Central Power Systems

Program Areas

- Clean Coal Technology Demonstrations
- Innovations for Existing Plants
- Turbine Systems
- Low-Emissions Boiler System (LEBS)
- Indirect Fired Cycles (IFC)
- Pressurized Fluidized-Bed Combustion (PFBC)
- Gasification Technologies
- Vision 21 Systems

Introduction

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—37 percent lower than the European average, 49 percent lower than Germany, and 73 percent lower than Japan.

An Invaluable Energy Asset

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 the generating capacity.

To maintain competitive energy rates and sustain economic growth requires that coal remain a mainstay in electric power generation. This requirement places importance 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.

However, 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, oxides of nitrogen, fine particulate matter, and mercury.

Installation of an advanced scrubber under the Clean Coal Technology Program enabled Northern Indiana Public Service Company's Bailly Generating Station to be the first to comply with SO_2 standards established in the Clean Air Act Amendments of 1990.

NEXT GENERATION PLANTS

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 impa cted reliability of delivery. Power generators are increasing capacity factors on existing plants rather than adding new capacity, which reduces reserve margins.

A 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, they must first undergo replication to reduce cost and optimize performance. This opportunity exists in foreign markets dependent on coal, such as developing Asia, in niche applications placing a premium on performance. This market is significant with nearly half of the 65 percent increase in worldwide energy consumption projected to occur in developing Asia.

Natural gas-based power systems are expected to provide more than 80 percent of the projected 363 gigawatts of new domestic capacity needed to meet new demand and replace plant retirements. 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. 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 would serve to protect our reserves of this premium fuel and address global climate change concerns as well.

VISION 21 PLANTS

Ultimately, to effectively respond to the expanding energy markets and growing regional and global environmental concerns in the 21st century, power systems must incorporate a number of features. Fuel flexibility is critical to enabling use of low-cost indigenous fuels, using wastes 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 capture for sequestration. Product flexibility is needed to enhance efficiency, broaden market applications, and potentially produce vital chemicals or transportation fuels. Near-zero emissions are requisite to environmental acceptability.

THE REQUIREMENT

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

Coal-fired electric generating capacity is the cornerstone of the nation's central power system. To preserve this foundation requires innovative, low-cost environmental compliance technologies for existing plants and new high-efficiency coal-based systems with near-zero emissions.

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 quantum jumps in efficiency and emissions reduction, and facilitate CO_2 capture and sequestration.

Program Drivers

- Preserve existing power generation infrastructure at minimal environmental compliance cost.
- Provide next generation power systems to meet near- to mid-term demands domestically and internationally.
- Build toward achieving Vision 21 plants to eliminate environmental concerns associated with fossil fuel use.

The Program

In partnership with its customers and stakeholders, The C&PS Central Power Systems Program seeks to: (1) preserve the existing central power generation infrastructure while meeting environmental requirements at minimal cost; (2) provide a next generation of advanced fossil-fueled power systems capable of meeting projected energy and environmental demands both domestically and internationally; and (3) build toward achieving Vision 21 plants capable of eliminating environmental concerns associated with fossil-fueled power generation.

Existing Plants

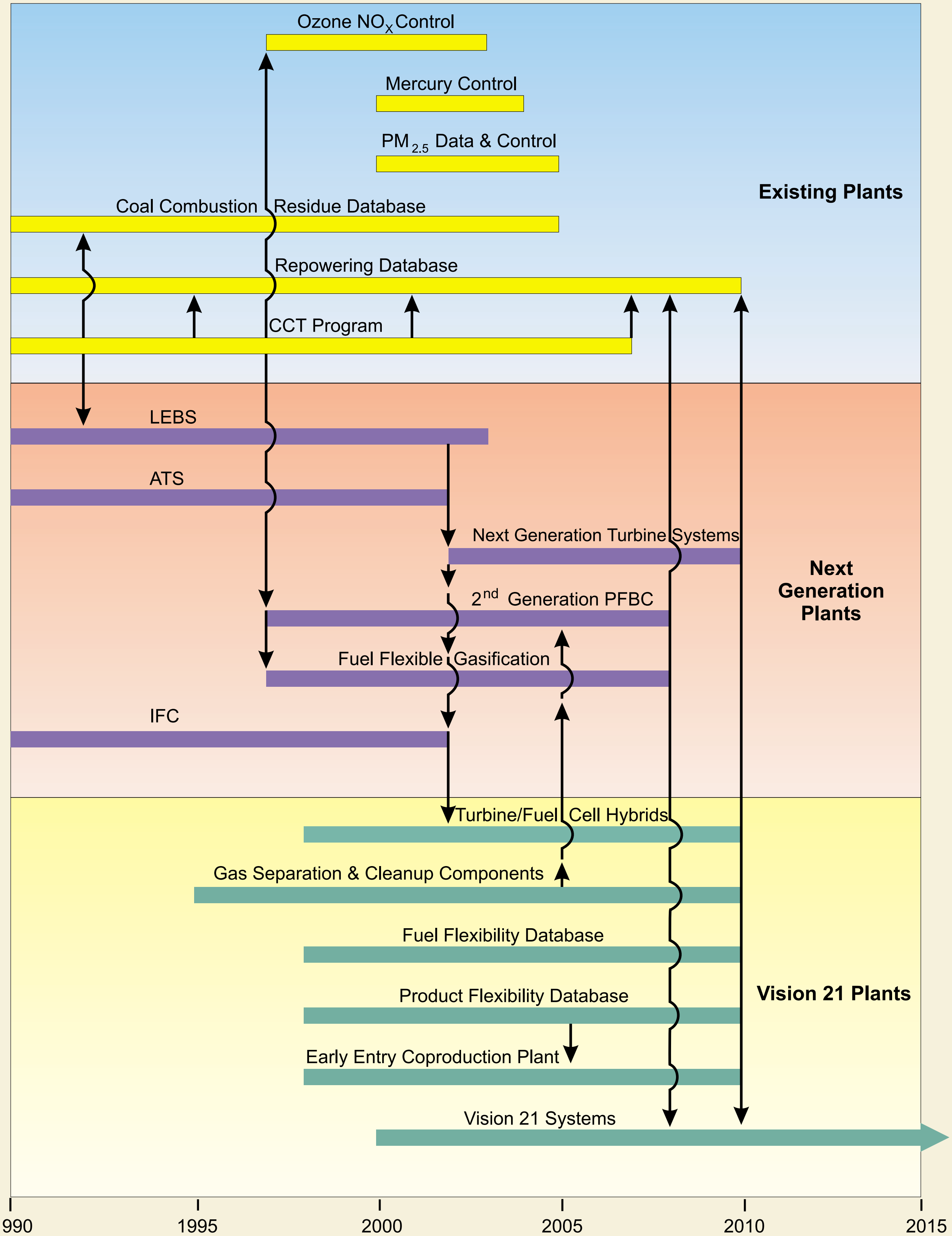
The Program builds on the cost-shared government/industry Clean Coal Technology (CCT) Program projects. These projects enable cost-effective compliance with the Clean Air Act, provide a foundation for meeting more stringent ambient air standards, and represent the first-of-a-kind advanced coal-based electric generation platforms for powering the 21st century. The results of SO_2, NO_x, and combined SO_2/NO_x control projects are available now. The results of all projects will be fully disseminated by 2007.

Drawing upon the CCT projects, cooperative research and development is continuing with state governments and industry to address the ambient NO_x, and $PM_{2.5}$, and vapor phase mercury source emission issues emerging subsequent to the CCT Program. Work is scheduled for completion on NO_x control systems designed to meet the latest ambient air standards associated with ozone levels at costs 25–50 percent below that of current technology. Demonstration of effective control of vapor phase mercury emissions from coal-fired plants is planned for 2004. Data collection and development of control strategies and technologies for respirable particulate matter 2.5 microns or less in size ($PM_{2.5}$) is scheduled for completion by 2005.

Cooperative research and development work with universities and industry is continuing toward characterizing solid residues from existing and advanced power generation systems and developing cost-effective uses for these materials. The results of this work are to be transferred to potential industry users and relevant regulatory agencies by 2005.

A database on coal-fired plant repowering options is being compiled using CCT Program project data, information from the Electric Power Research Institute and Gas Research Institute, cooperative government/industry work, and in-house research. Technologies include boiler augmentation with gas turbines, boiler replacement with advanced power systems, and integration of artificial intelligence controls.

Roadmap



Ozone NOX Control
Mercury Control
PM 2.5 Data & Control
Coal Combustion Residue Database
Repowering Database
CCT Program
Existing Plants
LEBS
ATS
Next Generation Turbine Systems
2nd Generation PFBC
Fuel Flexible Gasification
IFC
Next Generation Plants
Turbine/Fuel Cell Hybrids
Gas Separation & Cleanup Components
Fuel Flexibility Database
Product Flexibility Database
Early Entry Coproduction Plant
Vision 21 Systems
Vision 21 Plants
1990
1995
2000
2005
2010
2015

NEXT GENERATION PLANTS

Under development is a 2nd generation pulverized coal-fired power generation system—the Low Emissions Boiler System (LEBS). The system draws upon the environmental control technologies emerging from the CCT Program and fully integrates the environmental controls in the design. The goal is to demonstrate the capability to reduce cost of electricity by 10 percent and increase efficiency to 42 percent by 2003. LEBS will serve as an early entry, high-efficiency coal-based system for the Asian export market.

To meet the increasing demand for natural gas-based power, an ongoing Advanced Turbine System (ATS) program is scheduled to complete demonstration of two utility-scale gas 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 parts per million (ppm). The ATS developments will result in new commercial turbine offerings, and these turbines will be used to enhance the efficiency of the pressurized fluidized-bed combustion (PFBC), gasification, and indirect fired cycle (IFC) systems. A Next Generation Turbine System effort will be initiated in 2001, applying ATS lessons-learned to development of more efficient and fuel-flexible intermediate and larger size gas turbines.

Early efforts in the CCT Program resulted in demonstration and commercialization of 1st generation PFBC. PFBC systems apply fluidized-bed combustion in a pressurized atmosphere to generate

Demonstration of 1st generation PFBC at Ohio Power Company's Tidd Plant resulted in commercialization of the technology.

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 systems. A 2nd generation PFBC, currently under development, increases efficiency by integrating a coal gasifier (carbonizer) topping combustor to burn the coal derived syngas, hot gas particulate filtration, alkali removal system, Advanced Turbine System, and supercritical steam cycle. The goal is to demonstrate a 52 percent efficient 2nd generation PFBC by 2008. Plans are to have an active CCT Program project to serve as the primary mechanism for the demonstration.

The CCT Program is currently demonstrating integrated gasification combined-cycle (IGCC) technology. IGCC converts hydrocarbon feedstock into largely gaseous components from which pollutants are extracted and a clean syngas remains for use in a combined-cycle. IGCC demonstrations largely use conventional air separation, pollutant control, and bottom cycle, which either require energy intensive processing or sacrifice efficiency by operating at relatively low temperatures. Next generation gasification technology systems will integrate hot gas particulate filtration, hot gas sulfur/alkali removal, an air separation membrane, and turbine cycle advances to demonstrate a 52 percent efficient system by 2008.

An innovative IFC power system is under development. It uses a high temperature air furnace to separate combustion from an air working media and effectively transfers the heat energy to the air media, which drives an expansion turbine. Two teams are moving the technology toward Vision 21 demonstration.

Vision 21 Plants

An established Advanced Turbine System industry/university consortium and in-house researchers are carrying out cooperative research on low-emissions and low-Btu combustion in support of fuel flexibility and hybrid systems, as well as materials and heat transfer research in support of efficiency enhancement. The intent is to enhance efficiency and develop fuel flexibility for the basic energy platforms such as the ATS, PFBC, gasification technologies, and IFC, as well as the fuel cells and fuel cell/turbine hybrids being developed under the Distributed Generation Program.

