Commercial Design Development of Amine Enhanced Fuel Lean Gas Reburn (AEFLGR™) for NOx Reduction in Electric Utility Power Boilers

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Abstract:

Amine enhanced Fuel Lean Gas Reburn (AEFLGR™) offers a highly cost effective, easily retrofitted technology for NOx Reduction. NOx reduction levels of, typically, 50 to 70% are achievable with costs under $1500/ton of NOx removed. Installation entails minimal interruption of plant operations. Substantial interest has developed in commercial applications to enable a number of electric power companies to meet the demands of upcoming tightening in EPA NOx emission requirements.

Data from field experience provides a basis for validating and refining the technology for AEFLGR™ product design. A commercial installation was recently started on two 320 MW electric utility boilers firing bituminous coal. NOx reductions of 60% were achieved from baselines of approximately 1 lb/10^6 Btu. In a recent test program on a 605 MW unit firing powder river basin coal greater than 55% reduction from a baseline of 0.44 lb/10^6 Btu was demonstrated. Each required tuning to the specific operating conditions of these units.

Modeling techniques and injector development provide a basis for the AEFLGR™ design technology. The NOx reduction processes operate under "fuel lean" conditions in the upper furnace. Overall flue gas oxygen content is maintained above stoichiometry. Thus, the cost of an air system for completing combustion is avoided. However, highly reducing conditions are maintained in the jets carrying the hydrocarbon and amine reactants. This requires careful "targeting" of the jets within the furnace. Computational models combined with field measurements are used to target these jets and assess the performance potential for a specific application.

The equipment systems are simple, similar in cost to SNCR systems. Typically the candidate application will have sufficient natural gas capacity, e.g. start-up fuel, to accommodate the gas requirement of 7-10% of total fuel heat input. The amine equipment is essentially an SNCR system. The "FLGR™" and SNCR systems when combined in effect double the reduction that can be achieved separately by either process. Consequently, NOx reduction can be greatly increased over that of the separate processes while maintaining a low cost per ton of reduction.

Introduction

Amine Enhanced Fuel Lean Gas Reburn (AEFLGR™) provides a flexible method for reducing the oxides of nitrogen (NOx) emissions from stationary power plants. The need for flexibility is especially important with the current uncertainties in regulatory requirements. Title IV of the Clean Air Act as amended in 1990 led to requirements affecting many existing utility units. The Ozone Transport Assessment Group (OTAG) has developed additional requirements under Title I. These work toward achieving ozone attainment in 37 eastern states, which is a seasonal summertime problem. Tropospheric ozone formation is closely interrelated with ambient NOx concentration. Recent court challenges to implementation requirements have delayed action on improving air quality. Cost effective, easily installed techniques are important to meeting air quality needs.

AEFLGR™ is another option in post combustion NOx reduction technologies[1]. It provides a synergistic combination of the Fuel Lean Gas Reburn (FLGR™) and NOxOUT® technologies. FLGR™ is licensed from the Gas Research Institute (GRI). NOxOUT® is the urea based selective non-catalytic reduction (SNCR) process commercialized by Fuel Tech, Inc.(FTI). FTI is the exclusive licensee of AEFLGR™. NOxOUT® when combined with a back-end catalyst provides the SNCR/SCR hybrid, NOxOUT Cascade® product. Each and all of these products can be applied to achieve cost effective NOx reduction. They require low capital investment and can be installed with minimal impact on plant operations.

AEFLGR™ Chemistry

The injection of amine enhanced natural gas in the proper temperature window results in chemical reactions that reduce NO to molecular nitrogen within this window. The process relies on using controlled velocity turbulent jets for dispersing the chemical additives in the furnace. The amount of natural gas is controlled so as to maintain an overall fuel lean stoichiometry in the upper furnace.

