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CLEAN COAL TECHNOLOGY

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The U.S. Department of Energy

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# Executive Summary

The Clean Coal Technology (CCT) Demonstration Program is a government and industry co-funded effort to demonstrate a new generation of innovative coal utilization processes in a series of facilities built across the country. These projects are carried out on a commercial scale to prove technical feasibility and provide the information required for future commercial applications.

The goal of the CCT Program is to furnish the marketplace with a number of advanced, more efficient coal-based technologies that meet strict environmental standards. These technologies minimize the economic and environmental barriers that limit the full utilization of coal.

Beginning in 1985, a multi-phased effort consisting of five separate solicitations was administered by the U.S. Department of Energy's (DOE) National Energy Technology Laboratory. The CCT Program has successfully demonstrated a number of coal utilization technologies that are being applied commercially with beneficial results to the environment and increased efficiency in the use of energy.

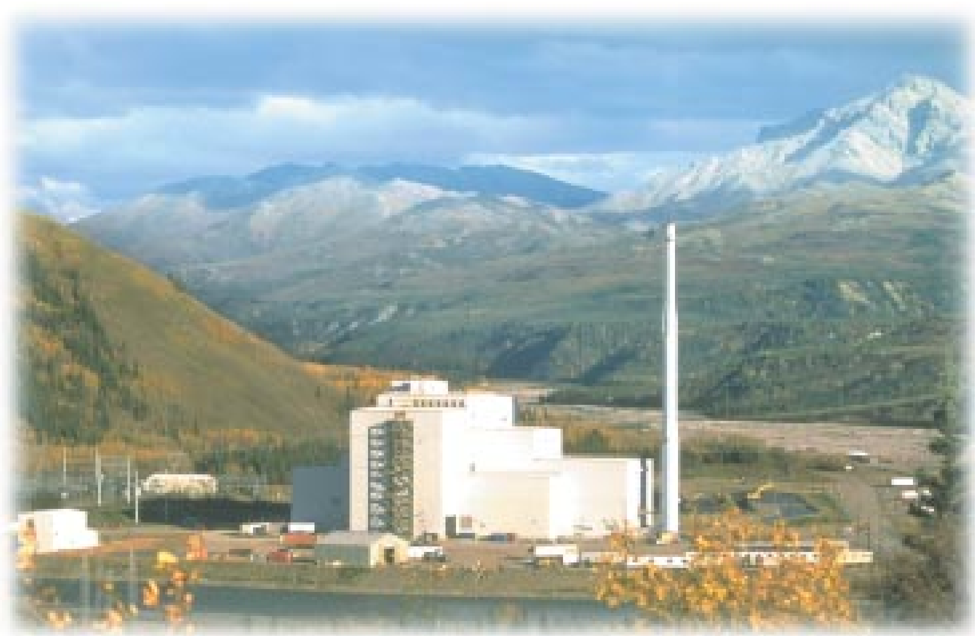
A major criticism of coal as a fuel source for power generation is that it produces large amounts of pollutants, primarily sulfur dioxide ($SO_2$), nitrogen oxides (NOx), and particulate matter (PM), as well as carbon dioxide ($CO_2$), which is implicated in global climate change. This report summarizes the contributions of the CCT Program in achieving significant reductions in emissions of these pollutants.

Uncontrolled $SO_2$ emissions from U.S. coal-burning power plants could exceed 20 million tons/yr. As a result of controls already in place, $SO_2$ emissions have been reduced to about 12 million tons/yr. If CCT-developed technologies were applied to all coal-fired boilers, it is estimated that $SO_2$ emissions could be further reduced by another 10 million tons/yr.

Total NOx emissions from coal-fired boilers are about 6.8 million tons/yr, equivalent to an emissions rate of 0.75 lb/million Btu. If average NOx emissions were reduced to 0.35 lb/million Btu, a goal easily reached using demonstrated technologies, total NOx emissions would be reduced by an additional 3.6 million tons/yr to approximately 3.2 million tons/yr.

CCT Program successes include:

- Advanced technologies that have dramatically improved the economic and environmental performance of flue gas desulfurization systems for $SO_2$ control. By-product gypsum is now recovered for sale as wallboard, thereby eliminating a major waste disposal problem.
- NOx reduction technologies that have been or are being retrofitted to a large segment of the nation's coal-fired power generating capacity. Low-NOx burners now cost a fraction of the cost of NOx pollution controls available in the 1980s.
- New power generation systems now in commercial operation, based on coal gasification. These systems are among the cleanest power plants in the world, with extremely low emissions of $SO_2$, NOx, and particulates.



**The Healy power plant is located near the Denali National Park and Preserve, an environmentally sensitive area in Alaska.**

# Environmental Benefits of Clean Coal Technologies

## *Background*

The Clean Coal Technology (CCT) Demonstration Program, sponsored by the U.S. Department of Energy (DOE) and administered by the National Energy Technology Laboratory (NETL), has been underway since 1985. Its goal is to develop innovative, environmentally friendly coal utilization processes for the world energy marketplace. The CCT Program involves a series of demonstration projects that provide data for design, construction, operation, and technical/economic evaluation of full-scale commercial facilities.

The CCT Program represents an investment of over $5 billion in the demonstration of advanced coal-based technologies, with industry and state governments providing a significant share — 66% — of the funding. With 26 of the 38 projects having completed operations, the CCT Program has yielded a variety of processes that are capable of meeting existing and emerging environmental regulations and competing economically in a deregulated electric power marketplace.

# *Clean Coal for a Better Tomorrow*

## *Environmental Regulations*

The Clean Air Act Amendments (CAAA) of 1990 is one of the most complex and comprehensive pieces of environmental legislation ever written. It authorized the Environmental Protection Agency (EPA) to establish regulations controlling emissions from a variety of stationary sources, including coal-fired boilers.

The CCT Program has introduced a variety of options to policy-making bodies by providing data from cutting-edge technologies to aid in formulating regulatory decisions. As an example, DOE and the industrial participants in several CCT projects have provided EPA with data to help establish realistic emissions targets for coal-fired boilers.

The CAAA addresses six major substances, referred to as criteria pollutants: carbon monoxide (CO), lead (Pb), nitrogen dioxide ($NO_2$), ozone ($O_3$), particulate matter (PM), and sulfur dioxide ($SO_2$). Ozone is not emitted directly into the air, but is formed by interaction of volatile organic compounds (VOCs) and nitrogen oxides (NOx). Although $NO_2$ is a criteria pollutant, the CAAA has focused on NOx, owing to its direct connection with ozone formation.

The portions of the CAAA of greatest relevance to the CCT Program are Title I and Title IV. Title I addresses the issue of ozone in ambient air, and targets NOx emissions reduction as a means of achieving compliance. Title IV, referred to as the Acid Rain Program, addresses emissions of $SO_2$ and NOx.

## $SO_2$ Formation

All coals contain sulfur. Some of this sulfur, known as organic sulfur, is intimately associated within the coal matrix. The rest of the sulfur, in the form of pyrites or sulfates, is associated with the mineral matter. High-sulfur bituminous coals contain 1-4% sulfur, whereas low-sulfur Western coals may have sulfur content below 1%. Upon combustion, most of the sulfur is converted to sulfur dioxide ($SO_2$), with a small amount being further oxidized to sulfur trioxide ($SO_3$).

### *$SO_2$ Emissions*

$SO_2$ is formed during coal combustion by oxidation of sulfur in the coal. $SO_2$ control is achieved by removing it from the flue gas. Even before enactment of the CAAA, the CCT Program was cognizant of the likely effects of the anticipated regulations on electric power generation. Several projects in the CCT Program were conducted at units designated as Phase I units under Title IV, which were required to meet $SO_2$ reductions by January 1, 1995. CCT Program projects installed at Phase I units successfully reduced $SO_2$ emissions using advanced flue gas desulfurization (FGD) processes.

With the arrival of the January 1, 2000 deadline for Phase II of Title IV, the CCT Program had developed a portfolio of technologies to help industry meet the more stringent $SO_2$ emission limits. Unit operators now have the option of either meeting $SO_2$ reduction requirements or exceeding them to generate $SO_2$ credits that can be sold in the emissions credit market.

### *NOx Emissions*

NOx is formed from oxidation of nitrogen contained within the coal (fuel NOx) and oxidation of the nitrogen in the air at high temperatures of combustion (thermal NOx).

NOx became the focus of a series of regulatory actions to severely limit emissions after being identified as a source of both acid rain (targeted under Title IV) and urban smog (targeted under Title I). Coal-fired boilers represent a primary source of NOx emissions and a specific target of regulatory action. Although combustion of gas and oil also results in NOx emissions, and mobile sources contribute significantly to this problem, the focus of the CCT Program is control of pollution resulting from coal combustion/gasification.

The Acid Rain Program (Title IV of the CAAA) calls for major reductions in NOx emissions. The CCT Program has successfully demonstrated control techniques that are applicable to all major boiler types. Furthermore, these technologies are applicable not only to Title IV but also to Title I NOx reductions.

The issue of ozone nonattainment, covered under Title I, took on new proportions in 1997 as EPA issued a call for state implementation plans (SIP) to 22 states and the District of Columbia. These plans required action to reduce regional transport of pollutants that contribute to ozone nonattainment in the U.S. Northeast. The SIP Call requires the 23 affected jurisdictions to reduce power plant NOx emissions by 85% from 1990 rates or achieve a 0.15 lb/million Btu emission rate. These reductions were to be achieved by the target compliance date of May 2003.

In addition, EPA tightened the New Source Performance Standards (NSPS) for electric and industrial boilers built or modified after July 9, 1997.

### *Particulate Emissions*

Particulate matter is the general term for a mixture of solid particles and liquid droplets found in the atmosphere. Some particles are large enough to be seen as soot or smoke. Others are so small that they can be detected only with an electron microscope. $PM_{2.5}$ describes the fine particles that are less than or equal to 2.5 microns (μ) in diameter. A micron is one millionth of a meter, or about 0.00004 inch. Coarse particles are those greater than 2.5 μ and less than 10 μ in diameter. The latter are referred to as $PM_{10}$.

PM originates from many different stationary and mobile sources as well as natural sources. Fine particles result from fuel combustion in motor vehicles, during power generation, and in industrial facilities. Coarse particles are generally emitted from sources such as vehicles traveling on unpaved roads, materials handling, crushing, and grinding operations, as well as windblown dust. Some particles are emitted directly from their sources, such as smokestacks and cars. In other cases, gases such as $SO_2$, NOx, and volatile organic compounds (VOCs) interact with other compounds in the air to form fine particles. Their chemical and physical compositions vary depending on location, time of year, and weather.

$SO_2$ reduction may contribute to meeting emissions requirements for $PM_{2.5}$ because some sulfur species are also included in $PM_{2.5}$.

