter	34.80
Moisture	10.32
Ash	9.54
Total	100.00
Ultimate Analysis, wt%	
Carbon	64.23
Hydrogen	4.46
Nitrogen	1.51
Sulfur	0.45
Oxygen	9.54
Moisture	10.19
Ash	9.62
Total	100.00
Higher Heating Value, Btu/lb	11,268

Table 2. Effect of Excess Air on NO_x Reduction, Unburned Carbon, and CO Emissions

Furnace exit O_2, %	**3**	**4**	**5**
NO_x, lb/10^6 Btu			
Baseline	0.68	0.77	0.86
LNB	0.42	0.49	0.54
Reduction, %	38	36	37
Carbon-in-ash, %			
Baseline	5	5	4
LNB	8	5	2
CO, ppm			
Baseline	<300	<50	<50
LNB	<1000	<500	<100

Table 3. Title IV NO_x Emissions Limits

lb/10^6 Btu

Phase	I	II
Compliance Date	January 1, 1996	January 1, 2000
Group 1 Boilers		
Dry Bottom Wall-Fired	0.50	0.46
T-fired	0.45	0.40
Group 2 Boilers		
Wet Bottom Wall-Fired > 65 MWe	NA	0.84
Cyclone-Fired > 155 MWe	NA	0.86
Vertically Fired	NA	0.80
Cell Burner	NA	0.68
Fluidized Bed	NA	Exempt
Stoker	NA	Exempt

NA = Not applicable

Table 4. Summary of Performance and Cost Data
1996 Dollars

Coal Properties	Units	Value
Higher heating value (HHV)	Btu/lb	12,000
Power Plant Attributes With Controls		
Plant capacity, net	MWe	300
Power produced, net	10^9 kWh/yr	1.71
Capacity factor	%	65
Coal feed	10^6 tons/yr	0.68
NO_x-Emissions-Control Data		
Removal efficiency	%	64.0
Emissions standard (Title IV)	lb/10^6 Btu	0.46
Emissions without GR-LNB	lb/10^6 Btu	0.73
Emissions with GR-LNB	lb/10^6 Btu	0.26
NO_x removed	tons/yr	3990
Total Capital Requirement	$/kW	26

	Levelization Factor [a]	mills/kWh	$/ton NO_x removed
Levelized Cost, Current $			
Capital charge	0.160	0.73	313
Fixed O&M	1.314	0.25	107
Variable O&M	1.314	1.79	767
Total		2.77	1187
SO_2 credits, $95/ton	1.314	(0.37)	(160)
Total with SO_2 credits		2.40	1027
Levelized Cost, Constant $			
Capital charge	0.124	0.57	244
Fixed O&M	1.000	0.19	81
Variable O&M	1.000	1.36	583
Total		2.12	908
SO_2 credits, $95/ton	1.000	(0.28)	(122)
Total with SO_2 credits		1.84	786

a Levelization based on 15-year project life, 38% tax rate, 4% inflation, and the following capital structure: 50% debt @ 8.5% return, 15% preferred stock @ 7.0% return, and 35% common stock @ 7.5% return.

Table 5. Comparison of Economics
Constant 1996 Dollars
300-MWe Plant Capacity

Technology	NO_x Reduction, %	Capital Cost, $/kWe	Levelized Cost, $/ton of NO_x Removed
GR Only	60	12	527
LNB Only	45	14	227
GR-LNB (Second Generation)	64	26	786
Coal Reburning	50	28	592
SNCR	35	9	700
SCR	50	44	575

