

COAL & POWER SYSTEMS

STRATEGIC & MULTI-YEAR PROGRAM PLANS



GREENER, SOONER...
THROUGH
TECHNOLOGY

U.S. DEPARTMENT OF ENERGY • OFFICE OF FOSSIL ENERGY



STRATEGIC & MULTI-YEAR PROGRAM PLANS



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STRENGTH THROUGH SCIENCE...

A "GREENER, SOONER" PHILOSOPHY

Coal, natural gas, and oil fuel about 70 percent of the electricity generated in the United States. As promising as renewable and other alternative fuels are, it will be several decades before they can make significant energy contributions to the Nation's generation mix.

A "greener, sooner" philosophy means that the country does not have to wait for the promising energy contributions from renewables and other alternative fuels. This philosophy has been applied to all coal and power systems research and development. By applying technological advances, the Nation can continue to improve environmental quality and reap the economic benefits of the fuels the United States counts on most, until alternative energy resources move into the market.

The Office of Fossil Energy's Coal & Power Systems program is taking the lead on meeting the energy, environmental, and economic challenges of the next century by managing high-tech research and development in fossil fuel technologies.

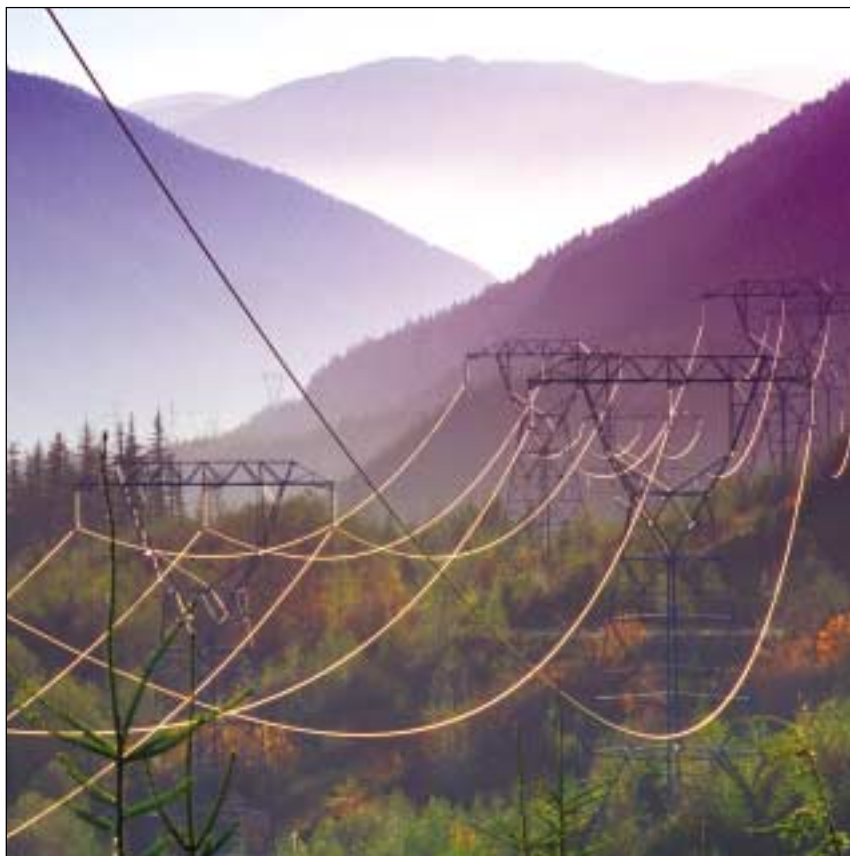
INTRODUCTION

The Department of Energy's (DOE) Office of Fossil Energy (FE), through the Coal & Power Systems (C&PS) program, funds research to advance the scientific knowledge needed to provide new and improved energy technologies; to eliminate any detrimental environmental effects of energy production and use; and to maintain U.S. leadership in promoting the effective use of U.S. power technologies on an international scale.

Further, the C&PS program facilitates the effective deployment of these technologies to maximize their benefits to the Nation.

The following *Strategic Plan* describes how the C&PS program intends to meet the challenges of the National Energy Strategy to: (1) enhance America's energy security; (2) improve the environmental acceptability of energy production and use; (3) increase the competitiveness and reliability of U.S. energy systems; and (4) ensure a robust U.S. energy future. It is a plan based on the consensus of experts and managers from FE's program offices and the National Energy Technology Laboratory (NETL).

More importantly, the C&PS plan reflects a broad cross-section of stakeholder and customer input and recommendations. The Office of Fossil Energy recognizes that these groups are ultimately responsible for choosing and deploying its portfolio of programs. The Office of Fossil Energy works closely with



these groups in technology development and deployment facilitation in order for the public to receive the full benefit from federal investments in these areas.

The overall process takes into consideration the current situation and future trends in energy production and use. In defining its mission, vision, objectives, and strategies, FE continually analyzes these trends to ensure that C&PS programs are focused on those activities (consistent with a proper federal role) that will fulfill critical national interests and meet program goals in an efficient and cost-effective manner.

Through the use of individual *Program Plans*, the C&PS program annually reexamines its portfolio of programs to assure the appropriate

balance both among and within programs. In conjunction with these efforts, the C&PS program also conducts periodic reviews of its *Strategic Plan* to ensure that the plan evolves in parallel with changes in power production and use, C&PS programs, and national and DOE policy.

The following *Strategic Plan* and the accompanying *Program Plans* advance the Department's missions through a set of crosscutting strategic goals, objectives and strategies — elements that bring focus to the dynamic challenges that lay ahead. Supporting this crosscutting framework are the scientific disciplines focused on technology research and development (R&D) embodied within the C&PS program.

LINK TO NATIONAL ENERGY STRATEGY

In relation to other plans, the C&PS *Strategic Plan* is derived from the FE program strategy, mission, and vision. The FE program, in turn, supports the National Energy Strategy through DOE's mission and its Energy Resources R&D Portfolio strategic goal "to promote the development and deployment of energy systems and practices that will provide current and future generations with energy that is clean, reasonably-priced, and reliable."

A key aspect of the National Energy Strategy is to develop technologies that will permit the use of abundant, domestic fossil fuels while meeting current and future air quality standards. Clearly, a multi-faceted approach is needed to meet the Nation's goal for energy production and use in the 21st century. The C&PS program is responding by offering energy solutions to advance the National Energy Strategy. These solutions are discussed in greater detail in the following *Strategic Plan* and individual *Program Plans*.

Vision 21. A multi-product, pollution-free energy plant — producing electricity, fuels and/or industrial heat — could extract 80 percent or more of the energy value of coal and 85 percent or more of the energy value of natural gas.

Central Power Systems. Break-through turbines and revolutionary new fuel cells that burn less coal and gas to obtain energy, while reducing emissions.

Distributed Generation Technologies. Fuel cell technology providing highly efficient, clean modular power.



C&PS PROGRAM

Vision 21 Program

- Systems Analysis
- Enabling Technologies
- Supporting Technologies
- Systems Integration
- Plant Designs

Central Power Systems Program

- Innovations for Existing Plants
 - Advanced NO_x Control
 - PM_{2.5}/Air Toxics Control
 - Coal Combustion By-Products
- Advanced Systems
 - Low-Emissions Boiler System
 - Indirect Fired Cycles
 - Pressurized Fluidized-Bed Combustion
 - Gasification Technologies
 - Advanced Turbine Systems
 - Next Generation Turbines

Distribution Generation Program

- Second Generation Fuel Cells
- Vision 21 Fuel Cell/Turbine Hybrids
- SECA Solid State Fuel Cell

Fuels Program

- Transportation Fuels and Chemicals
- Solid Fuels and Feedstocks
- Advanced Fuels Research

Carbon Sequestration Program

- Separation and Capture
- Sequestration in Geologic Formations
- Ocean Sequestration
- Terrestrial Sequestration
- Advanced Concepts
- Modeling and Assessments

Advanced Research Program

- Materials and Advanced Metallurgical Research
- Coal Utilization Science
- Bioprocessing of Coal
- University Coal Research
- Historically Black Colleges and Universities/Other Minority Institutions
- International/Coal Technology Export

Fuels. The co-production of coal-derived transportation fuels and power from gasification-based technologies.

Carbon Sequestration Technologies. Capturing greenhouse gases from the exhaust gases of combustion or other sources, or from the

atmosphere itself, and storing them for centuries or recycling them into useful products.

Advanced Research. Going beyond conventional thinking in the areas of computational science, biotechnology, and advanced materials.

FEDERAL ROLE IN ENERGY R&D

The role of government in energy R&D focuses on the important tasks of investing in technology development that generates societal benefits using competitive market forces, and addressing the market's inherent limits to respond to public needs.

Ultimately, the C&PS program invests public funds in R&D for new technologies that protect the Nation against risks to its energy supplies, and eliminate any detrimental environmental effects of energy production and use — public benefits that are not necessarily the focus of private sector investment.

Government also encourages the commercialization of cleaner, more efficient energy technologies by supporting energy research, development, and demonstration almost always in partnership with the private sector. This active participa-

tion by DOE and industry partners helps position the United States as a leader in growing global markets for clean energy technologies.

The Department of Energy, in partnership with the private sector, invests in energy research to protect the Nation against risks to energy supplies and damage to the environment. Through co-investment with industry in promising technologies, DOE accelerates investment in expertise to develop commercially higher risk technologies. Given the potential financial risks involved, such development investments are not adequate to attract sufficient levels of private sector investment without risk-sharing from the government. Currently, private industry is limiting its own energy R&D to the near term, largely because of uncertainty related to future regulation, the perceived need to minimize long-term capital investments, and risks relating to the deregulation of the electric power industry.

With respect to the energy sector, the federal government's role relating to coal and power systems R&D is to:

- Foster clean, efficient, reliable power systems at reasonable costs, while meeting more stringent environmental regulations;
- Support efficient and sustainable use of domestic energy resources, particularly coal and gas;
- Create a science-based approach in the establishment of environmental policies and regulations;
- Enhance global market opportunities for U.S. energy-related technologies, services, and energy resources;
- Contribute to U.S. science and technology leadership; and
- Apply a broad national perspective to technology development beyond company-specific or parochial interests.



PAYOFFS FROM C&PS RESEARCH AND DEVELOPMENT

While ambitious, the C&PS program goals are achievable because they build on a solid technological foundation — a foundation that exists because the U.S. has invested in clean, secure coal power system technologies. Today, the United States uses more than two-and-a-half times the amount of coal for electric power generation as it did in 1970. Yet, emissions of SO₂ and NO_x have declined by 70 percent and 45 percent respectively.

The Department of Energy's coal and power systems R&D has shown a significant return on the taxpayers' investment including:

- Flue gas scrubbers today are one-fourth as expensive to build as they were in the 1970s and cost much less to operate. Additionally, many can produce a powdery waste product (rather than wet sludge) that is being recycled into wallboard or can be easily and safely disposed. Because of the investment in advanced scrubber technology, American ratepayers have saved more than \$40 billion since 1975.

- Low-NO_x burners and post-combustion controls that satisfy emissions reduction requirements have been installed in nearly 75 percent of U.S. coal-fired capacity at a small fraction of the cost of previously available technology.
- To date, more than 5 gigawatts worldwide in integrated gasification combined-cycle (IGCC) plants have been installed in commercial service with:
 - 10 percent to 20 percent improvement in efficiency (an increase from 33 percent to near 40 percent) with proportional reductions in carbon emissions;
 - 98 percent reduction in SO₂ emissions; and
 - NO_x emissions rates well below New Source Performance Standards.
- Pressurized fluidized-bed combustion (PFBC) technology is experiencing commercial success outside of the United States with over 1,000 megawatts installed in Sweden, Spain, Japan, and Germany.
- Atmospheric fluidized-bed combustion technology has been commercially deployed with \$8 billion in sales.

Cost reductions realized by consumers because of these accomplishments are important to the U.S. economy. In fact, the United States enjoys some of the lowest electricity rates among free market economies.

For Additional Program Benefits Information

Additional sources exist that outline the benefits of OC&PS research including:

Powering the New Economy: Energy Accomplishments, Investments, Challenges (September 2000) highlights DOE's energy accomplishments, and examines the energy challenges facing the Nation as we enter the 21st century.

The Investment Pays Off (November 1999) is a record of the Clean Coal Technology (CCT) Demonstration Program's success stories showing solid evidence that the taxpayers' investment continues to pay real and measurable dividends.

Investments in Fossil Energy Technology: How the Government's Fossil Energy R&D Program Has Made a Difference (March 1997) provides a synopsis of the major innovations from DOE's Office of Fossil Energy and the resultant consumer benefits accrued from taxpayer investment in energy R&D. The National Research Council is compiling a similar document that will provide an update of these benefits within the C&PS program and the Office of Fossil Energy. This report is scheduled to be released in early 2001.



THE FOUNDATION: CLEAN COAL TECHNOLOGIES

The Clean Coal Technology demonstration program, a model of government and industry cooperation, represents the Nation's single largest successful government and industry cooperative investment in environmental technology. Started in 1985, the CCT program demonstrates full-scale technology that reduces environmental impacts and increases the efficiency of coal-fired electric generators. Five competitive solicitations sponsored by DOE resulted in selection of the most advanced coal-based technology concepts available anywhere in the world. Federal funding was leveraged two-fold through partnerships encompassing utilities, state governments, technology developers, and research organizations. With 26 of the 38 active projects having completed operation, the CCT program has yielded clean coal technologies that are capable of meeting existing and emerging environmental regulations and competing in a deregulated electric power marketplace.

The CCT program, under the guidance of the Central Power Systems program in C&PS, is providing a portfolio of technologies that will assure that the U.S. recoverable coal reserves of 274 billion tons can continue to supply the Nation's energy needs economically and in an environmentally sound manner. Many of the clean coal technologies have realized commercial application. For existing power plants, there are cost-effective environmental control devices to control SO₂, NO_x, and particulate matter. Also available are a new generation of technologies that can produce electricity and other commodities, such as steam and synthetic gas, and provide the efficiencies and environmental performance responsive to global climate change concerns. The CCT program took a pollution prevention approach as well, demonstrating technologies that produce clean coal-based solid and liquid fuels by removing pollutants or their precursors before being burned. Lastly, new technologies were introduced into major coal-using industries to enhance environmental performance. Thanks in part to the CCT program, coal — abundant, secure and economical — can continue its role as a key component in the U.S. and world energy markets.





NEAR TERM CHALLENGES

Many Americans have suffered through recent power outages and soaring electric bills. The large growth in power demand, particularly peak demand, has resulted in a real and growing concern over electricity grid reliability and reduced reserve margins (the amount of excess power generating capacity above customer demand). The grid's reliability is being stressed by the increasing peak customer demand from the growing industrial, commercial, and residential sectors of the economy. This problem is exacerbated by bouts of extreme weather in parts of the United States, an outdated power delivery grid, uncertainty in the restructuring and deregulation of the power industry, and the Nation's growing dependence on electronic end-use devices (many of which are sensitive to minor power disruptions). Unless grid reliability is urgently addressed, the Nation's electric infrastructure will be seriously challenged to keep up with new demands.

Typically, grid reliability is addressed from the standpoint of transmission and distribution of power. A recent initiative by the C&PS program, however, seeks to improve grid reliability by taking a more "front-end" approach — focusing on improvements to generating capacity and efficiency, subsequently increasing reserve margins. By

maintaining sufficient reserve margins, the risks of rolling blackouts, fluctuating voltage, and price spikes can be reduced.

The Power Plant Improvement Initiative (PPII) is a congressional action, signed in October 2000, aimed at addressing grid reliability resulting from the projected surge in U.S. demand for electric power in the coming years. The PPII is a government/industry co-funded solution to maximize the output from existing coal-fired power plants in the near term. PPII will meet the challenge of "increasing the competitiveness and reliability of the U.S. energy system" contained in the Comprehensive National Energy Strategy of 1998. PPII will benefit the Nation by emphasizing the demonstration of new technologies in the next few years that can boost the efficiency of a power plant — increasing the amount of electricity it can generate — reduce air emissions, or perhaps a combination of both.

The initial program will apply to existing and new coal-based, central power plants. Later, the program could include a wider span of more flexible generation technologies such as fuel cells and turbines that can operate on natural gas as well as coal. The initiative will be a cost-shared, public-private partnership that will retain the funding guidelines of the CCT demonstration program. The first round of projects in the PPII will be selected after September 30, 2001.

LOOKING AHEAD

To sustain economic growth in the 21st century, the United States must become more energy efficient. To most Americans, energy efficiency has meant the wiser end-use of energy. Perhaps as great, however, are the opportunities to improve efficiencies at earlier stages in the fuel cycle, particularly in the generation of electricity.

Higher generating efficiencies translate into fewer environmental emissions. Compared to today's technology, a 50 percent efficient coal plant would emit 40 percent less carbon dioxide. Moreover, remarkable advances in pollution control concepts now offer the potential for these high-efficiency coal systems to be ultra-clean in terms of acid rain emissions.

Research and development within the C&PS program may make it

possible in the early 21st century to build a coal power system that:

- Emits only one-tenth the levels of SO₂ and NO_x allowed by federal air standards (reductions of well over 99 percent for SO₂ and particulates, and 90 percent for NO_x);
- Reduces CO₂ by 40–47 percent from current levels;
- Produces electricity at a cost savings of 10–20 percent compared to current technology.

Global Market Opportunities.

Coal-fired power stations generate almost 40 percent of the world's electricity — more than twice the proportion of any other fuel. As newly industrialized nations expand their energy demand, world coal use is projected to at least double in the next 30 years.

The worldwide market for clean power technologies will range between \$270 billion and \$750 billion over the next 20 years.

Exporting clean power technologies could enable the United States to increase the value of its annual coal exports from \$4.5 billion to between \$13–\$18 billion by 2010.

Global Emissions Reductions.

Advanced coal power systems also offer worldwide CO₂ reduction at a significantly greater cost-effectiveness than imposing new regulatory requirements in the United States.

If the world's power producers could adopt high-efficiency coal technologies by 2075, global CO₂ emissions would almost level off, at about 15,000 million tons per year. This would occur even as world coal use rises dramatically, growing as much as 750 percent over the 2000–2075 time period. The effect would be to cut CO₂ emissions by more than half over what they would have been without high efficiency coal technologies.

TECHNOLOGY GOALS IN THE ERA OF EFFICIENCY

	2000	2005	2010	2015	Vision 21
Electric Generation Efficiency	42–45%	48–55%	55%	60%	60%+
Total Thermal Efficiency	42–45%	48–55%	55%	60%	85%+
Pollutant Emissions ¹	1/3 NSPS	1/4 NSPS	1/10 NSPS	1/10 NSPS	Zero
Reduction in CO ₂ Emissions	29%	42%	42%	47%	100% with sequestration
Reduction in Cost of Electricity	10–20%	10–20%	10–20%	10–20%	10–20%

¹ NSPS: New Source Performance Standards

COAL & POWER SYSTEMS PROGRAM BENEFITS

National Benefits

- Sustains economic growth by maintaining low-cost electricity vital to U.S. industry;
- Establishes a strong U.S. environmental and power generation technology position for export to the world market;
- Reduces greenhouse gas emissions through efficiency gains and potential renewable resource use;
- Positions the United States to export distributed generation technologies in a rapidly growing world energy market, the largest portion of which is devoid of a transmission and distribution grid;
- Provides an alternative supply of transportation fuels from domestic resources, thus hedging against national security risks associated with importing fuels from abroad;
- Eases the economic transition to a sustainable climate; and
- Captures the diverse research contributions of academia and industry, and contributes to the Nation's scientific knowledge base in fossil-related research.

Supplier Benefits

- Enables electricity suppliers to cost-effectively adjust to regional energy and environmental demands;
- Allows significant capacity additions at existing sites, which precludes the need for additional plant siting and transmission line installations;
- Limits capital exposure and risk because of the size, siting flexibility, and rapid installation time afforded by the small, modularly constructed, environmentally friendly, and fuel-flexible distributed generation systems;
- Provides, through gasification-based coal conversion, a way to store energy from a power plant during off-peak periods when demand is low;
- Removes a major environmental concern related to the continued operation of existing fossil fuel plants; and
- Develops international partnerships and markets for U.S. energy-related technologies, services, and energy resources by facilitating both new market entries and expansion of existing markets.

Customer Benefits

- Maintains low-cost electricity rates, which are already among the lowest in the world;
- Serves to bolster electric generating capacity reserve margins critical to reliable customer service;
- Ensures reliability of energy supply increasingly critical to business and industry in general, and essential to some where interruption of service is economically unacceptable or where health and safety are impacted through distributed generation technologies;
- Enables savings on electricity rates by self-generating with distributed generation technologies during high-cost peak power demand periods, and adopting relatively low-cost interruptible power rates;
- Protects against price shocks in the transportation fuels arena by providing an additional domestic source for transportation fuels;
- Provides insurance against potential adverse environmental consequences associated with global climate change; and
- Improves the U.S. economy and increases the number of high-skill jobs for Americans by increasing international technology exports.

STRATEGIC PLAN



PLANNING FOR
SUSTAINABLE DEVELOPMENT

INTRODUCTION

Energy is the fuel that drives the Nation's economy and allows the United States to enjoy a superior standard of living.

As the United States stands on the threshold of a new millennium, it faces both tremendous opportunities for continued economic growth and the challenges of providing the clean, affordable energy necessary to sustain that growth without harming the environment.

For the foreseeable future, the energy needed to sustain economic growth will continue to come largely from fossil fuels. In supplying this energy need, however, the Nation must address growing global and regional environmental concerns and energy prices. Maintaining low-cost electricity in the face of growing demand and increasing environmental pressure requires new technologies. These technologies must allow the Nation to use its indigenous resources more wisely, cleanly, and efficiently. These resources include inherently clean natural gas and the Nation's most abundant and lowest cost resource, coal; while expanding the resources base to include "opportunity" fuels and feedstocks, such as biomass and wastes for use in co-firing.

The role of the federal government will be to provide support in developing advanced fossil energy technologies that ensure continued environmental and economic benefits. The Coal & Power Systems (C&PS) programs, which include Vision 21, Central Power Systems, Distributed Generation, Fuels, Carbon Sequestration, and Advanced

Research, were developed to align with and directly support the goals and objectives of the Comprehensive National Energy Strategy. This strategy was developed by the U.S. Department of Energy (DOE) in concert with other federal agencies and major stakeholders. The C&PS programs address key domestic and global environmental concerns, while being responsive to the DOE strategies to promote secure, efficient, and comprehensive energy systems, and enhance scientific understanding.

More than 15 years ago it was recognized that, given the need to respond to increased environmental objectives, new technologies would be necessary if coal was to continue as a viable source of secure energy. In 1985, the U.S. Clean Coal Technology (CCT) Demonstration Program was initiated with the objective to demonstrate a new generation of advanced coal utilization technologies.

The projects conducted under the CCT program have generated, and are continuing to generate, an enormous amount of valuable technical, environmental, and economic performance data on commercial-scale technologies. This investment in technology forms a solid foundation for addressing growing global and regional environmental concerns while continuing to provide low-cost energy. The C&PS program builds upon the successes of the CCT program and, in turn, provides a solid foundation for a new total energy concept called Vision 21.

The Vision 21 concept allows the Nation to realize the full potential of its abundant fossil fuel resources

by maintaining and strengthening the integral role of fossil fuels in the Nation's energy mix. Vision 21 is the long-range strategic vision of where coal and power systems will be in 2015 and beyond. Vision 21 is a new approach to clean, efficient energy production from fossil fuels in the 21st century. It will integrate advanced concepts for high-efficiency power generation and pollution control into a new class of fuel-flexible facilities capable of producing electric power, process heat, and high-value fuels and chemicals with virtually no emission of air pollutants. In doing so, Vision 21 can create the opportunity for long-term, clean, and efficient use of fossil fuel resources to meet growing national energy demand while stabilizing greenhouse gas emissions.

The following *Strategic Plan* outlines how C&PS intends to continue the legacy of the CCT program successes in pursuit of Vision 21. Goals, objectives, and strategies for the C&PS program are provided. Additionally, program management and portfolio analyses are addressed and reflect stakeholder feedback on C&PS research and development (R&D) efforts. The chapters that follow the *Strategic Plan* are the C&PS individual *Program Plans*, which contain more detailed descriptions of individual program activities and milestones.

COAL & POWER SYSTEMS PROGRAM

Mission

The mission of the Coal and Power Systems R&D program is to foster the development and deployment of advanced, clean, affordable fossil-based power and alternative fuels systems. Fuel-flexible power generation and conversion technologies will be developed to efficiently utilize coal, natural gas, opportunity fuels, and other feedstocks. The long-term focus is on the effective utilization of coal — the Nation’s most abundant energy resource — and natural gas. Government-sponsored research in partnership with industry, laboratories, and academic organizations will promote U.S. global leadership in coal fuels and power system technologies, creating U.S. jobs and contributing to a stronger economy.

Vision

Economically viable technologies will be available for clean production of low-cost electricity, and low-cost fuels from coal will raise global living standards for future generations.

As the leader in developing ultra-high-efficiency energy technologies with near-zero emissions, the United States will benefit from plentiful, low-cost electricity supplies and alternative fuel sources. The United States will produce a significant share of the products and services being used in the fast-growing world energy market, while enhancing its trade balance, and creating highly skilled, well-paying jobs.

ENERGY OUTLOOK

Fossil fuels are, and will continue to be, the primary source for power generation and fuel systems.

The DOE Energy Information Administration's (EIA) *Annual Energy Outlook 2000* projects that U.S. reliance on fossil fuels will rise from the present level of 85 percent to 90 percent by 2020 under current trends of price and usage. The EIA also projects that the use of fossil fuels to produce electricity will rise from the current 67 percent to 78 percent by 2020. Approximately 300 gigawatts of new electricity generating capacity is expected to be required by 2020. Of this, 50 percent will be gas-fired peaking units, and 40 percent will be gas combined-cycle. In addition to the EIA projections, the existing fleet of coal-based power plants is aging and much of it will be nearing retirement by 2020.

By 2020, U.S. petroleum imports, already representing over 50 percent of consumption, are projected to rise to 65 percent and increase the U.S. negative balance of payments. Total worldwide petroleum demand will double, creating a very competitive market for increasing amounts of imports from sources that may be politically unstable. The challenge is to provide the technical basis for a clean fuels industry capable of producing transportation fuels from coal and other carbonaceous, non-petroleum, domestic resources.

Of greater interest though, is energy consumption in the developing world (Asia, Africa, the Middle East, and Central and South America),

which is expected to more than double by 2020, with the highest growth rates expected in developing Asia and Central and South America. In fact, energy use in the developing world is projected to surpass that of the industrialized world by 5 percent in 2020 — some 12 quadrillion Btu — whereas in 1997 energy consumption in the developing countries was about 40 percent lower than that in industrialized countries.

Opportunities abound for enhanced economic prosperity, with the challenge lying in providing the energy to sustain both economic and population growth while addressing global and regional environmental concerns, particularly carbon emissions. Fossil energy is the only means of fueling the tremendous

worldwide economic growth envisioned over the next two decades. As much of the world makes the transformation to industrialization, electricity represents an increasingly large part of the energy requirement. The worldwide demand for low-carbon-emitting technologies and cost-effective, safe carbon capture and disposal techniques will be enormous. The C&PS program is responding to these realities by introducing, and continuing to improve upon, a new generation of more efficient, affordable, and environmentally friendlier fossil fuel systems. With much of the developing world planning to use fossil fuels, particularly coal, the deployment of high-efficiency fossil systems is key in the approach to addressing global climate change concerns.



PLANNING ASSUMPTIONS

Planning assumptions, used to develop the strategy for the C&PS program research and development needs through the planning period 2000 to 2020, are summarized below.

Environmental Challenges with Fossil Fuels. Fossil fuel combustion, especially coal combustion, is likely to be subjected to increasingly stringent emissions limits. Pressure to reduce emissions of SO₂ and NO_x will come from several directions: the reduction in acid deposition; reductions in smog in major metropolitan areas; lowering ambient levels of fine particulate matter; and elimination of visibility impairment in 156 national parks and wilderness areas in the United States. Pressure to reduce emissions of mercury from coal-fired power plants is also likely. The emissions control requirements for the Organization for Economic Cooperation & Development countries are also expected to be more stringent.

Competition Among Fuels. In most instances, coal cannot compete economically or environmentally with natural gas as the fuel for new power plants in the U.S. under current price scenarios. This situation is likely to persist for the next few decades, primarily because advances in gas turbine technology (and other conversion technologies) will continue to favor gas, and deregulation of the generation portion of the electric system will likely make gas the preferred fuel for new sources and for repowering.

However, the cost of coal is likely to remain low and the cost of gas

may rise as demand for it increases. Also, coal power is projected to grow rapidly in some parts of the world, most notably in China and India, where indigenous non-coal fuels are scarce and expensive.

Global Energy Concerns. World carbon emissions are expected to reach 8.0 billion metric tons by 2010 and 9.8 billion metric tons by 2020. In developing countries, carbon emissions are projected to grow more quickly. Emissions from the developing countries were about 60 percent of those from the industrialized countries in 1990, but by 2010, developing countries will surpass industrialized countries with respect to carbon emissions. The sharp increase is expected to be caused both by rapid economic growth, accompanied by growing demand for energy, and by continued heavy reliance on coal, especially in developing Asia.

International concerns over the future impacts of greenhouse gases produced by anthropogenic activities have led to an international consensus that cost-effective measures to reduce the growth of greenhouse gas emissions are prudent. Some nations remain concerned about the uncertainties of potential longer-term impacts (2100 and beyond). Domestic and international sources are also pressing for large absolute reductions in the near term. Technologies being developed to allow the use of indigenous resources must address these concerns.

Electric Utility Restructuring. The uncertainties associated with utility restructuring have exacerbated concerns over the reliability

and quality of electric power delivery. Reserve margins are shrinking as energy suppliers increase capacity factors on existing plants, rather than install new capacity to meet growing demand. This increases the probability of forced outages and reduced power quality. Utility restructuring also shifts the burden of financing new energy ventures from the consumer to the power supplier. This favors less capital-intensive projects, and projects that can be permitted and constructed in the shortest possible time, including smaller, modular power systems for the distributed generation and combined heat and power markets.

Programmatic Challenges. Federal funding for fossil energy research will remain relatively constant. However, supporting the R&D necessary to achieve widespread deployment of new technologies with reduced investments from industry requires an expansion of public/private partnerships, a focusing of R&D efforts, and introduction of new approaches to mitigate development costs.



DRIVERS

- One-half of the world increase in energy use by 2020 will occur in Asia (primarily China and India). Energy use in developing countries that rely primarily on fossil fuels will surpass that of the industrial world by six percent.
- The global market for electric power systems is estimated to be as high as \$290 billion by 2030; as such, it will represent the most significant market for U.S.-produced power systems.
- By 2020, the electric utility industry will have been totally restructured; its markets will demand economic competitiveness and environmental performance.
- By 2020, nearly 70 percent of the petroleum used in the U.S. will be imported; as is the case today, most of this oil may still come from politically unstable countries.
- The regional and global environmental challenges of ozone, PM_{2.5}, global climate change, CO₂, and hazardous air pollutants need cost-effective solutions if fossil fuels are to remain an economically viable energy source.
- Over time, the energy sector will be transformed, and in some instances, converge with other industry sectors to create a different energy landscape and interdependent industrial infrastructures in which fossil fuels will continue to dominate. Flexible, advanced technologies will be needed to address the needs of the new industries.
- Escalating demands for electricity coupled with an outdated power delivery grid pose a serious threat to the national economy.

GOALS

- Eliminate environmental issues as barriers to fossil fuel production and use, while maintaining the availability and affordability of fossil fuels.
- Ensure the availability of secure, affordable liquid fuels and reliable electricity.
- Provide scientific and technological information and analysis to assist policymakers and regulators in their decision making.
- Focus on public benefits-driven investment in high-risk, high-return technology that private companies alone cannot undertake.
- Create viable fossil energy technology options to address global climate change.
- Improve electricity grid reliability from a power generation standpoint.

OBJECTIVES

- Develop near-term, advanced, coal-based technologies to improve power generating capacity and grid reliability.
- By 2006, provide the capability to produce ultra-clean transportation fuels that will help vehicles meet U.S. EPA Tier II emissions standards.
- By 2015, provide the Nation with a sustainable supply of ultra-clean fuels produced from diversified feedstocks that meet all environmental requirements, are produced at economic costs, and meet performance requirements of advanced transportation systems.
- Between 2003 and 2008, provide technologies to improve the environmental performances of existing coal-fired power plants and reduce compliance costs by 25–75 percent, compared to existing technologies and strategies.
- By 2007, deploy commercially-scale, fully integrated coproduction plants that demonstrate the benefits of producing fuels, electricity, and other products from gasification technologies.
- By 2008, develop and deploy in initial markets key advanced power technologies including fuel cells, turbines, and enabling technology such as gas separation membranes.
- By 2015, make commercially available a new generation of advanced power, fossil fuel-based systems (e.g., Vision 21 Systems) that can use multiple feedstocks, coproduce multiple products, achieve near-zero emissions of traditional pollutants, nearly double the average fleet efficiency of today's power plants, and be compatible with carbon sequestration systems.
- By 2015, develop low-cost carbon sequestration technologies that can be integrated with advanced fossil fuel systems (e.g., Vision 21 systems) that will be commercially available in the same time frame.
- Remove barriers for U.S. companies in markets for clean, efficient fossil-fuel technologies in developing countries.

STRATEGIES

- Complete multiple demonstrations under the Power Plant Improvement Initiative.
- Produce ultra-clean fuels for testing, and develop advanced processes for production from feedstocks including crude oil, coal, natural gas, and biomass.
- Develop control technologies that will help ensure the ability to meet, at reasonable cost, planned or anticipated future regulation governing conversion of fossil fuels to electricity, clean fuels, and related products.
- Deploy one or more early entrance coproduction plants that demonstrate the feasibility of producing fuels, electricity and other coproducts from coal and other carbonaceous materials.
- Advance three-phase slurry reactor technology to cost-effectively produce premium fuels and other products.
- Complete the development of a suite of power systems, including pressurized fluidized-bed combustion, integrated gasification combined-cycle, indirect fired cycles, turbines, and combined cycles for application in central power generation.
- Advance the development of small generating units, focusing on fuel cell and fuel cell/turbine hybrids for distributed generation applications under 30 MWe.
- Integrate advanced power modules with other advanced fossil systems to achieve Vision 21 fleet of plants that can maximize economic, energy, and environmental efficiency.
- Develop low-cost technology options for CO₂ management that would include capture, separation, use, and disposal.
- Provide/exchange information relating to the development and deployment of clean and efficient energy systems.

PROGRAM EVALUATION AND ANALYSES

Changes in energy markets and Administration policies will affect R&D initiatives being pursued under the guidance of C&PS. As such, management of the C&PS Strategic Plan and supporting Program Plans is achieved through a number of different “checks and balances” on the current and projected R&D within C&PS.

C&PS conducts periodic reviews of its *Strategic Plan* to ensure that it remains dynamic and flexible to accommodate changing market behaviors, policy mandates, public perceptions, and other social science aspects of technology adoption. Development of solutions to knowledge and engineering gaps are achieved through a number of program evaluations as described below.

Portfolio Analysis

A number of studies have analyzed or reviewed all or parts of the C&PS portfolio of R&D. This section reports on the most relevant of those studies, including key conclusions and recommendations for future C&PS direction.

Federal Energy Research and Development for the Challenges of the Twenty-First Century (PCAST). This report, issued by the President’s Committee of Advisors on Science and Technology in 1997, was a review of the current national energy R&D portfolio. The report had many findings and recommendations. Specific to C&PS, PCAST recommended strengthening the emphasis on energy efficiency and

advanced coal-power programs, carbon capture and sequestration, fuel cell technology, and the marketing of U.S. energy technology internationally.

Vision 21: Fossil Fuel Options for the Future. In response to a request from the Deputy Assistant Secretary for C&PS, the National Research Council formed a committee to review the goals of the Vision 21 concept and to recommend systems and approaches for moving from concept to reality. Some of the committee’s key findings from the 2000 study include:

- Vision 21 should eventually move toward becoming a separate program within FE and the primary focus of the C&PS program. Currently, Vision 21 has components of R&D within each of the C&PS programs, but is not yet a stand-alone program;
- Vision 21 should be linked to other federal agencies and programs in and beyond DOE;
- DOE should work with industry to develop a commercial deployment program to facilitate the early commercialization of significantly improved technologies;
- Computer-based modeling and simulation are critical to identifying and designing Vision 21 plant configurations;
- High priority should be placed on the development of fuel cell technology for centralized power systems, high-temperature coatings and materials, oxygen separation technology, and carbon capture and sequestration technologies.

Powerful Partnerships: The Federal Role in International Cooperation on Energy Innovation (PCAST). This report was issued by PCAST in June 1999 to review the U.S. stake in international cooperation on energy innovation. A key conclusion is that world energy demand and use are tightly linked to the U.S. economic, environmental, and security interests. To capitalize on this realization, recommendations include an increased focus on international technology transfer of innovations for energy supply technologies such as fossil-fuel decarbonization and CO₂ sequestration, as well as energy end-use technologies such as combined heat and power applications.

Carbon Sequestration: State of the Science. This joint study between the Office of Science and FE was commissioned to identify key areas for R&D that could lead to an understanding of the potential for future use of carbon sequestration as a major tool for managing carbon emissions. Under the leadership of DOE, researchers from universities, industry, other government agencies, and DOE national laboratories were brought together to develop the technical basis for conceiving a science and technology roadmap. This effort formed the basis for the Carbon Sequestration program within C&PS.

Roadmapping

Technology roadmaps seek to identify the scientific and technological developments needed to achieve a specific technology goal (e.g., efficiency gains and/or environmental performance). The use of roadmaps by C&PS is designed to show how specific R&D activities can create the integrated technical capabilities needed to achieve strategic objectives.

C&PS directs its R&D to align with achieving the public benefits of energy research in concert with industry needs. Specifically, C&PS constructs its individual program technology roadmaps to complement industry's near- and long-term expectations for advanced energy systems research. Through review of the Electric Power Research Institute's Electricity Technology Roadmap and the Coal Utilization Research Council's technology roadmaps, C&PS is able to parallel its R&D to complement industry's needs and developments.

C&PS Portfolio Response

The contents of this *Strategic Plan* have been defined and are continually re-focused through an ongoing process of portfolio planning and analysis, and technology roadmapping activities. The following highlights some of the recent C&PS initiatives in response to C&PS program evaluations. They combine the scientific strengths of the C&PS program, the national laboratories, and industry to provide a strong base for achieving the efficiency and environmental goals set forth in this plan.

Ultra-Clean Transportation Fuels Initiative (UCTFI). The UCTFI, jointly led by DOE's Office of Fos-

sil Energy and the Office of Energy Efficiency and Renewable Energy, in conjunction with industry, was created to develop advanced technologies for the fuels-sensitive elements of engines and emissions control systems, and to improve the quality of fuels used in transportation by supporting the development and deployment of ultra-clean fuels. The Fuels program within C&PS supports this initiative by developing coal-derived fuels to provide stable, clean, and affordable energy supplies for transportation.

Solid State Energy Conversion Alliance (SECA). SECA is a national-level concept to achieve mass production of low-cost, technically superior ceramic fuel cell technology. The National Energy Technology Laboratory (NETL), in partnership with Pacific Northwest National Laboratory, is coordinating industry, university, and national laboratory activities to reach the ambitious goal of providing solid state fuel cell technology at a cost of less than \$400/kW for stationary applications, and less than \$200/kW for transportation applications. This

breakthrough will allow widespread penetration into stationary distributed generation power markets and ultimately, into central station power markets in Vision 21 plants.

Early Entrance Coproduction Plant (EECP). An EECP is a gasification-based coproduction plant that is capable of processing multiple feedstocks (coal, biomass, municipal waste, etc.) and producing some combination of electricity, heat, transportation fuels, or chemicals. The concept of producing a varied slate of products — the exact combination of which could be tailored for specific markets — is a departure from traditional energy facilities.

NETL recently selected three companies — Waste Management and Processors, Inc.; Dynegy Power Corporation; and Texaco Natural Gas, Inc. — to lead teams that will design an EECP. The research completed by the three companies feeds directly into C&PS technology programs and provides important insights into the ultimate Vision 21 facility.

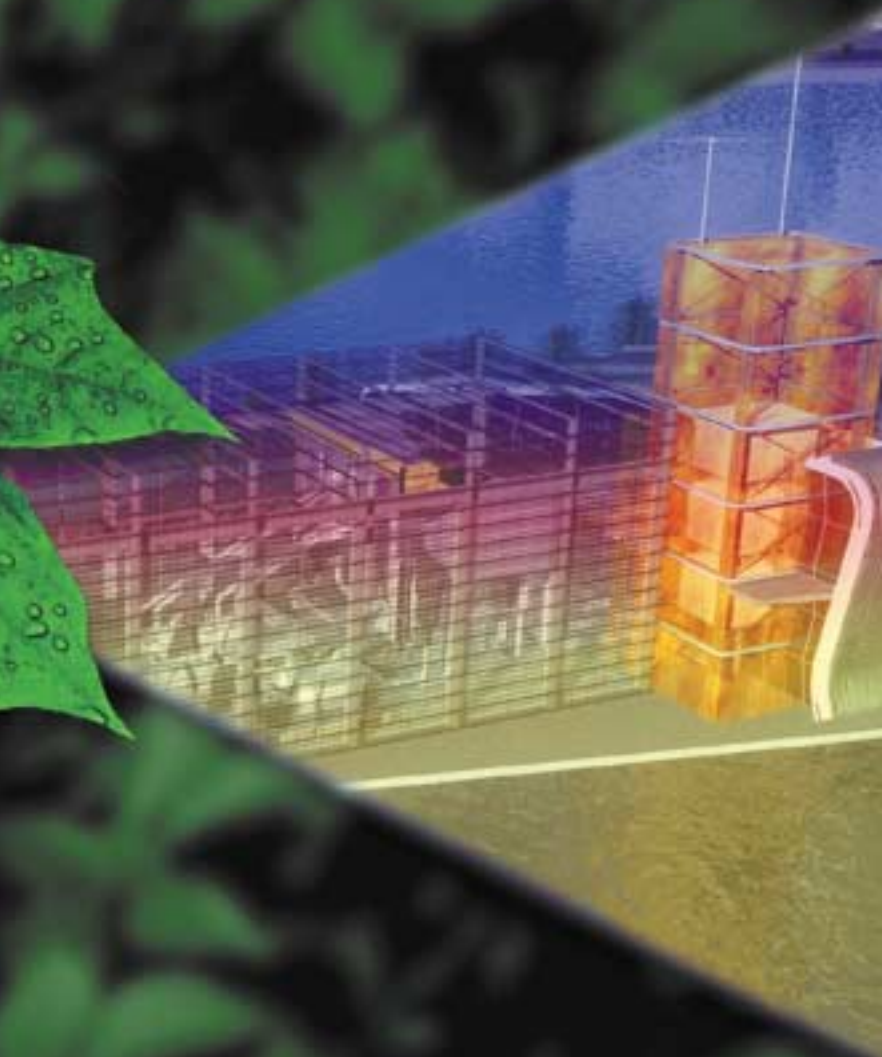
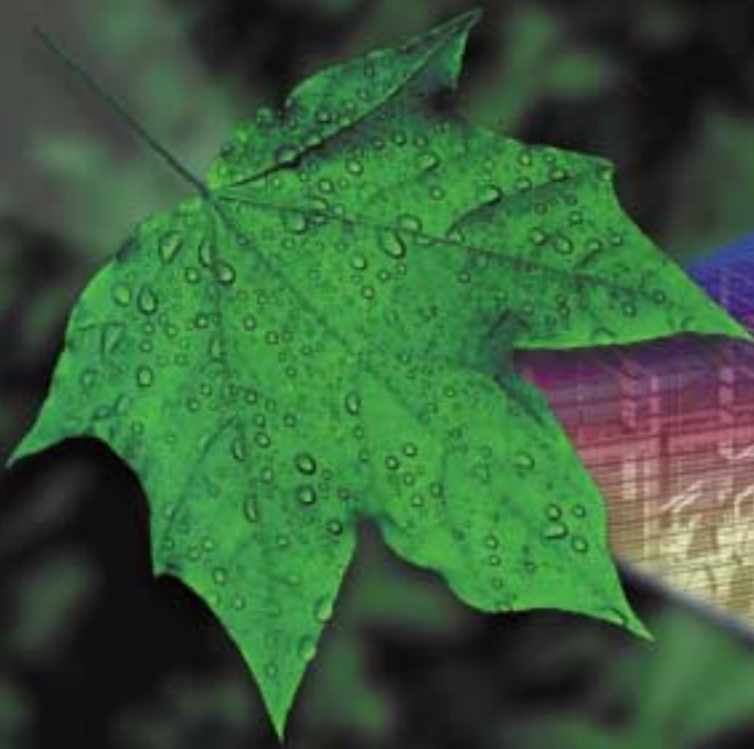




COAL & POWER SYSTEMS

TECHNOLOGIES FOR THE NEW MILLENNIUM

VISION 21



FOSSIL FUEL OPTIONS
FOR THE FUTURE

INTRODUCTION

Program Areas

Systems Analysis
 Enabling Technologies
 Supporting Technologies
 Systems Integration
 Vision 21 Plant Designs

The Department of Energy's (DOE) Office of Fossil Energy (FE), through the Coal & Power Systems (C&PS) program, has begun a new approach for developing 21st century energy plants that would have virtually no environmental impact.

A new approach is timely because of the unprecedented changes in the electric power industry — electric utility deregulation and restructuring, the availability of relatively low-cost natural gas, and environmental issues surrounding power production, including global climate change.

The new approach is called Vision 21. Vision 21 is a government/industry/

academia cost-shared partnership to develop the technology basis for integrated energy plants that will, early in the 21st century, result in the deployment of ultra-clean plants that produce electricity and “opportunity” products, including clean transportation fuels, high-value chemicals, synthesis gas, and hydrogen.

The overall objective of the Vision 21 program is to effectively eliminate, at competitive costs, environmental concerns associated with the use of fossil fuels for producing electricity and transportation fuels. Vision 21 is based on three premises: (1) that the Nation will need to rely on fossil fuels for a major share of its energy needs well into the 21st century; (2) that it makes good sense to rely on a diverse mix of energy resources, including coal, gas, biomass and other renewables and nuclear, rather than on a limited subset of these resources; and (3) that reasearch and development (R&D) directed at resolving energy and environmental issues can find affordable ways to make energy conversion meet ever stricter environmental standards.

Today, a typical power plant uses one type of fuel, usually coal, and produces only one thing — electricity. A Vision 21 plant would be fuel-flexible, meaning it could use one or more of several different feedstocks including, coal natural gas, or petroleum coke. Any of these could be mixed with biomass. In turn, the plant could produce one or more high-value products such as electric power, clean fuels, chemicals, or hydrogen. Secondary products such as heat/steam for industrial use could also be produced. A Vision 21 plant will be capable of a variety of configurations to meet differing market needs, including both distributed and central power generation.