### *Air Toxics Emissions*

Air toxics is another important area of environmental concern addressed by the CCT Program. Under Title I of the CAAA, EPA is responsible for determining the hazards to public health posed by 189 identified hazardous air pollutants (HAPs). The CCT Program has made a significant contribution to a better understanding of this issue from power plant emissions by monitoring HAPs from several project sites. The results of these and other studies have significantly mitigated concerns about HAP emissions from coal-fired power plants and focused attention on only a few flue gas constituents. EPA has recently determined that emissions of mercury, a HAP of major concern, will require control. Regulations are to be proposed by the year 2003, with implementation by 2005.

### *Climate Change*

Global climate change is one of the primary environmental concerns of the 21st century. Response to climate change could dictate fundamental changes in the ways that we generate and use energy. Such measures as energy efficiency improvements, forest management options, and renewable energy applications are potentially important methods for reducing greenhouse gas (GHG) emissions in the short to medium term.

The CCT Program addresses climate change concerns. Advanced coal-based technologies being demonstrated in the CCT Program offer utilities an option to make substantial reductions in GHG emissions through enhanced efficiency of first-generation systems.

## $SO_2$ Emissions Control Technologies

**Wet Scrubbing**

Wet scrubbing or flue gas desulfurization (FGD) is the most frequently used technology for post-combustion control of $SO_2$ emissions. Wet FGD is frequently used with existing boilers and has the advantage that no modifications either to the boiler or to the particulate emission control device are required. Typically, the flue gas is contacted with an aqueous slurry of limestone ($CaCO_3$) in a countercurrent absorber, or scrubber. The $SO_2$ reacts to form $CaSO_3$ which is then oxidized to $CaSO_4$ (gypsum).

Allowable gas flow per unit cross sectional area is determined by the mass transfer characteristics of the system. This determines the diameter of the scrubber. These vessels and the accompanying equipment used for slurry recycle, gypsum dewatering, and product conveyance tend to be quite large. Some variations of this technology produce high quality gypsum for sale. Less pure waste product may be sold for use in cement production. If neither of these options is practiced, the scrubber waste must be disposed of in a sludge pond or similar facility.

**Dry Sorbent Injection (DSI)**

In DSI, a reactive calcium- or sodium-based sorbent is injected into the economizer or flue gas duct to react directly with the $SO_2$ in the flue gas. The two most common calcium-based sorbents are limestone and slaked lime, $Ca(OH)_2$. Limestone, which generally requires a higher reaction temperature, is usually injected as a dry powder. Slaked lime, on the other hand, is usually handled as a slurry, which dries as soon as it is injected into the hot flue gas. Upon injection, $Ca(OH)_2$ immediately begins to dehydrate. The escaping water vapor creates internal pores that provide access for $SO_2$ diffusion into the interior of the particles. The CaO produced by dehydration reacts with $SO_2$ to give $CaSO_3$, which can be oxidized to $CaSO_4$.

Typical sodium-based sorbents are sodium bicarbonate ($NaHCO_3$), sodium sesquicarbonate ($NaHCO_3 \cdot Na_2CO_3 \cdot 2H_2O$), and sodium carbonate ($Na_2CO_3$). Below 300 $^oF$, $NaHCO_3$ reacts immediately with $SO_2$ to form $Na_2SO_3$. At higher temperatures, $NaHCO_3$ decomposes to $Na_2CO_3$ before reacting with $SO_2$. As water and $CO_2$ are given off by the sorbent particles, additional surface area becomes available for reaction with $SO_2$. Although $CO_2$ is a product of $CaCO_3$, $NaHCO_3$, and $Na_2CO_3$ decomposition, the amount generated is minimal compared to that already present in the flue gas.

In some cases, flue gas humidification may be necessary for proper operation of the downstream particulate removal system.

**Production of Sulfuric Acid**

In this process option, the $SO_2$ in the flue gas is first converted to $SO_3$ by passing the flue gas over a catalyst bed. The $SO_3$ reacts with water to form sulfuric acid, which is recovered for sale.

# *CCT Program Market Sectors*

This report focuses primarily on the success of the CCT Program in reducing emissions of $SO_2$, NOx, and particulates. CCT demonstration projects have covered a wide variety of processes, addressing four market sectors:

**Environmental Controls**

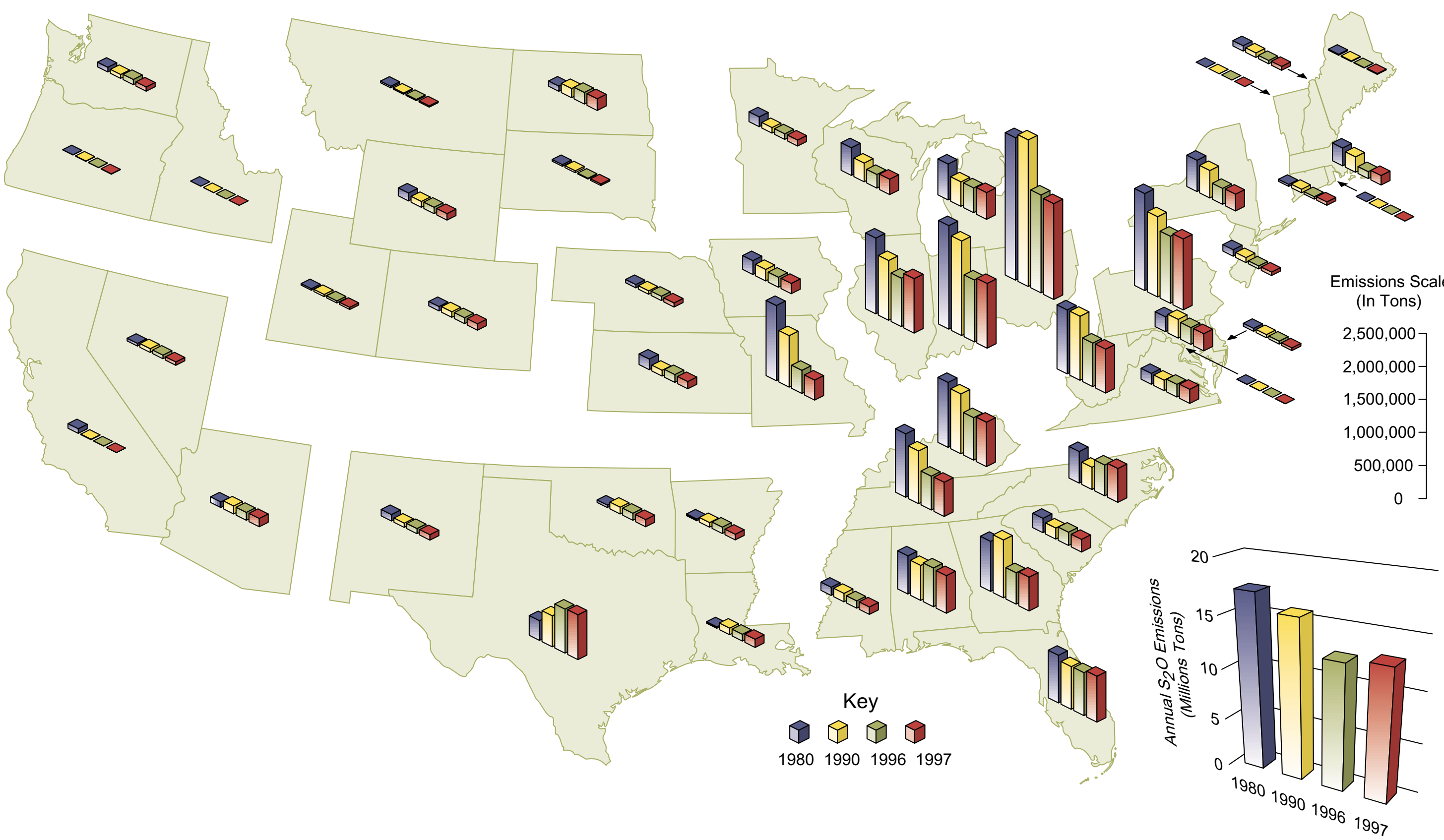
These technologies were developed to remove or prevent the formation of $SO_2$, NOx, and particulates when coal is burned to generate electric power using conventional technologies.

**Advanced Power Generation**

These are advanced, coal-fired technologies designed to replace conventional coal-fired power generation. They are characterized by high thermal efficiency, very low pollutant emissions, reduced $CO_2$ emissions, few solid waste problems, and enhanced economics. Three major areas of technology are considered to be advanced electric power generators:

- Fluidized-Bed Combustion (FBC)
- Integrated Gasification Combined Cycle (IGCC)
- Advanced Combustion/Heat Engines.

FBC reduces emissions of $SO_2$ and NOx by controlling combustion parameters and by injecting a sorbent into the combustion chamber along with the coal. Crushed coal mixed with the sorbent (e.g. calcium carbonate) is fluidized on jets of air in the combustion chamber. Sulfur released from the coal as $SO_2$ is captured by the sorbent to form a solid calcium compound that is removed with the ash. Greater than 90% $SO_2$ removal can be achieved. FBCs operate at a much lower temperature than that of conventional pulverized-coal boilers, greatly reducing the amount of thermal NOx formed.




**$SO_2$ emissions reductions are occurring where they are needed – in some of the highest emitting areas of the country.**

1970 1980 1990 2000 2010 2020

**Air Quality Act of 1967** ESP's or baghouses required for coal-fired power plants

**New Source Performance Standards** established for NOx, $SO_2$, and PM

**PM** emissions limits for new coal-fired boilers reduced by 70%

**Acid Rain** program initiated, resulting in widespread switching to low-sulfur coal and installation of low-NOx burners

**Coal Combustion By-Products** (fly ash, bottom ash, boiler slag and FGD residue) cited by EPA as non-hazardous solid wastes, with disposal and use to be regulated by states under RCRA Subtitle D

**Fine Particulates** cited by EPA as a health hazard, corresponding primary PM, NOx and/or $SO_2$ emissions to be reduced by 70% in 19 eastern states by 2007

**Ground-Level Ozone,** NOx emissions to be reduced by 70% in 19 eastern states by 2007

**Mercury** EPA report to Congress suggests a plausible link between mercury emissions from power plants and contamination on fish

**Information Collection Request,** EPA requires certain U.S. coal utilities to sample coal feedstock and stack emissions and test for mercury content

**Regional Haze** rule cites fine particulates as the primary cause of haze and sets a goal of achieving natural background visibility in 60 years

**Toxics Release Inventory,** power plants begin reporting releases of mercury, acid gases ($SO_3$, HCl, HF) and other species

**Environmental regulation of coal-fired electricity generating plants is becoming increasingly stringent.**

IGCC systems involve gasification of coal, cleaning the gas, and combusting it in a gas turbine generator to produce electricity. Residual heat in the exhaust gas from the gas turbine is recovered in a heat recovery boiler as steam, which can be used to produce additional electricity in a steam turbine generator. IGCC systems are among the cleanest and most efficient of the emerging clean coal technologies. Sulfur, nitrogen compounds, and particulates are removed before the gas is burned in the gas turbine.