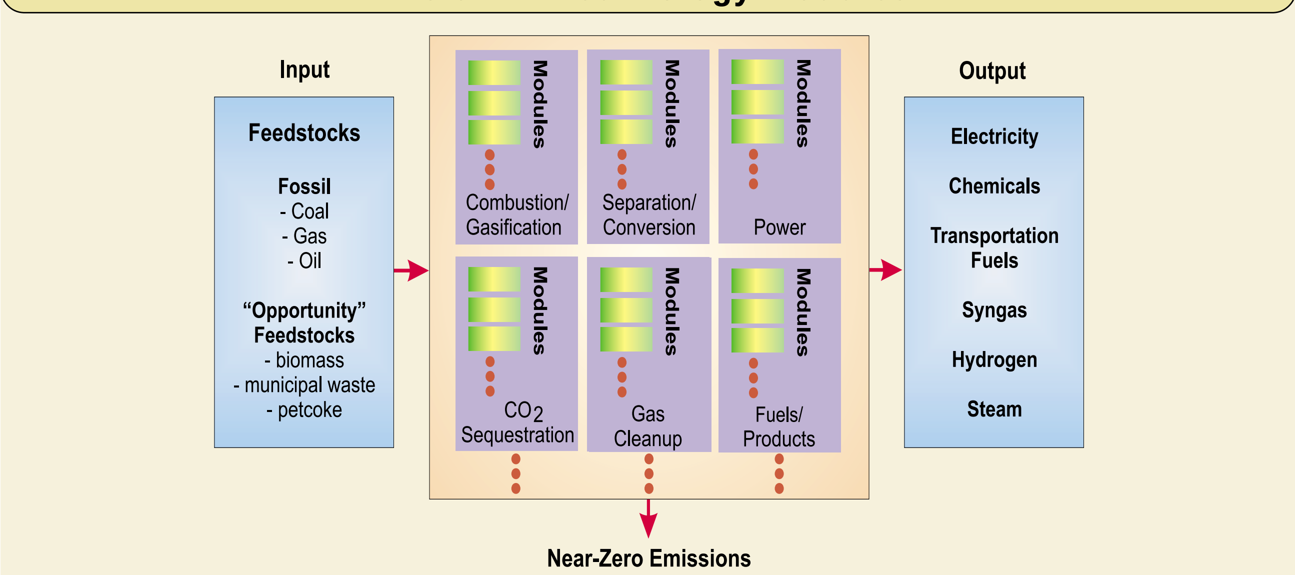
Component research is ongoing in process gas separation and cleanup (essential to improving cost and performance of PFBC, gasification technologies, and IFC systems), and using these energy platforms in hybrid systems capable of significant jumps in efficiency, such as integration with fuel cells. Activities include development of gas separation membranes for air, the development of advanced, low-cost, high-temperature hydrogen separation membranes for gasification technologies/fuel cell applications, and development of advanced gas purification technologies for meeting the more stringent gas quality requirements for fuel cell integration. Gas cleaning and conditioning are essential to meeting rigid syngas quality specifications for fuel cells and catalytic conversion processes used in coproduction of chemicals and fuels.

The contractor-operated Power Systems Development Facility and in-house Gas Processing Development Unit are being used to conduct government/industry cooperative research in fuel and product flexibility, and process gas filtration and cleanup systems.

By 2005, development is to be completed on gas purification and cleanup components essential to 2nd generation PFBC and gasification technologies and an early hybrid system linking coal gasification and a fuel cell. Component development will continue in support of further system cost and performance enhancements and Vision 21 through 2010. Work to enhance fuel and product flexibility will continue through 2010. Product flexibility efforts will feed into development of an Early Entry Coproduction Plant integrating power production and chemical/fuel production, scheduled for completion in 2010. These developments also support both the repowering database for existing plants and Vision 21 systems.

The Vision 21 concept is structured around efforts to successfully demonstrate a portfolio of technology modules. These modules will enable users to optimize system configurations to allow a multiplicity of fuels (gas, coal, biomass, and municipal, forestry, and refinery wastes) and produce a slate of commodities (electricity, steam, chemicals, and clean fuels) with near-zero emissions and thermal efficiencies of 60 percent or more for coal-based systems and 75 percent or more for natural gas-based systems. Advanced computational technology (virtual demonstration techniques) and existing operating systems will be used to minimize the cost of demonstrating Vision 21 systems.

Vision 21 Technology Modules



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 emission standards.
- To maintain 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 80 percent of the 363 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 65 percent increase by 2020—with coal-dependent Asia 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.

Goals

- Disseminate results from the CCT Program. (Present–2007)
- Complete development of retrofit NO_x control technologies necessary to meet the latest ambient air standards associated with ozone levels. (2003)
- Demonstrate technologies to effectively control vapor phase mercury emissions from coal-fired plants. (2004)
- Complete development of data and technology to control respirable particulate matter 2.5 microns or less in size ($PM_{2.5}$). (2005)
- Develop and transfer a database to support environmentally acceptable, cost-effective uses of coal combustion residues. (Present–2005)
- Demonstrate a 60% efficient (LHV) natural gas-based Advanced Turbine System with NO_x emissions less than 9 parts per million (ppm). (2002)
- Complete Next Generation Turbine Systems development. (2010)
- Demonstrate a 42% efficient 2nd generation pulverized coal-fired power generation system—the Low Emissions Boiler System (LEBS). (2003)
- Develop gas purification and particulate cleanup components essential to 2nd generation PFBC and gasification technology goals and for linking early hybrid systems to fuel cells. (2005)
- Demonstrate 52% efficient 2nd generation PFBC and fuel flexible gasification systems capable of near-zero pollutants. (2008)
- Complete development of a hybrid gasification/fuel cell system, fuel and product flexibility databases, and an Early Entry Coproduction Plant integrating power production and chemical/fuel production. (2010)
- 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 states and industry to address current ambient NO_x, $PM_{2.5}$, and vapor phase mercury source emission issues.
- Continue cooperative work with universities and industry to characterize and develop uses for solid residues from existing and advanced power plants.
- Compile database on repowering options using CCT data, information from EPRI and GRI, cooperative government/industry work, and in-house research.
- 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 more efficient and fuel-flexible intermediate size gas turbines.
- Use LEBS as early entry, high-efficiency, coal-based system in Asian export market.
- Use an existing CCT project to demonstrate 2nd generation PFBC.
- Use established ATS industry/university consortium and in-house research to carry out research in fuel flexibility, hybrids, and efficiency enhancement.
- Use Power Systems Development Facility and in-house Gas Processing Development Unit to conduct cooperative research in fuel and product flexibility and process gas separation and cleanup.
- Use a CCT project to demonstrate the Early Entry Coproduction Plant.
- Develop and use advanced computational technology and existing operating systems to demonstrate feasibilty of Vision 21 systems.

Measures of Success

- CCT environmental control and power system technologies realize widespread deployment and significantly reduce regulatory compliance costs.
- Existing U.S. coal-fired capacity is retained and operates at low cost with acceptable environmental performance.
- 1st generation PFBC and IGCC systems emerging from CCT Program realize market entry overseas and begin to bring basic system costs down. (1995)
- Leveraging fuel and product flexibility with PFBC and IGCC results in niche market applications improving cost and performance. (2003)
- ATSs supplant current turbines, reduce pressure on natural gas supply in meeting growing electricity demand, and enhance performance of PFBC and IGCC. (2002)
- Fuel 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 1st generation PFBC and IGCC overseas and in U.S. niche markets, and performance enhancements coming out of demonstration of 2nd generation PFBC and fuel-flexible gasification technologies competitively position technologies to enter domestic energy market. (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 quantum jumps in cost and performance. (2010)
- The Early Entry Coproduction Plant significantly enhances cost and performance of gasification-based systems and increases market penetration.
- Industry participants begin to site Vision 21 plants. (2015)

Benefits

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.

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.

National Benefits

- Sustains economic growth by maintaining low-cost electricity vital to U.S. industry;
- 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.

Program Areas

The C&PS Central Power Systems Program focuses on large stationary fossil energy-based power generation technologies with the capability to also use biomass and opportunity fuels such as municipal, agricultural, forestry, and refinery wastes.

Linkages to other DOE offices include C&PS and the Office of Energy Efficiency and Renewable Energy (EERE) sharing responsibility for the ATS Program component. C&PS supports the utility-scale ATS system development, industry/university consortium, materials research for advanced alloys, ATS applications for coal fuels, and the in-house R&D. EERE supports the industrial-scale system development, materials research on thermal coatings, ceramic retrofit engine development, and ATS applications for biomass fuels. EERE's efforts as they relate to C&PS activities are discussed in the Distributed Generation Program Plan.

Together, the portfolio of central power generation systems presented here will enable the nation's consumers to benefit from continued low energy rates, and U.S. industry to remain competitive in the world marketplace and establish a leadership position in key technologies.

Clean Coal Technology Demonstration Program

The Clean Coal Technology Demonstration Program (CCT Program) is a government/industry partnership established to address environmental concerns associated with coal use. The CCT Program represents an investment of over $5.2 billion in advanced coal-based technology, with industry and state governments providing an unprecedented 66 percent of the funding. 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 19 projects involve coal processing for clean fuels and industrial applications, which are addressed in the Fuels section.

All but one of the environmental control projects have completed operation. Three of the 11 advanced electric power generation projects are complete, four are in operation, and the balance are either in design or construction.

The CCT Program has provided a portfolio of NO_x control technologies applicable to all boiler types. These technologies and associated databases have enabled the utility industry to cost-effectively comply with the first wave of NO_x control requirements promulgated to address acid rain concerns, and have positioned the utility industry to respond to emerging standards prompted by ozone concerns. Technologies include: (1) low-NO_x burners and reburning systems that modify the combustion process to limit NO_x formation, (2) selective catalytic and non-catalytic reduction technologies (SCR and SNCR) that act upon and reduce NO_x already formed, and (3) artificial intelligence-based control systems that effectively handle numerous dynamic parameters to optimize operational and environmental performance of boilers.

A portfolio of SO_2 control technologies also resulted from the CCT Program. Technologies are available for the full range of units from old, space-constrained boilers to relatively new large boilers. The two advanced wet flue gas desulfurization projects redefined the state-of-the-art for lime/limestone-based scrubbers by nearly halving capital and operating costs, producing by-products instead of wastes, and mitigating plant efficiency loses.

A demonstration of atmospheric circulating fluidized-bed combustion (ACFB) provided the operating experience and database needed to reduce risk and achieve commercialization for utility-scale systems. Currently, there is an estimated 9.5 gigawatts of commercial ACFB capacity installed worldwide.

Pressurized fluidized-bed combustion (PFBC) technology is achieving market entry as a result of work performed at The Ohio Power Company's Tidd Plant. The CCT demonstration and associated development work have resulted in several commercial sales, including a 360-MWe unit in Japan. The work at Tidd has also provided a foundation for development of a 2nd generation system.

Four integrated gasification combined-cycle (IGCC) projects, representing a diversity of gasifier types and cleanup systems, are pioneering the introduction of this technology by evaluating the systems in commercial service. 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 the commercial sales and to provide a foundation for gasification technologies systems development.

Innovations for Existing Plants

The CCT Program has provided a portfolio of environmental control technologies enabling power generators to cost-effectively comply with the Clean Air Act Amendments of 1990 (CAAA) for SO_2, NO_x, and particulate matter. The CAAA set emission standards for SO_2 and NO_x in two phases, with the more stringent standards coming into effect in 2000. Air toxics emissions were also addressed in the CAAA, with 189 organic and inorganic species identified. A comprehensive DOE/EPA/industry cooperative program was initiated through the CCT Program to evaluate air toxics emissions from a cross section of coal-fired plants. The results helped to establish further technology enhancements and focus follow-up efforts to be implemented through the R&D program.

Subsequent to the CAAA, action was taken to tighten ambient air quality standards for ozone and particulate matter. The ozone standards in turn impacted NO_x emissions because NO_x is a precursor to ozone formation. The new particulate matter standards focus on the very fine particulate matter in the respirable range of 2.5 microns or less ($PM_{2.5}$), whereas the CAAA addressed particulate matter in the range of 10 microns or less (PM_{10}). These actions require technology improvements in both NO_x and particulate matter control, and possibly SO_2, as SO_2 forms sulfate particles upon leaving the stack.

Dealing with the solid by-products of combustion and associated environmental controls represents a growing problem because of their sheer volume and dwindling landfill space. Combustion by-products have the potential for many uses, of which potential customers must be made aware.

NO_x Control

The NO_x control work being undertaken entails leveraging CCT Program developments and databases in the areas of low-NO_x burners, selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR), and coal and gas reburning. Technology improvements and validations are being carried out through collaborative projects with industry. One such project involves evaluation of an SNCR system on a 640-megawatt (MW) unit at American Electric Power's Cardinal Plant, with participation by a utility consortium and the Electric Power Research Institute (EPRI).

$PM_{2.5}$ Control

Particulate matter efforts include: (1) data collection to establish characteristics and levels of $PM_{2.5}$ in representative ambient air samples; (2) data collection to understand the formation, transport, and chemical composition of coal-fired fine particulate matter; (3) evaluations to determine the impact of coal-fired systems on air quality; and (4) development of improvements in $PM_{2.5}$ control, leveraging CCT Program technologies and conducting testing in partnership with industry. C&PS is collaborating with EPA, EPRI, and the utility industry in the operation of several ambient air monitoring sites through the Upper Ohio River Valley Project. In this project, four monitoring sites around Pittsburgh, Pennsylvania are enabling comparison of ambient $PM_{2.5}$ in rural and urban settings and providing an understanding of pollutant transport. C&PS is also participating in ambient $PM_{2.5}$ monitoring and characterization studies with the Tennessee Valley Authority in Great Smoky Mountain National Park and with Southern Company Services in the Atlanta, Georgia area.

