Update on DOE/NETL's Advanced NOx Emissions Control Technology R&D Program

Bruce W. Lani[1], Thomas J. Feeley, III[1],
Charles E. Miller[1], Barbara A. Carney[1], and James T. Murphy[2]

[1.] U.S. Department of Energy, National Energy Technology Laboratory
[2.] Science Applications International Corporation

Executive Summary
Advanced nitrogen oxide (NOx) emissions control technology research is an important component of the Innovations for Existing Plants (IEP) Program conducted by the U.S. Department of Energy Office of Fossil Energy's National Energy Technology Laboratory (DOE/NETL). The short-term goal of the research is to develop advanced in-furnace technologies for coal-fired power plants capable of controlling NOx emissions to a level of 0.15 pounds per million Btu heat input (lb/MMBtu) by 2007 and 0.10 lb/MMBtu by 2010, while achieving a levelized cost savings of at least 25% compared to state-of-the-art selective catalytic reduction (SCR) control technology. The program's long-term goal is to further develop a combination of advanced in-furnace and SCR control technologies to achieve a NOx emission rate of 0.01 lb/MMBtu by 2020. The advanced NOx research program takes a holistic approach to pollutant control by not only addressing NOx emissions control technologies, but also important balance-of-plant issues associated with those technologies such as unburned carbon, ammonia slip, and sulfuric acid emissions.

This paper provides an update on the status of DOE/NETL's advanced in-furnace NOx control R&D efforts. Commercially-available low-NOx burners (LNB) and SCR NOx control technologies are enabling industry compliance with today's regulatory requirements. However, the NOx control technologies under development by DOE/NETL will provide more cost-effective options for coal-fired power plants to comply with the ever more stringent environmental regulatory and legislative requirements of tomorrow. NOx emission control costs are significant and can exceed 20% of the total cost for environmental controls on today's coal-fired power plants. The capital and operating costs of SCR controls are relatively high and may not be cost-effective for older, smaller coal-fired power plants, or even for some larger base load plants. In particular, the high capital cost for SCR can result in a levelized cost of control significantly greater than today's NOx allowance price of $2,500 per ton for units with capacity factors less than 55%. Potentially more stringent state, regional, and/or federal regulations in the near future will require the retrofit of NOx controls on a greater proportion of existing coal-fired power plants. As a result, a portion of these plants could be at-risk for early retirement if more cost-effective control technologies than today's SCR are not developed. DOE/NETL's NOx R&D program focuses on the development of advanced in-furnace NOx controls that can approach the performance of SCR, but at significantly lower cost. The development of these advanced in-furnace technologies – such as ultra-low NOx burner systems, oxygen-enhanced combustion, and rich reagent injection – is leading to successful commercial demonstrations.

Introduction

DOE/NETL is carrying out a comprehensive, integrated R&D effort under its IEP Program. The overall goal of the IEP Program is to enhance the efficiency and environmental performance of the existing fleet of coal-fired power plants, representing more than 300 gigawatts (GW) of generating capacity, as well as apply these concepts to advanced power systems. An important component of the program is advanced NOx emission control technology R&D. The present R&D effort focuses primarily on developing systems capable of controlling NOx emissions to a level of 0.15 lb/MMBtu by 2007 and 0.10 lb/MMBtu by 2010, while achieving a levelized cost savings of at least 25% compared to state-of-the-art SCR control technology. The program's long-range goal is to further develop a combination of advanced in-furnace and SCR control technologies to achieve a NOx emission rate of 0.01 lb/MMBtu by 2020. The development of these advanced NOx control technologies is necessary to assure the U.S. power generation industry can continue to comply with the federal nation-wide NOx emission tonnage caps as the size of the coal-fired power plant fleet continues to grow. According to the latest projections from the Energy Information Administration (EIA), coal-fired power plant capacity is expected to increase to over 340 GW by 2020 and 450 GW by 2030.[1] The technologies under development are: (1) to have negligible balance-of-plant impacts; (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 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. The IEP portfolio of NOx control technology R&D projects encompasses laboratory studies, modeling, and pre-commercial full-scale testing. The success of the projects is intimately tied to key collaborations and partnerships with industry, federal, state, and local agencies, and the academic and research communities. The advanced NOx control technologies under development by DOE/NETL will provide more cost-effective options for coal-fired power plants to comply with ever more stringent environmental regulatory and legislative requirements. Without compliance options that are more cost-effective than today's SCR controls, a portion of the existing fleet of coal-fired power plants could be at-risk for early retirement, potentially disrupting the cost and/or reliability of electricity supply in the United States.

Background

Although commercially available LNB and SCR NOx control technologies are enabling compliance with today's regulatory requirements, more cost-effective NOx control technologies must be developed to address the more stringent regulatory requirements of tomorrow. DOE/NETL's current NOx R&D program focus is the development of advanced NOx in-furnace control technologies that approach the performance of SCR, but at a significantly lower cost. Some of the technologies currently under development include ultra-low NOx burner systems, oxygen-enhanced combustion, and rich reagent injection. For the remainder of this paper, the term ULNB (ultra-low NOx burner) will be used to generically describe the advanced NOx in-furnace control technologies. Descriptions of these technologies, as well as cost and performance estimates, are provided later. As NOx emission control requirements become more stringent, a larger proportion of the existing fleet of coal-fired generation could require additional controls. In that regard, there are several issues that support the need for further DOE/NETL advanced NOx control technology R&D.

Cost-Effectiveness – Under a cap-and-trade regulatory program, the most important economic metric for retrofitting pollution control equipment to existing coal-fired power plants is the levelized marginal cost of control, typically measured in terms of dollars per ton ($/ton) of pollutant removed. The levelized marginal cost of control is reflected in the market price of pollution allowances. For example, NOx allowance prices under current regulations averaged approximately $2,500/ton in 2005-2006. The projected market allowance price serves as a reference point for plants to decide whether or not to retrofit control equipment. A plant would likely not retrofit controls if the estimated cost of control exceeds the projected allowance price. The levelized marginal cost of control includes capital and operating cost components. Table 1 provides an estimate of the capital and operation and maintenance (O&M) costs for conventional LNB and SCR based on U.S. Environmental Protection Agency (EPA) data used for their Integrated Planning Model (IPM) analyses of the power generation industry.[2] The original EPA cost data was expressed in 1999 dollars, but was escalated to 2005 dollars as shown in Table 1. However, EPA's $119/kW capital cost estimate for SCR is relatively low compared to a recent utility survey that indicates an average SCR capital cost of $167/kW for a unit size less than 301 MW and $148/kW for unit sizes ranging from 301 to 600 MW.[3] The utility survey also noted that deviations from average costs were correlated to year of installation. For example, the 25 SCRs completed after 2003 cost an average of $23/kW greater than the 47 SCRs completed in 2003 or earlier. This increase in average cost is thought to reflect increased retrofit difficulty compared to "easier" projects that were previously completed and increased competition for skilled construction labor.

