COAL AND POWER SYSTEMS:

INNOVATIONS FOR EXISTING PLANTS

Technology Roadmap & Program Plan

Knowledge and Technology Products for Clean Power

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U.S. Department of Energy
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National Energy Technology Laboratory

Innovations for Existing Plants
Technology Roadmap and Program Plan

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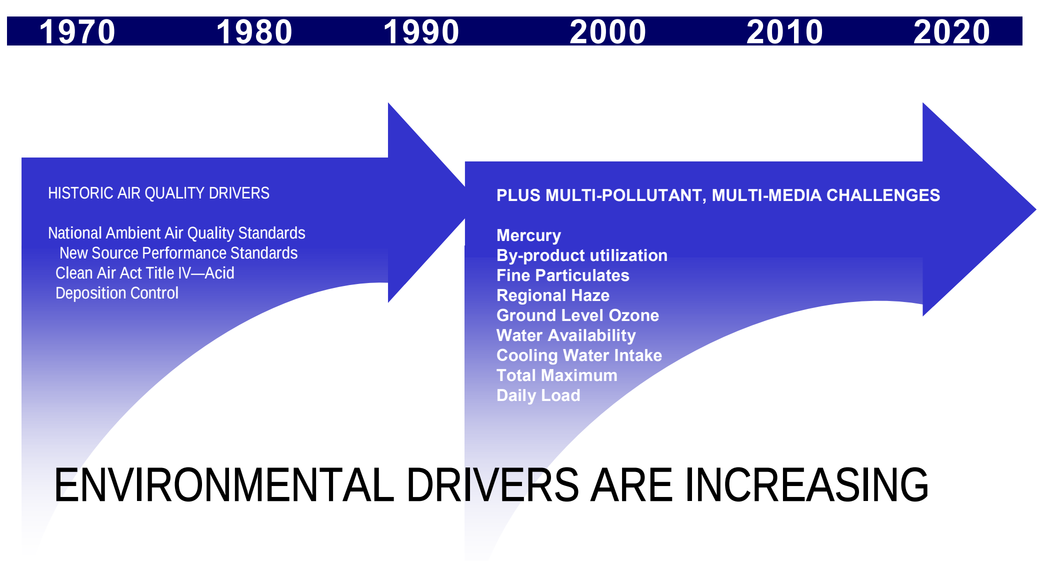
I. Overview

COAL-fueled power plants today provide over 50% of the nation's electricity. These plants have the critical attributes that help enable a strong economy – low cost of electricity, a secure and abundant supply of fuel, and price stability. Yet while dramatic improvements have been made in the environmental performance of these plants to date, continued improvement is needed to meet new environmental drivers and reduce the cost of existing technologies.

The National Energy Technology Laboratory (NETL) of the Department of Energy (DOE) Office of Fossil Energy (FE) manages the Innovations for Existing Plants (IEP) Program, which has the mission of developing innovative environmental control technologies that will enable full use of the nation's vast coal reserves. The IEP Program is one component of FE's Strategic Center for Coal Research and Development (R&D) portfolio for coal resources, which includes:

- Clean Coal Power Initiative
- Innovations for Existing Plants (a.k.a. Environmental and Water Resources)
- Advanced Systems
- FutureGen
- Carbon Sequestration
- Coal Fuels
- Advanced Research
- Combustion
- Distributed Generation – Fuel Cells
- Gasification
- Turbines

This document presents the IEP Roadmap, defining *what* obstacles challenge the coal-based power generation community, and the IEP Program Plan, defining *how* science and technology pathways will meet these challenges.



There are critical regulatory, market, and security factors that drive the program mission, which in turn provides enormous benefits to the public:

- The nation's coal reserves are among the largest in the world. They are geographically well distributed, but have very different combustion characteristics that require varying control strategies.
- Environmental impacts increasingly have multi-pollutant, multi-media (air, water, solids) characteristics that are significantly more complex than those addressed by single-pollutant, air quality-based regulations of the past 30 years.
- Continued use of coal for electric power can ensure stable, base-load electric power – essential to the nation's economic health – that is independent of the oil and gas supply and price fluctuations seen in the market today. According to the 2006 Annual Energy Outlook, coal use for electricity generation is estimated to increase approximately 1.1 percent annually, reaching 1,272 million tons in 2015. From 2015 through 2030, the production rate increases 2 percent annually.

To respond to the changing factors, the IEP Program continually refines and adjusts its research portfolio to reflect critical issues. These changes are addressed by a proactive approach to collaboration in both program planning and program implementation. For example, recent focus of the IEP Program has been directed at the following R&D areas:

- *Mercury Control*: as the largest U.S. source of man-made mercury emissions, mercury removal systems suited to coal power generation are needed. These needs vary according to the type of coal used and the presence and configuration of other environmental control systems. Program activity is directed to low-cost technology solutions that will enable clean use of all coal ranks.
- *By-Product Characterization*: the ultimate fate of mercury once it has been removed from the flue gas of a power plant has been raised as a concern. The IEP Program is sponsoring research on evaluating the potential release of mercury and other trace metals from coal utilization by-products such as fly ash and flue gas desulfurization solids, and developing innovative beneficial uses for these materials.
- *Water Management*: with increases in the nation's population and demand for water, efficient, clean use of water is increasingly important, particularly in regions of the West, Southwest, and Southeast. The program is researching new approaches to reducing the amount of freshwater used by power plants, to effectively reuse the water that is used, and to meet current and future discharge restrictions.
- *NO_x Control:* as the nation moves forward with more stringent regulations on NO_x emissions from the electric power sector, it is critical that research continues to address these challenges. The program is working to develop advanced control concepts to achieve high levels of NO_x removal at costs considerably lower than current selective catalytic reduction (SCR) technology while also enhancing the capture and performance of existing technology.

The IEP Roadmap builds on interactions with program stakeholders. The roadmap content draws from and supplements the technical thrusts of the overall FE program, as defined in the *Coal and Power Systems Strategic Plan* and the *Clean Coal Technology Roadmap*.

Moving forward, the IEP Program will continue to work with a broad spectrum of stakeholders – the regulatory community, power producers, academia, environmental organizations, equipment manufacturers, R&D performers, and the public – to ensure that the program focus is responsive to current and emerging drivers, thus assuring the continued public benefit of clean, affordable, and secure electric power.

II. Enabling Affordable, Clean Power

COAL has provided the nation with an abundant and affordable source of power for decades. Coal provides approximately half of the electricity supply in the United States, accounting for 305 GW of generation capacity and is projected to be a major component of the energy mix for decades to come. According to DOE Energy Information Administration's (EIA) *Annual Energy Outlook*, coal steam will account for 385 GW of electric generating capacity in 2025 and 453 GW by 2030. Maintaining coal's position in the future, however, will require enhanced scientific knowledge and advanced technology products to enable cost-effective improvements in environmental performance.