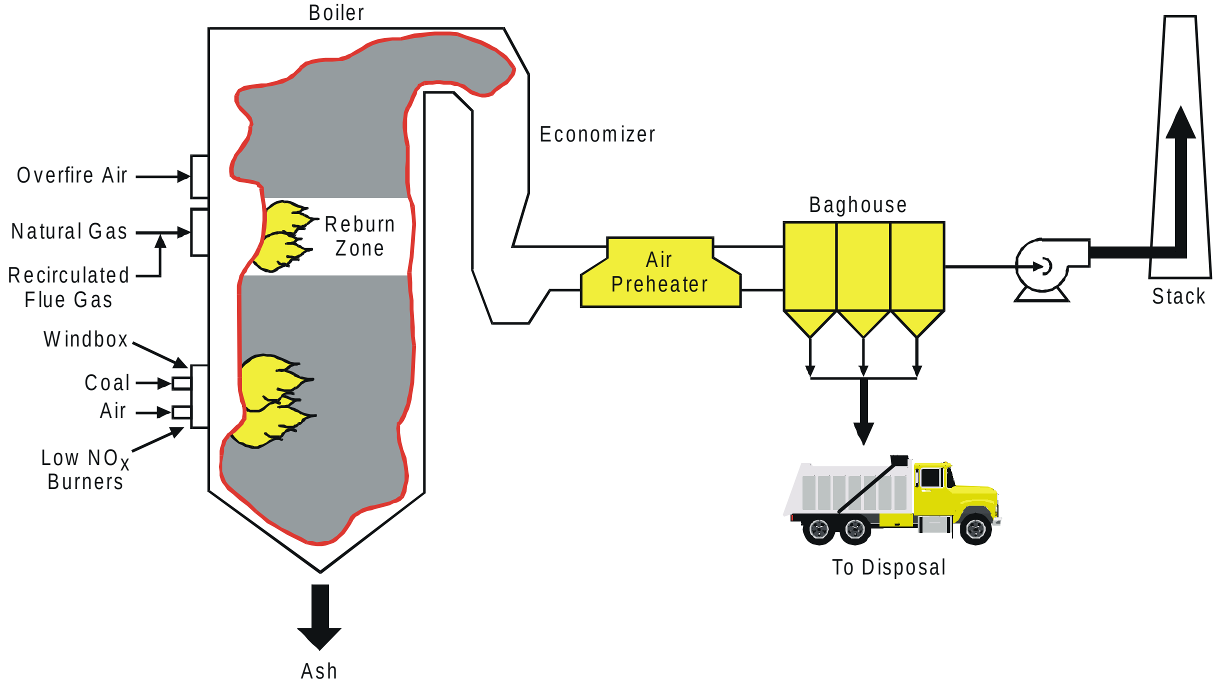

Figure 1. Schematic Flowsheet of GR-LNB Process

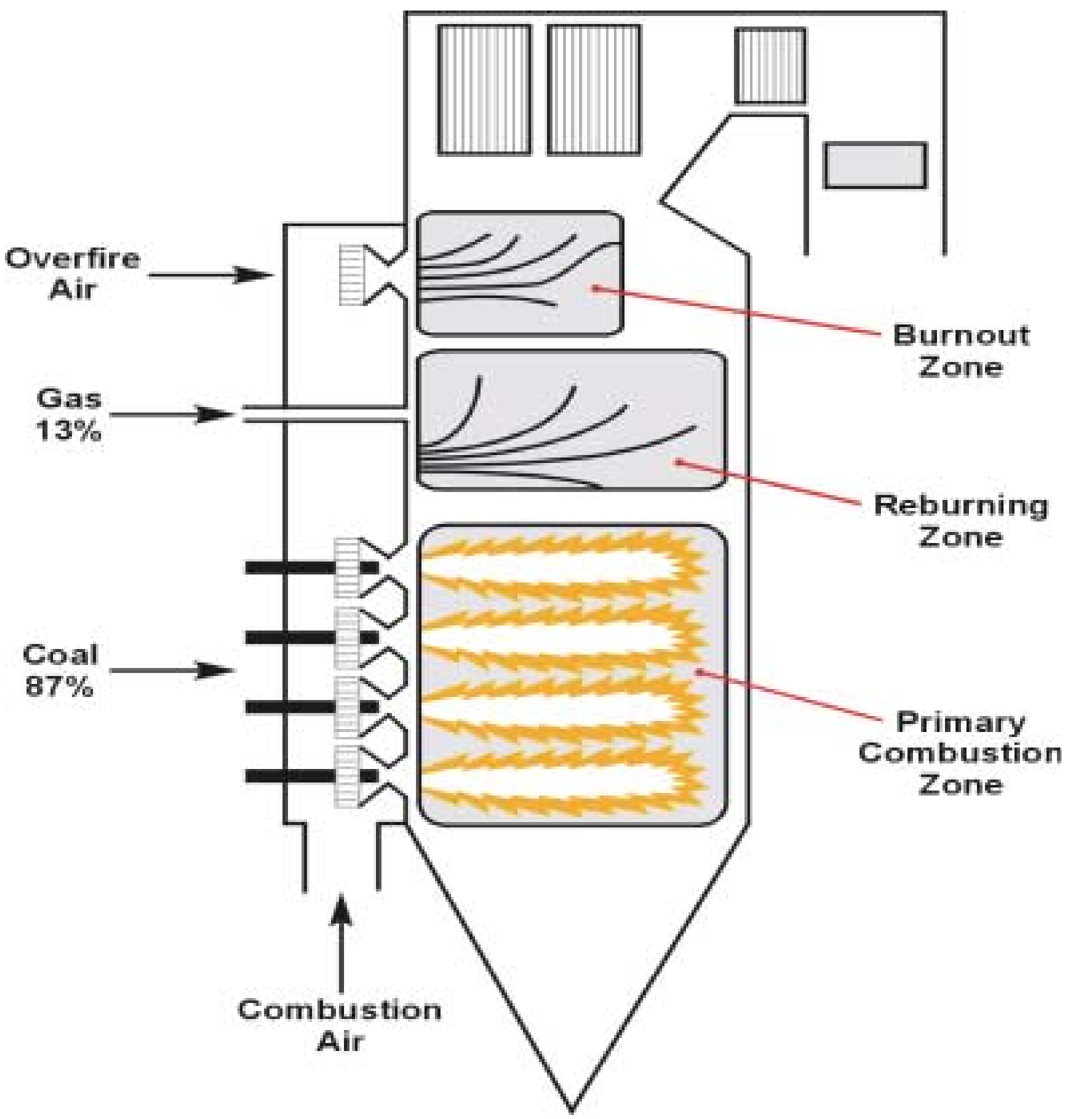

Figure 2. Schematic Flowsheet of Gas Reburning System