Table 1 – Estimated Capital and O&M Costs for NOx Control (2005 Dollars)

Component	Capital, $/kW	Fixed O&M, $/kW-yr	Variable O&M, mills/kWh*
Conventional LNB	23	0.35	0.06
SCR	119	0.64	0.66

* One mill equals 1/10 cent or 1/1000 dollar

The ratio of capital to operating cost for various control technology options can drastically alter their cost effectiveness for particular plant design conditions. The capital cost component of the levelized marginal cost of control is primarily a function of plant size, capacity factor, and remaining service life. All else being equal, an older, smaller plant with a low capacity factor will have a significantly higher capital cost component compared to a younger, larger plant with a high capacity factor. Although capacity factor doesn't affect the total capital cost, it does affect unit costs such as mills/kWh generation or $/ton pollutant removed. For example, a lower capacity factor decreases the size of the denominator in the calculation and results in a higher unit cost. However, the operating cost component for the two plants would essentially be identical. Therefore, NOx control technologies with a relatively high capital to operating cost ratio – for example SCR – are typically not a cost-effective option for older, smaller plants. These plants would greatly benefit from DOE/NETL's advanced NOx in-furnace control technologies that offer significantly lower capital cost compared to SCR.

As an example, Figure 1 presents the levelized marginal cost of control – as measured in $/ton of NOx removed for conventional LNB at 50% control and SCR at 90% control – versus capacity factor for a baseline NOx emission rate of 0.4 lb/MMBtu. In this example, the SCR cost of control exceeds the current $2500/ton NOx allowance price when the capacity factor is less than approximately 55%. It is also important to put the cost of NOx control in perspective with the total cost of electricity (COE) for a coal-fired power plant.

Figure 1 –Levelized Cost of NOx Control versus Capacity Factor

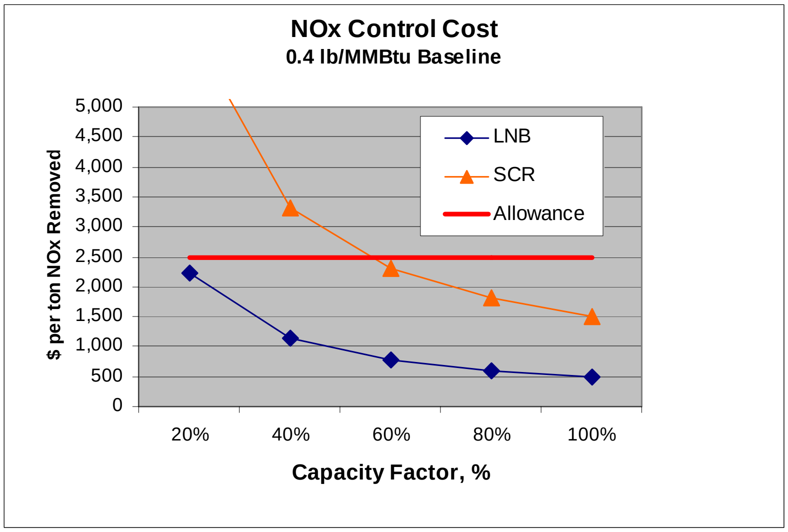


Table 2 provides a summary of an internal DOE/NETL analysis of the contribution of various components of environmental control to the total COE for a hypothetical 500-MW reference coal-fired power plant. The 3.79 mills/kWh cost for NOx control (0.58 for LNB plus 3.21 for SCR) represents 21% of the 18.35 mills/kWh total for environmental control of the reference plant. NOx control costs, therefore, can significantly affect the overall economic viability of the power plant in a de-regulated power generation market.

Table 2 – Cost of Electricity for 500-MW Reference Coal-Fired Power Plant

Component	Baseline COE, mills/kWh (2005$)	% Total Environmental Control Cost
Environmental Controls	--	--
Sulfur Dioxide	7.58	41
NOx - LNB	0.58	3
NOx - SCR	3.21	18
Particulate Matter	2.45	13
Acid Gas	0.33	2
Mercury	1.67	9
Solid Waste Disposal	0.43	2
Cooling Water	2.11	11
Total Environmental Control	18.35	100
Base Power Plant & Fuel	33.25	--
Total Power Plant	51.60	--

Retrofit Difficulty – Each coal-fired power plant has unique site-specific conditions that affect the relative economics of various NOx compliance options. Site layout constraints can affect retrofit difficulty, particularly with SCR controls that have a relatively large footprint. The retrofit of SCR controls can also require other modifications to major equipment such as the economizer, air heaters, ductwork, and fans. For example, the additional flue gas pressure drop across the SCR catalyst can require an upgrade of fan capacity.

Unburned Carbon – The ULNB systems offer the potential of lower unburned carbon levels compared to traditional LNBs. Therefore, a retrofit with an ULNB system could increase boiler efficiency and provide greater opportunities for fly ash sales as a substitute for Portland cement in concrete.

Adverse Balance-of-Plant Effects of SCR – The use of today's SCR control technology has significant balance-of-plant issues including: 1) safety concerns associated with the transportation and storage of hazardous reagents; 2) operational and environmental concerns associated with ammonia slip; 3) increased fan power to overcome flue gas pressure drop across the SCR decreases plant efficiency; and 4) operational and environmental concerns associated with excessive sulfuric acid (H_2SO_4) emissions. In addition, SCR performance can be adversely impacted by catalyst poisoning and ash pluggage.

Retrofit of SCR on units burning high sulfur bituminous coal may incur increased costs to control excessive sulfur trioxide (SO_3) levels that lead to H_2SO_4 emissions from the stack. The SO_3 is produced from the oxidation of SO_2 across the SCR catalyst. Over the last few years, several power plants equipped with SCR have had to install chemical additive systems to reduce H_2SO_4 emissions, including AEP's Gavin Station, FirstEnergy's Bruce Mansfield Station, and Cinergy's Gibson Station. While there are several H_2SO_4 control technologies that have recently been tested, there have been performance problems and therefore it remains an area for further R&D. Although H_2SO_4 is not a regulated pollutant, it is reportable under the Toxic Release Inventory (TRI) program and environmental advocacy groups have used TRI to apply public pressure on companies to further reduce emissions.

Current Regulatory/Legislative Drivers

Regulatory and legislative requirements have predominantly driven the need to develop NOx control technologies for existing coal-fired power plants. The first driver was the Title IV acid rain program, established through the 1990 Clean Air Act Amendments (CAAA). This program included a two-phase strategy to reduce NOx emissions from coal-fired power plants – Phase I started January 1, 1996 and Phase II started January 1, 2000. The Title IV NOx program was implemented through unit-specific NOx emission rate limits ranging from 0.40 to 0.86 lb/MMBtu depending on the type of boiler/burner configuration and based on application of LNB technology.

The second driver was the Title I National Ambient Air Quality Standards (NAAQS) for ozone that led to EPA's NOx SIP (state implementation plan) Call Rule in 1998, requiring 21 eastern states and the District of Columbia to participate in a regional cap-and-trade program based on an equivalent NOx emission rate of 0.15 lb/MMBtu beginning in 2003-04. Since conventional LNB could not achieve this level of emissions, compliance required the development and implementation of post-combustion NOx controls such as SCR. Recent experience with SCR indicates that emission rates as low as 0.05 lb/MMBtu are achievable. However, being a cap-and-trade program, power plants had the option to either reduce their NOx emissions to the level of their NOx allowance allocation or acquire additional NOx allowances from other plants that over comply. EPA has estimated that approximately 111 GW of SCR will have been installed on U.S. coal-fired power plants by 2010 for compliance with the NOx SIP call.