Vision 21 builds on the Clean Coal Technology (CCT) demonstration program experience and a portfolio of advanced technologies already being developed within the C&PS program — including integrated gasification combined-cycle, pressurized-fluidized bed combustion, advanced gas turbines, fuel cells, and fuels synthesis — and adds other critical technologies and system integration techniques.

Endorsed by the President's Committee of Advisors on Science and Technology (PCAST) in 1997 and further supported by the National Research Council in 2000, C&PS' Vision 21 program serves as a “roadmap” for future electric power and fuels R&D. Vision 21 technologies, once achieved, will offer the United States, and the world, a new method of coal-based power generation that would have significant advantages over current methods.



An artist's rendering of a Vision 21 plant.

DRIVERS

The United States currently has a diverse and relatively low-cost supply of energy, primarily based on fossil fuels, for the production of electricity, process heat, transportation fuels, and chemical feedstocks.

Relatively low-cost fossil fuel energy supplies are a critical component of the current economic prosperity and favorable trade position of the United States globally and are likely to be so for the foreseeable future. As recent PCAST studies (1997 and 1999) have shown, preserving options for using diverse energy sources is an essential element of a national energy R&D policy.

Electric Power Restructuring.

One of the most significant driving forces dictating the future state of power production in the United States is electric power restructuring. As the power industry deregulates, utilities that were heretofore protected against competition and guaranteed returns on their investments are now being forced to compete for market share and profits. As a result, deregulation is changing the way the industry operates and invests in new facilities and technology. In a market-driven environment, power plant owners must be concerned about profitability and ability to finance new investments. This may cause owners to avoid technical risk and favor low capital cost and short-term alternatives, especially when such alternatives are coupled with a fuel supply contract for a period long enough for the investment to be recovered.



Competition Among Fuels. Today's relatively low cost of natural gas is causing power producers to favor low capital cost turbines over relatively high-cost coal-fired boilers for new capacity. The Energy Information Administration (EIA) projects that in the U.S. about 300 gigawatts (GW) of new generating capacity will be needed in the next 20 years to meet growing demand and to replace retiring units. The EIA estimates that 90 percent (270 GW) of this new capacity will be fueled by natural gas, or both natural gas and oil. Coal-based capacity will account for seven percent (21 GW) of the new capacity, and 82 percent of the 21 GW will come online between 2010 and 2020. Renewables will make up the balance of new capacity.

Competition between coal and natural gas after 2015 will be affected by many factors related to the resources themselves. Coal and natural gas are both readily available. World coal reserves are estimated to be adequate to accommodate 1996 production levels for more than 200 years. In the United States, fossil energy resources are dominated by

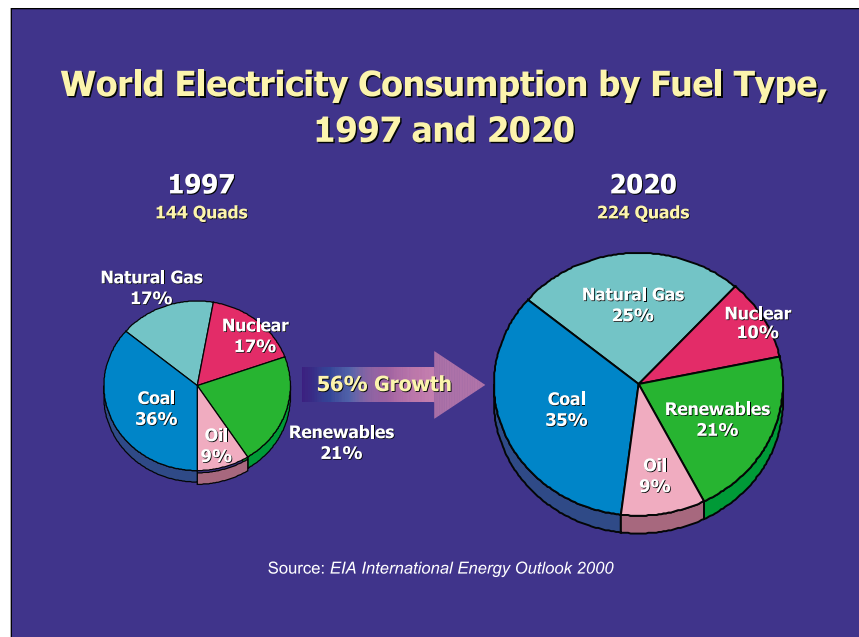
coal (85 percent), followed by gas (10 percent) and oil (5 percent).

Natural gas production is not as widespread. In the United States, coal is exported, but natural gas is imported. By 2020, imported natural gas is projected to account for approximately 15.5 percent of total gas consumption. Six areas contain 71 percent of the proven dry natural gas reserves in the United States. Approximately half of the remaining untapped conventional natural gas resource base is on federally owned land.

In most instances, natural gas must be transported by pipeline. By contrast, coal can be transported by rail, water, or truck, and many users have access to multiple modes of transportation. A major uncertainty about the rate of increase in gas-fired power generation is the difficulty of routing natural gas pipelines to power generation sites. Difficulties in obtaining regulatory approvals for installing the new pipelines to meet future commitments may limit the rate at which baseload capacity can be partially shifted from coal to natural gas.

Global Energy Demands. Globally, energy consumption in the developing world (Asia, Africa, the Middle East, and Central and South America) is expected to more than double in the next twenty years, with the highest growth rates expected in developing Asia and Central and South America. The use of coal is projected to dominate the generation of electricity, especially in China, where in 1995, coal accounted for 88 percent of power generation. By 2020, China's demand is projected to represent 36 percent of the total worldwide demand for coal.

Similar growth is expected in energy consumption for transportation. The worldwide demand for transportation fuels and chemical feedstocks is expected to increase by 66 percent between 1995 and 2020; in the developing world, the demand for oil is projected to increase by 77 percent. The demand for refined petroleum products in the United States is expected to increase by 33 percent between 1998 and 2020. The greatest share of the increase is expected to be in transportation fuels, where gasoline, jet fuel, and distillate are projected to increase by



38 percent, 86 percent, and 19 percent respectively. The demand for chemical feedstocks and other nonfuel petroleum products is projected to increase by 24 percent.

Environmental Concerns. The Clean Air Act of 1970 and subsequent amendments have brought about major reductions in emissions of the acid gases, i.e. sulfur dioxide (SO₂) and nitrogen oxides (NO_x), and particulates for new coal-fired plants. Existing plants are increasingly being required to cut emis-

sions. Moreover, renewed concern about fine particulate and its precursors (nitrogen and sulfur oxides), trace element emissions (especially mercury), and ozone (and its nitrogen oxides precursor) have created new pressures for cleaner plants. These pressures are unlikely to ease in the future; rather, each new generation of power plants will be expected to be cleaner than the last.

Perhaps the biggest change in energy production and consumption will be driven by concern over global climate change. Emissions of greenhouse gases, especially carbon dioxide (CO₂) from fossil fuel use, may need to be reduced in the future. Although a portion of this reduction may be achieved through emissions trading and credits for investing in emissions reduction projects in developing countries, it is likely that substantial reductions in carbon emissions will be necessary. Increasing the efficiency of power generation is a step in the right direction, but a technological solution that would provide sufficient reductions in carbon emissions has yet to be identified.



Conclusion. The implications of these drivers for the future economic competitiveness and prosperity of the United States cannot be underestimated. The Nation's economic future depends on a supply of affordable electricity to run factories and heat and light offices and homes, and on clean fuels for transportation. Predictions have been made about the devastating effects that limits on carbon emissions will have on the economy. However, predictions often underestimate the impacts of technological innovation. Indeed technology innovation is the best, and perhaps the only way, to address the coming challenges to the Nation's electric power and fuel supply infrastructure.

The bottom line is that the United States will need to rely on fossil fu-

els for the major share of its electricity and transportation fuels well into the 21st century. The Nation cannot endanger its economic future by depending on any single fossil energy source. Although the current situation favors natural gas, for the long term the wisest policy is to depend on a balanced mixture of energy sources, including gas, coal, oil, and renewables. Without new and radically better technology, the costs of energy will increase substantially and the predictions of "devastation" may turn out to be correct. On the other hand, by taking the lead on developing the needed technology, the Nation will not only meet the energy and environmental challenges it faces, but also make the economy stronger.



ACTIVITIES

The focus of the Vision 21 program will be on flexible components and subsystems to enable modular designs for plants that can use multiple feedstocks or produce multiple products in the 2010–2015 time frame.

To establish a blueprint, FE plans to focus Vision 21 on several elements that will be common to all of the facilities under consideration:

- **Systems analysis** will be used to develop various system configurations that satisfy the program objectives, define the performance targets for individual subsystems, and identify supporting technology needs.
- **Enabling technologies**, such as advanced, low-cost hydrogen and oxygen separation and advanced gas cleaning, form the building blocks of Vision 21 plants.

- **Supporting technologies**, such as higher-strength, more durable materials, improved catalysts, environmental control technologies, sensors and controls, and virtual demonstrations, are cross-cutting technologies that are necessary for multiple subsystems and components and are important for other applications.

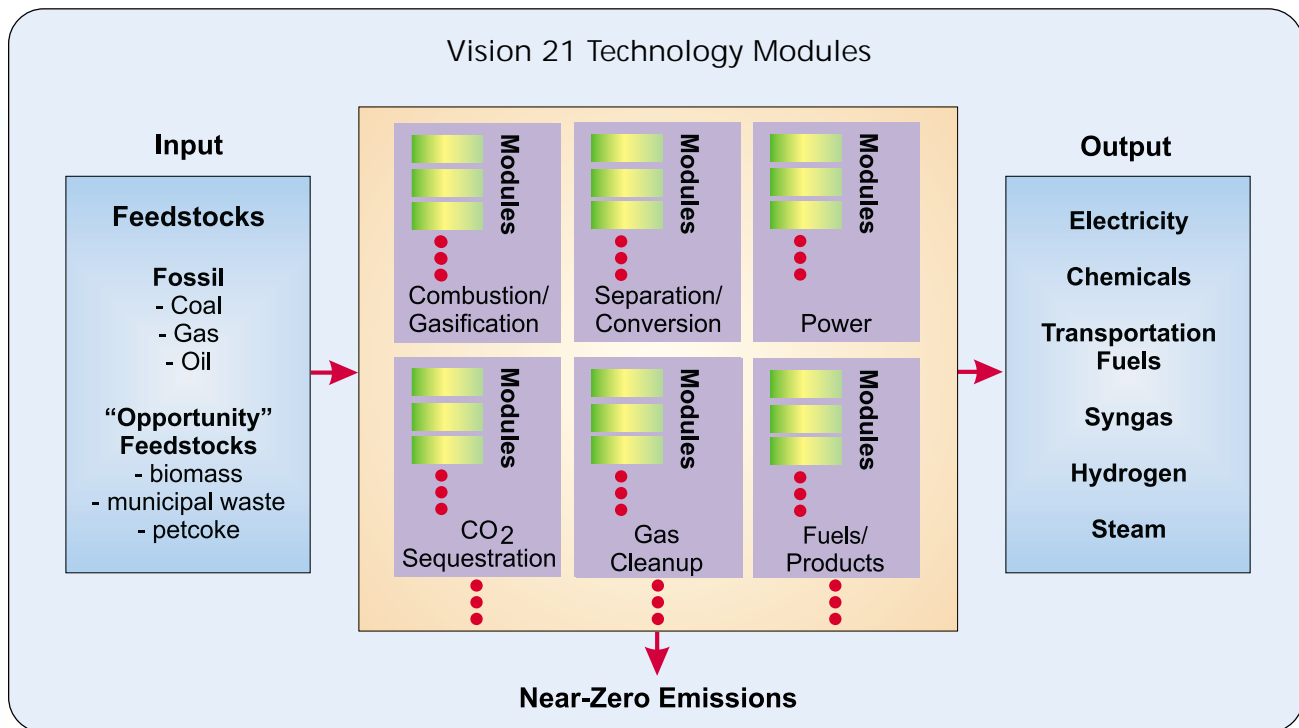
- **Systems integration** in a Vision 21 plant configuration will use “smart” systems integration techniques to combine high-performance subsystems into very clean and efficient low-cost plants.

- **Plant designs** that would serve as the basis for a new fleet of commercial-scale Vision 21 plants.

Modeling, analysis, and experimental work of Vision 21 technologies will range from laboratory-, bench- and pilot-scale, up to and including scales needed to obtain data for

demonstrating feasibility for prototype and commercial-scale plants. However, construction of Vision 21 prototype and commercial-scale plants is not part of the Vision 21 program. These activities, the exact timing of which will depend on prevailing economic conditions and market forces, will be left to private industry. The role of the C&PS program will be to facilitate the transfer of the Vision 21 database to industry.

A more detailed discussion of the program activities and milestones for each program area within Vision 21 can be found in the Vision 21 Program Plan located on the Internet at http://www.fe.doe.gov/coal_power/vision21/v21plan.pdf.



ROADMAP

Process Definition

Market Analysis

Process Evaluation

Economic Analysis

Vision 21 Technology Portfolio

	1999	2015
Enabling Technologies		Low Cost Gas Separation/Purification High-Temperature Heat Exchangers Fuel-Flexible Gasification High-Performance Combustion Fuel Cells Fuel-Flexible Turbines Advanced Fuels & Chemicals Development
Supporting Technologies		High-Temperature Materials Environmental Control Technology Controls and Sensors Manufacturing & Modularization Computational Modeling/Virtual Simulation
Systems Analysis/Integration		Technical/Economic/Market Analyses Systems Engineering Industrial Ecology Dynamic Response/Control

Designs for Components & Subsystems

Designs for Prototype Plants

Designs for Commercial Plants

Virtual Demonstration Capabilities

Drivers

- Continued global economic growth will lead to greatly increased consumption of electricity and fuels.
- The world's total primary energy supply will continue to be dominated by fossil fuels. In 2020, fossil fuels are projected to account for 88 percent of the total primary energy supply.
- Utility deregulation is changing the way the industry operates and invests in new facilities and technology, causing power plant owners in the near term to avoid technical risk and favor low capital cost investments for continued power plant viability and profitability.
- The outlook for future energy supplies and conversion technologies indicates a growing reliance on affordable natural gas as the economic fuel of choice for new electric power generation.
- Restricted availability of gas supplies in many regions and extensive replacements of both coal and nuclear power plants could create many new market opportunities for coal.
- Current technology for producing fuels and chemicals from coal is not only less economical than using natural gas, but also produces at least twice as much carbon dioxide per unit of product as competing technologies based on natural gas.
- Environmental pressures will lead to a global regime of carbon management and widespread, stringent local regulations of air emissions.
- The worldwide demand for low-carbon-emitting and high efficiency technologies and cost-effective carbon capture and disposal techniques is projected to be enormous.
- Technology innovation is the best, and perhaps the only way, to address the coming challenges to the Nation's electric power and fuel supply infrastructure.

Objectives

- Remove environmental barriers to fossil fuel use including smog- and acid-rain-forming pollutants, and particulate and hazardous air pollutants.
- Eliminate solid waste from electricity production by converting it to useful products.
- Reduce carbon dioxide emissions through thermal efficiency improvements and sequestration.
- Keep energy costs affordable.
- Produce useful coproducts from coal including environmentally superior liquid transportation fuels that are cost-competitive with equivalent petroleum products.
- Continue U.S. leadership role in clean energy technology.
- Create partnerships with industry, universities, public and private R&D laboratories, and federal and state agencies to develop cost-effective, marketable Vision 21 components.

Strategies¹

- Through competitive solicitations, promote public and private sector R&D for the purpose of supporting the continued availability of cost-competitive options for a diverse mix of fossil fuels.
- Through systems analysis, develop Vision 21 system configurations that satisfy program objectives, define performance targets for individual subsystems, and identify supporting technology needs.
- Oversee development of existing enabling technologies in other C&PS programs to ensure technology objectives correspond with Vision 21 objectives and timeline.
- Take the lead in promoting revolutionary R&D in emerging enabling technologies, such as advanced gas separation.
- Guide the Fuels program R&D in pursuing breakthrough technologies for reducing the cost of producing synthesis gas from coal and other high-carbon content fuels.
- Direct R&D in supporting technologies that are necessary for the enabling technologies of Vision 21 to function in commercial applications.
- Enhance CO₂ capture in power systems by promoting oxygen-based (rather than air-based) gasification and combustion that yields a more concentrated, and thus more easily captured and separated, CO₂ effluent stream.
- Develop computer-based capabilities for system simulation, integration, and analysis of Vision 21 technologies at both the component and system levels.
- Promote commercialization of Vision 21 technologies, both domestically and internationally, through continued outreach to educate potential stakeholders and the general public about the credibility, affordability, and productivity that would be provided by Vision 21 plants.

Performance Measures

- Electricity generation efficiencies of 60 percent for coal-based systems and 75 percent for natural gas-based systems. (2015)
- Combined heat and power thermal efficiencies above 85 percent. (2015)
- Achieve 75 percent fuels utilization efficiency when producing fuels such as hydrogen or liquid transportation fuels alone from coal. (2015)
- Near-zero emissions of sulfur and nitrogen oxides, particulate matter, trace elements, and organic compounds. (2015)
- Reduction in CO₂ emissions of 40–50 percent through efficiency improvements; 100 percent reduction with sequestration. (2015)
- Products of Vision 21 plants must be cost-competitive with market clearing prices when commercially deployed. (2015–2020)
- Issue three to five rounds of solicitations for public and private R&D investments in Vision 21 technologies, and promote early commercialization of components, subsystems, and systems. (2001–2015)

¹ A more detailed description of the Vision 21 program strategies including individual program area activities and milestones can be found in the *Vision 21 Program Plan* at www.fe.doe.gov/coal_power/vision21/

PROGRAM AREAS



Systems Analysis

Systems analysis is a critical part of the Vision 21 program and serves as the “brain” or guiding force for all activities. The key role of systems analysis is to develop Vision 21 system configurations that satisfy the program objectives, to define the performance targets for individual subsystems, and identify supporting technology needs.

Market analysis. These analyses will suggest what features and characteristics of Vision 21 plants are desired by potential purchasers. Adjustments of program emphasis may be made after the market study results are reviewed.

Process definition. Solicitations will be issued in 1999 and again in 2006 to tap into industry’s best ideas for defining high-efficiency, high environmental performance Vision 21 systems using natural gas, coal, and other solid fuels such as petroleum coke and municipal and industrial wastes. Contractors will describe their power systems and use computer models to estimate system performance predicated on assumed performance of one or

more subsystems or key components that are not yet commercial, but are in development.

Process evaluation. At five-year intervals, a formal assessment will be conducted of current and near-term capabilities for building Vision 21 systems.

Subsystem performance requirements. Following each process evaluation, key process components whose performance must be upgraded to permit significant improvement of overall process efficiency and/or economics will be identified.

Economic analysis. An assessment of capital and operating costs of candidate Vision 21 systems gained during the development phase will be performed after the two reviews of Vision 21 systems and subsystem/component performance requirements.

Subsystem data analysis and model development. Subsystem models will be developed from experimental data and physical principles. State-of-the-art modeling capabilities will be developed.





Enabling Technologies

Enabling technologies are those upon which the subsystems, or modules, that form the building blocks of a Vision 21 plant depend. Some enabling technologies, like gasification and advanced combustion, are already under development, and some are being demonstrated in the CCT demonstration program. Others, such as gas separation, require major improvements to existing technologies. Enabling technologies include:

Gas separation. Examples include membranes that can be used to separate oxygen (O_2) from air, hydrogen from syngas, and CO_2 from combustion products.

High-temperature heat exchangers. Examples include alloy-tube exchangers capable of heating high-temperature steam or air for use in advanced, high-efficiency cycles.

Fuel-flexible gasification. R&D is focused on thermally efficient gasification to allow the use of low-cost feedstocks, such as municipal waste, petcoke, and biomass, with coal.

Gas stream purification. Research is focused on systems capable of operating at high temperatures for removing sulfur compounds and other constituents that may corrode

or erode downstream components (e.g., turbines), or poison downstream catalysts.

High-performance combustion systems. Examples include both suspension-fired and fluidized bed, including ultra-low- NO_x combustion and combustion systems that burn fuels in O_2/CO_2 mixtures and produce exhaust streams containing only CO_2 and water.

Fuel-flexible combustion turbines and engine systems. Of particular interest are turbines and engines capable of operating on coal-derived gases or hydrogen; fuel cell/turbine-engine hybrids capable of 70-80% efficiency; advanced combustion turbines, including ceramic turbines and engines; and advanced steam turbines.

Fuel cells. Examples include high-efficiency, low-cost fuel cells; cascaded fuel cell systems capable of operating at multiple temperatures and pressures; fuel cells bottomed by fuel cells; fuel cell/turbine hybrids; new, low-cost fuel cell concepts capable of approaching \$100/kilowatt stack costs and, when incorporated into a system, 70-80% system efficiency.

Advanced fuels and chemicals development. R&D is focused on systems and catalysts for fuels and chemicals production as well as hydrogen production and storage.



Supporting Technologies

The ability of a process or power plant to perform to its design capabilities depends in large part on the engineering integrity of its components and support systems. Supporting technologies under Vision 21 are cross-cutting technologies that are necessary for multiple Vision 21 subsystems and components and also important in other, non-Vision 21 applications.

Advanced materials for high-temperature applications. Examples include boiler tubes for high-temperature steam bottoming cycles, and very high-temperature (> 2000 °F) heat exchangers for use in indirect-fired cycles and other applications, as well as functional materials needed for gas cleanup or separation.

Advanced controls and sensors. Research is focused on advanced controls and sensors for highly integrated Vision 21 plants; new algorithms that use state-of-the-art hardware to assure reliable performance, optimum plant efficiency, and low emissions.

Environmental control technologies. Technologies for low NO_x emissions, control of fine particulate matter, and management of byproducts from Vision 21 plants; improved concepts for CO_2 capture and separation.

Advanced manufacturing and modularization techniques to reduce costs and improve quality.

Advanced computational modeling. The advanced modeling initiative will assist in the design process by providing physically based simulations of Vision 21 plant components. These transient 3-D simulations will realistically account for all the physically relevant phenomenon such as fluid flow, heat transfer, chemistry, and material stress.

Systems Integration

Vision 21 plants will use “smart” systems integration techniques to combine high-performance subsystems. Systems integration is a principal part of Vision 21 and is necessary to ensure the safe, reliable, and economic operation of Vision 21 plants.

Systems engineering. System configurations that achieve Vision 21 efficiency targets will be examined in the context of identifying factors that can affect compatibility, operability, and system cost. Potential issues include linking gasifiers and combustion turbines, turbines and fuel cells, fuel cells and combustion systems, and gas cleanup devices with other subsystems.

Dynamic response and control. The dynamic response of Vision 21 subsystems to startup and shutdown, changes in load and other operating parameters will be studied, modeled, and validated.

Industrial ecology. Research will focus on recycling, or utilizing in some other manner, *all* process effluents that would otherwise be regarded as waste streams.



Vision 21 Plant Designs

This program area produces the major products of the Vision 21 program and includes the following design elements:

Designs for components and subsystems. Key components (e.g., heat exchangers, pumps, compressors) and subsystems (e.g., turbines, furnaces, gas separators) will be selected and engineering designs will be prepared. Modularity will be emphasized.

Designs for prototype plants. Prototype plants are small, first-of-a-kind, commercial plants intended to show industry that such plants can be built and operated reliably, safely, and economically. Prototype plant designs will be selected based on feedback from market analyses.

Designs for commercial plants. Several configurations for commercial-scale Vision 21 plants will be selected based on the results of market analyses. Sites will be selected and the plant feedstocks, products, configuration, and size will be based on market requirements. Systems integration techniques developed in the Systems Integration program area will be used extensively in the final plant designs.

Virtual demonstration capability. Virtual demonstration of commercial-scale Vision 21 will be conducted in 2015. These demonstrations will illustrate equipment configuration and orientation and include details of plant operation, including dynamic response to changes in load, variations in feedstock properties, changes in component or subsystem operation, and upset conditions.



An example of a Vision 21 plant design is shown above. To learn more about its components, see a video demonstration of this plant at www.fe.doe.gov/coal_power/vision21/index.shtml.

IN PARTNERSHIP WITH INDUSTRY

Industry knows best what its needs are for the short term. But for the long term, industry will need help determining which technologies should be developed and when.

The Vision 21 program addresses anticipated needs in the mid- and long-term, beyond the usual planning horizon of the energy industry.

However, the key to success of the Vision 21 program will be the down-selection of the most promising technologies from many competing technologies, and industry must be closely involved in this process. DOE is providing incentives to share the broad outlines of the Vision 21 plan for the future by creating partnerships with industry, universities, private and public R&D laboratories, and federal and state agencies to plan and implement Vision 21. The National Energy Technology Laboratory (NETL) will issue a series of competitive solicitations (the first of which was issued on September 30, 1999), create

consortia, and develop Cooperative Research and Development Agreements (CRADAs) and other agreements. Overall program guidance and coordination will be provided by a board of high-level representatives from industry, academia, and government.

Guidance on specific Vision 21 technologies will be provided by technical committees consisting of industry and academic stakeholders. The most recent of these committees met in late August 2000 at the *Vision 21 Roadmapping Workshop* sponsored by NETL. The one-and-a-half day workshop consisted of 101 industry and academic participants organized to revise the Vision 21 technology roadmap, and to make recommendations on critical program priorities.

Because no one knows exactly what future energy plants will look like, the focus of the Vision 21 program is on developing flexible components and subsystems ("modules") that are the building blocks of future Vision 21 plants rather than on

the complete plants themselves. The feedstocks, products configuration, environmental controls, and plant size will be site specific and determined by prevailing market and economic conditions.

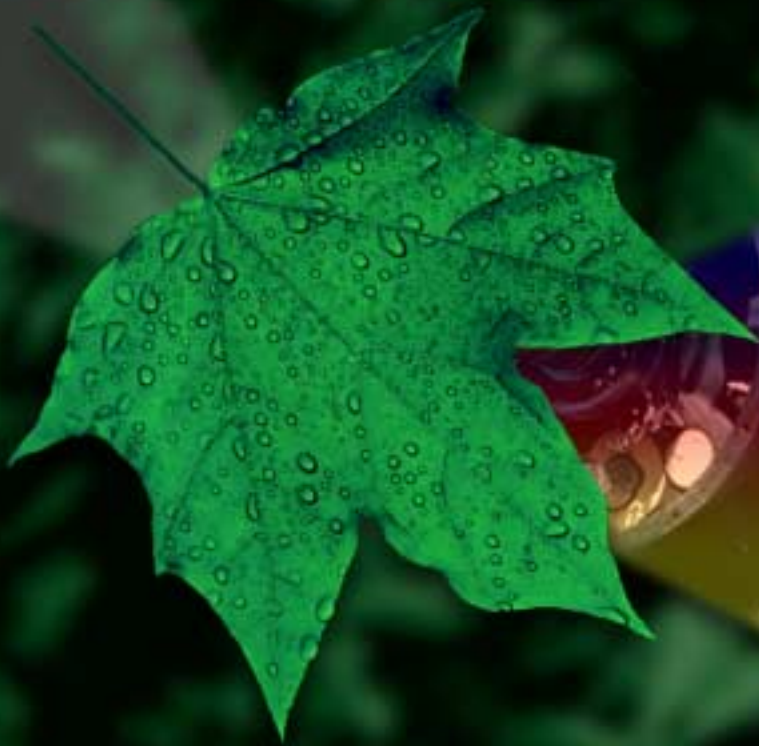
These activities, the exact timing of which will depend on prevailing economic conditions and market forces, will be left to private industry. DOE's role will be to facilitate the transfer of the Vision 21 data base to industry.

Through the Vision 21 Program, industry-led design and engineering projects will provide the critical building blocks necessary to turn vision into reality. Below is a list of the current industry and academic partners participating in developing Vision 21 technologies:

- FuelCell Energy, Inc.
- Siemens Westinghouse Power Corporation
- Eltron Research, Inc.
- Clean Energy Systems, Inc.
- National Fuel Cell Research Center
- Fluent, Inc.
- Huntington Alloys
- Foster Wheeler Development Corporation
- ITN Energy Systems
- GE Energy and Environmental Research Corp.
- Reaction Engineering International
- CFD Research Corporation
- Princeton University



CENTRAL POWER SYSTEMS



ENSURING LOW-COST ELECTRIC POWER

INTRODUCTION

Program Areas

Innovations For Existing Plants

- Advanced NO_x Control
- PM_{2.5} /Air Toxics Control
- Coal Combustion By-Products

Advanced Systems

- Low Emissions Boiler Systems
- Indirect Fired Cycles
- Pressurized Fluidized-Bed Combustion
- Gasification Technologies
- Advanced Turbine Systems
- Next Generation Turbines

The United States has a central electric power generation infrastructure unsurpassed in the world. It is an invaluable asset that affords U.S. industrial customers some of the lowest power rates in the world.

INNOVATIONS FOR EXISTING PLANTS

A major factor in realizing these low rates is the use of coal, our most abundant energy resource, for more than 50 percent of U.S. generating capacity.

Maintaining competitive energy rates and sustaining economic growth require that coal remains a mainstay in electric power generation. This requirement places impor-

tance on retaining existing coal-fired capacity and developing new capacity in the face of increased electric power demand and projected nuclear and hydroelectric plant retirements.

The challenge is that existing coal-fired plants must comply with increasingly stringent source emission and ambient air standards. For many of these plants, repowering rather than simply modifying the boilers may be necessary to meet environmental standards and remain competitive in a deregulated power market. There is a need to enhance the cost and performance of both environmental control retrofit and repowering technologies aimed at reducing emissions of sulfur dioxide (SO₂), oxides of nitrogen (NO_x), fine particulate matter (PM), mercury, and solid wastes.



New York State Electric & Gas Corporation's Milliken Station hosted a Clean Coal Technology Project to demonstrate high efficiency SO₂, NO_x, and particulate control without discharge of solid or liquid wastes

ADVANCED SYSTEMS

Coal

New coal-fired capacity faces even greater challenges, particularly with the implementation of utility restructuring. To maintain ambient air standards, new capacity additions will have to achieve near-zero pollutant emissions. Concerns over global climate change have placed a premium on efficiency and use of carbon-neutral renewable fuels. Solid waste disposal is becoming an increasingly difficult permitting issue. Moreover, under utility restructuring, power generators must shoulder the cost and risk of installing new capacity rather than the consumer. This fact makes the capital intensive, difficult to permit coal-fired plant somewhat less attractive. In addition, uncertainty associated with utility restructuring has impacted reliability of delivery. Power generators are increasing capacity factors on existing plants rather than adding capacity, which reduces reserve margins and improves system reliability.

The next generation of coal-fired power plants is emerging. These systems offer the potential to be competitive from a cost and performance standpoint with all other power systems. But, these plants must first undergo replication to reduce cost and optimize performance. This opportunity exists in foreign markets dependent on coal as a feedstock, such as developing Asia. China and India alone are projected to account for 33 percent of the total increase in world energy consumption over the next two decades. Opportunities exist for advanced coal-based systems offering superior environmental performance, fuel flexibility, and coproduction and cogeneration capabilities.

Natural Gas

Natural gas-based capacity is expected to provide the primary domestic response to new power demands over the next two decades. Ensuring conservation of this premium fuel resource requires increasingly efficient natural gas-powered systems.

The U.S. Energy Information Administration (EIA) projects that: (1) 300 gigawatts of new capacity will be needed to meet growing demand and to replace plant retirements; and (2) natural gas will fuel nearly 90 percent of the new capacity requirement. The reasons for the move to increased natural gas-based systems include the relatively low capital costs, short permitting and construction time, and superior environmental performance of gas turbines. The concern is the strain such demand might have on natural gas supplies and infrastructure. Strides toward enhancing the efficiency of natural gas-based power systems serve to protect U.S. reserves of this premium fuel and address global climate change concerns as well.

VISION 21

Ultimately, a new generation of Vision 21 technologies is needed to expand the fuel resource base to wastes and renewables, provide a multiplicity of high-value products in lieu of wastes, realize significant improvements in efficiency and emissions reduction, and facilitate CO₂ capture and sequestration.

Fuel flexibility is critical to enabling use of low-cost indigenous fuels, using wastes as fuel to address growing solid waste management problems, and incorporating renewable fuels to reduce greenhouse gas emissions. Highly efficient use of the fuels is important for reducing

cost, lowering emissions, and facilitating carbon dioxide (CO₂) capture for sequestration. Product flexibility is needed to enhance efficiency, broaden market applications, produce vital chemicals or transportation fuels, and improve return on investment. Near-zero emissions are requisite to environmental acceptability.

CLEAN COAL TECHNOLOGY PROGRAM

The Clean Coal Technology (CCT) demonstration program supports both the Innovations for Existing Plants and Advanced Systems efforts under the Central Power Systems program. This \$5.2 billion cost-shared government/industry partnership addresses environmental concerns associated with coal use. Of the 38 active CCT projects, there are 29 projects, valued at \$3.5 billion, that address central systems applications — 18 environmental control projects and 11 advanced electric power generation projects. The other 9 projects involve coal processing for clean fuels and industrial applications, which are addressed in the Fuels section. All 18 environmental control projects have completed operation. Four of the 11 advanced electric power generation projects completed operations, two are in operation, and the balance are either in design or construction.

The CCT program will be discussed in this section in the context of contributions and accomplishments relative to Innovations for Existing Plants and Advanced Systems efforts.

DRIVERS

Title IV of the Clean Air Act Amendments of 1990 (CAAA) established source emissions standards for SO_2 , NO_x , and particulate matter applicable to existing plants in two phases. The more stringent second phase came into effect in January 2000. Title IV requires Group 1 boilers, which represent 80 percent of the U.S. coal-fired boiler capacity, to meet NO_x emission levels of 0.40–0.46 lb/10⁶ Btu, and Group 2 boilers to meet NO_x emission levels ranging from 0.68–0.86 lb/10⁶ Btu. All existing boilers must meet SO_2 emission levels of 1.2 lb/10⁶ Btu and a sliding scale reduction of 70–90 percent depending on the input fuel sulfur content. The resultant SO_2 emission levels are generally 0.3 lb/10⁶ Btu for low-sulfur coals and 0.6 lb/10⁶ Btu for high-sulfur coals. Furthermore, Title IV caps SO_2 emissions at 8.9 million tons per year beyond 2000 (as a reference, 1970 emission levels were 16 million tons). Over the coming years, as stockpiled SO_2 trading allowances expire and as coal use increases with economic growth, the cap on SO_2 emissions serves to further limit source emission rates.

Title III of the CAAA, Hazardous Air Pollutants (HAPs), requires the U.S. Environmental Protection Agency (EPA) to implement regulatory standards, if warranted, for 189 air toxics from sources emitting 25 tons annually of any combination of pollutants or 10 tons annually of a single pollutant. Mercury was specifically identified for study and possible regulation development. In December 2000, EPA decided to proceed with mercury regulation development. Proposed regulations are to be issued by De-

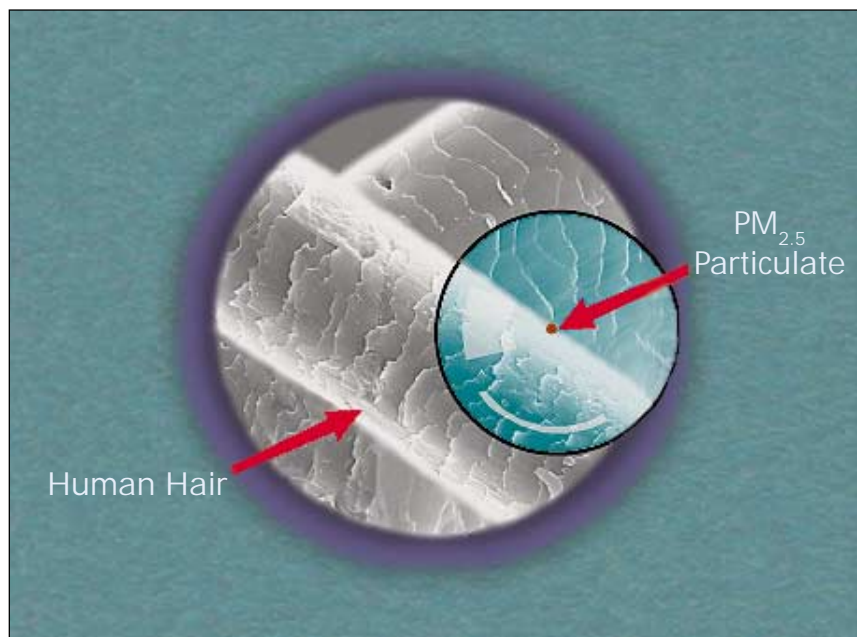
ember 2003 and final regulations are to be issued by December 2004.

Under Title I of the CAAA, EPA revised the National Ambient Air Quality Standards (NAAQS) in July 1997 to address ambient air concentrations of particulate matter (PM) in the respirable range of 2.5 micrometers (microns) in diameter or less ($\text{PM}_{2.5}$). Previous fine particulate standards dealt with airborne material in the inhalable dust range of 10 microns in diameter or less (PM_{10}). The $\text{PM}_{2.5}$ standard brings into play primary sources such as fly ash, carbon soot, and acid mists (aerosols), and secondary sources such as ammonium sulfates and nitrates from precursor SO_2 and NO_x gases. Monitoring to ascertain $\text{PM}_{2.5}$ attainment is ongoing, with designations of non-attainment expected by 2003–2004, and State Implementation Plans (SIPs) for compliance expected by 2007–2008, with compliance by 2013–2014. Some analysts project that an interim action to further reduce SO_2

may evolve in the form of a “SIP Call,” which could call for substantial SO_2 reductions by 2006.

The Toxic Release Inventory (TRI) also has potential ramifications for $\text{PM}_{2.5}$ control. The TRI is a public database maintained by EPA on releases of toxic substances from various industries. Electric utilities began reporting for the first time under TRI in July 1999. Acid aerosols in the $\text{PM}_{2.5}$ size range, such as sulfuric acid, and trace element emissions are reported substances. While emission rates are quite low, the cumulative numbers appear significant and may precipitate further regulatory action.

Also under Title I, EPA revised the NAAQS in July 1997 for ozone. The ozone standards in turn impact NO_x emissions because NO_x is a precursor to ozone formation. As an interim measure, EPA issued a rulemaking in response to recommendations of a 37 state Ozone Transport Assessment Group





NETL PM_{2.5} monitoring site

(OTAG). The rulemaking, in the form of a “SIP Call,” requires 22 eastern states and the District of Columbia to reduce NO_x emissions by specified amounts (budgets) by May 2003. The expected emission limits for power plants is 0.15 lb/10⁶ Btu, which generally requires relatively expensive selective catalytic reduction (SCR) technology. Under the general provisions of the ozone NAAQS provisions, revised SIPs are expected by 2003, with compliance ranging from 2003–2018 depending on the air quality in a particular area.

The EPA also proposed regional haze regulations in July 1997 focused on the impact of PM_{2.5} on visibility impairment in Class I (“pristine”) areas of the United States. However, there remain numerous uncertainties regarding linkage between coal-fired boiler emissions and the concentration and composition of ambient fine particulate matter. Moreover, the National Research Council (NRC) recently recommended that EPA

place a high priority on better understanding the relationship between actual personal exposure to PM_{2.5} and ambient concentrations measured at stationary outdoor monitors. The NRC also recommended greater chemical speciation of both emission sources and ambient PM_{2.5} to improve understanding of biologically important components and characteristics of PM_{2.5}.

The Fiscal Year 1998 Congressional Appropriations called for DOE, through the National Energy Technology Laboratory (NETL), to build upon its existing PM_{2.5} efforts toward addressing the issues of coal-based power generation contributions to ambient air degradation, and more specifically, the contribution of substances having known health and environmental effects. NETL is to add to the science of source-receptor relationships between power plants and public exposure to adverse airborne substances, and assess the impact of the new NAAQS provisions on coal-based power systems.

In April 2000, EPA formally concluded that coal combustion by-products (CCBs) — fly ash, bottom ash, boiler slag, and flue gas desulfurization (FGD) by-products — do not warrant regulation as hazardous wastes. Barriers remain, however, as to the most effective management option for CCBs such as use in a variety of applications from road bed stabilization and cement supplements to value-added construction materials. Barriers include: (1) lack of liability exclusion for CCBs under the federal Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA); (2) treatment of fly ash by most states as a solid waste through restrictive regulations; (3) lack of information on the availability, quality, and beneficial uses of CCBs supported by state and federal agencies; and (4) changes to CCB characteristics brought about by combustion modification for NO_x control. While these barriers persist, incentives for CCB use exist as well, including reduced CO₂ generation in cement processing through CCB substitution and declining landfill capacity and increasingly stringent disposal regulations.



ACCOMPLISHMENTS

The CCT program provided a portfolio of environmental control technologies enabling power generators to cost-effectively comply with Title IV of the CAAA for SO₂, NO_x, and particulate matter. The CCT projects redefined the state-of-the-art for sorbent-based scrubbers, nearly halving operating and capital costs, and producing valuable by-products instead of wastes. Lower cost sorbent injection and spray dryer options also emerged for space constrained, older and smaller plants. Also demonstrated were more sophisticated synergistic integrated control systems offering high SO₂, NO_x, and PM capture efficiency. Demonstrations completed the development of low-NO_x burners for all boiler types except cyclone boilers, making low-NO_x burners the centerpiece for Title IV NO_x compliance. Another combustion modification technique, reburning technology using both natural gas and coal, was also demonstrated to address cyclone boilers and serve as an adjunct to low-NO_x burners. Applicability and effectiveness of post-combustion SCR and selective non-catalytic reduction (SNCR) was evaluated as well.

The CCT program also provides the foundation for development of advanced NO_x controls to address requirements precipitated by Title I NAAQS provisions and possible additional reductions under future regulations. The projects produced a comprehensive database on the mechanisms for NO_x formation and mitigation. To supplement the database, further evaluations were carried out through collaborative R&D projects with industry. The R&D addressed such areas as advanced

reburning, SNCR and SCR/SNCR hybrids, improved electrostatic precipitator (ESP) design, and ESP/baghouse hybrids.

Through both the CCT and R&D programs, DOE coordinated an effort with EPA and industry to characterize air toxics emissions from a representative sample of coal-fired

critical factor in a report to Congress on HAPs, which served to guide future regulatory direction. The result was a focus on mercury and no direct action to regulate power plant trace element or VOC emissions.

In recent years DOE, through NETL, has taken the lead role in CCB utilization R&D. NETL was



Low NO_x burner installation at Gulf Power Company's Plant Hammond, Coosa, Georgia

power plants. The effort was instrumental in establishing that: (1) trace elements, except for mercury, stay with the solid combustion residues (bottom ash, fly ash, and FGD by-products), making control a function of particulate matter collection efficiency; (2) combustion modification via low-NO_x burners and reburning does not produce semi-volatile or volatile organic compounds (VOCs); and (3) mercury adopts a vapor phase and largely escapes capture by flue gas cleanup equipment (e.g., scrubbers and electrostatic precipitators). Air toxics emissions characterization data, collected under the effort coordinated by DOE/EPA/industry, became a

instrumental in preparing a 1994 DOE Report to Congress (RTC) entitled *Barriers to the Increased Utilization of Coal Combustion/Desulfurization By-Products by Government and Commercial Sectors*, as well as an update of the RTC in 1998. These documents have served as road maps for coal combustion by-product R&D. More recently, NETL joined with the National Mine Reclamation Center, headquartered at West Virginia University, to forge a consortium of state agencies and universities, the Combustion By-Products Recycling Consortium (CBRC), with a mission to increase overall CCB utilization by 10 percent.

ACTIVITIES

Under the Innovations for Existing Plants program area, there are three major technical activities: Advanced NO_x Control, PM_{2.5}/Air Toxics, and Coal Combustion By-Products.

Advanced NO_x Control. Advanced NO_x Control activities include two major thrusts: (1) retrofitable NO_x controls capable of meeting Title I CAAA provisions for ozone and PM_{2.5} (Title I NO_x Control); and (2) advanced low-NO_x combustion technology capable of far exceeding Title I CAAA provisions in response to projected future tightening of source emission and ambient air requirements. The effort draws upon combustion modification and post-combustion NO_x control technology development pursued under the CCT Program, as well as follow-up assessments of particularly promising technologies.

PM_{2.5}/Air Toxics Control. There are three basic thrusts under the PM_{2.5}/Air Toxics Control activity: (1) PM_{2.5} characterization analyses, (2) PM_{2.5} control development, and (3) mercury control development. PM_{2.5} characterization analyses combine ambient air monitoring and source emission characterization to establish source-receptor relationships and to better understand formation and transport mechanisms. PM_{2.5} control development seeks to develop and evaluate technologies to cost-effectively control both primary and secondary PM_{2.5}. Mercury control development pursues technology options that either augment existing flue gas cleanup controls or provide stand-alone control.

All PM_{2.5}/Air Toxics Control activities support the goal of negligible primary and secondary PM_{2.5} constituents from Vision 21 plants.

Coal Combustion By-Products (CCBs). The CCB activities follow industrial ecology principles of recycling, or utilizing in some other manner, all process effluents that would otherwise be regarded as waste streams. The activities in-

clude: (1) addressing identified barriers to widespread CCB use through application of science and technology, and technology transfer; and (2) addressing evolving CCB issues associated with application of advanced power generation and pollution control systems. The goal is to increase the CCB utilization rate from the current 30 percent to 50 percent by 2010.



DOE, EPRI, and Public Service Company of Colorado are evaluating carbon injection as a mercury control option on a 600-actual cubic feet per minute test rig located at Public Service of Colorado's 350-MWe Comanche facility

INNOVATIONS FOR EXISTING PLANTS

LINKS AND CROSSCUTS

The exhibit below summarizes the basic steps taken, participants involved, and anticipated outcomes, along with parallel related activities in the Innovations for Existing Plants program area. Early activities supporting definition of technology needs include CCT projects and follow-on R&D projects to further explore promising technologies, the joint DOE/EPA/industry efforts to evaluate HAPs emissions at power plants, and extensive CCB characterization and utilization testing activities conducted largely through the Combustion By-Products Recycling Consortium (formerly the Emission Control By-Products Consortium). The Combustion By-products Recycling Consortium (CBRC) is overseen by NETL,

structured on a regional basis, and carried out by state agencies and key universities.

