The U.S. Department of Energy–National Energy Technology Laboratory's NOx Control Program for Coal-Fired Power Plants

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ABSTRACT

The environmental performance of the United States' fleet of coal-fired boilers has steadily improved over the last three decades in response to concerns on the potential impact of emissions on the environment. Emissions of sulfur dioxide (SO_2), nitrogen oxide (NOx), particulate matter (PM) have been significantly reduced during this period while coal use has almost doubled. However, further restrictions on emissions from power plants have been proposed in response to issues such as mercury, acid rain, ground-level ozone, nitrification of aquatic ecosystems, ambient fine particulate matter, and visibility impairment (regional haze). Several multi-pollutant bills have been offered in Congress, including the President's Clear Skies Act, to further control power plant emissions

In response to these environmental challenges, the U.S. Department of Energy-National Energy Technology Laboratory (DOE-NETL) is carrying out a comprehensive, integrated research and development (R&D) effort under its Innovations for Existing Plants (IEP) Program The overall goal of the IEP Program is to continue to enhance the efficiency and environmental performance of the existing fleet of fossil-fuel-fired power systems that represent more than 320 gigawatts of generating capacity as well as apply these concepts to advanced power systems. An important component of the program is the R&D of advanced NOx control technologies. This effort focuses primarily on systems capable of controlling NOx emissions to a level at or below 0.15 lbs/million Btu at a cost significantly lower than state-of-the-art technology. The research also provides an improved understanding of the impact of these advanced technologies on related issues such as unburned carbon, waterwall wastage, and mercury speciation and capture. NETL's portfolio of NOx control technology R&D projects encompasses laboratory studies, modeling, and full-scale demonstrations. The success of the projects is intimately tied to key collaborations and partnerships established with industry, federal, state, and local agencies, and the academic and research communities. This paper will provide an update on the status of these projects covering ultra-low-NOx burners (LNB), selective non-catalytic reduction (SNCR), selective catalytic reduction (SCR), and enhanced-oxygen combustion.

BACKGROUND

Coal consists of both organic and inorganic matter. In the high-temperature environment during and after the combustion process, the components of coal and air are physically and chemically transformed into a suite of products. One of the products is nitrogen oxides (NOx), which can be formed by (1) nitrogen and oxygen in the combustion air reacting at high temperature to produce "*thermal NOx*" and (2) fuel-bound nitrogen reacting with the combustion air to produce *"fuel NOx."* The amount of NOx formed depends on numerous factors including flame temperature, nitrogen content of the coal, combustion excess air, residence time, and degree of mixing.

The emission of NOx to the atmosphere can contribute to a number of environmental concerns. NOx can react with volatile organic compounds in the presence of sunlight to form ozone. NOx is also a precursor to secondary fine particulate matter that may impact human health or contribute to regional haze and can form acidic compounds ("acid rain") through reactions with water, and oxidants in the atmosphere. The deposition of nitrogen compounds in and around bodies of water has been linked to "eutrophication" – an over-enrichment of nutrients that can deplete the oxygen content of lakes and rivers. Atmospheric deposition has been identified as a primary source of nitrogen in the Chesapeake Bay. EPA has recently proposed using the Clean Water Act as a mechanism to further reduce NOx emissions near sensitive waters. Finally, one compound of NOx, nitrous oxide (N_2O), is a greenhouse gas.

Since passage of the 1990 Clean Air Act Amendments (CAAA), the U.S. electric-utility industry has taken considerable action to control emissions of NOx. Title IV (the "acid rain" provision) of the CAAA consisted of a two-phase strategy to reduce NOx emissions from electric-utility boilers. For Phase 1, EPA promulgated emission limitations for two boiler types – dry-bottom, wall-fired boilers and tangentially fired boilers (known as Group 1 boilers). Starting January 1, 1996, dry-bottom boilers were required to meet a 0.50 lbs NOx/MMBtu emission limit, while T-fired boilers were limited to 0.45 lbs NOx/MMBtu.