A third regulatory driver for NOx control technology development resulted from EPA's revision to the fine particulate matter (PM) and ozone NAAQS in 1997, which eventually led to the Clean Air Interstate Rule (CAIR) finalized in May 2005. The NOx emission reductions under CAIR, impacting 28 eastern states and the District of Columbia, will be implemented as a cap-and-trade program in two phases, with a Phase I compliance date of January 1, 2009, and a Phase II compliance date of January 1, 2015. The NOx emission caps were calculated using emission rates of 0.15 lb/MMBtu for 2010 and 0.125 lb/MMBtu for 2015. EPA has estimated that a total of approximately 154 GW of SCR will have been installed on U.S. coal-fired power plants by 2020 for compliance with the NOx SIP call and CAIR.[4]

Future Regulatory/Legislative Drivers

The three regulatory drivers described above led to the commercial development and deployment of LNB and SCR NOx control technologies that enables power industry compliance with those requirements. However, it is likely that future regulatory/legislative drivers will increase the stringency of NOx emission control requirements. As a result, a larger proportion of the existing fleet of coal-fired power plants could be required to install additional NOx control technologies. The following is a brief summary of those drivers.

Regional Haze Rule – In July 1999 EPA published a regional haze regulation to improve visibility in national parks and wilderness areas. Further reductions in power plant NOx and SO_2 emissions are being targeted as compliance strategies. The regional haze rule requires the installation of best available retrofit technology (BART) for existing pre-New Source Performance Standard (NSPS) power plants that entered operation between 1962 and 1977. The BART provision could require the installation of advanced in-furnace or post-combustion NOx controls on these plants. According to the EPA, states are required to identify BART sources and submit implementation plans by December 2007. Implementation of BART NOx controls would then occur between 2014 and 2018. However, EPA published amendments – known as the Clean Air Visibility Rule, (CAVR) – to the regional haze rule in July 2005 to clarify BART emission control requirements. CAVR allows states covered by CAIR to use the CAIR NOx and SO_2 controls as a substitute for BART. As a result, the regional haze rule primarily affects power plants in the western U.S. not covered by CAIR.

Multi-pollutant Control Legislation – In the past several years, the Administration and Congressional members have proposed legislation for multi-pollutant control that would limit emissions of SO_2, NOx, mercury, and in some cases CO_2 from fossil-fueled power plants. Although enactment of such legislation is uncertain, there is significant potential for more stringent NOx emissions control requirements in the near future.

In 2002, the Bush Administration announced its Clear Skies Initiative (CSI) multi-pollutant control proposal. The CSI proposal would require significant emission reductions of SO_2, NOx, and mercury implemented in two phases using an allowance-based cap-and-trade program. The

CSI proposal required a reduction in NOx emissions equivalent to an approximately 59% reduction below 2001 baseline levels beginning in 2008 and a 67% reduction beginning in 2018.[5] The Clear Skies Act (CSA) legislation to adopt the CSI requirements was originally introduced in both the U.S. House and Senate in 2002, 2003, and 2005, but has yet to be enacted.

In addition to CSA, alternative CAA amendments have been introduced in Congress over the past few years. Of those alternatives, the two that have received the most attention are The Clean Power Act (Sen. Jeffords) and The Clean Air Planning Act (Sen. Carper). The three legislative proposals are significantly different on matters such as compliance methods, targets, deadlines, and regional definitions. Additionally, both the Clean Power Act and the Clean Air Planning Act regulate CO_2 to some degree. Table 3 provides a summary of annual NOx emission caps under each proposed Act.[6,7] The most stringent of the proposals is the Clean Power Act, in which the 1.51 million ton NOx emissions cap is approximately 16% lower than the CSA Phase II cap of 1.79 million tons, and comes much sooner, 2010 verses 2016/18.

Table 3 - Summary of U.S. NOx Emission Caps Under Proposed Multipollutant Legislation[6]

Proposed Legislation	Annual NOx Emission Caps, million tons				
	2008	2009	2010	2013	2016/18
Clear Skies Act	2.19	--	--	--	1.79
Clean Air Planning Act	--	1.87	--	1.7	--
Clean Power Act	--	--	1.51	--	--

Regional NOx Emission Reduction Regulations – The District of Columbia and 12 Northeast state members of the Ozone Transport Commission (OTC) are developing a model rule – known as CAIR-Plus – to achieve NOx and SO_2 reductions in the Northeast greater than required under EPA's CAIR as a means to better achieve attainment with the revised PM and ozone NAAQS. For NOx, the proposed CAIR-Plus imposes annual caps based on an emission rate of 0.12 lb/MMBtu in 2009 and 0.08 lb/MMBtu in 2012.[8] As a result, CAIR-Plus is approximately 20% more stringent than CAIR for Phase I (0.15 lb/MMBtu) and 36% more stringent than CAIR for Phase II (0.125 lb/MMBtu).

State-Specific NOx Emission Reduction Regulations – In addition to complying with the national and regional NOx requirements discussed above, several states have also implemented more stringent NOx emission reduction regulations for coal-fired power plants to address local PM and ozone NAAQS nonattainment areas. As EPA continues to review and revise the NAAQS, it is likely that more states may decide to further regulate NOx emissions. Three recent examples of state NOx regulatory actions are New York, North Carolina, and Texas.

In 2000, New York began enforcement actions against eight in-state coal-fired power plants for violating the New Source Review (NSR) provisions of the CAA that require power plants to install best available control technology (BACT) to reduce emissions of NOx, PM, and SO_2 when they make major modifications to plant equipment that would otherwise increase emissions.[9] Although some plants will install additional pollution control equipment, eight units located at three of the power plants will retire early instead.[10] These retiring units represent approximately 40% (950 MW of 2,500 MW) of the total capacity subject to the NSR enforcement action.

In 2002, North Carolina enacted legislation known as the Clean Smokestacks Act that requires coal-fired power plants to reduce annual NOx emissions by 77% from their 1998 baseline beginning in 2009.[11] The impetus for the North Carolina legislation was to address local concerns with acid rain, ozone, and visibility. The electric utility industry is still regulated in North Carolina and the additional costs for installation and operation of the necessary air pollution control equipment can be included in customer rates.

In December 2002, Texas adopted revisions to its SIP for the eight-county Houston/Galveston area that requires coal-fired power plants to reduce NOx emissions by 88% from their 1997 baseline emissions to help the eight-county area achieve attainment with the one-hour average ozone NAAQS. [12] The reductions are being phased in between April 2003 and April 2007 and are being implemented through a NOx allowance cap-and-trade program. The NOx reductions are rather stringent and equate to a 0.045 lb/MMBtu NOx emission rate for tangential-fired boilers and 0.05 lb/MMBtu rate for wall-fired boilers. As a result, all four coal-fired boilers (located at the W.A. Parish Power Station that burn subbituminous coal from the Powder River Basin - PRB) in the nonattainment area required the installation of SCR to meet compliance. If similar NOx requirements were imposed throughout Texas to meet the more stringent revised eight-hour average ozone NAAQS, it is possible a majority of the states' coal-fired power plants would need to install SCR. However, this could pose a problem since there is currently no operating experience with SCR on plants burning Texas lignite, or Texas lignite/PRB blends that are commonly burned at other plants in the state. Without the option of advanced NOx in-furnace controls, these plants might need to switch to PRB coal, thus disrupting the Texas lignite coal industry.