The chemical kinetic mechanisms of FLGR™ and SNCR have similar selective reactions. The injection of natural gas in hot, low oxygen furnace gas results in the formation of hydrocarbon radicals (CH_i), and the injection of urea (NH_2-CO-NH_2) results in the formation of amine radicals (NH_i). Both of these radicals reduce NO to molecular nitrogen reactions. In very simplified terms (unbalanced):

$$CH_4 + NO \rightarrow \Sigma CH_i + NO \rightarrow HCN + NO \rightarrow N_2 + \ldots$$

$$NH_2CONH_2 + NO + O_2 \rightarrow NH_i + NO + CO + O_2 \rightarrow N_2 + CO_2 + H_2O$$

The detailed chemistry is complex. The Gas Research Institute has developed GRI Mech 3.0[2]. It computes the kinetics of 53 species in 325 steps to predict reburn performance. The temperature window is wide with a range of 1900°F to 2700°F under reducing conditions. With reburn sufficient fuel must be injected to produce reducing conditions. Oxygen is then reintroduced to complete burn-out. Fuel Tech developed its Chemical Kinetic Model (CKM) for predicting SNCR performance. The FTI CKM uses 31 species in 93 reactions. The window is narrower with highly effective performance from 1800°F to 2200°F under oxidizing conditions. The window can be widened to roughly 2500°F when oxygen levels are very low. Computational fluid dynamics (CFD) tools provide information on the furnace conditions affecting the chemistry.

AEFLGR™ achieves effective NOx reduction under overall oxygen available, or fuel lean, conditions. Substantial cost savings are realized by avoiding the need for complex equipment and extensive boiler modifications for installing completion air. The injection of natural gas is limited to about 9% of heat input in order to avoid the need for completion air. In many cases a NOxOUT® system will already exist. It can readily be converted to provide the amine reagent. Using natural gas as a carrier for the amine reagent widens the acceptable reaction temperature window in comparison to the SNCR process, allows amine injection at higher temperatures without amine oxidation to NO, and improves the kinetic rates of the critical chemical reduction mechanisms. The natural gas creates a locally reducing environment for the amine chemistry that raises the acceptable temperature window and prevents the oxidation reactions. Completion of the reactions at higher temperatures also decreases the chances of ammonia "slip", a byproduct of both SNCR and selective catalytic reduction (SCR) processes.

All three of the processes discussed earlier are employed with AEFLGR™. Reduction takes place in the immediate vicinity of gas jets where the local conditions are fuel rich. High temperature SNCR takes place in the region downstream of the jet where oxygen concentrations are still low. Conventional

SNCR provides reduction in the upper furnace regions where temperatures are lower and oxygen and CO conditions are favorable. These effects were studied in Fuel Tech's flame tube laboratory combustion unit. NOx reduction of approximately 5% per percent gas input were achieved in simulation of the FLGR™ process. The reduction could be more than doubled by injecting urea into the gas jet plume.

Modeling to Predict Performance

The challenge is to predict the effect of sensitive processes under complex furnace conditions. CFD modeling does a good job of predicting, with a high level of detail, the flows, temperatures, and species from combustion in the region beyond the firing zone of a combustor. Chemical kinetics models such as GRI Mech 3.0 and FTI CKM require enormous computing power when incorporated within CFD models. The kinetics models tend to become unstable when the number of species and steps are substantially reduced to simplify computation. This is further complicated by the need to use fine CFD griding to capture jet behavior details. Methods that concentrate on the jet dynamics and mixing at the expense of CFD detail may miss critical influences of temperature and velocity.

However, empirical methods for capturing the chemistry can be effective. In Figure 1, the results of computations with GRI MECH 3.0 are shown. NOx and CO emissions are plotted versus fuel-to-oxygen equivalence ratio, the inverse of the air-to-fuel molar ratio to stoichiometry, for three temperatures. The behavior is relatively simple to describe empirically when applied to the appropriate conditions. Separate calculation of detailed kinetics and experience from practice can be applied to calibrate the fundamental behavior. Essentially nothing happens with regard to NOx reduction when the equivalence ratio is less than stoichiometry. Heat release from natural gas raises the local temperature. This can result in NOx formation even at stoichiometry when gas temperatures are already high. CO formation under fuel rich conditions tends to increase with increasing temperature.