Air Toxics Control

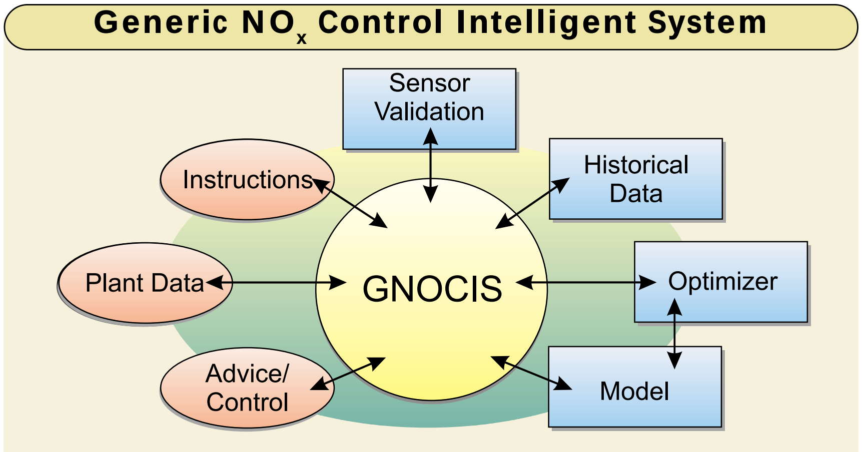
Air toxics research focuses on control of vapor phase mercury. Approaches include: (1) injecting sorbents upstream of electrostatic precipitator and fabric filter particulate controls; (2) augmenting SO_2 scrubbers; and (3) developing stand-alone controls. Under the Advanced Emissions-Control Development Project, activities are

In DOE's Upper Ohio River Valley Project, an air sampler verifies that $PM_{2.5}$ standards are met, and collects representative samples for detailed information on the chemical composition of fine particulate matter in outdoor air (Greene County, Pennsylvania).

focused on maximizing use of existing controls. Alternately, the Carbon-Based Sorbent Injection for Mercury Control Project is evaluating the mercury-capture effectiveness of various carbon-based sorbents under a joint effort by C&PS, EPRI, and the Public Service Company of Colorado.

Advanced Control Systems

Advanced computer-based controls are an essential component to the increasingly sophisticated environmental control systems being applied today. Optimizing boiler operating and emissions performance requires embedding artificial intelligence (AI) or other advanced computer-based controls into a power plant's digital control system. This need arises from the large number of parameters involved and their dynamic interrelationships. A CCT project at Georgia Power Company's 500-MWe Plant Hammond demonstrated the importance and potential of AI systems. The Generic NO_x Control Intelligent System (GNOCIS™) AI system was installed at Plant Hammond and the plant subsequently achieved an efficiency improvement of 0.5 percent, a reduction in fly ash unburned carbon of 3 percent, and a NO_x reduction of 15 percent. GNOCIS™ is the result of a joint development effort by C&PS, EPRI, PowerGen, Radian International, Southern Company, and the U.K. Department of Trade and Industry. An estimated 35 plants, representing approximately 20,000 MWe of capacity, have either installed or are in the process of installing GNOCIS™.



Combustion By-Products Utilization

An ongoing coal-combustion by-products (CCB) utilization program is addressing the solids residue streams from existing and advanced power generation systems and associated environmental controls. Under the program, solids are characterized, large volume applications identified, necessary equipment developed, and demonstrations conducted. The results are transferred to state and federal regulators and potential users to facilitate application. Applications demonstrated include: (1) injection of large volumes of flue gas desulfurization material and fly ash into underground mine openings to reduce surface subsidence and mitigate acid mine drainage; and (2) use as aggregate for road construction, soil stabilization, and other construction applications. C&PS supports a CCB consortium, managed by West Virginia University. The consortium is chartered to form partnerships with power generators, federal and state agencies, universities, and special interest groups for the purpose of carrying out research, development and demonstration to expand usage options for CCBs.

Repowering

Another environmental compliance option is repowering an existing facility rather than simply adding environmental controls. This is particularly attractive for older plants and plants facing increasing power demands. Repowering integrates new power generating systems, while using much of the existing equipment, and typically increases capacity. This approach leverages the intrinsic value of existing sites, which are already permitted and have established infrastructure such as power line and fuel access. A relatively simple repowering option is to integrate a gas turbine with an existing boiler, using the exhaust to either heat feedwater or replace the primary air. Such approaches can increase capacity by 25–30 percent and efficiency by 5–15 percent. More sophisticated repowering options with greater pay-off in efficiency and capacity increases include PFBC, IGCC, and HIPPS power systems. Gas turbine and power systems developments applicable to repowering and new plant installations are discussed in the following sections. The results of these developments and other related studies are captured and incorporated into a database residing at the NETL.

Turbine Systems: Advanced Turbine System

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, through combustion, 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.

To achieve the efficiency objective requires significantly higher turbine inlet temperatures. 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 two 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.

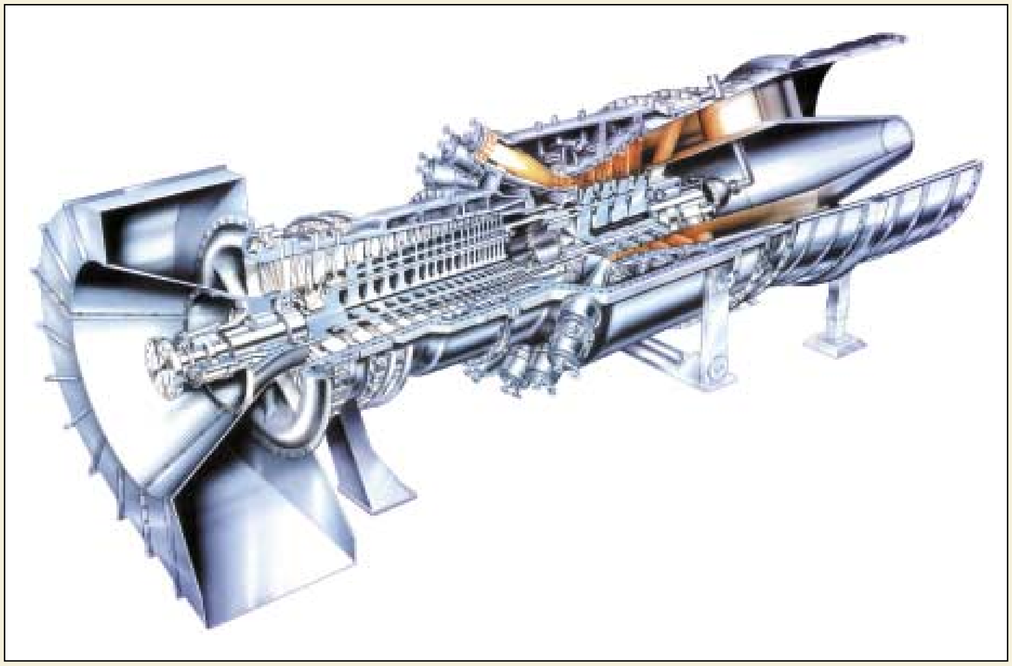
The focus of General Electric's effort is an "H" series gas turbine. To accommodate elevated turbine inlet temperatures, General Electric is employing a novel steam cooling system and newly developed single-crystal turbine blades. Development of the single-crystal casting technique for large complex 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 contributing to capital cost reduction and efficiency enhancement. These include a piloted ring combustor, which uses a lean, premixed multi-stage design to produce ultra-low pollutant emissions and stable turbine operation. Siemens-Westinghouse has also 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.

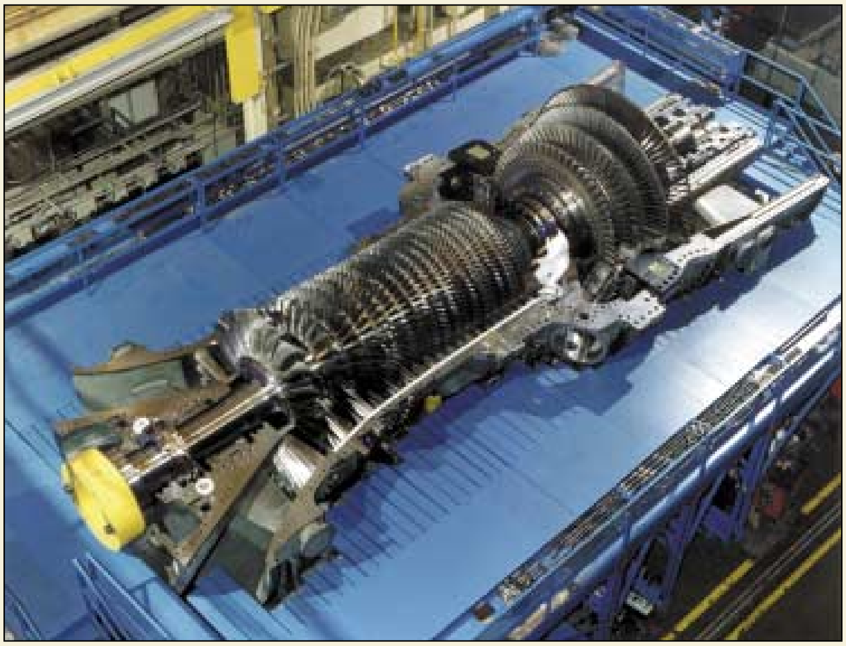
The technology base development effort includes both the advancements in materials, cooling, instrumentation, and control and combustion techniques needed for operation at elevated temperatures; as well as specific studies in support of component and systems development in areas such as heat transfer 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 supports 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 the 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 95 U.S. universities, including workshops and student internships at industry facilities. Under the direction of the South Carolina Energy and Research Development Center, contracted universities perform applied research specific to the needs of the ATS developers in combustion, aerodynamics, materials, and heat transfer.



Siemens-Westinghouse's utility-scale advanced turbine



General Electric's utility-scale advanced turbine

Turbine Systems: Next Generation Turbine Systems

Performance Targets

Size: >30 MW
Efficiency: 15%>existing
NO_x/CO Emissions: <5 ppm
Cost: 15% reduction (capital/O&M)
Fuels: Gas and liquids
Operation: Variable
Year: 2010

A follow-on program to the ATS is called the Next Generation Turbine Systems (NGTS) Program. The NGTS goals are to:

- Develop Next Generation Gas Turbine Systems in sizes and duty cycles that will provide public benefits and fill market needs not covered by the ATS Program.
- Target natural gas but provide options to use renewable energy and coal-derived fuels.
- Address both greenfield and repowering applications
- Provide power generation modules as building blocks for Vision 21 plants.

NGTS will provide significant public benefits through increased reliability, superior performance, reduced costs, and near- and long-term reductions of CO_2, NO_x, and other emissions. Because NGTS will be fuel flexible, they will expand the options for high-efficiency conversion of domestic fuels into electric power.

In the near term, NGTS will be suitable for new capacity, repowering of older fossil units, combined heat and power applications, and as efficiency enhancement units for existing fossil-fueled steam plants. In the long-term, NGTS 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 NGTS 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, and help keep U.S. businesses competitive.

The NGTS Program includes three elements:

1. Systems Development. The Flexible Gas Turbine System (FGTS) is the major thrust of the systems development activity. DOE envisions that most of the R&D will be done by gas turbine developers and vendors of gas turbine system components. FGTS will:

- Be greater than 30 MW in size range;
- Be optimally designed for intermediate and peaking duty, i.e., have high turndown ratios, high part-load efficiency, flexibility of 400 starts per year, and be capable of running in base load operation;
- Have a 15% improvement in net system efficiency over current systems;
- Reduce NO_x and CO emissions to less than 5 ppm to ensure permitting in the post-2008 time frame;

- Have low life-cycle costs, a requirement of the deregulated market (a 15% reduction in operation and maintenance costs and a 15% reduction in capital costs compared to current systems);
- Be able to use multiple fuels (gas and liquid);
- Where applicable, be developed in cooperation with DOD for dual use in civilian and military (propulsion, ship service, and weapon systems) applications; and
- Where applicable, enabling technology or systems components will contribute to the long-term goals of the Vision 21 program. FGTS systems may ultimately be enhanced for applications as Vision 21 power modules.

2. Supporting R&D and Enabling Technology. This R&D will broadly support all gas turbine development and operation. It will be conducted by universities, industry, academia, and research institutes. Technology development needs include:

- High temperature materials and coatings;
- Integration of aircraft turbine-based technology into industrial turbine designs;
- Robust combustion systems;
- Improved computational methods;
- Advanced cooling schemes; and
- Technology for advanced system operation and life cycle cost reduction.