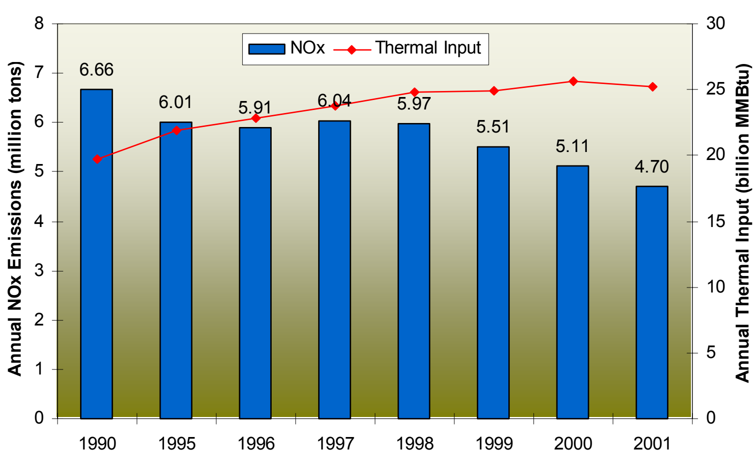
In Phase II of the Title IV Program, EPA determined that more effective low NOx burner (LNB) technology was available to establish more stringent standards for Group 1 boilers not impacted by Phase I. Also, Phase II established limitations for other boilers known as Group 2 (wet bottom boilers, cyclones, cell burner boilers, and vertically fired boilers) based on technologies that are comparable in cost to LNB. Beginning in 2000, Group I units were required to meet NOx emission limits of 0.40 (T-fired) or 0.46 (wall-fired) whereas the Group II units needed to comply with limits between 0.68 to 0.86 lbs NOx/MMBtu. These new standards targeted the NOx reductions from the Title IV Program to 2.1 million tons per year below 1980 levels.

NOx emissions from coal-based power production are also affected by Title I of the 1990 CAAA. Title I addresses six priority pollutants including ozone. The CAAA established the Ozone Transport Commission (OTC) to help states in the Northeast and

Mid-Atlantic region (Connecticut, Delaware, District of Columbia, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and Virginia) meet the National Ambient Air Quality Standard (NAAQS) for ground-level ozone. The goal of the OTC is to reduce effected states' annual NOx emissions from the 1990 baseline of 473,000 to 141,000 tons. The OTC states established a three phase approach for reducing NOx emissions from large combustion sources. Phase I involved year-round Reasonably Available Control Technology (RACT) controls to achieve a 40% NOx reduction. Phases II and III focused on NOx reductions during the summer ozone season of May 1st through September 30th. Phase II started in 1999 with a target emission of 0.20 lb NOx/MMBtu and the more stringent Phase III began in 2003. Subsequent to the initial plan, Phase III reductions have been replaced by the broader regional cap and trade program under EPA's NOx SIP Call. The emission reduction targets under the NOx SIP Call are comparable to the original OTC Phase III reduction targets, approximately 70% from 1990 baseline levels.

In October 1998, EPA promulgated a rule for reducing regional transport of ground-level ozone beyond the OTC states' borders. Currently, 21 eastern states and the District of Columbia have been required to submit State Implementation Plans (SIP) to address ozone transport through reductions in NOx emissions. Under what is commonly referred to as the NOx SIP Call, most states as part of their compliance strategy, have readily adopted EPA's application of a population-wide 0.15 lb NOx/MMBtu emission rate for large electricity generating units (EGUs) and utilization of a cap and trade program. Impacted states of the OTC (Connecticut, Massachusetts, Rhode Island, New Jersey, New York, Delaware, Maryland, Pennsylvania, and District of Columbia) have a May 1, 2003 compliance date. All others (Alabama, South Carolina, Tennessee, Illinois, Kentucky, North Carolina, Ohio, Virginia, West Virginia, Indiana, and Michigan) have a compliance date of May 31, 2004 with the exception of Georgia and Missouri, which have May 1, 2005. Once fully implemented, EPA estimates that the SIP Call will reduce total summertime emissions of nitrogen oxides by about 1.2 million tons.

Title IV has dramatically decreased NOx emissions from 1990 to 1999. Since 1999, the utility industry's initial response to the OTC Program and the NOx SIP Call of Title I has continued the downward trend in NOx emissions. This feat was accomplished in a time of increasing thermal input (a measure of fuel burned to produce electricity) as the demand for electricity increased. This trend in decreasing NOx emissions appears to continue for the foreseeable future as additional NOx reductions are required by current legislation to address regional haze and the NAAQS for fine PM and 8 hour ozone standards as well



as proposed multi-pollutant legislation such as the President's Clear Skies Act.

DOE-NETL NOx Control Program

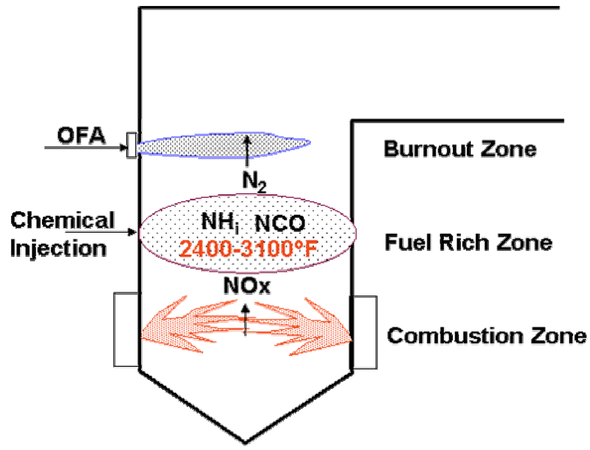
The Office of Fossil Energy's National Energy Technology Laboratory (NETL) is teaming with industry and academia through its Innovations for Existing Plants (IEP) Program to research and develop advanced NOx control technologies. The electric power generating industry is the second largest producer of NOx in the United States, responsible for over 22% of the emissions. Prior to 1990, coal-fired boilers represented slightly above 50% of the U.S generating capacity, but accounted for nearly 90% of 6.7 million tons of NOx emitted As a result of regulations and the corresponding technologies implemented on coal-fired facilities, the 2001 utility NOx emissions have been reduced to 4.7 million tons.