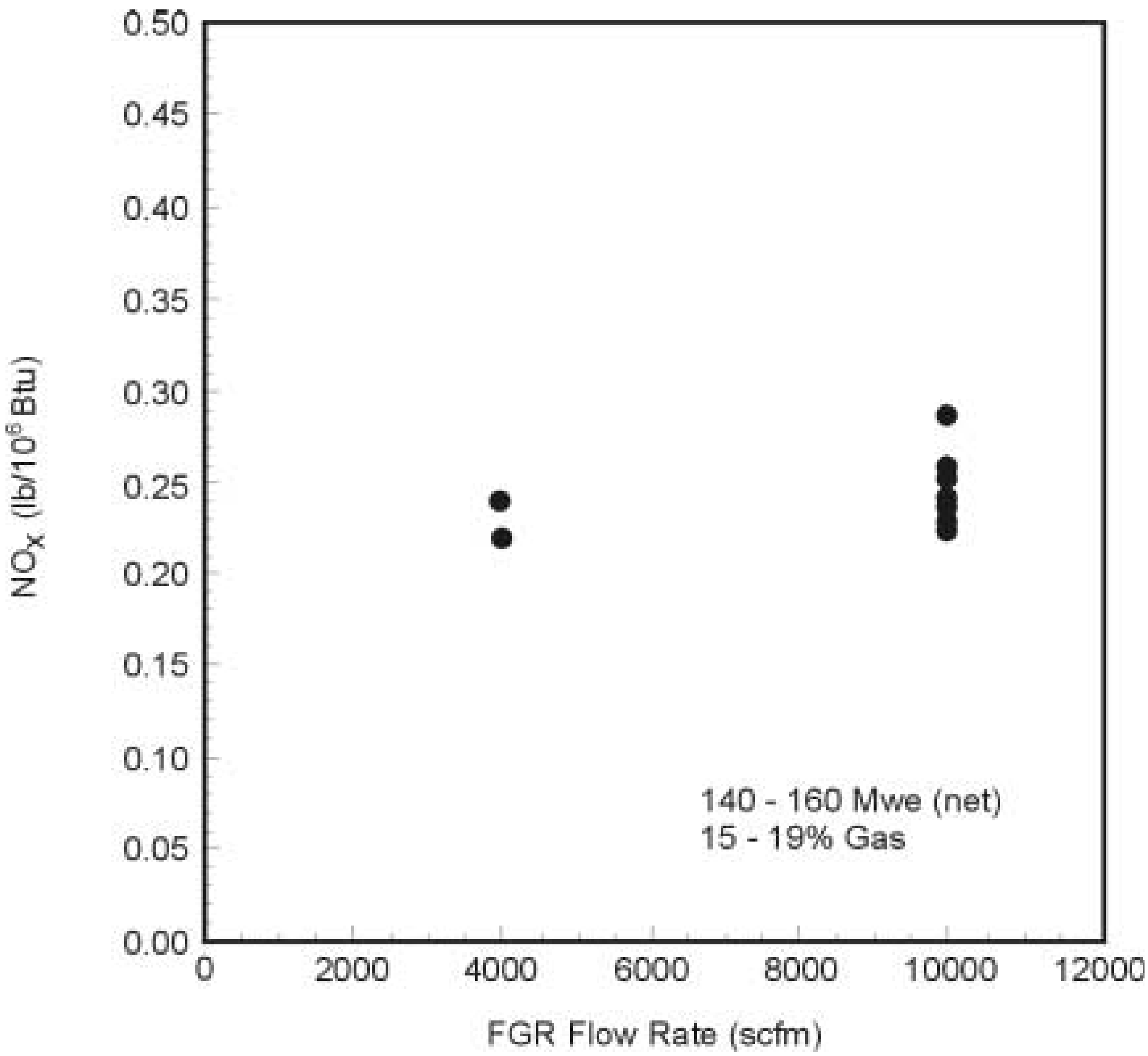

Figure 3. Effect of FGR Flow Rate on NO_x Emissions, First-Generation GR-LNB

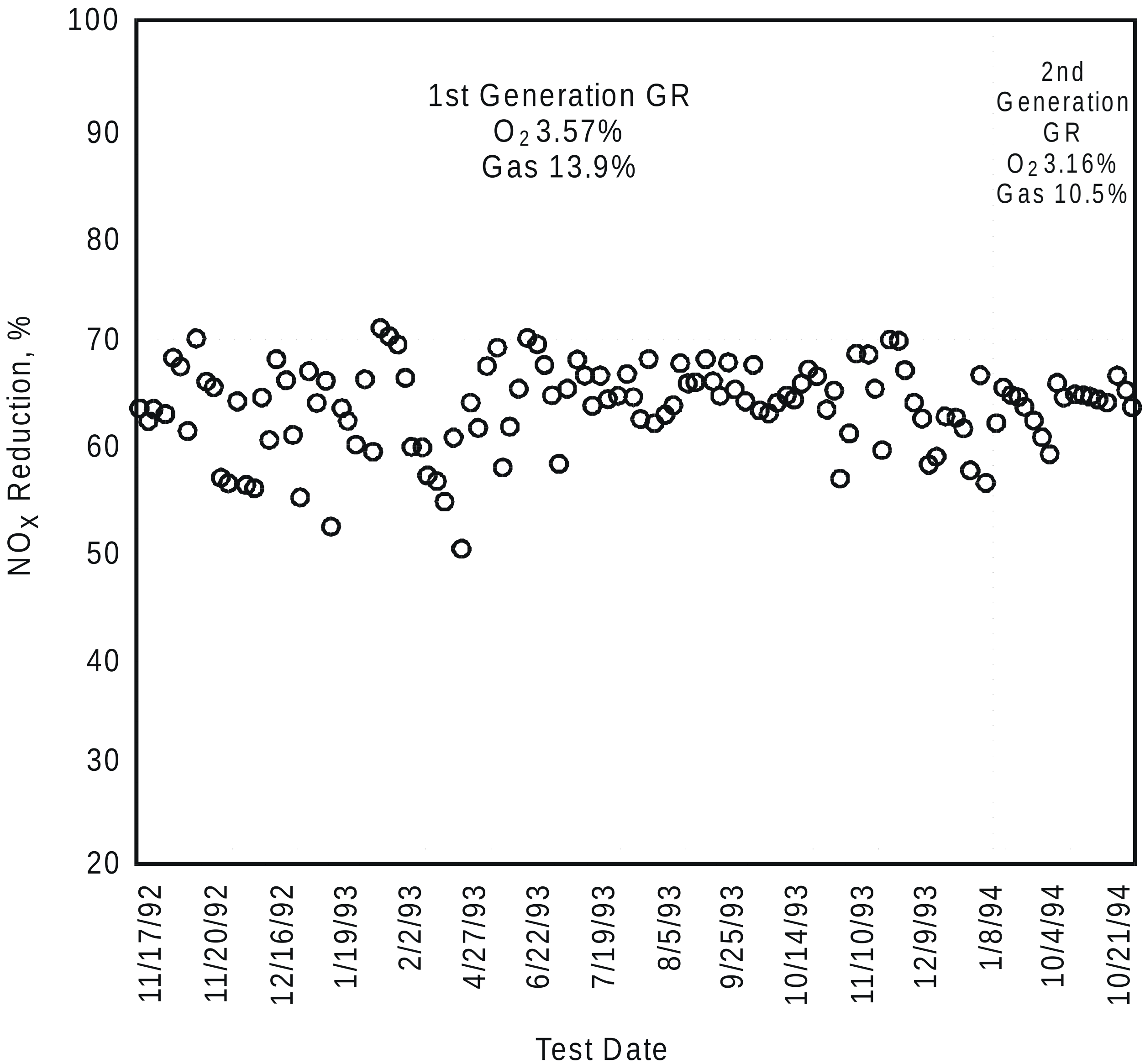