Recently Completed DOE/NETL NOx Control R&D

DOE/NETL has been at the forefront of conducting advanced NOx control technology R&D for coal-fired power plants.[13,14,15] Recent research has included advanced in-furnace controls, advanced flue gas treatment, and integrated control systems. Achievement of the near-term IEP performance goals in 2007 and 2010 will provide industry with more cost-effective control technology options in response to CAIR's Phase I and II compliance dates of 2009 and 2015, respectively. Additional information on DOE/NETL's advanced NOx emissions control activities can be found at: http://www.netl.doe.gov/technologies/coalpower/ewr/nox/index.html.

The following is a brief description of some of the advanced NOx in-furnace control technologies recently developed under the IEP program. The technologies include ultra-low NOx burner systems, oxygen-enhanced combustion, and rich reagent injection. Test results for these projects have been published previously and will not be repeated here.

Ultra-Low NOx Burners for Tangentially-Fired Boilers – ALSTOM Power Inc. completed a pilot-scale study to develop retrofit NOx control technology for tangentially-fired boilers.[16,17] ALSTOM refined its TFS 2000™ low-NOx firing system to further improve NOx emissions and related combustion performance. Among the refinements evaluated were finer coal grinding, oxidative pyrolysis burners, windbox auxiliary air optimization, and various burner zone firing arrangements in concert with overfire air. Other technologies, such as an advanced boiler control system, coal and airflow balancing, and a Carbon Burn Out combustor, were also evaluated. The pilot-scale modified TFS 2000 system was able to achieve less than 0.1 lb/MMBtu while firing PRB coal and less than 0.15 lb/MMBtu while firing high volatile bituminous coal.

Ultra-Low NOx Burners for Wall-Fired Boilers – McDermott Technology, Inc. (MTI), Babcock & Wilcox Company (B&W), and Fuel Tech teamed to conduct pilot-scale testing of an integrated NOx control solution for wall-fired boilers.[18,19] The system was comprised of B&W's DRB-4Z™ LNB technology and Fuel Tech's NOxOUT®, a urea-based selective non-catalytic reduction (SNCR) technology. The ULNB + SNCR combination achieved a controlled NOx emission rate of approximately 0.23 lb/MMBtu with bituminous coal and 0.11 lb/MMBtu with subbituminous coal.

Rich Reagent Injection for Cyclone-Fired Boilers – Reaction Engineering International (REI) optimized EPRI's Rich Reagent Injection (RRI) process for NOx reduction on cyclone burners.[20,21] RRI uses a nitrogen-containing additive, such as ammonia or urea, to non-catalytically reduce NOx in the lower furnace. Full-scale field testing of RRI was conducted at Conectiv's 138 MW B.L. England Unit 1 and AmerenUE's 500 MW Sioux Unit 1. This project also included testing of optional SNCR. The RRI + SNCR combination achieved a controlled NOx emission rate of approximately 0.25 lb/MMBtu with bituminous coal.

Oxygen-Enhanced Combustion – Praxair, Inc. and its partners developed a novel oxygen-enhanced combustion (OEC) technology that can reduce NOx emissions from pulverized coal-fired (PC-fired) boilers, while improving combustion characteristics such as loss-on-ignition (LOI).[22,23] This novel technology replaces a small fraction of the combustion air with oxygen. Praxair is also developing an oxygen transport membrane (OTM) process that uses pressurized ceramic membranes for separation of oxygen from air. Pilot-scale testing conducted using a commercially-available wall-fired burner with OEC demonstrated less than 0.15 lb/MMBtu NOx emissions could be achieved while firing Illinois No. 6 bituminous coal. In November 2005, Praxair's OEC NOx control system was recognized as one of five finalists for *Chemical Engineering* magazine's prestigious Kirkpatrick Award for Chemical Engineering Achievement.[24]

Market Potential

DOE/NETL conducted an assessment of the market potential of the four recently completed advanced NOx in-furnace control technology R&D projects discussed above. The assessment showed a U.S. market potential for approximately 151 GW of ULNB technologies resulting in levelized annual cost savings of $729 million per year in constant 2005 dollars. Table 4 presents a summary of the cost and performance estimates developed for the various technologies that were used in the assessment.[a] For reference, the table also includes the cost and performance estimates assumed for SCR. The capital cost of the various ULNB technologies is approximately one-fourth the cost of SCR. While the O&M costs for the various ULNB technologies vary somewhat, they are typically less than the cost of SCR. The levelized COE in

[a] The controlled NOx emission rates in Table 5 reflect performance of the ULNB technology without the additional reductions that were achieved during testing with selective non-catalytic reduction (SNCR) technology. The combination of ULNB and SNCR meets the IEP 2007 near-term performance goal of 0.15 lb/MMBtu.

constant 2005 dollars is also provided in the table for each technology assuming a 13.5% capital recovery factor and a 75% capacity factor.

Table 4 – Cost and Performance Assumptions for Advanced NOx In-furnace Control Technologies

Technology	ULNB	ULNB	RRI	OEC	SCR
Researcher	ALSTOM	B&W/MTI	REI	Praxair	--
Boiler/Burner Type	Tangential	Wall	Cyclone	Wall	All
Controlled NOx rate, lb/MMBtu (Bituminous)[b]	0.20	0.30	0.38	0.15	0.05 or 90%
Controlled NOx rate, lb/MMBtu (Low Rank)	0.14	0.15	0.27	0.15	0.05 or 90%
Capital Cost, $/kW[c]	24	28	20	32	119
Fixed O&M Cost, $/kW-yr	0.26	0.43	0.30	1.42	0.64
Variable O&M Cost, mill/kWh	0.03	0.08	1.00	0.21	0.66
Total levelized COE, mill/kWh	0.56	0.72	1.47	1.08	3.21

Recent Commercial Applications

The market potential for DOE/NETL's advanced NOx in-furnace control technology R&D projects has begun to be realized as the following examples illustrate:

- In November 2005, Ameren announced that based on the successful test results of REI's RRI and SNCR – now known as Advanced Layered Technology Application (ALTA) – that it was reconsidering its plans to install SCR. Ameren is now evaluating full-scale implementation of ALTA for both 500-MW units at the Sioux Station.[25]
- Many of the components developed in ALSTOM's TFS 2000™ low NOx firing system project have been applied to the commercially-available equipment, resulting in improved NOx emissions without significantly affecting the unburned carbon levels. To date, 19 commercial boilers firing PRB coal that utilize aspects of the technologies demonstrated in this project are achieving NOx emissions at or below 0.15 lb/MMBtu.
- Subsequent testing of Praxair's oxygen-based technology at two utility boilers, City Utilities' James River Unit 3 and Northeast Utilities' Mt. Tom Generating Station, has demonstrated the benefits of the technology. The Praxair technology has also been installed on two coal-fired boilers at the P.H. Glatfelter pulp and paper mill in Spring Grove, Pennsylvania. Preliminary economic analysis indicates that cost savings of 40-50% can be realized when compared to SCR.