The success in achieving this reduction in NOx for Title IV of the CAAA can be attributed largely to the adoption of the low NOx burner (LNB) technology by the utility industry. These advanced burners control the interaction of air and fuel in a manner that reduces the formation of NOx. The LNBs which are currently installed in 75% of the nation's coal burning power stations are a direct result of the Clean Coal Technology Program's government–industry partnerships.

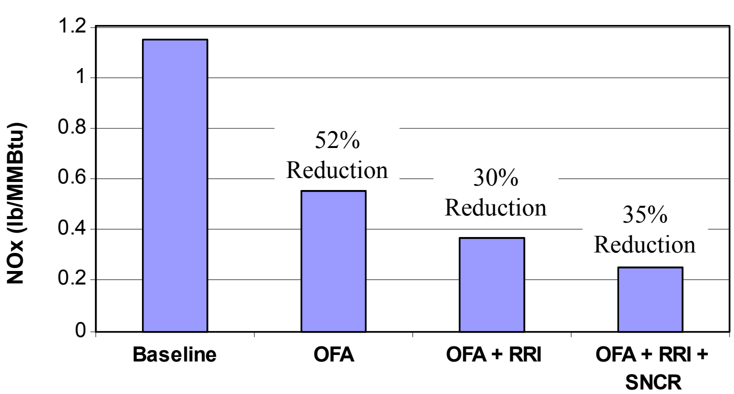
The continuing ratcheting down of NOx emissions by new regulations resulting from Title I and the President's recently proposed Clear Skies Act, which has a target NOx cap of 1.7 million tons, will require some plant emissions to be reduced to 0.15 lb/MMBtu and others to 0.11 lb/MMBtu. To meet these challenges, power producers will need to retrofit existing boilers with additional NOx control technologies, some of which will adversely impact plant efficiency and performance. The new NOx requirements, which demand an increase in R&D, capital, and operating expenditures from utilities to implement, come at an inopportune time for an industry that has been adversely impacted financially by deregulation and the associated capital market pressures, aging facilities, homeland security, in addition to the environmental issues.

In response to the environmental concerns and the prevailing market conditions facing the utility industry, the IEP Program develops and manages a portfolio of cost effective NOx control projects resulting from strategic partnerships. The specific performance target is a NOx emission limit of 0.15 lb NOx/MMBtu or lower while achieving a levelized cost savings of at least 25% over state-of-the-art control technology, which is defined as Selective Catalytic Reduction (SCR). The levelized cost is based on uncontrolled NOx levels and includes the total cost of all NOx control systems required to achieve the emissions target. However in a cap and trade program, it is realized that low cost NOx control technologies that do not achieve the target can still have a prominent role in reducing NOx. Further, the technologies under development are: (1) to have negligible impact on balance-of-plant issues; (2) applicable to a wide range of boiler types and configurations, and (3) capable of maintaining performance over a wide range of feed coals and operating conditions. The projects also provide an improved understanding of the impact of these advanced technologies on related issues such as unburned carbon, waterwall wastage, and mercury speciation and capture The research portfolio includes advanced combustion controls, advanced flue gas treatment, and integrated control systems.