The extent and complexity of potential control requirements is increasing. Emerging multi-media, multi-pollutant regulatory challenges require new technology solutions. Concerns such as fine particulates, air toxics, ground-level ozone, and regional haze complicate traditional approaches to improve air quality. With increasing demands on available freshwater, particularly in more arid parts of the country, water use by power plants is increasingly under scrutiny. Similarly, the large volumes of solid materials − known as coal utilization by-products − produced by plants make beneficial reuse of this material a major objective, both to enhance environmental quality and to improve plant economics. Finally, the often complex interactions among air, water, and solid media require new integrated approaches that recognize and mitigate any unfavorable interactions.

A. Vision and Goals

- The vision for the IEP Program is to ensure the sustainability of coal as an abundant, affordable, and environmentally acceptable resource for satisfying the nation's need for energy throughout the 21^{st} century. The program's long-term goal is to develop the knowledge and technologies that can enable the following:
- Development of low cost, high efficiency mercury, NO_x, particulate and acid gas emissions controls;
- Increased beneficial use of coal utilization by-products from coal combustion and gasification systems; and
- Reduce freshwater use and impacts of fossil fuel electric generation on the nation's freshwater resources.

The program seeks to create technology options that will enable the current fleet of coal-fired power plants to comply with future environmental regulations at a low cost. While the IEP Program focuses primarily on conventional coal-combustion plants, there are significant program synergies with other clean coal technologies such as coal gasification, coal liquefaction, and FutureGen—a government/industry partnership to create the world's first coal-based, zero emissions electricity and hydrogen plant.

B. The Public Benefits of Advanced Technology

The basis for coal's importance to power generation is powerful and pervasive: coal is abundant, affordable, and enjoys the distinct market advantage of long-term price stability. In the United States, over 300 Gigawatts of coal-fired combustion power plants are currently in operation (DOE/EIA, *Electric Power Annual,* 2004). They provide the stable and affordable baseload power supply that has fueled the nation's economic growth and prosperity for decades. The majority of these power plants were designed and built well before current air emission requirements became law. Great progress has been made in improving their environmental performance, with this improvement based in large part on technology products sponsored by DOE. For example, the 2001 National Academy of Sciences study, *Energy Research at DOE: Was It Worth It,* reports that upwards of $60 billion in benefits have been gained from DOE's research in NO_x and SO_2 control technology. As shown in the following graph, the emissions rate of U.S. coal plants has dramatically decreased while coal use has increased by more than 680 million tons since 1970.

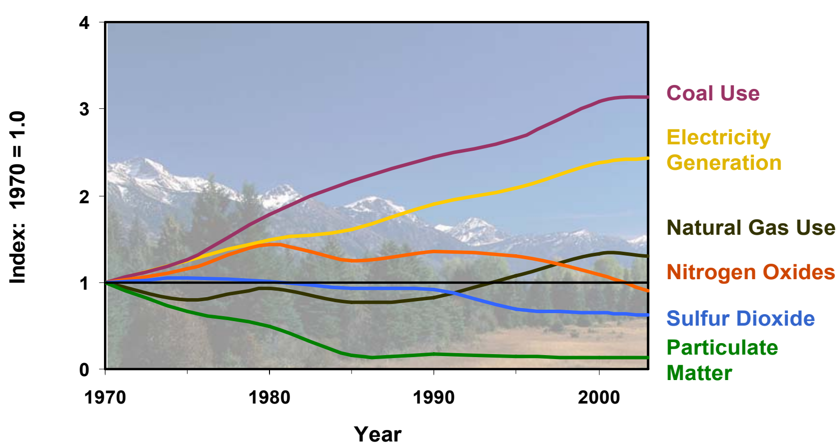
The research and development products of the IEP Program will contribute to four key market opportunities.

- Upgrading the current fleet of coal-combustion power plants, thus maintaining the reliable and affordable power that underpins the nation's economic strength.
- Enabling a new generation of coal-fired power plants to meet the nation's growing need for electric power with an abundant domestic resource.
- Enhancing technology to foster the globalization of clean power generation, thus providing economic benefits to U.S. technology firms and improved environmental performance worldwide, particularly important given the long-distance transport and deposition of many pollutants such as mercury.
- Development of technologies to support the FutureGen Initiative, particularly in the areas of advanced SCR technologies and reducing water use through advanced cooling technologies.

Coal's leading competitor for power generation is natural gas, which has an inherent cleaner-burning capability, but is a more expensive resource with greater price volatility. Domestically, the competition with gas means that coal technologies must be able to achieve high environmental performance at less cost than the price "premium" of natural gas. Coal power is experiencing resurgence in the United States as oil and natural gas prices continue to rise with large price fluctuation. According to EIA's *Annual Energy Outlook 2006,* 102 Gigawatts of new coal power additions are projected between 2004 and 2025.

Contaminant Emissions Down Sharply

U.S. Power Plants



Source: EPA, National Air Quality and Emissions Trends Report, 2003
DOE, EIA Annual Energy Review

C. Change and Challenge in Environmental Drivers

The compliance landscape is undergoing the most significant changes since the passage of the original Clean Air Act. There is a broad range of new environmental drivers that address the following:

- Further reductions in NO_x and SO_x are being required to improve ozone and fine particulate ambient air quality to address areas not meeting national standards;
- Control of mercury under a market-based cap-and-trade system that requires a phased reduction of national emissions to less than thirty percent of the current emissions of 48 tons;
- Water-quality and use issues associated with power production, including air pollutant loading to surface water, constraints in water availability, cooling water intake structure regulations, and effluent discharge restrictions; and
- Solid by-product issues, including increased volumes and assurance of the acceptability of reuse and disposal options associated with more stringent regulatory requirements.

Moreover, state and local regulations will also impact virtually all aspects of plant performance, including air emissions, plant water management and solid-waste management. Whatever requirements are ultimately implemented, the products of the IEP Program will provide the following necessary components for effective compliance:

- Improved scientific understanding that can support well-grounded decisions; and
- Technology solutions that can support cost-effective, timely implementation.

EPA Clean Air Rules: Changes Have Major Coal Power Plant Impacts

- **Clean Air Interstate Rule**: using a cap-and-trade system, NO_x and SO_x are targeted for reductions approximately 2/3 below current levels.
- **Clean Air Mercury Rule**: for the first time, mercury emissions from power plants will be regulated. By 2018, national mercury emissions from coal-fired power plants will be capped at 15 tons.