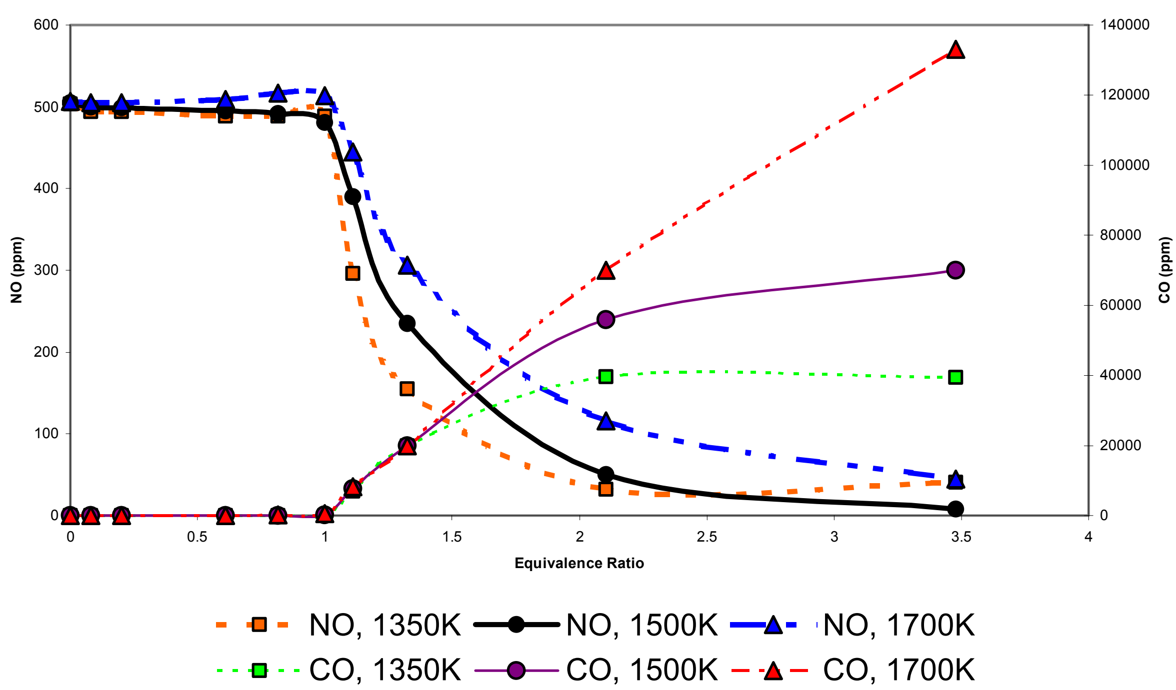

Figure 1

With AEFLGR™ the reducing conditions are found in the vicinity of the gas injection jets. NOx is deeply reduced promptly in this region. Some of the amine reagent participates in reactions to further deepen the local reduction. Visualization from a detailed model of the upper furnace of Carolina Power and Light's Ashville unit #1 is shown in Figure 2. This unit will begin AEFLGR™ start-up this summer. One of a number of AEFLGR™ injectors is shown. The model enables a determination of how much of the total flue gas is affected by the localized jets. The urea co-injected with the jet takes time to evaporate. Consequently, depending on the droplet size selected, a proportion of the amine is released in the regions downstream of the jet. The color contours represent unreacted natural gas. Well down-stream of the jets, conventional SNCR chemistry is calculated.

The dominating effect is the amount of flue gas affected by the jets. The errors introduced by empirical simplification tend to wash out. Over-prediction in an area will be off-set by under-prediction in the remainder of the region. Calibrating factors from experience are used to make adjustments. This is analogous to techniques now in use for NOxOUT®. CFD calculations for NOxOUT® determine the treatment effectiveness. Detailed kinetics in conjunction with a database of field results tunes the results. Prediction precision with AEFLGR™ will improve as experience grows.