In the gasifier, the sulfur in the coal is released in the form of hydrogen sulfide ($H_2S$), which is readily removed by commercially available processes. By-products are salable sulfur or sulfuric acid. Sulfur removal exceeds 99.9%, and thermal efficiencies of over 50% can be achieved. High levels of nitrogen removal are also possible. Some of the coal's nitrogen is converted to $NH_3$, which can be almost totally removed by established chemical processes. NOx formed in the gas turbine can be held to well within allowable levels by staged combustion or by adding moisture to control flame temperature.

Advanced combustion/heat engines include slagging combustors that are designed to remove coal ash as molten slag in the combustor rather than the furnace, and coal-fired diesel engines. These engines use either a coal-oil or coal-water slurry fuel to drive an electric generation system.

**Coal Processing for Clean Fuels**

This area includes a variety of technologies designed to produce solid and clean liquid fuels having high energy density and low sulfur.

**Industrial Applications**

This category includes a steel-making process in which coal replaces a portion of the coke traditionally used in iron-making furnaces. It also includes a process to remove $SO_2$ from the flue gas produced in cement manufacture.

## Responding to New Marketplace Realities

DOE programs developing coal utilization technologies and power generation systems are responding to dramatic changes occurring in the energy marketplace. Energy industry deregulation is creating intense cost-reduction pressures on power producers. DOE programs are geared to provide these producers with cost-competitive solutions to environmental challenges. At the same time, natural gas, electric, water, and oil companies are merging into larger business entities that are investing less in research. Therefore, DOE programs must leverage limited private-sector research dollars more effectively than ever. Deregulation is also creating new markets for energy concepts that use natural gas, coal, and biomass fuels to generate a mix of products that include electricity, liquid fuels, and chemicals, with virtually zero environmental impact.

# Environmental Progress

Overall, air quality levels measured at thousands of monitoring stations across the country have shown improvement (i.e. reductions) over the past 20 years for all six criteria pollutants.

Between 1900 and 1970, emissions of these six pollutants had increased significantly, with increases of 690% in NOx, 260% in VOCs, and 210% in $SO_2$. Without the controls imposed by the 1970 Clean Air Act and its 1977 and 1990 Amendments, emissions would have increased at a higher rate. Since enactment of the CAAA, emissions of the criteria pollutants have decreased significantly, with the exception of NOx.

Efforts to protect the stratospheric ozone layer have also been effective. Concentrations of methyl chloroform and chlorofluorocarbons in the upper layers of the atmosphere have begun to decrease.

## Acid Rain Program

Compliance with Title IV of the CAAA has resulted in significant progress in reducing emissions of $SO_2$ and NOx from U.S. coal-burning power plants, with major contributions resulting from widespread use of control technologies developed in the CCT Program.

### $SO_2$ Emissions Reductions

The CAAA sent a clear signal to industry in the statement, "$SO_2$, a primary precursor to acid rain, must cease to be a major pollutant emission by the beginning of the 21st century." Interim response to the regulation included fuel switching, allowance trading, and some installation of available emissions controls. However, to meet the post-2000 cap on $SO_2$ emissions, high-efficiency control technologies are required.

Prior to the CCT Program, scrubbers capable of high $SO_2$ removal were costly to build, difficult to maintain, placed a significant parasitic load on plant output, and produced a sludge waste requiring extraordinary disposal measures with considerable land use.

The demonstration projects conducted under the CCT Program have redefined the state of the art in scrubber technology. Use of innovative capture technologies have nearly halved capital and operating costs, produced valuable by-products such as wallboard-grade gypsum instead of waste, mitigated plant efficiency losses, and captured multiple air pollutants.

As a result, advanced FGD systems are now in operation that provide $SO_2$ removal efficiencies of 95-98%. The CCT demonstration projects involving $SO_2$ scrubbers predated the Title IV Phase 1 compliance date by two to three years. In 1995, the first year of compliance under Title IV, $SO_2$ emissions dropped dramatically, by 3 million tons. Over the first four years of the CCT Program, $SO_2$ emissions from the 263

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# NOx Reduction Technologies

NOx reduction technologies can be grouped into two broad categories: combustion modifications and post-combustion processes. Some of the more important NOx control technologies are briefly discussed below.

## Combustion Modification

*Low-NOx Burners* — LNBs are designed to control the mixing of fuel and air to achieve what amounts to staged combustion. This results in a lower maximum flame temperature and a reduced oxygen concentration during some phases of combustion. This results in both lower thermal NOx and lower fuel NOx production.

*Overfire Air* — OFA is air that is injected into the furnace above the normal combustion zone. OFA is generally used in conjunction with operating the burners at a lower than normal air-to-fuel ratio, which reduces NOx formation. The OFA completes the combustion at a lower temperature. OFA is frequently used in conjunction with LNBs.

*Reburning* — With reburning, part of the boiler fuel input (typically 10-25%) is added in a separate reburn zone. In this zone, the fuel-rich reducing conditions lead to the reduction of NOx formed in the normal combustion zone. OFA is injected above the reburn zone to complete combustion. Thus, with reburn there are three zones in the furnace: (1) a combustion zone with an approximately normal air-to-fuel ratio; (2) a reburn zone, where added fuel results in a fuel-rich condition; and (3) a burnout zone, where OFA leads to completion of combustion. Coal, oil, or gas can be used as the reburn fuel.

*Flue Gas Recirculation* — FGR, in which part of the flue gas is recirculated to the furnace, can be used to modify conditions in the combustion zone (lowering the temperature and reducing the oxygen concentration) to reduce NOx formation. Another use for FGR is as a carrier to inject fuel into a reburn zone to increase penetration and mixing.

*Operational Modifications* — These modifications involve changing certain boiler operational parameters to create conditions in the furnace that will lower NOx production. Examples are burners-out-of-service (BOOS), low excess air (LEA), and biased firing (BF). In BOOS, selected burners are removed from service by stopping fuel flow, but air flow is maintained to create staged combustion in the furnace. LEA involves operating at the lowest possible excess air level without interfering with good combustion, and BF involves injecting more fuel to some burners (typically the lower burners) while reducing fuel to other burners (typically the upper burners) to create staged combustion conditions in the furnace.

## Post-Combustion Treatment

*Selective Catalytic Reduction* — In SCR, a catalyst vessel is installed downstream of the furnace. Ammonia ($NH_3$) is injected into the flue gas before it passes over the fixed-bed catalyst. The catalyst promotes a reaction between NOx and $NH_3$ to form nitrogen and water vapor. NOx reductions as high as 90% are achievable, but careful design and operation, such as control of the reagent dosage and assuring good mixing, are necessary to keep $NH_3$ emissions (referred to as $NH_3$ slip) to a concentration of a few ppm.

*Selective Noncatalytic Reduction* — In SNCR, a reducing agent (typically $NH_3$ or urea) is injected into the furnace above the combustion zone, where it reacts with NOx as in the case of SCR. Critical factors in applying SNCR are sufficient residence time in the appropriate temperature range and even distribution and mixing of the reducing agent across the full furnace cross section.

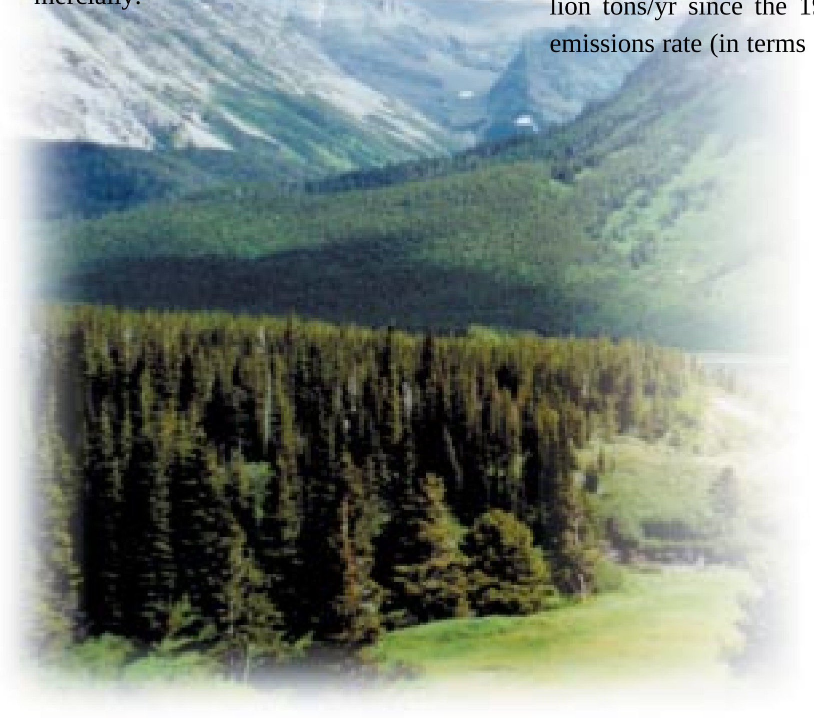
*Hybrid Processes* — SNCR and SCR can be used in conjunction with each other with some synergistic benefits. Also, either process can be used in conjunction with LNBs.

largest, highest emitting utility plants were about 5 million tons below their 1980 levels. The overall reduction in $SO_2$ emissions between 1990 and 1999 was 21%.

These reductions in emissions have occurred where they are most needed — in some of the highest emitting areas of the country. For example, affected power plants in Ohio and Indiana reduced $SO_2$ emissions by about 44% and 50%, respectively. Moreover, this decrease supports an economic premise of the Acid Rain Program. Utilities have more incentive to make substantial emissions reductions at the highest emitting plants because they can achieve them at a lower cost per ton. Concerns that the largest emitters of $SO_2$ would simply buy allowances and continue to emit at their historical levels have proved unwarranted thus far.

**NOx Emissions Reductions**

Prior to the CCT Program, NOx control technology proven in U.S. utility service was essentially nonexistent. Today that situation has changed dramatically. The CCT Program has met the regulatory challenge by developing and incorporating emerging NOx control technologies into a portfolio of cost-effective compliance options for the full range of boiler types being used commercially.



Products of the CCT Program for NOx control include:

- Low-NOx burners (LNBs), overfire air (OFA), and reburning systems that modify the combustion process to limit NOx formation.
- Selective catalytic and non-catalytic reduction technologies (SCR and SNCR) that remove NOx already formed.
- Artificial intelligence-based control systems that effectively handle numerous dynamic parameters to optimize operational and environmental performance of boilers.