3. Vision 21 Applications and Integration. This element focuses on very high-efficiency hybrid turbine/fuel cell systems and advanced cycles for central station and other large power plants. The goal is to achieve systems with 75% (LHV) efficiencies on natural gas fuels and 60% HHV efficiencies on coal fuels. C&PS will conduct hybrid turbine/fuel cell activities in collaboration with EERE's industrial power program and with C&PS' Fuel Cell and Vision 21 programs. R&D performed under this element will contribute to the enhancement of ATS, FGTS, or other advanced systems to achieve Vision 21 performance and cost goals.

NETL supports hybrid system development in its Low-Btu Combustion Studies Facility. Fuel cell anode gases can be simulated for combustor design studies. The fully instrumented facility is made available for cooperative research between NETL and industry under Cooperative Research and Development Agreements (CRADAs), which are designed to protect industrial participants' intellectual property.

NETL Low-Btu Combustion Studies Facility

Low-Emissions Boiler System

Performance Targets

Efficiency: 42% HHV

Emissions:
NO_x – 0.1lb/10^6 Btu
SO_2 – 0.1lb/10^6 Btu
PM – 0.01lb/10^6 Btu

Year: 2003

The Low-Emissions Boiler System (LEBS) is a 2nd generation pulverized-coal-fired power system. LEBS uses the knowledge gained through the CCT Program and parallel research in pursuit of advanced environmental controls, and applies the knowledge in the design of a new system that leverages effective control mechanisms.

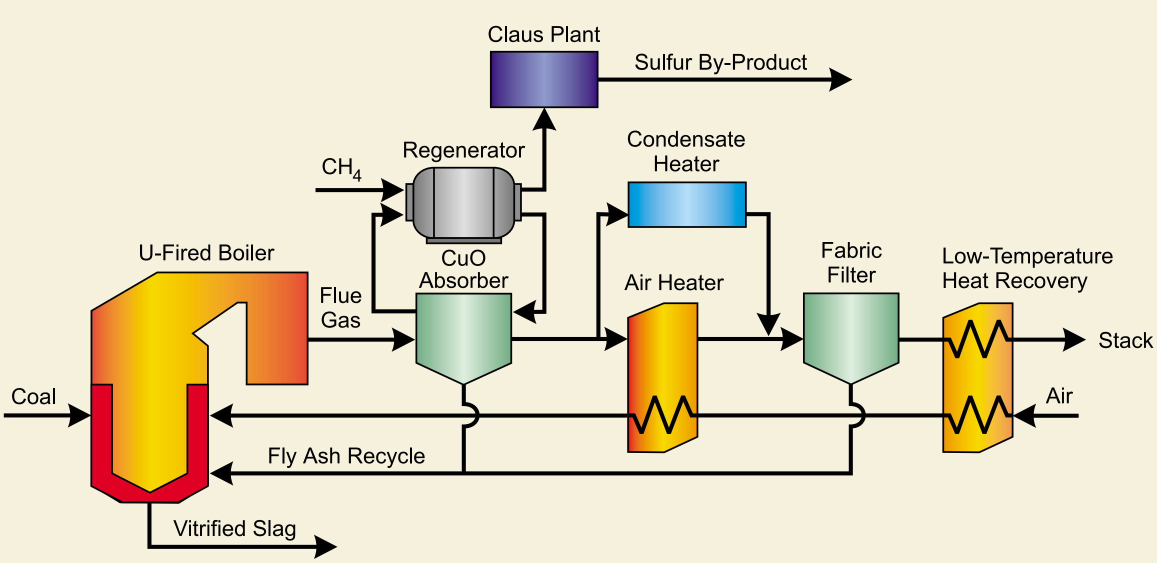
Three teams were competitively selected to participate on a cost-shared basis in the LEBS program. Three boiler manufacturers headed up technology teams, each with a "user" advisory panel comprised of utilities and non-utility generators. After engineering development and testing, the three industry teams submitted designs for a 400-MWe commercial plant along with proof-of-concept approaches. In September 1997, the DB Riley team was selected to construct and operate an 80-MWe LEBS unit in Elkhart, Illinois.

The DB Riley LEBS design features a novel U-fired furnace and moving-bed copper-oxide flue-gas cleanup system. The U-fired furnace converts nearly all of the coal ash into a glass-like slag. Particulate matter (PM) is controlled by a fabric filter. This glass-like slag represents about one-third the volume of fly ash and is a high-value product used as blasting grit and roofing granules. To further reduce or eliminate solid waste management problems, the copper-oxide moving-bed system employs a reusable alumina-based and copper-oxide coated sorbent for SO_2 and NO_x removal.

SO_2 is controlled by reacting with the copper-oxide on the alumina sorbent and oxygen to form copper sulfate. The sulfated sorbent is regenerated by introducing methane, which removes the sulfur as a concentrated stream of SO_2 easily converted to high-value sulfur products.

NO_x control starts in the U-fired furnace where combustion is staged by reburning — a process creating a fuel-rich zone above the main burners to strip oxygen from nitrogen compounds and completing combustion in an oxygen-rich zone at relatively low temperatures. Further NO_x reduction is achieved by injecting ammonia upstream of

Low-Emissions Boiler System



Advanced, low-NO_X, U-fired boiler produces environmentally benign inert slag

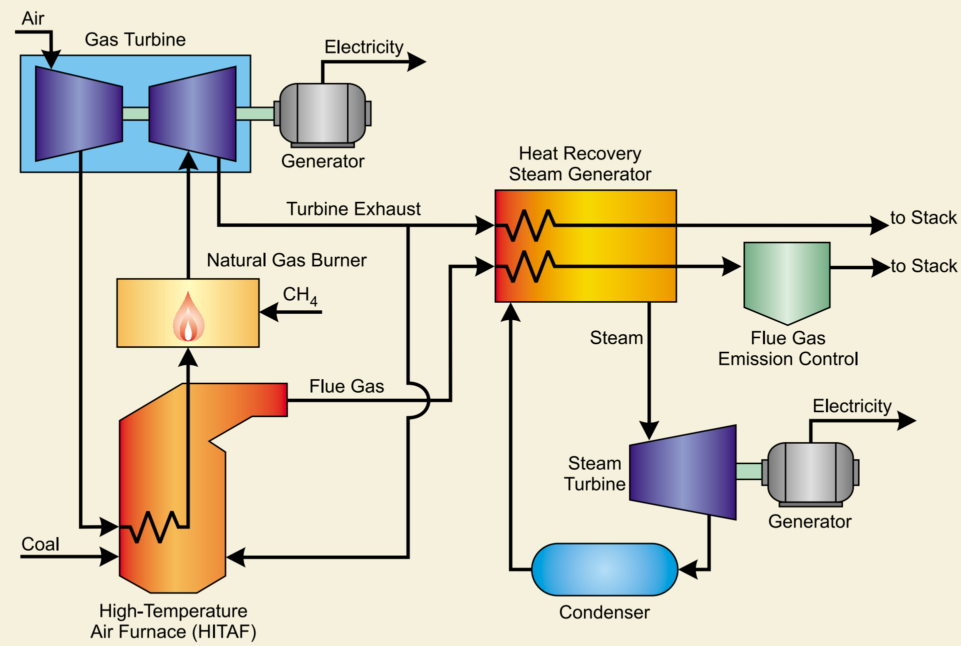
Copper-oxide flue-gas cleanup system removes 96%–99% of SO_2 and, if needed, 99% of NO_X

Heat recovery to air, condensate

Fabric filter for particulate collection

Air heater recovers heat from flue gases for increased efficiency

Indirect Fired Cycle



the sulfated sorbent, which serves as a catalyst to convert ammonia and NO_x into nitrogen and water.

LEBS is expected to exceed new source performance standards for pollutant emissions and to have efficiencies far beyond the 35 percent efficiency of 1st generation pulverized coal-fired systems. Plans are to initiate proof-of-concept testing in 2000 and realize market entry by 2003.

Indirect Fired Cycles

Performance Targets

Efficiency: 55% HHV

Emissions:

NO_x – 0.06 lb/10^6 Btu
SO_2 – 0.06 lb/10^6 Btu
PM – 0.003 lb/10^6 Btu

Year: 2010

Indirect Fired Cycle (IFC) is an indirectly fired gas turbine combined-cycle where the high-temperature corrosive gas from coal combustion does not contact the gas turbine. The heat is transferred to a clean working media —air— avoiding the need to clean coal combustion gases at high-temperature to achieve high-efficiency. Air under pressure from a gas turbine compressor is heated in a high-temperature air furnace (HITAF) and is expanded in the gas turbine. The option exists to add further energy to the air working media by combusting a clean fuel gas, such as natural gas or coal-derived fuel gas. Heat recovered from the gas turbine exhaust and HITAF flue gas is used to raise steam for a steam turbine.

The challenge to realizing the benefits of this indirectly fired cycle lies in the development of an effective high-temperature heat exchanger, the HITAF. Two competitively selected teams are presently addressing this challenge, led by Foster Wheeler Development Corporation and United Technologies Research Center. When fully developed, both versions of High-Performance Power Systems are expected to achieve efficiencies of 55 percent.

The teams are currently engaged in component and subsystem testing and refining system designs. Both IFC designs are capable of efficiencies of 55 percent. The teams are currently testing components and subsystems for consideration as Vision 21 modules.

Pressurized Fluidized-Bed Combustion

Performance Targets

Efficiency: 52% HHV

Emissions:

NO_x – 0.06 lb/10^6 Btu
SO_2 – 0.06 lb/10^6 Btu
PM – 0.003 lb/10^6 Btu

Cost: <$1,000/kW

Year: 2008

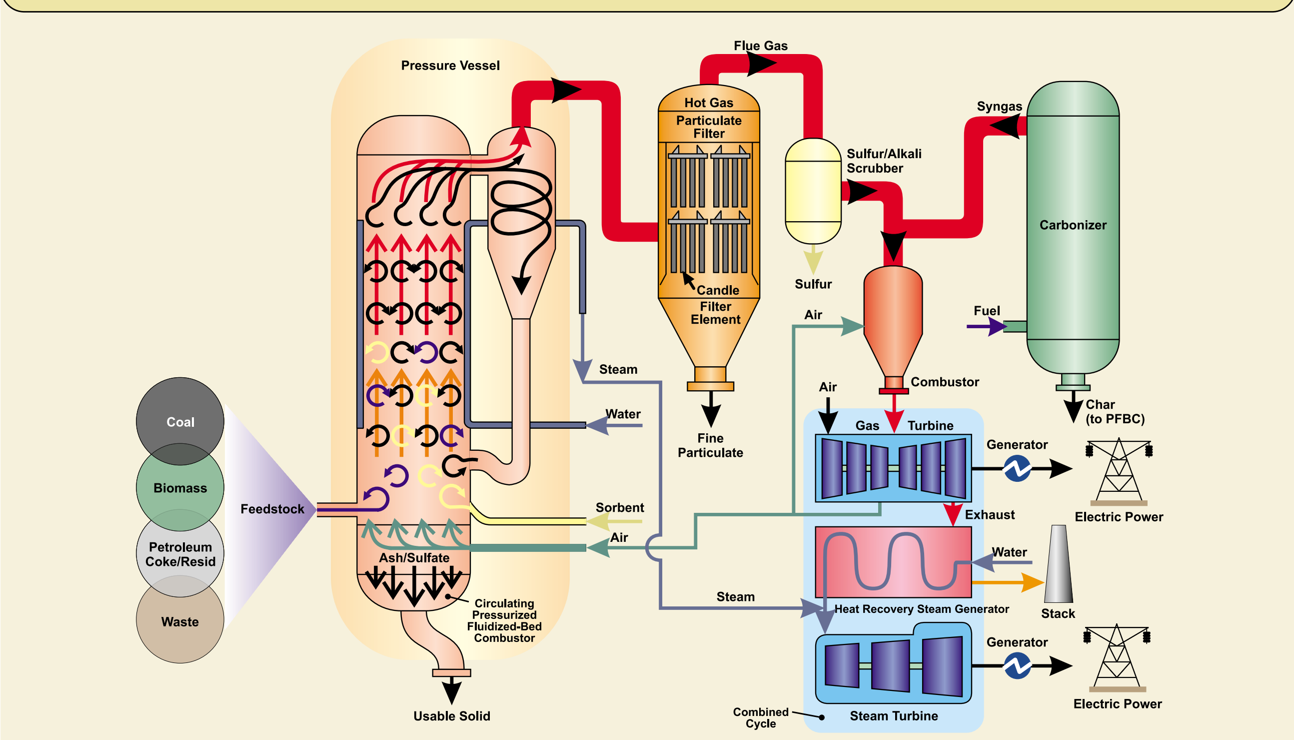
Fluidized beds use a gas such as air to entrain solids. The result is a turbulent tumbling and mixing of gas and solids acting much like a fluid, which is effective for chemical reactions and heat transfer. Fluidized-bed combustion (FBC) evolved from efforts to find a combustion process able to control pollutant emissions without external controls. FBC enables efficient combustion at temperatures of 1,400–1,700°F, well below the thermal NO_x formation temperature (2,500°F), and results in high SO_2 capture efficiency through effective sorbent/flue gas contact.