III. TECHNOLOGY PATHWAYS: The IEP Roadmap

THE Innovations for Existing Plants roadmap presents a consensus on the critical technology pathways that must be researched to meet the goals of the Program. It defines *what* the science and technology challenges are, including the drivers, R&D pathways, R&D goals, and desired outcomes. These pathways will be pursued in concert with other elements of the FE Coal program, collaborative R&D partners, the regulatory community, and others. Section IV, Program Strategy and Implementation, defines *how* the IEP Program is implementing the research.

The IEP Roadmap draws from and supplements the *Clean Coal Technology (CCT) Roadmap*, (see http://www.netl.doe.gov/technologies/coalpower/futuregen/pubs/CCT-Roadmap.pdf). The CCT Roadmap is a collaborative product of FE, the Coal Utilization Research Council (CURC), and the Electric Power Research Institute (EPRI) that provides a unified coal program roadmap to promote improved collaboration and efficiency in coal R&D.

The development of the IEP Roadmap was guided by a series of long-range public-benefit targets.

- Meet current and emerging environmental regulatory targets at costs equal to or less than today's cost of electricity.
- Enable full use of the nation's vast and varied coal reserves, thus maintaining diversity in the nation's portfolio of energy resources.
- Provide a secure, stable supply of baseload electricity generation that is resistant to supply disruptions resulting from natural disasters or terrorist actions.
- Maintain U.S. technology leadership and manufacturing capability to supply both the domestic and international power markets.

The IEP Roadmap has six major pathways.

- **Mercury Emissions Control**
- **Coal Utilization By-Products**
- **Water Management**
- **Advanced NO_x Emissions Control**
- **Air Quality Research**
- **Particulate-Matter and Acid-Gas Emissions Control**

These pathways address both the need for advanced environmental control technology and ancillary systems and the need for high-quality scientific data and analysis. Advances can aid current systems, as well as provide the foundation for lower cost systems for new plants. Table 1 shows the pathways and their drivers, goals, and outcomes. The IEP Roadmap is not static; it will change as new information becomes available from progress in current research and new R&D opportunities.

Table 1. The IEP Technology Roadmap				
DRIVERS	**R&D PATHWAYS**		**GOALS**	**OUTCOMES**
• Demand for low-cost power as a foundation of economic strength • Increasing scope and complexity of environmental regulations • Need to increase the efficiency of generation by minimizing parasitic load of environ-mental controls • Enhance the synergies in multi-media interrelation-ships while mitigating negative effects	**Mercury Emissions Control**	• Advanced control technologies • Emissions characterization • Development of measurement methods	• 50-70% reduction by 2007 at <3/4 cost of commercial ACI • $\geq$ 90% capture by 2010 at <3/4 cost of commercial ACI	• Reduced cost of compliance with environ-mental requirements • Integrated control systems with high efficiency and low cost • Continued reliance on low-cost domestic resources • Improved regional, national, and international environ-mental quality
	Coal Utilization By-Products	• Utilization research • Environmental impact characterization	• Increase CUB utilization to 50% by 2010 • Develop solutions to future environmental issues	
	Water Management	• Use of impaired waters • Water recovery and cooling technology • Cooling water intake technology • Effluent detection and treatment technology	• Reduce freshwater use by 5%-10% by 2015 • Minimize impacts of plant operations on water quality	
	Advanced NO_x Control	• Advanced combustion control • Post-combustion control • New SCR catalysts	• $\leq$ 0.15 lb NO_x/MMBtu at <3/4 cost of Selective Catalytic Reduction by 2007 • $\leq$ 0.10 lb NO_x/MMBtu by 2010	
	Air Quality Research	• Emissions characterization • Ambient monitoring and analysis • Predictive modeling and evaluation • Health effects	• Address scientific uncertainties associated with the formation, transport, and deposition of coal-fired power plant emissions	
	Particulate-Matter and Acid-Gas Emissions Control	• Primary fine particulates • Gaseous precursors • Acid gases	• 99.99% capture of primary PM < 10 micron in size • Control SO_3 vapor to < 5ppm in stack exhaust by 2015; $\leq$ 2ppm by 2020	

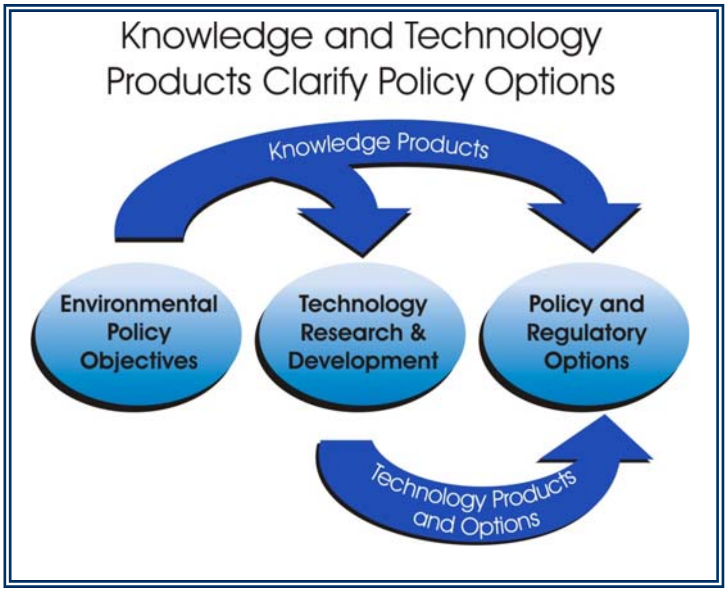
IV. THE PATH FORWARD: The IEP Program Plan

GIVEN the technical challenges outlined in the IEP Roadmap – *what* needs to be accomplished – this section delineates *how* the IEP Program R&D portfolio will be implemented. The program strategy has several key elements that guide implementation.

- Work collaboratively with regulators, technology developers, utilities, academia and the public.
- Seek market-based technology solutions that maximize public benefits in a cost-effective manner.
- Respond to differences in regional requirements related to water use, air-quality attainment, and the specific characteristics and requirements of the nation's varied coal reserves.
- Build the program's research portfolio on projects that are competitively selected and peer-reviewed for performance results.
- Serve a facilitating role in providing the data and analysis to resolve scientific and technology issues that hinder effective regulatory and policy pathways.
- Working with environmental non-governmental organizations and others to elucidate perspectives and opportunities for improved environmental acceptability.
- Engaging in jointly-sponsored research programs to achieve common objectives.
- Continuing public outreach activities that provide information and educational materials about technology options for compliance.