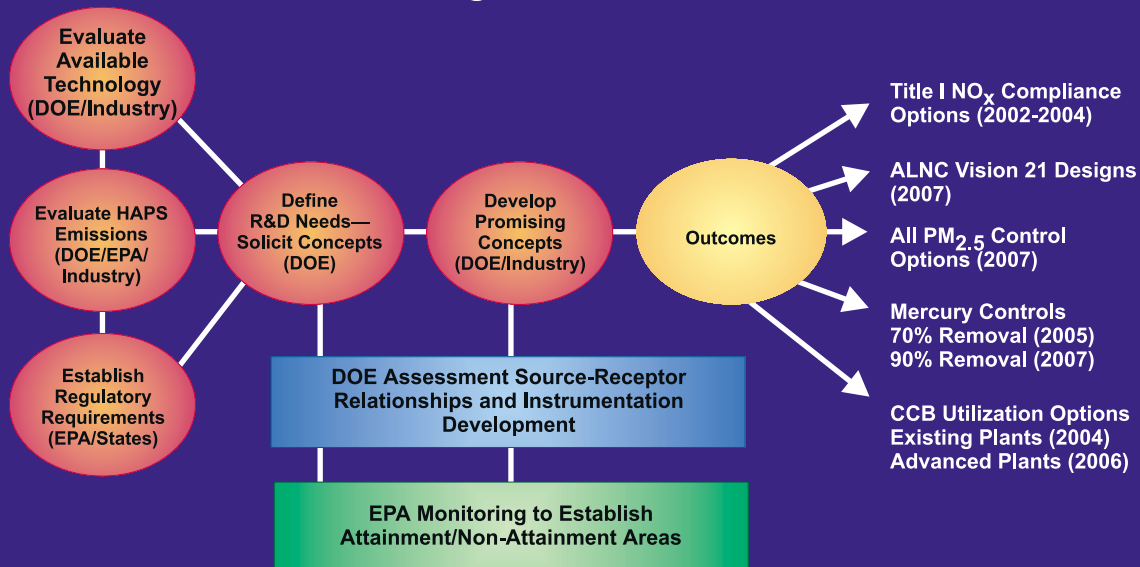
DOE's approach to developing requisite environmental controls is issuance of a series of solicitations for promising concepts based on R&D needs analyses. Concept development draws on parallel national ambient air monitoring efforts.

DOE, through NETL, is participating in a national ambient air monitoring effort with EPA, local, and state environmental agencies, academia, and industry. EPA is establishing a national network of 1,500 $PM_{2.5}$ monitors to identify areas of attainment and non-attainment with the new $PM_{2.5}$ standard. DOE's role is to establish and oper-

ate several $PM_{2.5}$ "supersites" to provide increased temporal, chemical, phase, and size fraction resolution of $PM_{2.5}$ measurements.

DOE's monitoring effort is composed of four sites (two major and two supplemental) under the Upper Ohio River Valley Project, and five (one major and four supplemental) under the Steubenville Comprehensive Air Monitoring Project. The ambient air research station at NETL in South Park, Pennsylvania forms the third key component of the regional monitoring network. A fourth project, the Carnegie-Mellon University (CMU)/EPA Pittsburgh Supersite, was selected by DOE under a Fiscal Year 2000 broad-based solicitation.

Linkages & Outcomes



DRIVERS

Providing new domestic generation capacity presents a major challenge both from an environmental and institutional standpoint. Overseas markets represent a major economic incentive and the opportunity to significantly reduce the projected growth in global greenhouse gas emissions for decades to come.

New capacity must vie with existing capacity in areas struggling to comply with the cap on SO₂ emissions and new ambient air standards for ozone and PM_{2.5}. Moreover, with available landfill capacity declining, solid waste management becomes an increasingly serious issue.

Both global climate change and pollutant emission concerns provide impetus for major improvements in efficiency, which enables less fuel use for a given quantity of energy. Public policy reflecting global climate change concerns promotes use of carbon-neutral fuels through mechanisms such as Renewable Portfolio Standards, which require a certain percentage of power generation capacity to be from renewable sources. Ultimately, carbon sequestration may be required to satisfy global climate change concerns. A key aspect of carbon sequestration is capture of carbon dioxide from the power generation system, which is facilitated by concentrating the carbon dioxide in the process of converting fuel to energy.

Under utility restructuring, the power generator, not the ratepayer, assumes the cost and risk of installing new capacity. Technology characteristics sought in this regime are low capital cost, rapid installation, and reliable performance. Uncertainty in the restructured utility



New capacity is needed to effectively power our economy

market has resulted in limited investment in new capacity, as power generators await further definition of the rules of engagement under utility restructuring. The lack of new capacity coupled with retirements of a significant amount of nuclear capacity has severely reduced reserve margins in much of the country. The result has been an increasing number of power disruptions and occasions of reduced power quality as generators attempt to meet growing demand by increasing capacity factors on an aging fleet of power plants. These occurrences, along with a growing customer base requiring high-quality power for computer-based systems and sensitive electronic components, have escalated customer concern for reliability.

The projected reliance on natural gas to provide nearly 90 percent of new domestic electric power over the next two decades places a premium on efficiency to reduce operating costs by using less fuel and dampening demand-induced price increases. Strategic benefits include ensuring adequate reserves of this clean fuel for the foreseeable future.

World energy consumption is projected to increase by 60 percent between 1997 and 2020. More than one-half of the world's total projected increase in energy consumption is to come from coal-dependent Asia and natural gas-dependent Central and South America. Capturing a significant portion of these enormous markets with advanced U.S. power generation systems would not only boost the economy but impact greatly on global carbon emissions for the foreseeable future.

ACCOMPLISHMENTS

The CCT program was instrumental in the commercial deployment of atmospheric fluidized-bed combustion (AFBC) by providing needed databases and commercial-scale demonstration. The AFBC technology offers tremendous fuel flexibility and provides SO₂ and NO_x control without the efficiency penalties of add-on equipment. There are nearly 10 gigawatts of installed utility-scale AFBC capacity worldwide.

Pressurized fluidized-bed combustion (PFBC) technology, designed to build on AFBC performance, also progressed under the CCT program. Demonstration at a major utility led to a first-generation PFBC commercial design, offering 40 percent efficiency and the beginning of market penetration. Sales include several 80-MWe units throughout

Europe and a 360-MWe unit in Japan. The CCT program also provided the foundation for follow-on work designed to realize the full potential of PFBC.

Four CCT program integrated gasification combined-cycle (IGCC) demonstration projects, representing a diversity of gasifier types and cleanup systems, are pioneering the introduction of this technology by evaluating the systems in commercial service. As with PFBC, these early IGCC units are roughly 40 percent efficient. IGCC is realizing commercial sales, with an estimated 5 gigawatts of installed capacity expected by 2003. The CCT projects are serving to reduce risk for commercial sales and to provide a foundation for gasification systems development.

The DOE Advanced Turbine Systems (ATS) program has produced the most advanced combustion turbines in the world, incorporating breakthroughs that were barely imagined a decade ago. Two sizes of turbines emerged commercially through the ATS program — industrial-scale products less than 20 MW, and large, combined-cycle utility-scale products greater than 400 MW. Developers surpassed the original aggressive goals of the program. Achievements include increased fuel-to-electricity efficiency from about 50 percent to 60 percent for utility-scale gas turbines, and reduced NO_x emissions to single digits (9 ppm or less). Advances in the underlying science and technology have enabled pursuit of a next generation of turbine systems targeting intermediate capacity and further cost and performance improvements.



Tampa Electric Company's 250-MWe IGCC Polk Power Station

COMBUSTION SYSTEMS ACTIVITIES

Under the Advanced Systems program for Combustion Systems, there are three major technical activities: Low Emission Boiler Systems, Indirect Fired Cycles, and Pressurized Fluidized-Bed Combustion.

Low Emission Boiler Systems (LEBS). LEBS is an advanced pulverized coal-fired (PCF) system that takes pulverized coal-firing, the proven standard in coal-fired power generation, to new levels of performance. LEBS draws upon extensive design databases established for PCF systems over decades of service, developed for environmental controls under the CCT program, and evolved for supercritical steam cycles through hundreds of applications. Improved performance is realized by integrating environmental controls and a supercritical steam cycle into a PCF plant design.

A LEBS design by D.B. Riley emerged from nearly a decade of competitive evaluation of three designs. Evaluation included component and subsystem testing and research into high-temperature materials and advanced cycles, such as use of an ammonia-based “Kalina” cycle in lieu of steam. The D.B. Riley design incorporates an innovative low- NO_x U-fired slagging furnace, a regenerative moving-bed copper-oxide process for SO_2 and NO_x control, and a supercritical steam cycle. The design target is 42 percent efficiency and a 10 percent reduction in the cost of electricity.

These technologies and high-temperature materials developments supporting supercritical steam cycle advancement will become base technologies for Vision 21 combustion systems.

Indirect Fired Cycles (IFC). The IFC efforts are focused on concepts that support Vision 21 goals emerging from competitive development of High Performance Power Systems (HIPPS). The HIPPS designs transfer the heat of combustion to a cleaner working medium (air), which in turn drives an expansion turbine to generate electricity. Separating the combustion gases from the turbine avoids: (1) the temperature limitations imposed by flue gas cleanup technologies; (2) the need for extensive purification of the flue gas; and (3) exotic turbine blade metallurgy to avoid corrosion. Central to HIPPS and Vision 21 hybrids is a high-temperature air furnace to transfer the heat of combustion to the air working media. Also important is the development of a coal pyrolysis system to convert coal into a fuel gas, and development of a fuel gas cleanup system. Pyrolysis and fuel gas cleanup provide highly effective means of controlling pollutant emissions on the combustion side of the process. IFC designs emerging from the HIPPS effort are targeting efficiencies of 55 percent.

Pressurized Fluidized-Bed Combustion (PFBC). PFBC systems apply fluidized-bed combustion in a pressurized atmosphere to generate sufficient flue gas energy to drive a gas turbine and generate steam from the exhaust to drive a steam turbine. This combination, termed “combined-cycle,” affords significantly higher efficiency than conventional single cycle combustion systems. Early efforts in the CCT program resulted in demonstration and commercialization of a first-generation PFBC, which simply uses the energy derived in the

PFBC boiler to drive the gas turbine, and uses cyclone separators for particulate removal. Current activities are focused on development of a second generation PFBC that increases efficiency by integrating a coal pyrolysis unit (carbonizer) to produce a syngas for combustion in the gas turbine. This topping combustion addition provides more energy to the more efficient element of the combined-cycle — the gas turbine.

Realizing the potential of a second-generation PFBC requires development of several critical components. Hot gas particulate filtration (HGPF) and multi-contaminant filter (MCF) systems capable of operating at combustor and gasifier exit gas temperatures (1,200 °F–1,700 °F) are needed to enable use of high-efficiency gas turbines, and an efficient low- NO_x burner is needed to combust the syngas. To further leverage PFBC and address future environmental concerns, parallel efforts are ongoing to: develop more efficient sorbents to reduce operating costs and CO_2 emissions; pursue cofiring of carbon neutral fuels (biomass, forestry and agricultural wastes); ensure effective control of HAPs; and conduct systems studies on integrating supercritical steam and fuel cell cycles.



LINKS AND CROSSCUTS

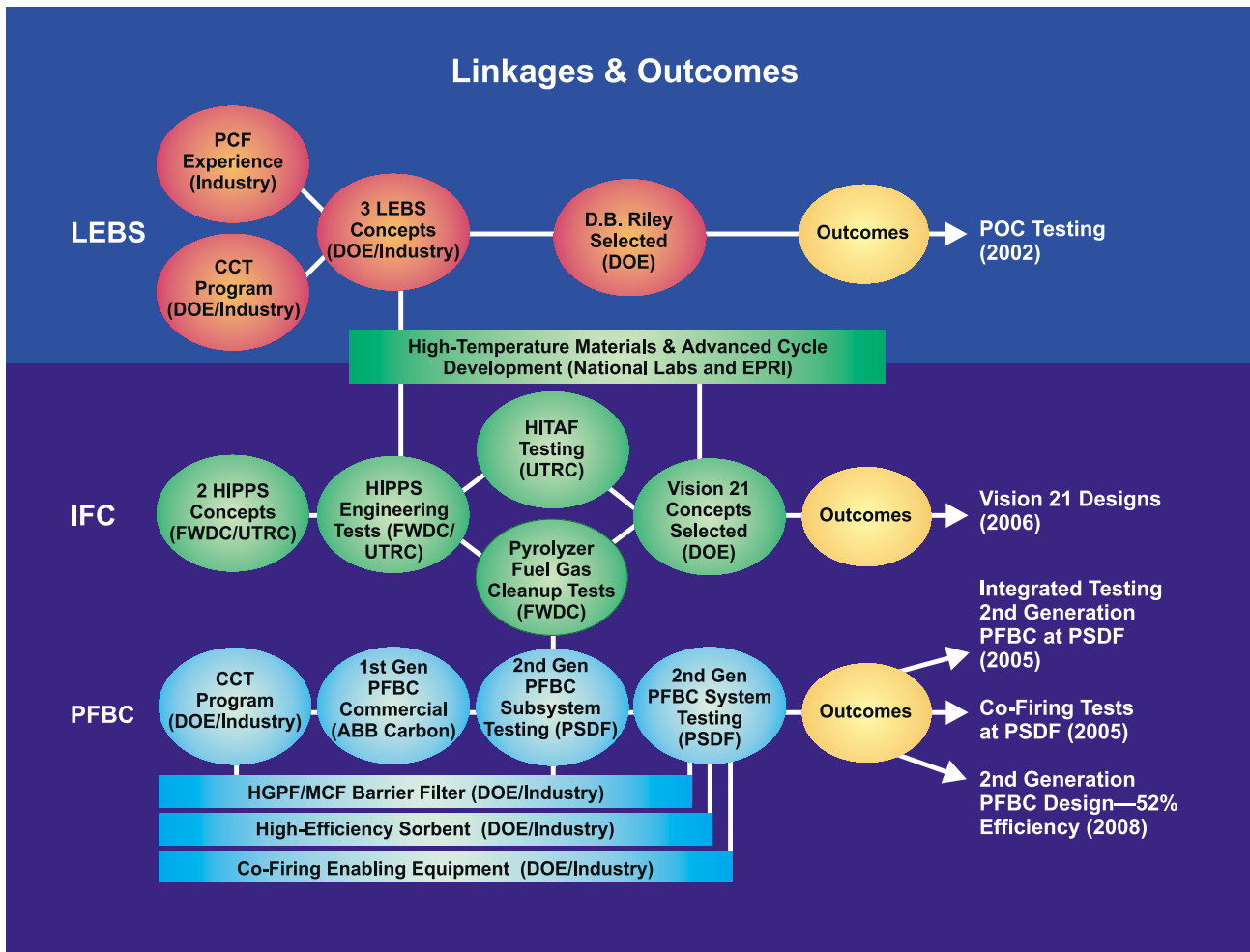
The exhibit below summarizes the linkages and outcomes in Combustion Systems. LEBS evolved from industry experience with PCF and efforts in advanced environmental controls under the CCT program. Cost-shared cooperative agreements were awarded to three industry teams to develop LEBS concepts. Subsequent testing led to selection of a D.B. Riley LEBS design for Proof-of-Concept (POC) testing.

IFC efforts are focused on concepts emerging from HIPPS, which resulted from competitively selected awards of cost-shared cooperative agreements to two industry teams. Engineering tests have led to further

development of key components needed to support Vision 21 goals — HITAF, coal pyrolysis, and pyrolysis fuel gas cleanup. Key components will be incorporated into Visions 21 plant concepts. Testing of the pyrolysis unit and pyrolysis fuel gas cleanup system may take place at the Power Systems Development Facility (PSDF) in conjunction with PFBC development activities.

PFBC efforts are directed primarily at development of a second-generation system, drawing heavily upon first-generation experience gained through the CCT program. Both PFBC system and component

testing will take place largely at the PSDF, which is operated under a cost-shared agreement with Southern Company Services, Inc. Southern Company Services operates the facility in Wilsonville, Alabama for industry participants who fund 20 percent of the projects. DOE funds the balance and NETL oversees the activities. Component development activities critical to achievement of a second-generation PFBC are combined HGPF/MCF barrier filters, alternate high-efficiency sorbents, and equipment to enable co-firing, which are conducted primarily under cost-shared cooperative agreements.



GASIFICATION TECHNOLOGIES ACTIVITIES

Under the Gasification Technologies program, there are two key elements: Gasification Systems Technology, and System Engineering/Product Integration. Gasification Systems Technology has four major technical activities: (1) Advanced Gasification; (2) Gas Cleaning and Conditioning; (3) Gas Separation; and (4) Products/By-Products Utilization. The System Engineering/Product Integration activity provides updated analyses of gasification-based processes, identifies impediments to commercial deployment, and develops R&D performance targets.

Gasification technologies offer tremendous potential by converting hydrocarbon feedstocks into clean fuels, chemicals, and other saleable by-products. Essentially, no waste streams need result from gasification processes. Gas derived from gasification can produce nearly pollutant-free power and co-produce clean fuels and chemicals, if desired. Gasification used in an IGCC application has near-term potential for greater than 50 percent efficiency, and when applied in combination with fuel cells has the potential for greater than 60 percent efficiency.

Gasification Systems Technology

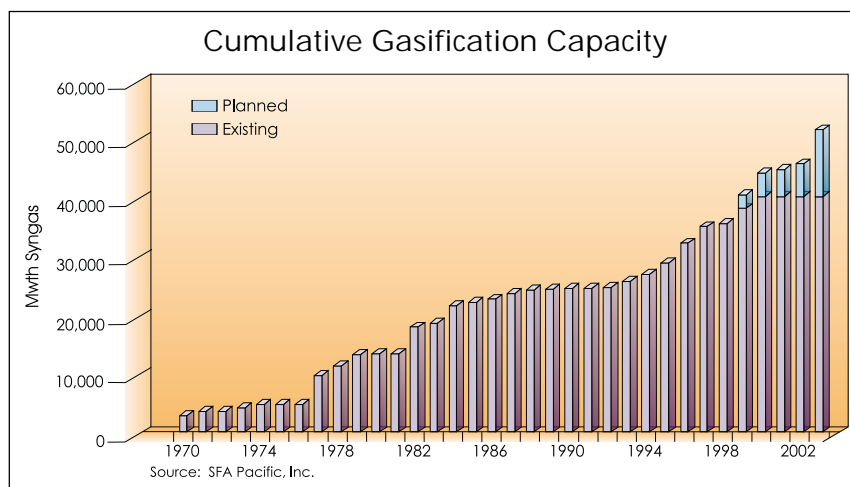
Advanced Gasification. The Advanced Gasification activities focus on the development of a novel transport gasifier through an integrated program involving the University of North Dakota Energy and Environmental Research Center (UNDEERC), the PSDF, and NETL. Efforts also are directed at developing technologies for co-feeding coal

and alternative feedstocks to high pressure gasifiers, the development of advanced materials, instrumentation, and controls; and exploring novel advanced gasifier concepts for application to Vision 21 systems.

Gas Cleaning and Conditioning. The Gas Cleaning and Conditioning

tion, and utilization.

Products/By-Products. The Products/By-Products element focuses on the development and utilization of process and waste streams to generate value-added marketable products and to minimize waste disposal. New approaches for recovering the



area focuses on both hot gas and novel gas cleanup technologies that support Vision 21 goals by providing the gas quality needed for integration with fuel cells, advanced turbines, and synthesis gas conversion technologies. Work will continue on the development of high-temperature, attrition resistant regenerable sorbents and reactor models for the transport desulfurization reactor, particulate filters, and novel cleaning approaches operating at temperatures above 540 °C to meet near-zero emission requirements.

Gas Separation. Gas Separation activities primarily support Vision 21 by developing technologies for hydrogen separation and air separation, and developing concepts for carbon dioxide mitigation, separa-

sulfur from process waste streams will be explored and a strategy will be developed and implemented to explore new products and markets for gasifier ash and slag, particularly from co-feed operations.

System Engineering/Product Integration

The System Engineering/Product Integration activity efforts include analyses of novel hot and warm gas cleaning technologies, CO₂ concentration using regenerable sorbents, membrane-based air and hydrogen separation technologies, and co-feeding applications. A strategy also will be developed and implemented for the development and validation of advanced models of gasification-based technologies and processes in support of Vision 21.

LINKS AND CROSSCUTS

The exhibit below summarizes the linkages and outcomes in Gasification Technologies. Gasification Systems Technology efforts support both the introduction of advanced gasifiers with enhanced cost and performance, and the improvement of gasification technologies emerging from the CCT Program. The work on the transport gasifier takes place primarily at the PSDF and is supported by NETL, UNDEERC, and the technology developer, Kellogg Brown & Root (Kellogg). Also ongoing is development of advanced corrosion-resistant refractories to enhance performance of existing slagging coal gasifiers, and enable use of corrosive alternative feedstocks and development of instrumentation for real-time measurement of critical process conditions. Products from the refractory and instrumentation development are to be

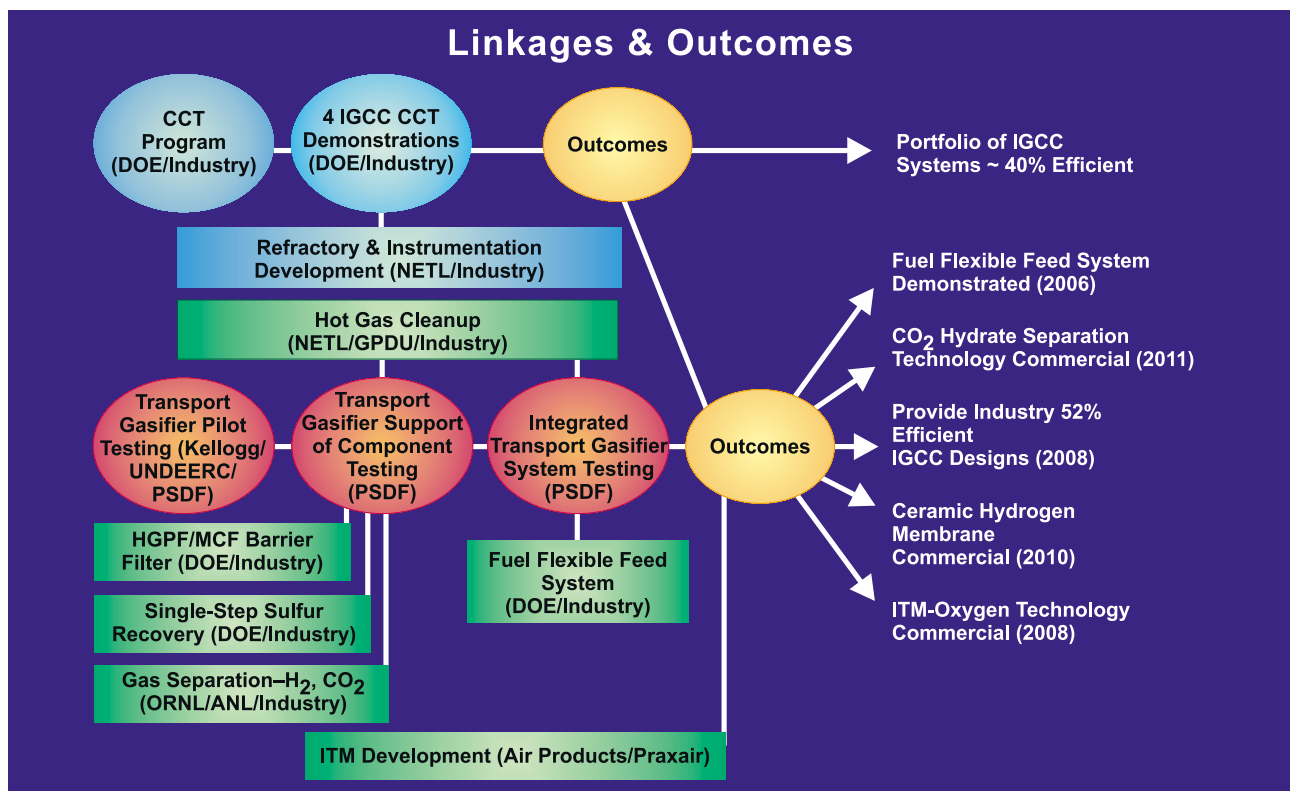
evaluated at CCT projects demonstrating IGCC. Development of a fuel-flexible feed system is ongoing in conjunction with industry to accommodate biomass, and industrial/municipal/agricultural/refinery wastes.

Gas cleaning and conditioning activities include HGPF and MCF development under the PFBC area and development of hot gas cleanup systems using regenerable sorbents. NETL supports hot gas cleanup through in-house research and testing of promising concepts, emerging from both in-house and DOE/industry joint research at their Gas Process Development Unit (GPDU). The PSDF is used for integrated subsystems testing.

Air Products and Chemicals, Inc. and Praxair are participating with NETL in the development of ionic

transport membrane (ITM) and oxygen transport membranes for oxygen separation. Oak Ridge National Laboratory (ORNL) and Argonne National Laboratory (ANL) are developing hydrogen separation membranes. CO₂ and pollutant separation is a combined National Laboratory, university, and industry effort.

By-Products activities support ongoing CCT projects by improving the quality and marketability of ash and slag, and address single step sulfur removal processes at the PSDF. Synthesis gas utilization activities focus on ensuring coal-derived synthesis gas quality meets the needs of coproduction, in cooperation with the Fuels program, and meets the needs of fuel cell applications, in cooperation with the Distributed Generation program.



TURBINE ACTIVITIES

An ongoing Advanced Turbine Systems (ATS) program is scheduled to complete demonstration of two utility-scale turbines by 2002. These systems will be capable of achieving 60 percent efficiency on a lower heating value basis (LHV) and NO_x emissions less than 9 ppm. Research at NETL and an industry/university consortium continues to provide the technology base in materials science, combustion modeling and testing, heat transfer, instrumentation and controls, and aerodynamics. The ATS developments will be used to enhance the efficiency of the PFBC, gasification, and IFC systems.

A Next Generation Turbine (NGT) program has been initiated, drawing on the technology advances and lessons learned in structuring effective partnerships under the ATS program. The NGT program will again use industry/academia/government partnerships to achieve a new set of aggressive goals made feasible by the derivative technology from the ATS program. There are three elements of the NGT program — Systems Development and Integration; Reliability, Availability, and Maintainability (RAM) Improvement; and Crosscutting Research and Development.

Systems Development and Integration. Turbine systems will be developed to meet the needs of new, emerging, deregulated power supply markets. These systems will respond to stakeholder needs by providing highly efficient, reliable, and ultra-clean operations, and by offering flexibility to perform effectively independent of duty cycle or fuel used. Systems currently under



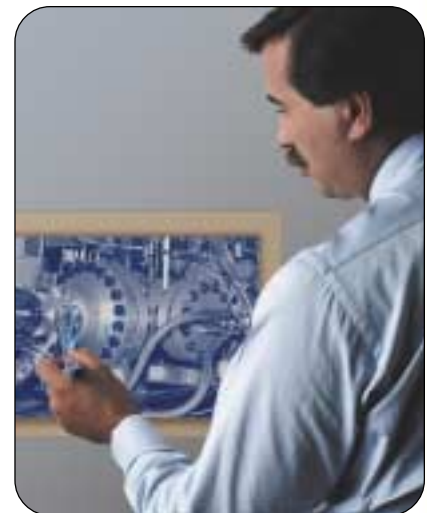
NETL Low-Btu Combustion Facility

evaluation and development are flexible turbine systems and turbine/fuel cell hybrids greater than 30 MW in output rating.

RAM Improvement. RAM Improvement efforts will develop the instrumentation, inspection and examination technology, analytical modeling, and evaluation techniques necessary to monitor turbine performance and determine when maintenance is needed based on turbine condition. System information technology platforms will be developed and demonstrated at host sites.

Crosscutting Research and Development. Crosscutting Research and Development will be conducted by a consortia of U.S. government organizations, industries, universities,

and national laboratories. These consortia will provide combustion modeling, materials science, computer simulations, and instrumentation needed to support achievement of the program goals.



LINKS AND CROSSCUTS

The exhibit on the next page summarizes the linkages and outcomes in Turbine Systems research and development. The ATS program was carried out by two major turbine manufacturers — General Electric (GE) and Siemens Westinghouse (SW) — with supporting research provided by NETL and an industry/university consortium. The South Carolina Institute for Energy Studies (SCIES) directed the consortium, contracting universities to perform applied research specific to the needs of the ATS developers. As many as 100 U.S. universities have contributed to ATS development.

The NGT program intends to broaden public and private sector participation through workshops. More research contracts with industry are anticipated and a government sponsored committee is to be established

to coordinate activities with the DOE Office of Energy Efficiency and Renewable Energy (EERE), National Aeronautics and Space Administration (NASA), Department of Defense (DoD), National Association of State Energy Officials (NASEO), California Energy Commission (CEC), National Institute for Standards and Testing (NIST), and other federal and state organizations. Specific linkages include: the EERE micro-turbine program, NASA Ultra-Efficient Engine Technology program (UEET), and DoD propulsion programs — Integrated High Performance Turbine Engine Technology (IHPTET), Versatile, Affordable Advanced Turbine Engines (VAATE) program, and the Navy Future Ships programs. An Industry Peer Review Board is also being established to ensure program quality and relevance.

Four companies have been selected by DOE to define Flexible Turbine Systems: Rolls Royce Allison (RRA), Pratt and Whitney (PW), GE, and SW.

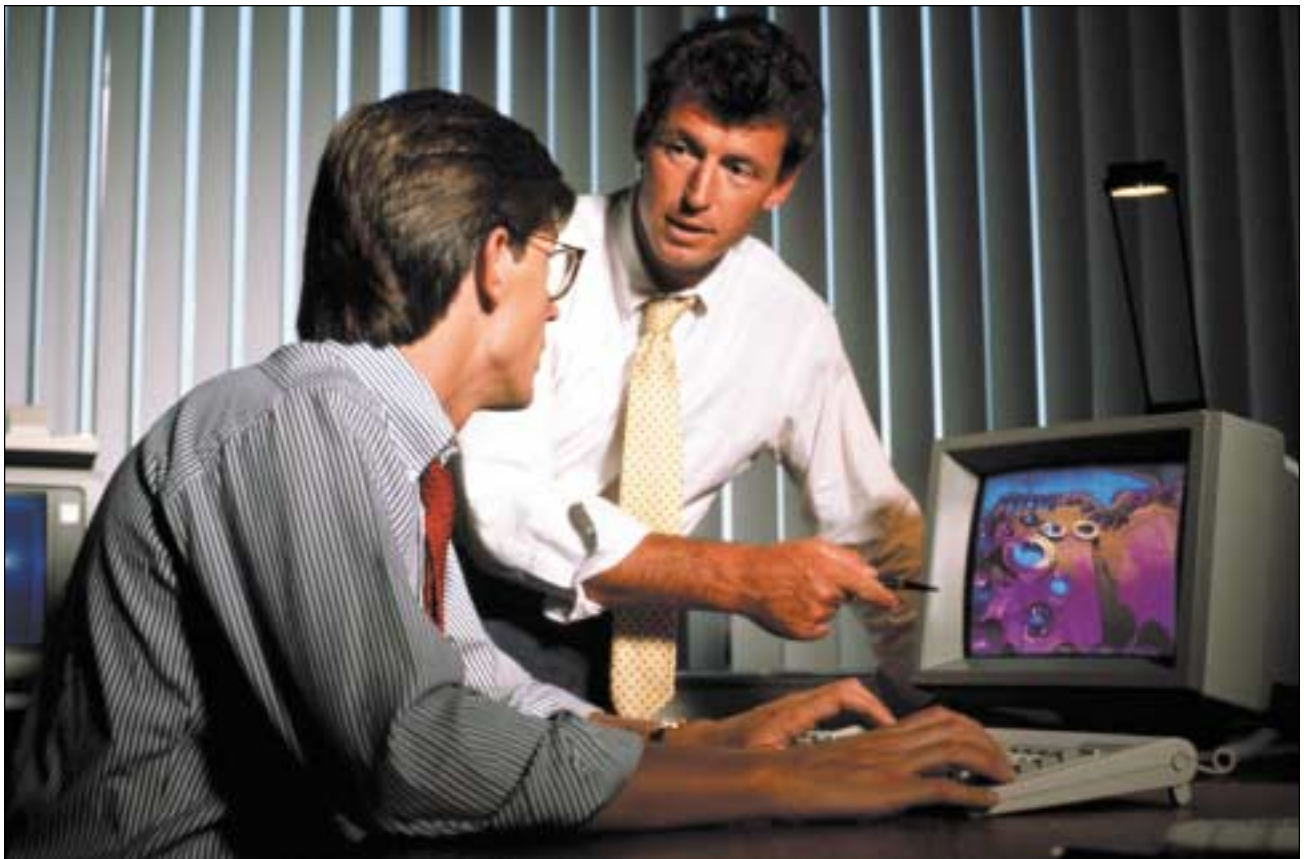
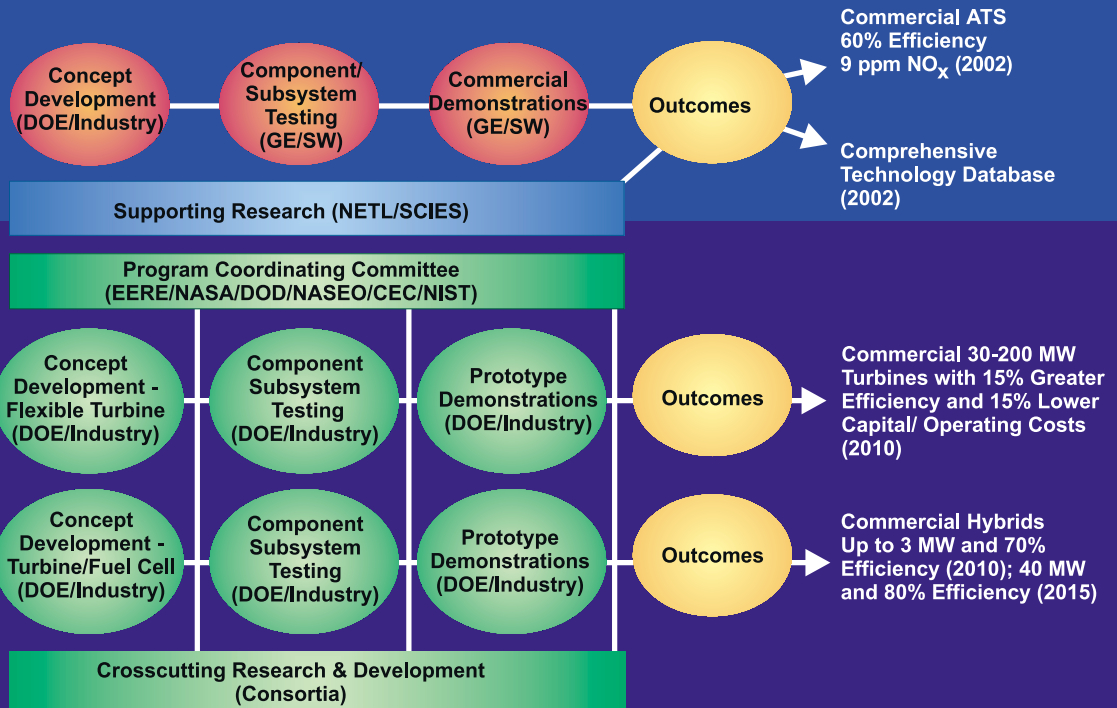
In Turbine/Fuel Cell Hybrids, systems studies by SW, RRA, FuelCell Energy (FCE), Caterpillar, and Northern Research and Engineering Corporation laid the foundation for follow-on efforts. DOE selected FuelCell Energy-Capstone Turbine and RRA to conduct 280-kW hybrid demonstrations and develop designs for a 40-MW hybrid system. DOE also has agreements with SW to conduct hybrid demonstrations at 250-kW and 1-MW scales. Both EPA and the European Commission anticipate partnering with DOE on the demonstrations.

Two companies are currently pursuing testing of NGT components — Ramgen Power Systems, Inc., and Clean Energy Systems. Both RAM Improvement and Crosscutting Research and Development activities will be implemented by consortia consisting of government organizations, industry, universities, and National Laboratories.



Photos by Siemens Westinghouse illustrate the complexity of turbine blades

Linkages & Outcomes



DRIVERS

- Existing coal-fired electric generating capacity must be retained to sustain economic growth.
- Retaining existing plants requires a portfolio of advanced environmental controls and repowering technologies to meet increasingly stringent emissions standards.
- To maintain or improve ambient air standards in most regions of the United States, new capacity additions will have to achieve near-zero pollutant emissions.
- Public policy is placing a premium on efficiency, use of renewable fuels, and elimination of solid waste.
- Natural gas-based power systems are expected to provide more than 90 percent of the 300 gigawatts of projected new domestic capacity by 2020.
- Utility restructuring requires power generators to shoulder the cost and risk of installing new capacity additions.
- Unprecedented worldwide growth in energy consumption is projected — a 60 percent increase by 2020 — with coal-dependent Asia and gas-dependent Central and South America accounting for nearly half of the growth.
- Fuel and product flexibility enhances the market potential of power systems by enabling use of low-cost indigenous and opportunity fuels, and production of vital chemicals and transportation fuels.
- Achieving radical improvements in performance of fossil fuel-based power systems and eliminating environmental barriers to fossil fuel use requires integration of power and fuel system “modules” into systems capable of meeting continuing cost and performance challenges.
- Stabilizing global greenhouse gas emissions requires both developed and developing countries to adopt advanced, high-efficiency power technologies.
- Concentrating carbon dioxide emissions from power systems facilitates capture and mitigates sequestration costs.

OBJECTIVES

- Disseminate results from the CCT program. (Present-2007)
- Complete development of retrofit NO_x control technologies necessary to meet the latest ambient air standards for ozone and PM_{2.5} levels. (2003)
- Demonstrate technologies to effectively control up to 70 percent mercury emissions from coal-fired plants by 2005 and up to 90 percent by 2007.
- Complete development of data and technology to control primary and secondary PM_{2.5}. (2005)
- Develop CCB utilization options for existing plants by 2004 and advanced plants by 2006.
- Demonstrate a 60 percent efficient (LHV) natural gas-based Advanced Turbine System with NO_x emissions less than 9 ppm. (2002)
- Complete development of 30- to 200-MW NGT turbine with 15 percent improvement in efficiency and cost, and turbine/fuel cell hybrids with 70 percent efficiency. (2010)
- Complete proof-of-concept testing of LEBS. (2003)
- Demonstrate 52 percent efficient second-generation PFBC. (2008)
- Develop advanced gasifier and associated components and subsystems necessary to achieve fuel flexibility and greater than 52 percent efficiency in an IGCC mode. (2008)
- Develop gas purification and particulate cleanup components essential to second generation PFBC and gasification technology goals and for linking early hybrid systems to fuel cells. (2006)
- Complete commercialization of ITM-oxygen separation technology. (2008)
- Complete commercialization of ceramic hydrogen (H₂) separation membrane. (2010)
- Complete commercialization of CO₂ hydrate separation technology. (2011)
- Complete design of commercial-scale Vision 21 plants and simulate plants using virtual demonstration capability. (2015)

STRATEGIES

- Build on the cost-shared government/industry CCT projects.
- Continue cooperative work with EPA, states, and industry to address current ambient NO_x, PM_{2.5}, and vapor phase mercury source emission issues.
- Continue cooperative work through the CBRC to characterize and develop uses for CCBs from existing and advanced power plants.
- Integrate ATS developments into new commercial turbine offerings, and use to enhance efficiency of PFBC and gasification technologies.
- Apply ATS lessons learned and supporting research to develop NGT products.
- Introduce LEBS as a substitute for conventional pulverized coal-fired systems in Asian market.
- Demonstrate second generation PFBC under the CCT program.
- Evaluate advanced refractory materials and instrumentation at existing CCT project sites demonstrating IGCC.
- Apply PSDF and in-house GPDU facilities to support cooperative research in fuel and product flexibility and process gas separation and cleanup.
- Use PSDF to develop advanced gasifier and associated components and subsystems necessary to achieve fuel flexibility and greater than 52 percent efficiency in an IGCC mode.
- Develop and use advanced computational technology and existing operating systems to demonstrate feasibility of Vision 21 systems.

PERFORMANCE MEASURES

- Advanced environmental control and power system technologies reduce regulatory compliance costs by 25–75 percent and enable coal-fired units to maintain 50 percent of U.S. electric generating capacity.
- Leveraging fuel and product flexibility, gasification-based power generation is increased by 10,758 MWth in the near term. (2003)
- ATSS supplant current turbines, reduce pressure on natural gas supply in meeting growing electricity demand, and enhance performance of PFBC and IGCC. (2002)
- Flexible Gas Turbine Systems emerge and expand market applications. (2010)
- LEBS technology gives U.S. competitive position in overseas markets and results in exports. (2003)
- Success of first generation PFBC and IGCC overseas and in U.S. niche markets, and performance enhancements coming out of demonstration of second generation PFBC and fuel-flexible gasification technologies reduce costs to <\$1,000/kW in the mid-term. (2008)
- IFC technology emerges as high-efficiency combustion module for Vision 21 systems. (2008)
- Gas separation membrane and high-temperature cleanup technology enable hybrid systems to achieve greater than 60 percent efficiency while reducing costs by 10-20 percent. (2010)
- Industry participants begin to site Vision 21 plants. (2015)

CENTRAL POWER PROGRAM BENEFITS

National Benefits

- Sustains economic growth by maintaining low-cost electricity vital to the U.S. economy;
 - Ensures energy security by using abundant indigenous resources for a significant component of the energy mix, and by using natural gas resources efficiently;
 - Provides alternative means of producing critical chemicals and fuels;
 - Responds to regional and global environmental concerns; and
 - Establishes a strong U.S. environmental and power generation technology position for export to the world market.
-

Supplier Benefits

- Enables electricity suppliers to cost-effectively adjust to regional energy and environmental demands;
 - Broadens the market beyond simply supplying electricity; and
 - Allows significant capacity additions at existing sites, which precludes the need for additional plant siting and transmission line installations.
-

Customer Benefits

- Maintains low-cost electricity rates, which are already among the lowest in the world;
- Provides U.S. industrial users a competitive edge for their products in the world marketplace;
- Serves to bolster electric generating capacity reserve margins critical to reliable service;
- Enhances the local, regional, and global environment; and
- Protects against price shocks in industrial chemicals and transportation fuels.

ADVANCED NO_x CONTROL

Performance Targets

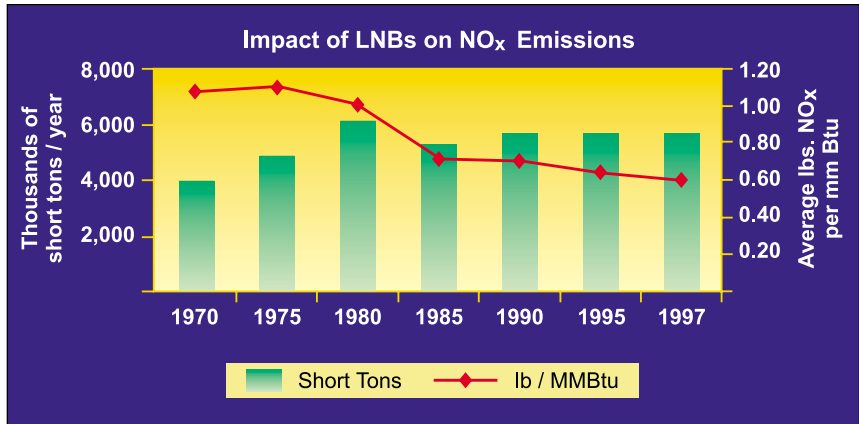
NO_x Emissions:
0.15 lb/10⁶ Btu

Levelized Cost:
25% less than SCR

Year: 2003

Advanced NO_x Control research is driven by continuing pressure for further reductions in NO_x emissions from coal-fired boilers to address ground-level ozone, ambient fine particulates, visibility, eutrophication, and climate change. The current portfolio of NO_x control activities ranges from modeling to full-scale demonstration. These efforts include the successful completion in April 2000 of a demonstration of SNCR technology at American Electric Power's 600-MWe Cardinal Plant in Brilliant, Ohio.

The success of the Advanced NO_x Control research is intimately tied to close coordination and cooperation with users, technology developers, and state agencies, and builds on success achieved through the CCT program. One such CCT program success was the development of low-NO_x burners (LNBs) applicable to over 90 percent of existing coal-fired capacity. Nearly half of the domestic coal-fired boiler population have incorporated LNBs. As shown in the adjacent table, LNBs nearly halve industry-wide emissions and stabilize annual emissions despite significant increases in coal-fired capacity.



Metering pumps for the Cardinal Plant SNCR system's urea injection



American Electric Power's 600-MWe Cardinal Plant in Brilliant, Ohio

Advanced NO_x Control activities include two major thrusts: (1) retrofitable NO_x controls capable of meeting Title I CAAA provisions for ozone and PM_{2.5} (Title I NO_x Control); and (2) advanced low-NO_x combustion (ALNC) technology capable of far exceeding Title I CAAA provisions in response to projected future tightening of source emission and ambient air requirements.

Title I NO_x Control performance targets are to: (1) achieve NO_x emission rates of 0.15 lb/10⁶ Btu or less; (2) reduce levelized costs by 25 percent relative to SCR; (3) produce negligible impact on balance of plant; (4) apply to most boiler types; and (5) maintain performance over a wide range of coals and operating conditions. The research portfolio sought includes advanced combustion controls, advanced flue gas treatment, and integrated control systems.

Title I NO_x Control activities are being carried out through collaborative research resulting from competitive solicitations under the Advanced Environmental Control Technologies (AECT) program, which addresses both primary and secondary PM_{2.5} control. Recently concluded Phase I AECT investigations examined advanced reburning, SNCR, and SCR/SNCR hybrid technologies. Under Phase II, the NO_x control focus is on development of: (1) a second-generation advanced reburning (SGAR) process using reagent injection, sponsored by Energy and Environmental Research Corporation (EERC); and (2) an SNCR/SCR hybrid process sponsored by GPU Generation, Inc.

The SGAR system achieved 98 percent NO_x removal at 1 x 10⁶ Btu/hour pilot scale and will be scaled-up to 10 x 10⁶ Btu/hour under Phase

II testing. GPU Generation is carrying out a full-scale demonstration of the SNCR/SCR hybrid at the 147-MWe Seward Station near Johnstown, Pennsylvania, with co-funding from EPRI, CONSOL, and EPA.

The work is expected to result in control options for power generators in the 2002–2004 time frame to support NO_x SIP Call compliance and satisfy the PM_{2.5} control milestone for NO_x precursor control.

ALNC concepts are being sought through competitive solicitation that include oxygen enhanced combustion. ALNC goals are more long-term, with pilot-scale testing projected by 2005 and commercial design availability by 2007. These activities support Vision 21 Advanced Emission Control goals of near-zero emissions by 2015.



SCR test facility at Gulf Power Company's Plant Crist

PM_{2.5}/AIR TOXICS CONTROL

Performance Targets

Establish Source-Receptor Relationships

PM_{2.5} Capture:
99.99% by 2007

Mercury Capture:
50% by 2005
90% by 2010

There are three basic thrusts to the PM_{2.5}/Air Toxics Control activity: (1) PM_{2.5} characterization analyses, (2) PM_{2.5} control development, and (3) mercury control development.

PM_{2.5} characterization analyses combine ambient air monitoring and source emission characterization. Ambient air monitoring evaluates the concentration and chemical and physical composition of PM_{2.5}, PM_{2.5} precursor gases, ozone, and mercury in order to provide improved resolution of deposition patterns and source-receptor relationships. Source emissions entails evaluation characterization of both primary and secondary PM_{2.5} from fossil fuel-based power systems to better understand their potential impacts on ambient air quality and regional haze and their role in human exposure. Included in the source emissions characterization are investigations into the atmospheric formation and transport mechanisms associated with PM_{2.5}, and the interactions between secondary PM_{2.5} and ozone precursors.