As a result, over three quarters of U.S. coal-fired generation plants have installed LNBs. Reburning and artificial intelligence systems have made significant market penetration as well. All sites that developed these NOx control technologies have retained them for commercial use. In addition, numerous commercial installations of SCR and, to some extent SNCR, are planned or are under construction to meet the May 1, 2003, target date for implementation of Title I NOx control requirements.

While overall NOx emissions have remained relatively constant at about 23 million tons/yr since the 1980s, the average emissions rate (in terms of lb NOx/million Btu) for power plants participating in Title IV has decreased by 42% since 1996. Power plants generate about 30% of total NOx emissions, with motor vehicles and other industrial sources contributing most of the remainder. Although cleaner technologies are now being used in power plants, the total amount of electricity generated has increased significantly, as has the number of vehicle-miles traveled per year.

The IGCC demonstration projects have achieved excellent environmental performance, with emissions as low as 0.02 lb/million Btu for $SO_2$ and 0.08 lb/million Btu for NOx.

**Other Emissions Reductions**

During the 1990-1999 time period, U.S. emissions reductions have been 7% for CO, 23% for Pb, 15% for VOCs, and 16% for $PM_{10}$. CO and Pb emissions are almost entirely associated with automotive exhaust. Between 1970 and 1999, total emissions of the six principal pollutants decreased 31%. While this result can be attributed only in part to the implementation of technologies developed in the CCT Program, it is worthy of noting that substantial progress has been made.

## *Air Quality Improvements*

The emissions reductions cited above are contributing to measurably improved air quality. Data collected for the past 10 years show that ambient $SO_2$ concentrations also are declining, as are ambient sulfate concentrations. Sulfates are compounds formed from $SO_2$ emissions and are capable of being transported long distances. They are fine particulates that aggravate respiratory health problems, can lead to premature mortality, and degrade visibility, resulting in a hazy view of the horizon.

Long-term trends in annual mean aerosol sulfate concentrations show significant decreases at upwind locations in the U.S. Midwest and at two downwind rural locations in New York State. During the period from 1978 through 1996, sulfates declined sharply,

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# Integrated Gasification Combined-Cycle (IGCC)

IGCC technology consists of four basic steps: (1) fuel gas is generated from coal reacting with high-temperature steam and an oxidant (oxygen or air) in a reducing atmosphere; (2) the fuel gas is either passed directly to a hot-gas cleanup system to remove particulates, sulfur, and nitrogen compounds, or first cooled to produce steam and then cleaned conventionally; (3) the clean fuel gas is combusted in a gas turbine generator to produce electricity; and (4) the residual heat in the hot exhaust gas from the gas turbine is recovered in a heat-recovery steam generator. The steam is used to produce additional electricity in a steam turbine generator.

IGCC systems are among the cleanest and most efficient of the emerging clean coal power production technologies. Sulfur, nitrogen compounds, and particulates are removed before the fuel is burned in the gas turbine, that is, before combustion air is added. For this reason, there is a much lower volume of gas to be treated than in a postcombustion scrubber. The chemical composition of the gas requires that the gas stream be cleaned to a high degree, not only to achieve low emissions, but to protect downstream components, such as the gas turbine, from erosion and corrosion.

In the gasifier, the sulfur in the coal is released in the form of hydrogen sulfide ($H_2S$) rather than as $SO_2$. In some IGCC systems, much of the sulfur-containing gas is captured by a sorbent injected into the gasifier. Others use proven commercial $H_2S$ removal processes, which remove up to 99+ % of the sulfur. By-products include salable sulfur or sulfuric acid.

High levels of nitrogen removal are also possible. Some of the coal's nitrogen is converted to $NH_3$, which can be almost totally removed by commercially available chemical processes. NOx formed in the gas turbine can be held to well within allowable levels by staged combustion or by adding moisture to control flame temperature.

IGCC provides industry with highly efficient options for meeting a wide spectrum of market applications. Gasification technology can process all carbonaceous feedstocks, including coal, petroleum coke, residual oil, biomass, and municipal and hazardous wastes. It is the only advanced technology capable of coproducing electric power and a wide variety of commodity and premium products, such as ultra-clean transportation fuels and chemicals, to meet future market requirements. IGCC technology is applicable to both domestic and international baseload and repowering applications. Industrial markets also include the production of environmentally superior transportation fuels, premium chemicals, and commodity products. IGCC systems are also very effective in converting hazardous industrial wastes into valuable, benign products.

By converting carbonaceous feedstocks, such as coal and biomass, to high-value and commodity products as well as to baseload power, IGCC can meet diverse national and international energy market needs. Coproduction of energy products maximizes return on investment in these facilities while minimizing waste and environmental impact. Thanks to investments in energy R&D by the Federal Government and industry partners, U.S.-based companies are well-positioned to apply IGCC systems at home and to capture a healthy share of what promises to be a multi-billion-dollar export market for clean power generation technologies.

## Environmental Concerns are the Driving Force

The environmental drivers influencing the operation of existing coal-fired power plants over the next decade are being defined today. Key environmental regulations have been proposed or promulgated, thus establishing a need for new compliance technology. These environmental factors include but are not limited to the following:

- Revised NAAQS for fine particulate matter and ozone.
- Instructions to revise State Implementation Plans to address ozone concerns in the eastern United States.
- Petitions by northeastern states for the EPA to require upwind states to reduce NOx emissions from power plants.
- Requirements for states to address regional haze.
- Proposals to regulate mercury emissions from power plants.

The cost to comply with these regulations is expected to be several billion dollars per year; the research challenge is to find improved technologies that dramatically reduce these costs and fill technology gaps.

**Tampa Electric's Polk Power Plant, uses 1500 acres of its site to enhance the environment by the creation of public fishing lakes for the Florida Fish and Game Commission. This IGCC power plant uses makeup water from on-site wells and all process water is recycled.**

with air quality improving by 30% at one of the downwind locations and 47% at the other. Correspondingly, field data on sulfate deposition show declines of up to 30% in the U.S. Northeast and Mid-Atlantic regions. As anticipated, no statistically significant regional trends have been measured for nitrate concentration levels.

### *Additional Environmental Effects*

In the period before the CAAA, acidification of lakes and streams, believed to be a direct consequence of acid rain, had a serious impact on the survival of fish and other aquatic species. Many streams were reported to have suffered substantial losses of sensitive fish species. The loss of fish occurred primarily in surface waters resting atop shallow soils that were not able to buffer, or counteract, acidity. This situation existed most commonly in the Northeast and Mid-Atlantic, especially in the Adirondack Mountains in New York State.

Subsequent to the CAAA, many acidic surface waters have shown declines in sulfate concentrations consistent with objectives of the Acid Rain Program's emissions reduction. However, further reductions are needed before soil buffering capacity is restored.

The pollutants associated with acid deposition also are believed to reduce visibility. Visibility impairment, or haze, occurs when particles and gases in the atmosphere, including sulfates and nitrates, scatter and absorb light. Sulfate particles account for more than 50% of the impaired visibility, particularly in combination with high summertime humidity. In the U.S. West, nitrogen and carbon compounds also impair visibility, and sulfur oxides have been implicated as a major cause of haze in many national parks. However, some improvement has been achieved as a result of the Acid Rain Program, but further progress is needed if pristine conditions are to be fully restored in these areas.

It has been reported that acid deposition, combined with other pollutant and natural stress factors, can damage forest ecosystems, sometimes contributing to the death of certain tree species. The Acid Rain Program appears to be reversing some of these trends. However, the Adirondacks continue to present a challenge. Despite declining emissions and even declining surface water sulfate concentrations, lakes in this region are not showing any measurable increase in buffering capacity. This can be attributed to a number of causes that are not fully understood. Recent research and modeling efforts suggest that, although conditions would likely have been substantially worse without the Acid Rain Program, full recovery of the Adirondacks ecosystems may require further reductions in $SO_2$ and NOx emissions.

The fine particles of sulfates and nitrates in the atmosphere are believed to cause serious health effects as well. Although both fine and coarse particles are of concern, fine particles are particularly important because they easily penetrate the deepest portions of the lungs. Exposure to these particles has been implicated in a variety of cardiac- and respiratory-related problems. The significant reductions in fine particulate emissions since implementation of the CAAA, especially from coal-burning power plants, have been estimated to result in substantial health benefits representing major cost savings.

Sulfur oxides, sulfates, and, to a lesser degree, nitrates are corrosive to most materials, and thus can severely damage man-made objects exposed to the atmosphere. Acid deposition degrades materials beyond natural weathering. The Eastern United States, with its high concentration of historic buildings and outdoor monuments, also has some of the highest levels of acid deposition in the nation. Materials potentially damaged also include bridges, buildings, and automotive finishes. Ultimately, cultural preservation, as well as monetary benefits, should accompany reductions in acid rain emissions, but these effects have not yet been quantified.

Emissions of air toxics have decreased somewhat since enactment of the CAAA, but programs to monitor these emissions and establish control targets have only recently been put in place.

## *CCT Participant Comments*

One measure of the success of the CCT Program is the number of favorable comments provided by industrial Participants in the Program. Sample responses are as follows:

- "Our experience with the Clean Coal Program allowed us to make informed decisions on how to best control NOx emissions throughout our ... service area. It has saved our customers millions of dollars." — Randall Rush, Southern Company Services
- "We view our Clean Coal technology project as a natural solution. Our customers will benefit from a reliable, economical fuel. Our environment will benefit from superior emissions reduction performance. And our company will benefit by producing reliable generation in a way that more than meets the Clean Air Act." — Girard F. Anderson, President, Tampa Electric Company

## *EPA Comments*

Paul Stolpman, Director of the Office of Atmospheric Programs in EPA's Office of Air and Radiation, says, " In the late 70's one could see the effects of acidity in the Northeast, particularly in the Adirondacks. It was related to emissions of sulfur, three-fourths of which came from burning coal and oil in our power plants. But over the past ten years, the emissions of sulfur from power plants have greatly dropped ... The Acid Rain Program cost only about one-third of what we thought it would in 1990." This significant savings has been due in part to the greatly reduced cost of FGD technologies, largely as a result of developments demonstrated in the CCT Program coupled with improvements generated through competitive forces in the industry.

Peter Tsirigotis, Chief of the Program Development Branch in EPA's Clean Air Markets Division, states that "Some CCT projects have helped to advance technology before there was a regulatory driver for the reductions that such a technology could achieve. This provides an incentive for industry to begin making technical innovations earlier than they otherwise would have. We can see this in the work that NETL has done on NOx controls in the past and I think we are seeing it in the work that NETL is doing on multi-pollutant controls today."