Current Advanced In-furnace NOx Control Efforts

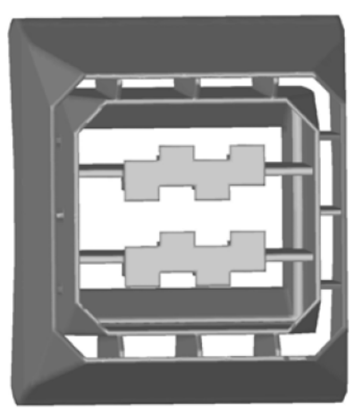
The IEP NOx R&D program targets are continuously reevaluated and redefined. In anticipation of CAIR and possible Congressional multi-pollutant legislation, DOE/NETL issued a solicitation

[b] Controlled NOx emission rates used for this assessment are considered conservative estimates for full-scale installations. The pilot-scale testing showed lower emission rates that were adjusted based on the project developers previous scale-up experience.
[c] The capital cost includes installation of OFA for the ULNB-Tangential and ULNB-Wall technology options. This is probably a conservative estimate since many boilers would already have OFA as part of their current LNB system.

in 2004 to continue R&D efforts to meet the 2007 goal and to initiate R&D targeting the 2010 goal of achieving 0.10 lb/MMBtu using in-furnace technologies in lieu of SCR. As a result, four new NOx R&D projects are currently underway and will be completed over the next three years. These new projects focus on boiler applications firing medium-volatile eastern bituminous coal, which historically has shown to be more difficult for controlling NOx emissions using combustion technologies compared to low-volatile bituminous and subbituminous coals. The challenge is 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 controls because of space constraints and the reluctance of owners to invest significant capital in aging plants. These facilities, with a generating capacity of 300 MW or less, comprise 65% of the boilers – representing 27% of total U.S. generation capacity –and have an average age of 46 years as compared to the remainder of the fleet with an average age of 30 years.[26] The benefits of this program will be realized by both the existing fleet and new capacity as the targeted NOx control technologies are adopted. The following is a brief description of these on-going projects:

Enhanced Combustion Low NOx Burner for Tangentially-Fired Boilers – ALSTOM is developing an enhanced combustion, low NOx PC burner for tangentially-fired boilers.[27] The objective is to optimize combustion via control of near-burner time, temperature, turbulence, and stoichiometry. Candidate low-NOx burner components being tested include enhanced coal nozzle tips and internal and external air and fuel separators. These components are being integrated into ALSTOM's latest generation of the TFS 2000 firing system. The enhanced low-NOx burner is designed to achieve an emission rate of less than 0.15 lb/MMBtu and have minimal balance-of-plant impacts while burning high-volatile bituminous coal. The project includes computational fluid dynamics (CFD) modeling and large pilot-scale testing (approximately 50 MMBtu/hr) to provide information for designing a full-scale version of the enhanced low-NOx burner. An illustration of ALSTOM's baseline low-NOx concentric firing system (LNCFS) P2 coal nozzle tip is shown in Figure 2.

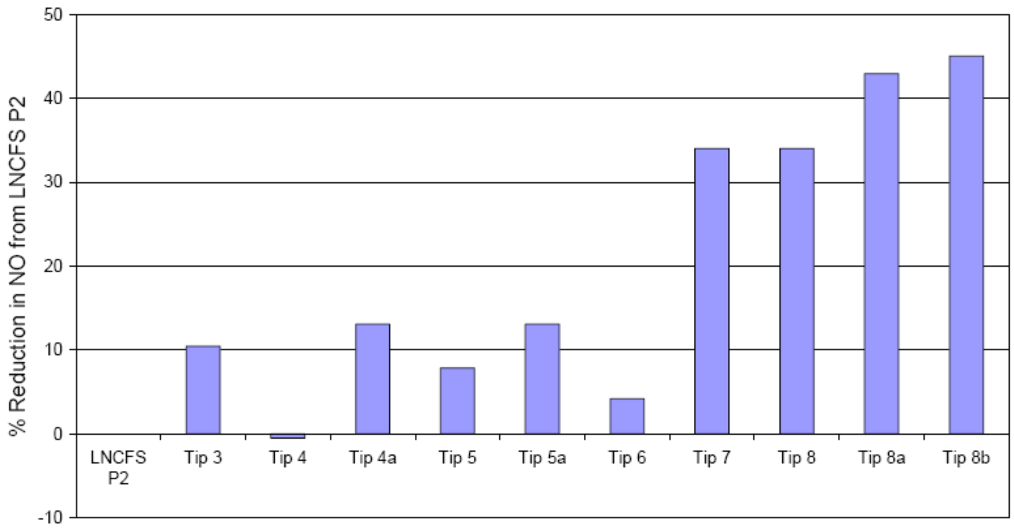
Figure 2 – ALSTOM LNCFS P2 Coal Nozzle Tip



ALSTOM conducted pilot-scale testing of improved coal nozzle tips firing an Illinois No.6 high-volatile bituminous coal in November 2005. Figure 3 presents the NOx reduction achieved for each of the tested coal nozzle tips relative to the baseline LNCFS P2 tip. It is apparent that the coal nozzle tip design can have a significant impact – some of the new tip designs resulted in

NOx emissions 40% lower than those achieved with the baseline P2 tip. ALSTOM will test the new coal nozzle tip designs in a full-scale tangential-fired boiler to evaluate burner-to-burner interactions.

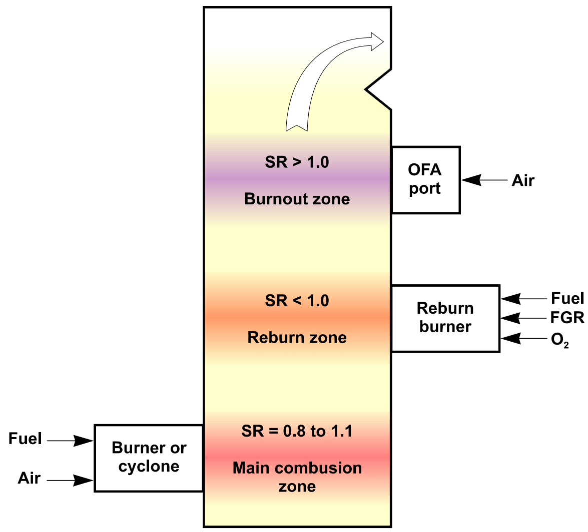
Figure 3 – ALSTOM Pilot-Scale Low NOx Burner Tip Performance Results



Advanced In-Furnace NOx Control for Wall- and Cyclone-Fired Boilers – B&W is developing and demonstrating an advanced NOx control technology capable of achieving an emission rate of 0.10 lb/MMBtu while burning high-volatile bituminous coal for both wall- and cyclone-fired boilers. The technology is based on a "layered" strategy that combines deep air staging using overfire air (OFA), continuous corrosion monitoring, advanced combustion control enhancements, and a proprietary combustion technique using oxygen injection. Figure 4 shows a schematic of the layered process, which includes three zones: main combustion, reburn, and burn-out. The stoichiometric ratio (SR) in the main combustion zone is varied from 0.8 to 1.1. The reburn zone features oxygen-enhanced combustion of the re-burn fuel and flue gas recirculation (FGR), at a SR of less than 1. The burnout zone utilizes OFA to achieve complete combustion, at a SR greater than 1.