NAAQS calls for the establishment of a national network of 1,500 PM_{2.5} monitors, starting in 1998, to identify areas of attainment and non-attainment with the new PM_{2.5} standard. Some 300 sites will be used to collect data on chemical characteristics and a small subset of these will include “supersites” to provide increased temporal, chemical, phase, and size fraction resolution of PM_{2.5} measurements. DOE’s role is to establish and operate several PM_{2.5} supersites.

DOE’s monitoring effort is composed of four sites (two major and two supplemental) under the Upper Ohio River Valley Project (UORVP), and five (one major and four supplemental) under the Steubenville Comprehensive Air Monitoring Project (SCAMP). The ambient air research station at NETL in South Park, Pennsylvania, forms the third key component of the regional monitoring network. A fourth project, the Carnegie-Mellon University (CMU)/EPA Pittsburgh Supersite, was selected by DOE under a Fiscal Year 2000 broad-based solicitation.

The primary sites in the UORVP are the Lawrenceville, Pennsylvania urban site operated by the Allegheny County Health Department, and the Holbrook, Pennsylvania rural monitoring facility located at a site operated by the Pennsylvania Department of Environmental Protection. Lawrenceville and Holbrook contain several types of filter-based particulate matter monitoring equipment, continuous samplers for co-polluting gases, and surface me-

teorological stations. The UORVP is scheduled to complete sampling in the summer of 2001 and enter the principal analysis and interpretation phase later this year.

The SCAMP site is a location featured in the 1993 Harvard University School of Public Health “Six Cities” study cited by EPA in establishing ambient PM_{2.5} standards because of correlations noted in the study between ambient PM_{2.5} mass and adverse health effects. The SCAMP project, which includes both indoor and outdoor monitoring, will offer complete characterization of the relationships between ambient PM_{2.5} and human exposure, including the chemical components of PM_{2.5} at various locations. The information will provide a comprehensive database for use in subsequent epidemiological studies, long-range transport studies, and State Implementation Program development. CONSOL Energy is the primary performer of SCAMP, and will provide the necessary coordination and data integration between the various components of the study.

DOE is supporting the outdoor SCAMP study, which includes daily, and in some cases, continuous measurements of PM_{2.5} mass and composition. For the outdoor study, which began measurements in the summer of 2000, CONSOL has formed a team with the Harvard University School of Public Health, Ohio University, Franciscan University of Steubenville, Wheeling Jesuit University, and Saint Vincent College. The indoor component of SCAMP is being performed by the

Harvard University School of Public Health under subcontract to CONSOL, and is supported by a consortium of non-DOE sources.

The Pittsburgh supersite, located on the CMU campus, will expand on the DOE/NETL UORVP by adding a wide range of state-of-the-art measurements and increasing monitoring frequency. An ultimate goal is the development and evaluation of current and next-generation aerosol monitoring techniques. Both DOE and EPA will collaborate in the effort with a team from academia, private industry, and local and state air pollution agencies.

Baseline monitoring at the central Pittsburgh site is planned for an 18-month period that will include detailed characterization of particulate matter size, surface, volume distribution, and chemical composition — all as a function of size and on a single particle basis. Three 14-day intensive sampling periods are planned to examine temporal variation and to collect detailed data for model testing and validation.

The CMU project also will create a database of ambient particulate matter measurements for source-receptor and deterministic modeling in

the Pittsburgh region. Estimates will be made of the impact of the various sources (transportation, power plants, natural, etc.) to the particulate matter concentrations in the area.

In a separate effort (not co-funded by DOE), EPA will conduct comprehensive modeling, and epidemiology and indoor exposure studies to test critical hypotheses relating to health effects, exposure, and control strategies.

Also, through an Interagency Agreement, DOE is partnering with the Tennessee Valley Authority (TVA), EPRI, and state and local environmental agencies to evaluate the impact of $PM_{2.5}$ on visibility in the Great Smokey Mountain (GSM) National Park in Tennessee. A supersite is being established in the GSM to address the degree to which emissions of sulfur and nitrogen oxides from power plants contribute to $PM_{2.5}$ and regional haze. As part of the TVA Interagency agreement, DOE also is supporting the Aerosol Research Inhalation Epidemiology Study in Atlanta, Georgia.

Source emission characterization is aimed at developing better source “signatures” that can be used in source-receptor modeling and hu-

man exposure studies, and developing instrumentation and methods for sampling $PM_{2.5}$ in the absence of no direct sampling methods. Specific activities include: (1) plume and atmospheric chemistry studies at TVA’s Cumberland station using fully instrumented helicopters; (2) NETL in-house combustion emission characterization; (3) McDermott Technology, Inc. LNB emission characterization focused on ultra-fine soot formation; and (4) Brookhaven National Laboratory development of perfluorocarbon tracer technology for tagging source emissions.

The $PM_{2.5}$ characterization analyses follow parallel paths of ambient air monitoring and source emission characterization through 2002, converging into models defining source-receptor relationships in the 2003–2004 time frame. The parallel efforts will support EPA’s five-year scientific review of the efficacy of fine particulate NAAQS due in 2002. The follow-on activities will contribute to $PM_{2.5}$ control development and SIP strategies for compliance.

$PM_{2.5}$ control development seeks to develop and evaluate technologies to cost-effectively control both primary and secondary $PM_{2.5}$. Activities to address NO_x precursor control are being pursued under Advanced NO_x Control, and are to be integrated into the $PM_{2.5}$ control development technology portfolio. The current focus of research under $PM_{2.5}$ control development is on controlling primary $PM_{2.5}$ emissions. Extensive emissions monitoring at coal-fired plants, through a DOE/EPA/industry coordinated effort, firmly established that trace elements and other air toxics are largely bound to the ash. Control of airborne toxics is, therefore, largely a function particulate matter collec-



tion efficiency. While particulate matter controls such as electrostatic precipitators (ESPs) and fabric filter baghouses have evolved into highly efficient systems (99 percent capture efficiency for total particulates), capture efficiency for particulates in the 0.01–10 micron range is far lower.

As in the case of precursor NO_x control development, primary $\text{PM}_{2.5}$ control activities are being carried out through collaborative research resulting from competitive solicitations under the AECT program. Phase I AECT investigations have concluded and Phase II development is underway. Performance targets are 99.99 percent capture of all particle sizes in the range of 0.01–10 microns, an emissions rate not to exceed 0.01 lb/10⁶ Btu, and levelized cost savings of 25 percent relative to conventional systems.

Phase II projects include: (1) the UNDEERC development of an advanced hybrid particulate collector (AHPC) that combines the best features of ESPs and baghouses in a novel configuration; and (2) ABB Combustion Engineering development of an ESP using cooling, humidification, sorbent injection, and pulsed energizing. Both concepts will move to pilot-scale testing under Phase II.

Assessments of the Phase II concepts are scheduled through 2003. Precursor NO_x control options are to be made available in the 2003–2004 time frame, which is addressed in the Title I NO_x control effort. All $\text{PM}_{2.5}$ control options are to be completed by 2007.

Mercury control development draws upon prior efforts in augmentation of existing flue gas cleanup controls and stand alone control concepts, and seeks the

most promising mature concepts for field testing and novel concepts for pilot testing.

Prior work included sorbent injection techniques for direct mercury capture, and catalytic conversion of mercury to a soluble form for capture in wet scrubbers. In 2000, DOE issued a solicitation for industry proposals on cost-cutting mercury control methods for coal-based power systems. Also considered will be controls that remove mercury along with other pollutants, including sulfur trioxide, carbon dioxide,

nitrous oxides, and hydrogen chloride. Assessments are to take place for three years.

The goal is to develop more effective options that will cut mercury emissions 50–70 percent by 2005, and 90 percent by 2010 at one-quarter to one-half of current cost estimates.

All $\text{PM}_{2.5}$ /Air Toxics Control activities support the goal of negligible primary and secondary $\text{PM}_{2.5}$ constituents from Vision 21 plants.



$\text{PM}_{2.5}$ and sequential filter samplers at Holbrook monitoring site, UORVP



Central SCAMP monitoring site, Steubenville, Ohio

COAL COMBUSTION BY-PRODUCTS

Performance Targets

Increase CCB Utilization Rate from 30% to 50% by 2010

Coal combustion by-products (CCBs) include flyash, bottom ash, boiler slag, and flue gas desulfurization (FGD) residues. The CCB activities follow industrial ecology principles of recycling, or utilizing in some other manner, all process effluents that would otherwise be regarded as waste streams. The activities include: (1) addressing identified barriers to widespread CCB use through application of science and technology and technology transfer; and (2) addressing evolving CCB issues associated with application of ad-

vanced power generation and pollution control systems. The goal is to increase the CCB utilization rate from the current 30 percent to 50 percent by 2010.

Drawing upon previous CCB characterization and utilization work, the Combustion By-Products Recycling Consortium issued a regionally based solicitation in May 2000 for: (1) research into utilization issues introduced by NO_x controls; (2) unique utilization techniques and technologies; (3) development of standards for state and federal use specifications; (4) development of tools to assess benefits of CCB use; and (5) development of information processes to promote CCB use. Solicitation targets are to achieve, by 2005, a doubling of the current rate of FGD by-product use, a 10 per-

cent increase in overall national rate of by-product use, and a 25 percent increase in the number of uses considered “allowable” under state and federal regulations.

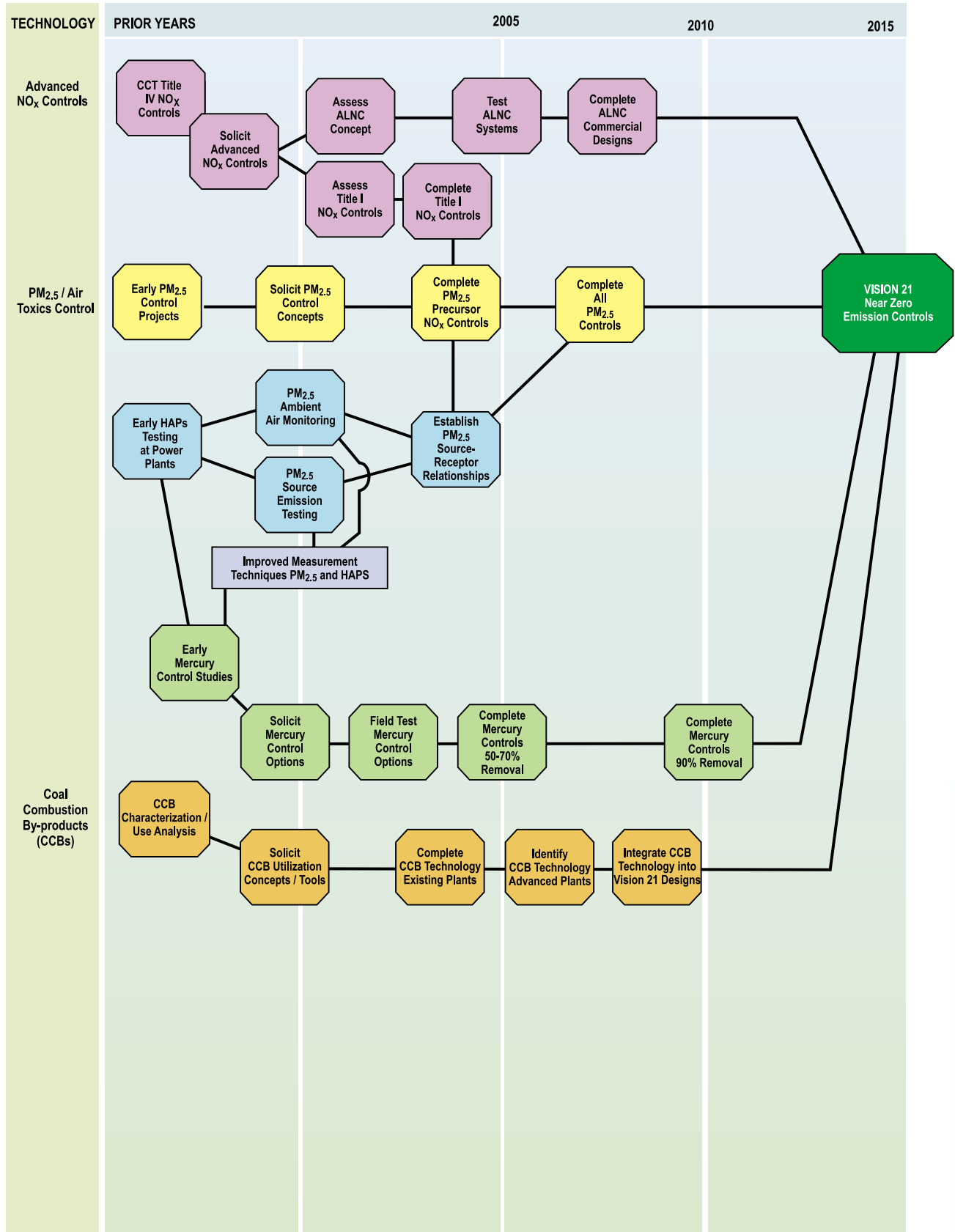
Plans are to continue activities on all fronts, with the goal of having a portfolio of technologies and information systems in place to significantly enhance use of CCBs from existing plants by 2004. Similar CCB management tools are expected for advanced power systems by 2006. Integration of CCB technologies into Vision 21 plant designs is scheduled for 2008.

The following roadmap summarizes activities under the three Innovations for Existing Plants program areas.



Current FGD residue disposal method

ROADMAP



INDIRECT FIRED CYCLES

Performance Targets

Efficiency: 55% HHV

Emissions:

NO_x – 0.06 lb/10⁶ Btu

SO_2 – 0.06 lb/10⁶ Btu

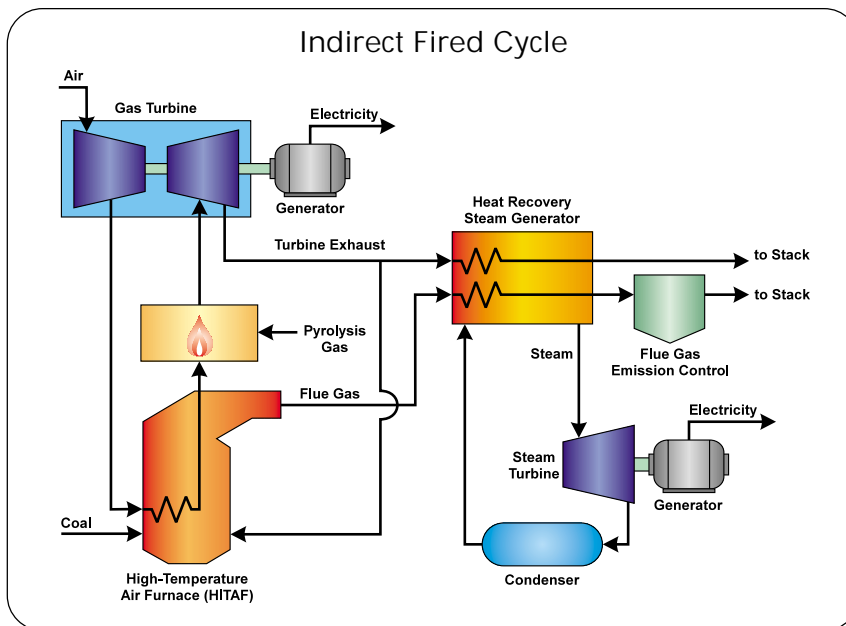
PM – 0.003 lb/10⁶ Btu

Year: 2010

Indirect Fired Cycle (IFC) activities build on concepts and components emerging from two competitively selected teams developing High Performance Power Systems (HIPPS). HIPPS designs feature use of: (1) a high-temperature air furnace (HITAF) to transfer the heat of combustion to a clean working medium (air); and (2) coal pyrolysis and pyrolysis gas cleanup to produce a clean coal-based gas for combustion.

The adjacent schematic shows the conceptual application of HITAF and coal pyrolysis components. Air under pressure from a gas turbine compressor is heated in the HITAF and receives a further energy boost from combustion of clean pyrolysis gas before expanding in the gas turbine. Heat recovered from the gas turbine exhaust and HITAF flue gas is used to raise steam for a steam turbine (combined cycle).

The advantage of IFC lies in producing a clean, high-temperature working medium, which enables use of highly efficient, high-temperature gas turbines. While gas turbines offer increasingly greater efficiency with temperature, gas turbine components become increasingly susceptible to chemical corrosion and erosion as temperatures rise. Furthermore, the gas tur-



bine Brayton cycle is inherently more efficient than the steam cycle, and use of the gas turbine/steam turbine combined cycle leverages efficiency. IFC avoids hot gas cleanup systems and the associated temperature limitations. IFC designs emerging from the HIPPS effort are targeting efficiencies of 55 percent.

IFC activities are focused on further development and systems studies of those components and subsystems identified in the HIPPS projects as having the greatest potential for supporting Vision 21 goals. United Technologies Research Center (UTRC) is pursuing HITAF development and Foster Wheeler Development Corporation is addressing pyrolyzer and pyrolysis gas cleanup. Plans are to tie the pyrolysis and pyrolysis gas cleanup work into PFBC support work at the PSDF.

For the period 2001–2006, HITAF, pyrolyzer, and fuel gas cleanup component/subsystem development will proceed in parallel with system

studies to explore optimum advanced concepts. Advanced concepts in support of Vision 21 goals are to be selected for further development.



PRESSURIZED FLUIDIZED-BED COMBUSTION

Performance Targets

Efficiency: 52% HHV

Emissions:

NO_x - 0.06 lb/10⁶ Btu

SO₂ - 0.06 lb/10⁶ Btu

PM - 0.003 lb/10⁶ Btu

Cost: <\$1,000/kW

Year: 2008

Fluidized-bed combustion (FBC) uses air to entrain and induce a turbulent mixing action to solid fuels and sorbent materials. The result is very low NO_x emissions through efficient combustion at temperatures of 1,400–1,700 °F, well below the thermal NO_x formation temperature

(2,500 °F), and efficient SO₂ capture through effective sorbent/flue gas contact.

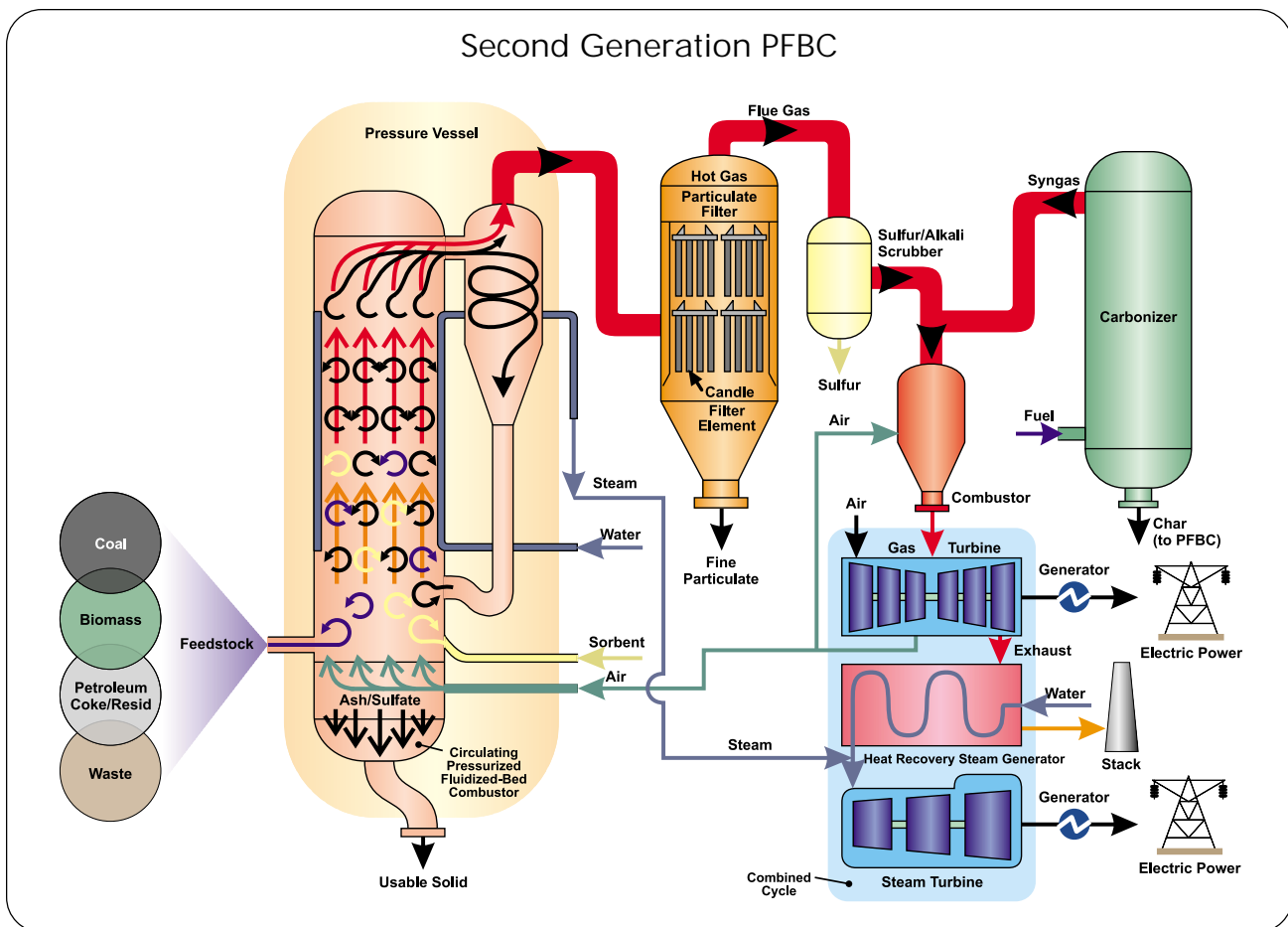
FBC performance is enhanced by performing the combustion under pressure (up to 30 atmospheres) in what is called pressurized fluidized-bed combustion (PFBC). Pressure improves combustion and sorbent capture efficiency, and generates sufficient flue gas energy to drive a gas turbine, which can be used in a combined cycle for further efficiency gains.

Under the CCT program, American Electric Power sponsored demonstration of ABB Carbon PFBC technology. ABB Carbon's PFBC is a first-generation system, which sim-

ply uses the energy derived in the PFBC boiler to drive a gas turbine in a combined-cycle mode. The resultant commercial ABB Carbon system, offering a nominal 40 percent efficiency, is currently realizing market penetration.

DOE efforts now are directed toward development of a second-generation PFBC having significantly higher efficiency and lower emissions and cost than first-generation systems. Emphasis is on enabling use, and fully utilizing the potential of advanced high-temperature, high-efficiency gas turbines. By realizing this potential, PFBC efficiencies greater than 50 percent are possible.

Second Generation PFBC

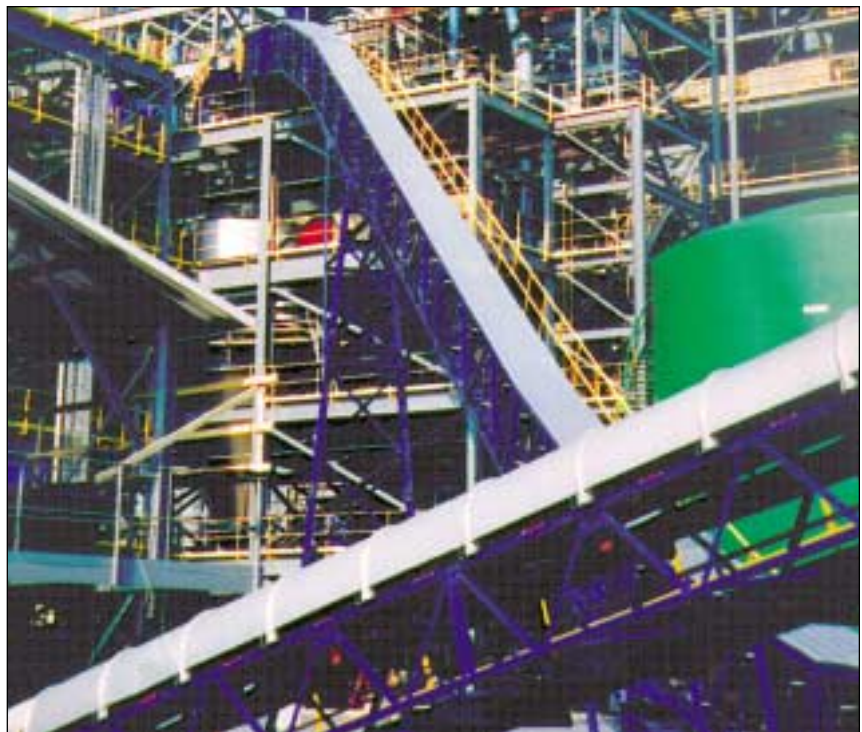


Activities in support of integrating and fully utilizing advanced gas turbines include: (1) integrating a coal pyrolysis (carbonizer) unit to produce fuel gas for combustion in the gas turbine; (2) a low-NO_x burner to combust the fuel gas; and (3) hot gas particulate filtration and chemical contaminant removal systems capable of operating at combustion and carbonizer exit gas temperatures (1,200–1,700 °F).

To further leverage PFBC and address future environmental concerns, parallel efforts are ongoing to: (1) develop more efficient sorbents to reduce operating costs and CO₂ emissions; (2) pursue cofiring of carbon neutral fuels; (3) ensure effective control of HAPs; and (4) conduct systems studies on integrating supercritical steam and fuel cell cycles.

Much of the PFBC development is to be carried out at the PSDF in Wilsonville, Alabama, operated by industry under a cost-shared partnership with DOE. The facility employs an innovative transport reactor to simulate fluidized-bed combustion flue gas streams and gasifier syngas, which enables evaluation of gas stream cleanup systems. Also in place is a PFBC unit consisting of a circulating pressurized fluidized-bed combustor, low-NO_x Multiannular Swirl Burner, and an HGPF system comprised of cylindrical ceramic filter element arrays (candle filters).

Plans are in place to complete development of ceramic and metallic candle filter-based HGPF systems (filter elements, failsafes, and support system) by 2002. Research on alternate HGPF materials and configurations will proceed in parallel, resulting in pilot-scale tests of advanced HGPF designs (ceramics for



The Power Systems Development Facility, located in Wilsonville, Alabama and operated by Southern Company Services, focuses on power system components and subsystems

combustion and metallic for gasification) in 2004.

Multi-contaminant filter (MCF) concepts addressing gas phase chemical contaminants will be solicited in 2001, and will be integrated with advanced HGPF systems in 2005. In 2006, pilot-scale tests of an MCF/HGPF barrier filter system are to be conducted.

Development of a limestone sorbent utilization model to optimize sulfur capture and minimize solid by-product is to be completed by 2001. Evaluation of alternate fluidized-bed combustion sorbents will begin in 2001, concluding in pilot-scale testing of selected sorbents in 2008.

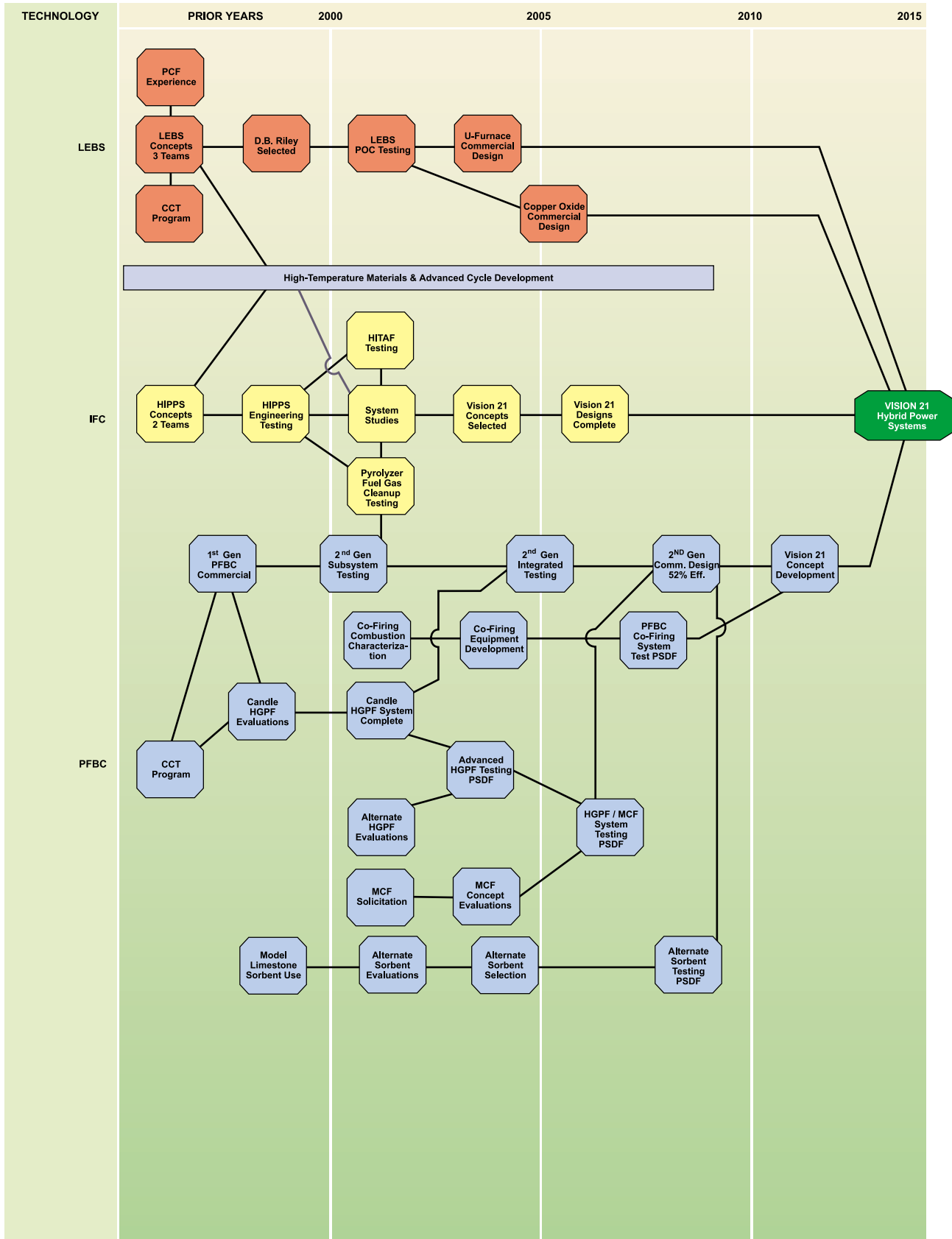
PFBC systems plans include integrated pilot-scale testing of a second-generation PFBC at the PSDF in 2005, and development of a 52-percent efficient second-generation PFBC by 2008. Combustion characterization of co-fired

carbon neutral fuels, such as biomass, in 2001 and subsequent development of appropriate feed, sorbents, and cleanup systems will lead to a PFBC co-firing capability by 2007. PFBC concepts, integrating other Vision 21 enabling technologies such as fuel cells, are to be developed by 2010.

The roadmap on the following page summarizes activities under the three Combustion Systems program areas.



ROADMAP



GASIFICATION TECHNOLOGIES

Performance Targets

Efficiency: >52%

Emissions:

NO_x – 0.06 lb/10⁶ Btu

SO₂ – 0.06 lb/10⁶ Btu

PM – 0.003 lb/10⁶ Btu

Cost: <\$1,000/kW

Year: 2008

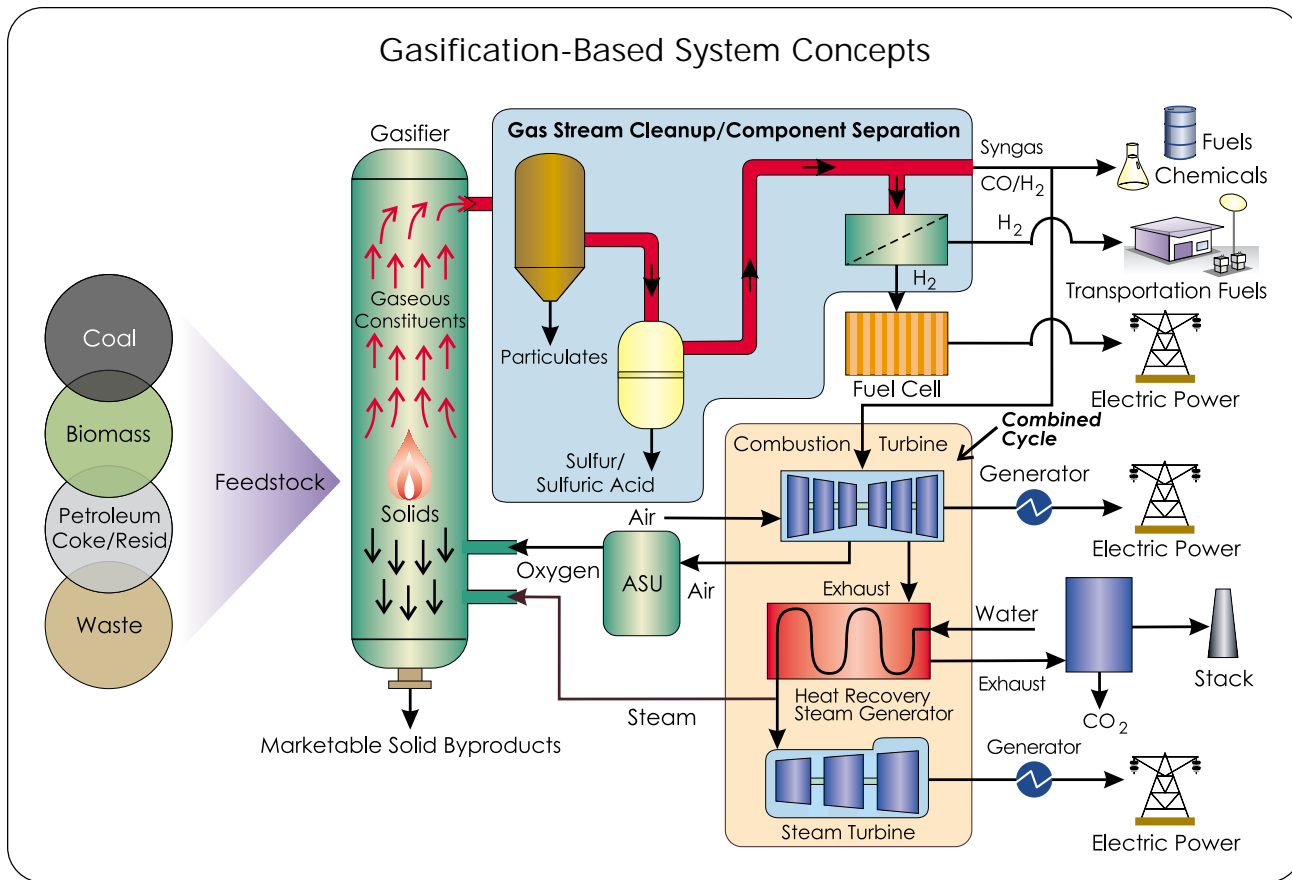
Gasification technologies represent the next generation of solid feedstock-based energy production systems. The heart of these systems is the gasifier. This unit is responsible for converting any carbon-based feedstock into synthesis gas (syngas), which is a mixture of carbon monoxide (CO) and hydrogen (H₂). This conversion is

accomplished under high pressures and temperatures in the presence of steam and air/oxygen. Under these conditions, chemical bonds in the feedstock are broken and the constituents are further reacted to form synthesis gas.

The mineral matter in the feedstock separates from the gaseous products and leaves the bottom of the gasifier either as an inert glass-like slag or other marketable solid product. The synthesis gas from the gasifier, in addition to containing CO and H₂, also has smaller quantities of hydrogen sulfide, methane, ammonia, and particulate matter. The synthesis gas subsequently is cleaned of these impurities to meet downstream process unit requirements.

Once cleaned, the synthesis gas can be used, in whole or in part, to produce electricity, steam, fuels, chemicals, hydrogen, and substitute natural gas. One configuration of gasification-based processes, IGCC, uses clean synthesis gas to fuel a gas turbine. The gas turbine drives an electric generator and its exhaust gas is used to produce steam to drive a steam turbine/generator. IGCC is one of the most efficient and environmentally friendly of today's commercially advanced power generation technologies, and can be further enhanced through integration with fuel cells.

Gasification-based processes are the only advanced technologies that offer both feedstock and product flexibility, while simultaneously



achieving near-zero emissions of sulfur, nitrogen oxides, and particulates. High operating efficiency of future gasification technologies (>52 percent) reduces CO₂ emissions, and the processes are readily adaptable for concentrating the remaining CO₂ for sequestration, a Vision 21 requirement. Through the development of advanced technologies, capital costs are expected to be reduced to below \$1,000/kW by 2008, making gasification competitive with natural gas combined-cycle, and the technology of choice for solid feedstocks.

To meet energy market demands and facilitate global commercial acceptance of gasification-based technologies, the program strategy emphasizes increased efficiencies, cost reduction, high system reliability and availability, feedstock and product flexibility, and near-zero emission of pollutants. The strategy consists of two key elements: Gasification Systems Technology, and Systems Analysis/Product Integration.

Gasification Systems Technology

Gasification Systems Technology supports both the introduction of new gasifiers with enhanced cost and performance characteristics, and the improvement of gasification technologies emerging from the CCT program.

Advanced gasification activities in the area of new gasifier development are primarily directed at a novel entrained-flow transport gasifier, which offers the potential for high efficiency, fuel flexibility, and low capital cost. Exploration continues in parallel for other emerging novel concepts that show promise. Development work on the



Wabash River Generating Station was repowered with a 262-MWe IGCC unit shown here

transport gasifier is currently centered at the PSDF and supported by the developer, Kellogg Brown & Root, NETL, and UNDEERC. The 2-ton/hour pilot-scale transport gasifier at the PSDF will serve as both a development unit and support unit for key gasification technology and PFBC component development.

Supporting research for enhancing gasification technology performance includes development of: (1) fluid dynamic data and advanced computational fluid dynamic modeling; (2) technologies for co-feeding coal and alternative feedstocks to high pressure gasifiers; (3) instrumentation for real-time measurement of critical process conditions; and (4) corrosion resistant refractories for harsh slagging gasifier and alternate feedstock operating environments. Products from the instrumentation and refractory development are to be evaluated at CCT projects demonstrating IGCC.

Industry efforts, through the PSDF, support development of a fuel-flex-

ible feed system capable of handling biomass, and wastes from refinery, municipal, industrial, agricultural, and forestry activities.

Milestones include: (1) demonstration of a fuel-flexible feed system by 2006, and (2) commercial designs for a gasification-based power system having greater than 52 percent efficiency (HHV), SO₂ and NO_x emissions at or below 0.06 lb/10⁶ Btu, particulate matter emissions at or below 0.003 lb/10⁶ Btu, and capital costs less than \$1,000/kW.

Gas cleaning and conditioning activities support development of particulate and chemical contaminant gas cleanup technologies necessary to achieve Vision 21 efficiency and emissions goals. This requires systems capable of operating in gasifier environments, and providing the downstream gas quality needed for integration with fuel cells, advanced turbines, and synthesis gas conversion technologies. HGPF and MCF research under the PFBC program area is leveraged by ensuring that

gasifier requirements are met along with those of PFBC. In addition, hot gas cleanup using regenerable sorbents is being addressed, with current emphasis on a transport desulfurization reactor and associated attrition-resistant sorbent and reactor model development. Other novel concepts are under study, the most promising of which will undergo testing at NETL's GPDU, and if successful, subsequently at the PSDF.

Plans are to complete development of ceramic and metallic candle filter-based HGPF systems (filter elements, failsafes, and support system) by 2002. Research on alternate HGPF materials and configurations will proceed in parallel resulting in pilot-scale tests of advanced HGPF designs (ceramics for combustion and metallic for gasification) in 2004.

MCF concepts addressing gas phase chemical contaminants, solicited in 2001, will be integrated with advanced HGPF systems in 2005. In

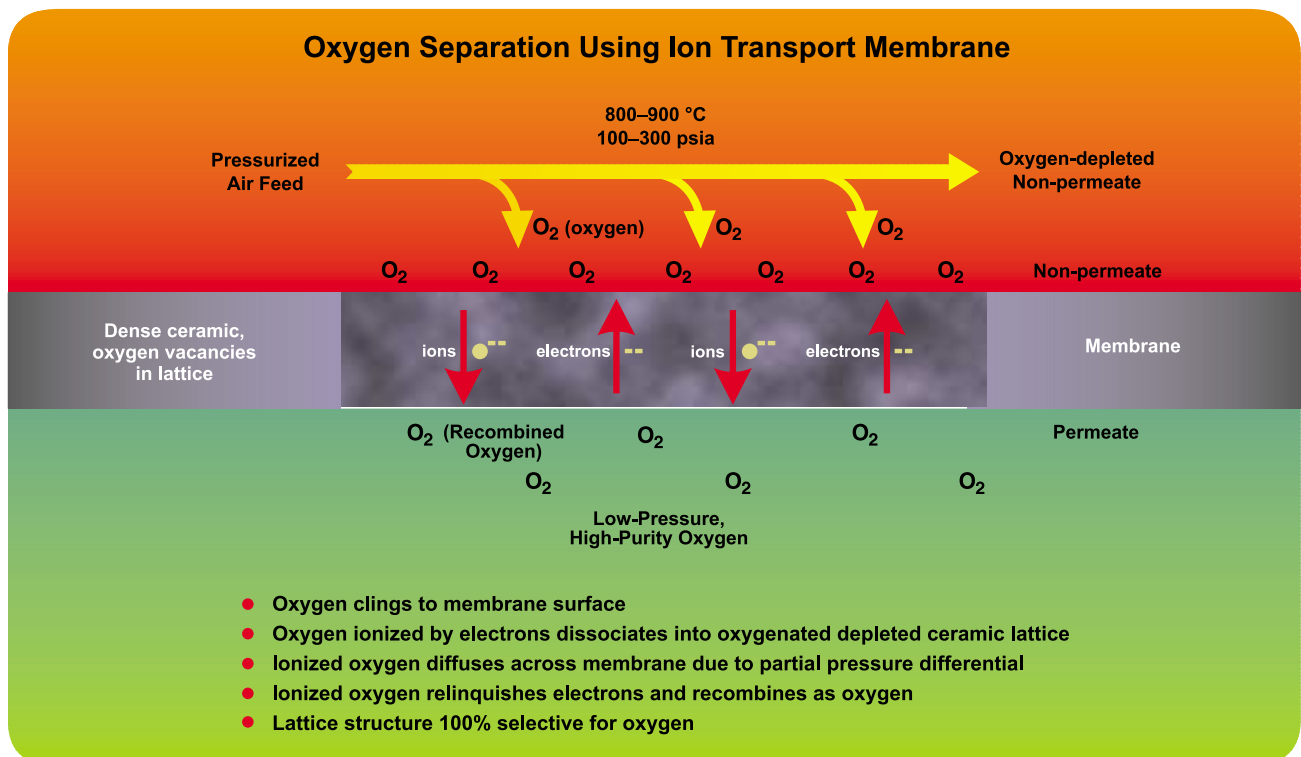
2006, pilot-scale tests of an MCF/HGPF barrier filter system will be conducted.

Gas separation activities are focused on development of a new breed of technologies using membranes and other novel approaches to dramatically reduce the energy required for gas separations critical to achieving Vision 21 goals. Two of the largest gas producing companies in the United States — Air Products and Chemicals, and Praxair — are developing ionic transport membranes (ITMs) for separating oxygen from air. These ITMs will displace energy-intensive cryogenic air separation plants, which represent a major cost for current gasification technologies. The Oak Ridge and Argonne National Laboratories are taking the lead in development of hydrogen separation membranes, which will reduce the cost of fuel cell applications and open the door to a hydrogen economy. Development of CO₂ separation technolo-

gies is also underway, including membrane and CO₂ hydrate separation techniques, through the combined efforts of industry, academia, and National Laboratories. CO₂ separation enables sequestration and hydrogen separation from gasifier-derived syngas.

Milestones include: (1) commercial availability of ITM/oxygen separation technology by 2008; (2) commercial offering of ceramic hydrogen separation membrane technology by 2010; and (3) commercial designs for a CO₂ hydrate separation technology by 2011.

Products/by-products activities are aimed at producing value-added products in lieu of waste streams to improve gasification technology economics. Efforts are ongoing to improve the quality and marketability of ash and slag derived from CCT projects demonstrating IGCC, and to evaluate a single step sulfur removal process at the PSDF.



Systems Analysis/ Product Integration

Process engineering and analyses are carried out by DOE's Gasification Product Team composed of Headquarters and NETL personnel. These activities provide the studies necessary to guide future R&D efforts, define R&D initiatives, and support domestic and international commercialization activities. Process optimization studies are being pursued to determine the lowest cost and highest efficiency approaches for baseload, co-generation, and co-production applications. Similar studies also will be pursued for advanced configurations that incorporate fuel cells and CO₂ capture technologies. Life cycle analyses are being performed to evaluate cradle-to-grave performance.

Technology demonstration is also supported by DOE. Demonstrations include CCT program demonstrations of four IGCC technologies using different gasifiers and gas cleanup systems. DOE ensures that important cost and performance data is collected and disseminated to support market acceptance of the technologies. Also, the data collected and the lessons learned are used to build a foundation for a

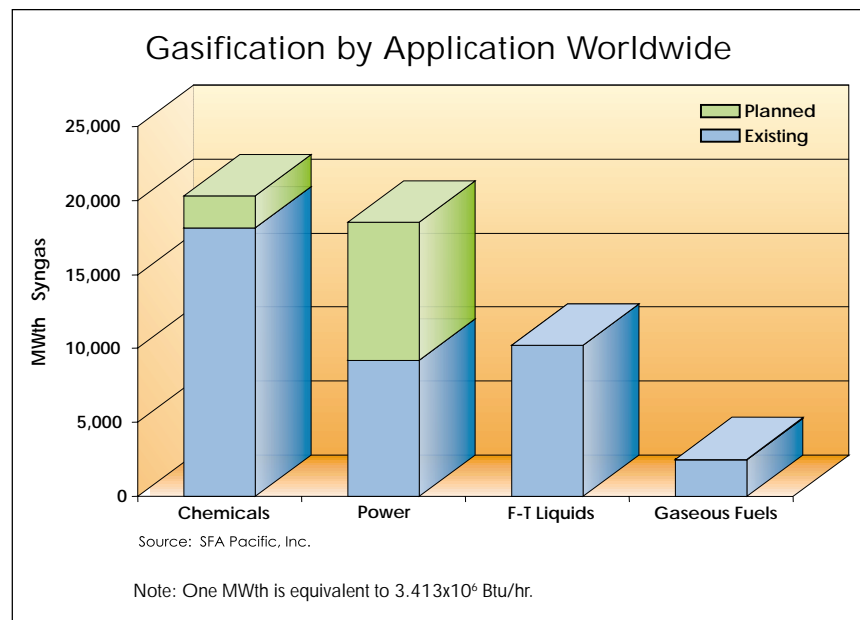
next generation of gasification technologies.