The IEP Program seeks market-based technology solutions to environmental management, and has two major products:

- Knowledge: High-quality scientific data and analysis for use in policy and regulatory determinations; and
- Technology: Advanced environmental control systems for coal-fired power plants.



As we move forward, some pathways may not be viable due to environmental, economic, technical, or other reasons. Particularly in multi-pollutant approaches, new concepts may open novel pathways. Through the process of roadmap development, these new pathways can be identified and explored.

The availability of high-quality information and knowledge is key to the development of cost-effective control technology and the formulation of balanced regulatory policy. Knowledge that is accepted by all stakeholders has multiple benefits. It can clarify the specific contributions of power plants to air, water, and solid-waste issues, thus providing a scientific basis for control needs. The result is improved policy and regulatory approaches that can yield the greatest public benefits at the least cost to the power sector and society at large.

To achieve the transfer of technology and knowledge products, the IEP Program works closely with power producers, the Environmental Protection Agency (EPA), state and local agencies, and other stakeholders. The program has made significant contributions through the Interagency Review process to the formulation of policy addressing toxic releases, coal utilization by-product disposal, mercury regulations, fine particulate matter, and cooling water intake structures.

The IEP Program funding has averaged approximately $21 million/yr over the past three years. FY 2006 funding is $25.1 million. Program R&D performers include universities, nonprofit organizations, and industry, as well as NETL in-house research.

As a collaborative effort with multiple stakeholders, two factors are particularly significant:

- The majority of research efforts are selected based on competitive, open bidding processes; and
- A significant portion of the R&D is cost shared with industry, at an average rate of 20%.

Roadmapping is an iterative process that incorporates new information as it becomes available. In order to guide technology development along market-based options, the roadmapping effort relies on widespread collaboration to develop a scientific and technical consensus.

PARTNERSHIP IN COLLABORATIVE PLANNING AND IMPLEMENTATION: Working for Mutual Benefits

Representative R&D Partners

- Environmental Protection Agency
- EPRI
- CURC
- NARSTO (formerly North American Research Strategy for Tropospheric Ozone)
- Tennessee Valley Authority
- Department of Commerce/National Institute of Standards and Technology
- Department of Interior National Park Service
- Department of Interior Office of Surface Mining, Reclamation, and Enforcement
- Utilities Solid Waste Activities Group
- U.S. Geological Survey
- American Society for Testing and Materials
- National Association of Environmental Professionals
- American Coal Ash Association
- State Governments
- Local and Regional Planning Organizations

A. Mercury Emissions Control

Mercury is found in extremely small concentrations in coal, but the large amount of coal burned for electric generation results in power plants being the largest man-made source of mercury emissions in the United States. Mercury is released into the air as vapor, ultimately being deposited in soils and water where it may bioaccumulate in the food chain and present a human health risk, primarily via fish consumption.

Major Objectives

- By 2007, technology ready for commercial demonstration of 50-70% mercury reduction
- By 2010, technology ready for commercial demonstration of 90% or greater mercury capture
- Reduce cost by 25-50% compared to baseline cost estimates of $50,000 to $70,000/lb of mercury removed

U.S. anthropogenic mercury emissions are estimated to account for roughly three percent of the total global release, and emissions from the U.S. power plants are estimated to account for about one percent of total global emissions. (United Nations Environment Program, Chemicals, Global Mercury Assessment, 2002).

Table 2 presents the three major research pathways for the mercury emissions roadmap: control technologies, emissions characterization, and the development of measurement methods.

Effective control options that can be retrofitted cost effectively are needed to meet the requirements of the Clean Air Mercury Rule. The program has been working over the past decade to develop technology to lower the cost of mercury emissions reductions. Technology development is complicated by many factors. The type of coal, the type of air pollution control systems present, flue gas temperature, and mercury speciation in the flue gas all impact the efficiency of mercury capture. Phase I field testing of activated carbon injection (ACI) and enhanced flue gas scrubbing for mercury control has been completed and a second phase of field

Table 2. Mercury Emissions Control

Pathway	Barriers and Issues	Technology Approaches	Technology Objectives
Control Technologies *Develop cost-effective options for new and retrofit applications*	• Different coal ranks produce different forms (species) of mercury • Elemental and oxidized forms of mercury behave differently • Flue gas contains very dilute concentrations of mercury making capture difficult and expensive	• Develop comprehensive cost and performance data • Field testing of most promising control concepts • Continued pilot and bench-scale development of novel technologies	Commercial demonstration of technologies to achieve: • 50-70% reduction by 2007 for all coal ranks • $\geq$90% capture by 2010 • <3/4 or less the cost of baseline estimates
Emissions Characterization *Develop methods and data to support control system needs*	• Variability in the forms of mercury found in flue gas • Variability in the amounts of mercury in different coal feedstocks • Variability in the speciation of mercury in coal flue gas	• Apply best available measurement methods to characterize Hg emissions • Focus on impact of conventional APCD such as Selective Catalytic Reduction on mercury	• Reliable data on emissions and control from coal-based power systems
Development of Measurement Methods *Develop standard methodology for mercury speciation in flue gas*	• Understanding of mercury behavior in flue gas is limited	• Evaluate and develop advanced mercury CEM technology as part of field testing program	• Provide for a reliable, inexpensive method for continuous measurement of total and speciated mercury

90% Removal of Mercury from Flue Gas: The Proverbial Needle in a Haystack

- Mercury is present in flue gas at a concentration of approximately 1 part per billion. Consider that Detroit's Ford Field could hold roughly 30 billion ping pong balls. So, analogously, 30 of the 30 billion ping pong balls are "mercury" and the technology challenge is to sift through the Ford Field full of ping pong balls and capture 27 of the 30 "mercury" ones (90% removal).

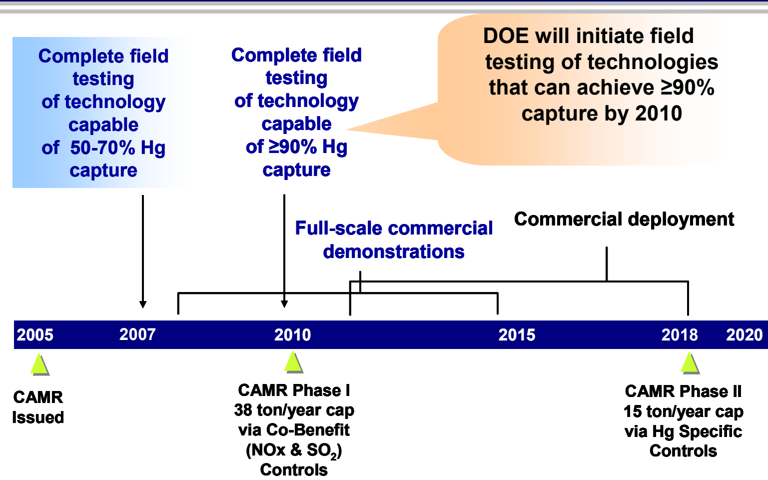
testing is underway. The Phase II projects focus on longer-term (approximately one month at optimized conditions), large-scale field testing of ACI and oxidation technologies on low-rank coals and coal blends. These technologies take advantage of the potential co-benefit mercury capture by existing air pollution control systems and address the 2007 target for 50-70% reduction of mercury. Recently selected phase III projects will focus on additional long-term field testing of mercury control technologies capable of 90% or greater mercury capture, as well as additional field testing of technologies to achieve 50-70% capture.