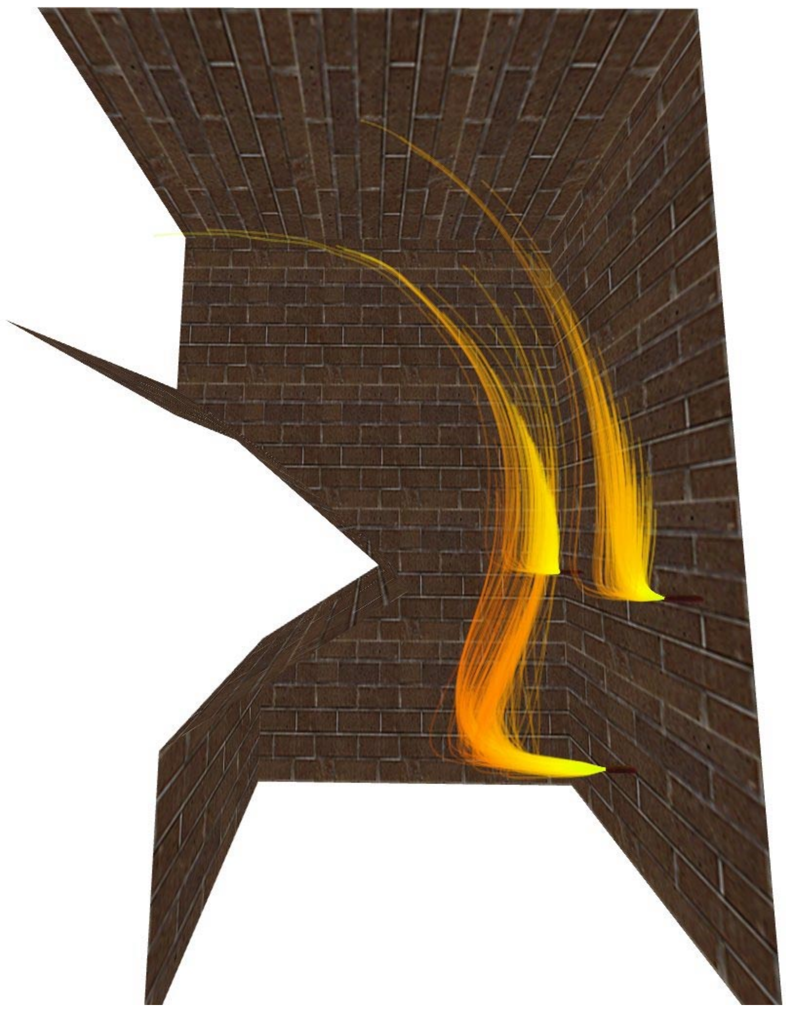

Figure 2

Injector Design

The effectiveness of the process for any mode of boiler operation depends entirely on the location and performance of the injectors. The CFD and kinetics modeling provide information on what will happen when the reburn fuel and urea are injected with a particular set of jet and spray conditions. The injectors are then selected to accomplish the effective strategy.

The injector equipment are designed and fabricated to produce the desired conditions. Jet velocities can be calculated for selections of gas flow and injector diameter. The range of spray performance is most effectively determined with laboratory testing and prototype development. The results from laboratory testing provide a database of injector performance. Figure 3 is a view of the discharge from one prototype injector. Here the urea is kept at the center of the jet. This is desirable in high temperature zones where the urea would promptly oxidize to NOx if exposed to oxygen. Another design enables a well mixed discharge of reburn fuel and urea for zones with cooler temperatures. In other cases it may be desirable to offset the urea spray from the gas jet.

Retractable injector mounts enable automatic control of injector insertion (Figure 4). Automatic controls select and insert the injectors as needed for a particular operating mode. The injectors are purged and withdrawn when not

Figure 3

needed. Should a condition be detected that would be unsafe for injecting gas into the furnace, a rapid shut down of injection is programmed.

AEFLGR™ and NOxOUT® work very well together. The retracts are designed for easy conversion from AEFLGR™ to SNCR operation. It is practical to use AEFLGR™ during the summer ozone season when increased NOx reduction is needed and natural gas is readily available. The system can shift to NOxOUT® during the remainder of the year.

Technology Application

AEFLGR™ has been applied commercially on two 320 MW coal fired unit at PSE&G's Mercer station, achieving 60% average reduction[3]. Start-up was conducted in 1999. Extensive demonstration testing was performed in 1997 and 1998, which led to the commercial project. Performance optimization during the demonstration was largely "seat-of-the-pants" tuning. Modeling is now providing additional insight into why some approaches worked better than others.