Rich Reagent Injection for Cyclone Burners

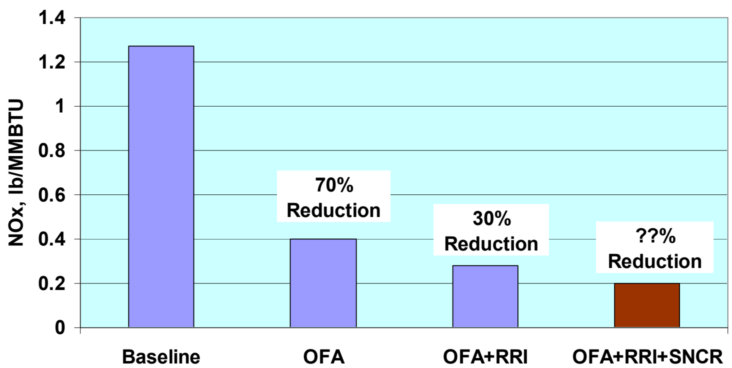


Cyclone burners create an intense flame that is so hot that it melts the ash to form slag. The high temperature generated by this burner results in higher uncontrolled NOx emissions, typically exceeding 1.2 lb/MMBtu. Research has shown that the injection of ammonia (NH_3) or urea into the high temperature NOx-containing flue gases can lead to significant noncatalytic NOx reductions. With support from EPRI's Cyclone NOx Control Interest Group (CNCIG), Reaction Engineering International (REI) has developed, implemented, and tested an enhanced chemistry model with their proprietary Computational Fluid Dynamics (CFD) code *GLACIER* to simulate this process, named Rich Reagent Injection (RRI). The concept of RRI applied to staged cyclone fired furnaces is to use a nitrogen-containing additive to increase the NOx reduction rate in the lower furnace. Field testing of RRI has been successfully completed at the commercial scale at Conectiv's 138 MW B.L. England Unit 1 and AmerenUE's 500 MW Sioux Unit 1.



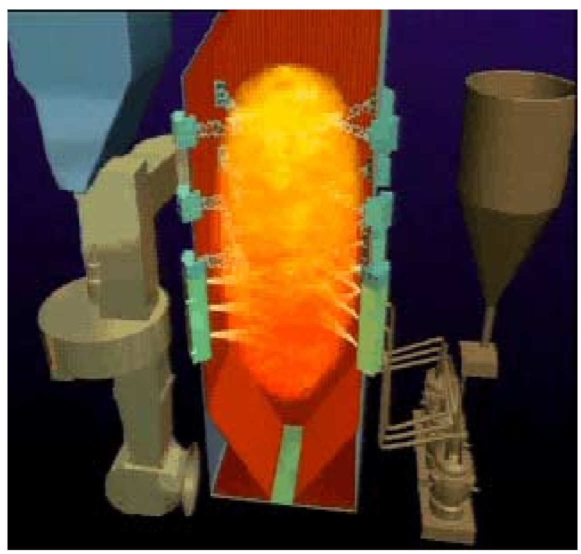
At Conectiv's B.L. England Unit 1, prior installation of overfire air (OFA) has reduced uncontrolled NOx emissions from 1.2 lb/MMBtu to 0.5 lb/MMBtu. An existing SNCR system reduces these emissions an additional 30%. REI's combustion simulation software was used to design an amine-based injection system for the staged lower furnace and to evaluate NOx reduction performance of the RRI system. Field-testing confirmed modeling predictions and demonstrated that the RRI system alone could achieve 25-30% NOx reduction beyond OFA levels with less than 1 ppm ammonia slip and that the inclusion of SNCR could achieve an additional 35% NOx reduction to 0.25 lb/MMBtu with less than 5 ppm NH_3 slip.

The objective of the testing at AmerenUE's Sioux Unit 1 was to determine whether similar performance could be obtained with RRI in a significantly larger unit. The field test results were found to be consistent with the CFD model predictions, both showing NOx reduction of 30% to 0.27 lb/MMBtu to be achievable with RRI from full load baseline emissions with OFA of 0.38 lb/MMBtu. These reductions were achieved with no predicted or measurable ammonia slip. Modeling of this unit also suggests that NOx reductions could be improved through modification



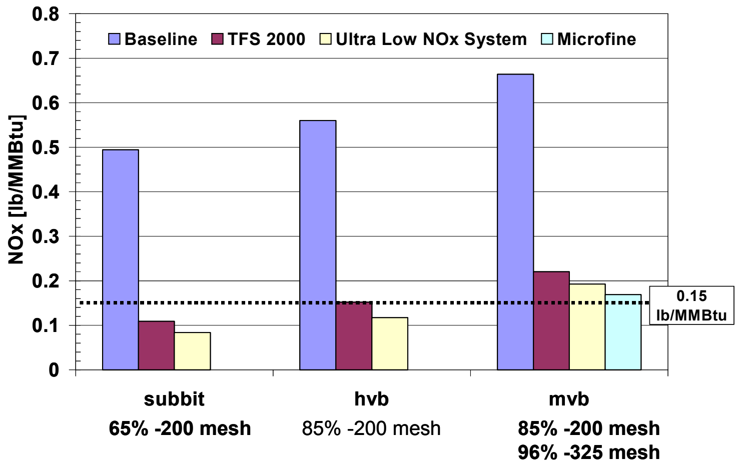
of FGR operation, reduction of lower furnace stoichiometry or utilization of SNCR. Although the target emissions of 0.15 lb/MMBtu was ambitious for this style of burner, these results are substantial when compared to the Title IV NOx limit of 0.86 lb/MMBtu for cyclone-fired boilers. These units, which account for only 8% of the US generating capacity, emit nearly 20%of the coal-fired NOx emissions.