To evaluate the oxygen injection process, wall- and cyclone-fired pilot-scale testing is being conducted at B&W's 5 million Btu/hr Small Boiler Simulator (SBS) facility. Oxygen will be injected at various locations in the combustion zone and data gathered by optical sensors will be used to optimize the combustion process. Corrosion monitoring sensors will assess potential waterwall wastage that could occur under severe operating conditions. Testing will also evaluate the effects of oxidizer composition, extent of deep air staging, and overall excess oxygen level on combustion behavior, heat transfer characteristics, and emissions levels. Finally, results from the pilot-scale testing will be used to design and prepare a cost estimate for a full-scale version of the technology. Pilot-sale testing began in July 2006, but results are not yet available.

Figure 4 – Schematic of B&W's Layered NOx Combustion Control Concept

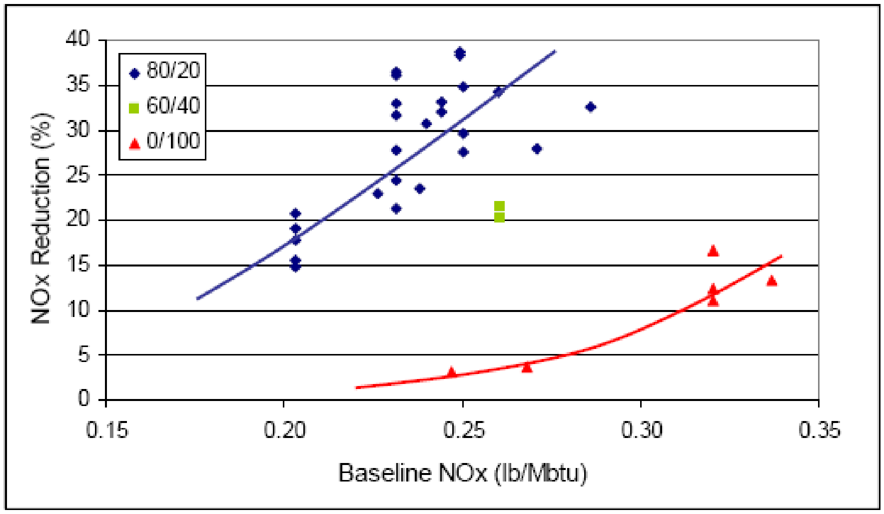


Full-Scale Field Testing of ALTA NOx Control for Cyclone-Fired Boilers – REI conducted CFD modeling and full-scale field testing to evaluate the ALTA technology on a cyclone-fired boiler.[28,29] This project was a follow-up to the previously completed "Rich Reagent Injection for Cyclone Burners" project discussed earlier in this paper. ALTA combines deep staging with OFA, RRI, and SNCR to achieve a NOx emission rate of near 0.10 lb/MMBtu for a cyclone boiler. Developed by REI and the Electric Power Research Institute, RRI uses a nitrogen-containing additive, such as ammonia or urea, to non-catalytically reduce NOx in the lower furnace. REI conducted field testing in May and June of 2005 at AmerenUE's Sioux Station Unit 1, a 500 MW cyclone boiler unit that typically burns an 80/20 blend of Powder River Basin subbituminous coal and Illinois No. 6 bituminous coal. Parametric testing was also conducted with 60/40 and 0/100 blends. The testing also evaluated process impacts on balance-of-plant issues such as the amount of unburned carbon in the ash, slag tapping, waterwall corrosion, ammonia slip, and heat distribution.

Prior to field testing, REI used CFD modeling to optimize the number and location of the urea reagent injection locations for both the RRI and SNCR systems. Previous ALTA testing in 2001 and 2002 used 20 RRI injectors and 4 SNCR injectors. Based on the CFD modeling results, 8 additional RRI injectors and 14 additional SNCR injectors were installed for the 2005 field testing. The majority of field testing was conducted using the 80/20 coal blend at 480 MW, under two levels of air staging with OFA, resulting in baseline NOx emission rates of 0.25 lb/MMBtu with normal air staging and 0.20 lb/MMBtu with deep staging.

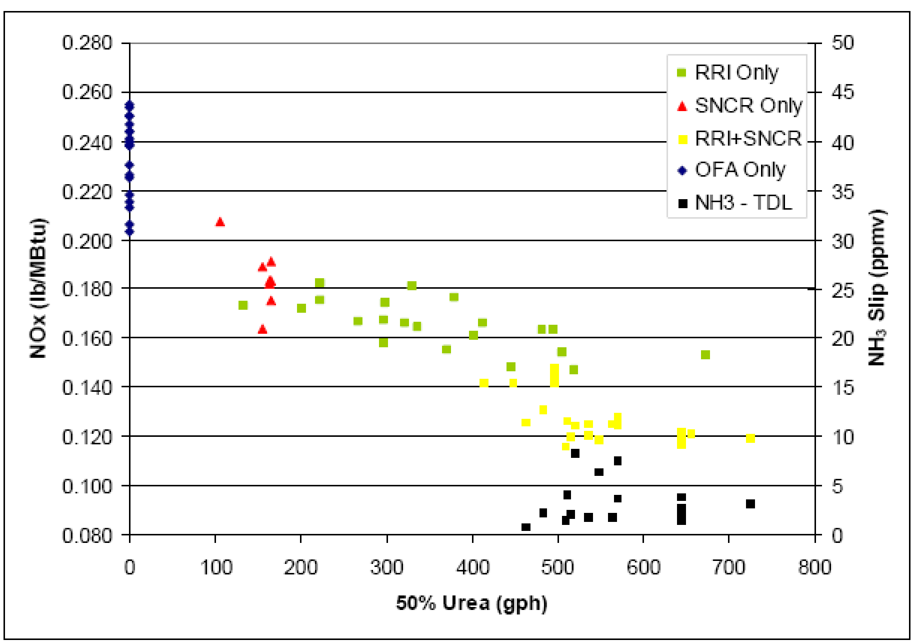
REI conducted parametric testing for the complete ALTA configuration and with RRI and SNCR separately. Using the 80/20 coal blend, the NOx emission rate achieved with ALTA averaged 0.12 lb/MMBtu with ammonia slip less than 5 ppm. For the 60/40 and 0/100 coal blends, the ALTA configuration achieved NOx emission rates of 0.15 and 0.165 lb/MMBtu, respectively. RRI alone reduced NOx emissions to 0.15 to 0.18 lb/MMBtu with less than 1 ppm ammonia slip when firing the typical 80/20 coal blend. Figure 5 presents the additional NOx reduction during RRI parametric testing for the three coal blends and varying levels of baseline NOx.