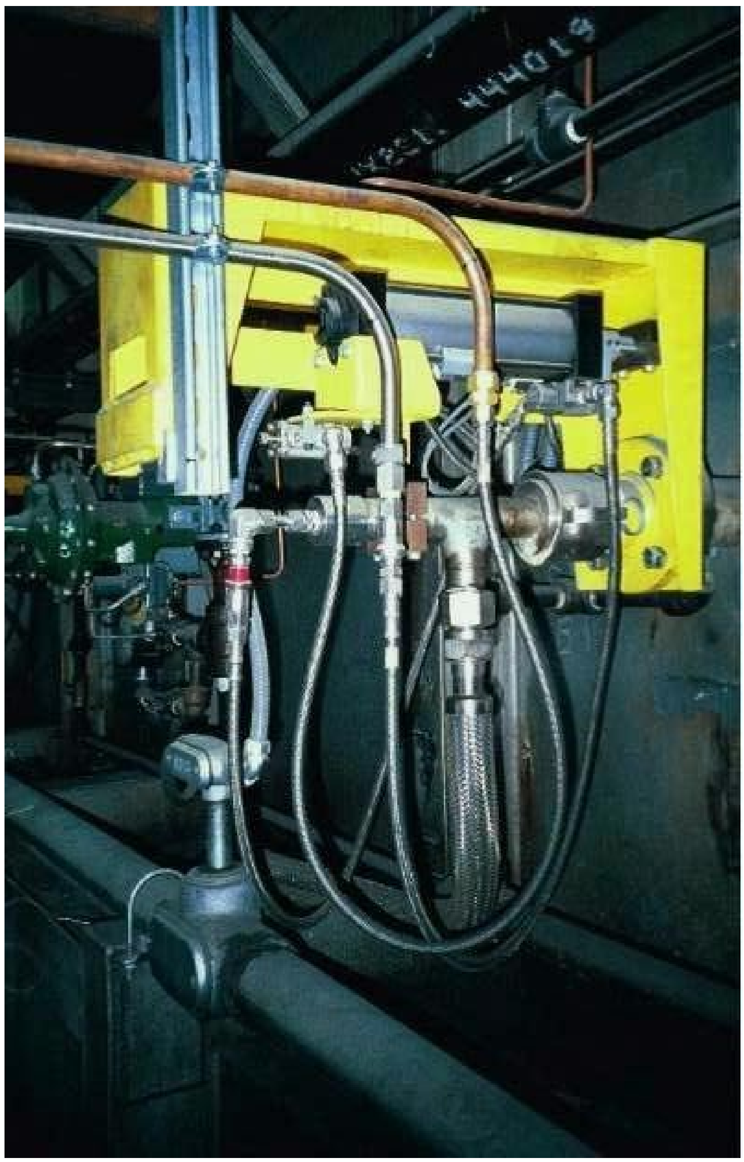

Figure 4

A demonstration program was conducted in 1999 at Wisconsin Electric's Pleasant Prairie Power Plant Unit #1[4]. It is a nominal 600 MW Riley Reheat Type "ISR" Turbo Furnace steam generating unit fueled by Powder River Basis (PRB) coal. At full load, reductions of more than 50% were consistently attained. Baseline conditions were typically in the range of 0.42 to 0.46 lb/10^6 Btu. As experience was gained, reductions improved. In the final testing NOx was reduced to 0.18 lb/10^6 Btu. CFD modeling and temperature probing were performed to identify conditions within the unit. Data from the demonstration provides an additional basis for testing and validating advanced modeling techniques.

The modeling will guide the start-up at CP&L Ashville. This unit is a 210 MWg pulverized coal, wall fired, Riley Stoker unit with low NOx burners. The NOx baseline is 0.58 lb/10^6 btu. Reduction will be provided with NOxOUT® to a guaranteed value of 0.44 lb/10^6 btu. Reduction to below 0.29 lb/10^6 btu is the target with AEFLGR.

Cost Characteristics

The economics of AEFLGR™ are very consistent with that of NOxOUT®. With SNCR modest reduction can be quickly obtained with inexpensive wall injectors. For a 400 MW unit the capital cost is typically around $7/kW installed. Capital costs increase to around $10/kW when more expensive multi-nozzle lances are utilized. These increase reduction while maintaining good chemical utilization. Reduction can be further increased by adding a small amount of catalyst in the back-end. Capital cost then rises to around $20/kW depending strongly on the specific application. AEFLGR has capital cost at about $15/kW. Except for the catalyst option, the amortized capital cost per ton of NOx removed decreases with each step. This is because the gains in NOx reduction effectiveness are proportionately less than the increases in capital.

Chemical cost per ton of NOx reduced does tend to increase with additional steps in any one technology. This a natural result of diminishing returns. The last molecule is always harder to