Low NOx Firing System for Tangential-Fired Boilers



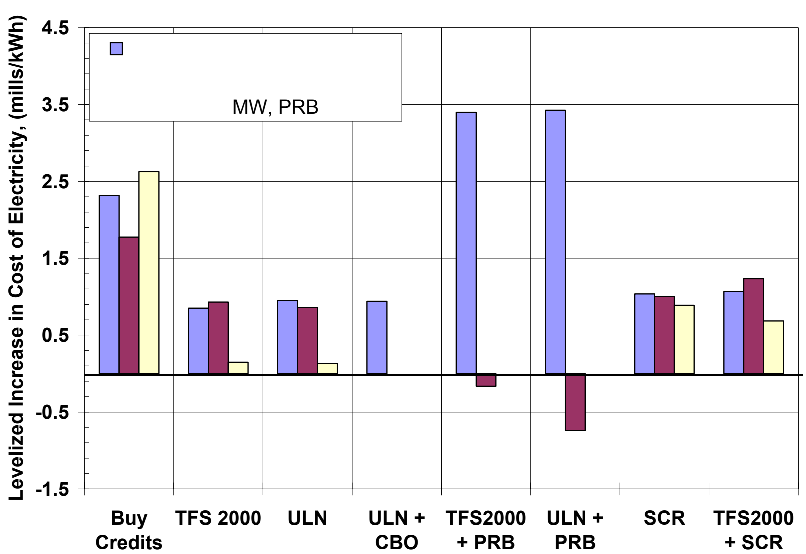
ALSTOM Power Inc.'s Power Plant Laboratories recently completed a comprehensive pilot-scale study to develop/evaluate low-cost, efficient NOx control technologies for retrofit to pulverized coal fired utility boilers. The objective of this project was to develop retrofit NOx control technology to achieve less than 0.15 lb/MMBtu NOx (for bituminous coals) and 0.10 lb/MMBtu NOx (for subbituminous coals) at a cost which is at least 25% less than SCR technology. In this project, ALSTOM's TFS 2000 low NOx firing system served as a basis for comparison to other low NOx systems evaluated and was the foundation upon which refinements were made to further improve NOx emissions and related combustion performance.

Three coals, ranging from a very reactive Powder River Basin coal (PRB) to a moderately reactive Midwestern bituminous coal (HVB) to a less reactive medium volatile Eastern bituminous coal (MVB), were evaluated in ALSTOM Power's Boiler Simulation Facility (BSF). The testing evaluated a number of low NOx subsystems under realistic boiler combustion system conditions at a large pilot-scale of 50-60 MMBtu/hr (15-18 MWt). Among the technologies evaluated in the BSF were finer coal grinding, oxidative pyrolysis burners, windbox auxiliary air optimization, and various burner zone firing arrangements in concert with strategic deployment of overfire air. Other technologies, such as an advanced boiler control system, coal and air flow balancing, and a Carbon Burn Out combustor, were also evaluated.



Pilot-scale testing of the three test coals showed that both NOx and combustion performance are a strong a function of coal properties. The most reactive coal (PRB) showed the lowest NOx, followed by the moderately reactive HVB and least reactive MVB coals. From the standpoint of combustibles in the flue gas, the PRB showed the lowest combustibles (carbon in ash and CO), followed by the HVB and MVB coals. The combination of firing system modifications resulting in the lowest NOx emissions is referred to as the Ultra Low NOx Integrated System. In general, firing system modifications, which reduce NOx emissions, also result in higher levels of carbon in the fly ash. When both NOx and combustion efficiency were equally weighed, the standard TFS 2000™ set of operating conditions/system components gave the best results for the HVB and MVB coals and the Ultra Low NOx Integrated System gave the best results on the PRB coal. Many of the firing system components developed in this project can also be applied to the TFS 2000 firing system, resulting in improved NOx emissions without significantly impacting the carbon in fly ash levels.

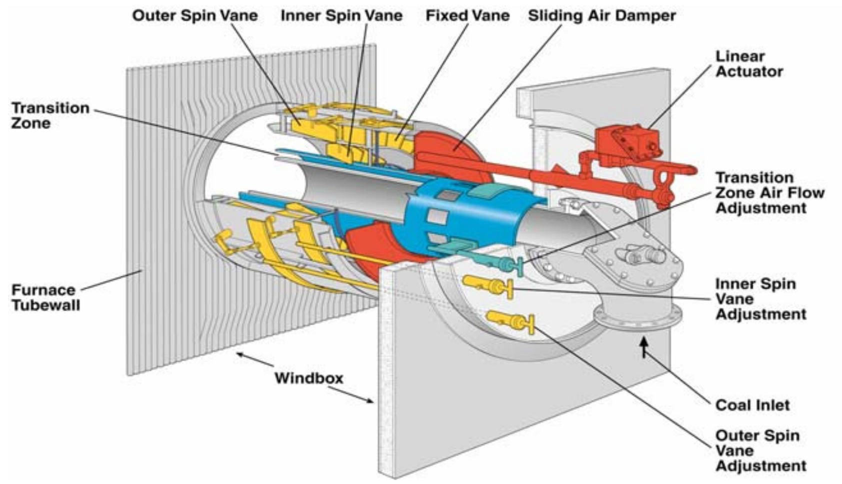
An engineering systems analysis and economic evaluation was performed to evaluate various NOx reduction options including the commercially available TFS 2000 firing system, the Ultra Low NOx Integrated System developed in this project, and SCR. The various NOx reduction alternatives were evaluated as retrofit options for three tangential-fired utility boilers in the U.S.: (1) a 400 MW boiler on the East coast firing an Eastern bituminous compliance coal, (2) a 500 MW boiler in the Midwest firing a Midwestern bituminous coal, and (3) a 330 MW boiler in the West firing a subbituminous coal from the Power River Basin (PRB). The objective of the Engineering Systems Analysis and Economics Task was to evaluate the economics of various NOx reduction options to gain insight into the optimum NOx reduction strategy for different pulverized coal-fired units.