Figure 4. NO_x-Reduction Performance

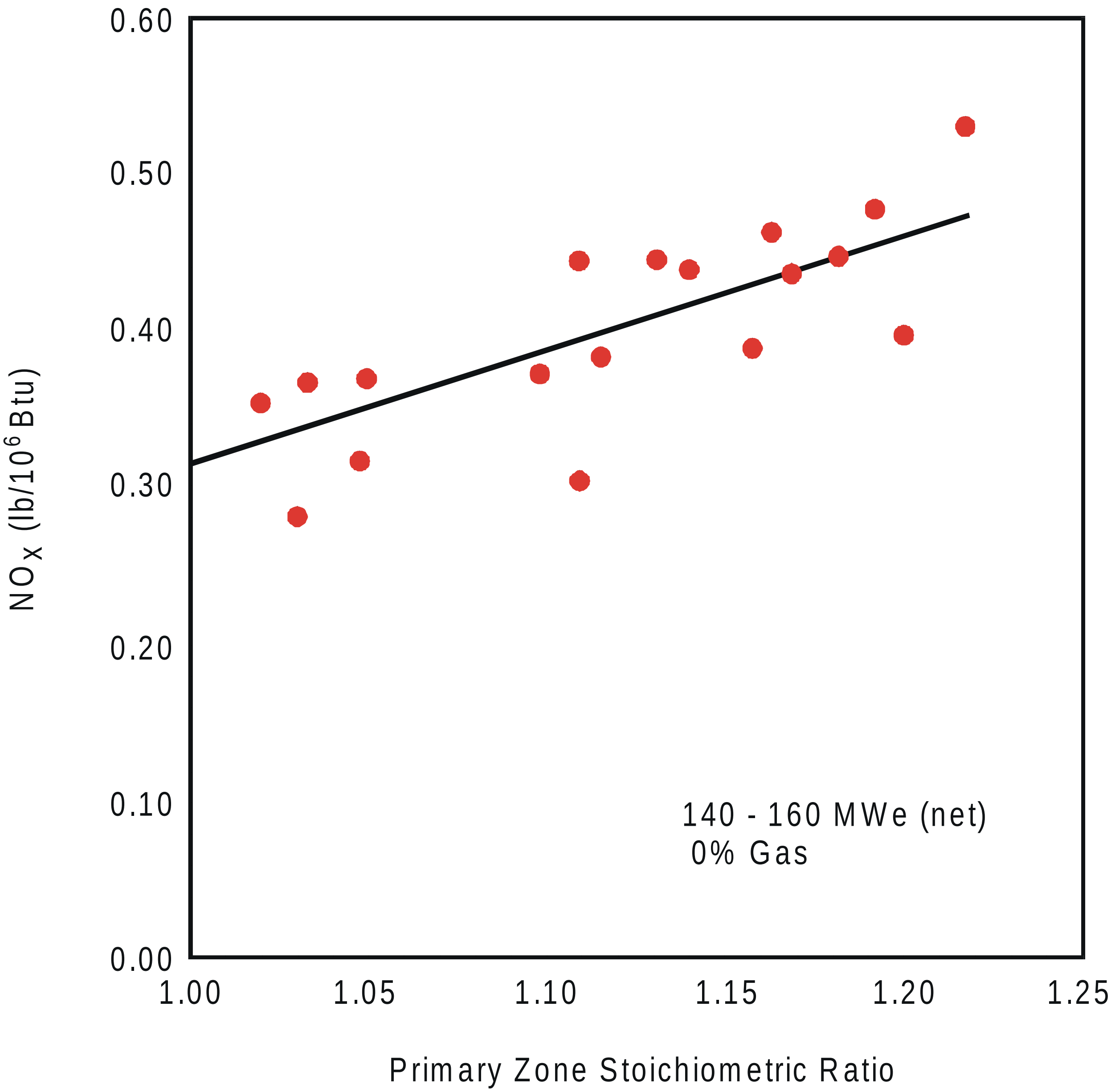

Figure 5. Effect of Primary Zone Stoichiometric Ratio on NO_x Emissions, First-Generation GR