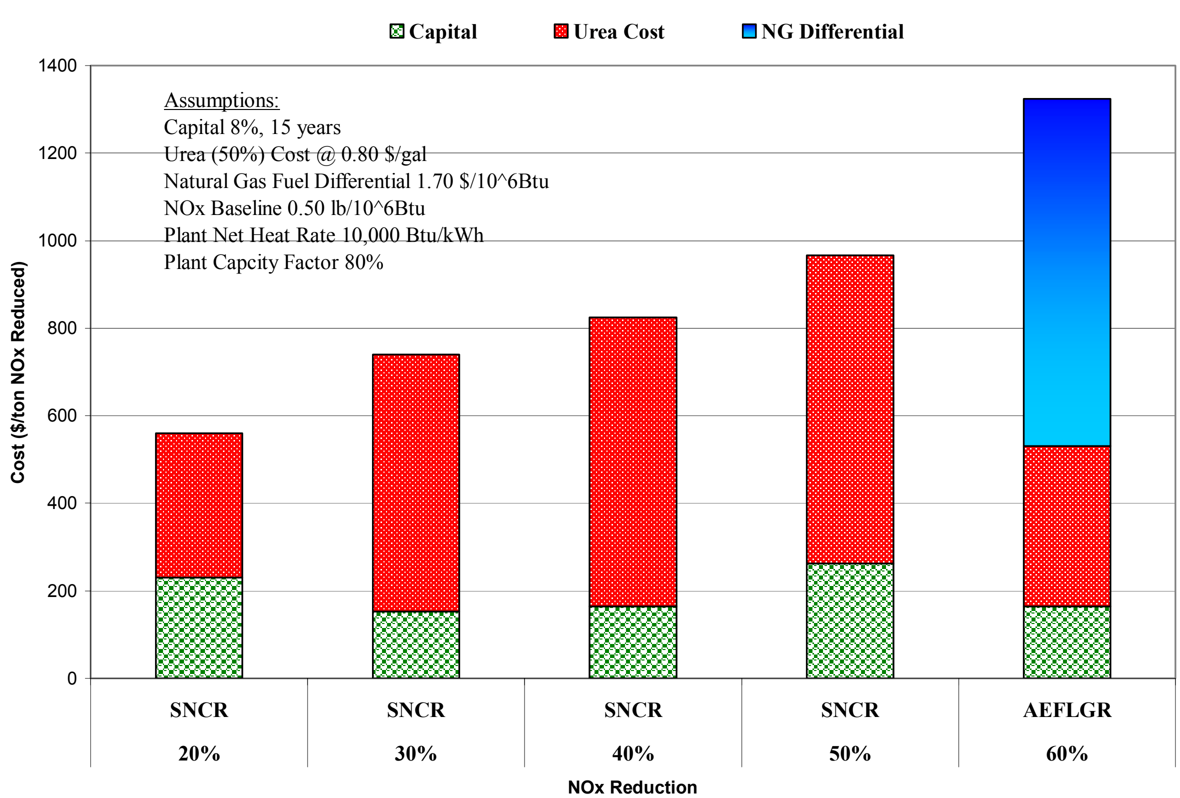

Figure 5

capture than the first. In this regard AEFLGR™ is more a shift than a step in technology. Natural gas is substituted for some of the urea. The dominant operating cost with reburning is the fuel price differential for natural gas. This assumes of course that natural gas is readily available on the site. This is often the case since AEFLGR uses less than 10% heat input from natural gas.

Typical cost trends are plotted in Figure 5 for various levels of reduction. The assumption is for a typical large electric power boiler firing coal. The capital costs per kW of capacity tend to decrease with increasing boiler size. Capital is amortized over 15 year with an 8% internal rate of return. A urea cost of $0.80/gallon was used. Natural gas fuel differential is $\$1.70/10^6$ Btu. A NOx baseline of 0.50 $lb/10^6$Btu was used. Plant heat rate is 10,000 btu/kWh and plant capacity factor was assumed as 80% of MWh annual potential at MCR. The capital costs in $/kW are as described previously. These assumed values are sufficient to compute the cost per ton of NOx reduced for capital and reagent consumption. By comparison, other operating costs such as maintenance, power, and water are small.

In Figure 5 the cases for 20% and 30% represent a system using only wall injectors. For 40% reduction multi-nozzle lances are selected with the expectation that temperatures are hot and residence time short as is common with a large utility power boiler. A small catalyst is used to control improve reagent utilization and control ammonia slip as reduction with SNCR is extended to 50%. At 60% the AEFLGR™ is designed with reburn fuel at 7% of heat input and urea at a normalized stoichiometric ratio (NSR) of 1.0 relative to untreated baseline.

The cost increases with rising reduction are nearly linear. With a single pollution control technology the norm is that costs increase as a power function of efficiency. The effectiveness comes with the stepwise applicability of the available options. Reburn is strongly affected by fuel cost differential, which has seen recent rapid increases that may return to normal economic levels.

AEFLGR™ is a highly cost effective method for post combustion NOx reduction. The design methods for predicting performance are developing rapidly. Recent applications have provided a basis for testing design techniques. Upcoming projects provide the opportunity for fully validating the technology.

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