*continued on page 16*

*"There is no better example of America's energy strength than in our abundant coal reserves"*

**. . . Energy Secretary Spencer Abraham**

# Benefits to the Nation of DOE's Coal Technology Programs

**Economic security**

A major benefit of near- and mid-term power technologies is low-cost electricity for all users. Because electricity expense is a major factor in the cost of providing goods and services, sustaining low electricity production costs is critical for U.S. industry's competitiveness in the world market. Energy technology provides the foundation for competitive alternatives needed to meet varying marketplace situations. The United States will also realize economic benefits from exporting clean energy technologies resulting from DOE programs. International opportunities for advanced fossil energy technology exports are enormous.

**Reduced balance-of-trade deficit**

Because U.S. industry is de-emphasizing longer term research as part of short-term survival strategies, Federally sponsored technology development is critical to sustaining U.S. industry's competitiveness in the world marketplace.

**Energy security**

Providing technologies that use our abundant indigenous resources as a significant component of our nation's fuel mix is critical to achieving energy independence and security.

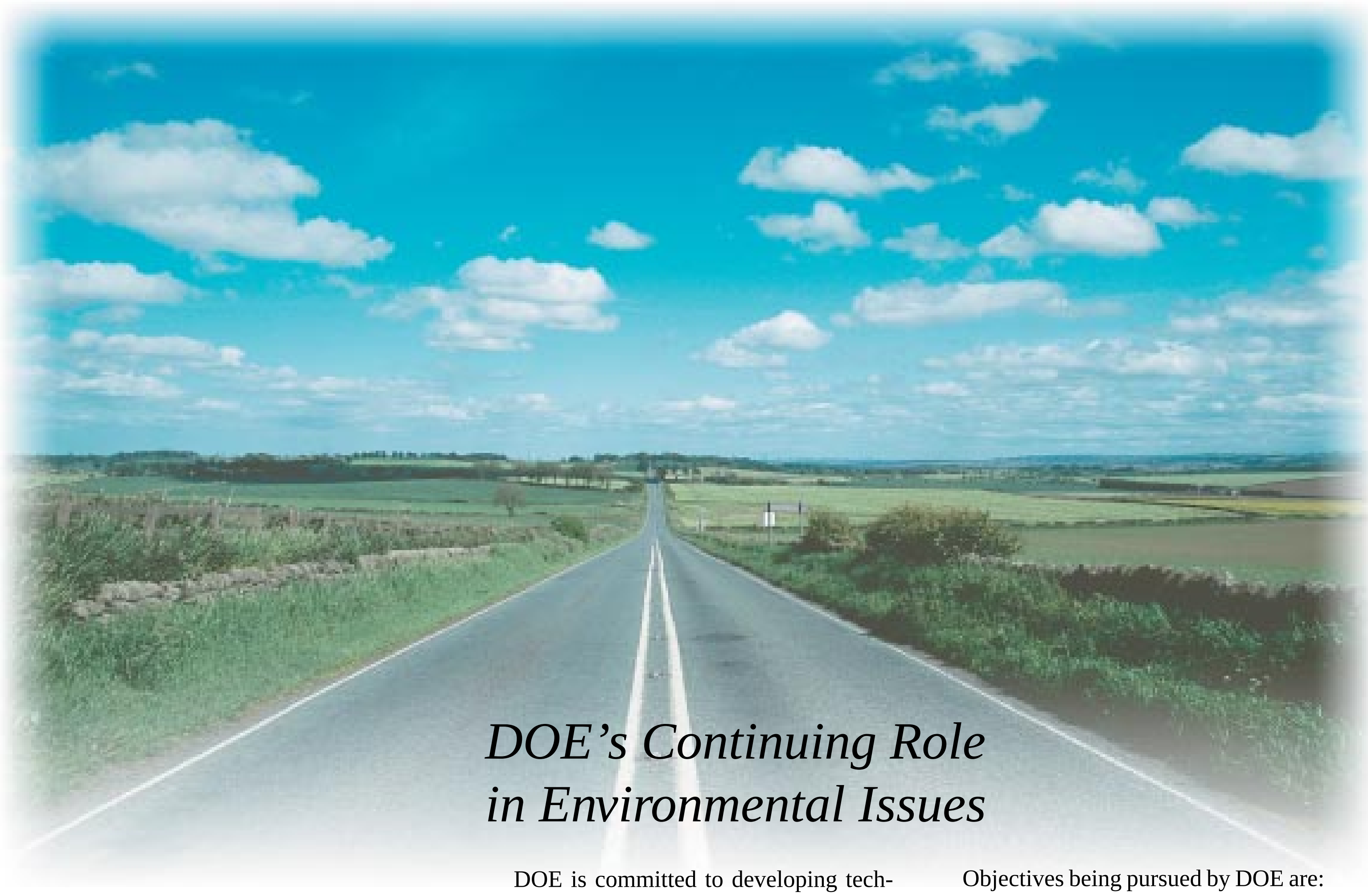
**Environmental acceptability**

Advanced technologies for improved plant performance and environmental compliance will yield benefits to human health as well as to the environment. Technologies developed under the CCT Program offer the means to produce energy from abundant, low-cost fossil fuels without detriment to the environment.

**Lower $CO_2$ emissions**

With their high-efficiency energy conversion, advanced power generation technologies will greatly reduce the release of $CO_2$ into the atmosphere as they replace less efficient technologies.

Continued value of investments. The existing infrastructure at older fossil-energy power plants will be maintained using repowering and cofiring technologies, thus reducing the need for investment in new facilities.



# *DOE's Continuing Role in Environmental Issues*

DOE is committed to developing technologies for reducing pollutants from coal-burning power plants through cost-shared collaboration between government and industry. The intent has been to achieve this goal quickly enough to allow for demonstration and deployment of new technologies prior to regulatory deadlines. Some of these regulations have already been promulgated. For example, instructions to revise SIPs to address ozone concerns will require many Eastern U.S. coal-fired power plants to significantly reduce NOx emissions (to 0.15 lb/million Btu) by 2003. Power generators are already ordering hardware for compliance. On the other hand, many plants are not subject to these regulations, but may need similar reductions to meet future regional haze or $PM_{2.5}$ standards likely to be enacted in the 2007 to 2015 time frame. Because most of these regulations on the horizon are not yet finalized, and because the implementation dates for some regulations have not yet been clearly articulated, judgment must be used in estimating the effectiveness and timing of needed technologies.

Objectives being pursued by DOE are:

- Develop and demonstrate extremely low NOx burner technologies (augmented by advanced computer-based controls).
- Refine post-combustion NOx reduction technologies, such as SCR, to reduce compliance costs.
- Foster the commercialization of gasification-based processes that convert low-cost carbonaceous feedstocks to electricity, steam, fuels, chemicals, or hydrogen.
- Develop and demonstrate technologies to address mercury emissions.
- Develop a database in partnership with other public- and private-sector organizations on the sources and receptors of ambient fine particulate matter.

*continued on page 18*

# Emissions Standards

## History

The Clean Air Act of 1970 established a major air regulatory role for the Federal Government. The act was further extended by amendments in 1977 and, most recently, in 1990. The 1990 CAAA is one of the most complex and comprehensive pieces of environmental legislation ever written. It authorized EPA to establish standards for a number of atmospheric pollutants, including $SO_2$ and NOx. Two major portions of the CAAA relevant to $SO_2$ and NOx control are Title I and Title IV.

## Title I

Title I establishes National Ambient Air Quality Standards (NAAQS) for six criteria pollutants, including $SO_2$, NOx, and ozone ($O_3$). The NAAQS for ozone is 0.08 ppm (8-hour average), and the NAAQS for $SO_2$ is 0.14 ppm (24-hour average).

NOx and volatile organic compounds (VOCs) in the atmosphere react in the presence of sunlight to form ground-level $O_3$, which is a major ingredient of smog. Many urban areas do not meet the $O_3$ standard and are classified as nonattainment. A large number of power plants are situated within these nonattainment areas. This nonattainment status is attributable not only to NOx emissions in a given locality but also to significant amounts of NOx and VOCs transported by winds over a wide geographical region.

To address regional pollutant transport, EPA issued a rule governing NOx emissions from electric power plants and other large stationary boilers in 22 U.S. Eastern and Midwestern states and the District of Columbia. EPA's rule sets statewide NOx emissions budgets, which include budget components for the electric power industry and certain industrial stationary sources. These sources are expected to make large NOx emissions reductions to decrease transport of pollutants from one region of the country to another. Federal NOx emissions limits for utility boilers are specified at 0.15 lb/million Btu. States must develop State Implementation Plans (SIPs) for NOx to achieve the required statewide emissions budgets.

## Title IV - The Acid Rain Program

The overall goal of the Acid Rain Program is to achieve environmental and public health benefits through reductions in emissions of $SO_2$ and NOx. Both the NOx and $SO_2$ control programs use a two-phase approach to achieve compliance.

For NOx control, Title IV focuses on a particular set of NOx emitting sources— coal-fired electric utility plants. Phase I, begun in 1996, has reduced NOx emissions in the United States by over 400,000 tons/year. These reductions were achieved by installation of low-NOx burner (LNB) technology on dry-bottom, wall-fired boilers and tangentially fired boilers (Group 1). In Phase II, which began in January 2000, EPA has established lower emissions limits for Group 1 boilers and established limits for Group 2 boilers. Group 2 boilers include boilers using cell-burners, cyclone boilers, wet-bottom boilers, and other types of coal-fired boilers. It is projected that the more stringent Phase II limits will result in an additional NOx reduction of 820,000 tons/year.

The regulations allow for emissions averaging in which the emissions levels established by EPA are applied to an entire group of boilers owned or operated by a single company.

A primary goal of the $SO_2$ control program is the reduction of annual $SO_2$ emissions by 10 million tons below 1980 levels. Phase I, which began in 1995, affects 263 units at 110 mostly coal-burning electric utility plants located in 21 Eastern and Midwestern states. An additional 182 units joined the program as substitution or compensating units, bringing the total of Phase I affected units to 445. Phase II, which began in 2000, tightens the annual emissions limits and also sets restrictions on smaller plants fired by coal, oil, and gas. The Title IV, Phase I $SO_2$ emissions limit is 2.5 lb/million Btu, which decreases to 1.2 lb/million Btu in Phase II.

The Acid Rain Program provides flexibility in achieving compliance through an allowance trading system that harnesses the incentives of the free market to reduce pollution. Each allowance permits emitting one ton of $SO_2$. Affected utility units have been allocated allowances based on their historic fuel consumption. For each ton of $SO_2$ discharged in a given year, one allowance is retired. Allowances may be bought, sold, or banked, and any person may acquire allowances and participate in the trading system. However, regardless of the number of allowances held, a source may not emit pollutants at levels that would violate any federal or state standards, including ambient air standards set under Title I. During Phase II, the CAAA set a permanent ceiling (or cap) of 8.95 million annual allowances allocated to utilities. This cap firmly restricts $SO_2$ emissions and ensures that environmental benefits will be achieved and maintained.