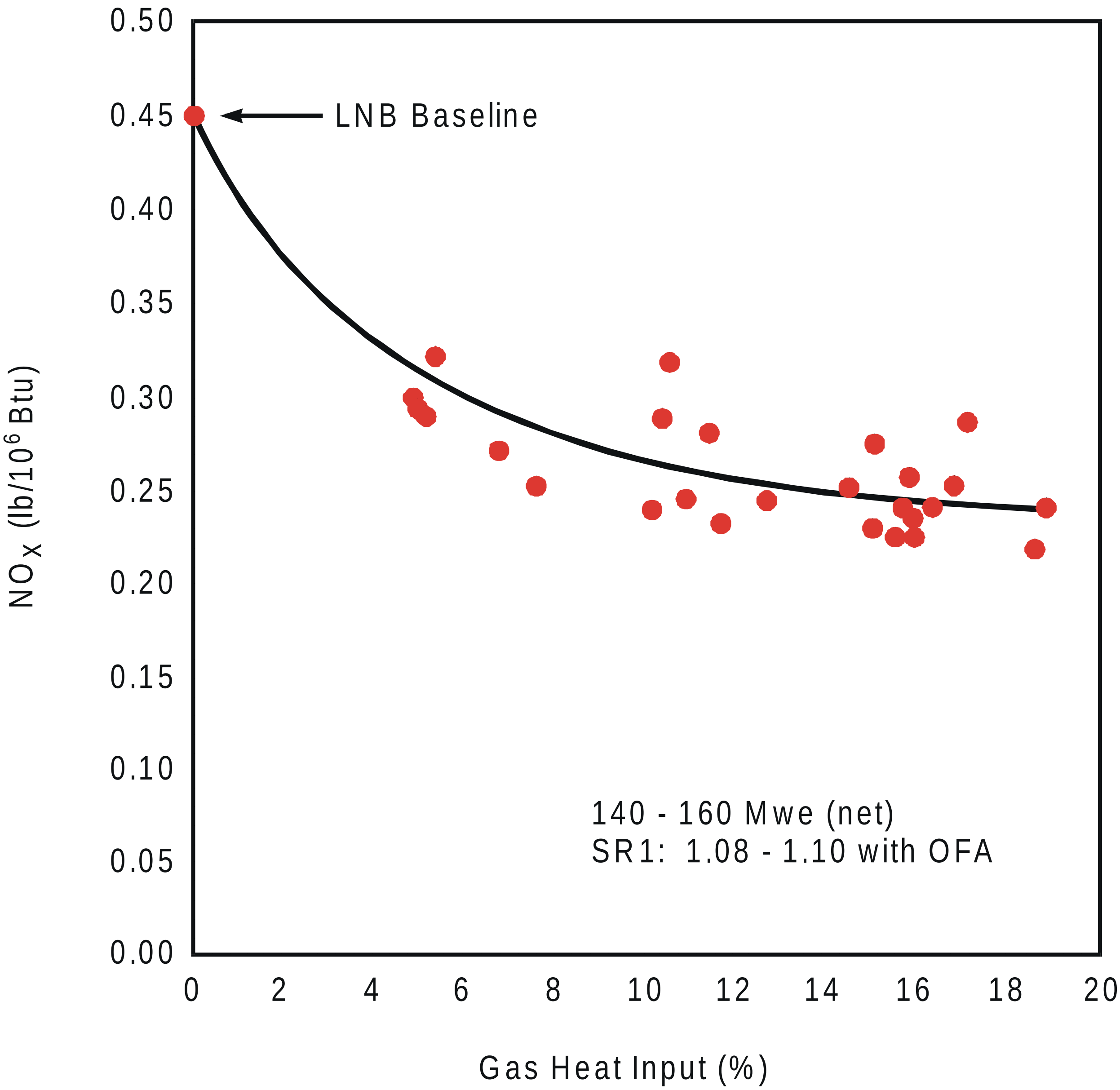

Figure 6. Effect of Gas Heat Input on NO_x Emissions, First-Generation GR

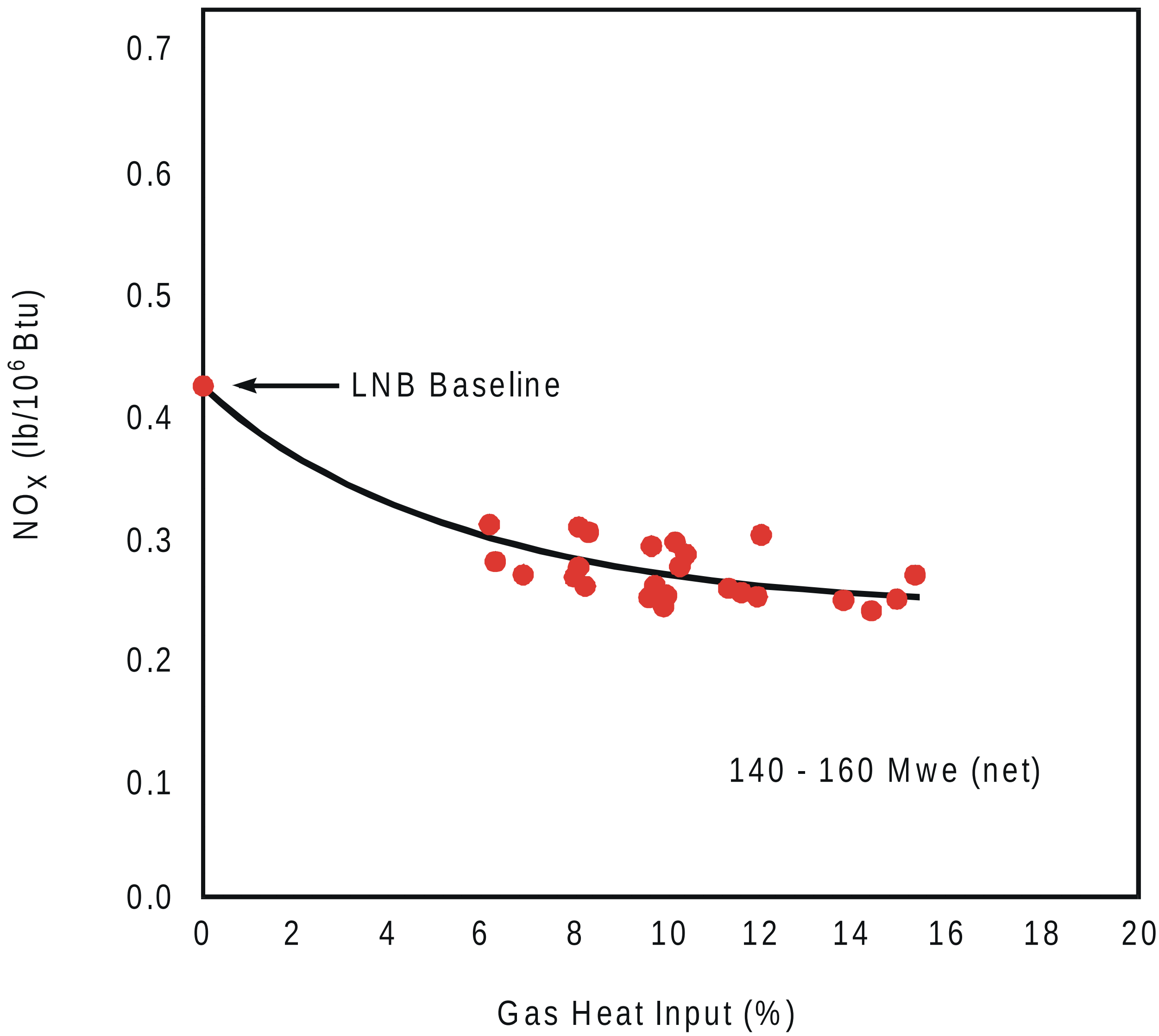