Figure 5 –REI Parametric Test Results with RRI at Sioux Unit 1



Parametric testing with SNCR alone demonstrated average NOx emissions of 0.156 and 0.165 lb/MMBtu for the 80/20 and 0/100 coal blends, respectively, at less than 5 ppm ammonia slip under most test conditions. Figure 6 shows the NOx emission rate for various test conditions using the 80/20 coal blend: baseline, using only OFA; OFA with RRI; OFA with SNCR; and the complete ALTA configuration with OFA, RRI, and SNCR. Also included in Figure 6 are measured levels of ammonia slip at various urea feed rates.

Figure 6 – REI Parametric Test Results with OFA, RRI, SNCR, and ALTA at Sioux Unit 1



Pilot-Scale Testing of ALTA NOx Control for Wall-Fired Boilers – REI is also developing and verifying performance of the ALTA NOx control technology for wall-fired boiler applications to achieve an emission rate of less than 0.15 lb/MMBtu. The burners are being designed for complete near-burner combustion, rather than traditional staged combustion. Near-burner design provides greater homogeneity of the combustion products in the boiler. Not only does this create ideal conditions for combustion-related NOx control, it also results in a stoichiometry and temperature distribution above the burners that is ideal for the chemistry involved in RRI. REI is conducting CFD modeling and pilot-scale testing to optimize the near-burner combustion system and reagent injection. The pilot-scale testing is being conducted on a 5 million Btu/hr coal combustion furnace operated by the University of Utah. Testing began in summer 2006, but results are not yet available. REI will be conducting a second set of CFD modeling studies based on initial pilot-scale combustion results to refine the process design. The final task of the project will involve CFD modeling of a full-scale boiler to evaluate the impact of burner modifications combined with deeper staging and RRI on NOx emissions, unburned carbon, waterwall corrosion, and boiler heat balance.

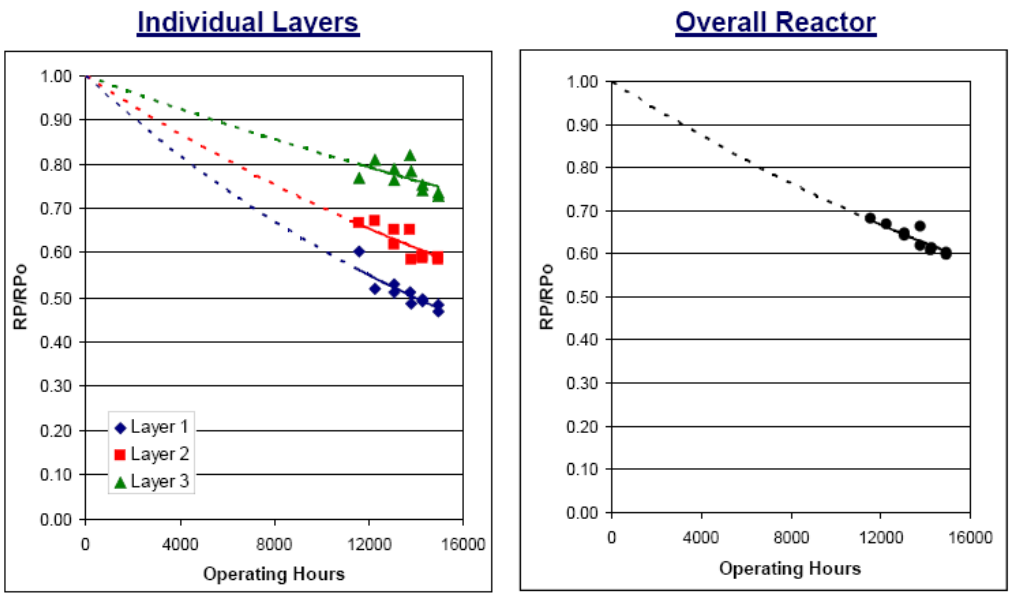
Current Advanced Post-Combustion NOx Control R&D

In addition to the four advanced in-furnace NOx control technology projects discussed above, DOE/NETL has also begun an R&D effort to optimize the performance of SCR controls to support the program's long-range goal to achieve a NOx emission rate of 0.01 lb/MMBtu by 2020. At this time, only one R&D project focuses on SCR performance.

In Situ Device for Real-Time Catalyst Deactivation Measurements in Full-Scale SCR Systems – Fossil Energy Research Corporation (FERCo) is developing an *in situ* catalyst deactivation measurement device to reduce SCR operating costs through optimized catalyst management.[30] The device will collect real-time SCR performance data by continuously measuring catalyst activity. As the data is collected, it is analyzed by an existing catalyst management software program, providing information on boiler operating conditions that negatively impact catalyst activity. This information can then be used to optimize boiler operation with respect to catalyst deactivation rate and the catalyst replacement schedule.

FERCo is conducting tests on the SCR installed at Southern Company's 700 MW tangentially-fired Gorgas Unit 10, which burns bituminous coal. The SCR started operation in 2002 and is designed with two parallel SCR reactors containing three extruded honeycomb catalyst layers plus a spare. FERCo installed its *in situ* measurement device on each of the three catalyst layers in one of the reactors prior to the 2005 ozone season, and took six sets of catalyst activity measurements throughout the summer at four-week intervals. The *in situ* measurement device uses a self-contained ammonia feed system to control ammonia concentration and extracts upstream and downstream flue gas samples to analyze the inlet and outlet NOx concentration. Catalyst activity is assessed using a metric known as reactor potential (RP), which provides a measure of the overall potential of the SCR reactor to reduce NOx by accounting for both catalyst deactivation and catalyst layer blockage. The reduction in reactor potential can be characterized by the ratio RP/RP_o, where RP is the current measurement and RP_o is the value for the initial fresh, unexposed catalyst layer. Figure 7 presents the results of the *in situ* RP/RP_o measurements for the individual layers and the overall SCR reactor taken during the 2005 ozone season. The RP/RP_0 results for the individual layers illustrate the accelerated deterioration of catalyst performance that occurs over time in the first layer compared to the second layer and similarly the second layer compared to the third. As shown, the RP/RP_0 ratio for the overall reactor dropped from approximately 0.7 to 0.6. The results of these 2005 *in situ* measurements were then compared to *ex situ* laboratory measurements. Although there was general agreement between the two methods, some differences are being investigated. Additional *in situ* measurements were taken during the 2006 ozone season, but results are not yet available.

Figure 7 – FERCo In Situ SCR Reactor Potential Measurements for 2005



Summary

While our knowledge of the formation and capture of NOx from coal-fired power plants has greatly advanced over the past two decades, many challenges remain. As the nation moves toward ever-tightening regulation of NOx emissions from the electric power sector, it is critical that research continues to address these challenges. In response, DOE/NETL has partnered with industry and other key stakeholders in carrying out a comprehensive advanced NOx control technology R&D program. This effort is focused on enhancing the NOx capture performance of existing technologies and developing advanced control concepts to achieve high levels of NOx removal at costs considerably lower than current SCR technology. The cost and performance of the advanced NOx in-furnace control technologies currently being developed under the IEP program are meeting the DOE/NETL R&D goals for 2007 and are likely to achieve the R&D goals for 2010, as well. A preliminary DOE/NETL assessment shows a U.S. market potential for approximately 150 GW of advanced NOx in-furnace control technologies that could cost-effectively replace 75 GW of new SCR controls that would be required for compliance with upcoming NOx control requirements.