Pressurized fluidized-bed combustion (PFBC) builds on earlier work in atmospheric fluidized-bed combustion (AFBC) technology. AFBC is achieving significant market penetration, with most boiler manufacturers currently offering AFBCs as a standard package. This success is largely due to CCT Program efforts and the C&PS and industry partners' R&D leading to demonstration. The popularity is attributed to the tremendous fuel flexibility and SO_2 and NO_x emission control without the need for add-on controls.

The CCT Program has also resulted in market entry of 1st generation PFBC, with an estimated 1 gigawatt of capacity installed worldwide. These PFBC systems pressurize the fluidized bed to generate sufficient flue gas energy to drive a gas turbine and operate it in a combined-cycle. The 1st generation PFBC uses a "bubbling-bed" technology. A relatively stationary fluidized-bed is established in the boiler using low air velocities to fluidize the material, and a heat exchanger (boiler tube bundle) immersed in the bed to generate steam. Cyclone separators are used to remove particulate matter from the flue gas prior to entering a gas turbine, which is designed to accept a moderate amount of particulate matter (i.e., "ruggedized").

A 2nd generation PFBC, currently under development, uses "circulating fluidized-bed" technology and a number of efficiency enhancement measures. Circulating fluidized-bed technology has the potential to improve operational characteristics

2nd Generation Pressurized Fluidized-Bed Combustion



by using higher air flows to entrain and move the bed material, and recirculating nearly all the bed material with adjacent high-volume, hot cyclone separators. The relatively clean flue gas goes on to the heat exchanger. This approach theoretically simplifies feed design, extends the contact between sorbent and flue gas, reduces likelihood of heat exchanger tube erosion, and improves SO_2 capture and combustion efficiency.

A major efficiency enhancing measure for 2nd generation PFBC is the integration of a coal gasifier (carbonizer) to produce a fuel gas. This fuel gas is combusted in a topping combustor and adds to the PFBC flue gas energy entering the gas turbine, which is the more efficient portion of the combined cycle. The topping combustor must exhibit flame stability in combusting low-Btu gas and low-NO_x emission characteristics. To take maximum advantage of the increasingly efficient commercial gas turbines, the high-energy gas leaving the topping combustor must be nearly free of particulate matter and alkali/sulfur content. Also, releases to the environment from the PFBC system must be essentially free of mercury, a soon-to-be regulated hazardous air pollutant.

To reduce cost and CO_2 emissions, new sorbents are being evaluated. Sorbent utilization has a major influence on operating costs, and CO_2 emissions streams can result in the production and use of alkali-based sorbents.

Efforts are ongoing at the Power Systems Development Facility (PSDF) in Wilsonville, Alabama to ensure critical components and subsystems are ready for demonstration of 2nd generation PFBC. The PSDF is operated by Southern Company Services under DOE contract to conduct cooperative R&D with industry. Plans are to demonstrate 2nd generation PFBC at Lakeland Electric's McIntosh Power Station in 2006.

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

Tests conducted at the PSDF in 1998 verified that a newly developed multi-annular swirl burner (MASB) provided the needed flame stability and low-NO_x performance characteristics. Tests of promising new hot gas filter components and systems are continuing at the PSDF. Advances made to date in this critical technology area include the development of clay-bonded silicon carbide candle filters and the associated filter vessel. Efforts are currently focused on improved candle filter materials for enhanced durability under extreme temperatures and corrosive environment. New ceramics and ceramic-metallic composites are showing promise. Those passing laboratory screening tests will undergo testing at the PSDF.

Alkali and sulfur compounds have the potential to cause chemical corrosion of gas turbine blades at the temperatures sought for efficient operation. Data must be obtained to determine the maximum allowable limits and control systems must be developed to ensure that the limits are not exceeded. The PSDF will play a role in verifying that the appropriate controls are developed.

Moreover, the PSDF and NETL in-house facilities will be used: (1) to examine new sorbents that have the potential to more efficiently capture SO_2 and lessen or eliminate CO_2 emissions; and (2) to evaluate HAPs control measures to ensure compliance with anticipated standards.

To further enhance efficiency, 2nd generation PFBC will incorporate the gas turbines emerging from the ATS Program, and eventually will include a supercritical steam cycle. With all these features, 2nd generation PFBC is expected to achieve a 52 percent efficiency and have near-zero NO_x, SO_2, and particulate emissions. Market entry is projected for 2008.

Gasification Technologies

Performance Targets

Efficiency: >52% HHV

Emissions:
NO_x – 0.06 lb/10^6 Btu
SO_2 – 0.06 lb/10^6 Btu
PM – 0.003 lb/10^6 Btu

Cost: <$1,000/kW

Year: 2008

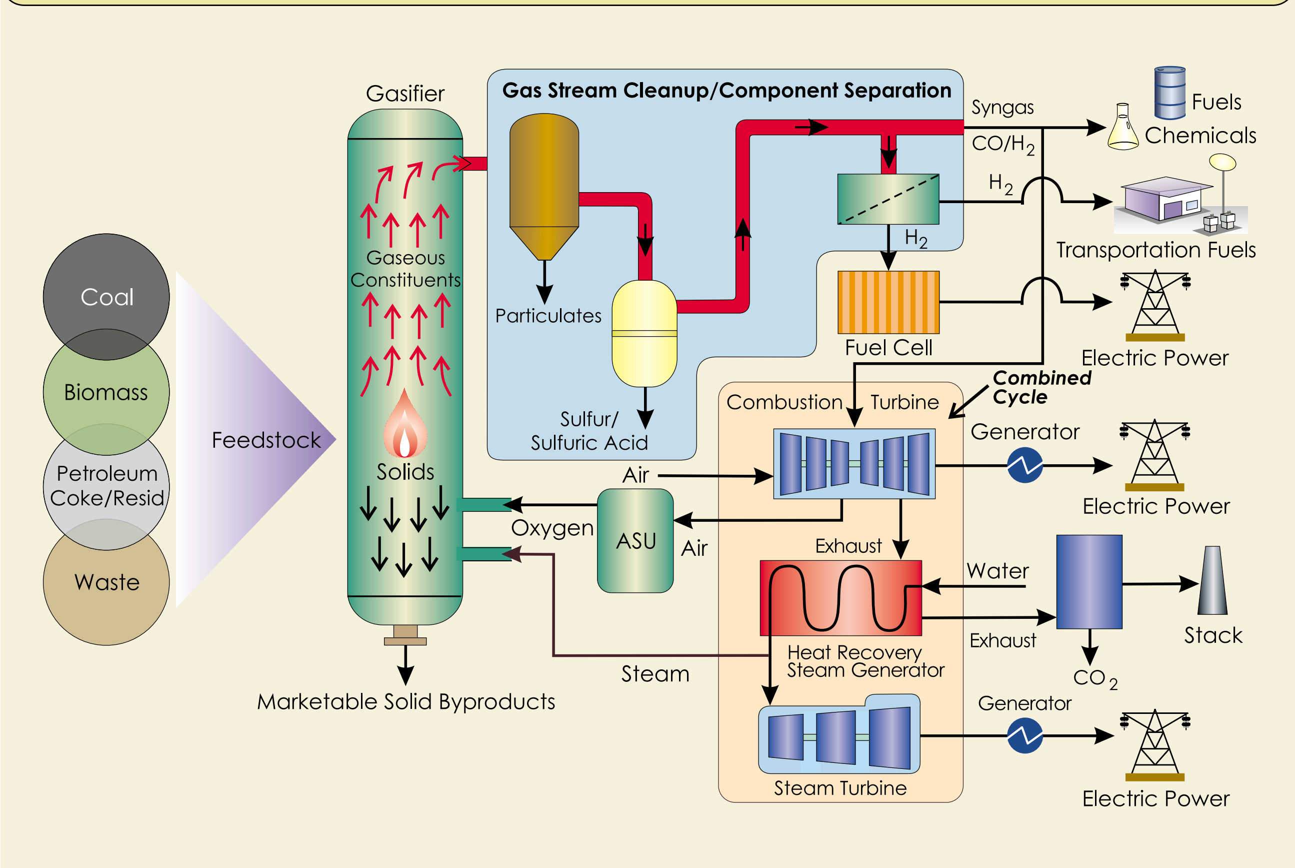
Gasification technologies represent the next generation of solid feedstock-based energy production systems. The heart of these systems is the gasifier. This unit is responsible for converting any carbon-based feedstock into synthesis gas, a mixture of carbon dioxide and hydrogen. This conversion is accomplished 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, besides containing carbon monoxide and hydrogen, also has smaller quantities of hydrogen sulfide, methane, ammonia, and particulate matter. The synthesis gas is subsequently cleaned of these impurities to meet the requirements of downstream process units.

Once cleaned, the synthesis gas can be used, in whole or in part, to produced electricity, steam, fuels, chemicals, hydrogen, and substitute natural gas. Integrated Gasification Combined-Cycle (IGCC), one configuration of gasification-based processes, utilizes the 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 commercial and 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 and nitrogen oxides and particulates. High operating

Gasification-Based Systems Concepts



efficiency of future gasification technologies (>52%) reduces CO_2 emissions, and the processes are readily adaptable for concentrating the remaining CO_2 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 emissions of pollutants**.** The strategy consists of two key elements: Gasification Systems Technology and Systems Analysis/ Product Integration.

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

Gasification Systems Technology

R&D conducted by industry, academia, nonprofit institutions, and government laboratories focus on gasification, gas cleaning, gas separation, and product/by-product utilization. Research on ***advanced gasifiers*** such as the transport gasifier offers potential for achieving performance goals and increasing feedstock flexibility. Fluid dynamic data and advanced computational fluid dynamic modeling are being used to support the development of advanced gasifiers. The use of alternative feedstocks, such as biomass and refinery, industrial, and municipal wastes, is being explored to improve gasifier flexibility. Advanced refractory materials and process instrumentation are being developed to improve gasifier performance, operational control, and reliability.

To achieve near-zero emissions while simultaneously reducing capital and operating costs, novel ***gas cleaning and conditioning*** technologies are undergoing development. Such technologies are also needed to meet the gas quality requirements for fuel cell and synthesis gas conversion technologies. Technologies that operate at mild to high temperatures and incorporate multi-contaminant control are being explored. Successful technologies will undergo further development at NETL's Gas Processing Development Unit (GPDU) or at the PSDF.

Research into ***advanced gas separation*** technologies offers the key to expanded opportunities for gasification-based technologies through the elimination of conventional energy intensive processes. Novel membrane-based air separation technologies offer potential for substantial reductions in the cost of oxygen compared to today's cryogenic technologies while simultaneously enhancing process efficiency. New advances for the manufacture of hydrogen will make gasification an important technology in the transition to a hydrogen economy. Development of advanced membranes and CO_2 hydrate technologies will result in the separation of a pure hydrogen stream for fuel cell applications while simultaneously concentrating CO_2 for sequestration.

Finally, the economics of gasification-based processes can be improved by producing ***value-added products*** from waste streams and minimizing waste disposal. Technologies are being developed to improve the quality of the gasifier ash and slag, and to develop new market applications.

New approaches for recovering sulfur are also being explored to reduce processing costs.

Systems Analysis/Product Integration

Economic analyses, process performance assessments, and market studies will provide the necessary engineering and economic guidance for future R&D initiatives and will support domestic and international commercialization opportunities. Process optimization studies are being pursued to determine the lowest cost and highest efficiency approaches for baseload, cogeneration, and coproduction applications. Similar studies will also be pursued for advanced configurations that incorporate fuel cells and CO_2 capture technologies. Life cycle analyses are being performed to evaluate cradle to grave performance. Scoping studies to help define research needs and goals for all R&D projects is a continuing activity.

Technology integration and demonstration is an important component of the program to achieve market acceptance of the technologies. Under the CCT program, 1st generation IGCC technologies are being demonstrated at four separate facilities. Each project uses different gasifiers and gas cleanup systems. These processes largely employ conventional air separation, pollutant controls, and bottom cycles that are either energy intensive or sacrifice efficiency by operating at low temperatures. Next generation gasification technologies will seek to enhance performance by integrating thermally efficient particulate and sulfur control technologies, advanced turbine systems, new air separation technologies, and improved materials, instrumentation, and controls while incorporating lessons-learned from the CCT demonstration projects and optimization studies. Such systems are expected to have efficiencies in excess of 52% with near-zero emissions of SO_2, NO_x, and particulates.