Results from this economic

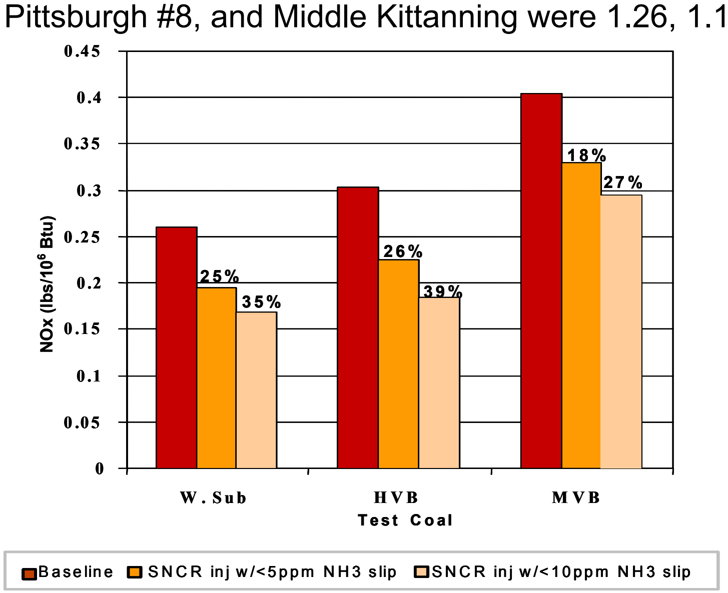
analysis showed that switching to a PRB coal, in concert with installation of either a TFS 2000 System or Ultra Low NOx Integrated System, was the most cost effective option (75-80% less than the cost of an SCR) if the cost of shipping the PRB coal to a particular site was not prohibitive. However, it was recognized that the optimum NOx reduction strategy is unit, site, and system specific.

Integrated Low NOx Burners and Selective Non-Catalytic Reduction for Wall-Fired Boilers



McDermott Technology, Inc. (MTI), the Babcock & Wilcox Company (B&W), and Fuel Tech teamed together to investigate an integrated solution for NOx control. The system was comprised of B&W's DRB-4Z™ LNB technology and Fuel Tech's NOxOUT̃, a urea-based SNCR technology. Large-scale testing was conducted in B&W's 100-million Btu/hr Clean Environment Development Facility (CEDF) that simulates the conditions of large coal-fired utility boilers. The facility is equipped with one near full-scale burner and is constructed with water walls and is insulated with refractory to simulate the thermal conditions of the middle row burner in a commercial boiler.

A wide range of commercially available utility coals including Spring Creek, a Montana high volatile subbituminous coal from the PRB region, Pittsburgh #8, a high- volatile bituminous coal, and Middle Kittanning, a medium-volatile bituminous coal, were tested. Under the most challenging boiler temperatures at full load conditions, the DRB-4Z™ burner alone without air staging achieved NOx emissions of 0.26 lb/MMBtu for the PRB coal, 0.30 lb/MMBtu for the Pittsburgh #8, and 0.40 lb/MMBtu for the Middle Kittanning coal. The NOx variations with fuel can be explained with the fuel ratio (fixed carbon over volatile matter, FC/VM) and fuel nitrogen content. Fuel ratios for Spring Creek, Pittsburgh #8, and Middle Kittanning were 1.26, 1.19, and 2.38 respectively. In addition, the lower fuel nitrogen content and higher moisture with the Spring Creek coal reduced the overall NOx emissions.