References

[1] *Annual Energy Outlook 2006.* Energy Information Administration, Report No. DOE/EIA-0383(2006). See http://www.eia.doe.gov/oiaf/aeo/aeoref_tab.html.
[2] Khan, Sikander. *Updating Performance and Cost of NOx Control Technologies in the Integrated Planning Model*. Presented at the A&WMA/EPA/DOE/EPRI Combined Power Plant Air Pollutant Control Mega Symposium, Washington, DC, August 30 – September 2, 2004.
[3] Marano, Mark and Sharp, George. *Estimating SCR Installation Costs*. Power Magazine, January/February 2006.
[4] *Regulatory Impact Analysis for the Final Clean Air Interstate Rule*. U.S. Environmental Protection Agency, Report No. EPA-452/R-05-002, March 2005. See http://www.epa.gov/cair/technical.html.
[5] *Clear Skies Basic Information.* U.S. Environmental Protection Agency. See http://www.epa.gov/air/clearskies/basic.html.
[6] *Analysis of S.1844, the Clear Skies Act of 2003; S.843, the Clean Air Planning Act of 2003; and S.366, the Clean Power Act of 2003.* EIA Report No. SR/OIAF/2004-05; Energy Information Administration; May 2004.
[7] Senate Bill 131. See http://thomas.loc.gov/.
[8] *Control Measure Summary for Electric Generating Units.* Ozone Transport Commission, January 12, 2006. See http://www.otcair.org/.
[9] Office of New York State Attorney General. See http://www.oag.state.ny.us/.
[10] *Comprehensive Reliability Planning Process, Reliability Needs Assessment.* New York Independent System Operator, December 21, 2005. See http://www.nyiso.com.
[11] *North Carolina's Clean Smokestacks Act*. North Carolina Department of Environment and Natural Resources, Division of Air Quality. See http://daq.state.nc.us/news/leg/cleanstacks.
[12] *Houston/Galveston/Brazoria SIP Revision*. Texas Natural Resource Conservation Commission. See http://www.tnrcc.state.tx.us/oprd/sips/capandtrade.html.
[13] Watts, J.; Mann, A.; and Russell, D. *An Overview of NOx Control Technologies Demonstrated under the Department of Energy's Clean Coal Technology Program.* Presented at American Institute of Chemical Engineers Conference, New Orleans, LA, March 1998.
[14] Feeley, T.; Mayne, A.; and Plasynski, S. (2002) 'The U.S. Department of Energy's NOx control technology R&D programme for existing power plants', *Int. J. of Environment and Pollution,* Vol. 17, Nos. 1/2, pp. 00-00.
[15] Lani, Bruce; et al. *A Review of DOE/NETL's Advanced NOx Control Technology R&D Program for Coal-Fired Power Plants.* National Energy Technology Laboratory, March 2005. See http://www.netl.doe.gov/technologies/coalpower/ewr/nox/index.html.
[16] *Ultra Low NOx Integrated System for NOx Emission Control From Coal-Fired Boilers;* Final Report to the U.S. Department of Energy under Contract No. DE-FC26-00NT40754; ALSTOM Power Inc., December 30, 2002. See http://www.netl.doe.gov/technologies/coalpower/ewr/nox/control-tech/ultranox1.html
[17] Richards, Galen; et al. *Ultra-Low NOx Integrated System for Coal-Fired Power Plants*. Presented at the 2001 International Joint Power Generation Conference, New Orleans, LA, June 4 - 7, 2001. See http://www.netl.doe.gov/technologies/coalpower/ewr/nox/control-tech/ultranox1.html
[18] LaRue, A; Nikitenko, G.; Blinka, H.; Hoh, R. *Lower NOx / Higher Efficiency Combustion Systems*. Presented at the A&WMA/EPA/DOE/EPRI Combined Power Plant Air Pollutant Control Mega Symposium, Chicago, IL, August 2001.
[19] *Cost-Effective Control of NOx with Integrated Ultra Low-NOx Burners and SNCR;* Final Report to the U.S. Department of Energy under Contract No. DE-FC26-99FT40717; McDermott Technology, Inc., July 2003.
[20] Cremer, Marc; et al. *Design and Demonstration of Rich Reagent Injection (RRI) for NOx Reduction at Conectiv's B.L. England Station*. Presented at the A&WMA/EPA/DOE/EPRI Combined Power Plant Air Pollutant Control Mega Symposium, Chicago, IL, August 2001.
[21] Cremer, M.; et al. *Improved RRI Performance for NOx Control in Coal-Fired Utility Boilers.* Presented at DOE/NETL 2003 Conference on SCR and SNCR for NOx Control, Pittsburgh, PA, October 2003.
[22] Bool, Lawrence; Bradley, Jurron. *NOx Reduction from a 44 MW Wall-Fired Boiler Utilizing Oxygen Enhanced Combustion*. Presented at the A&WMA/EPA/DOE/EPRI Combined Power Plant Air Pollutant Control Mega Symposium, Washington, DC, May 2003.
[23] *Oxygen Enhanced Combustion for NOx Control;* Final Report to the U.S. Department of Energy under Contract No. DE-FC26-00NT40756; Praxair, Inc., March 2004.
[24] *Novel Pollution Control Technology Recognized.* NETL TechNews, November 17, 2005. See http://www.netl.doe.gov/publications/TechNews/tn_novel_pollution.html.

[25] *DOE-Funded Technology Slashes NOx, Costs in Coal-Fired Cyclone Boiler.* NETL TechNews, November 7, 2005. See http://www.netl.doe.gov/publications/TechNews/tn_doe_fund.html.
[26] Platts UDI North American Power Plant Database. Accessed March 2006.
[27] Richards, G.; et al. *Development of an Enhanced Combustion Low NOx Pulverized Coal Burner*. Proceedings of the 31st International Technical Conference on Coal Utilization & Fuel Systems, Clearwater, FL, May 2006.
[28] Cremer, Marc; et al. *Sub 0.15 lb/MBtu NOx Emissions Achieved with ALTA on a 500 MW Cyclone-Fired Boiler*. Proceedings of the 31st International Technical Conference on Coal Utilization & Fuel Systems, Clearwater, FL, May 2006.
[29] *Cyclone Boiler Field Testing of Advanced Layered NOx Control Technology in Sioux Unit 1;* Final Report to the U.S. Department of Energy under Contract No. DE-FC26-04NT42297; Reaction Engineering International, September 2006.
[30] Smith, R; et al. *In situ Determination of SCR Catalyst Activity*. Proceedings of the NETL 2006 Environmental Controls Conference, Pittsburgh, PA, May 2006. See http://www.netl.doe.gov/publications/proceedings/06/ecc/index.html