Figure 7. Effect of Gas Heat Input on NO_x Reduction, Second-Generation GR

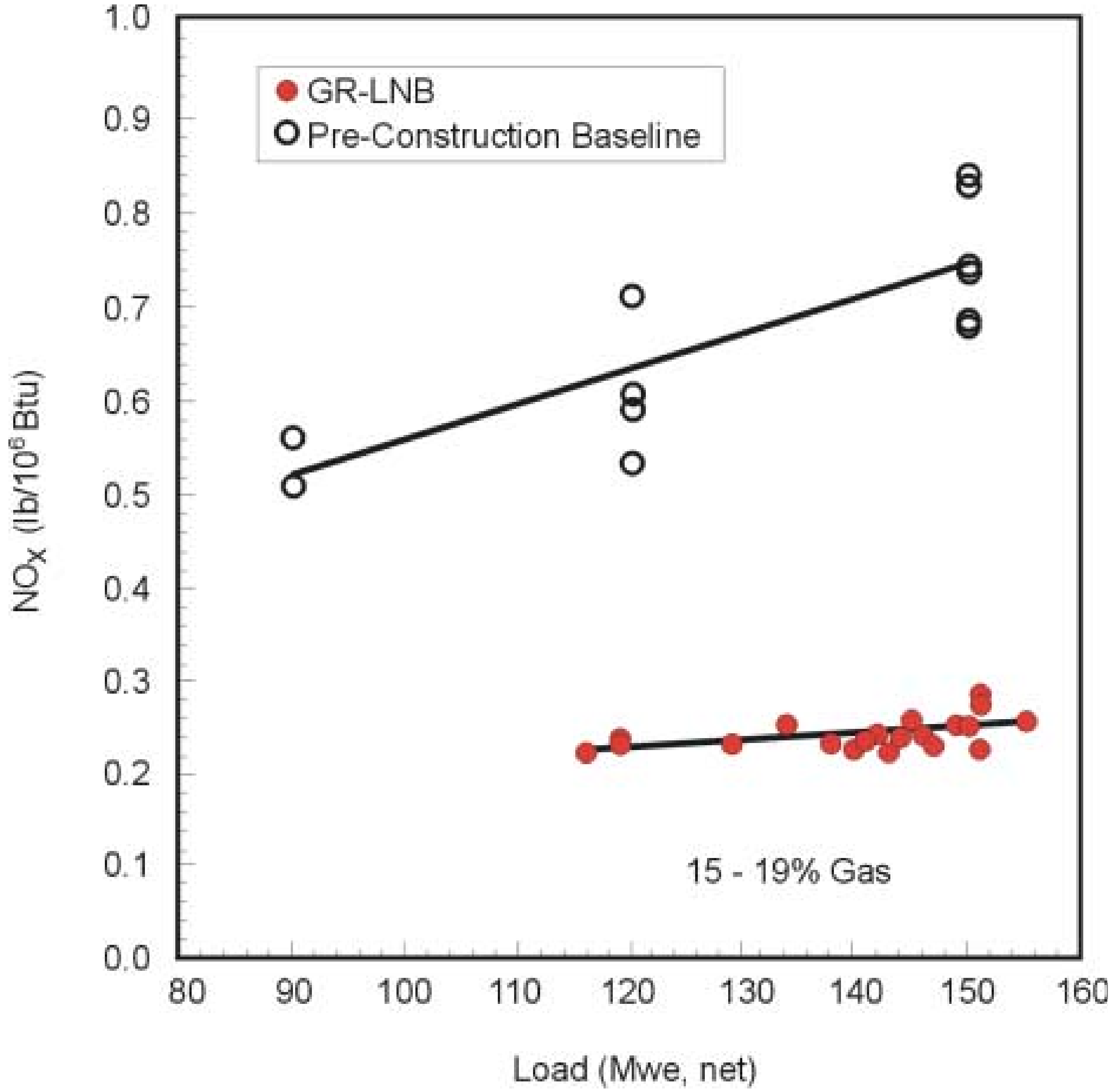

Figure 8. Effect of Load on NO_x