# *Track Record of Environmental Progress*

## CCT Program Successes

Successful CCT Program demonstration projects are benefiting existing plants as well as next-generation systems:

- Advanced technologies have dramatically improved the economic and environmental performance of FGD systems for $SO_2$ control.
- NOx reduction technologies have been or are being retrofitted to a large segment of the nation's coal-fired power generating capacity.
- Two new IGCC power generation systems now in commercial operation are among the cleanest coal-based power plants in the world.

The CCT Program has resulted in the successful development of cost-effective pollution control technologies applicable to a wide range of coal-fired boilers. Application of these technologies on a widespread commercial scale has resulted in significant emissions reductions that are meeting EPA regulatory targets.

The value of the environmental technologies demonstrated in the CCT Program can be shown by considering the impact of applying these technologies to all coal-fired utility boilers in the United States. In 1997, total emissions for these boilers were over 12 million tons of $SO_2$ and 6.8 million tons of NOx. Based on the quality of coal burned, uncontrolled $SO_2$ emissions would have amounted to over 20 million tons.

If CCT-developed technologies were applied to all U.S. coal-fired boilers at a demonstrated average efficiency of 90%, total $SO_2$ emissions could be further reduced by approximately 10 million tons/year.

The 1997 NOx emissions of about 6.8 million tons are equivalent to a national NOx emission rate of 0.75 lb/million Btu. Combustion modification technologies demonstrated in the CCT Program readily reduce NOx emissions to as low as 0.30 lb/million Btu. Even greater reductions are possible with post-combustion treatment. If average NOx emissions from all coal-fired boilers were reduced to 0.35 lb/million Btu using commercially available technology, total NOx emissions would be reduced by an additional 3.6 million tons/year to approximately 3.2 million tons/year.

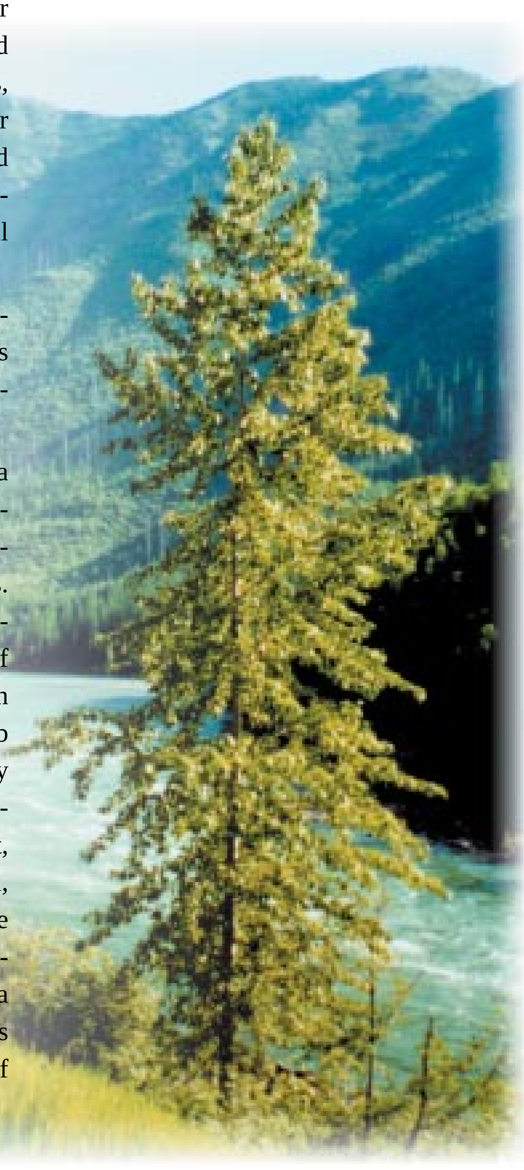
Similar or better reductions are possible if older, existing coal-fired units were replaced by newer power generation technologies, such as FBC and IGCC, that have been demonstrated under the CCT Program. IGCC systems also reduce emissions of $CO_2$ because of their higher thermal efficiency.

Some highlights of the CCT Program are as follows:

- The CCT Program enabled power generators to respond cost-effectively to the first wave of NOx control requirements and positioned industry to respond to more stringent standards in the 21st century. Today, three-fourths of all U.S. coal-fired capacity is equipped with LNBs that cost a fraction of the cost of NOx pollution controls available in the 1980s.
- The CCT Program has directly contributed to meeting the initial $SO_2$ reduction requirements defined by the CAAA by installing advanced technology at affected plants. The resultant portfolio of technologies redefined the state of the art in scrubber technology, enabling industries to respond to the more stringent standards imposed by the CAAA in 2000.
- The United States has the largest number of FGD installations in the world. There are about 260 units having a total capacity of 85,000 MWe, representing over one-fourth of total U.S. coal-fired capacity.
- Substantial reductions in atmospheric emissions have been achieved through CCT-supported demonstration projects involving FGD. For the Pure Air on the Lake project conducted at Bailly Station, total $SO_2$ removal from 1992 through 2000 exceeded 700,000 tons. At Plant Yates, use of the CT-121 FGD process has removed about 80,000 tons of $SO_2$ during the period from 1993 through 2000. For the Milliken Station, operation of the S-H-U FGD process has removed about 260,000 tons of $SO_2$ during the period from 1995 through 2000.
- Investment in improved FGD systems in the United States has saved $40 billion in the last 30 years.
- CCT-sponsored R&D on FGD has turned

a concept once thought to be too expensive and unreliable into a U.S. technology sold throughout the world.

- Innovative FGD processes now permit recovery of large quantities of salable, wallboard-grade by-product gypsum. This eliminates the need to store waste gypsum in sludge ponds as was practiced when FGD operations first began. At the Bailly Station, the amount of wallboard recovered annually is sufficient to build nearly 19,000 homes.
- As a result of technological innovations in the last 30 years, the Nation has cut sulfur pollutants by more than 40% while at the same time tripling the use of coal. The cost of electric power to U.S. consumers remains the lowest of any industrial nation.
- The CCT Program has provided the foundation for powering the 21st century through successful demonstration of FBC and IGCC projects on a commercial scale. These technologies are inherently clean, producing negligible emissions of $SO_2$, NOx, and particulates.
- Development of innovative, economically viable FGD technologies has provided new opportunities for continued use of high-sulfur U.S. Eastern coal.
- In March 2000, the Ozone Transport Commission and EPA jointly announced that emissions of NOx in the U.S. Northeast and Mid-Atlantic states from major stationary sources were less than half the emissions from the same sources in 1990. This is a result of the widespread use of combustion modification technologies, especially the CCT technologies LNBs and OFA.
- In response to the requirements of Title I of the CAAA for more complete removal of NOx from power plant stack gases, SCR technology demonstrated under the CCT Program is achieving increased commercial application. For example, AEP is investing $175 million for an SCR installation at its 2600-MWe Gavin Station, PP&L is installing SCR at its 1500-MWe Montour Station, and Southern Company has several major SCR projects underway.
- With the availability of appropriate environmental technologies, significant expenditures on pollution control systems are anticipated. Worldwide sales of hardware and the accompanying engineering and monitoring services exceeded $26 billion in 2000. Of this total, about $9 billion was spent by the power industry. During the first decade of the 21st century, U.S. power plants will commit over $25 billion to FGD systems in new and existing facilities. Over the next 20 years, more than $25 billion will be spent for NOx reduction equipment in the United States, including combustion modification and post-combustion systems as well as monitors and other components.
- According to *Power* magazine, the development of FBC for coal combustion was “the commercial success story of the decade in the power generation business.”
- The CCT Program has made available a number of technologies capable of preventing pollution rather than simply removing pollutants from exhaust gases. These technologies include: (1) the substitution of coal for a substantial portion of the coke used in blast furnace operation and (2) the use of cement kiln dust to scrub $SO_2$ from cement plant stack gas, thereby converting a waste material into a marketable product. In the latter CCT project, savings on tipping fees for waste disposal, reuse of the waste products and sale of the by-products not only offset costs but enable the cleanup system to operate at a profit. In addition, many CCT processes achieve minimum or zero discharge of waste water.



## Five Powerplant Awards Presented to CCT Projects by *Power* Magazine

- Tidd PFBC Demonstration Project (The Ohio Power Company) - 1991
- Advanced Flue Gas Desulfurization Demonstration Project (Pure Air on the Lake, L.P.) - 1993
- Demonstration of Innovative Applications of Technology for the CT-121 FGD Process (Southern Company Services, Inc.) - 1994
- Wabash River Coal Gasification Repowering Project (Cinergy Corporation/PSI Energy Inc.) - 1996
- Tampa Electric Integrated Gasification Combined-Cycle Project (Tampa Electric Company) - 1997

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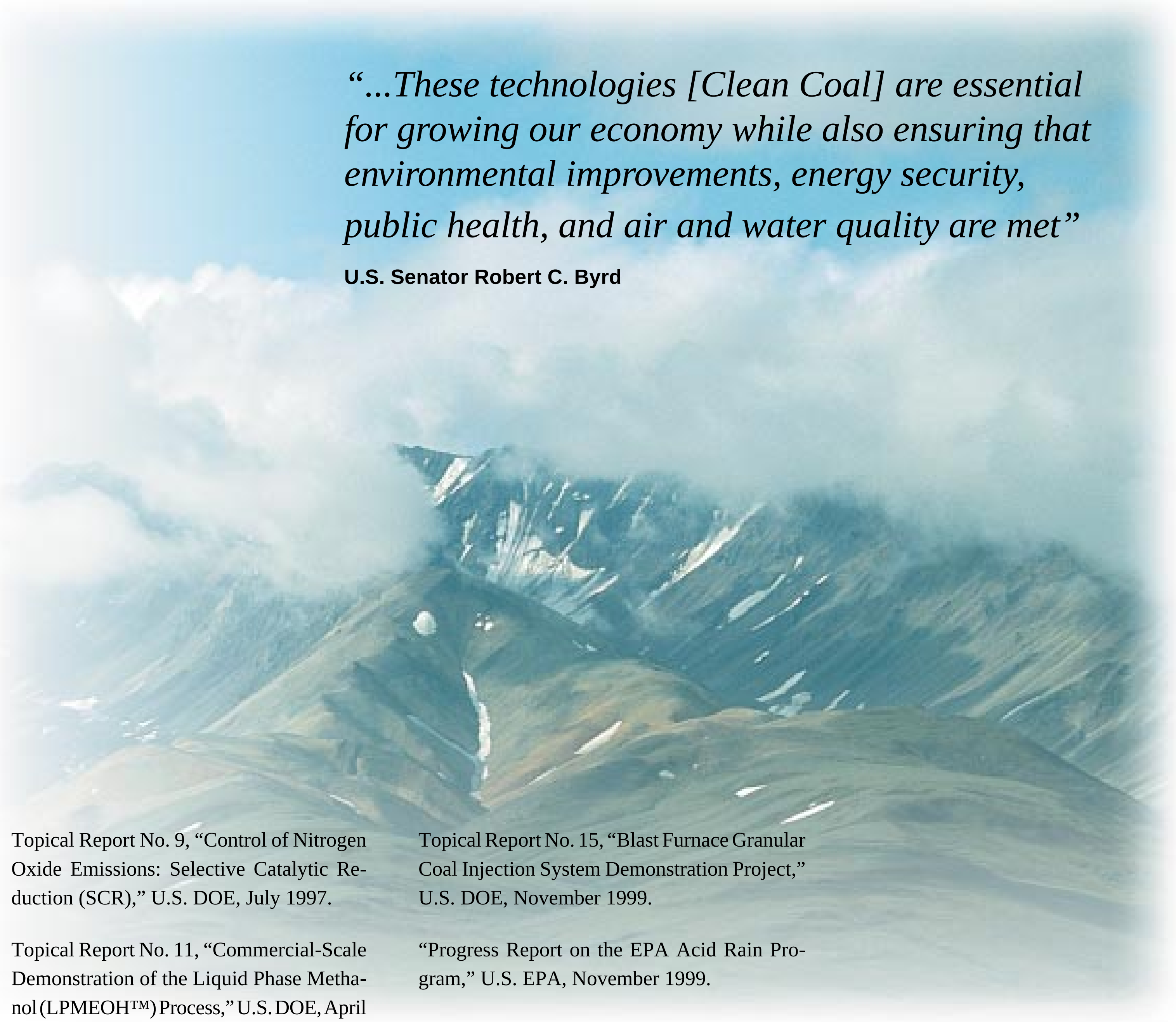
*"...These technologies [Clean Coal] are essential for growing our economy while also ensuring that environmental improvements, energy security, public health, and air and water quality are met"*