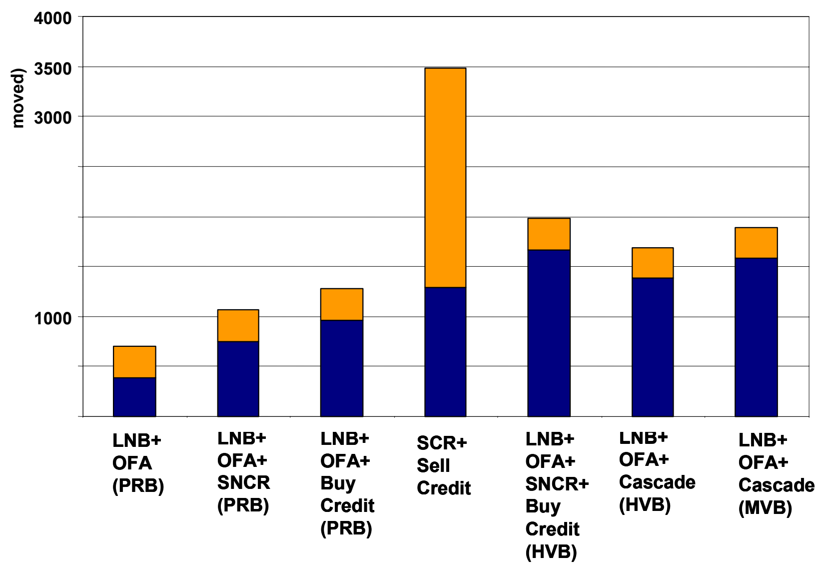


The baseline DRB-4ZTM NOx levels at full load were reduced by the SNCR system (configured with wall injectors only) to 0.19

lb/MMBtu for western subbituminous, 0.22 lb/MMBtu for Pittsburgh No. 8, and 0.32 lb/MMBtu for Middle Kittanning coal. The NOx reduction was 25% for western subbituminous, 26% for Pittsburgh No. 8, and 18% for Middle Kittanning coal. These data indicate that a nominal 25% NOx reduction is feasible from a low-NOx combustion system firing western subbituminous and eastern high volatile coals with a baseline NOx of 0.2 to 0.3 lb/MMBtu when the NH_3 slip is limited to less than 5 ppm. Higher reductions were possible when the ammonia slip was between 5 to 10 ppm. For units firing coals with lower volatile content such as Middle Kittanning, the higher boiler gas temperatures could limit NOx reduction to 15-20%.

Under the more favorable reduced load conditions, NOx emissions were lower for both baseline (burner only) and SNCR operation. Baseline NOx emissions of 0.17 lb/MMBtu for PRB coal at 60 million Btu/hr were reduced to 0.13 lb/MMBtu by SNCR. The lowest NOx of 0.09 lb/MMBtu was achieved at a 40 million Btu/hr firing rate. These data were obtained while the ammonia slip was below 5 ppm.

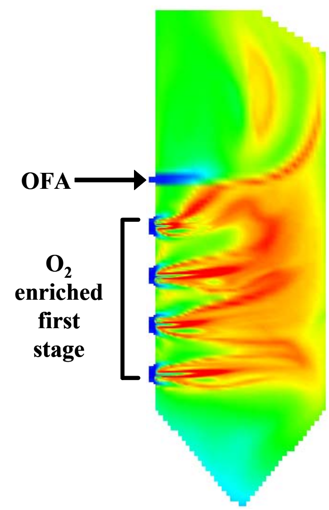
To demonstrate the application and benefits of various NOx control options, their cost effectiveness was calculated for a reference 500 MWe wall-fired, coal-burning boiler. Three integrated NOx control options were considered in this evaluation with the goal of reducing the baseline emissions from 0.5 to 0.15 lb/MMBtu. Also, the SCR-only scenario as specified in the DOE's program solicitation represents the base case for comparing with the costs of other cases.



The LNB in combination with OFA was considered a potential technology for boilers using PRB coal. The LNB/OFA plus NOxOUT® was considered when burner NOx level is 0.2 lb/MMBtu. Also, Fuel Tech investigated the NOxOUT Cascade® for cases with high reagent injection rates (burner NOx @ 0.3 lb/MMBtu) where ammonia slip can be reduced with a catalyst. In some of the CEDF tests, the SNCR system was forced to slip 10-20 ppm ammonia. There was no catalyst available in the CEDF to promote reaction between ammonia and NOx which is the basis for the NOxOUT Cascade® technology. For the purpose of this economic analysis, the NOxOUT Cascade® NOx reduction was estimated based on the Fuel Tech's experience. The economic analysis normalized the costs to an emission rate of 0.15 lb/MMBtu based on the buying and selling of NOx credits at a value of $3,500.