Reduction, First-Generation GR

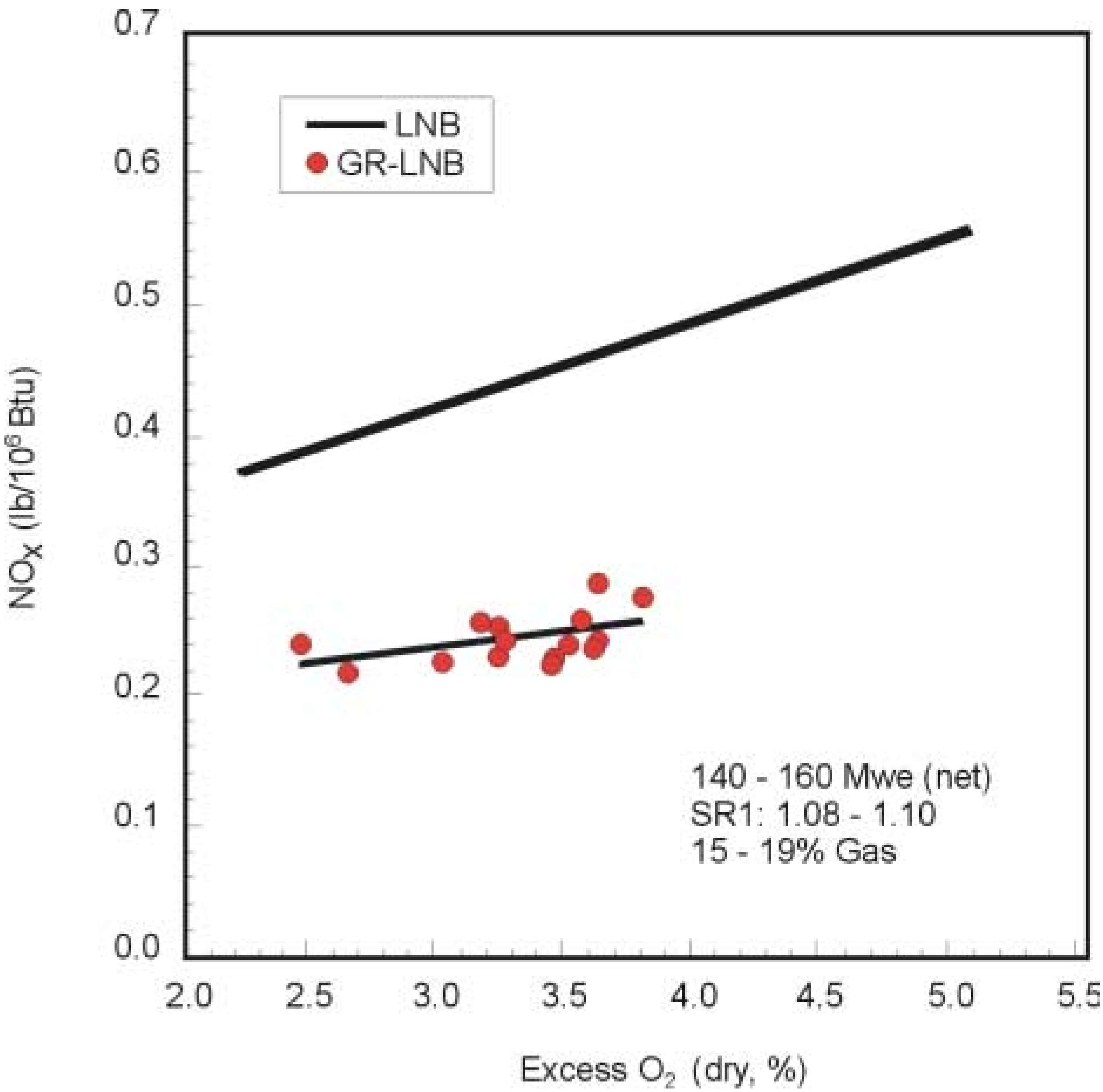

Figure 9. Effect of Exit Flue Gas O_2 Concentration on NO_x Emissions, First-Generation GR