**U.S. Senator Robert C. Byrd**

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## An Environmental Success Story

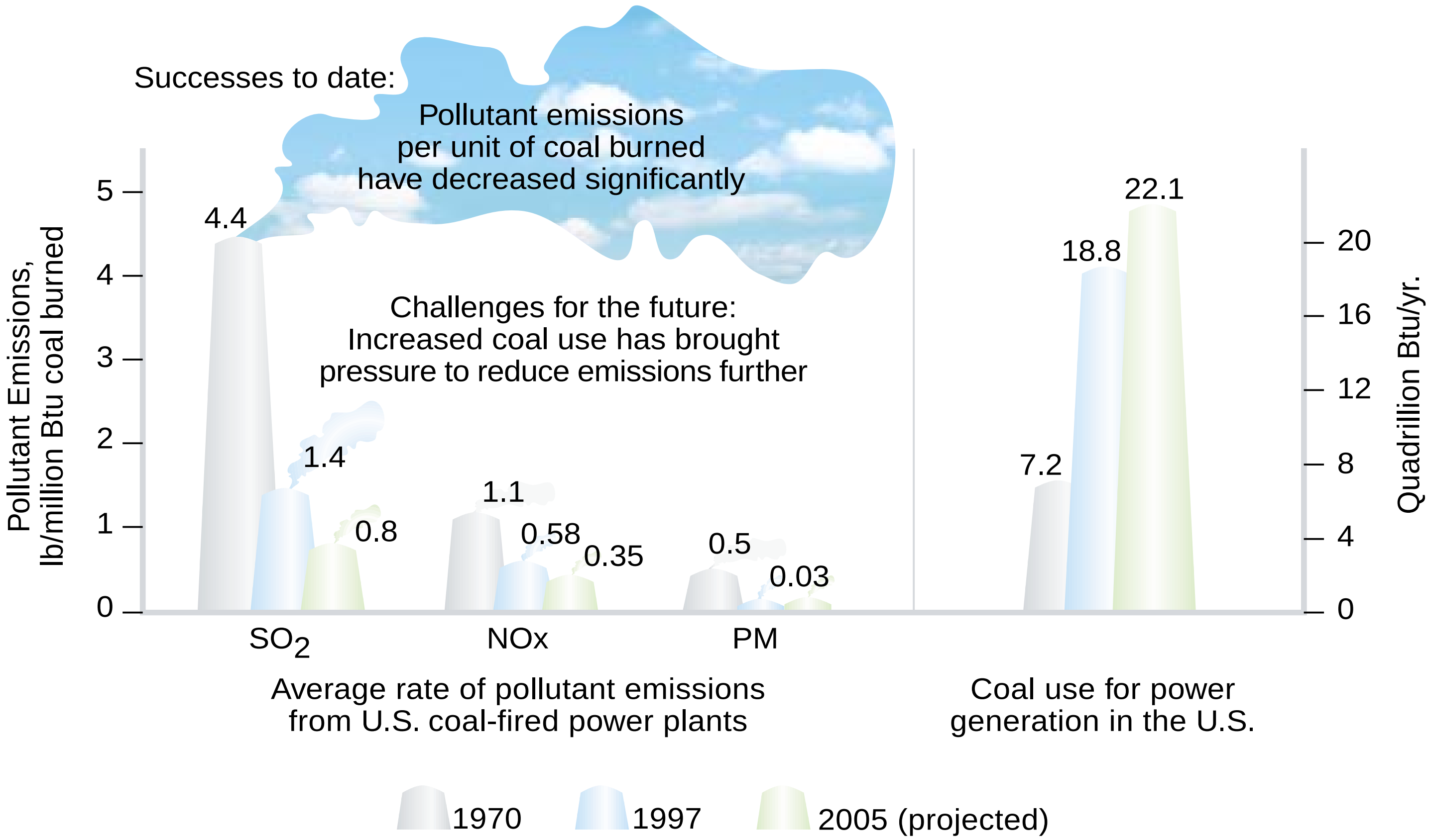
Three quarters of the coal-fired capacity in the United States today uses low-NOx burners developed through DOE programs, significantly reducing emissions of one of the chief pollutants responsible for smog and ozone buildup. A portfolio of cost-effective NOx control technologies suitable for the full range of existing boilers is now available.

A number of low-NOx burners are now widely marketed, total sales of which are about $4 billion. Reburning has also been successfully demonstrated for NOx reduction. This process breaks down NOx into environmentally benign gases by using oil, natural gas or finely ground micronized coal to reburn the residues of coal-firing.

The Generic NOx Control Intelligent System (GNOCIS™) is the latest innovation to lead the way to the zero-NOx plants of the future. There are over 50 active or planned GNOCIS™ installations, representing more than 25,000 MWe of generation capacity. GNOCIS™ has been shown to result in an overall efficiency improvement of 0.5%, a 3% reduction in unburned carbon content of utility fly ash, and a 15% reduction in NOx emissions. This efficiency improvement would allow a typical eastern U.S. power plant rated at 1000 MWe to reduce its coal consumption by up to 25,000 tons/year.

The costs of reducing NOx emissions by retrofitting power plants are now up to 90% lower than they would have been without the Federal Government's research investment.

**Milliken Station is located in an environmentally sensitive area on the shores of Cayuga Lake, one of the famous Finger Lakes in New York State.**




**Since 1970, the environmental performance of U.S. coal-fired power plants has improved while coal use has increased.**

## Tackling Global Energy Issues of the 21st Century

Worldwide, the demand for power is increasing exponentially. At the same time, the energy sectors of many countries are undergoing major transformations. Increasingly stringent environmental regulations, growing international concerns over global climate change, and increased competition among fuels drive the need for advanced power technologies that deliver electricity efficiently, cleanly, and economically. These trends offer great opportunities for clean coal technologies and advanced power generation systems, the wide-scale adoption of which would protect local, regional, and global environments.

# The CCT Program

The Clean Coal Technology (CCT) Demonstration Program, a model of government and industry cooperation, responds to the mission of the Department of Energy (DOE) to foster the development and implementation of secure and reliable energy systems that are environmentally and economically sustainable. The CCT Program represents an investment of over $5 billion in advanced coal-based technology, with industry and state governments providing a significant share — 66% — of the funding. With 26 of the 38 active projects having completed operations, the CCT Program has yielded technologies that are capable of meeting existing and emerging environmental regulations and competing in a deregulated electric power marketplace.

Estimated coal reserves in the United States are 4 trillion tons, of which over 270 billion tons are recoverable using current methods. The CCT Program provides a portfolio of technologies that will assure that this resource can continue to supply the nation's energy needs economically and in an environmentally sound manner. As the new millennium begins, many of the clean coal technologies have achieved commercial status. Industry stands ready to respond to the energy and environmental demands of the 21st century, both domestically and internationally. For existing power plants, there are cost-effective environmental control devices to control $SO_2$, NOx, and PM. Also ready are a new generation of technologies that can produce electricity and other commodities, such as steam and synthesis gas, at high efficiencies consistent with concerns about global climate change.

The CCT Program has taken a pollution prevention approach as well, demonstrating technologies that produce clean coal-based solid and liquid fuels by removing pollutants or their precursors. Lastly, new technologies have been introduced into major coal-using industries, such as iron making, to enhance environmental performance. Thanks in part to the CCT Program, coal — abundant, secure, and economical — can continue in its role as a key component in the U.S. and world energy markets.