The Gasification Technologies program is also embarking on projects that will lead to the demonstration of coproduction technologies for the manufacture of electricity, fuels, and chemicals and the application of gasification in the pulp and paper industry.

In FY 2000, a major new initiative focusing on the application of gasification to the pulp and paper industry is being implemented. Since the early 1970s, this industry has been looking for a safer, less expensive, and environmentally friendly alternative to conventional pulping liquor processing and wood residual combustion. Gasification has the potential for exceeding known and anticipated emission standards for SO_2 and NO_x, and achieving higher thermal efficiency, enhanced separation and regeneration of pulping chemicals, higher electric power generation, and improved safety. This new government/private sector initiative is focusing on the commercial demonstration of gasification-based technologies at existing U.S. mills. Successful demonstration of these technologies will provide the industry with the information needed to make informed decisions on replacing existing technologies with new technologies that are far superior in terms of environmental performance and efficiency.

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. To ensure that industry has the technologies to meet future market applications and environmental requirements, interviews will be conducted with industry to determine underlying needs. Based on these reviews and other ***outreach activities***, a technology roadmap will be developed jointly with industry.

Carbon dioxide emissions are captured and, along with flyash, are removed by barge for recycling or safe disposal.

Vision 21 Systems

Performance Targets

Efficiency:
Coal-powered – >60% HHV
Gas-powered – >75% LHV
Combined Heat/Power – 85-90% Thermal

Emissions:
Pollutants – zero
CO_2 – zero w/ sequestration

Cost: Electricity at market rates

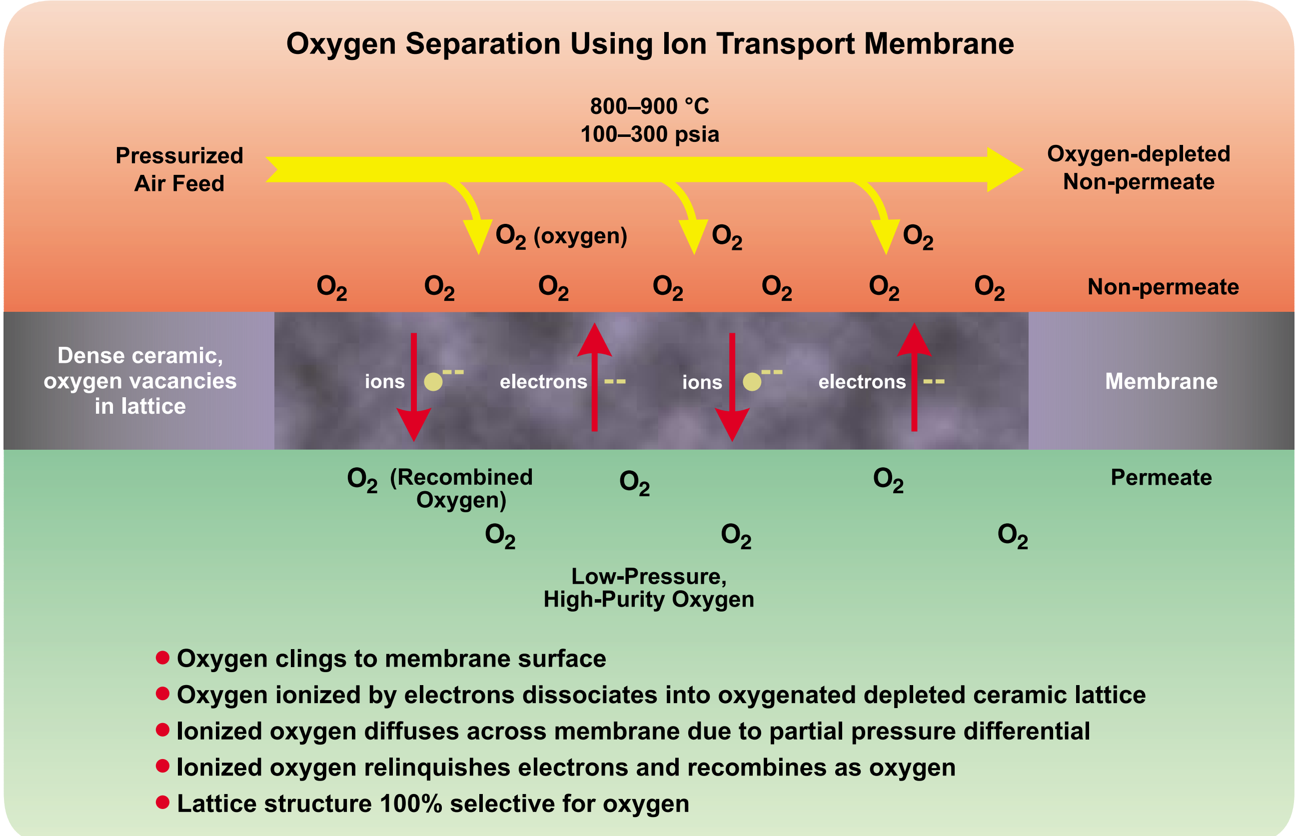
Year: 2015

Vision 21 is a government-industry-academia collaboration to develop technologies to effectively remove all environmental concerns associated with the use of fossil fuels. The approach is to develop a suite of technology modules that can be interconnected in different configurations to produce selected products. These modular facilities will be capable of using a multiplicity of fuels to competitively produce a number of commodities at efficiencies greater than 60 percent for coal-based systems and 75 percent for natural gas-based systems with near-zero emissions. Vision 21 builds on a portfolio of technologies already being developed, including PFBC, IGCC, HIPPS, advanced gas turbines, fuel cells, and fuels synthesis, and adds other critical technologies and system integration techniques. When coupled with CO_2 capture and recycling or sequestration, Vision 21 systems would achieve no net CO_2 emissions and no adverse environmental impacts.

Many of the Vision 21 activities complement and extend focused activities to achieve 2nd generation PFBC and IGCC. For example, hot gas particulate filtration, hot gas sulfur/alkali control, and air separation are critical elements to one or both. Vision 21 addresses gas separation and cleanup, but extends the development effort to: (1) increasingly efficient and cost-effective measures for particulate and sulfur/alkali control and air separation; and (2) measures dealing with a broader range of gases, such as hydrogen and CO_2.

Advanced gas separation and cleanup are critical to achieving hybrid systems, fuel and product flexibility, and carbon sequestration. Hybrids and fuel and product flexibility offer the potential for major improvements in cost and performance. And effective CO_2 capture is a prerequisite to carbon sequestration.

A hybrid system showing great promise is integration of gasification with a fuel cell (IGFC). Fuel



cells offer very high efficiencies, with emerging fuel cells having 60 percent efficiency. These emerging fuel cells also produce very high-temperature exhaust gases that can either be used directly in combined-cycle or used to drive a gas turbine. IGFC hybrids have the potential to achieve up to 60 percent efficiency and near-zero emissions. Moreover, the concentration of CO_2 lends itself to removal by separation or other capture means. Such systems require that the syngas derived from gasification be free of contaminates for use in the fuel cell, or that the hydrogen be separated from the syngas (hydrogen is the fuel element for the fuel cell).

Fuel flexibility enables the use of low-cost indigenous fuels, renewables, and waste materials. Use of renewables and wastes contributes to solving environmental problems as well as reducing operating costs. The challenge is in developing effective feed mechanisms for these alternative fuels, establishing effective operating parameters, and providing the means to achieve the operating parameters and to control any new pollutants that might be formed. For ATS gas turbines, and hybrids incorporating ATS/fuel cells, fuel flexibility requires research to address combustion of low-Btu gases and maintaining low-NO_x emissions at increasingly higher temperatures.

Product flexibility allows power suppliers to supplement revenues by designing plants to site- or region-specific markets for high-value by-products. Many chemical and fuel processes, however, require nearly contaminant-free syngas and warrant improvements to enhance product quality.

Carbon sequestration is the ultimate solution to stabilizing global carbon emissions. A prerequisite to carbon sequestration is carbon capture, which for power systems is CO_2 capture. Power system developments are moving toward higher efficiency to lower CO_2 emissions on a per-Btu basis and toward more concentrated CO_2 emission streams through oxygen- rather than air-based gasification and combustion. Air separation efforts support the move to oxygen-based systems. Ultimately, the CO_2 must be captured either through chemical or physical separation methods.

Vision 21 is addressing the challenges outlined above through a cooperative effort involving industry, universities, and National Laboratories. It includes fundamental research in materials science, novel concept evaluation at bench-scale, and process verification at pilot-scale. Facilities such as the GPDUnit at NETL and the PSDF at Wilsonville, Alabama, along with industry/National Laboratory/university facilities, are being enlisted to address these challenges.

Specific examples of Vision 21 activities include development of: (1) a dense ceramic ion transport membrane for air separation (ITM), (2) a transport reactor for fuel-flexible gasification and sulfur/alkali control, (3) a CO_2 hydrates system for CO_2 capture and hydrogen separation, (4) a ceramic proton-transfer membrane (PTM) for hydrogen separation, (5) an early-entry IGFC system, (6) an early-entry coproduction plant (EECP), and (7) a hybrid gas turbine fuel cell power module.

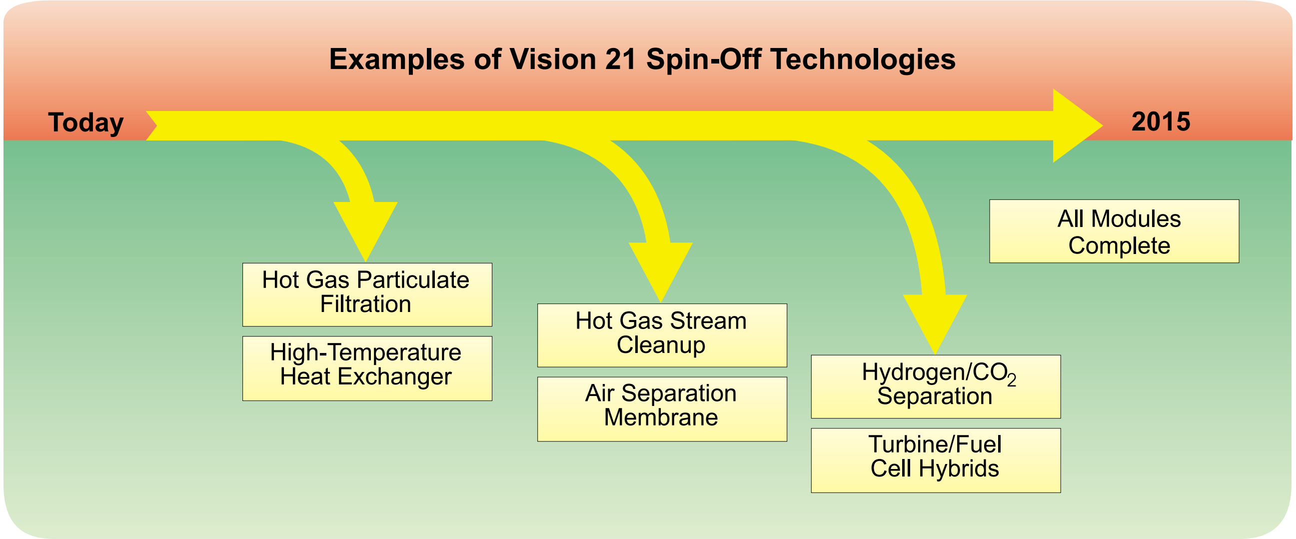
The ITM can reduce IGCC plant costs and opens the way for oxygen-rich advanced combustion systems. Air separation represents 15–25 percent of IGCC plant costs. Oxygen-rich combustion along with CO_2 recycle shows promise for efficient, low-NO_x combustion and concentration of the CO_2 in the flue gas, which facilitates capture.

The transport reactor used at the PSDF is a unique system capable of emulating both fluidized-bed combustion and gasification. This reactor also exhibits a high degree of fuel flexibility, and for that reason, is a subject of development efforts to fully evaluate its potential as a commercial gasifier. In addition, the reactor provides the platform for a hot gas cleanup system using regenerable sorbents for sulfur/alkali removal.

Integration of a CO_2 hydrates system with IGCC offers a low-temperature approach to chemical separation of hydrogen from the synthesis gas, and formation of a concentrated CO_2 stream. The PTM separates hydrogen from the hot synthesis gas using a ceramic membrane.

Early hybrid designs, such as IGFC and Early Entry Coproduction Plant, are examining integration issues related to incorporating gasifiers with fuel cells and fuel process technologies.