Moreover, the Gasification Technologies program is embarking on projects that will lead to the demonstration of co-production technologies for the manufacture of electricity, fuels, and chemicals; and the application of gasification in the pulp and paper industry.

The market potential for gasification-based processes is expected to grow considerably in the next few

decades because of gasification's environmental performance and operational flexibility. Databases on existing and planned gasification-based projects have been developed and are continually being updated. This information will be used to develop market strategies for both domestic and international markets.

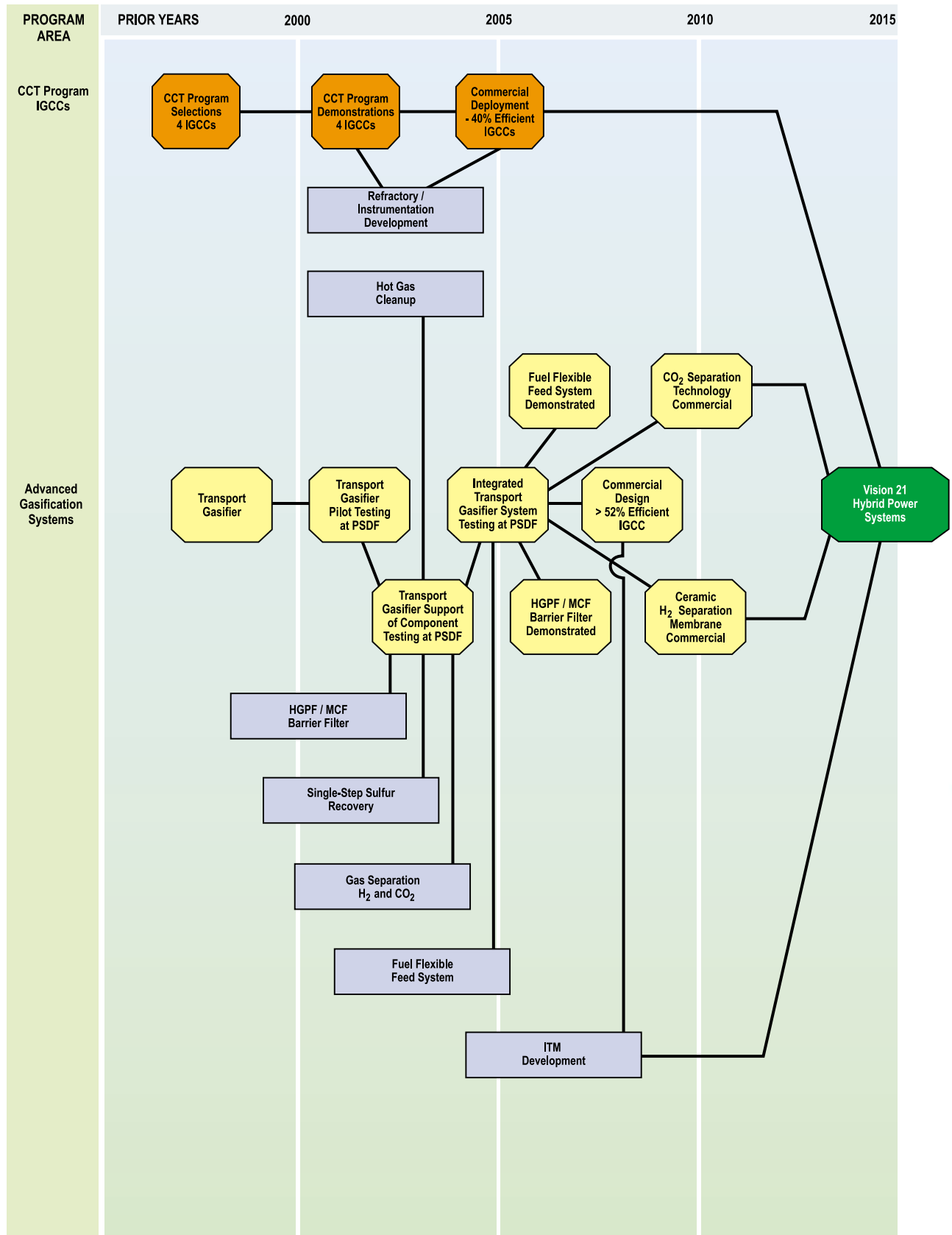
The following roadmap summarizes activities under the Gasification Technologies program area.



A recent surge in gasification-based technology applications has raised existing capacity to around 40,000 MWh (a measure of syngas heat energy). Much of the movement has been in the power industry.



ROADMAP



ADVANCED TURBINE SYSTEMS

Performance Targets

Size: Utility-Scale
 Efficiency: >60% LHV
 NO_x Emissions: <9 ppm
 Cost of Electricity:
 10% reduction
 Year: 2002

A gas turbine produces a high-temperature, high-pressure gas working fluid to induce shaft rotation by impingement of the gas upon a series of specially designed blades. The shaft rotation drives an electric generator and a compressor for the air used by the gas turbine. Many turbines also use a heat exchanger called a recuperator to impart turbine exhaust heat into the combustor's air/fuel mixture.

The gas turbine, once used solely in aviation applications, has evolved into a workhorse in industry and has become the premier electric generation system for peak and intermediate loads. Gas turbines are compact, lightweight, easy to operate, and come in sizes ranging from several hundred kilowatts to hundreds of megawatts.

The Advanced Turbine System (ATS) effort, in support of central power systems, is seeking to enhance the efficiency and environmental performance of utility-scale gas turbines. The utility-scale ATS objectives for operation on natural gas are to achieve 60 percent efficiency or more in a combined-cycle mode, NO_x emission levels less than 9 ppm, and a 10 percent reduction in the cost of electricity. Significantly higher turbine inlet tempera-

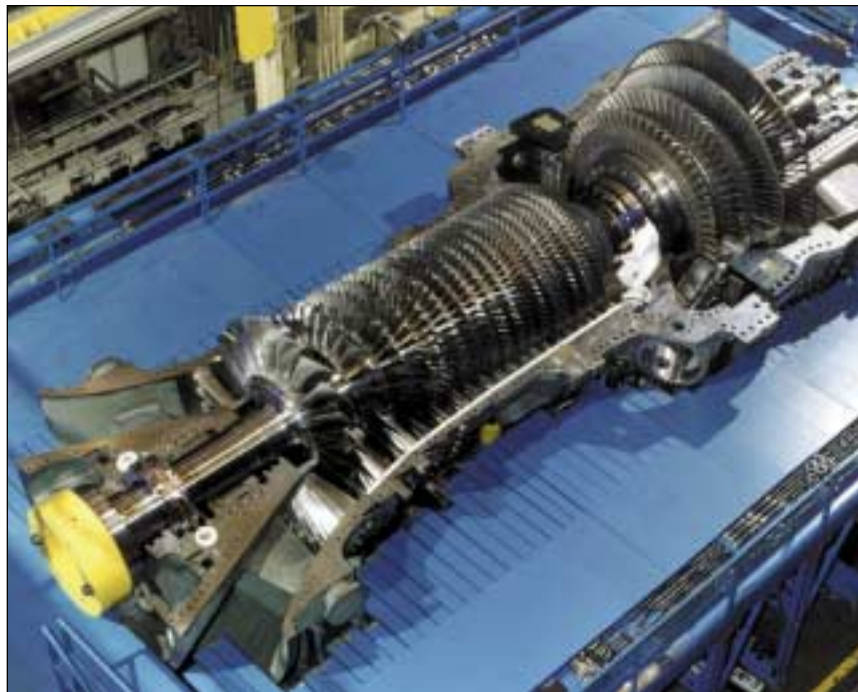
tures are required in order to achieve the efficiency objective. These higher temperatures in turn require advancements in materials, cooling systems, and low-NO_x combustion techniques.

The utility-scale ATS program is being carried out along parallel paths: (1) major systems development; and (2) technology base development, which supports ongoing and future major systems development. General Electric and Siemens Westinghouse, world renowned turbine manufacturers, are conducting the major systems development work. Each is developing their own concept under separate cost-shared cooperative agreements with DOE. Both companies have completed component and subsystem testing. Completion of prototype system testing to evaluate combustion, heat transfer, and aerodynamic design under actual operating conditions is

scheduled for 2001. Commercial units are scheduled for market entry in 2002, to meet increasing demands for natural gas-based power.

The focus of General Electric's effort is an "H" series gas turbine. To accommodate elevated turbine inlet temperatures, General Electric is employing a novel steam cooling system and newly developed single-crystal turbine blades. Development of the single-crystal casting technique for large complex components represents a breakthrough in manufacturing methods. Single-crystal materials are stronger than polycrystalline materials and provide superior resistance to high-temperature corrosive conditions.

Siemens Westinghouse is using its 501G turbine as a test bed for the ATS design. Computer modeling has allowed design refinements that are contributing to capital cost re-



General Electric's utility-scale advanced turbine



Siemens Westinghouse house utility-scale advanced turbine

duction and efficiency enhancement. These include lean, premixed combustion and catalytic systems. Siemens Westinghouse also has developed brush and abradable coating seals to reduce internal leakage, and thermal barrier coatings for turbine blades to permit higher temperatures. These developments have already been incorporated into the commercial 501G turbine.

The ATS technology base development effort includes both the advancements in materials, cooling, instrumentation, and control and combustion techniques needed for operation at elevated temperatures,

as well as specific studies in support of component and systems development in areas such as heat transfer and aerodynamics. The work is carried out through in-house research at NETL and an industry/university consortium established under the ATS program.

NETL conducts collaborative research with universities and industry in low-emissions and low-Btu combustion at highly instrumented, established facilities. The low-emissions activities support ATS NO_x emission reduction goals. The low-Btu combustion work supports expanding the fuel flexibility of gas

turbines by developing the capability to operate on gases derived from gasification of coal, biomass, and wastes. The in-house work also involves development of the associated instrumentation and controls. An example of a specific NETL activity is its partnership with United Technology Research Center. The work entails identifying and modeling combustor configurations to efficiently burn high-moisture, high-pressure gas/air mixtures. This humid air turbine (HAT) concept has the potential for very low emissions and enhanced power and efficiency.

The industry/university consortium supports applied research for 100 U.S. universities, including workshops and student internships at industry facilities. Under the direction of the South Carolina Institute for Energy Studies, contracted universities perform applied research specific to the needs of the ATS developers in combustion, aerodynamics, materials, and heat transfer.



NEXT GENERATION TURBINES

Performance Targets

- Flexible Turbine Systems:
15% net efficiency gain
- Turbine/fuel cell hybrid:
70% efficiency mid-term
80% efficiency long-term

A follow-on program to the ATS is the Next Generation Turbine (NGT) program. The NGT goals are to:

- Reduce the life-cycle cost and improve the RAM of the existing and future turbine power plant infrastructure;
- Develop and demonstrate ultra-clean, high performance turbine power systems for near-term power markets and long-term integration into Vision 21 power plants;
- Develop advanced materials, combustion systems, computational tools, and sensors/controls/instrumentation to solve crosscutting technical barriers; and
- Collaborate with regulatory agencies and develop sound technical information to produce appropriate and beneficial regulatory decisions related to gas turbine power plants.

NGT systems will provide significant public benefits through increased reliability, superior performance, reduced life-cycle costs, and near- and long-term reductions of CO₂, NO_x, and other emissions. Because NGT systems will be fuel-flexible, they will expand the options for high-efficiency conversion of domestic fuels into electric power.

In the near term, NGT systems will be suitable for new capacity, re-powering of older fossil units, combined heat and power applications, and as efficiency enhancement units for existing fossil-fueled steam plants. In the long term, NGT systems will be adapted and integrated into Vision 21 fossil-fueled plants.

Enabling technologies developed under the program may benefit and support other missions of the U.S. government, such as enhancing defense capability and serving the needs of future-generation military operations. Another large benefit of the NGT program is the creation and maintenance of U.S. jobs directly related to the manufacture of turbine systems, and those indirectly created and maintained because of the low-cost, environmentally superior performance that will result, helping to keep U.S. businesses competitive.

The NGT program intends to establish a committee to coordinate activities with members from the DOE Office of Energy Efficiency and Re-

newable Energy (EERE), National Aeronautics and Space Administration (NASA), Department of Defense (DoD), National Association of State Energy Officials, California Energy Commission, National Institute for Standards and Testing, and other federal and state organizations. Specific linkages include: the EERE micro-turbine program; NASA Ultra-Efficient Engine Technology program, and DoD propulsion programs — Integrated High Performance Turbine Engine Technology, the Versatile, Affordable Advanced Turbine Engines program, and the Navy Future Ships programs. In addition, an Industry Peer Review Board is being established to ensure program quality and relevance; and workshops and planning meetings will be held throughout program implementation to seek stakeholder input.

There are three elements of the NGT program — Systems Development and Integration, RAM Improvement, and Crosscutting Research and Development.



Systems Development and Integration

Turbine systems will be developed to meet the needs of emerging deregulated power supply markets. These systems will respond to stakeholder needs by providing highly efficient, reliable, and ultra-clean performance, and by offering flexibility to perform effectively independent of duty cycle or fuel used. Systems currently under evaluation and development are flexible turbine systems and turbine/fuel cell hybrids greater than 30 MW in output rating.

Six companies have been selected by DOE to define **Flexible Turbine Systems**:

- *Pratt and Whitney*, will conduct a study of an intercooled aero-derivative industrial gas turbine that is based on a commercial aircraft engine (PW8160) now being developed.
- *Rolls Royce Allison*, will enhance and simplify a gas turbine engine design now used in U.S. Navy ships (WR21) by modifying recuperation and intercooling technologies.
- *Siemens Westinghouse Power Corp.*, will pursue a modular gas turbine with new “enabling” technologies in a single, low-cost system design that holds worldwide applications.
- *GE Power Systems*, will recommend an engine configuration after performing a parametric study of three broad categories of gas turbines: aero-derivative, heavy duty, and a potential hybrid combining components of the other two categories.

- *Ramgen Power Systems, Inc.* is using established ramjet principles applied in missiles and military aircraft in the development of a stationary power generator. Aerodynamics at supersonic velocities are applied to compress and expand a working fluid in lieu of mechanical parts, thereby simplifying design and enabling low capital costs. Moreover, complete pre-combustion fuel mixing and high fuel conversion efficiency enable simple cycle efficiencies greater than 50 percent, use of dilute waste fuels, and NO_x emissions below 4 ppm.

Under a partnership with NETL, Ramgen Power Systems, Inc. is now testing a pre-prototype (beta) Ramgen engine. Work will commence on the manufacture of a second smaller scale beta engine in 2001 for field testing. Longer-term development plans are to build a Mach 3.25 unit with a simple cycle efficiency of approximately 44 percent and to ultimately build a Mach 3.5 unit with an initial cycle efficiency of 50 percent, and eventually 55 percent as materials and cooling systems improve. The size range envisioned is 500 kW to 40 MW.

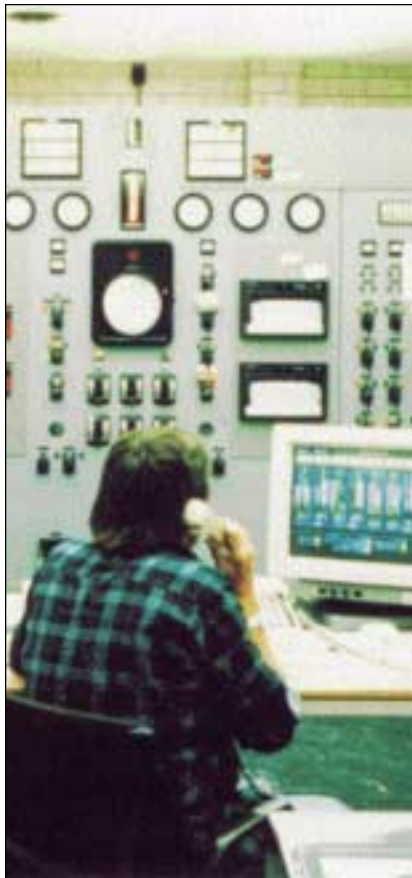
- *Clean Energy Systems* is using a process that injects water into a reactor where oxygen (in lieu of air) is used to combust natural gas. The resultant gas, which is 95 percent steam and 5 percent carbon dioxide, is used to drive steam turbines at pressures of 3,000 pounds per square inch, or more, and at temperatures of 2,600–3,200 °F. The high temperatures and pressures produce efficient performance, no combustion products are released to the atmosphere, and CO₂ can be effectively separated for sequestration.

NETL is partnering with Clean Energy Systems to fabricate and demonstrate a 10-MW gas generator by 2002. Ultimately, if successful, the system will be integrated into a Vision 21 power plant concept.

Promising concepts could become the basis for more detailed engineering designs, component development and testing, and ultimately, the manufacturing of prototype machines. If the development effort is successful, the first NGT turbine systems could be ready for market entry around 2008. Integration of NGT technology into Vision 21 plants is planned for the 2010–2015 time frame.

Turbine/Fuel Cell Hybrids use synergistic integration of high-temperature fuel cells and gas turbines. The goals for these hybrids are to achieve 60 percent efficiency in the near term, 70 percent in the midterm, and 80 percent in the long term (lower heating value) at costs 10–20 percent lower than comparably sized conventional power plants.

Hybrid systems studies by Siemens Westinghouse Power Corp., Rolls Royce Allison, FuelCell Energy, Caterpillar, and Northern Research and Engineering Corporation laid the foundation for follow-on efforts. DOE selected FuelCell Energy-Capstone Turbine and Rolls Royce Allison to conduct 280-kW hybrid demonstrations and develop designs for a 40-MW hybrid system. DOE also has agreements with Siemens Westinghouse to conduct hybrid demonstrations at 250-kW and 1-MW scales. EPA and the European Commission are to partner with DOE on the demonstrations.



RAM Improvement

Reliability, Availability, and Maintainability (RAM) Improvement efforts will develop the instrumentation, inspection and examination technology, analytical modeling, and evaluation techniques necessary to monitor turbine performance and determine when maintenance is needed based on turbine condition. Plant operations technologies will be integrated into advanced information platforms for multi-facility management. The power industry is moving toward managing plant maintenance through condition-based monitoring and expert health prediction tools. The introduction of increasingly high turbine temperatures requires close operational surveillance of critical hot-gas-path components, which in turn requires development of predictive models and instrumentation to assess their integrity.

RAM Improvement activities will be implemented by a consortia consisting of government organizations, industry, universities, and National Laboratories.

Crosscutting Research and Development

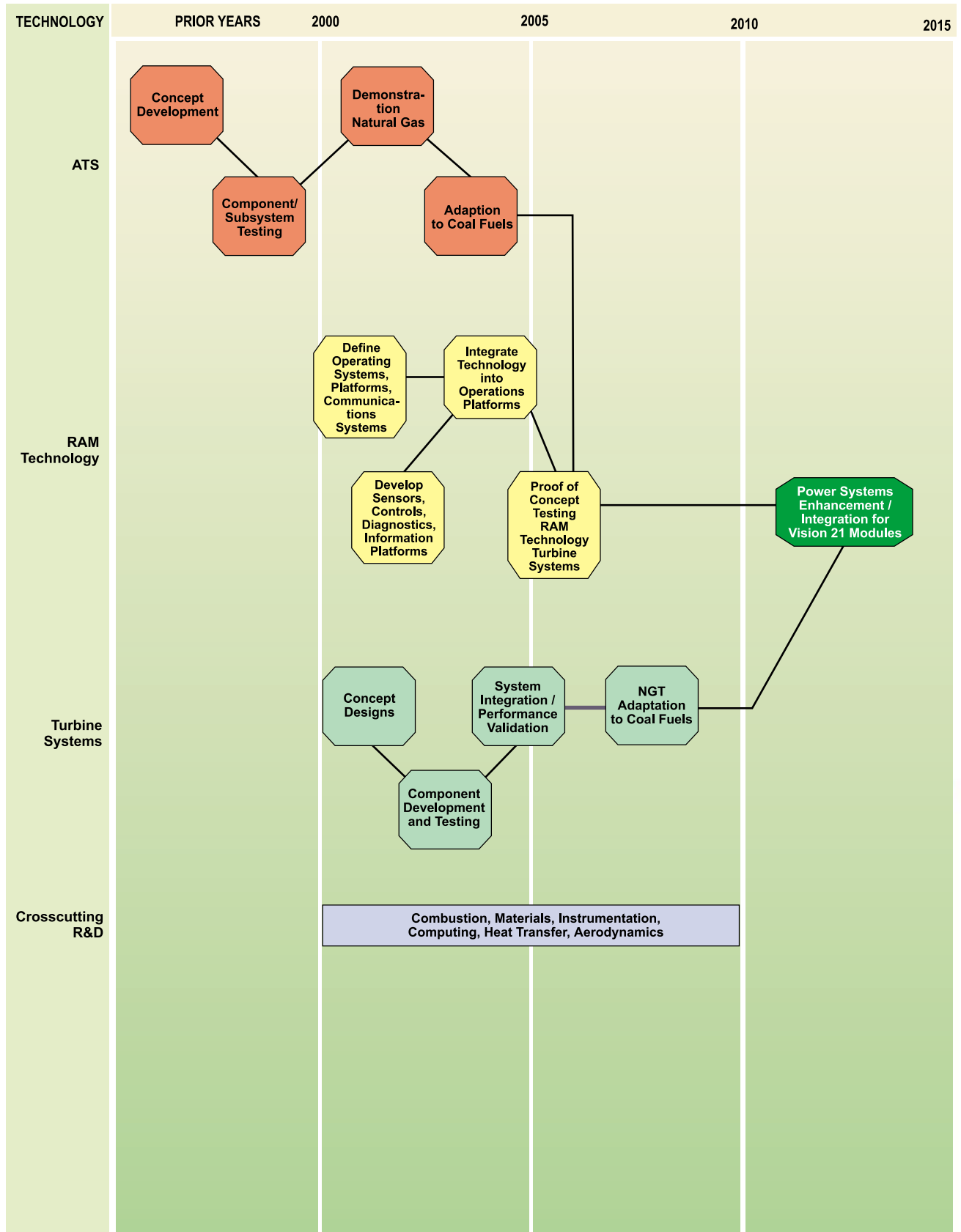
Crosscutting Research and Development provides the combustion modeling, materials science, computer simulations, and instrumentation needed to support new technology development. Activities will be conducted by a consortia of U.S. government organizations, industries, universities, and National Laboratories.

The following roadmap summarizes activities under the two Turbine Systems program areas.

Ramgen Engine Prototype



TURBINE SYSTEMS ROADMAP



IN PARTNERSHIP WITH INDUSTRY

TAMPA ELECTRIC COMPANY

In 1989, Tampa Electric Company embarked on a mission to respond to customer needs for additional power in the most fiscally and environmentally responsible manner possible. Tampa Electric first engaged environmental groups to identify a plant location that represented the least threat to the environment. A consensus was reached on an abandoned phosphate mine site in Polk County, Florida. Coal was chosen as the fuel to keep operating costs low, and IGCC technology was selected to provide the least environmental impact.

Tampa Electric Company's collaboration with environmental groups resulted in the creation of uplands, wetlands, and a wildlife corridor.

In 1996, the 250-MWe IGCC Polk Power Station, Unit No. 1 went on line and continues in commercial service. The heart of the unit is a Texaco oxygen-blown, entrained flow gasifier. As of September 2000, the

IGCC system had accumulated over 18,000 hours of operation and produced over 7,000,000 MWh of electricity.

The project has drawn visitors from around the world, and the Texaco gasifier-based IGCC is realizing a significant number of commercial sales.

For its accomplishments, the project is the recipient of *Power* magazine's 1997 Powerplant Award, the 1993 Ecological Society of America Corporate Award, the 1993 Timer Powers Conflict Resolution Award, and the 1991 Florida Audubon Society Corporate Award.

GENERAL ELECTRIC'S H SYSTEM™ TURBINE

In September 1999, General Electric announced that its newest H System™ gas turbine was ready to move over the commercial threshold. Having passed a critical verification test, the H System™ gas turbine will be sited at Sithe's Heritage Station in Scriba, New York.

This turbine is a culminating achievement of the DOE's Advanced Turbine System research and development program that began in the early 1990s, when General Electric was one of six developers selected to begin designing concepts for a breakthrough turbine system.

Designed to work in a combined-cycle mode, the H System™ gas turbine will be the first to break through the 60 percent efficiency threshold, beating the efficiency of prior best available turbines by five percentage points. This significant jump in efficiency makes the H System™ turbine the lowest producer of carbon dioxide per kilowatt of electricity of any gas turbine available today.

Moreover, the H System™ turbine operates cleaner than any of today's utility gas turbines. Its NO_x emission levels of 9 ppm will be half the average of the turbines now in use, making the new technology suitable for siting in the Nation's most environmentally sensitive areas.



Tampa Electric Company's 250-MWe Polk Power Station, Unit 1 IGCC facility



The 400-ton Model MS7001H (H System™) turbine is the size of a locomotive

DISTRIBUTED GENERATION



PROVIDING RELIABLE, FLEXIBLE POWER

INTRODUCTION

Program Areas

- Second Generation Fuel Cells
- Vision 21 Fuel Cell/Turbine Hybrids
- SECA Solid State Fuel Cell

A confluence of utility restructuring, technology evolution, public environmental policy, and an expanding electricity market are providing the impetus for distributed generation to become an important energy option in the new millennium.

Distributed generation is the strategic application of relatively small generating units (typically less than 30 MWe) at or near consumer sites to meet specific customer needs, to support economic operation of the existing power distribution grid, or both. Reliability of service and power quality are enhanced by proximity to the customer and efficiency is improved in on-site applications by using the heat from power generation.

While addressing distributed generation potential in general, the program presented here focuses on fuel cells and the U.S. Department of Energy (DOE) efforts to bring them into the marketplace.

The Distributed Generation program contributes to two of the energy challenges that are being addressed in the National Energy Strategy: (1) improving the environmental acceptability of energy pro-

duction and use by improving the efficiency and economics of the use of natural gas through the use of advanced technologies, and (2) increasing the competitiveness and reliability of U.S. energy systems. This is achieved through the strategy of encouraging the development and deployment of distributed power technologies to satisfy market forces for smaller, modular power technologies that can be installed quickly, close to consumer demand centers.

Fuel cells offer a distributed generation option with the potential to

revolutionize power generation. Fuel cell systems have few moving parts, making them reliable as well as quiet. No solid wastes are produced and pollutant emissions are negligible. The potential electrical efficiencies can reduce carbon dioxide emissions by 50 percent compared to existing power plants. Moreover, their modular construction and electrochemical processing allow suppliers to match demand and maintain efficiency. Fuel cells are beginning to enter the market, but require additional research and development to realize widespread deployment.

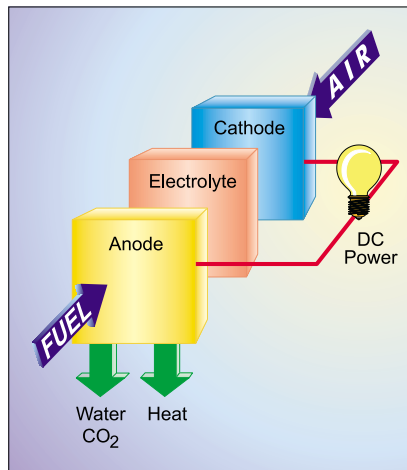


Phosphoric acid fuel cells (manufactured by the ONSI Corporation) have been sited, permitted, installed, started, operated, and maintained in a real-world environment. The fleet of ONSI fuel cells continues to demonstrate reliable, safe operation in a variety of climates, applications, and service scenarios. Here, an ONSI fuel cell unit is being installed in a location in Times Square in New York City. [Photo courtesy of ONSI Corporation]

Fuel Cell Defined

Fuel cells work without combustion and its environmental side effects. Power is produced electrochemically by passing a hydrogen-rich fuel over an anode, and air over a cathode, and separating the two by an electrolyte. In producing electricity, the only by-products are heat, water, and CO₂. Hydrogen fuel can come from a variety of hydrocarbon resources by subjecting them to steam under pressure (called reforming or gasification). The electrolyte, which induces the fuel cells electrochemical reactions, can be composed of liquid or solid media. The media used differentiates the type of fuel cell.

The direct electrochemical reaction in lieu of moving parts to produce electricity has inherent efficiency advantages. Overall system efficiency can be enhanced by using the high energy heat derived from the fuel cell reactions either in combined heat and power (CHP) or in combined-cycle applications (gen-



erating steam for additional electric power). The CO₂ is in concentrated form, which facilitates capture for recycling or sequestration. The absence of moving parts results in very low noise levels. Stacking of cells to obtain a usable voltage and power output allows fuel cells to be built to match specific power needs.

Fuel cell systems also require a power conditioner to convert direct current (DC) from the fuel cell to the more commonly used alternating current.



Applications

There are a number of basic applications, outlined below, that represent typical patterns of services and benefits derived from distributed generation.

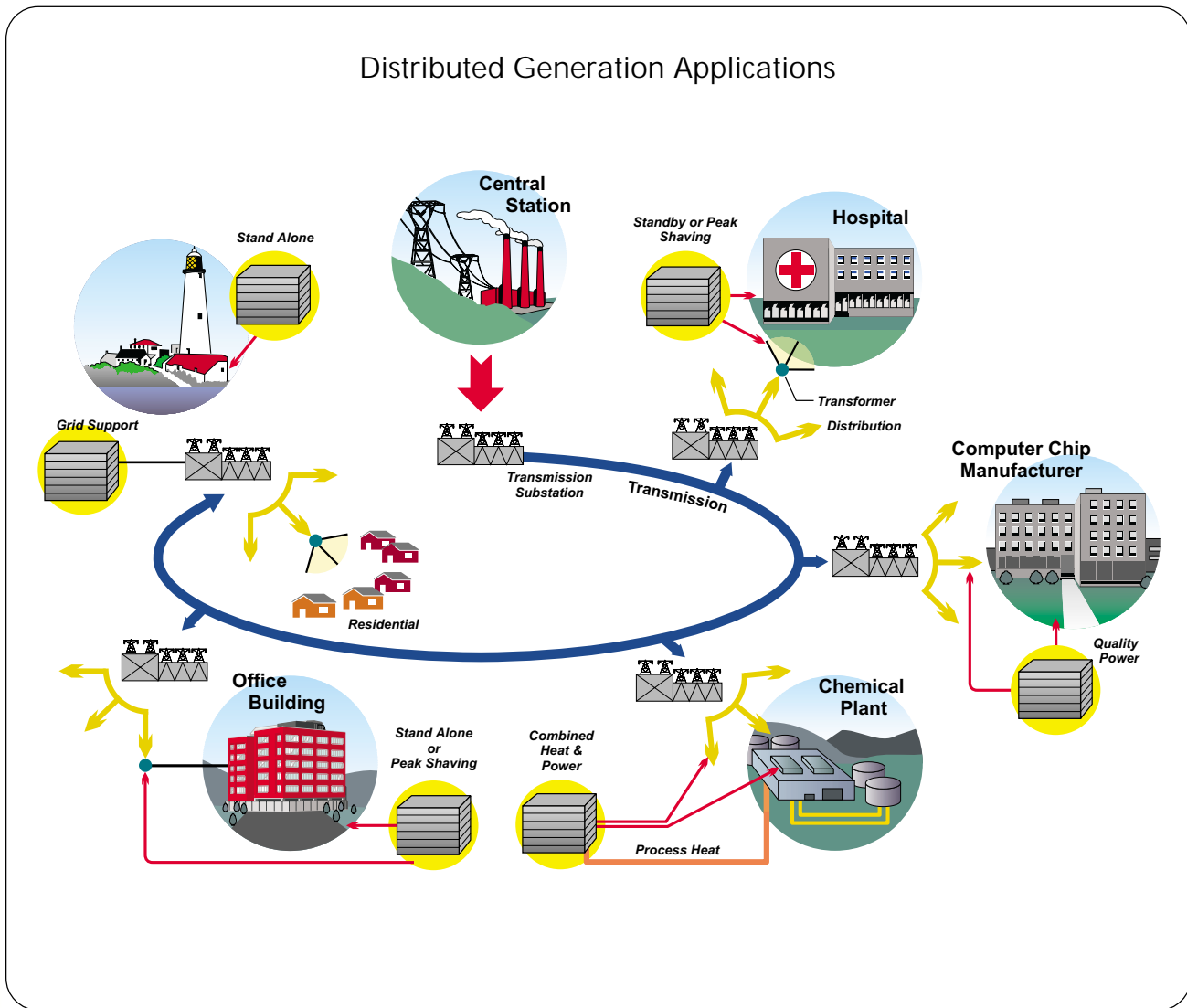
- **Standby Power.** Standby power is used for customers that cannot tolerate interruption of service for either public health and safety reasons, or where outage costs are unacceptably high. Since most outages occur as a result of storm or accident related transmission and distribution (T&D) system breakdown, on-site standby generators are installed at locations such as hospitals, water pumping

stations, and electronic-dependent manufacturing facilities.

- **Combined Heat and Power.** Power generation technologies create a large amount of heat in converting fuel to electricity. If located at or near a customer's site, heat from the power generator can be used by the customer in what are called CHP or cogeneration applications. CHP significantly increases system efficiency when applied to mid- to high-thermal use customers such as process industries, large office buildings, and hospitals.
- **Peak Shaving.** Power costs fluctuate rapidly depending upon de-

mand and generation availability. These fluctuations are converted into seasonal and daily time-of-use rate categories such as on-peak, off-peak, or shoulder rates. Customer use of distributed generation during relatively high-cost on-peak periods is called peak shaving. Peak shaving benefits the energy supplier as well, when energy costs approach energy prices.

- **Grid Support.** The power grid is an integrated network of generation, high voltage transmission, substations, and local distribution. Strategic placement of distributed generation can provide system benefits and precludes the need for expensive upgrades.



DRIVERS

While central power systems remain critical to the Nation's energy supply, their flexibility to adjust to changing energy needs is limited.

Because central power is composed of large, capital-intensive plants and a T&D grid to disperse electricity, significant investments of time and money are required to increase capacity. Distributed generation, on the other hand, complements central power by: (1) providing a relatively low capital cost response to incremental increases in power demand; (2) avoiding T&D capacity upgrades by locating power where it is most needed; and (3) providing the flexibility to put surplus power back into the grid at user sites.

Utility restructuring opens energy markets, allowing the customer to choose the energy provider, method of delivery, and attendant services. The market forces favor small, modular power technologies that can be installed quickly in response to market signals. This restructuring comes at a time when:

- Demand for electricity is escalating domestically and internationally;
- Impressive gains have been made in the cost and performance of small, modular distributed generation technologies;
- Regional and global environmental concerns have placed a premium on efficiency and environmental performance; and
- Concerns have grown regarding the reliability and quality of centralized electric power generators.



Robotic fabrication, as shown here, is becoming commonplace in the manufacturing industry and is mandating high-quality power for the associated electronic components.

During recent years the term “new economy” has emerged in the nation’s lexicon to describe the rapidly growing electric, telecommunication, biotechnology, and computer industries. Coincident with the explosive growth in the new economy comes the deregulation of the electric utility industry and the emphasis on competition in wholesale power markets, along with pressure to keep costs low. Deregulation has contributed to lower capacity margins in some regions of the country with the attendant increase in likelihood of power outages and reduction in power quality that can deal a crippling blow to the bottom line of new economy firms that must rely on reliable, high quality power sources. Industries are examining alternatives to reliance on the conventional grid supplied power. Distributed power generation systems provide an effective alternative for use by new economy industries, which represent an enormous market opportunity.

Worldwide demand for electricity is expected to double in the next twenty years. International markets are expected to expand rapidly, increasing nine trillion kilowatt-hours by 2020. Much of this increase is likely to occur in developing countries where the electricity infrastructure is modest or non-existent. The market potential in remote power generation is very large and represents a major opportunity for U.S. equipment manufacturers, suppliers, and power developers of distributed generation.



ACCOMPLISHMENTS

In fiscal year 1995, fuels cells became an integral part of the federal government's strategy to address global climate change concerns.

Through a Defense Department appropriations bill, Congress authorized the Climate Change Fuel Cell program — a joint effort of the U.S. Department of Defense (DoD) and DOE to accelerate commercialization of fuel cells. The National Energy Technology Laboratory (NETL) is responsible for implementing the program, which is managed by the U.S. Army Construction Engineering Research Laboratory.

The program is a key element of the Federal Administration's Climate Change Action Plan designed to curb greenhouse gas emissions

through expedited deployment of highly efficient, clean technologies. Defense Department goals were addressed as well by helping to create a fuel cell manufacturing capability critical to their energy security and readiness needs. The Climate Change Fuel Cell program leveraged cooperative government/industry fuel cell development efforts and resulted in successful commercialization of a first generation of fuel cells using a phosphoric acid electrolyte. To date, there have been over 200 turnkey installations of 200-kW phosphoric acid fuel cell (PAFC) units, using ONSI PC25 technology around the world. PAFC systems operate at temperatures sufficient for providing hot water and space heating and have electrical efficiencies ranging from 40–45 percent on a lower heating value (LHV) basis.

Development of second generation high-temperature fuel cells is proceeding efficiently. Both molten carbonate fuel cells (MCFCs) and solid oxide fuel cells (SOFCs) are in advanced stages of development. These high temperature systems offer fuel-to-electricity efficiencies of 50–60 percent and overall thermal efficiencies of 80 percent in CHP and combined-cycle applications. The NETL is working with FuelCell Energy to bring the MCFC to commercial fruition, and is working with Siemens Westinghouse Power Corporation (SWPC) to commercialize the SOFC. Both participants have demonstrated their technologies and shown the promise needed to proceed with commercial prototype demonstrations.



A FuelCell Energy (formerly Energy Research Corp) molten carbonate fuel cell

ACTIVITIES

High-temperature MCFCs and SOFCs are entering the commercial demonstration phase.

High temperatures enable internal reforming of fuels, fuel-to-electricity efficiency up to 60 percent LHV, and production of high quality heat for CHP and combined-cycle applications. Moreover, these units either tolerate or use reformed fuel constituents such as carbon monoxide, which represents a poison to PAFCs and proton exchange membrane fuel cells (PEMFCs). The heat developed in producing electricity also makes MCFCs and SOFCs ideal candidates for integration with gas turbines.

Market entry for natural gas-based MCFCs and SOFCs is planned for 2003. Demonstration objectives include reducing capital costs to \$1,500/kW. Subsequent to market entry, capital costs are expected to decline as manufacturing capacity and capability increase. Follow-on testing will address expanding the fuel options by operating on coal-derived synthesis gas.

Development of turbine/fuel cell hybrids using MCFCs and SOFCs in combination with gas turbines is underway. The synergy offers the potential for fuel-to-electricity efficiencies of 60–70 percent. Systems studies by SWPC, Rolls Royce Allison, FuelCell Energy, Solar Systems, and Northern Research and Engineering Corporation laid the foundation for follow-on efforts. DOE selected FuelCell Energy-Capstone Turbine and Rolls Royce Allison to conduct 280-kW hybrid demonstrations and develop designs for a 40-MW hybrid system. DOE



100-kW SOFC cogeneration system operating in the Netherlands, built by Siemens Westinghouse

also has agreements with SWPC to conduct hybrid demonstrations at 250-kW and 1-MW scales. The U.S. Environmental Protection Agency (EPA) and the European Commission are to partner with DOE on the demonstrations. Commercial application of a 70 percent efficient turbine/fuel cell hybrid is planned for 2010.

Under a Solid State Energy Conversion Alliance (SECA) initiative, a solid state fuel cell is being developed. The SECA initiative is attempting to break the capital cost barrier, ultimately producing fuel cells with a factory cost of less than \$400/kW for stationary power generation and even lower for transportation applications. The key will be the *mass customization* of ceramic-based fuel cells using techniques adapted from recent revolutionary advances in solid state electronics, materials, and fuel cell designs.

SECA is structured to accelerate the development of the industrial base needed to produce low-cost solid state fuel cells in the near term. By leveraging government and industry resources, SECA objectives are to introduce an \$800/kW solid state fuel cell having between 40 percent to 60 percent fuel-to-electricity efficiency within three years and a \$400/kW fuel cell by 2010. The basic building block for this is a 5-kW module that can be combined like batteries to meet the particular power requirement. Ultimately, the SECA solid state fuel cell technology will become a key Vision 21 enabling technology.



LINKS AND CROSSCUTS

The Office of Fossil Energy (FE) and the Office of Energy Efficiency and Renewable Energy (EERE) jointly manage the DOE Distributed Generation Systems program. DOE's internal R&D council provides assistance in the management and implementation of the program.

Both FE and NETL are building an alliance of government agencies, commercial developers, universities, and materials laboratories committed to the development of low-cost, high-power-density solid state fuel cells for a broad range of applications. The alliance is SECA. SECA

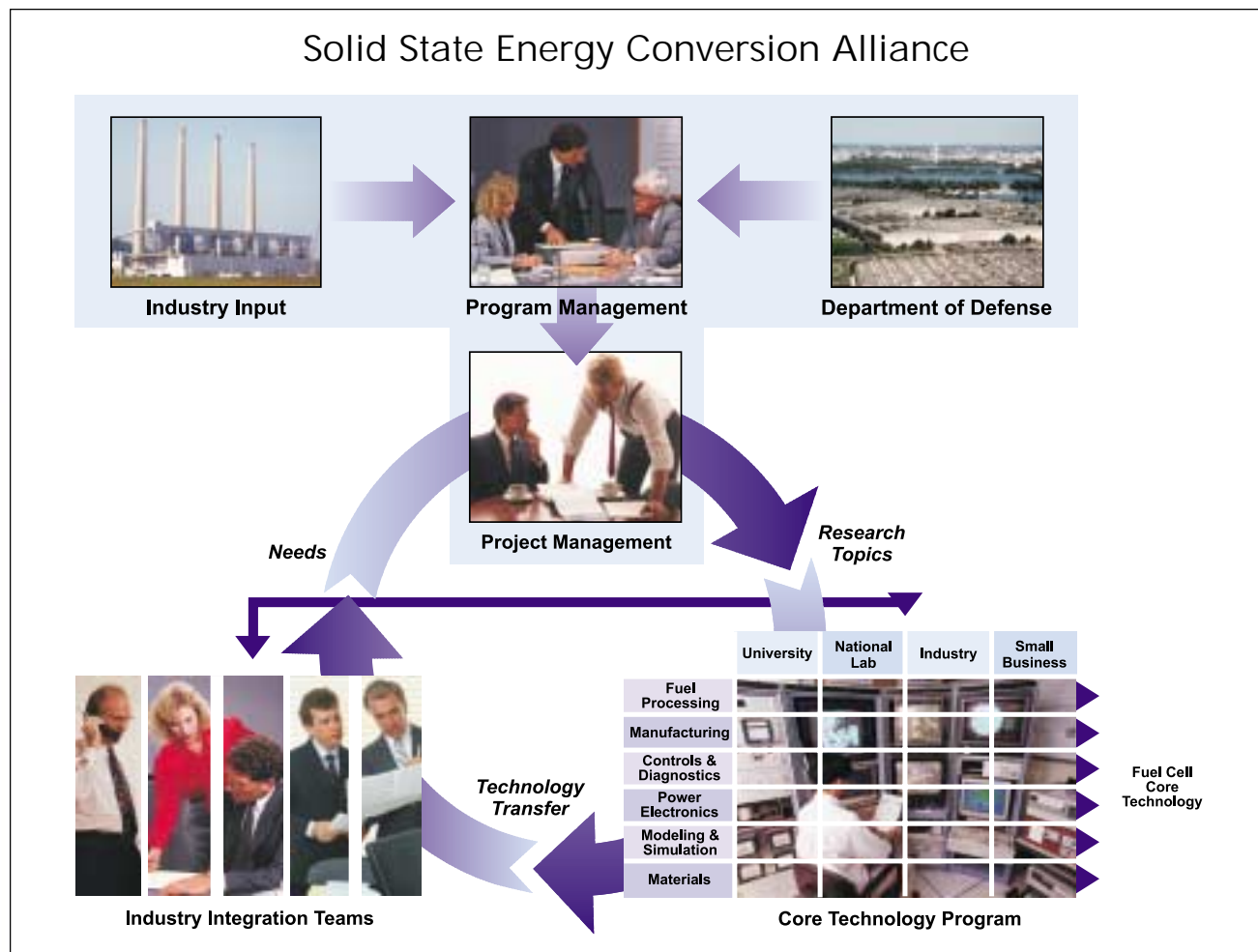
represents a new model for joint government and industry technology development. The structure of SECA is designed to leverage resources to overcome the most difficult technical barriers, while enabling industry to maintain a competitive posture. Two DOE national laboratories, NETL and Pacific Northwest National Laboratory (PNNL) are the driving forces behind SECA, providing the leadership, focus, and integration needed to bring solid-state fuel cell technology into near-term markets.

Both FE and the Department of Defense collaborate to accelerate the commercial deployment of fuel

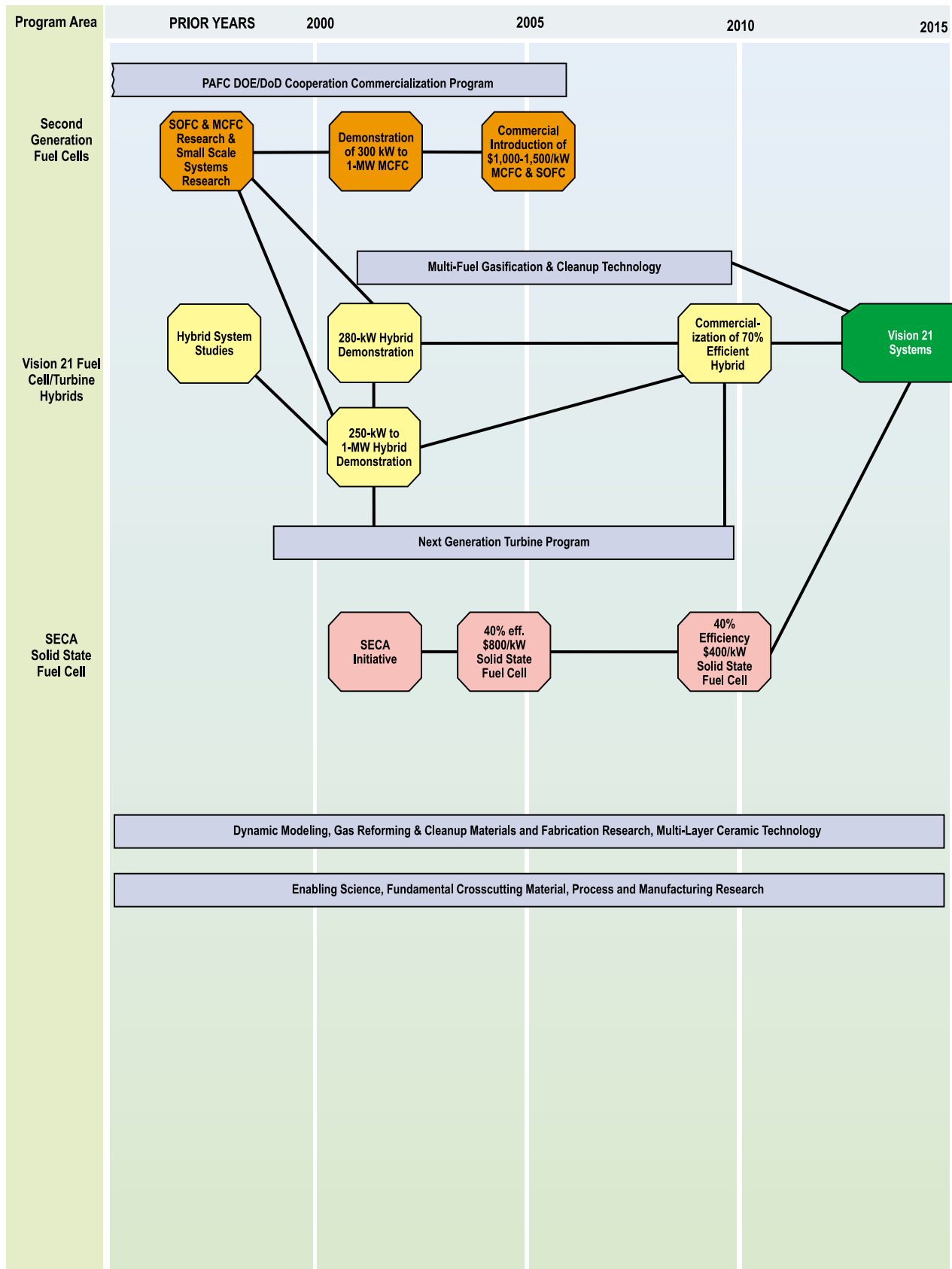
cells. Under this program, the Department of Defense provides \$1,000/kW of the cost of installing a PAFC. DOE administers the program, which to date has resulted in the installation of over 149 PAFCs.