The mercury control effort involves partnership with EPA and the electric-utility industry. This helps to ensure that the policy and regulatory process benefits from the program's information on mercury emission characteristics and reliable cost and performance data on control system options. Additional information is available in an NETL *Program Facts* document at http://www.netl.doe.gov/publications/factsheets/program/prog050.pdf.

Implementation Highlights

Successes to Date

- Helped to develop and validate a standard protocol for measurement of mercury speciation in flue gas, known as the Ontario-Hydro method. This effort provided a dramatic improvement in understanding mercury behavior, which is fundamental both to regulatory determinations and to guiding the requirements for control strategies and technologies.
- Demonstrated the capability of enhancing co-benefit mercury capture in existing wet flu-gas desulfurization systems by the addition of a liquid reagent.
- Initiated Phase II testing of advanced controls, with 14 projects encompassing 28 different plants using a range of bituminous, subbituminous and lignite coals.
- Recent field testing of brominated (chemically-treated) ACI has demonstrated that high mercury control is achievable for plants firing low-rank coal.



Moving Forward

- In February 2006, twelve new mercury control projects were selected under a Phase III mercury solicitation. The primary focus of the new projects is on field testing advanced post-combustion mercury control technologies that achieve 90% or greater mercury removal with a cost reduction of 50% or more. Other objectives center on field-testing in specific areas of need, and bench- through pilot-scale testing of novel mercury control technologies.

B. Coal Utilization By-Products

U.S. coal-fired power plants generated approximately 122 million tons of solid by-product materials in 2004, of which about 40% were recycled in various commercial applications. The IEP Program seeks to expand the technology pathways that can provide power producers with cost-effective utilization alternatives to traditional disposal methods, and has established a goal of increasing the commercial use of coal utilization by-products (CUBs) to 50% by 2010. Meeting this goal entails four challenges:

- Increased scrutiny of by-products due to concerns about the fate of mercury and other trace elements removed from flue gas;
- The Clean Air Interstate Rule (CAIR) could double the amount of scrubber solids currently generated;
- ACI for mercury control can negatively impact fly ash use as a substitute for cement in concrete; and
- NO_x emission restrictions under CAIR may result in increased use of ultra-low NO_x burners and SCR, thus negatively impacting the beneficial use of fly ash due to excessive levels of unburned carbon and/or ammonia.

Table 3 presents the CUB roadmap that includes two major pathways:

- Utilization research
- Environmental impact characterization

Research is carried out to characterize the fate of mercury and trace metals in CUBs (including by-products from both advanced combustion and gasification technology), to expand existing and develop new commercial markets for CUBs, and to develop advanced separation technologies. By developing these technologies, the IEP Program provides the pubic benefits of reduced waste volumes while maintaining the low cost of coal-based electricity generation.

Table 3. Coal Utilization By-Products

PATHWAY	BARRIERS AND ISSUES	TECHNOLOGY APPROACHES	TECHNOLOGY OBJECTIVES
Utilization Research *Technology and processes to expand by-product use*	• Existing state and Federal construction specifications can limit use of by-products • Ammonia carryover from NO_x reduction • Increased unburned carbon due to combustion NO_x control • Use of ACI for mercury control • Increased wet FGD solids due to SO_2 control technology • Capture of mercury in FGD solids	• Develop advanced technologies for increased by-product use • Develop advanced technologies for separating carbon from fly ash • Evaluate mercury sorbents that do not adversely affect use of fly ash in concrete • Participate in Coal Combustion Products Partnership to promote high-volume use of by-products	• Increase utilization rate to 50% by 2010 • Increase utilization rate to near 100% by 2020
Environmental Impact Characterization *Characterize environmental acceptability of by-products*	• Mercury control regulations could increase concerns about use and disposal of fly ash and scrubber solids	• Determine fate of mercury and other trace metals in CUBs from Phase I and II mercury control technology field testing projects • Conduct leaching, volatilization, and microbial release evaluation of coal by-products	• High quality data on fate of mercury and other trace metals in coal utilization by-products

Collaboration is a hallmark of the CUB program. For example, the Combustion By-Products Recycling Consortium (CBRC) is an industry-based group formed to help develop and implement new approaches to by-product production and use. The CBRC is administered through West Virginia University's Water Research Institute. Its members represent three regions (Eastern, Mid-Western, and Western) with different CUB needs based on the types of coal used and the unique disposal and by-product market options in each region. Similarly, the Coal Combustion Products Partnership, a collaboration with industry and EPA's Office of Solid Waste, will aid the expanded use of improved CUB materials for a variety of high-volume industrial and commercial applications including:

- Construction Materials
  - Lightweight aggregate
  - High-performance concrete
- Beneficial Land-Application Materials
  - Agricultural time substitute/soil amendment
  - Surface mine reclamation
  - Livestock feedlot stabilization
- Underground Mine-Emplacement Materials
  - Surface mine highwall stabilization
  - Underground mine subsidence control

Implementation Highlights

- **Successes to Date**
  - Scale-up and demonstration of fly ash ozonation process at PPL's Montour Power Station.
  - Charter member of EPA's Coal Combustion Products Partnership.
  - Completed evaluation of fate of mercury during wallboard manufacturing using synthetic gypsum.
  - Completed topical report on leaching of mercury and other trace metals from fly ash. Completed initial studies on re-use of IGCC by-products.
- **Moving Forward**
  - Selected Frontier Geosciences to perform detailed characterization of mercury in by-products from Phase II mercury field testing program.
  - Further investigation of mercury release during high temperature processing of CUBs.
  - Develop new high-volume uses for FGD and IGCC by-products.