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## To Receive Additional Information

To be placed on the Department of Energy's distribution list for future information on the Clean Coal Technology Program, the demonstration projects it is financing, or other Fossil Energy Programs, please contact:

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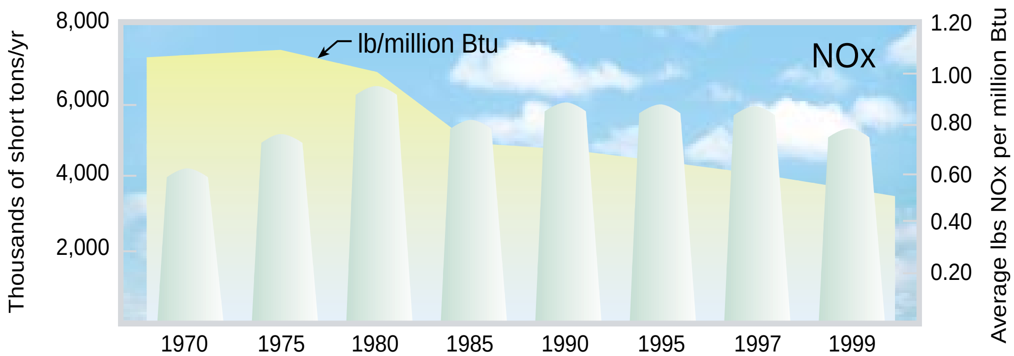
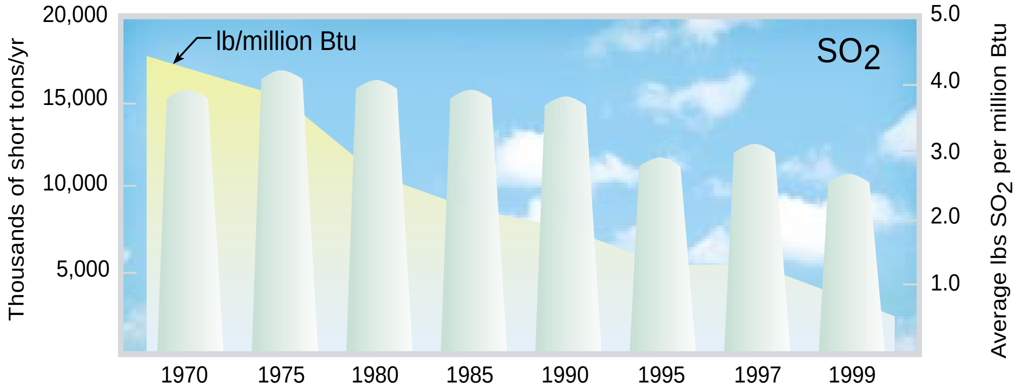
This report is available on the Internet at U.S. DOE, Office of Fossil Energy's home page: www.fe.doe.gov

and on the Clean Coal Technology Compendium home page: www.lanl.doe.gov/projects/cctc



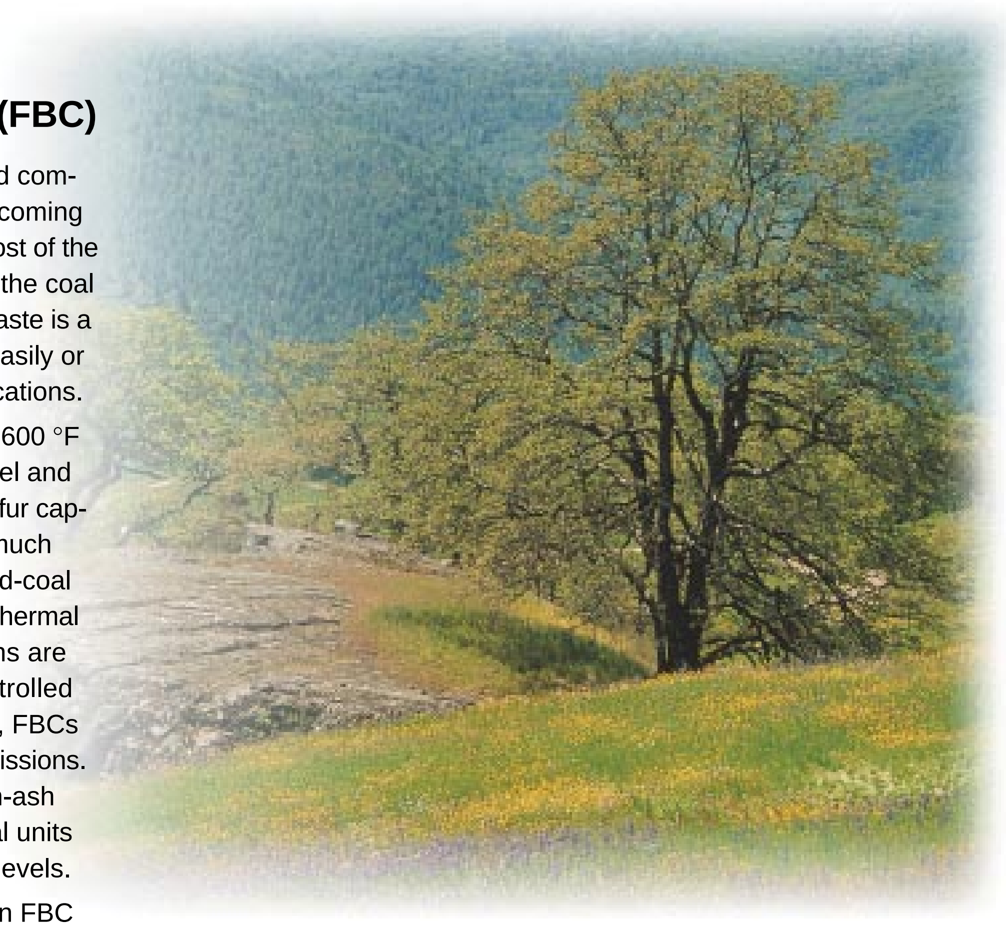

**Emission rates of NOx and $SO_2$ have decreased significantly since 1970.**

## How NOx Is Formed in a Boiler

Most of the NOx formed during the combustion process is the result of two oxidation mechanisms: (1) reaction of nitrogen in the combustion air with excess oxygen at elevated temperatures, referred to as thermal NOx; and (2) oxidation of nitrogen that is chemically bound in the coal, referred to as fuel NOx. For most coal-fired units, thermal NOx typically represents about 25% and fuel NOx about 75% of the total NOx formed. However, for cyclones and other boilers that operate at very high temperatures, the ratio of thermal to fuel NOx is different, and thermal NOx can be considerably higher than fuel NOx. In addition, minor amounts of NOx are formed early in the combustion process through complex interactions of molecular nitrogen with hydrocarbon free radicals to form reduced nitrogen species that are later oxidized to NOx, referred to as prompt NOx.

The quantity of thermal NOx formed depends primarily on the "three t's" of combustion: temperature, time, and turbulence. In other words, flame temperature, the residence time at temperature, and the degree of fuel/air mixing, along with the nitrogen content of the coal and the quantity of excess air used for combustion, determine NOx levels in the flue gas. Combustion modifications manage the mixing of fuel and air, thereby reducing temperature and initial turbulence, which minimizes NOx formation.

## Fluidized-Bed Combustion (FBC)

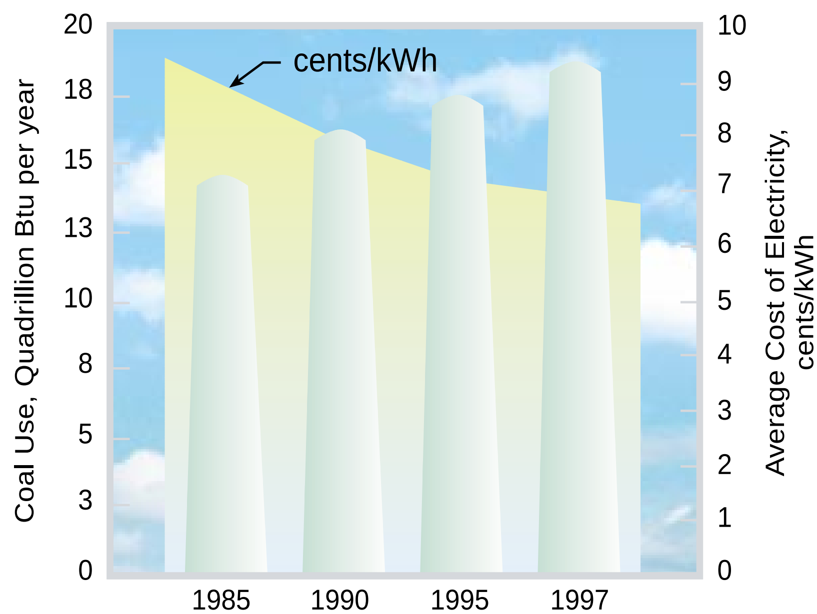


In FBC, coal is mixed with a sorbent and combusted with air in a reaction vessel. The incoming air stream fluidizes the reactor contents. Most of the $SO_2$ produced by oxidation of the sulfur in the coal is captured by the sorbent. The resultant waste is a dry, benign solid that can be disposed of easily or used in agricultural and construction applications.

At combustion temperatures of 1,400-1,600 °F (760-870 °C), the fluidized mixing of the fuel and sorbent enhances both combustion and sulfur capture. The operating temperature range is much lower than that of a conventional pulverized-coal boiler and below the temperature at which thermal NOx is formed. In fact, FBC NOx emissions are about 70-80% lower than those for uncontrolled conventional pulverized-coal boilers. Thus, FBCs substantially reduce both $SO_2$ and NOx emissions. They also have the capability of using high-ash coal, whereas conventional pulverized-coal units must limit ash content in the coal to lower levels.

Two parallel paths have been pursued in FBC development — bubbling and circulating beds. Bubbling beds use a dense fluid bed and low fluidization velocity to effect good heat transfer and mitigate erosion of an in-bed heat exchanger. Circulating beds use a relatively high fluidization velocity, which entrains the bed material, usually in conjunction with hot cyclones to separate and recirculate the bed material from the flue gas before it passes to a heat exchanger. Hybrid systems have also evolved from these two basic approaches.

FBCs can be either atmospheric (AFBC) or pressurized (PFBC). AFBC operates at atmospheric pressure while PFBC operates at pressure 6-16 times higher. PFBC offers potentially higher efficiency and, consequently, reduced operating costs relative to AFBC, as well as smaller size per unit of power output. Second-generation PFBC integrates the combustor with a pyrolyzer (coal gasifier) to fuel a gas turbine (topping cycle), the waste heat from which is used to generate steam for a steam turbine (bottoming cycle). The inherent efficiency of the gas turbine and waste heat recovery in this combined-cycle mode significantly increase overall efficiency. Such advanced PFBC systems have the potential for thermal efficiencies over 50%.




**Since 1985, coal use has increased while the cost of electricity has gone down.**

# *List of Acronyms and Abbreviations*

Btu ........ British thermal unit
CAAA ........ Clean Air Act Amendments of 1990
CCT ........ Clean Coal Technology
$CO_2$ ........ carbon dioxide
CT-121 ........ Chiyoda Corporation Thoroughbred-121 Process
DOE ........ U.S. Department of Energy
EPA ........ U.S. Environmental Protection Agency
ESP ........ electrostatic precipitator
FBC ........ fluidized bed combustion
FGD ........ flue gas desulfurization
FGR ........ flue gas recirculation
GHG ........ greenhouse gas
GNOCIS™ ........ Generic NOx Control Intelligent System
HAPs ........ hazardous air pollutants
$H_2S$ ........ hydrogen sulfide
IGCC ........ integrated gasification combined-cycle
LNBs ........ low-NOx burners
MWe ........ megawatts of electric power
NAAQS ........ National Ambient Air Quality Standards
NETL ........ National Energy Technology Laboratory
$NH_3$ ........ ammonia
NOx ........ nitrogen oxides
NSPS ........ New Source Performance Standards
OFA ........ overfire air
PM ........ particulate matter
SCR ........ selective catalytic reduction
S-H-U ........ Saarberg-Holter-Umwelttechnik
SIP ........ State Implementation Plan
SNCR ........ selective noncatalytic reduction
$SO_2$ ........ sulfur dioxide
$SO_3$ ........ sulfur trioxide
μ ........ micron (one-millionth of a meter)
VOCs ........ volatile organic compounds