Argonne National Laboratory (ANL) and Oak Ridge National Laboratory (ORNL), along with NETL and PNNL, support all the activities previously discussed.

The adjacent roadmap summarizes activities under the four Distributed Generation Systems program areas and shows the interrelationships.



DISTRIBUTED GENERATION ROADMAP



Drivers

- Utility restructuring is underway, exacerbating concerns over reliability and quality of electric power.
- Electric power producers will seek energy ventures that are less capital-intensive, offer flexibility in siting, closely couple generation capacity to load growth, increase efficiency, and reduce environmental intrusion.
- Efficiency and environmental performance of small, modular systems have begun to exceed the performance of central station power systems in some applications.
- High quality and reliable power supplies are critical to many “new economy” industries employing highly sensitive electric components. Studies indicate that nationwide power fluctuations cause annual losses of \$12–26 billion.
- Electric utilities will seek to reduce capital expenditures associated with installing and/or upgrading peaking generation capacity and transmission and distribution system expansion.
- Civil, military, and special requirements for electric power need to be met in environmentally sensitive and pristine areas where transmission and distribution systems are nonexistent and only zero pollutant emissions will be tolerated.
- Rapid growth is expected in the export market to bring electricity to an estimated two billion people in rural areas currently without access to a power grid.
- Fuel flexibility in power generation will provide the consumer with options to maintain low-cost electricity, even under the pressures of increased power demand and environmental concerns.
- Regional and global environmental objectives will continue to place a premium on efficiency and environmental performance.
- Fewer resources are being devoted to research and development by the utility industry.

Objectives

- In the near term (2003), assure the deployment of current and second-generation distributed generation systems. Ensure that these systems receive appropriate environmental credits and existing regulations do not serve as barriers to their use.
- In the midterm (to 2010), foster the development of advanced distributed generation systems including fuel cell/gas turbine hybrids with improved efficiency, environmental, and economic performance.
- In the midterm (to 2010), foster development, through SECA, of a 40–60 percent efficient \$400/kW solid state fuel cell.
- In the long term (to 2015), develop high efficiency (up to 80 percent), near-zero emissions, low-cost distributed generation systems capable of operating on natural gas or gas derived from coal, biomass, or opportunity fuels.
- In the long term (to 2020), encourage the maximum use of advanced distributed generation systems that will permit U.S. industry to offer domestic and international users innovative approaches to achieving low-cost, environmentally benign distributed generation, meeting all reliability and power quality requirements independent of geographic location.

Strategies

- Continue cooperative efforts with DoD and industry to accelerate commercial deployment of phosphoric acid fuel cells.
- Develop, demonstrate and commercially introduce high temperature, natural gas-fueled molten carbonate fuel cells and solid oxide fuel cells capable of 50–60 percent efficiency in the multi-kilowatt range at a cost of \$1,000–1,500/kW. (2003)
- Advance the SOFC/turbine hybrid through small-scale performance and environmental tests. (2003)
- Support the SECA goals of achieving fuel cell distributed generation solid-oxide technology of 5-kW modules basic blocks, with 40–60 percent efficiency, at a cost of \$400/kW or less. (2010)
- Develop and demonstrate the fuel cell/turbine hybrids with efficiencies over 70 percent and commercially introduce coal-fueled, multi-megawatt power plants at competitive costs. (2010)
- Advance the critical, high-risk technology that will permit industry to establish the commercial viability of a low-cost, ultra-high efficiency (80 percent) Vision 21 hybrid. (2015–2020)

Performance Measures

- Complete construction for demonstration of a commercial scale 300-kW to 1-MW MCFC that will verify the commercial design for combined heat and power and distributed generation. (2001)
- Fully implement the SECA national level concept to achieve mass production of low-cost, technically superior ceramic fuel cell technology. (2001)
- Begin testing of a 300-kW to 1-MW SOFC/turbine hybrid commercial prototype in support of Vision 21. (2001)
- Achieve commercial introduction of natural gas-fueled high-temperature MCFC and SOFC at a cost of \$1,000–1,500/kW. (2003)
- Have the gasification and gas cleanup technology in place to expand fuel cell fuels to coal, biomass, and municipal, forestry, and refinery wastes. (2010)
- Achieve SECA goal of \$400/kW ceramic fuel cell modules with 40–60 percent efficiency and improved fuel flexibility. (2010)
- Introduce commercially-viable, near-term fuel cell/turbine hybrids capable of 70 percent efficiency. (2010)
- Introduce commercially, a Vision 21 hybrid at a cost of \$400/kW, 80 percent efficiency, and near-zero emissions that is compatible with carbon sequestration technologies and stack life of five years. (2015)
- Establish stronger U.S. technology leadership position in multi-megawatt fuel cell/turbine hybrids using solid state fuel cells. (2015)

Distributed Generation Program Benefits

National Benefits

- Reduces greenhouse gas emissions through efficiency gains and potential renewable resource use;
- Responds to increasing energy demand and pollutant emission concerns while providing low-cost, reliable energy essential to maintaining competitiveness in the world market;
- Positions the United States to export distributed generation technologies in a rapidly growing world energy market, the largest portion of which is devoid of a transmission and distribution grid;
- Establishes a new industry worth billions of dollars in sales and hundreds of thousands of jobs; and
- Enhances productivity through improved reliability and quality of power delivered, valued at billions of dollars per year.

Supplier Benefits

- Limits capital exposure and risk because of the size, siting flexibility, and rapid installation time afforded by the small, modularly constructed, environmentally friendly, and fuel flexible systems;
- Avoids unnecessary capital expenditure by closely matching capacity increases to growth in demand;
- Avoids major investments in transmission and distribution system upgrades by siting new generation near the customer;
- Offers a relatively low-cost entry point into a competitive market; and
- Opens markets in remote areas without transmission and distribution systems, and in areas without power due to environmental concerns.

Customer Benefits

- Ensures reliability of energy supply, increasingly critical to business and industry in general, and essential to some where interruption of service is economically unacceptable or where health and safety are impacted;
- Provides the right energy solution at the right location;
- Provides the power quality needed in many industrial applications dependent upon sensitive electronic instrumentation and controls;
- Offers efficiency gains for on-site applications by avoiding line losses and using both electricity and the heat produced in power generation for processes or heating and air conditioning;
- Enables savings on electricity rates by self-generating during high-cost peak power periods, and adopting relatively low-cost interruptible power rates;
- Provides a stand-alone power option for areas where a transmission and distribution infrastructure do not exist or is too expensive to build;
- Allows power to be delivered in environmentally sensitive and pristine areas by having characteristically high efficiency and near-zero pollutant emissions;
- Affords customers a choice in satisfying their particular energy needs; and
- Provides siting flexibility by virtue of the small size, superior environmental performance, and fuel flexibility.

SECOND GENERATION FUEL CELLS

PERFORMANCE TARGETS

Efficiency: 50-60%

Cost: \$1000-1,500/kW

Year: 2003

Phosphoric acid fuel cells (PAFCs) represent the current state-of-the-art in fuel cell technology.

While fuel-to-electricity efficiencies of PAFCs are reasonably high, 40–45 percent LHV, the 200 °C (400 °F) operating temperature limits thermal efficiency, the ability to internally reform fuels, and effective use in hybrid cycles (such as fuel cell/turbine hybrids) to further improve efficiency.

Two second generation, high-temperature fuel cells are in the final stages of development — molten carbonate fuel cells and solid oxide fuel cells. These systems offer both major improvements in stand-alone fuel-to-electricity efficiency, and overall thermal efficiency.

FuelCell Energy has developed an MCFC and brought the system to the point of commercial demonstration. The system operates at approximately 650 °C (1,200 °F) and offers fuel-to-electricity efficiencies of 50–60 percent LHV. The high temperature enables effective internal reforming of fuels, use in hybrid cycles, and thermal efficiencies up to 80 percent LHV in CHP and combined-cycle applications.



FuelCell Energy's first commercial prototype 250-kW MCFC full-size stack demonstration unit



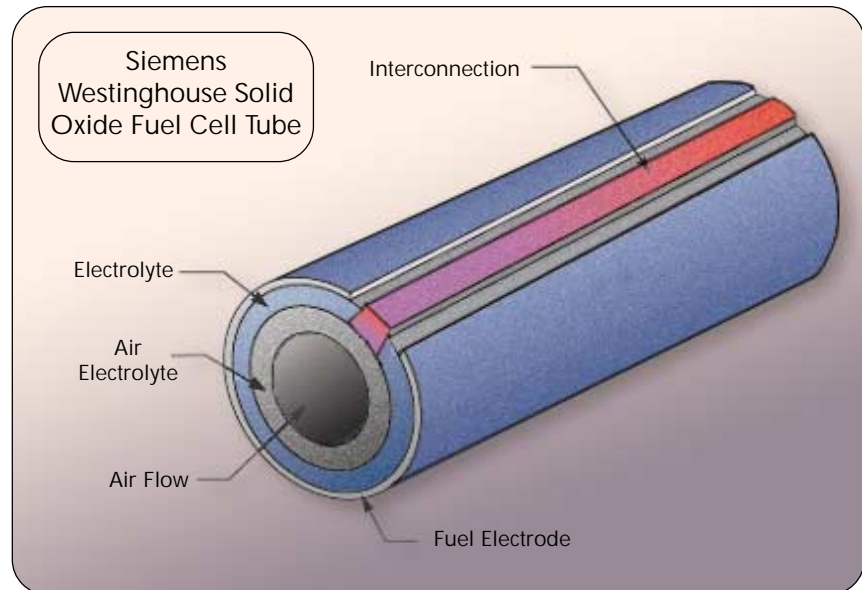


In parallel, Siemens Westinghouse has brought the SOFC to the commercial demonstration stage. SOFCs operate at temperatures up to 1,000 °C (1,800 °F) and also offer fuel-to-electricity efficiencies of 50–60 percent LHV. The temperature enhances internal fuel reforming, and hybrid cycle and thermal efficiency potential. The solid state ceramic construction enables the high temperatures, allows more flexibility in fuel choice, and contributes to stability and reliability.

In fiscal year 2001, an MCFC will be demonstrated at commercial scale, 300 kW to 1 MWe. The demonstration is expected to verify the commercial design of MCFC technology for distributed generation applications in 2003. As market acceptance and manufacturing capacity increase, natural gas-fueled MCFC plants in the multi-megawatt range will become available for central power applications.

SOFC technology is proceeding along two paths. As will be discussed in subsequent sections, an SOFC/turbine hybrid system is soon to undergo demonstration, and SOFC technology is to be a building block for a next generation of solid state fuel cells under the SECA initiative.

Follow-on testing of second-generation fuel cells will address expanding the fuel options by first operating on coal-derived synthesis gas. Gasification technologies using coal, petroleum coke, and waste fuels for power generation are currently experiencing market penetration. As these technologies mature, integrated gasification fuel cell systems become an obvious next step. Both MCFCs and SOFCs are compatible with carbon monoxide, a major constituent of synthesis gas, unlike PAFCs and PEMs (PEMs are another fuel cell option being considered for transportation and residential power applications).



VISION 21 FUEL CELL/TURBINE HYBRIDS

PERFORMANCE TARGETS

Efficiency: 70% LHV

Cost: 20–25% lower than comparably sized fuel cell

Year: 2010

The Vision 21 hybrid effort is conducted in coordination with the Next Generation Turbine (NGT) program.

The focus is on integration of the fuel cell and gas turbine into a single system that can achieve 70 percent efficiency LHV at a cost 20–25 percent lower than a comparably sized fuel cell.

Systems studies by SWPC, Rolls Royce Allison, FuelCell Energy, Solar Turbines, McDermott, and Northern Research and Engineering Corporation laid the foundation for follow-on efforts. NETL selected FuelCell Energy-Capstone Turbine and Rolls Royce Allison teams to:

- Evaluate fuel cell networking approaches in which fuel cells are used to “bottom” other fuel cells;
- Develop key system components including a modified anode exhaust oxidizer and heat exchange equipment;
- Demonstrate a 280-kW hybrid by 2003; and
- Complete a systems study for a 40-MW hybrid system.

In addition, SWPC has an agreement with DOE to conduct hybrid demonstrations at 250-kW and 1-MW scales, which are scheduled to start in 2001. SWPC, in conjunction with



Siemens Westinghouse fuel cell/turbine hybrid system

Praxair, will conduct a 30-month project to develop the technology leading to near-zero emissions Vision 21 power plants based on SOFC and ceramic ITM oxygen separation membranes.

Finally, a multi-disciplinary team led by the National Fuel Cell Research Center at the University of California at Irvine will define the

systems engineering issues associated with the integration of key components and subsystems into Vision 21 power plants.

EPA and the European Commission are partnering with DOE on the demonstration projects. Other efforts include dynamic and detailed modeling and exploration of market issues.



SECA SOLID STATE FUEL CELL

PERFORMANCE TARGETS

Efficiency: 40%–60%

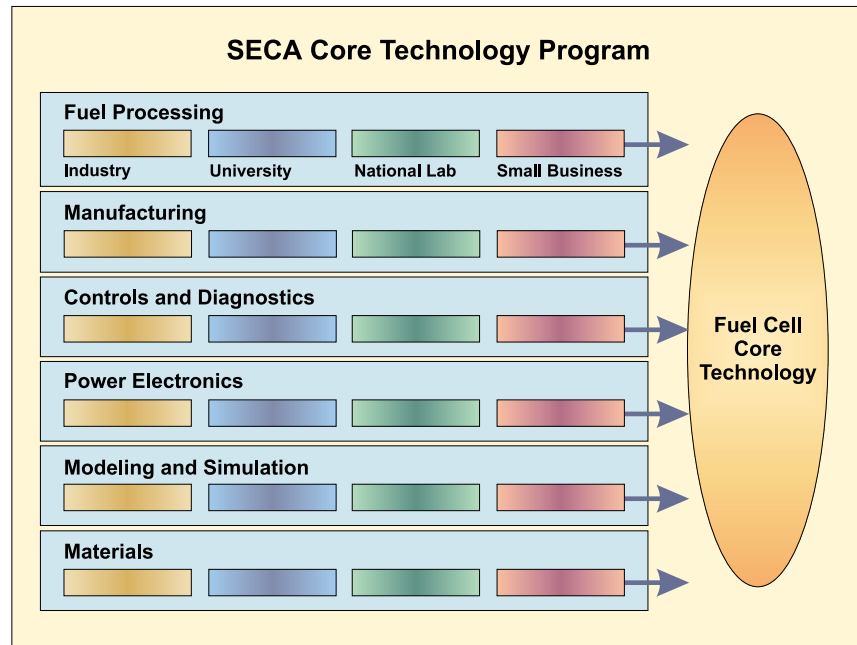
Cost: \$400/kW

Year: 2010

An initiative is underway to develop a solid state fuel cell offering low capital cost.

To achieve this goal, a unique public/private sector alliance has been forged and market targets broadened to accelerate the development of the industrial base needed to produce fuel cells at the targeted low-cost.

A convergence of technological advances and market forces has set the stage for the initiative. Advances in technology include: SOFC development, thin-film capabilities with solid state fuel cells, high power density enabling innovations (such as anode supported cells), compact fuel processing technology, improved power electronics at the device level, and integration of manufacturing technology from related industries (such as the semiconductor industry). Market forces include: incentives for distributed



generation under utility deregulation, a commitment by the Department of Defense to use electric drive for future ship propulsion and to pursue “dual use” technology, and a move by the utility and transportation sectors to explore advanced technology options that address global climate concerns.

To effectively leverage the technology gains and market forces, SECA was formed. SECA comprises government agencies, commercial developers, universities, and National Laboratories committed to the development of low-cost, high power density, solid state fuel cells for a broad range of applications. Both NETL and PNNL are taking a leadership role to provide the focus and coordination needed to bring solid state fuel cells into near-term markets.

A driving force behind SECA is the accelerated development of the infrastructure to mass produce solid state fuel cells in the near term. A

mass customization approach is being taken that involves development of standard fuel cell components for use in multiple market applications. Components encompass the fuel cell stack and balance-of-plant equipment. The basic building block will be a mass produced 5-kW solid state fuel cell that can be combined like batteries to meet larger power needs.

A number of factors contribute to solid state fuel cell technology being chosen to meet performance goals. The efficiency is inherently high; temperatures are conducive to internal reforming of fuels; materials are compatible with available liquid fuels (gasoline and diesel); heat removal designs are simple, efficient, and enable compact design; power density is very high; and components can be fabricated with advanced manufacturing techniques much like computer chips.

SECA represents a new model for joint government and private indus-

try technology development. The structure of SECA is designed to leverage resources across the federal agencies to overcome the most difficult technology barriers, while enabling private partners to maintain a competitive position.

The essence of the SECA organization is integration of a crosscutting core technology program (involving universities, National Laboratories, and other research-oriented organizations) with industry development team efforts to design and produce the commercial systems. The core technology research to address fundamental barriers is made available to the industry teams, and the industry teams provide input to core technology research direction. Industry teams are to be selected through competitive solicitations for cost-shared cooperative agreements. Commercialization decisions to meet market requirements remain the purview of the development teams, with intellectual property protection provided by virtue of their meeting cost-sharing requirements.

The number of teams and program success will be determined in part by the extent of participation by the Department of Defense and other government agencies (coordinated through NETL). The intent is to establish as broad a market as possible to provide the incentive for investment in the manufacturing infrastructure.

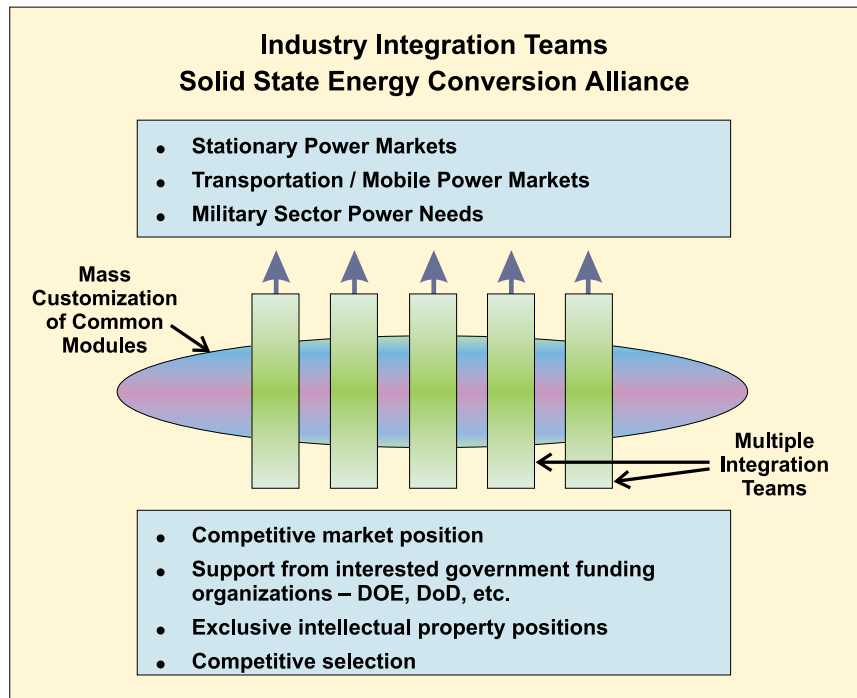
A workshop was held in June 2000 to launch the SECA initiative and obtain input for the first program solicitation. After posting a draft solicitation on the NETL web site for comment, the solicitation was issued in Fall 2000. Selections were planned for the end of 2000.

Goals established for the SECA program are \$400/kW for stationary

applications, with fuel-to-electricity efficiencies of over 40–60 percent by 2010. An interim goal is commercial introduction of an \$800/kW solid state fuel cell by 2004, with fuel-to-electricity efficiencies of around 40 percent.

If the technical goals are achieved, fuel cell technology will move from niche markets to widespread use in

both stationary and transportation applications. The result will be a revolutionary positive impact on the environment and energy security. Moreover, forging a U.S. industrial base to produce low-cost fuel cells will place the U.S. in a strong position to leverage global markets clamoring for energy. Finally, the solid state fuel cell will become a key Vision 21 enabling technology.



IN PARTNERSHIP WITH INDUSTRY

While more than 200 PAFC fuel cells have been manufactured for sale at various locations around the world, a recent installation in New York City's Central Park underscores several important advantages offered by fuel cells.

The DOE, in partnership with the New York Power Authority, installed a 200-kW PAFC in Central Park to provide electricity in the Police Department's 22nd precinct station. Prior to the fuel cell installation, power supply to the 148-year-old precinct station, a converted horse stable, often precluded simultaneous operation of all office equipment. This on-site fuel cell avoided an estimated \$1.2 million power line upgrade, provided an inconspicuous clean power supply about as large as a double-size garden shed, and allowed recharging of non-polluting electric vehicles used by the police department. The government provided about one-third of the project cost under a Department of Defense-funded program administered by the DOE.



ONSI Corporation PAFC similar to the unit installed in Central Park.



FUELS



EXPANDING CLEAN FUEL
AND FEEDSTOCK RESOURCES

INTRODUCTION

Program Areas

- Transportation Fuels and Chemicals
- Solid Fuels and Feedstocks
- Advanced Fuels Research

The need for liquid fuels is forecast to be a critical element of this Nation's energy future in the 21st century.

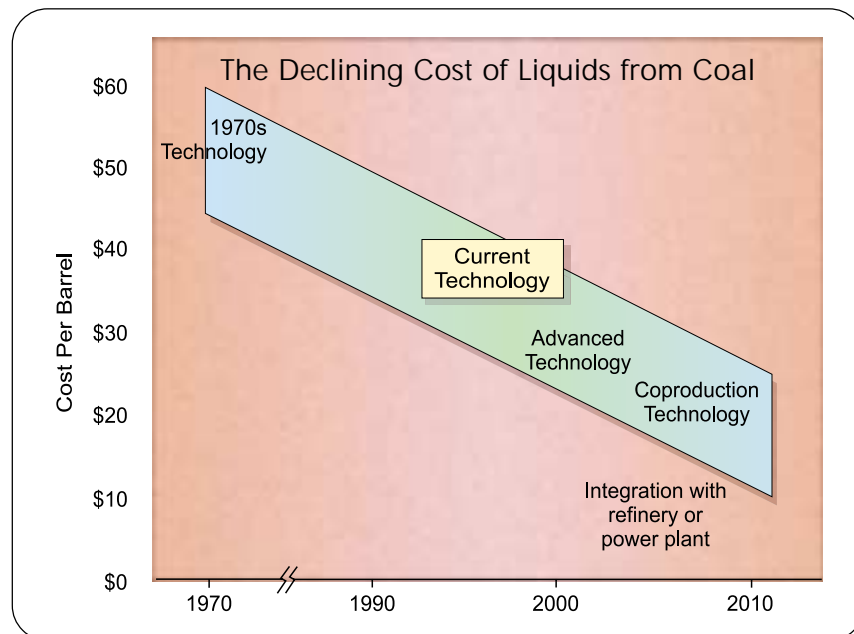
Using abundant, domestic coal resources to produce fuels and chemicals, instead of imported petroleum, can act as a cushion against future oil price increases and reduce the Nation's reliance on imported oil. It also could serve as the core of a new domestic industry that would produce a slate of alternative fuels that would meet increasingly stringent environmental standards and help boost fuel efficiencies in the Nation's transportation fleet.



The Coal & Power Systems (C&PS) Fuels program seeks to ensure the development and demonstration of environmentally responsible coal-based technologies that produce ultra-clean transportation fuels, utility and boiler fuels, chemicals, and carbon products for metallurgical and industrial applications. By conducting research in advanced fuel science — hydrogen separation and storage technologies, catalyst development, and conversion processes for converting solids and gases to gasoline and diesel fuels — the C&PS Fuels program is providing affordable conversion technologies to exploit coal's potential for producing a wide array of valuable fuels and other products. This research is undertaken in conjunction with industry and other federal agencies.

The Transportation Fuels and Chemicals program area encompasses several approaches to produce ultra-clean transportation fuels for use in high-efficiency vehicles and light- and heavy-duty trucks. The Solid Fuels and Feedstocks program area examines the environmental and economic benefits of co-firing biomass and waste feedstocks with coal, develops tailored feedstocks for making premium carbon products, and provides the means to remove trace contaminants from coal.

The advances in technology for coproducing power, fuels, and chemicals will enable the Nation to use its plentiful fossil resources to fulfill a broader range of energy and chemical feedstock needs while reducing impacts to the environment.



Historically, the obstacle to producing coal-based liquid fuels has been cost. In the late 1970s, the projected cost of coal liquids approached \$60 per barrel. With today's technology, costs have been reduced to below \$35 per barrel. By integrating Early Entrance Coproduction Plants with existing petroleum refining facilities and using coal combined with low-cost feedstocks, such as petroleum coke and wastes, costs are projected to go even lower — perhaps to the \$25 per barrel range.

Fuels Program Benefits

National Benefits

- Reduces emissions through efficiency gains;
 - Use of ultra-clean transportation fuels provides an alternative supply of transportation fuels from domestic resources, thus hedging against security risk; and
 - Reduces the U.S. balance of payments.
-

Supplier Benefits

- Boosts fuels development processing efficiencies leading to lower capital and maintenance costs which, in turn, influences supplier economics;
 - Provides, through gasification-based coal conversion, a way to store energy from a power plant during off-peak periods when demand is low; and
 - Allows for flexibility in affordable, substitute feedstocks for power generation.
-

Customer Benefits

- Protects against price shocks in the transportation fuels arena;
- Dramatically improves the mileage efficiency of transportation vehicles;
- Ensures reliability of fuel supply; and
- Improves economics of fuels, chemicals, and power through coproduction.

DRIVERS

Environmental Regulations.

Transportation accounts for approximately 473 million metric tons (MMT) of carbon emissions, or 32 percent of total U.S. carbon emissions. The Energy Information Administration (EIA) projects that, by 2020, total carbon emissions in the United States will increase to 1,975 MMT under business-as-usual assumptions with transportation accounting for 665 MMT, or 34 percent of total U.S. carbon emissions. In addition, of the total manmade air emissions in the United States, highway transportation is responsible for 57 percent of the carbon monoxide (CO), almost one-third of the nitrogen oxides (NO_x), and almost one-third of the volatile organic compounds. Combinations of these pollutants are responsible for ground level ozone that can significantly impact public health. Dramatic increases in vehicle numbers and miles traveled have been forecast by the Energy Information Administration. This growth will lead to greater transportation pollution unless significantly improved fuel/vehicle systems are developed and deployed. Much effort from both industry and government is currently directed toward improving fuel/vehicle systems.

From this effort it is clear that success in obtaining high efficiency and low emissions can only be achieved by simultaneously improving the engine, the exhaust after-treatment, and the fuel.

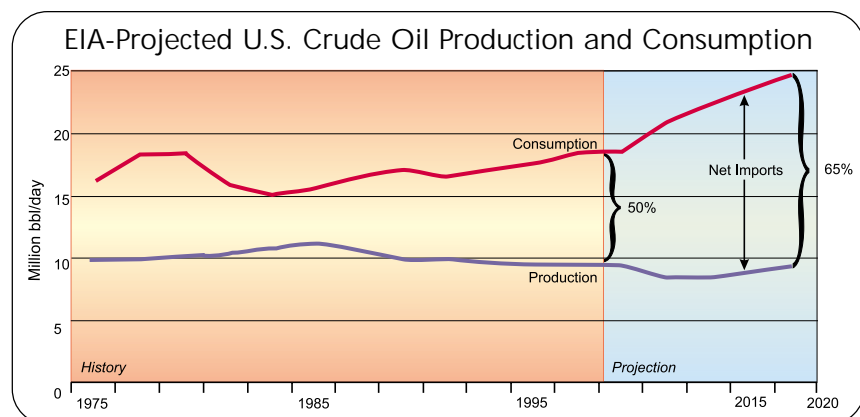
There also is a host of potential regulatory actions that could require major additional reductions in energy-related emissions during the next decade. Likewise, restructuring in the electric utility industry will place market pressures on utilities to find low-cost approaches to meeting stringent environmental regulations for potentially hazardous air pollutants.

Energy Security. The EIA also predicts that, by 2020, U.S. petroleum imports (already representing over 50 percent of consumption) will rise to 65 percent and increase our negative balance of payments. Currently, the United States imports approximately 11 million barrels per day of crude oil and finished products, 50 percent of which comes from the Organization of Petroleum Exporting Countries (OPEC). At current world oil market prices, oil imports cost the U.S. almost \$90 billion per year.

Projections of brisk growth in domestic and world oil demand sub-

stantially change the energy security outlook. Excessive reliance on a single geographic area to satisfy increased world demand for oil creates the potential for oil-importing nations to be vulnerable to supply disruptions and price volatility.

Further, petroleum is a finite resource, production of which will eventually peak and decline in the face of continually increasing demand. It cannot be known with any degree of certainty when this peak in production will occur. However, current estimates of ultimately recoverable conventional oil (approximately 2.7 trillion barrels) and projected world oil demand have led experts to predict a peak in petroleum production occurring around the year 2015 and declining thereafter. While there may be 2.7 trillion barrels of petroleum more than currently assessed, these additional resources are likely to reduce the rate of decline rather than increase peak production. As conventional oil resource production approaches its peak and eventual decline, there is the risk that the price of oil will rise significantly and permanently. This risk can be minimized through development of fuels from alternative domestic sources.



Tier II Emission Standards

On December 21, 1999, the U.S. Environmental Protection Agency (EPA) issued the final Tier II emissions regulations that were proposed in May 1999. The rule sets new, much more stringent exhaust emission standards for light-duty vehicles and establishes new maximum sulfur levels in gasoline.

The regulations focus on reducing emissions of ozone-forming gases, including nitrogen oxides and non-methane organic gases, and particulate matter from these vehicles. The standards, expressed in grams of pollutants emitted per mile (g/mi), apply to all new passenger cars, light light-duty trucks (LLDT), heavy light-duty trucks (HLDT), and medium-duty passenger vehicles (MDPV) regardless of the vehicle or engine size. Under this approach, which reflects the EPA's concern about the increasing market share and emissions from minivans and sport utility vehicles, larger vehicles will have to employ cleaner engine and emissions control technologies than those needed for smaller vehicles and engines. The same requirements will apply to all vehicles regardless of the fuel (i.e., gasoline- and diesel-fueled vehicles will be certified to the same emissions standards).

	Tier II Standard	Phase-In Period
New Vehicle NO_x Levels		
– Passenger and LLDT	0.07 g/mi	2004–2007
– HLDT and MDPV	0.07 g/mi	2008–2009
Gasoline Sulfur Levels		
(in parts per million)	120–300	2000–2004
	30–80	2004–2006
Particulate Matter		
– Passenger, LLDT, and HLDT	0.00–0.02 g/mi	2000–2006
– MDPV	0.00–0.02 g/mi	2000–2008

ACCOMPLISHMENTS

The C&PS Fuels program is developing and commercializing advanced technologies for carbon-based solid materials and fuels that will maintain U.S. industrial competitiveness, contribute to efficient power production, and promote environmental quality.

A number of significant successes have already been achieved by the program. For example, the Microcel[®] flotation column, developed with DOE support, has had significant commercial success in coal and mineral applications, with over 50 units in use worldwide. Other successes include development of the Micro-Mag[®] heavy-medium cycloning process for coal cleaning, and the GranuFlow[®] process for improved coal fines handling.

Two Clean Coal Technology (CCT) projects addressed the conversion of low-energy-density, low-sulfur western coals into high-energy-density, very low-sulfur products. ENCOAL's demonstration of the Liquids-from-Coal Process successfully completed operation in July 1997, and the technology is moving toward commercialization. During the demonstration, nearly 260,000 tons of raw coal were processed into 120,000 tons of solid process-derived fuel and more than 121,000 barrels of coal-derived liquid. A cross section of customers consumed almost all of the product.

Western Syncoal Partnership's demonstration of the Advanced Coal Conversion Process (ACCP) continues to operate under an eight-year contract to supply a high-energy-



Air Product's LaPorte coal liquefaction test facility contributes to R&D efforts that ensure future availability of clean, affordable coal-derived fuels.

density, low-sulfur solid Syncoal[®] fuel to Montana Power's 330-MWe Colstrip No. 2 unit using a dedicated pneumatic feed system. Through fiscal year 2000, the ACCP facility had processed over 2.6 million tons of raw coal to produce over 1.7 million tons of Syncoal[®].

As research progresses in the Fuels program from laboratory to bench-scale experiments, the advances in specific areas of the fuel production system are incorporated into production of specific products at the LaPorte, Texas proof-of-concept unit. This approach has worked very successfully over the past 15 years, as exemplified by the Liquid Phase Methanol Process (LPMEOH[™]) whereby technical viability was proven at LaPorte and is now being demonstrated at commercial scale by the Eastman Chemical Company. More recently, successful operations at LaPorte included production of Fischer-Tropsch liquids and dimethyl ether, both of which are of interest to industry for their potential use as premium fuels.

With the recent successes of the LPMEOH[™] process, the market for clean-burning, storable liquid fuel from coal is more promising than ever. The LPMEOH[™] process demonstration plant, located at Eastman Chemical Company's chemicals-from-coal complex in Kingsport, Tennessee, began its fourth year of operation on April 2, 2000, and has produced in excess of 66 million gallons of methanol from coal-derived synthesis gas. Due to its accomplishments, the project was extended recently until March 2003. As part of the project, a product-use test program has been developed to enhance the early commercialization of this type of clean coal technology processing facility. The objective of the testing program is to demonstrate commercial market application for the LPMEOH[™]-derived methanol as a replacement fuel and as a fuel supplement in the 2000–2003 timeframe. Specifically, methanol from the LPMEOH[™] project has been made available for seven different tests to determine its feasibility as a feedstock in transportation and power generation applications.

ACTIVITIES

The C&PS Fuels program response to the environmental, energy security, and economic challenges now and into the future is to provide the technical basis for a clean fuels industry capable of producing transportation fuels and chemicals from coal and other carbonaceous, non-petroleum resources.

The roadmap on page 4-9 provides an overview of the activities under the Fuels program. Specifically, research is focused on developing ultra-clean transportation fuels, feedstocks for power generation that will help to lower emissions, and high-value carbon products. Technology development in these research and development areas will ensure coal's continued role in the Nation's energy future.

Transportation Fuels and Chemicals

This program area encompasses several approaches to produce ultra-clean transportation fuels for use in high-efficiency vehicles and light- and heavy-duty trucks. The major R&D activities include: (1) feedstock conversion R&D; (2) reactor/process development; (3) early entrance coproduction plant; (4) product upgrading; and (5) systems engineering. These activities provide the technical underpinning to the Ultra-Clean Transportation Fuels Initiative (UCTFI), which is funded under the Oil and Gas Program budget within DOE's Office of Fossil Energy (FE) in fiscal year 2001.

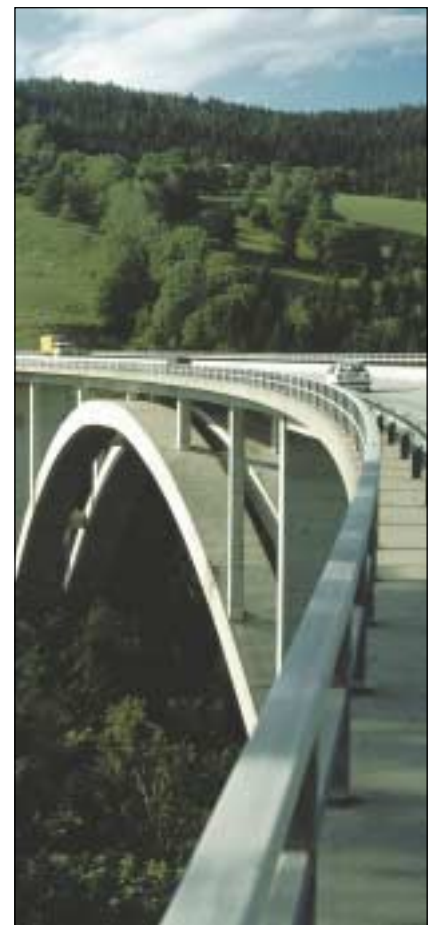
Coal-Based Synthesis Gas Conversion R&D. R&D is currently focused on the generation and production of synthesis gases (i.e., a mixture of carbon monoxide and hydrogen) and the subsequent catalytic conversion of the synthesis gas to liquid fuels and other products. Fischer-Tropsch (F-T) synthesis provides the best available means for conversion of natural gas- or coal-derived synthesis gas to clean transportation fuels. DOE's Fuels program is pursuing process improvements including the development of more efficient F-T reactors, more active and robust slurry catalysts, efficient product upgrading, and methods that produce hydrogen more economically.

Early Entrance Coproduction Plant (EECP). The Fuels program is cosponsoring the development of the EECP technologies with Central Systems Integrated Gasification Combined-Cycle (IGCC) program. These gasification-based plants would coproduce some combination of power, fuels, and chemicals with high efficiency and reduced capital cost, thus facilitating early commercial entry of both IGCC power and coal-derived fuels and chemicals. Three industry project teams were selected by DOE in 1999 to pursue industry/government cost-shared research and engineering studies that will be directed toward privately funded design, construction, and operation by 2007 of first-of-a-kind commercial facilities that coproduce multiple products.

Ultra-Clean Transportation Fuels Initiative. Concurrent with the EECP effort will be the development of ultra-clean fuels for the 21st

century through the UCTFI in partnership with the Natural Gas Processing and the Petroleum Processing programs. In February 2000, DOE issued a solicitation to industry for research and development of ultra-clean fuels and fuel conversion processes. Round I project selections occurred in September 2000. Round II project selections are expected in early March 2001.

In conjunction with midterm field testing of the UCTFI fuels and fuel conversion processes, laboratory testing for characterization of product quality, including emissions testing in engines, will also be conducted. UCTFI Round I projects are expected to yield results in the 2004–2005 timeframe.



Solid Fuels and Feedstocks

The Solid Fuels and Feedstock program area is developing and commercializing advanced technologies for processing carbon-based solid materials with the ultimate goal of sustaining a coal-based carbon products industry. Activities are organized into environmental solid fuels, tailored carbon feedstocks, and premium carbon industry.

Environmental Solid Fuels. Research in this area will result in the more efficient use of solid fuels and includes pilot-scale testing of an electrostatic separation process for dry, fine-size coal and proof-of-concept (POC) testing of an advanced flotation control system. Industrial-scale testing of an advanced technology will also be conducted for the production of carbonized slurry fuels for power production from coal, biomass, and waste.



Work will also continue on the development of a national coal quality database on trace elements. Cooperation with a broad-based, utility-sector consortium for coal utilization called the Upgraded Coal Interest Group will investigate coal desulfurization; removal of trace elements; upgrading of low-rank coals; technology for utilization of fine-coal products; and the preparation and utilization of new fuels, including coal-water slurries and coal/biomass/waste composites. DOE's participation extends (at present) until 2005. In that time, DOE will have access to, and will participate in, technology transfer reports expected to flow from the group.

Tailored Carbon Feedstocks. The Tailored Carbon Feedstocks activity concentrates on advanced technologies for the development of premium carbon products from coal and the preparation of specially designed (tailored) feedstocks for the production of advanced transportation fuels and chemicals from coal, biomass, and waste feeds. Current projects focus on economically recovering carbon through novel coal fines processing devices as well as dewatering/reconstitution systems.

Premium Carbon Industry. The primary focus of this research is to study ways to extract carbon from coal for producing such materials as carbon electrodes and carbon fibers for high-strength materials, and to reduce carbon dioxide from the coal-to-liquids process. The main activity focuses on development of an industry-driven consortium for the development of premium carbon products from coal. Research, development, demonstration, and commercial application programs will be determined for investigating technologies for non-fuel uses of

coal, including production of lightweight premium carbon products that will be used in the transportation industry—airplanes, cars, lightweight trucks, passenger vans, and sport utility vehicles. These new technologies will substantially reduce transportation vehicle weight and yield major improvements in fuel efficiency and environmental quality.

Advanced Fuels Research

The Advanced Fuels Research program area provides the scientific foundation for technology development in the Transportation Fuels and Chemicals program area, and develops concepts that will help address the challenges associated with Vision 21.

This long-term research centers on developing significantly improved and innovative technologies that produce economically competitive fuels with minimal environmental impact, and with reduced by-product CO₂ production. Examples of such technologies include: (1) innovative, coal-derived fuel technology that produces fuels at lower costs with less energy usage; (2) hybrid, renewable and fossil energy technology as part of Vision 21 concepts to produce fuels, electricity, chemicals, and carbon products with improved environmental performance and with less CO₂; (3) computational methods to improve catalyst development and experimental evaluation; and (4) bioprocessing systems that produce liquid transportation fuels with less CO₂ production. These technologies will provide the longer-term modular processes to be used in Vision 21 plants, which would produce energy and fuels products in a manner consistent with global climate change strategies.

Drivers

- EPA standards will require cleaner burning transportation fuels in order to reduce air pollutants including carbon monoxide, nitrogen oxides, volatile organic compounds, and particulate matter.
- Environmental and economic incentives will encourage the reduction of solid wastes associated with coal production and utilization.
- The U.S. economy is almost totally dependent on oil for its transportation needs.
- By 2015, it is projected that the demands for petroleum in non-industrialized countries will nearly double, and the U.S. will be importing more than 60 percent of its oil, much of which will come from the Middle East.
- The high level of imports have worrisome energy security and economic implications, through the potential for supply disruptions with the attendant economic dislocations, and negative balance of payments.
- Deregulation will place market pressures on utilities to find low-cost approaches to meet stringent environmental regulations for potentially hazardous air pollutants.
- The expanding export market for cost-effective coal technologies that are attractive to coal-intensive developing countries will lead to the creation of jobs, reduction of trade deficits, and improved regional and global environments.

Objectives

- Provide the technology base for a clean fuels industry capable of producing transportation fuels and chemicals from coal and other carbonaceous, non-petroleum domestic resources.
- Foster the development of advanced technologies to enable the efficient use of coal, biomass, and waste fuels while addressing environmental concerns associated with hazardous air pollutant and greenhouse gas emissions, and waste disposal issues.
- Develop a coal-based U.S. carbon products industry.
- Conduct the fundamental and exploratory research needed to support the fuels and chemical production aspects of Vision 21 technologies, and improved methods of producing liquid transportation fuels.

Strategies

- Successfully complete demonstration and product use test program of Liquid Phase Methanol CCT project.
- Advance three-phase slurry reactor technology to cost-effectively produce premium fuels, diesel-fuel blending compounds, or high-value chemicals from coal or natural gas.
- Deploy one or more Early Entrance Coproduction Plants that demonstrate the feasibility of producing some combination of power, fuels, and chemicals from coal.
- Continue support for, and participation in, engine/vehicle development and testing efforts.
- Through the Ultra-Clean Transportation Fuels Initiative, identify needs of transportation industry and select R&D projects to achieve ultra-clean fuels for transportation.
- Conduct research on advanced technologies for the reduction of greenhouse gases and for low-cost precombustion control of hazardous air pollutant precursors.
- Conduct research on technologies to enhance carbon recovery from coal and coal wastes and improve coal fines processing.
- Support the industry-led, cost-shared consortium to develop, demonstrate, and commercialize technologies for non-fuel uses of coal.
- Conduct research and early development of improved innovative concepts for Vision 21 modules.

Performance Measures

- To have the capability to produce 2 million barrels/day of premium transportation fuels, blendstocks, and additives. (2020)
- To have the capability to produce, by 2008, ultra-clean fuels that will help vehicles to meet EPA Tier II standards. (2008)
- To deploy commercially scalable, fully integrated coproduction plants that demonstrate the technical, economic, and environmental benefits of producing multiple products from gasification-based technologies. (2007)
- To increase output of U.S. finished carbon products five fold, while increasing core domestic employment from 50,000 to 150,000. (2010)
- To have fuel and chemical process modules as components of Vision 21 facilities or as stand-alone plants; and to meet requirements and schedules of advanced vehicle development program for clean fuels. (2020)

Clean Diesel from the Fischer-Tropsch Process

Indirect conversion of any hydrocarbon fuel involves: (1) gasification of the hydrocarbon source to produce syngas (a mixture of carbon monoxide and hydrogen), and (2) conversion of the syngas utilizing F-T chemistry to produce a transportation fuel product. The F-T process uses various catalysts to produce linear hydrocarbons and oxygenates, including unrefined gasoline, diesel, and wax ranges, which can be further refined to produce additional diesel fuel.

Today, there is significant commercial interest in F-T technology for producing diesel fuels that are primarily C10 to C20 paraffins. Current F-T chemistry leads inevitably to the production of waxes (or C20+ hydrocarbons), meaning as much as 50 weight percent of the F-T product needs to undergo post-synthesis treatment, such as hydro-cracking. This adds to capital cost and process complexity. If this cost can be eliminated, F-T synthesis of diesel fuels becomes much more cost competitive.

Research activities in the Transportation Fuels and Chemicals program area are focused on improving the chemistry of the F-T process by optimizing the catalyst and reaction conditions in order to maximize conversion of syngas, while producing a maximum diesel fuel-potential product mixture. Development work on iron and cobalt catalysts involves the preparation and evaluation of new, improved formulation for F-T synthesis. The emphasis is on achieving higher levels of activity, selectivity, and stability and the development of catalyst/wax separation techniques for use in slurry phase reactors.