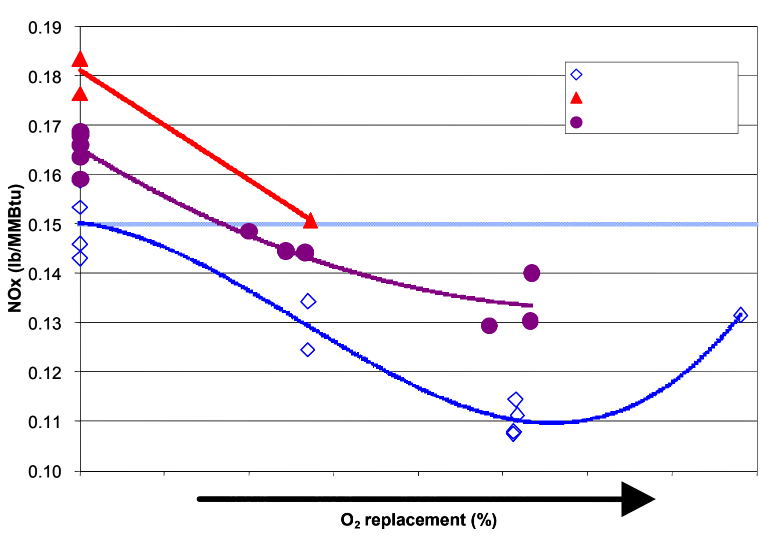
The analysis shows that the DRB-4ZLNB in combination with OFA has the lowest levelized cost (70 to 80% less than SCR). Since LNB are more cost-effective on a $/ton of NOx basis than SNCR or SCR technologies in general, there is a great incentive in using them in combination with post-combustion NOx control methods. LNB/OFA plus the NOxOUT® combination cost is $752 to $1066 per ton of NOx removed when the burner emissions are 0.20 lb/MMBtu which is 40% to 70% lower than the SCR cost ($1,287 to $3,489 per ton of NOx). The NOxOUT Cascade® levelized cost is close to the lower range of SCR due its lower capital cost. It has been assumed that the catalyst can be placed in-duct and a separate reactor is not necessary. It should be mentioned that these costs are site specific and the results may change from unit to unit.

Oxygen-Enhanced Combustion



Praxair and its partners have developed a novel oxygen based technology that can reduce NOx emissions from nitrogen containing fuels, including pulverized coal, while improving combustion characteristics such as LOI. This novel technology replaces a small fraction of the combustion air with oxygen. Conventional oxy-fuel knowledge would indicate that even this small replacement will have a beneficial impact on boiler performance independent of any reduction in NOx.

Experimental work was performed using the Industrial Boiler Simulation Facility (ISBF) at ALSTOM Power Inc.'s Power Plant Laboratory. The experiments were designed to demonstrate that the concept of oxygen-enhanced low combustion system can meet the emissions target of 0.15 lb/MMBtu with minimal impact on CO emissions and furnace performance. The ISBF is a water-cooled tunnel furnace designed to test burners up to 50 MMBtu/h in firing rate with time-temperature histories similar to PC fired boilers. The unit has two locations for separated over-fire air (SOFA) injection. An 'off the shelf' RSFC burner, ALSTOM's commercial wall fired low NOx burner, was used in these experiments. The burner was designed for a firing rate of 26 MMBtu/h and was typically fired at 24 MMBtu/h for these tests.



In the first full-scale test campaign, denoted Phase I-A, Illinois No. 6 coal was used. Initial tests were performed to shake down the furnace and to obtain baseline NOx data for this facility, burner, and coal combination. A series of experiments were then performed to explore the effect of oxygen addition on NOx emissions. In the second test campaign, denoted Phase II, selected experiments were repeated with the Illinois No. 6 coal. An eastern bituminous coal, the Mingo Logan, was then used in Phase I-B to evaluate both the effect of a lower volatile coal and the effect of oxygen addition method. Data from the Illinois No. 6 experiments show that even when the baseline (air only) emissions are very low, oxygen addition can drive the NOx emissions even further. The overall data further show that the reductions are relatively independent of the initial NOx concentration. Data from the Mingo Logan experiments show that the concept works even with the lower volatile coal, and that how the oxygen is mixed has a large impact on NOx reduction.

In addition to the reduction in NOx, benefits can be achieved in the areas of reduced LOI and opacity, increased boiler efficiency, and reduced fan limits. Preliminary economic analysis indicates that cost savings of 40-50% can be realized when compared to SCR.

As the successes of the program move toward commercialization and demonstration, the program targets are reevaluated and redefined. In light of the proposed multi-pollutant legislation, the IEP Program will be issuing a solicitation this year to target even lower NOx emissions for existing boilers. The challenge will be to develop cost effective NOx control technologies for the smaller, older, less efficient facilities that are not easy candidates for the current state of the art SCR NOx control equipment because of space constraints and the reluctance of owners to invest in the aging plants. These facilities, with a generating capacity of 300 MW or less, comprise 66% of the boilers in the US and have an average age of 38 years as compared to the remainder of the fleet with an average age of 24. The benefits of this program will be realized by both the existing fleet and new capacity as the targeted NOx control technologies are adopted.