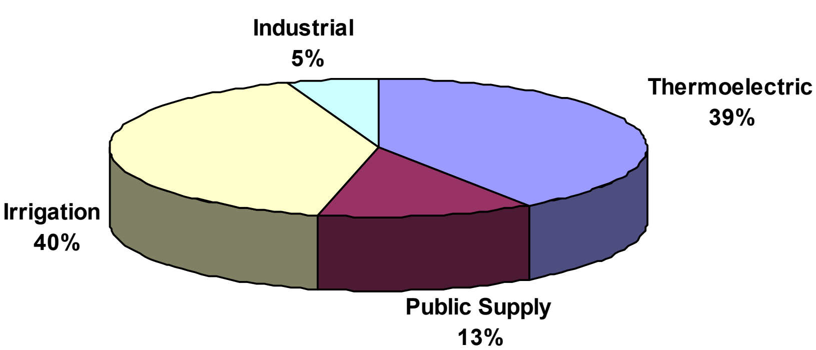
Partnership efforts will enhance the commercial use of coal by-products

Additional information about NETL's CUB program can be found at http://www.netl.doe.gov/technologies/coalpower/ewr/coal_utilization_byproducts/pdf/AWMA011806.pdf

C. Water Management

Significant quantities of water are necessary for the generation of electrical energy by coal-fired power plants. In fact, each kWh of thermoelectric generation requires approximately 25 gallons of water[1]. According to USGS's *Estimated Use of Water in the United States in 2000*, thermoelectric power generation ranks only slightly behind irrigation as the largest source of freshwater withdrawals in the United States, withdrawing over 136 billion gallons per day primarily for cooling purposes. The pie chart below shows the percentage of total U.S. freshwater withdrawal by source category. When discussing water and thermoelectric generation, it is important to distinguish between water use and water consumption. Water use represents the total water withdrawal from a source and water consumption represents the amount of that withdrawal that is not returned to the source. Although thermoelectric generation is the second largest user of water on a withdrawal basis, it was only responsible for approximately 3% of the total 100 billion gallons per day of freshwater consumed in 1995.

2000 U.S. Freshwater Withdrawal



Major Objectives

- Reduce freshwater use by 5%-10% by 2015
- Minimize impacts of plant operations on water quality

Growing concerns about water availability along with current and future water-related environmental regulations and requirements could impact both the permitting and operation of coal-based power systems, including advanced gasification technology. In response to these national energy sustainability and security challenges, the IEP Program has been proactive through a water strategy directed at developing technologies and approaches to better manage how power plants use and impact freshwater resources.

The program is sponsoring research that encompasses laboratory- and bench-scale activities through pilot-scale projects and is built upon partnership and collaboration with industry, academia, and other government and non-governmental organizations. The goal of this research is to reduce the amount of freshwater needed by power plants and minimize potential water quality impacts. Table 4 shows the energy-water interface roadmap that includes four major pathways:

- Non-traditional sources of process and cooling water
- Innovative water reuse and recovery
- Advanced cooling technology
- Advanced water treatment and detection technology

[1] This is a weighted average that captures total thermoelectric water withdrawals and generation for both once-through and recirculating cooling systems.

Table 4. Water Management

PATHWAY	BARRIERS AND ISSUES	TECHNOLOGY APPROACHES	TECHNOLOGY, POLICY, AND REGULATORY OBJECTIVES
Use of non-traditional* sources of process and cooling water *Substitute non-traditional water for freshwater in plant operations*	• Technical, environmental, economic, and social issues associated with use of impaired water • Limited information and experience with coal-based power plants	• Assess technical and economic feasibility of using underground mine water , produced water, from oil and gas extraction, and other impaired waters	• Develop and make available information on the technical and economic feasibility of using non-traditional water
Innovative Water Reuse and Recovery *Improve efficiency of water use*	• Thermoelectric generation is second largest user of water in the U.S., withdrawing 136 billion gallons per day • Cooling water intake regulations could further constrain water use by coal-based power systems	• Develop novel approaches to recover and reuse water from power plant flue gas and from flue gas desulfurization systems • Develop coal drying/water recovery technology	• Reduced freshwater withdrawal and consumption per kWh of power production
Advanced Cooling Technology *Improve performance and costs associated with cooling*	• Cooling technology requires large quantities of water to operate, and also consume significant volumes of water in their operation • Dry cooling technology has high capital costs, requires significant plant space for installation, and can have negative impacts on plant efficiency	• Develop advanced wet, dry, and hybrid cooling technology	• Reduce consumption and withdrawal of freshwater associated with wet and hybrid cooling technology • Reduce capital cost and efficiency penalties associated with dry (air cooled) technology
Advanced Water Treatment and Detection Technology *Enable reliable, cost-effective systems*	• Tightening of drinking water standards could impact effluent discharges from power plants • Concerns about the fate of mercury in by-products could result in more restrictive effluent standards	• Develop novel approaches to detect and control mercury, other trace metals, and nitrogen compounds from power plant effluents	• Ensure compliance with future Clean Water Act and Safe Drinking Water Act effluent guidelines and regulations

* "Non-traditional" or impaired water refers to water sources such as mine water, produced water, and treated municipal and industrial wastewater.

Implementation Highlights

♦ Successes to Date

– Developed an environmentally safe "green" technology to control the fouling of power plant water intake structures by zebra muscles.

– Completed feasibility assessment of using underground coal mine water for cooling and as a heat sink for coal-based power systems.

– Completed pilot-scale testing of a desiccant-based system for recovering and reusing water from power plant flue gas.

♦ Moving Forward

– In November 2005, the IEP Program announced the award of seven additional energy-water R&D projects aimed at reducing the amount of freshwater needed by coal-based power plants.

More information about NETL's Water Management program can be found at
http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/IEP_Power_Plant_Water_R%26D_Final_1.pdf

D. Advanced NO_x Emissions Control

Nitrogen oxide (NO_x) is a general term used to describe various nitrogen and oxygen-based gases that includes nitrogen dioxide (NO_2), nitrous oxide (N_2O), and nitric oxide (NO). The emission of NO_x to the atmosphere can contribute to a number of environmental concerns. NO_x can react with volatile organic compounds in the presence of sunlight to form ozone. NO_x is also a precursor to secondary fine particulate matter that may impact human health and contributes to regional haze and "acid rain". The deposition of nitrogen compounds in and around bodies of water has been linked to "eutrophication" – an over-enrichment of nutrients that can deplete the oxygen content of lakes and rivers. Such deposition has been identified as a primary source of nitrogen in the Chesapeake Bay. EPA has recently proposed using the Clean Water Act as a mechanism to further reduce NO_x emissions near sensitive waters. Finally, one compound of NO_x, nitrous oxide, is a greenhouse gas.

NO_x emissions from coal-based power plants subject to EPA's Title IV "acid rain" program were approximately 4 million tons in 2002, representing 18% of total U.S. NO_x emissions. EPA's CAIR will further lower power plant NO_x emissions through a cap-and-trade program, requiring Eastern U.S. plants to achieve an equivalent emission rate of 0.125 lb/MMBtu.