TRANSPORTATION FUELS AND CHEMICALS

The Transportation Fuels and Chemicals program area supports R&D technologies to produce ultra-clean transportation fuels, chemicals, and carbon products.

These technologies convert coal into liquid fuels and chemicals in two steps. In the first step, coal is gasified in the presence of oxygen and steam to generate a gas containing mostly carbon monoxide and hydrogen (i.e., synthesis gas). In the second step, the synthesis gas, after being cleaned of impurities, is converted into a variety of products. These products include:

- Hydrocarbon fuels, such as gasoline, diesel fuel, and jet fuel.
- Oxygenated compounds, such as alcohol fuels (e.g., methanol), and oxygenated fuel additives (e.g., ethers and esters).
- Premium chemicals, such as olefins and paraffinic wax.

Research within the Transportation Fuels and Chemicals program area is focused on developing clean fuels that: (1) are environmentally superior to those derived from conventional petroleum-based fuels; (2) can supplement the liquid fuel requirements of the Nation's transportation sector; (3) will use the existing transportation fuels infrastructure; and (4) will help engine and vehicle manufacturers achieve higher performance with significantly lower emissions in both conventional and advanced systems.

The research efforts address key technical issues associated with making premium fuels and chemicals and provide the foundation upon which to pursue initiatives

such as the Liquid Phase Methanol project currently being demonstrated in the CCT program; the Early Entrance Coproduction Plant initiative that is co-sponsored with Gasification Technologies; and the Ultra-Clean Transportation Fuels Initiative, which is jointly sponsored by Transportation Fuels and Chemicals, Natural Gas Processing, and Petroleum Processing programs.

Projects within this program areas currently emphasize the following.

Process Development

- Continued improvements in the three-phase slurry reactor technology where technology advances have shown significant productivity improvements.
- Development of low-cost iron-based catalysts for the slurry reactor, especially for their application and suitability to feedstocks that are low in hydrogen content such as coal, wastes, and petroleum coke.
- Separation techniques for both gaseous and liquid products to remove contaminants.

Product Testing/ Evaluation

- Laboratory characterization of product quality, including emissions tests in engines.

Systems Engineering

- Extensive life-cycle analyses to identify those areas of fuel conversion processing that offer the best opportunities for CO₂ mitigation.

Concurrently, R&D is underway on novel methods to reduce production

of greenhouse gases through process improvements and co-firing of multiple feeds such as waste material or biomass. Each of these projects is examining process details within the context of a system that is intended to make a specific product.

The following describes some of the key elements of the Transportation Fuels and Chemicals program area's research and key initiatives that are being emphasized over the next several years:

Ultra-Clean Transportation Fuels Initiative

Over the next several years, the United States will implement new, stricter federal and state clean air requirements for highway vehicles; encounter greater volatility in global energy markets; face increased economic competition in the international market for clean highway vehicles and fuels production technologies; and confront the threat of global climate change. Given this emerging situation, it is clear that R&D must be pursued aggressively to develop advanced technologies for high-efficiency, low-emissions highway vehicles, as well as for the production of ultra-clean fuels required for their operation. Furthermore, it is imperative that the Nation accelerate the transition toward the increased use of diversified domestic feedstocks, including natural gas, coal, and renewables to ensure the availability of these ultra-clean transportation fuels.

DOE's Office of Fossil Energy (FE) has created a strategic alliance among its petroleum, natural gas

NETL's Ultra-Clean Fuels Science and Technology

Presently, vehicle tailpipe emissions of unburned hydrocarbons and NO_x are dependent on the performance of catalytic systems. However, the performance of a vehicle's catalytic converter is degraded by very small amounts of sulfides present in the exhaust gases. An integrated technology development effort that encompasses fuels, engines, and after-treatment systems will be required in the near future.

The NETL Ultra-Clean Fuels Science and Technology research aims to develop the science for pollution-free, highly efficient, and affordable transportation systems. Ultra-Clean Fuels Science and Technology efforts will include research into hydrogen separation membrane technology, nano-scale storage of hydrogen, conversion of natural gas to liquid fuels free of sulfur and nitrogen, next-generation catalysts, analytical techniques to measure and characterize extremely low levels of sulfur, and environmentally acceptable oxygenated fuels.

Combined with the fuels R&D in C&PS, NETL's activities will strengthen the technical foundation available to ensure the success of this Nation's future energy plants by leveraging research by the DOE's Office of Science, EERE, the National Science Foundation, and the Department of Defense. NETL is also partnering with universities, other national laboratories, and the private sector, as well as participating in DOE's Ultra Clean Transportation Fuels Initiative.

and coal fuels programs that focuses on achieving the common vision of partnering with the U.S. energy industry to meet the growing demand for cleaner transportation fuels.

FE, in partnership with the Office of Energy Efficiency and Renewable Energy's (EERE) Office of Transportation Technologies (OTT), is working toward an integrated approach for ultra-clean fuels development, engine optimization, and post combustion emission controls to achieve significantly higher transportation vehicle efficiency and reduced regional tailpipe emissions. FE is expanding its government partnerships to include the Department of Defense.

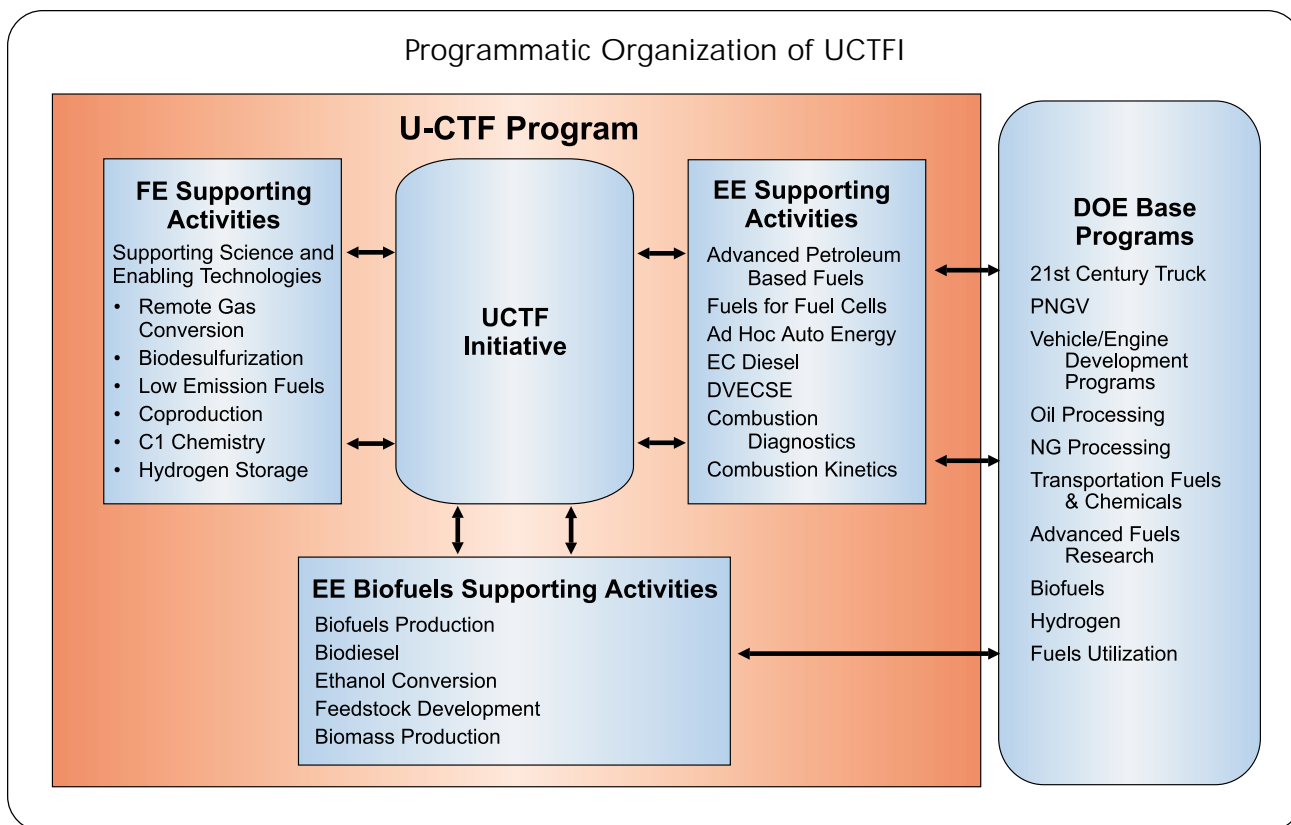
The primary objective of the UCTFI is to assist all elements of the U.S. refining and transportation industries in eliminating concerns associated with the use of fossil fuels for transportation purposes. This integrated FE activity has the common goal of promoting the production of

ultra-clean fuels from a diversity of resources including conventional and heavy crudes, bottom-of-the-barrel refinery products (residuals and petroleum coke), natural gas, coal, biomass, and other carbonaceous feeds. The partnership will also make more effective use of the skill mix, resources, and synergy among the programs. The result will be more efficient leveraging of federal government and private sector resources, and the more rapid commercialization and deployment of these fuels.

During 1999, workshops and meetings were held with several companies and individuals to structure a government/industry partnership that would address the burdens being placed on fuel producers. Concurrently, discussions with OTT provided the basis for DOE EERE-FE collaboration on a major solicitation that was issued in February 2000.

The UCTFI solicitation encompasses three R&D areas that will be





pursued over five years. The first, and core part of UCTFI, is directed toward systems-oriented R&D projects that will lead to the production of sufficient quantities of fuel to validate performance and emissions goals. Fuels testing will be done in collaboration with OTT. The second focus area is on development of advanced unit operations/processes for producing ultra-clean transportation fuels. The third focus area emphasizes the development of new and innovative emissions control systems.

On September 21, 2000, eight proposals were selected for award. Three research teams proposed advanced refinery processes, while one team proposed an advanced synthesis gas production process. Two other teams proposed to produce F-T fuels and/or dimethyl ether from synthesis gas. Yet another team proposed a new system for emissions control while the eighth

and final team proposed a novel hydrogen production process. Additional information on these proposals can be found on the Fossil Energy web site (www.fe.doe.gov).

In addition, an aggressive supporting research program is being set aside for a National Laboratory partnership that will focus on examining some of the key scientific issues (reaction chemistry, materials, etc.) associated with the conversion of natural gas, petroleum, and coal to ultra-clean transportation fuels. The goal of the UCTFI is to develop and deploy technologies that will produce ultra-clean-burning transportation fuels for the 21st century from both petroleum and non-petroleum resources. These fuels will:

- Enable vehicles to comply with future emissions requirements;
- Be compatible with existing liquid fuels infrastructure;
- Enable vehicle efficiencies to be significantly increased, with con-

comitantly reduced CO₂ emissions;

- Be obtainable from a fossil resource, alone or in combination with other hydrocarbon materials such as refinery wastes, municipal wastes, and biomass; and
- Be cost competitive with current fuels.



Early Entrance Coproduction Plant

The Early Entrance Coproduction Plant initiative examines the feasibility of coproduction technology where transportation fuels, chemicals, electric power, process heat, and other products are coproduced in

one facility from various feedstocks. This initiative is part of a joint effort with the gasification technologies program area under the C&PS Central Systems program. In these studies, teams will pursue industry/government cost-shared research and engineering studies that will be directed toward privately funded de-

sign, construction, and operation by 2007 of first-of-a-kind commercial facilities that coproduce multiple products. These activities will help industry teams refine their strategies, reduce technical risk, and define economic and environmental requirements.



The "First Step" to Tomorrow's Fuels

The ultimate objective of the EECP initiative is an energy facility that will extract virtually every useable molecule of energy from a range of fuels—coal, biomass, municipal wastes, or possibly various mixtures of these fuels. The following describes the first projects chosen by C&PS to further the EECP concept. NETL will oversee the projects.

Waste Management and Processors, Inc. (WMPI), Frackville, Pennsylvania, and its team will assess the feasibility and economics of a plant that converts coal residue into premium transportation fuels and electricity. Using coal waste not only provides a low-cost feedstock, but also benefits the environment by reclaiming land and preventing a potential pollution problem. If the concept proves feasible, the WMPI project team will develop an engineering design package for a plant to be built in Gilberton, Pennsylvania.

Dynegy Power Corporation, Houston, Texas, will evaluate producing power and chemicals from a plant fueled with coal and non-coal feedstocks. Dynegy will apply its gasification technology, which was being demonstrated at the Wabash River integrated gasification combined-cycle plant. Air Products & Chemicals will provide its novel Liquid Phase Methanol process, which produces methanol from coal-derived synthesis gas. Methanex will add its global expertise in producing and marketing chemical-grade methanol products, and Dow Corning and Dow Chemicals will serve as the customers for the methanol. If the concept proves feasible, the team will develop an engineering design package for a plant to be built at the Wabash River site in Terre Haute, Indiana.

Texaco Natural Gas, Inc. (TNGI), Houston, Texas, will combine its gasification technology with Rentech Inc.'s Fischer-Tropsch technology to produce high-quality transportation fuels and electricity from coal and petroleum coke. Texaco will use results from this project to determine the best configuration for commercial implementation of the integrated technology. If the concept proves feasible, TNGI's team will develop an engineering design package for a plant to be built at one of several sites.

SOLID FUELS AND FEEDSTOCKS

The Solid Fuels and Feedstocks program area is focused on activities to develop advanced technologies for the production of environmentally acceptable solid fuels and tailored carbon feedstocks.

The objectives of the Solid Fuels and Feedstocks program area are to: (1) develop and verify innovative technologies to improve the overall efficiency, economics, and environmental performance of energy utilization systems; (2) reduce environmental impacts associated with the generation of greenhouse gases and HAPs from coal utilization; (3) permit greater recoveries of useful energy in mined coal; (4) encourage the recovery of previously lost carbon raw materials from waste piles and tailing ponds; and (5) support the development of a technology that produces premium carbon and industrial products.

The product of Solid Fuels and Feedstocks research consists of a suite of advanced technologies that are highly efficient and cost-effective in converting raw solids into finished fuel and feedstocks suitable for customer needs. These technologies include a wide variety of processes that improve production, upgrading, handling, and transporting of various solid fuels. The range of solid fuels available for use is extensive and includes coal, alone or in combination with biomass, rubber, plastics, industrial residues, municipal solid wastes, and other solid wastes.

The Solid Fuels and Feedstocks program area is expected to lead to development of carbon products that improve fuel efficiency. New technologies will facilitate the pro-

duction of lightweight carbon products from coal to be used in airplanes, space vehicles, and the eight million passenger cars, lightweight trucks, passenger vans, and sport utility vehicles the United States produces each year. These technologies can help reduce transportation vehicle weight and yield major improvements in fuel efficiency and environmental quality.

Other research activities include development and demonstration of coal preparation, mild gasification, and industrial technologies. In the area of mild gasification, systems are employed which are simple, low-cost processes that, through

coal pyrolysis, create a broad spectrum of useful, environmentally acceptable and economical products. These products fall into three categories: gases, liquids, and solid char.

Mild gasification centers on advanced, integrated processes to develop these products into value-added fuels, chemicals, and industrial products. Char, for example, can be upgraded into carbon black, activated carbon, and specialty fuels. Liquids can be fractionated or catalytically cracked or hydro-treated to produce chemical feedstocks, carbon electrodes, octane enhancers, and diesel-fuel blenders.



NETL'S Solids Processing Research Facility is a one-of-a-kind, state-of-the-art center. Located in Pittsburgh, Pennsylvania, it is used to test a wide variety of advanced coal cleaning, processing, and handling methods.

Environmental Solid Fuels

Research in this area involves developing innovative methods for recovering usable fuels from materials that otherwise would be discarded at coal cleaning plants or utility power stations. Projects address the estimated 2–3 billion tons of coal fines that lie in waste impoundments at coal mines and washing plants around the country, the approximately 30 million tons of coal that is currently being wasted into ponds



each year by active mining operations, and the millions of tons of unburned carbon found in power plant fly ash landfills. Technologies are also being developed that combine coal and biomass or municipal solid waste into clean-burning fuels. Moreover, a method is under development for removing mercury from coal before it is burned, thus preventing the mercury from being released to form a hazardous air pollutant.

Other research in this area that will result in the more efficient use of solid fuels includes pilot-scale testing of an electrostatic separation process for dry, fine-size coal and POC testing of an advanced flotation control system.

Industrial-scale testing of an advanced technology will also be conducted for the production of carbonized slurry fuels for power production from coal, biomass, and waste. Work also will continue on the development of a national coal quality database on trace elements, through cooperation with a broad-based, utility-sector consortium for coal utilization.

Tailored Carbon Feedstocks

The Tailored Carbon Feedstocks activity concentrates on advanced technologies for the development of premium carbon products from coal, and the preparation of specially designed (tailored) feedstocks for the production of advanced transportation fuels and chemicals from coal, biomass, and waste feeds. Current projects focus on economically recoverable carbon through novel coal fines processing devices as well as dewatering/reconstitution systems.

Premium Carbon Industry. The Consortium for Premium Carbon Products from Coal (CPCPC) was established to focus on the development, commercialization, and promotion of technologies needed to produce value-added carbon products from coal and coal-derived feedstocks. The CPCPC is a unique, industry-driven consortium that is being led by the Pennsylvania State University, West Virginia University, and NETL. The CPCPC includes more than 50 members that represent a broad array of industries. The CPCPC identifies, selects, and partially funds projects that are deemed to have near-term potential for producing competitively priced premium carbon products from coal or coal-derived feedstocks. Among the members are manufacturers of specialty carbon and graphite products, activated carbon producers, municipally owned water treatment facilities, carbon fiber and composite producers, aluminum producers, carbon black and coal tar pitch producers, battery manufacturers, coal-fired electric utilities, and academia.

This research could result in new types of carbon-based products and applications such as:

- High-value premium carbon and graphite products;
- High-strength, lightweight materials for improving fuel efficiency/reducing weight of vehicles;
- Advanced feedstocks to reduce hazardous air pollutants, such as mercury;
- Improved rechargeable batteries;
- Fuel cell applications;
- Chemically tailored carbon molecular sieves;
- Adsorbents for water and air pollution control;
- Specialty chemicals and coke; and
- Material for heat-resistant applications.

ADVANCED FUELS RESEARCH

The objective of the Advanced Fuels Research program area is to lead the long-term development of advanced fossil energy technologies that will improve the Nation's economy, enhance energy security, and address relevant environmental and global climate change issues.



The strategy is to discover and apply new understandings of the chemistry and physics of carbon conversion to determine and overcome technical barriers that prevent the development of economically competitive, efficient, and environmentally responsible technologies.

These technologies would be designed to close the carbon cycle while ensuring sustained use of domestic carbon sources for the production of economic transportation and boiler fuels, chemicals, and high-value carbon products.

There are a number of hydrogen storage technologies in various stages of maturity, but the use of advanced carbon materials offers new and exciting possibilities. Finally, the development of better methods for separating other materials in a refinery environment will be necessary to better control the chemical properties of advanced fuels.

Ion Transport Membranes



Ion transport membranes (ITM), coupled with F-T reactors, produce synthesis gas and hydrogen from natural gas. An artist's rendering of the ITM process is shown above.

Carbon Science for the Hydrogen Economy

Hydrogen can be produced from natural gas or other fossil feedstocks. However, improvements in current methods for hydrogen separation from other gases remains a key issue for large-scale production of hydrogen (as in a refinery or Vision 21 plant), and for small-scale purification of hydrogen (as in fuel cell-powered vehicles). For hydrogen to be used widely as a transportation fuel, improvements are needed in hydrogen storage.

Hydrogen separation membrane development and its deployment in membrane reactor technology can offer potential advantages in hydrogen production and purification. An alternative approach is to use the appropriate starting fuels and novel reforming strategies.

Molecular Modeling/Catalyst Development

Advances in high-speed computing and improved understanding of chemical structures have led to increased use of molecular modeling as a predictive tool for research in chemistry. Applying these methods to processes that use catalysts is particularly challenging, but has enormous promise. The Advanced Fuels Research program area, through NETL's Ultra-Clean Fuels Science and Technology research, will investigate the use of computational science to improve the F-T process, hydrogenation, and hydrogen interactions with surfaces. The work will be conducted in collaboration with the University of Pittsburgh, Carnegie Mellon University, and Sandia National Laboratory.

C-1 Chemistry: Consortium for Fossil Fuel Liquefaction Science (CFFLS)

The CFFLS is a five-university research consortium with participants from the Universities of Kentucky, Pittsburgh, Utah, West Virginia, and Auburn. Since 1986, the CFFLS has been engaged in research on the development of alternative sources for transportation fuel. Currently, the CFFLS research program, through a recent research grant from DOE, is focused on “C-1” chemistry. C-1 chemistry is essentially the conver-

sion of single-carbon-bearing molecules — such as those that make up natural gas, carbon dioxide, or synthesis gas — into valuable liquid and other products.

Historically, much of the technical community’s C-1 chemistry research has focused on a specific category of chemical reactions called the F-T process. One of the consortium’s tasks will be to study an F-T process to generate oxygenated fuels using an iron-based catalyst.

The consortium’s main effort, however, will be to carry out a first-of-a-kind, nationally coordinated research

program on innovative chemical processes that may not follow the traditional F-T pathway. For instance, a better understanding of new types of C-1 chemistry could not only lead to lower-polluting transportation fuels, but also to the increased use of fuel cells — which operate using the hydrogen of carbon-containing materials — in automobiles and in stationary power plants. C-1 chemistry might also reveal ways to use carbon dioxide to convert natural gas into fuels and chemicals, perhaps providing a long-range option for dealing with climate change concerns.

Industry Research on Clean Fuels and Chemicals from Coal

In late 1999, four U.S. companies received research contracts from DOE’s Advanced Fuels Research program area to develop and test advanced technologies for producing clean fuels and high-value chemicals from coal. Administered by NETL (with partial funding from DOE’s Office of Energy Efficiency and Renewable Energy), the three-year projects are expected to provide new insights into technologies that future energy facilities can use to produce ultra-clean fuels that can help reduce air pollution and lower greenhouse gas emissions. The awarded projects are:

- **Research Triangle Institute, Research Triangle Park, North Carolina**, will develop and test an advanced system for maximizing premium-quality diesel fuel. The system will be based on the F-T process and will attempt to boost the proportion of diesel fuel and lower manufacturing costs by processing the coal gases in high-pressure, fixed bed columns filled with cobalt- and iron-based catalysts.
- **Energy and Environmental Research Corporation, Orange County, California**, will develop an advanced process capable of processing synthesis gas made in a coal gasifier into high-purity hydrogen and a concentrated stream of carbon dioxide that can be disposed of more easily through carbon sequestration techniques.
- **Media & Process Technology, Inc., Pittsburgh, Pennsylvania**, will use a new generation of inorganic (silicon carbide) membranes to separate hydrogen from the gases produced by a coal gasifier. Using data from the separation experiments, a process feasibility study will estimate the economic benefit of silicon carbide membranes in gasification-based power generation applications.
- **Hydrocarbon Technologies, Inc., Mercer County, New Jersey**, will study ways to increase the mechanical strength of catalysts used to convert coal gases into liquid fuels and chemicals. Researchers will develop a process for coating the catalysts with a strong, outside carbon shell. Based on the test results, an economic assessment will be prepared to compare the cost of using the carbon-coated catalyst and the uncoated catalyst in new advanced fuels production plants.

IN PARTNERSHIP WITH INDUSTRY

Liquid Phase Methanol Process

In recent years, many of the plastic handles of toothbrushes and screwdrivers have been made from an unusual source. Similarly, the plastic for some photographic film has had the same origin. The common feedstock? Coal gas — a mixture of valuable gaseous chemicals that can be formed by breaking apart coal with high temperatures and pressures.

Many of these products have been made — and are continuing to be made — at the Eastman chemical complex in Kingsport, Tennessee. Since the late 1970s, when natural gas was thought to be in short supply, the company has been gasifying coal to the chemical constituents that can be recombined into a variety of liquid and solid products. One of the products is methanol, which can be used directly as a fuel or as the intermediary for a wide array of petrochemical products, such as plastics.

For nearly a decade, the Kingsport plant relied solely on a conventional “dry” process to transform coal gas into methanol and other products. The coal gas would be blown through a bed of solid catalysts, which aid the chemical reactions that produce the desired products. In the mid-1980s, however, a new coal gas-to-methanol process was ready to be tested. It was a “liquid phase” process; the catalyst particles were suspended in a liquid-filled vessel through which the coal gases would be bubbled.



LPMEOH™ 80,000 gallon-per-day demonstration unit at Eastman Chemical Company's Kingsport, Tennessee Facility

Beginning in 1981, DOE invested over \$30 million in research and development of the Liquid Phase Methanol Process technology. The original process development work was performed at DOE's 3,200 gallon-per-day Laporte, Texas facility.

In 1989, the Liquid Phase Methanol technology was selected by DOE for demonstration in the third round of the CCT program. The Air Products Liquid Phase Conversion Company, L.P., a partnership between Air Products and Chemicals, Inc. and Eastman Chemical Company, was formed to complete the design, construction, and operation of the commercial-scale plant at Eastman's chemicals-from-coal complex in Kingsport, Tennessee.

Since startup of the unit in April 1997, overall availability has exceeded 96 percent, while calendar year 1998 achieved 99.7 percent availability. Over 66 million gallons of methanol have been produced to date. Due to this success, the project was recently extended an additional 15 months (from December 28, 2001, until March 31, 2003).

The Air Products' Liquid Phase Methanol™ demonstration plant may be the forerunner of either future stand-alone liquids production facilities or, more likely, the liquids-producing module of a multi-product energy plant such as DOE's Vision 21 plant.



C&PS FUELS PROGRAM

*Improving the Fuels
that Power our World*

CARBON SEQUESTRATION



ADDRESSING GLOBAL CLIMATE CHANGE

INTRODUCTION

Program Areas

- Separation and Capture
- Sequestration in Geologic Formations
- Ocean Sequestration
- Terrestrial Sequestration
- Advanced Concepts
- Modeling and Assessments

The potential impact of increasing greenhouse gases in the atmosphere will be a global concern well into the 21st century.

Predictions of global energy use in the next century suggest a continued increase in carbon emissions and rising concentrations of carbon dioxide (CO₂) in the atmosphere unless major changes are made in the way we produce and use energy, in particular, how we manage carbon.

In order to stabilize and ultimately reduce concentrations of this greenhouse gas, it will be necessary to employ carbon sequestration — carbon capture, separation, and storage or reuse. Carbon sequestration,



along with reduced carbon content of fuels and improved efficiency of energy production and use, must play major roles if the Nation is to enjoy the economic and energy security benefits which fossil fuels bring to the energy mix.

The President's Committee of Advisors on Science and Technology (PCAST) underscored the importance of carbon sequestration in two separate reports (issued November 1997 and June 1999). PCAST recommended increasing the U.S. Department of Energy's (DOE) research and development (R&D) for carbon sequestration. Specifically, the report stated that "a much larger science-based CO₂ sequestration program should be developed. The aim should be to provide a science-based assessment of the prospects and costs of CO₂ sequestration. This is very high-risk, long-term R&D that will not be undertaken by industry alone without strong incentives or regulations, although industry experience and capabilities will be very useful."

The peer-reviewed Office of Fossil Energy and Office of Science December 1999 report, *Carbon Sequestration: State of the Science*, assessed "key areas for research and development that could lead to an understanding of the potential for future use of carbon sequestration as a major tool for managing carbon emissions."

To be successful, the techniques and practices to sequester carbon must meet the following requirements: (1) be effective and cost-competitive; (2) provide stable, long-term storage; and (3) be environmentally benign. Using present technology,

estimates of sequestration costs are in the range of \$100–300/ton of carbon emissions avoided. The goal of the program is to reduce the cost of carbon sequestration to \$10 or less per net ton of carbon emissions avoided by 2015. Achieving this goal would save the United States trillions of dollars. Further, achieving a mid-point stabilization scenario (e.g., 550 ppm CO₂) would not require wholesale introduction of zero emission systems in the near term. This would allow time to develop cost-effective technology over the next 10–15 years that could be deployed for new capacity and capital stock replacement capacity.

The program portfolio covers the entire carbon sequestration "life cycle" of capture, separation, transportation, and storage or reuse, as well as research needs for two other energy-related greenhouse gases of concern, methane (CH₄) and nitrous oxides (N₂O). Specifically, the R&D program has six program areas:

- Cost-effective CO₂ capture and separation processes.
- CO₂ sequestration in geological formations including oil and gas reservoirs, unmineable coal seams, and deep saline reservoirs.
- Direct injection of CO₂ into the deep ocean and perhaps stimulation of phytoplankton growth.
- Improved full life-cycle carbon uptake of terrestrial ecosystems.
- Advanced chemical, biological, and decarbonization concepts.
- Models and assessments of cost, risks, and potential of carbon sequestration technologies.

DRIVERS

Global climate change. Burning coal, oil, and natural gas to heat homes, power cars, and illuminate cities produces carbon dioxide and other greenhouse gases as by-products. Deforestation and clearing of land for agriculture also allows the release of significant quantities of such gases.

The concentration of CO₂ in the atmosphere is rising and, due to growing concern about its effects, the United States and 160 other countries ratified the Rio Mandate, which calls for “...stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.”

Net increases in CO₂ emissions from energy systems and other human activity may be causing changes in the earth’s climate, changes that in the future could be harmful to human health and global economic prosperity. Much uncertainty is associated with the global climate change issue, but it is possible, even likely, that deep cuts in net CO₂ emissions from human activity will be required over the next 50–100 years.

Growing energy demand. Today, emissions of CO₂ into the atmosphere are an inherent part of electricity generation, transportation, and building systems. The energy sector is responsible for roughly 90 percent of U.S. greenhouse gas emissions, and 85 percent of the current U.S. energy system is based on fossil fuels. Moreover, even though the use of zero-carbon fuels is expected to grow substantially in the coming decades, there are economic and environmental limits on nuclear

and renewable-based energy technologies.

The challenge of global climate change also requires that we look out beyond our borders. Electricity is the fastest growing segment of the global energy market. Some have predicted that, by 2050, the forces of population growth, urbanization, expanding global commerce, and simple human aspirations could result in the global consumption of electric power that is four times greater than today.

Carbon management strategies.

To date, climate change strategies have emphasized energy efficiency and the greater use of lower carbon fuels — both promising options. However, global climate change is a long-term issue, and so too will be its solution. Changing the energy system that has largely been responsible for the Nation’s economic growth and prosperity — particularly changing the system overnight — is neither economically feasible nor socially responsible. Premature retirement of existing infrastructure would be prohibitively expensive and economically unwise.

Sequestration approaches have the potential to save hundreds of millions of dollars a year compared to other carbon management approaches. Sequestration also would allow continued use of much of the Nation’s current energy infrastructure.

Expanding markets for carbon management technology.

If the promise of sequestration is realized, a truly global market for carbon management technologies will emerge. Perhaps more important, widespread use of these technolo-

gies could significantly alter the environment. The United States needs to improve its participation in the research involved in carbon management so that, at a minimum, the United States would have its own independent capability to assess the viability, efficacy, and safety of any non-U.S. actions, such as sequestering CO₂ in the ocean. The United States will need to selectively cooperate and compete with other nations in developing these technologies, because the U.S. does not currently hold the leadership position in many key aspects of carbon management. For example, the Japanese budget in CO₂ capture and disposal appears to be 35–70 times as large as that of the United States. Moreover, various other nations (including Japan and some European nations) are leading the U.S. in the development of certain technologies and the understanding of certain phenomenon that are fundamental to implementing CO₂ capture and disposal methods.



CARBON SEQUESTRATION PROGRAM BENEFITS

National Benefits

- Results in an estimated cumulative benefit to the U.S. economy of \$2.4 trillion through 2050;
 - Provides for energy security by enabling use of vast domestic coal resources, which are expected to provide at least 50 percent of the electricity produced well into the 21st century; and
 - Eases the economic transition to a sustainable climate.
-

Supplier Benefits

- Enables U.S. industry to establish a leadership position in a new global market for a novel class of technologies;
 - Removes a major concern relative to the continued operation of existing fossil fuel plants;
 - Provides flexibility to power producers by enabling the use of indigenous fossil fuels for new generation capacity; and
 - Expands business opportunities for power producers by adding a commodity to the product slate.
-

Customer Benefits

- Keeps energy prices low by allowing continued use of low-cost indigenous fossil fuel resources; and
- Provides insurance against potential adverse environmental consequences associated with global climate change.

ACCOMPLISHMENTS

Promoting a new area of technical endeavor, such as carbon sequestration, is a process of collection and maturation of innovative ideas.

Given the federal government's role in supporting high-risk R&D in the long-term national interest, a carbon sequestration research and technology development program is being expanded significantly on the eventuality that such technology will be needed in the energy marketplace some time in the first quarter of this century.

Since the program's inception in 1998, the Carbon Sequestration program has conducted stakeholder

workshops, roadmapping exercises, and portfolio analysis leading up to its first solicitation for projects in 1998. This solicitation resulted in 12 exploratory studies to evaluate the feasibility of various sequestration technologies. Six of the 12 studies were given additional government funding in 1999 for further project development. A second solicitation in late 1999 has generated two phases of sequestration research. Phase I research projects emphasize both National Laboratory/private sector partnerships, and private sector research teams. Eight National Laboratory/private sector partnership projects were selected in February 2000. More recently, DOE selected 13 new private sector re-

search projects from more than 60 submitted concepts.

DOE's main achievements in carbon sequestration have been in its ability to integrate industrial participation, address environmental issues, and gain support for an expanded federal sequestration program. To date, research has concentrated largely on early exploratory ventures funded primarily with federal dollars. The more recent private sector projects, however, are larger-scale partnerships with private research institutions, industries, and universities contributing an average of 40 percent of the total costs — well above DOE's minimum requirement of 20 percent.

Inter- and Intra-Agency Crosscutting Coordination

The Carbon Sequestration program has built an extensive collaborative network of relationships with private and public sector stakeholders. Within DOE, the program builds on a cooperative effort between FE and the Office of Science that has already resulted in the December 1999 peer-reviewed joint report, *Carbon Sequestration: State of the Science* and a subsequent public/industry workshop. The research pathways defined in these efforts form the structure of the program.

Within FE, the program will work synergistically with the Vision 21 Program to jointly address the three basic options to reduce CO₂ concentrations: (1) improve the efficiency of energy production and end use; (2) reduce the carbon content of fuels; and (3) carbon sequestration. For the critical area of CO₂ capture and separation, the program has important linkages with the Innovations for Existing Plants program area within the Central Systems program. In particular, the potential of integrating CO₂ control with other emissions control systems would provide the option of integrated control at a lower cost.

In the area of terrestrial sequestration, which encompasses forestry and enhanced storage in soils and vegetation, FE is working closely with the U.S. Forest Service and the Office of Surface Mining and has established Interagency Agreements with them to cooperate and partner in areas of mutual interest. In the area of geologic sequestration, FE and the U.S. Geologic Survey have a long-standing history of cooperation and collaboration. As the program proceeds, similar collaborative agreements will be sought with other federal agencies, as well as with state agencies and their representative organizations.

The program has established highly synergistic relationships with industry and academic stakeholders. These relationships started with a government/industry/academia workshop hosted by the Massachusetts Institute of Technology in 1998, and include recent activities such as a joint FE/industry/international workshop in geologic sequestration and the selection of cost-shared industry/academic/National Laboratory R&D projects through competitive solicitations. The program combines these activities with international collaboration, including joint work with the International Energy Agency's Greenhouse Gas R&D Programme and its member countries.

ACTIVITIES

Carbon sequestration enables the use of fossil fuels in energy systems without emissions of CO₂ into the atmosphere.

The program goal is to reduce the cost of carbon sequestration to \$10 or less per net ton of carbon emissions avoided by 2015. Since initiation of the program in 1998, outreach and planning exercises have been conducted to help determine the appropriate direction and focus of the R&D activities.

The roadmap on page 5-7 identifies major milestones for the Carbon Sequestration program. In the program R&D portfolio, each project falls in a typical progression of R&D, where the carbon sequestration R&D stages are defined as:

- *Assessment*: conceptual designs, modeling analysis
- *Conceptual R&D*: experimental studies, prototype development
- *Bench-Scale Technology Development*: laboratory experiments, systems integration
- *Field Testing*: large-scale prototype development
- *Verification with Large Projects*: testing and monitoring during operation over extended periods of time

The near-term program will examine and identify a spectrum of science-based sequestration approaches that have the greatest potential to yield the cost-effective technologies that are required.

Separation and Capture. Current activities include: (1) development

of a high-temperature membrane that can separate CO₂ from gases formed when coal is reacted with steam and oxygen in a coal gasifier; (2) development of a low-cost way to separate CO₂ from the flue gas of existing fossil fuel combustion plants with a reusable sodium-based chemical; (3) demonstration of methane capture from landfills; (4) development of an inorganic, palladium-based membrane that will separate hydrogen and concentrated CO₂ from hydrocarbon fuels; (5) study of a CO₂ separation system for a power plant that uses iron- and copper-based sorbents; and (6) the study of hydrates in the removal of CO₂ from gas streams

Sequestration in Geologic Formations. R&D is focused on: (1) using enhanced coal-bed methane recovery technology to test the viability of storing CO₂ in coals seams; (2) using a nuclear magnetic resonance well-logging technique to identify the most suitable geologic formation for long-term CO₂ storage; (3) the study of deep saline reservoirs in the Colorado and Rocky Mountain region to determine how much CO₂ can be stored and associated environmental risks; (4) identification of storage sites for mass CO₂ sequestration; and (5) evaluation of geologic and geochemical processes that could be used to sequester CO₂ into deep aquifers.

Ocean Sequestration. Current DOE/industry R&D includes: (1) the use of a combination of remotely operated deep sea vehicle technology, time lapse photography, and other analytical techniques to determine the long-term fate of CO₂ injected into the ocean; (2) large-scale

CO₂ transportation and deep ocean sequestration; and (3) direct analysis of frozen CO₂ deposits (known as hydrates) on the sea floor.

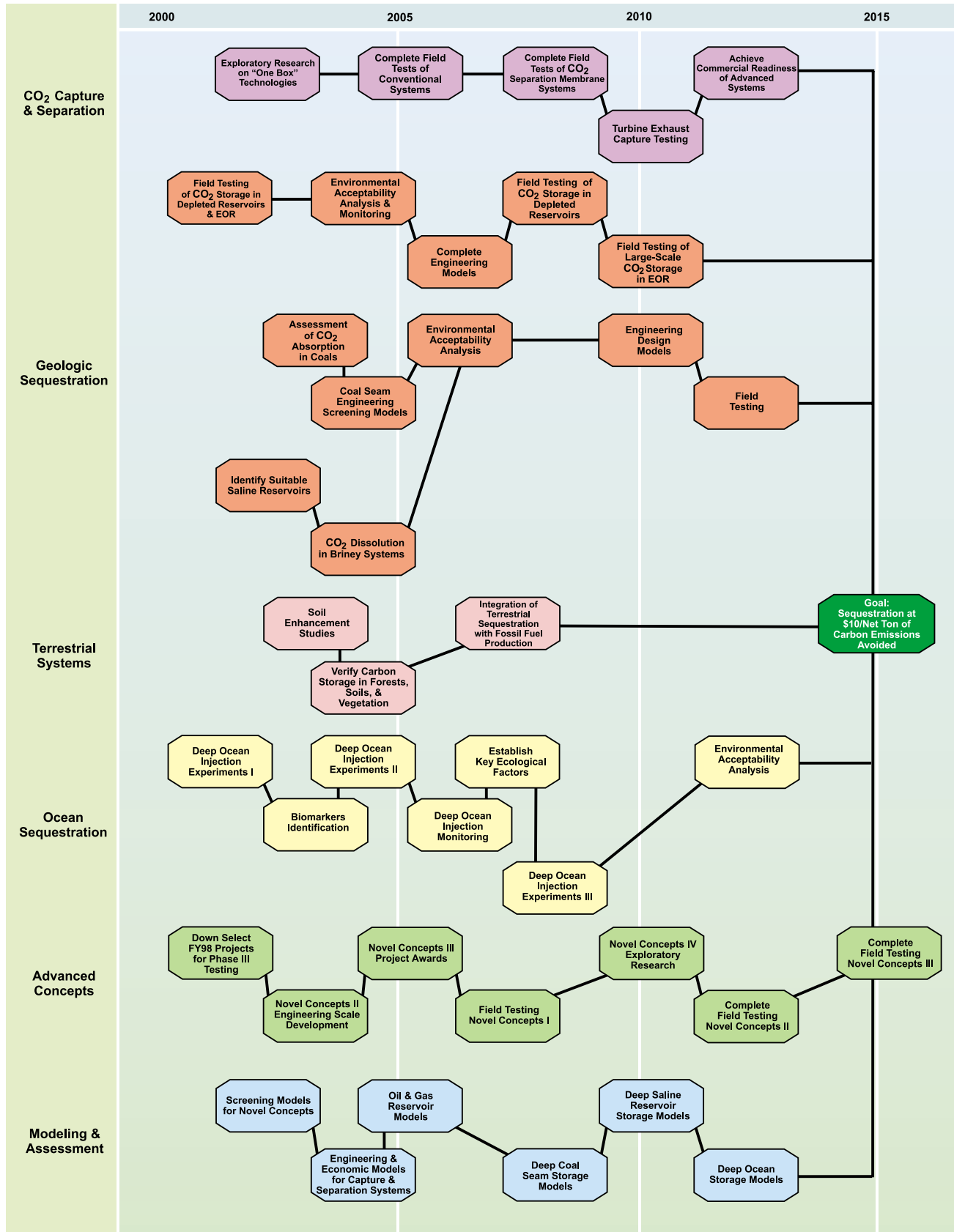
Terrestrial sequestration. Studies in this program area include evaluation of a reclamation/reforestation program that would sequester carbon in trees on abandoned mine lands in the Appalachian region and development of a system for trading carbon credits to lower the costs of CO₂ terrestrial sequestration.

Advanced Concepts. Advanced concepts R&D is focused on: (1) enhancing photosynthesis by attaching photosynthetic organisms to specially designed growths arranged in a “bioreactor,” with special lighting to enhance the rate of CO₂ conversion; and (2) development of technologies that use selected species of micro-algae to photosynthesize CO₂ from power plant exhaust gases.

Modeling and Assessments. Current research in the Modeling and Assessments program area centers on: (1) development of a state-of-the-art computer model to assess CO₂ sequestration options and costs from the local to national level; and (2) development of a digital database that catalogs CO₂ source-to-sequestration site information in five midwestern states.

In the midterm, sequestration pilot testing will develop options for direct and indirect sequestration. In the long term, the technology products will be more revolutionary and rely less on site-specific or application-specific factors to ensure economic viability.

CARBON SEQUESTRATION ROADMAP



DRIVERS

- Climate change and policies to address it may be the most influential consideration in energy use in the United States early in this century.
- Emission of CO₂ into the atmosphere is inherent to the use of fossil energy resources for electricity generation, transportation, industrial heat and power, and building systems.
- Fossil fuel's share of the domestic energy market will increase from 85 percent in 1995 to 90 percent in 2020, reflecting the abundance of the energy resource and the economic environmental limits on nuclear and renewable alternatives.
- Increased concentrations of CO₂ in the atmosphere due to carbon emissions are expected unless energy systems reduce carbon load.
- Carbon sequestration (carbon capture, separation, and storage or reuse) must: be effective and cost-competitive; provide stable, long-term storage; and be environmentally benign.
- The growing global market for carbon management technologies demands early action on the part of the United States in achieving a leadership position in the development of revolutionary sequestration technologies.

OBJECTIVES

- Provide economically competitive and environmentally safe options to offset all projected growth in baseline emissions of greenhouse gases by the U.S. after 2010 with offsets starting in 2015.
- Achieve the long-term cost goal of approximately \$10/ton of avoided net costs for carbon sequestration by 2015.
- Offset at least one-half of the required reduction in global greenhouse gases, measured as the difference in a business-as-usual baseline and a strategy to stabilize concentration at 550 ppm CO₂, beginning in 2025.

STRATEGIES

- Pursue evolutionary improvements in existing CO₂ capture systems and explore revolutionary new capture and sequestration concepts with a view toward significant cost reductions.
- Conduct fundamental studies and field tests to measure the degree to which CO₂ stays sequestered in geologic formations, including oil and gas reservoirs, coal beds and saline formations, and assess the long-term ecological impacts.
- Develop a better understanding of the ecological impacts of ocean fertilization and deep ocean direct injection of CO₂.
- Pursue integrated measures for improving the full life-cycle carbon uptake of terrestrial ecosystems, including farmland and forests, with fossil fuel production and use.
- Develop novel and advanced concepts using chemical, biological, and other approaches to capture, store, and reuse CO₂ from energy production and utilization systems.
- Develop assessment capabilities and analytical tools to assist in the selection of the most promising R&D efforts that have high potential, but significant uncertainties associated with their cost and effectiveness.
- Continue collaboration activities and workshops to keep all stakeholder groups — industry, end-users, non-profit organizations, academia, National Laboratories, the environmental community, and governments — apprised of new developments and maintain an open dialogue on the merits of carbon sequestration.

PERFORMANCE GOALS

- Reduce the cost of carbon sequestration from \$100–\$300/ton today to \$10 per net ton of carbon emission avoided by 2015.
- Develop options for “value added” sequestration with multiple benefits such as using CO₂ in enhanced oil recovery operations and in methane production from deep unmineable coal seams by 2010.
- Establish the viability of larger capacity sequestration approaches suitable for deployment by industry in the post-2015 timeframe.

SEPARATION AND CAPTURE

The goal of CO₂ separation and capture is to isolate carbon from its many sources in a form suitable for transport and sequestration.

Before CO₂ gas can be sequestered from point sources, it must be captured as a relatively pure gas. Carbon dioxide is routinely separated and captured as a by-product from industrial processes such as synthetic ammonia production, hydrogen production, and limestone calcination. At least one coal-fired power plant is currently capturing and separating CO₂ and subsequently trucking the CO₂ for food processing use. However, existing capture technologies are not cost-effective when considered in the context of CO₂ sequestration. Carbon dioxide capture is generally estimated to represent three-fourths of the total cost of carbon capture, storage, transport, and sequestration systems.

Opportunities for significant cost reductions exist since very little R&D has been devoted to CO₂ capture and separation technologies.



Several innovative schemes have been proposed that could significantly reduce CO₂ capture costs, compared to conventional processes. “One box” concepts that combine CO₂ capture with reduction of criteria-pollutant emissions will be explored.

The program area will pursue evolutionary improvements in existing CO₂ capture systems and also explore revolutionary new capture and sequestration concepts. The most likely options currently identifiable for CO₂ separation and capture are discussed below.

ABSORPTION

Carbon dioxide can be removed from gas streams by physical or chemical absorption. Physical absorption processes are temperature and pressure dependent with absorption occurring at high temperatures and low pressures. Chemical absorption is preferred for low to moderate CO₂ partial pressures. Because CO₂ is an acid gas, chemical absorption of CO₂ from gaseous streams such as flue gas depends on acid-base neutralization reactions using basic solvents.