To accelerate market entry of Vision 21 systems, the implementation strategy includes having early entry spinoff technologies, which become commercial products over the 15 year span of the program. The spinoffs will realize early commercialization because they represent significant breakthroughs in cost and performance, such as the air separation membrane for low-cost oxygen production. Oxygen represents the third most marketed commodity in the United States. The first Vision 21 plants will integrate many of these advanced spinoff components, which will have already been demonstrated in different applications. This method reduces risk and is expected to take the place of government funded full scale Vision 21 plant demonstrations. Subscale integration tests, using both computational simulation and hardware, will be conducted to prove out the systems integration technology. Improvement of these virtual demonstration techniques will also be a part of the Vision 21 effort.



Program Successes

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 collaboration with environmental groups resulted in the creation of uplands, wet lands, 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 1999, the IGCC system had accumulated over 16,000 hours of operation and produced over 4,500,000 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.

The 4,000-ton Model MS7001H (H System™) turbine is the size of a locomotive

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

General Electric's *H System*™ Turbine

In September 1999, General Electric (GE) 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 Department of Energy's Advanced Turbine System research and development program that began in the early 1990s, when GE 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 nitrogen oxide emission levels of 9 parts-per-million will be half the average of the turbines now in use, making the new technology suitable for siting in the nation's most environmentally constrained areas.

Distributed Generation

Providing Reliable, Flexible Power

Introduction

A New View on Energy Use

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 strategically applies 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 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 transmission and distribution (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.

Significant technological advances through decades of intensive research have yielded major improvements in the economic, operational, and environmental performance of small, modular gas-fueled power generation options. These distributed generation systems offer clean, efficient, reliable, and flexible on-site power alternatives. Fuel flexibility is also afforded by operating on natural gas, propane, or fuel gas derived from any hydrocarbon, including coal and biomass, and wastes from refineries, municipalities, and the forestry and agricultural industries.

Program Areas

- Fuel Cells
- Gas Turbines
- Fuel Cell/Turbine Hybrids
- Advanced Gas Reciprocating Engines

Technologies such as gas turbines and reciprocating engines are already making a contribution , but they have more to offer through focused development efforts. Fuel cells are beginning to enter the market, but will require additional research and development to realize widespread deployment. Also, fuel cell/turbine hybrid systems and 21st century fuel cells, currently in the embryonic stage, offer even greater potential.

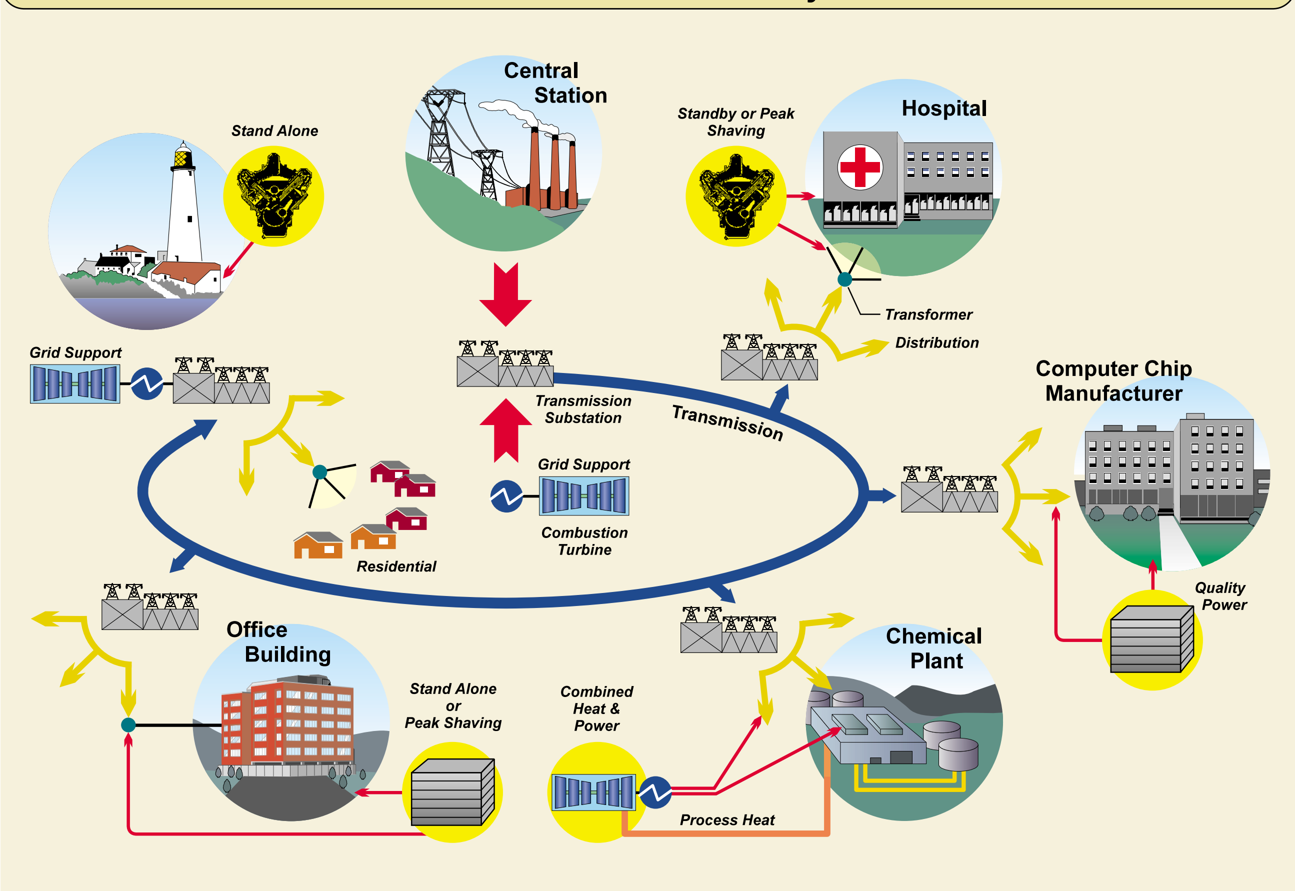
While addressing distributed generation potential in general, the program presented here focuses on stationary energy gas-based distributed generation technologies and the Department of Energy's efforts to bring them into the marketplace.

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 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 combined heat and power (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 hour by hour depending upon demand and generation availability. These hourly variations 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.

Distributed Generation Systems



Benefits

Customer Benefits

- Ensures reliability of energy supply, increasingly critical to business and industry in general, and essential to some where interruption of service is unacceptable economically 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 transmission and distribution infrastructure does 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.

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.

National Benefits

- Reduces greenhouse gas emissions through efficiency gains and potential renewable resource use;
- Responds to increasing energy demands 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.

THE OPPORTUNITY

The importance of distributed generation is reflected in the size of the estimated market. Domestically, new demand combined with plant retirements is projected to require as much as 1.7 trillion kilowatt-hours of additional electric power by 2020, almost twice the growth of the last 20 years. Over the next decade, the domestic distributed generation market, in terms of installed capacity to meet the demand, is estimated to be 5–6 gigawatts per year.

Worldwide forecasts show electricity consumption increasing from 12 trillion kilowatt hours in 1996 to 22 trillion kilowatt hours in 2020, largely due to growth in developing countries that lack nationwide power grids. The projected distributed generation capacity increase associated with the global market is conservatively estimated at 20 gigawatts per year over the next decade.

The projected surge in the distributed generation market is attributable to a number of factors. Under utility restructuring, energy suppliers, not the customer, must shoulder the financial risk of the capital investments associated with capacity additions. This favors less capital-intensive projects and shorter construction schedules.

Also, while opening up the energy market, utility restructuring places pressure on reserve margins as energy suppliers increase capacity factors on existing plants to meet growing demand rather than install new capacity. This squeezing of the margins increases the probability of forced outages. As a result, customer concerns over reliability have escalated, particularly those in the manufacturing industry.

With the increased use of sensitive electronic components, the need for reliable, high-quality power supplies is paramount for most industries. The cost of power outages, or poor quality power, can be economically devastating to industries with continuous processing and pinpoint-quality specifications. Studies indicate that nationwide, power fluctuations cause annual losses of $12–26 billion.

As the power market opens up, the pressure for enhanced environmental performance increases. In many regions in the U.S. there is near-zero tolerance for additional pollutant emissions as the regions strive to bring existing capacity into compliance. Public policy, reflecting concerns over global climate change, is providing incentives for capacity additions that offer high efficiency and use of renewables.

Overseas, the utility sector is undergoing change as well, with market forces displacing government controls, and public pressure forcing more stringent environmental standards. Electricity demand worldwide is forecasted to nearly double. Moreover, there is an increasing effort to bring commercial power to an estimated 2 billion people in rural areas that currently do not have access to a power grid.

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

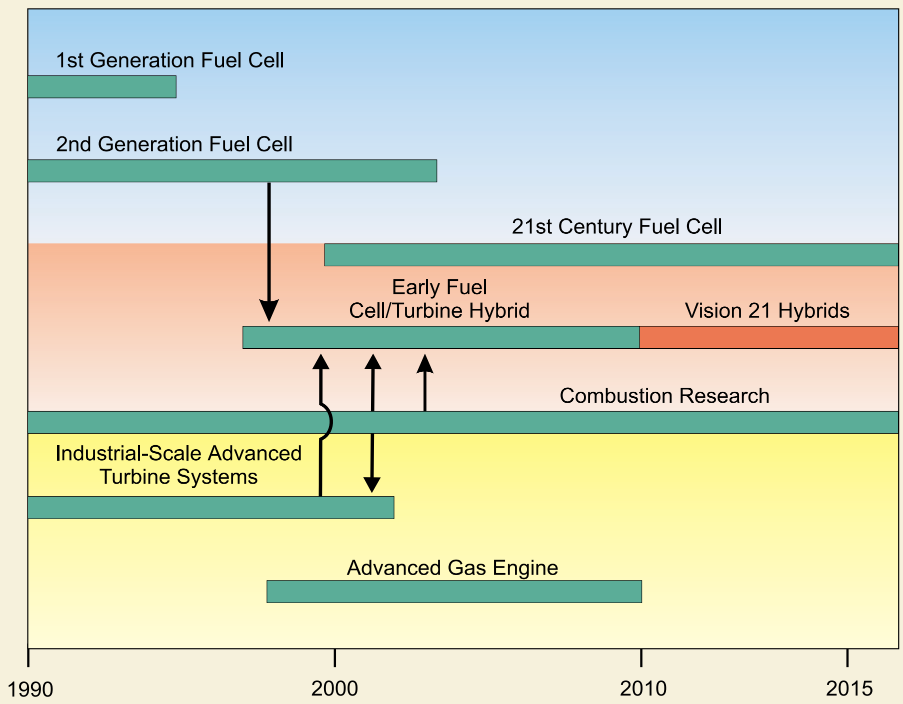
THE PROGRAM

The C&PS Distributed Generation Program involves: (1) research, development, and demonstration to optimize the cost and performance, and to accelerate the readiness of a portfolio of advance gas-fueled distributed generation systems for both domestic and foreign markets; and (2) policy development necessary to remove barriers to widespread distributed generation deployment. The Program is being carried out in partnership with other federal agencies, state governments, technology suppliers, industry research organizations, academia, power generators, energy service companies, and end users.

A cooperative government/ industry effort has resulted in successful commercialization of a first generation of fuel cells using a phosphoric acid electrolyte. Turnkey 200-kW phosphoric acid fuel cell (PAFC) plants have been installed at more than 165 sites around the world. PAFC systems operate at about 200ºC (400ºF) with electrical efficiencies ranging from 40–45 percent on a lower heating value basis (LHV).

Second-generation fuel cells are under development that provide both higher fuel-to-electricity efficiencies and temperatures. The technologies include the molten carbonate fuel cell (MCFC) and the solid oxide fuel cell (SOFC). The high temperatures (650ºC for MCFCs and 1,000ºC for SOFCs) enable internal reforming of fuels and provide high-quality heat for CHP and combined-cycle applications. The heat developed in producing electricity also makes MCFCs and SOFCs ideal candidates for integration with gas turbines. Both have the potential to reach fuel-to-electricity efficiencies of 50 to 60 percent LHV.