Table 5 shows the advanced NO_x emissions control roadmap that includes two major pathways:

- In-furnace control
- Post-combustion control

Major Objectives

- 0.15 lb/MMBtu emissions by 2007 via in-furnace control
- 0.10 lb/MMBtu emissions by 2010 via in-furnace control
- 0.01 lb/MMBtu emissions by 2020 via in-furnace control and SCR installations

Both pathways focus on the development of enhanced control technology that has negligible balance-of-plant impacts; apply to a wide range of boiler types and configurations; and maintain performance over a wide range of coal ranks and operating conditions.

While low NO_x burners and SCRs have been the workhorses for meeting current NO_x regulations, future requirements drive the need for the lower-cost technologies addressed in the roadmap. Power producers will need to retrofit additional boilers with NO_x controls, some of which will adversely impact plant performance. Hardest hit economically

Table 5. Advanced NO_x Emissions Control

Pathway	Barriers and Issues	Technology Approaches	Technology Targets
In-Furnace Control *Reduce NO_x formation in the combustion process*	• Multi-pollutant regulations will require deeper cuts in NO_x emissions • Current low- NO_x burners increase unburned carbon in fly ash	• Ultra-low NO_x burners • Pre-combustion modifications • Oxygen-enhanced combustion • Combustion catalysts	• Demonstration of advanced combustion NO_x control technology to provide cost and performance validation • Achieve 0.15 lb/MMBtu at <¾ cost of SCR by 2007 • Achieve 0.10 lb/MMBtu at <¾ cost of SCR by 2010
Post-Combustion Control *Convert NO_x to N_2 after combustion*	• SCR systems have high capital and operating costs • SCR systems can create balance-of-plant issues • Small, older plants may not be retrofitted with SCR	• Assess alternative reducing agents • Develop low-temperature SCR catalysts • Integrate advanced combustion NO_x control with SNCR and SCR	• Demonstration of advanced combustion/SCR technology to provide cost and performance validation • Achieve 0.01 lb/MMBtu at <¾ cost of current methods by 2020

will be the smaller, older, less efficient facilities that can not easily retrofit today's SCR equipment because of space constraints and the reluctance of owners to make substantial investments in the aging plants during a period of increasing market competition. These facilities, with a generating capacity <300 MW, comprise 66% of the U.S. boilers and have an average age twice that of the remainder of the fleet.

In response to these challenges, the NO_x program conducts R&D to enhance the performance of the existing fleet and apply these concepts to advanced power systems. This effort focuses on systems controlling NO_x emissions below 0.15 lb/MMBtu at costs lower than today's SCR technology. Estimates show that in achieving NO_x emission reductions by in-furnace concepts rather than SCR, U.S. coal-based power plants could realize a capital savings of $4.0 billion to comply with the proposed Clear Skies Act of 2005. The research also provides insights into the impact of these technologies on related issues such as unburned carbon, waterwall wastage, and mercury capture. These projects encompass laboratory studies, modeling, and full-scale field testing.

Advanced NO_x Control Has Major Co-Benefits

- Mercury – SCR and in-furnace advancements can oxidize mercury and increase the mercury capture efficiency of downstream FGD systems.
- PM2.5 – reduction of NO_x and NH_3 emissions minimizes nitrate formation, a significant component of PM2.5.
- Water – minimizing NO_x and NH_3 releases into air and fly ash landfills reduces nitrification of water.
- By-products – reduction of fly ash unburned carbon and NH_3 improves its marketability.

The success of the program is intimately tied to key collaborations and partnerships established with industry, Federal, state, and local agencies, and the academic and research communities.

Additional information is available in an NETL white paper at: http://www.netl.doe.gov/technologies/coalpower/ewr/nox/pubs/NOXcontrolRDwhite_paper.pdf.

Implementation Highlights

- **Successes to Date**
  - Field testing by REI of EPRI's Rich Reagent Injection (RRI) with overfire air (OFA) on Ameren's Sioux Unit 1 cyclone boiler achieved NO_x emissions below 0.15 pounds per million Btu.
  - Northeast Generation Services has licensed Praxair's Oxygen Enhanced Combustion at the Mt. Tom Station.
  - ALSTOM's combustion enhancements for tangential-fired boilers are achieving NO_x emissions of 0.15 lb/MMBtu on 19 units burning PRB coal.
- **Moving Forward**
  - NETL is conducting pilot- and full-scale NO_x control demonstrations under five new collaborative R&D projects that were announced in November 2004.
  - New projects selected focus on SCR monitoring, advanced firing systems, new burner development, and RRI and oxygen injection enhancements.
  - Collaborative projects with universities are researching new SCR catalysts.
  - Planning is underway to issue a solicitation of advanced NO_x control technologies at the pilot-scale and field testing-scale as alternative to current SCR technology.

E. Air Quality Research

The air quality research pathway is designed to expand the scientific data and understanding related to the ultimate fate of coal-based power system air emissions. The goal is to provide information that can guide future policy decision, both by providing improved information on the specific needs for controls and on control technology options. Further, research on atmospheric mercury chemistry will be invaluable for further debate on a global mercury strategy. Table 6 shows the air quality research roadmap that includes four major pathways:

- Ambient monitoring and analysis
- Emissions characterization
- Predictive modeling and evaluation
- Health effects

Major Objectives

- Establish the scientific basis for emission controls that maximize public-health benefits
- Resolve uncertainties in the transport, transformation, deposition, and health impacts of coal-fired power plant emissions

Research along this pathway is focused on bringing additional clarity to the scientific uncertainties associated with the emission, transport, transformation, and deposition of emissions from coal-based power systems. For example, of particular concern are coal plant emissions and their relationship and contribution to total ambient PM2.5 loading and impacts. Similarly, an improved understanding of mercury transformations in the atmosphere is key to targeting effective controls.