ADSORPTION

Selective separation of CO₂ may be achieved by the physical adsorption of the gas on high-surface-area solids in which the large surface area results from the creation of very fine surface porosity through surface activation methods using, for example, steam, oxygen or CO₂. Some naturally occurring materials (e.g., zeolites) have high surface areas and efficiently adsorb some gases. Adsorption capacities and kinetics are

governed by numerous factors including adsorbent pore size, pore volume, surface area, and affinity of the adsorbed gas for the adsorbent.

LOW-TEMPERATURE DISTILLATION

Low-temperature distillation is widely used commercially for the liquefaction and purification of CO₂ from high-purity streams (typically a stream with >90% CO₂). In low-temperature distillation, a low-boiling-point liquid is purified by evaporating and subsequently condensing it. Low-temperature distillation enables direct production of liquid CO₂ that can be stored or sequestered at high pressure via liquid pumping.

GAS SEPARATION MEMBRANES

Diffusion mechanisms in membranes are numerous and differ greatly depending on the type of membrane used. Generally, gas separation is accomplished via some interaction between the membrane and the gas being separated. For example, polymeric membranes transport gases via a solution-diffusion mechanism (i.e., the gas is dissolved in the membrane and transported through the membrane by a diffusion process).

Inorganic membranes, metallic or ceramic, are particularly attractive because of the many transport mechanisms that can be used to maximize the separation factor for various gas separations. In addition, inorganic membranes can be operated at high pressures and temperatures and in corrosive environments.

OCEAN SEQUESTRATION

CO₂ is soluble in ocean water, and through natural processes the oceans both absorb and emit huge amounts of CO₂ into the atmosphere.

It is widely believed that the oceans will eventually absorb most of the CO₂ in the atmosphere. However, the kinetics of ocean uptake are unacceptably slow, causing a peak atmospheric CO₂ concentration of several hundred years. The program will explore options for speeding up the natural processes by which the oceans absorb CO₂ and for injecting CO₂ directly into the deep ocean.

ENHANCEMENT OF NATURAL CARBON SEQUESTRATION

One approach to enhancing the rate of CO₂ absorption in the ocean involves adding combinations of micronutrients and macronutrients to those ocean surface waters deficient in such nutrients. The objective is to stimulate the growth of phytoplankton, which are expected to consume greater amounts of carbon dioxide. When carbon is thus removed from the ocean surface waters, it is ultimately replaced by CO₂ drawn from the atmosphere. The extent to which the carbon from this increased biological activity is sequestered is unknown at this point, and would require additional research. Any R&D on natural enhancement would also require complete examination of potential environmental issues.



Every year the ocean actively takes up one-third of our anthropogenic CO₂ emissions. Eventually (over 1,000 years), about 85 percent of today's anthropogenic emissions of CO₂ will be transferred to the ocean. Ocean sequestration strategies attempt to speed up this ongoing process to reduce both peak atmospheric CO₂ concentrations and their rate of increase.

DIRECT INJECTION OF CO₂

Technology exists for the direct injection of CO₂ into deep areas of the ocean; however, the knowledge base is not adequate to optimize the costs, determine the effectiveness of the sequestration, and understand the resulting changes in the biogeochemical cycles of the ocean. To assure environmental acceptability, developing a better understanding of the ecological impacts of both ocean fertilization and direct injection of CO₂ into the deep ocean is a primary focus of this program element. It is known that small changes in biogeochemical cycles may have large consequences, many of which are secondary and difficult to predict. Of particular concern is the effect of CO₂ on the acidity of ocean water.



SEQUESTRATION IN GEOLOGIC FORMATIONS

CO₂ sequestration in geologic formations includes oil and gas reservoirs, unmineable coal seams, and deep saline reservoirs.

OIL AND GAS RESERVOIRS

In some cases, production from an oil or natural gas reservoir can be enhanced by pumping CO₂ gas into the reservoir to push out the product, which is called enhanced oil recovery (EOR). The United States is the world leader in EOR technology, using about 32 million tons of CO₂ per year for this purpose. From the perspective of the sequestration program, EOR represents an opportunity to sequester carbon at low net cost, due to the increased revenues from recovered oil/gas. In an EOR application, the integrity of the CO₂ that remains in the reservoir is well understood and very high, as long as the original pressure of the reservoir is not exceeded. The scope of this EOR application is currently economically limited to point sources of CO₂ emissions that are near an oil or natural gas reservoir.

COAL BED METHANE

Coal beds typically contain large amounts of methane-rich gas that is adsorbed onto the surface of the coal. The current practice for recovering coal-bed methane (CBM) gas is to depressurize the bed, usually by pumping water out of the reservoir. An additional approach is to inject carbon dioxide gas into the bed. Tests have shown that CO₂ is roughly twice as adsorbing on coal as methane, giving it the potential to effi-

ciently displace methane and remain sequestered in the bed. Carbon dioxide recovery of CBM has been demonstrated in limited field tests, but much more work is necessary to understand and optimize the process.

Similar to the by-product value gained from EOR, the recovered methane provides a value-added revenue stream to the carbon sequestration process, creating a low net cost option. The U.S. coal resources are estimated at 6 trillion tons, and 90 percent of it is unmineable due to seam thickness, depth, and structural integrity. Another promising aspect of CO₂ sequestration in coal beds is that many of the large unmineable coal seams are near electricity generation facilities that are large point sources of CO₂ gas. Thus, limited pipeline transport of CO₂ gas would be required. Integration of coal-bed methane with a coal-fired electricity generation system can provide an option for additional power generation with low emissions.

SALINE FORMATIONS

Sequestration of CO₂ in deep saline formations does not produce value-added by-products, but it has other advantages. First, the estimated carbon storage capacity of saline formations in the U.S. is large, making them a viable long-term solution. It has been estimated that deep saline formations in the U.S. could potentially store up to 500 billion metric tons of CO₂. Second, most existing large CO₂ point sources are within easy access to a saline formation injection point, and therefore sequestration in saline formations is compatible with a strategy of trans-

forming large portions of the existing U.S. energy and industrial assets to near-zero carbon emissions via low-cost carbon sequestration retrofits.

Assuring the environmental acceptability and safety of CO₂ storage in saline formations is a key component of this program element. Determining that CO₂ will not escape from formations and either migrate up to the earth's surface or contaminate drinking water supplies is a key aspect of sequestration research. Although much work is needed to better understand and characterize sequestration of CO₂ in deep saline formations, a significant baseline of information and experience exists. For example, as part of EOR operations, the oil industry routinely injects brines from the recovered oil into saline reservoirs, and the U.S. Environmental Protection Agency (EPA) has permitted some hazardous waste disposal sites that inject liquid wastes into deep saline formations.

The Norwegian oil company, Statoil, is injecting approximately one million metric tons per year of recovered CO₂ into the Utsira Sand, a saline formation under the sea associated with the Sleipner West Heimdel gas reservoir. The amount being sequestered is equivalent to the output of a 150-MW coal-fired power plant. This is the only commercial CO₂ geological sequestration facility in the world.

SEQUESTRATION IN TERRESTRIAL ECOSYSTEMS

Carbon sequestration in terrestrial ecosystems is either the net removal of CO₂ from the atmosphere or the prevention of CO₂ net emissions from the terrestrial ecosystems into the atmosphere.

Enhancing the natural processes that remove CO₂ from the atmosphere is thought to be one of the most cost-effective means of reducing atmospheric levels of CO₂, and reforestation and deforestation abatement efforts are already under way.

The terrestrial biosphere is estimated to sequester large amounts of carbon (approximately 2 billion metric ton of carbon per year). R&D in this program area seeks to increase this rate while properly considering all the ecological, social, and economic implications. There

are two fundamental approaches to sequestering carbon in terrestrial ecosystems: (1) protection of ecosystems that store carbon so that sequestration can be maintained or increased; and (2) manipulation of ecosystems to increase carbon sequestration beyond current conditions.

This program area is focused on integrating measures for improving the full life-cycle carbon uptake of terrestrial ecosystems, including farmland and forests, with fossil fuel production and use. The following ecosystems offer significant opportunity for carbon sequestration:

- *Forest lands.* The focus includes below-ground carbon and long-term management and utilization of standing stocks, understory, ground cover, and litter.
- *Agricultural lands.* The focus includes crop lands, grasslands, and

range lands, with emphasis on increasing long-lived soil carbon.

- *Biomass croplands.* As a complement to ongoing efforts related to biofuels, the focus is on long-term increases in soil carbon.
- *Deserts and degraded lands.* Restoration of degraded lands offers significant benefits and carbon sequestration potential in both below- and above-ground systems.
- *Boreal wetlands and peatlands.* The focus includes management of soil carbon pools and perhaps limited conversion to forest or grassland vegetation where ecologically acceptable.

The program area is being conducted in collaboration with DOE's Office of Science and the U.S. Forest Service of the U.S. Department of Agriculture.



ADVANCED CONCEPTS/MODELING AND ASSESSMENTS

ADVANCED CHEMICAL AND BIOLOGICAL APPROACHES

Recycling or reuse of CO₂ from energy systems would be an attractive alternative to storage of CO₂. The goal of this program area is to reduce the cost and energy required to chemically and/or biologically convert CO₂ into either commercial products that are inert and long-lived or stable solid compounds.

Two promising chemical pathways are magnesium carbonate and CO₂ clathrate, an ice-like material. Both provide quantum increases in volume density compared to gaseous CO₂. As an example of the potential of chemical pathways, the entire global emissions of carbon in 1990 could be contained as magnesium carbonate in a space 10 km by 10 km by 150 m.

Concerning biological systems, incremental enhancements to the carbon uptake of photosynthetic

systems could have a significant positive effect. Also, harnessing naturally occurring, non-photosynthetic microbiological processes capable of converting CO₂ into useful forms, such as methane and acetate, could represent a technology breakthrough. An important advantage of biological systems is that they do not require pure CO₂ and do not incur costs for separation, capture, and compression of CO₂ gas. This program area will seek to develop novel and advanced concepts for capture, reuse, and storage of CO₂ from energy production and utilization systems based on, but not limited to:

- Biological systems;
- Advanced catalysts for CO₂ or CO conversion;
- Novel solvents, sorbents, membranes and thin films for gas separation;
- Engineered photosynthesis systems;
- Non-photosynthetic mechanisms for CO₂ fixation (methanogenesis and acetogenesis);
- Genetic manipulation of agricultural and tree to enhance CO₂ sequestering potential;
- Advanced decarbonization systems; and
- Biomimetic systems.

SEQUESTRATION MODELING AND ASSESSMENTS

Better assessments of the costs, risks, and the potential of carbon sequestration technology are essen-

tial to develop technological options for greenhouse gas mitigation.

Sound assessment capabilities are required to evaluate technological options in a total systems context, considering costs and impacts over a full product cycle, and societal and environmental effects to provide a basis for assessing trade-offs between local environmental impacts and global impacts. Analytical tools are needed to strategically select the most promising R&D efforts that have high potential, but significant uncertainties, associated with their costs and effectiveness.

Some of the projects in this cross-cutting activity include:

- Adapt existing oil and gas reservoir models used for fossil fuel production to carbon sequestration;
- Develop risk assessment models and life-time prediction models for geologic and ocean sequestration;
- Assess the capacities of geologic and ocean storage sites;
- Provide verification for the sequestration capabilities of various technological options;
- Develop criteria to guide selection of potential storage sites, including enhancing natural sinks; and permit uniform assessments of the carbon mitigation potential of novel and advanced systems; and
- Model naturally occurring CO₂ formations and processes to yield information that could serve as analogs for estimating the long-term CO₂ storage potential of depleted oil and gas reservoirs, and other approaches.



National Lab Participation in CO₂ Sequestration

As part of DOE's project selections in 2000, the Department is providing funds to the National Laboratories over the next three years to study sequestration innovations ranging from carbon dioxide filtering membranes to the development of "biofilms" made up of carbon converting microorganisms.

In seven of the eight projects selected, lab researchers are teaming with scientists from the private sector, universities, or other agencies. The National Laboratory projects are:

- **Los Alamos National Laboratory and Idaho National Engineering and Environmental Laboratory** will collaborate with the University of Colorado, Pall Corporation, and Shell Oil Company in a three-year project to develop an improved high-temperature polymer membrane for separating CO₂ from methane and nitrogen gas streams.
- **Sandia and Los Alamos National Laboratories** will join with Strata Production Company and the New Mexico Petroleum Recovery Research Center in a three-year study of ways to inject CO₂ into depleted oil reservoirs.
- **Lawrence Berkeley, Lawrence Livermore, and Oak Ridge National Laboratories** will cooperate with Chevron, Texaco, Pan Canadian Resources, Shell CO₂ Company, BP Amoco, Statoil, and the Alberta Research Council Consortium in a three-year study of geologic sequestration of carbon dioxide in formations such as brine reservoirs, depleted oil reservoirs, and coal beds.
- **Idaho National Engineering and Environmental Laboratory** will team with Purdue University, Pacific Gas and Electric, Southern California Gas, and BP Amoco to develop a novel "gas-liquid contactor" that creates a whirlwind-like vortex for separating CO₂ from natural gas and flue gas.
- **Argonne National Laboratory** will conduct a two-year study of ways to retrofit a coal power plant with recirculating technology to concentrate carbon dioxide sufficiently to transport it to sequestration sites.
- **Lawrence Livermore National Laboratory** will team with the U.S. Geological Survey and Monterey Bay Aquarium Research Institute in a two-year study of ice-like hydrates that form when cold CO₂ is pumped into deep ocean basins.
- **Oak Ridge National and Pacific Northwest National Laboratories** will join with Ohio State University and Virginia Polytechnic Institute in a two-year project to study the use of soil enhancers made from the solid wastes of coal plants, paper mills, and sewage treatment facilities to improve the natural carbon uptake of lands disturbed by mining, highway construction, or poor management practices.
- **Idaho National Engineering and Environmental Laboratory** will team with Montana State University and the University of Memphis in a two-year study of ways to grow microorganisms known as cyanobacteria as "biofilms" that could capture and convert carbon dioxide through photosynthesis.

IN PARTNERSHIP WITH INDUSTRY

CO₂ Capture and Geologic Sequestration: Progress through Partnerships was a collaborative workshop held in September 1999 to create new solutions to the challenge of CO₂ capture and geologic sequestration. The workshop was jointly sponsored by BP Amoco, DOE's Office of Fossil Energy, and the International Energy Agency's Greenhouse Gas R&D Programme (IEA/GHG). The workshop consisted of: (1) international, national, and industry perspectives on sequestration; (2) panel discussions on CO₂ capture and geologic sequestration technologies; (3) status reports from ongoing CO₂ sequestration projects; and (4) working sessions to develop an industry work program leading to breakthroughs in costs and performance.

The partnership between BP Amoco, DOE, and the IEA/GHG was successful in bringing together a diverse group of experts, with over 140 participants attending the conference. Seventy-five percent of the participants were from industry, with 30 percent of them coming from outside the United States.

BP Amoco will use the information and contacts from the workshop to help its efforts to form a Joint Implementation Project that sequesters CO₂ in Alaska's North Slope. The federal government and IEA will apply the information from the workshop to the management of their R&D activities. Additional information including a summary of the workshop findings can be found on the NETL website at www.netl.doe.gov.

BP Amoco and Alaska's North Slope

The opportunity on Alaska's North Slope stems from the fact that a number of large point sources of CO₂ emission are located near a large, undeveloped viscous oil reservoir. The concept is to capture the CO₂ from the point sources and inject it into the viscous oil reservoir where it will decrease the viscosity of the oil, thus increasing the productivity of the wells to the point where they are economical to operate. The potential scale of sequestration is large, 2–4 million metric tons of CO₂ sequestered per year against 9.1 million metric tons of CO₂ emitted per year.

BP Amoco, together with the National Laboratories and DOE, are investigating cost reductions to geologic sequestration. Based on current technology, the North Slope sequestration is not economical on its own merits. To improve project economics, BP Amoco is seeking to: (1) reduce the cost of CO₂ capture and gas treatment plants; (2) increase sequestration efficiency and EOR recovery; and (3) utilize economies of scale from broad application.

Given that BP Amoco is committed to reducing CO₂ emissions by 30 million metric tons per year by 2010, sequestration may be attractive compared to other options for emissions reductions. Meeting the goal of commercial-scale operation by 2010, BP Amoco is looking toward completion of the necessary technology development by 2002–2003 and pilot-scale demonstration by 2006.



ADVANCED RESEARCH



OPENING NEW FRONTIERS IN POWER

INTRODUCTION

Program Areas

- Materials and Advanced Metallurgical Processes
- Coal Utilization Science
- Bioprocessing
- University Coal Research
- Historically Black Colleges and Universities/Other Minority Institutions
- International/Coal Technology Export
- Computational Energy Science

The challenge of providing the Nation with a secure energy supply and devising ways to use energy more efficiently and less harmfully is a fundamental scientific challenge.

The Advanced Research program serves as a bridge between basic research and the development of innovative systems capable of improving efficiency, and environmental performance while reducing costs of fossil energy systems, both for electric power and liquid fuels

production. Advanced research provides the means by which advanced concepts are transformed into future working technologies for use in the U.S. and abroad. Improvement of the energy infrastructure — power plants, power transmission systems, fuel production and transportation systems, coproduction of higher value products (such as chemicals), environmental protection, and remediation efforts — is dependent on the products of advanced research.

The Advanced Research program provides two major products. The first is a set of crosscutting studies and assessment activities in environmental, technical, and economic analyses, coal technology export, and international program support. The second identifies and guides advanced research in new directions and provides a set of crosscutting fundamental and applied research programs focused on developing the technology base in the enabling science and technologies needed for the 21st century. These areas are critical to the successful development of both ultra-clean, very high efficiency coal-based power sys-

tems, and coal-based fuel systems with greatly reduced or zero emissions of carbon dioxide (CO₂). This second set of activities addresses the full spectrum of fossil the utilization research and development (R&D), technology transfer, outreach, and private sector partnerships.

Integral to achieving the goals of the Advanced Research program is expansion of the Focus Area for Computational Energy Science. Established at the National Energy Technology Laboratory (NETL), the Focus Area for Computational Energy Science will provide the computational technical support for innovative concepts, ideas, materials, components, and subsystems that will be the basis of success for the energy plants of the 21st century.

The Advanced Research program is directly related to other programs within Coal & Power Systems (C&PS). Advanced Research provides the key to developing innovative concepts for application in the commercial program areas by: (1) supporting the research necessary to graduate new technologies to the development stage; and (2) initiating research that is likely to lead to entirely new technology areas, and possibly to entirely new program areas.

It should be noted that often the processes and materials that advance one C&PS program may well have application in another with little or no modification. A major advantage of the Advanced Research program is its ability to see and foster applications of a given technology across a number of programs, and leverage scarce resources to accomplish common goals.



DRIVERS

The Advanced Research program supports Vision 21 and is an integral part of the Central Systems, Distributed Generation, and Carbon Sequestration programs. As such, the Advanced Research program is driven by many of the same market and environmental influences as other C&PS programs.

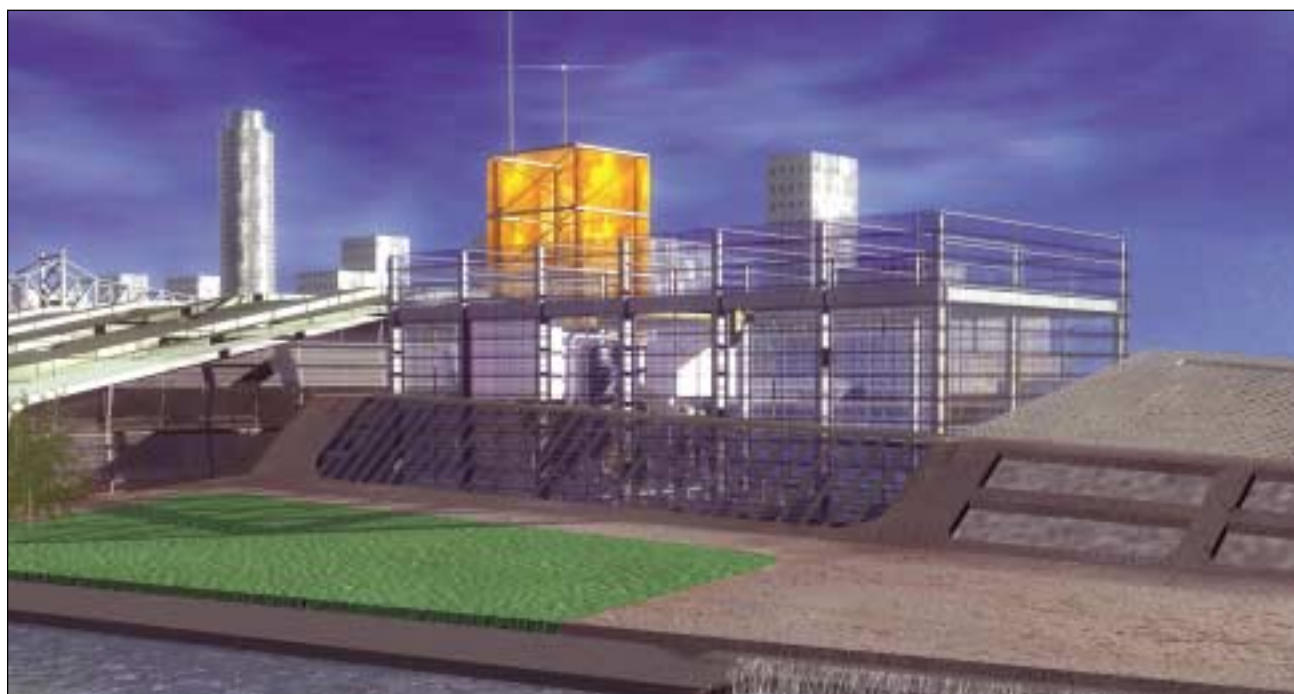
Utility deregulation, energy security, the growing global demand for energy, the aging fleet of U.S. coal-fired power plants, global climate change initiatives, and environmental compliance concerns all have implications for the long-term use of fossil fuels.

Link to Vision 21. The Vision 21 concept defines the activities of the Advanced Research program by setting priorities for the 21st century.

The research thrusts of the program include identifying a next generation of advanced fuel and power systems that can operate at greater efficiencies on coal and at an economic cost that is lower than for the present state-of-the-art, while emitting practically no pollutants and, with sequestration, having no net emissions of CO₂. The major goal of the Advanced Research program is to develop, by 2015, a series of advanced materials, subsystem technologies, and breakthrough process concepts that are essential to the success of Vision 21. To achieve these goals, an NETL Center of Excellence for Advanced Research is being developed. This center will allow applied research to be conducted now to produce a technology base from which the energy plants of the future will be designed, built, and operated.

In order to achieve the performance goals of Vision 21, a number of challenging R&D issues must be addressed by the Advanced Research program. Though not meant to be an exhaustive list of critical research needs to achieve Vision 21, these needs include:

- Low-cost oxygen separation technology;
- Advanced carbon products, such as nano-structural materials;
- High-temperature hydrogen separation technology;
- Heat exchanger materials capable of operating at combustion temperatures; and
- Approaches to effectively capture and sequester CO₂.



An artist's rendering of a Vision 21 plant

ADVANCED RESEARCH PROGRAM BENEFITS

National Benefits

- Provides Americans with a dependable domestic source of power by maintaining coal as the primary source of energy in electric production;
- Mitigates the global environmental impact of increased fossil fuel use by overcoming the obstacles to clean fossil-powered systems; and
- Captures the diverse research contributions of academia and industry, and contributes to the Nation's scientific knowledge base by engaging universities, historically black colleges and universities/ other minority institutions, and small businesses in fossil-related research.

Supplier Benefits

- Develops international markets for U.S. energy-related technologies, services, and energy resources by facilitating both new market entries and expansion in existing markets through the international program; and
- Enables the production of advanced, high-efficiency power systems that better utilize domestic fossil fuel resources through advanced coal research and development.

Customer Benefits

- Ensures continued economic well-being for U.S. citizens by reducing energy costs resulting from advanced technologies; and
- Improves the U.S. economy and increases the number of high-skill jobs for Americans by increasing international technology exports.

ACTIVITIES

The Advanced Research program is charged with coordinating and directing research that will lead the technological developments of the C&PS program.

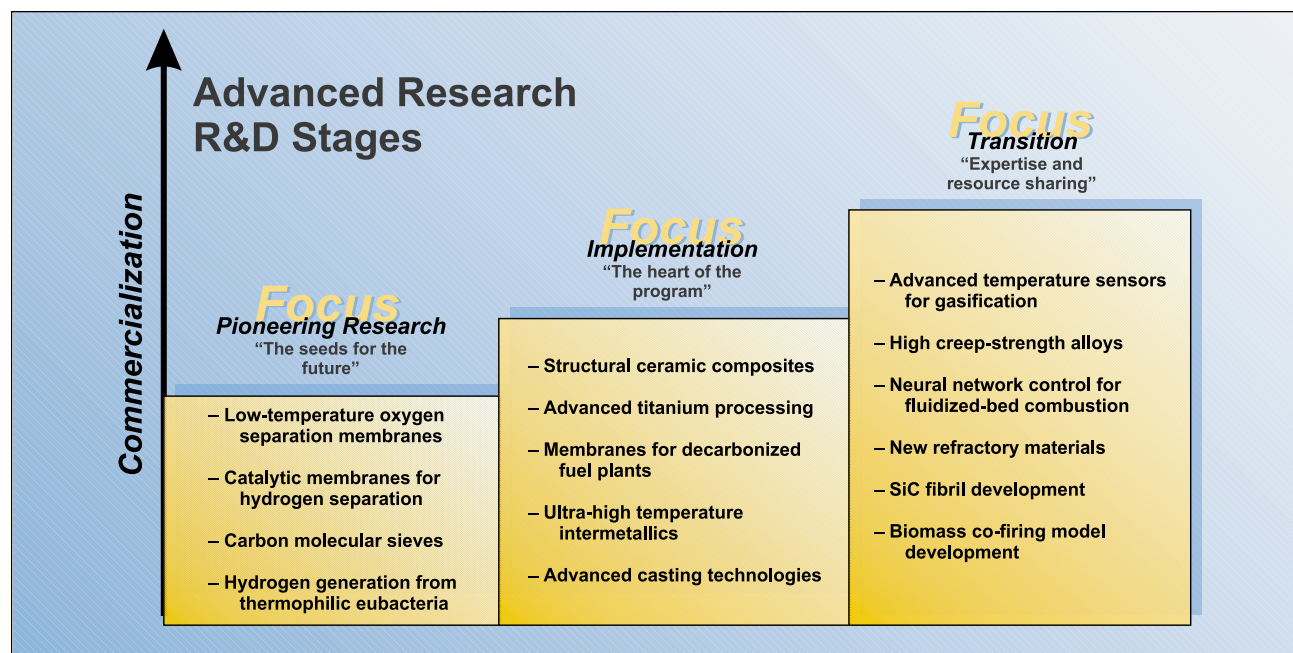
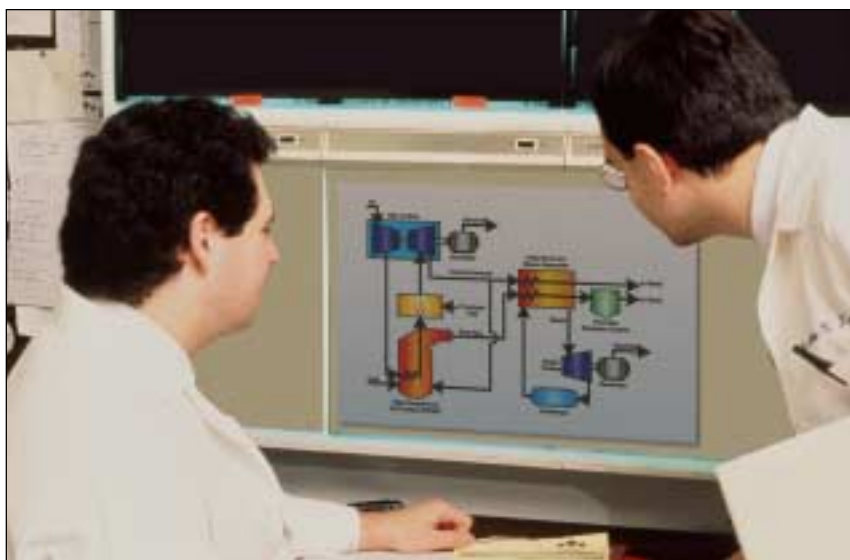
As such, the Advanced Research R&D portfolio does not lend itself to a traditional roadmap or timeline since nearly all Advanced Research R&D follows the same progression through three stages of development consisting of pioneering research, implementation, and transition. This cycle meets the Advanced Research program goal of sponsoring pioneering research (the seeds for the future); nurturing and implementing fundamental research (the heart of the program); and, with other C&PS programs, facilitating the transition of new technologies into practice (expertise and resource sharing).

Examples of ongoing research in the different stages can be found below. Individual program area research

can be found in the program areas discussion to follow.

The nature of the Advanced Research program is that virtually all of the products are in a pre-emerging phase of product development. Additionally, because the program is by nature crosscutting in its activities, it allows for a more integrated approach to evaluation of

potential development areas. As concepts are proven to have reasonable potential, they are graduated to the appropriate C&PS program to complete the emerging phase of development. As a corollary function, the Advanced Research program evaluates input from other programs and from potential stakeholders to assist in determining the direction of emerging research areas.



DRIVERS

- Climate change initiatives will likely require significant carbon reductions in the electrical generation and transportation sectors.
- Governments may enact new and, as yet, undefined environmental regulations that could require even further reductions in emissions from stationary and mobile sources.
- Coal not only faces environmental challenges, but faces competition from the other fossil fuels — oil and natural gas. With natural gas prices projected to be relatively stable through 2015, natural gas could be the fuel of choice of electric utilities and independent power producers to satisfy future electric demand.
- The existing stock of U.S. fossil-fueled power plants is growing older, and little new generating capacity is currently being added. After about 2010, this situation will result in the need for substantial new generating capacity over and above that required to meet the growing demand due to population and economic growth.
- With deregulation, the utility industry is consolidating and keeping older plants operating longer to remain economically competitive. The questions of how this will affect availability and reliability of electric supply, and the deployment of advanced technologies, will probably remain unanswered for some time.
- Demand for electricity overseas is expected to grow substantially over the next several years. This will create a huge market for new electrical generation capacity that is well matched to regional characteristics.
- U.S. dependence on imported oil and gas continues to grow. By 2015, imported oil is expected to amount to 61-66 percent of consumption, and imports of natural gas to 14 percent of consumption.

OBJECTIVES

- Overall, deliver the scientific understanding and technological innovations that are critical to the success of C&PS programs as well as the Office of Fossil Energy and Department of Energy missions.
- Leverage research opportunities through science partnerships and pursue international science collaborations.
- Generate fundamental knowledge and data to make significant improvements in power plant efficiency and environmental performance.
- Develop advanced materials and enabling technologies for Vision 21 power systems, with no negative impact on the environment.
- Promote strong relationships between the Department of Energy and the academic community through research activities directed toward advancements in advanced power systems.
- Support the Office of Fossil Energy in developing collaborative technical activities with international performers in the coal and advanced power system areas.

STRATEGIES

- Develop advanced materials for both functional and structural requirements of Vision 21 energy plants.
- Develop high-gas-flux oxygen separation device based on ion-transport membranes.
- Conduct refractory materials research.
- Design, evaluate, and scale up processes for CO₂ mineral sequestration.
- Develop advanced concepts for NO_x control.
- Research evolution of contaminants and air toxics.
- Develop instrumentation sensors and controls for advanced energy plants.
- Identify oxygen resistant bacteria for denitrification of flue gases.
- Investigate biohydrogen generation from carbon-containing waste products.
- Develop and test biological CO₂ sequestration processes.
- Develop toxins to safely control zebra mussels.
- Provide increased opportunities to train the next generation of American fossil fuel scientists and engineering researchers.
- Promote strong relationships between the Department of Energy and the academic community.
- Create partnerships with utilities and organizations to advance U.S. interests in carbon management by promoting deployment of clean energy systems.

PERFORMANCE MEASURES

- Complete development of novel activated carbon fiber filter material gas separation and storage. (2001)
- Complete exploratory development of use of low-cost inorganic membrane technology. (2001)
- Develop continuous casting process to produce reduced-cost titanium. (2001)
- Complete CO₂ mineral sequestration bench-scale testing.
- Complete models necessary to mitigate emissions caused by ash fouling and slagging. (2001)
- Complete model for coal char combustion. (2002)
- Complete small-scale model tests of enzymatic activities for coal beneficiation. (2003)
- Demonstrate production-scale biohydrogen generation using extremophiles. (2003)
- Provide between 20 and 25 grants annually to teams of university students and professors.
- Conduct studies and develop information to encourage and assist U.S. industry in deploying clean coal technology and cleaner energy systems globally. (2001–2005)
- Develop International Capacity Building initiative. (2001)
- Complete advanced modeling tools for sub-elements in turbines and fuel cells. (2003)

MATERIALS AND ADVANCED METALLURGICAL PROCESSES

Advanced materials are vital to enhancing the cost and performance of fossil energy systems. Today, research is focused on developing high-temperature, corrosion-resistant structural ceramic composites and alloys, and materials that perform specific functions in hostile fossil fuel environments.

The goal is to develop construction materials including the associated processing and fabrication methods, and the functional materials necessary for coal fuels and advanced power generation systems. These systems include coal gasification, heat engines, combustion systems, and fuel cells. The activities included in this program area focus on developing a technology base in the synthesis, processing, life-cycle analysis, and performance characterization of advanced materials. Research and development is aimed at developing ceramics (composite structural ceramics, solid-state electrolytes, membranes, and ceramic filters), new alloys (intermetallics, filters, advanced austenitic and ferritic alloys, and coating and claddings), corrosion research, and technology development and transfer.



New materials are being developed under the Materials and Advanced Metallurgical Processes program area to address the special needs of Vision 21. The ceramic materials required for novel membrane applications (including low-cost oxygen separation and hydrogen separation) and special alloys for high-temperature heat exchangers are examples of products of this activity that are critical to the timely deployment of Vision 21 energy plants.

Partnering and cost-sharing with industry are central components of the program area. FE's overall materials research program area includes widespread participation from industrial partners, universi-

ties, not-for-profit agencies, as well as the Advanced Research Materials program at Oak Ridge National Laboratory and the Advanced Metallurgical Research program at Albany, Oregon, and related activities within the Office of Science and Technology at NETL.

The Materials and Advanced Metallurgical Processes program area places special emphasis on technology transfer, ensuring that the materials will be available for subsequent fossil commercial applications. This emphasis enhances U.S. technological competitiveness, not only in the fossil arena, but also in the materials industry in general and other technology application areas as well.



COAL UTILIZATION SCIENCE

Creating efficient, economic, and environmentally acceptable advanced fossil energy systems requires new knowledge of the fundamental mechanisms and processes that influence and control these systems. The acquisition of this information — needed by developers, designers, manufacturers, and operators — is a primary objective of the Coal Utilization Science program area.

This program area supports research that develops technologies for clean, efficient power generation from coal and other fossil fuels. Its emphasis is on producing fundamental information on the underlying processes and mechanisms that form technological barriers, by performing experimental research and theoretical investigations. Novel processes that address environmental issues as well as power generation are included in the program area. The Coal Utilization Science program area contracts with businesses, universities, and government laboratories, often forming multi-laboratory, multi-disciplinary teams to address complex issues.

Strength Through Science

The following state-of-the-art virtual demonstration capabilities being performed by the Coal Utilization Science program area strengthen the scientific base of design and demonstration tools. These tools form the basis for the software necessary to design, evaluate, and optimize the performance of the next generation of fossil-fired power systems.

3-D Visualization. Consists of 3-D solid models, compatible with 2-D drawings allowing interactive virtual reality.

Information Systems. Involves development of a multi-modal (graphical, textual, alpha-numeric, video, etc.) data management system. This will allow one-step/one-time data entry, and guarantee data integrity.

Communication Systems. Allows for Internet collaboration between a geographically-separated work team.

Computer-Aided Drawing. Will provide engineering drawings (schematic diagrams, termination drawing, structural) to generate reports with total integrity using 3-D models.

Process Simulation. Integrates process optimization, economic valuation, component sizing, sensitivity analysis with visualization, CAD, and other components of the virtual demonstration.

Control Systems. Tightly coupled Vision 21 systems will require sophisticated transient control strategies for normal operation, load following, start up/shut down, and safety.

Mechanistic Modeling. Models are physics-based and include computational fluid dynamics (including single/multi-phase, heat transfer, chemical reactions, radiation), finite element structural simulation, material simulation, and event-based simulation.



BIOPROCESSING, UCR, AND HBCU

BIOPROCESSING

This program area sponsors research into biology, biochemistry, microbiology, and bioengineering technologies. Program area goals focus on the bioprocesses capable of fostering innovative uses for coal by-products, developing alternative fuels, identifying biomass sources for potential value in burning or co-burning technologies, developing biological processes to sequester and/or recycle greenhouse gases, addressing environmental issues affecting the power industry, and biologically mitigating fossil fuel mining and utilization issues.



Enzyme research aims to improve the bioconversion of coal to fuels

Six historically black universities and other minority institutions will share nearly \$1 million in federal funding this year for fossil energy projects ranging from oil reservoir characterization, to designs for low-emission burners, to pollution reduction from car engines

UNIVERSITY COAL RESEARCH

The Office of Fossil Energy conducts an annual competition to select and fund the best coal science and technology research proposals from the Nation's academic institutions. Grants are provided by the University Coal Research program area to U.S. universities in order to support fundamental research and develop improved fossil energy technologies. Novel and innovative approaches are sought to solve national and global environmental and energy-related issues. This research sustains U.S. global preeminence in the areas of fossil fuel science and engineering, by supporting fossil energy research at our Nation's universities. The result is a developing and expanding knowledge base in disciplines relevant to fossil fuels.



HISTORICALLY BLACK COLLEGES AND UNIVERSITIES/OTHER MINORITY INSTITUTIONS

This program area was established to provide a mechanism for cooperative research between historically black institutions and other minority institutions with U.S. industries and federal agencies. This program area strives to support the education of scientists and engineers, and sponsors research in support of FE's programs. The HBCU/OMI program area has emphasized improving the environmental compatibilities of advanced coal, oil, gas, and environmental technology concepts.

INNOVATIVE CONCEPTS: 2000 UNIVERSITY COAL RESEARCH GRANTS

Marking the 22nd year of a DOE program that combines student education with research, the University Coal Research program area recently awarded federal grants to 18 university research projects. Since its inception in 1979, approximately 1,385 students have participated, along with their teaching professors.

The wide range of research topics includes new ways to turn pollutants from coal into environmentally safe, commercially valuable products; innovative technologies that produce clean hydrogen for fuel cells; and novel approaches for preventing the release of greenhouse gases.

Seven of the 18 projects will focus on “innovative concepts,” an area created in 1997 to stimulate novel technological breakthroughs. In this category, proposers are free to submit projects on any coal-related topic for one-year study grants. Beginning this year, innovative concepts projects will be eligible for a future second phase of competition. This year’s recipient’s include:

- **University of Cincinnati, Cincinnati, Ohio**, will develop a new ceramic membrane that can remove carbon dioxide, a greenhouse gas, from high-temperature coal gases.
- **Drexel University, Philadelphia, Pennsylvania**, will synthesize another type of membrane for separating carbon dioxide from power plant exhausts. This membrane will use a ceramic material with more uniform and ordered pores than other types of membranes, and a chemical called a “surfactant” that is expected to move the CO₂ through the membrane faster.
- **University of Kentucky, Lexington, Kentucky**, will test membranes based on microscopic carbon nanotubes for separating CO₂ from the gases of coal-based power plants.
- **Brown University, Providence, Rhode Island**, will examine the major operational problems in co-firing coal and biomass by partially combusting only a fraction of the fuel to limit CO₂ emissions.
- **Pennsylvania State University, University Park, Pennsylvania**, will investigate a novel approach for converting the CO₂ in a power plant’s flue gas into industrially useful products.
- **University of Utah, Salt Lake City, Utah**, will use a 3-D computer model to study the effects of recycling CO₂ back into an oxygen-enriched coal combustor.
- **The State University of New York at Buffalo, Buffalo, New York**, will develop a computer-based method for designing the ideal way to capture the exhaust heat of a power plant and use it to generate additional electricity.

INTERNATIONAL/COAL TECHNOLOGY EXPORT

Worldwide, the demand for power is increasing exponentially.

The global market for electric power systems by 2010 has been estimated at nearly \$2.3 trillion, and over half of this investment will be for coal-fired units. 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 both in the U.S. and abroad.

The International program area within the Advanced Research program has four major strategies:

- *Provide leadership in international organizations.* FE holds leadership roles in several international organizations — the International Energy Agency, Latin America Energy Organization, Asia Pacific Economic Cooperation's Regional Energy Cooperation Working Group, United Nations Economic Com-

mission for Europe Clean Coal Technology Initiative, and the World Energy Council.

- *Maximize export opportunities.* The United States is the world leader in the development of clean fossil-powered technologies. The International program area works to ensure that United States companies get a share of the global market for clean power systems, thereby securing jobs, driving economic growth for the U.S., and contributing to global environmental protection.
- *Establish effective partnerships.* Partnerships play an important role in overcoming barriers facing U.S. companies that pursue export opportunities. Such barriers include trade, finance, inadequate understanding of U.S. clean power systems, and unfair competitive trade practices. Through its partnerships, the program facilitates business solutions to remove these barriers.
- *Facilitate electricity transactions across international borders.* The International program area ensures reliability and open-access transmission through border systems. The program area authorizes exports of electricity, collects and analyzes information on international electricity trade, conducts country-specific studies on electric power systems and the construction of international transmission lines, and provides electric power regulatory assistance.

To ensure that U.S. companies get a share of the global market for clean fossil-powered systems, bilateral efforts are ongoing in seven re-

gions — Africa, Eastern Europe, the Pacific Rim, Russia and the Newly Independent States, South Asia and the Near East, Western Europe, and the Western Hemisphere. In each region, countries are assisted with adapting their power sectors to meet local demands and environmental pressures. This assistance facilitates dialogue between financial institutions and U.S. companies.

International Capacity Building

To assist in the deployment abroad of U.S. clean coal technologies and advanced power systems, the C&PS Advanced Research program is developing the International Capacity Building initiative. Capacity building allows for technical training, operational skills development, and technical information transfer to impart operational experience and hardware understanding of U.S.-based technologies to international partners. This technology transfer will be accomplished via workshops, seminars, training, on-site visits, and technical exchanges through publications dissemination.

Technology outreach efforts through the International Capacity Building initiative will assist in developing policies and strategic plans for the use of U.S. clean coal technology as a means of furnishing possible solutions to the emerging electrification needs of African, Turkish and Middle Eastern, South American, Eastern European, and Asian communities.



COMPUTATIONAL ENERGY SCIENCE

The Focus Area for Computational Energy Science at NETL is developing a set of complex but flexible computation tools that will allow more rapid and efficient scale-up of new subsystems, devices, and components, and will reduce the need for large and expensive demonstration-scale testing of integrated energy systems. The Focus Area will be a significant contributor to the Vision 21 program, and work will be closely integrated with research and development activities sponsored by the Vision 21 program and other related FE programs. The Focus Area will perform three categories of modeling activities:

- Modeling sub-elements in an energy conversion device, such as reactive computational fluid dynamic simulation of a gas turbine combustor. These models will also define the characteristics of materials needed throughout the plant, which will be used to direct the research necessary for their physical development.
- Combining sub-element models to describe initially the steady-state operation, and ultimately the dynamics of a complete energy conversion device.
- Integrating these devices into a model of an overall energy plant.

The computational tasks will allow more rapid and efficient scale-up of new processes, and will reduce the need for large, expensive experimental testing units, thereby reducing operational risks at commercialization. A manufacturing model will be used to aid in commercialization of materials and devices produced from the research by



defining the most cost-effective mass production methods. Experiments and tests will be conducted for model validation.

The approach will be to establish an extensive network of interconnected partnerships. NETL will be the nucleus because of its extensive experience and background in advanced processes and simulations, and its implementation role in the

FE and C&PS programs. Partnerships with national laboratories, universities, software developers, and energy companies will be organized in several coordinated key technology areas to form the technical backbone of the Focus Area.

A stakeholder group consisting of industry, academia, and government, will be established to provide input to the Focus Area activities.



IN PARTNERSHIP WITH INDUSTRY

CERAMIC HOT-GAS FILTER MATERIALS

The difficult issue of removal of particulate matter from hot gas streams in pressurized fluidized-bed combustion (PFBC) and integrated coal gasification combined-cycle (IGCC) systems has been addressed by two developments of the Advanced Research Materials program area. In industry/DOE cost-shared collaborations, the 3M Company and Pall Corporation have, respectively, commercialized ceramic composite and metal alloy filters. The 3M Ceramic Composite Filter is a lightweight ceramic composite filter made of woven Nextel™ fibers coated with silicon carbide, which was produced under license of the DOE-developed technology. 3M has extended and patented its development to an all-oxide filter of similar design.

Pall Corporation's iron aluminide filter is a porous metal filter made of a highly oxidation- and sulfidation-resistant aluminide alloy. The application of this alloy as a filter



The Bilaspur Coal Washery Project in the state of Madhya Pradesh is India's first private commercial coal washery for electric power generation

material was explored in the Materials program area and extended to demonstration scale under the hot gas cleanup research.

Both the 3M and Pall filters are being demonstrated at the Power Systems Development Facility in Wilsonville, Alabama, as well as in the numerous installations in Europe and Asia. These are developments of considerable importance, both with respect to enabling technologies for PFBC and IGCC systems, and commercialization. For 300-MWe systems, over 3,000 of these filters would be required for

an oxygen-blown IGCC and over 30,000 would be required for a PFBC.

INTERNATIONAL

Since 1982, NETL has managed six coal-related projects in India for the U.S. Agency for International Development. The total value of these projects, including contributions from the various Indian partners, is about \$80 million.

One of these projects, the U.S. Asian Environmental Partnership's Indo-U.S. Coal Preparation and Beneficiation Project, supported deployment of an advanced coal-cleaning circuit (based on U.S. technology supported by DOE) at the first commercial non-coking coal washery in India. The objective of this project was to demonstrate production of coal with less than 30 percent ash in the 2.5-million ton/year commercial washery. Two U.S. firms, Spectrum Technologies, and CLI (a U.S. coal preparation design company), have been awarded a \$12-million engineer, procure, and construct contract and a \$4-million-per-year operation and maintenance contract.

A lightweight ceramic hot-gas filter material developed by the Advanced Research Program is now widely used to remove hot gas particulates in fossil-fueled power generation and industrial systems







For More Information,
Please Contact:

Office of Fossil Energy
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585
(202) 586-6503

National Energy Technology Laboratory (NETL)
U.S. Department of Energy

Morgantown Location:
3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880
(304) 285-4764

Pittsburgh Location:
626 Cochran's Mill Road
Pittsburgh, PA 15236-0940
(412) 386-4687

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