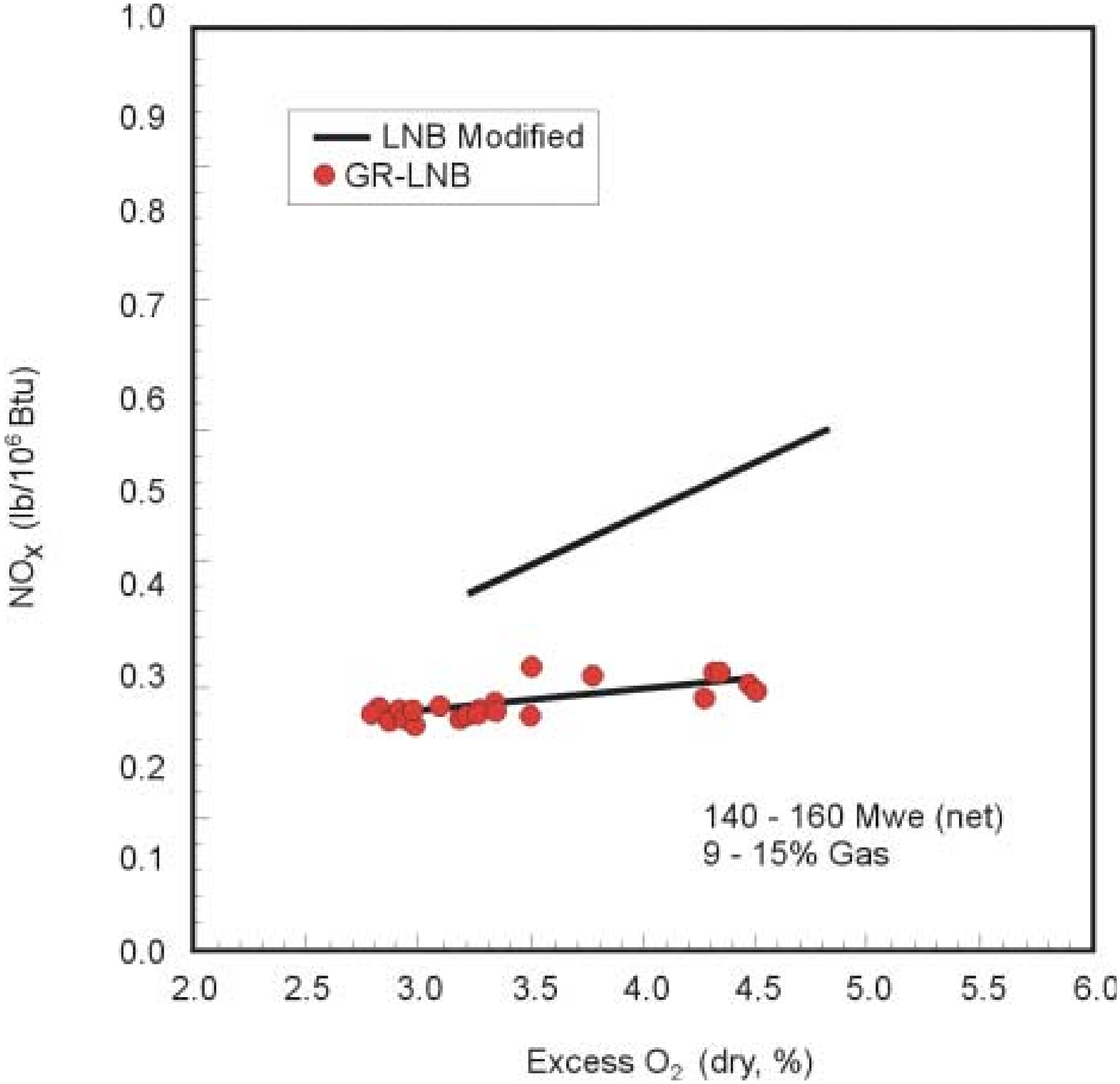

Figure 10. Effect of Exit Flue Gas O_2 Concentration on NO_x Emissions, Second-Generation GR

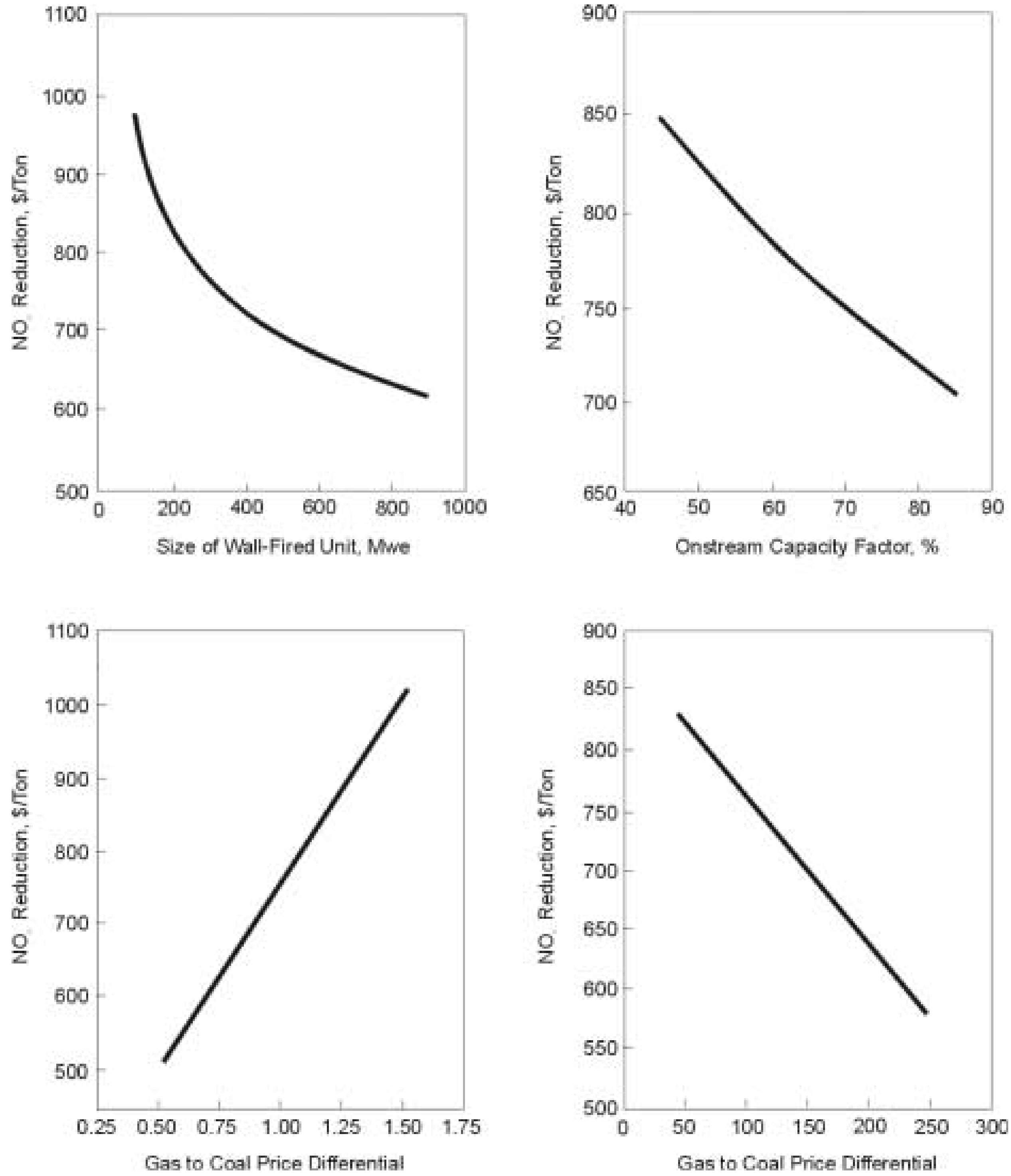

Figure 11. Effect of Operating Variables on Economics of GR-LNB Process

ABBREVIATIONS

CCT	Clean Coal Technology
EER	Energy and Environmental Research Corporation
PSCo	Public Service Company (of Colorado)
NO_x	Nitrogen oxides
GR	Gas Reburning
LNB	Low-NO_x Burners
GR-LNB	Gas Reburning used in conjunction with Low-NO_x Burners
OFA	Overfire Air
NSPS	New Source Performance Standards
CAAA	Clean Air Act Amendments
CH_4	Methane
FGR	Flue Gas Recirculation