Table 6. Air Quality Research

Pathway	Issues and Barriers	Science and Technology Approaches	Technology, Policy, and Regulatory Objectives
Ambient Monitoring and Analysis *Develop reliable database on the composition and characteristics of ambient particulate matter and gaseous species*	• Need for updated information on the characteristics of ambient fine particulate matter • Ambient air quality driving further reductions in coal-fired power plant emissions	• Establish collaborative regional monitoring networks working with EPA and industry • Apply advanced monitoring and analysis procedures and protocols • Support Mercury Deposition Monitoring site(s)	• Provide set of high quality data on ambient air quality to EPA • Assess trends in air quality relative to reductions in emissions
Emissions Characterization *Determine the chemical characteristics of emissions*	• Accurate source characterization is required to establish emission baselines • Data needed to update and validate source-receptor models	• Collection and analysis of primary particulates • Collection and analysis of secondary particulate matter and precursors • Develop dilution sampling methods	• Validated stack emissions data • Provide emission “signatures” to determine sources • Information on mercury transport and deposition for use in development of mercury trading programs
Predictive Modeling and Evaluation *Determine the likely emission sources of species of concern*	• Reliable information on atmospheric transport and deposition is needed • Improved understanding of transport and fate in ecosystems is needed • Lack of understanding of the action/response results from different control strategies	• Incorporate advanced knowledge of atmospheric chemistry into model algorithms • Develop and validate advanced emissions—specific protocols and models • Develop more detailed understanding of atmospheric chemical reactions involving SO_2, NO_x, PM and mercury	• Understanding the impacts of different control strategies for use in policy and regulatory deformations • Market-based compliance options
Health Effects *Improve scientific data on health effects of plant emissions vs. other sources*	• Reliable correlations between emissions sources and health impacts are non-existent • Correlations between individual chemical species and impacts are marginal	• Perform toxicological studies to establish potential for health impacts • Conduct epidemiologic studies on various PM2.5 components to determine health linkages	• Establish relationship between power plant emissions and health effects

Implementation Highlights

- **Successes to Date**
  - A network of about a dozen ambient air monitoring sites in the upper Ohio River valley was operated from 1999 through 2003 to serve as a foundation for modeling and source apportionment studies. Data from these monitoring sites has been transmitted to EPA.
  - Applied advanced receptor modeling and chemical transport models to provide improved simulation of responses to current and future regulations.
- **Moving Forward**
  - The ambient monitoring data collected from 1999 through 2003 are being incorporated into a web-based user interface that will: (1) allow easy access to the data by a wide variety of stakeholders; (2) provide detailed information on sampling, analytical and quality control parameters; and (3) include graphical tools for displaying, analyzing and interpreting the air quality data on-line.
  - The University of Pittsburgh has initiated a feasibility study to determine how the data collected in the ambient monitoring program could best be used to conduct an epidemiological study of particulate matter and health in the Pittsburgh region.
  - Two projects are currently focusing on the toxicity of coal plant emissions relative to emissions from other key sources. In one project, EPRI is taking a mobile toxicology laboratory into three different ambient settings – one known to be dominated by coal plant emissions, one dominated by motor vehicle emissions, and the third containing a diverse mixture of industrial sources. Lovelace Respiratory Research Institute is exposing laboratory animals to "simulated downwind" emissions of coal combustion, and comparing the observed health effects to those resulting from exposures to other key source emissions—diesel and gasoline engines, hardwood smoke, and street dust—using an identical laboratory protocol.

More detail on the Air Quality Research program, including individual projects is available in an NETL *Project Facts* document at http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/DOE_PMpgm.pdf

F. Particulate Matter and Acid-Gas Emissions Control

Major Objectives

- 0.01 lb/10^6 Btu emissions and 99.99% collection efficiency of PM < 10 micron in size by 2007
- Achieve SO_3 emissions of 5ppm or less by 20015

Fine particulate matter (particles with a diameter of less than 2.5 microns or PM2.5) can cause localized plume opacity, visibility impairment, and has been linked to adverse human health impacts. The particulate matter of concern for coal-based power systems can be placed in three broad categories:

- Primary – bits of mineral matter and unburned carbon that are entrained in flue gas along with trace metals;
- Fine acid aerosols created by the reaction of SO_3 and water vapor that can contribute to problems in operating flue gas systems; and
- Secondary particulates, those formed in the atmosphere by chemical reactions involving NO_x and SO_2.

An example of fine acid aerosol formation occurs in the SCR where approximately 1% of SO_2 entering the unit will react to form SO_3 that subsequently reacts with water vapor resulting in sulfuric acid emissions from the plant.

The goal of this IEP Program area is to develop cost-effective control technologies to address primary particulates, associated trace metals (e.g., lead, arsenic) and acid gases. For gaseous PM2.5 precursors, advanced control technology for NO_x is being carried out under the Advanced NO_x Emissions Control area of the program. There is currently no program activity for SO_2, for which mature control technologies are already available.

Currently, no active PM or SO_3 control projects exist—all projects have been completed. However, additional R&D may be needed if (1) health studies indicate that a specific component of primary PM may be especially problematic or (2) the increase in the use of SCR technology, in response to CAIR, results in greater SO_3 emissions. Table 7 presents the particulate matter emissions control roadmap that includes two major pathways: primary fine particulates; and acid gases.

Table 7. Particulate-Matter Emissions Control

Pathway	Barriers and Issues	Technology Approaches	Technology Objectives
Primary Fine Particulates *Capture <10 micron particles from flue gases*	• Future controls required to address potential link to health effects • Deteriorating performance of older electrostatic precipitator systems (ESPs) • Integration of particulate and mercury control	• Enhance efficiency of existing ESPs through flue gas conditioning and concentration • Develop advanced particulate collectors and separation systems	• Achieve 99.99% capture of fine particles in the 0.01-10 micron size range • Technology ready for commercial demonstration by 2007
Acid Gases *Develop acid-gas control strategies*	• Localized plume opacity and impacts on air quality • Toxics Release Inventory reporting required of power producers • No current continuous acid gas analyzers	• Injection of alkaline sorbents • Identify and characterize acid-gas production (e.g., from SCR systems) • Develop continuous SO_3 analyzers • Develop advanced SO_3 control technology	• Control SO_3 vapor to <5ppm in stack exhaust • Technology ready for commercial demonstration by 2010 • Field rugged SO_3 analyzer commercially available by 2007

. Implementation Highlights

- **Successes to Date**
  - Advanced hybrid particular collector developed under IEP Program was selected and is being commercially demonstrated at Otter Tail Power's Big Stone Power Station in North Dakota as part of DOE's Power Plant Improvement Initiative.
  - Furnace injection of calcium and magnesium alkaline sorbents tested at American Electric Power's Gavin Station to control SO_3 emissions resulting from operation of SCR system.
- **Moving Forward**
  - Additional research may be carried out to address acid gas emissions associated with the use of catalyst-based SCR systems to control NO_x emissions that can oxidize SO_2 to SO_3, and can impact effectiveness of ACI for controlling mercury.

For more information:

Additional information on Particulate Matter and Acid-Gas Emissions Control is available in a NETL Five-Year Research Plan at http://www.netl.doe.gov/technologies/coalpower/ewr/air_quality_research/docs/pm5yrfnl.pdf

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