Roadmap

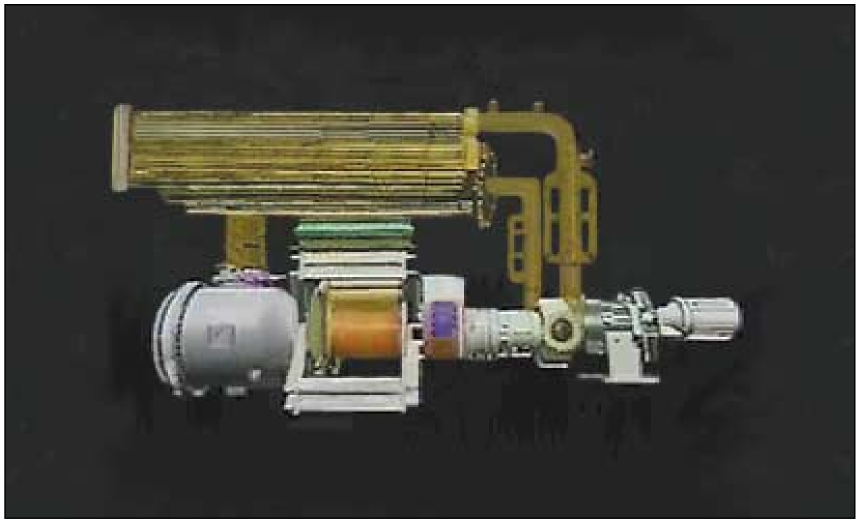


These second-generation systems are currently being demonstrated, with market entry for natural gas-based systems planned for 2003. Demonstration objectives include reducing capital costs to $1,500/kW. Subsequent to market entry, capital costs are expected to decline as manufacturing capacity and capability increase. Follow-on testing will address expanding the fuel options by testing other reformed fuels and associated cleanup systems.

Parallel research and development into new ceramic materials and manufacturing techniques is ongoing. It explores means to enhance performance and lower costs in support of both the MCFC and SOFC development as well as future 21st century fuel cells that can be manufactured at far lower cost and reach efficiencies of 80 percent LHV. These potentially very low-cost fuel cells promise deeper and wider market penetration.

Another an important element of the Distributed Generation Program is the Department of Energy's Advanced Turbine Systems (ATS) Program. The Office of Fossil Energy and the Office of Energy Efficiency and Renewable Energy (EERE) Office of Industrial Technologies share responsibility for implementing the Program with industrial partners. The Program encompasses simple-cycle industrial gas turbines for distributed generation applications and utility-scale gas turbine combined-cycle systems for central station markets.

In the near term, industrial gas turbines with efficiencies of 40–43 percent will be available as a result of two industrial-scale ATS



The Solar Mercury™ 50 Turbine System

Projects. As to future activities, these ATS designs will become platforms for fuel flexible turbine/fuel cell hybrids of increasingly better performance, as high-temperature materials are proven.

Efforts have also begun to develop a system that integrates a fuel cell with a gas turbine. Hybrid fuel cell/gas turbine technology for stationary power generation offers the potential to achieve efficiencies in excess of 80 percent, nitrogen oxides and carbon monoxide emissions less than 2 parts per million (ppm), and costs 25 percent below a comparably sized fuel cell.

Five teams of fuel cell and turbine manufacturers are currently conducting conceptual feasibility studies on fuel cell/turbine hybrids. The goal is to develop hybrid systems with efficiencies greater than 70 percent for market entry by 2010. More advanced Vison 21 hybrids configured with 21st century fuel cells could offer 80 percent efficiency by 2015.

Combustion research supports both the fuel cell/turbine hybrid and ATS efforts by developing effective means to combust low-Btu gases and to achieve low emissions in high-temperature combustion. The work includes expanding the fuel range to gasification derived fuel gases (syngas).

A joint FE/EERE workshop at NETL began an initiative to enhance the efficiency and environmental performance of natural gas-fired reciprocating engines. A set of performance goals was established for increasing efficiency by 15 to 20 percent by 2010.

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.
- High-quality and reliable power supplies are critical to many industries employing highly sensitive electric components. Studies indicate that, nationwide, power fluctuation causes 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.

Goals

- Commercially introduce high-temperature natural gas-fueled molten carbonate fuel cells (MCFC) and solid oxide fuel cells (SOFC) capable of 50 to 60 percent efficiency in the multi-kilowatt range at $1,000–1,500/kW. (2003)
- Expand MCFC and SOFC fuel use to gasified coal and other hydrocarbons. (2010)
- Achieve market entry for a 21st century fuel cell using solid state composition and advanced fabrication techniques to achieve 80 percent efficiency and reduce capital costs to $400/kW with stack costs of $100/kW. (2015)
- Commercially introduce early fuel cell/gas turbine hybrids capable of 70 percent efficiency. (2010)
- Commercially introduce an advanced natural gas-fired reciprocating engine with 50 percent efficiency and 5 ppm or less NO_x emissions. (2010)

Strategies

- Work in partnership with other federal agencies, state governments, technology suppliers, industry research organizations, academia, power generators, energy service companies, and end users.
- Complete the commercial-scale demonstrations on the MCFC and SOFC systems, and use subsequent commercial sales to build manufacturing capacity to produce larger units at reduced cost.
- Integrate gas cleanup systems to enable MCFC and SOFC operation on syngas derived from gasification of coal and biomass, and municipal, forestry, and refinery wastes.
- Use technology-based research into materials and manufacturing techniques to initiate development of a new solid state fuel cell system that significantly reduces fabrication cost and realizes quantum jumps in efficiency.
- Develop an early market entry fuel cell/gas turbine hybrid by integrating MCFC and SOFC fuel cells with industrial-scale ATS designs using teams comprised of the fuel cell and turbine developers.
- Use the technology base research in low-Btu combustion, materials, and manufacturing from both the fuel cell and turbine programs to enhance fuel cell/gas turbine hybrid system performance and expand fuel flexibility.
- Use U.S.-based engine and components manufacturers consortium and universities to develop a natural gas-fired reciprocating engine superior to any in the world.

Measures of Success

- Achieve early market entry for MCFC and SOFC fuel cells (2003), expand sales, and establish a strong U.S.-based manufacturing capability to competitively produce MCFC and SOFC fuel cells up to 100 MW capacity. (2010)
- Have the gasification and gas cleanup systems in place to expand fuel cell fuels to coal and biomass, and municipal, forestry, and refinery wastes. (2010)
- Establish the capability to manufacture solid state fuel cells at less than one-half the cost of today's MCFC and SOFC fuel cells. (2015)
- Establish a strong U.S. technology leadership position in fuel cell/gas turbine hybrids. (2010)
- Establish a strong U.S. technology leadership position in gas-fired reciprocating engines. (2010)

Program Areas

The following is a discussion of the Program Areas that comprise the OC&PS Distributed Generation Program. The program focuses on stationary energy gas-based distributed generation technologies. OC&PS and the Office of Energy Efficiency and Renewable Energy (EERE) share responsibility for the ATS Program component. Moreover, EERE has responsibility for developing non-gas-based distributed generation technologies such as photovoltaics, solar-thermal, wind, and modular biomass systems.

Distributed generation 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, (3) having the flexibility to put power back into the grid at user sites, and
(4) providing technologies that can be integrated with central power energy platforms to enhance performance.

Fuel Cells

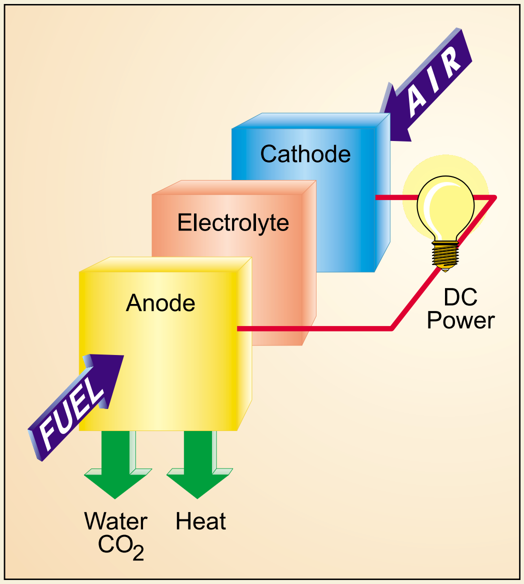
Performance Targets

2nd Generation
Efficiency: 50-60% LHV
Cost: $1,000–1,500/kW
Year: 2003

21st Century
Efficiency: 70-80% LHV
Cost: $400/kW
Year: 2015

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 CO_2. Hydrogen fuel can come from a variety of hydrocarbon resources by subjecting them to steam under pressure (called reforming or gasification).

Fuel Cell



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. Efficiency can be enhanced by using the high energy heat derived from the fuel cell reactions either in combined heat and power (CHP) or combined-cycle applications (generating steam for additional electric power). The CO_2 is in concentrated form, which facilitates capture for recycling or sequestration. The absence of moving parts results in very low noise levels. The stacking of cells to obtain a usable voltage and power output allows fuel cells to be built to match specific power needs, and the modularity makes capital cost relatively insensitive to scale.

While PAFCs operate at about 200°C (400°F) and 40–45 percent fuel-to-electricity efficiencies on a lower heating value basis (LHV), higher temperature second-generation fuel cells achieve higher fuel-to-electricity and thermal efficiencies. The higher temperatures contribute to improved fuel-to-electricity efficiencies and enable generation of steam for cogeneration, combined-cycle applications, and reforming of fuels.

One of two high-temperature fuel cells currently under development is the molten carbonate fuel cell (MCFC). MCFC technology has the potential to reach fuel-to-electricity efficiencies of 50 to 60 percent LHV. Operating temperatures for MCFCs are around 650°C (1,200°F), which allows total system thermal efficiencies up to 85

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

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

percent LHV in combined-cycle applications.

The other high-temperature fuel cell under development is the solid oxide fuel cell (SOFC). SOFCs operate at temperatures up to 1,000°C (1,800°F), which further enhances combined-cycle performance. The solid-state ceramic construction enables the high temperatures, allows more flexibility in fuel choice, and contributes to stability and reliability. As with MCFCs, SOFCs are capable of fuel-to-electricity efficiencies of 50 to 60 percent LHV and total system thermal efficiencies up to 85 percent LHV in combined-cycle applications.

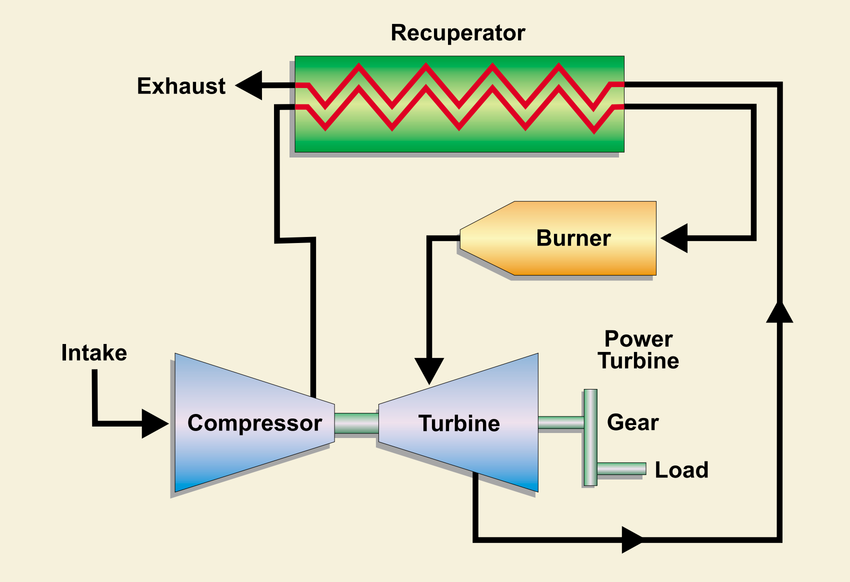
Second-generation fuel cell development is proceeding efficiently. NETL is working with Fuel Cell Energy and M-C Power to bring two versions of the MCFC to commercial fruition, and is working with Siemens-Westinghouse Power Corporation to commercialize the SOFC.

By 2003, natural gas-fueled MCFCs and SOFCs will be commercially available in sizes up to 2MW. As market acceptance and manufacturing capacity increases, natural gas-fueled plants in the 50- to 100-MW range will become available. Follow-on testing will address expanding the fuel options by testing other reformed fuels and associated cleanup systems. By 2010, a transition to coal-gas-powered fuel cells will occur as gasification and gas cleanup costs are reduced through commercial plant replications.

A set of cost and performance targets have been established for a 21st Century Fuel Cell that will provide wider and deeper penetration into a full range of market applications. These targets include achieving stack fabrication and assembly costs of $100/kW, system costs of $400/kW, efficiencies of 70-80 percent, near-zero emissions, and compatibility with carbon sequestration. Long-term materials development, integration of design, high-speed manufacturing, and materials selection from the start are deemed critical to meeting the goals. These targets represent order-of-magnitude improvements in power density and cost and a doubling improvement in efficiency.

Gas Turbines

Typical Gas Turbine



A gas turbine produces a high-temperature, high-pressure gas working fluid, through combustion, 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. As for capacity, recently emerging microturbines, evolved from automotive turbochargers, are about to enter the market with outputs as low as 25 kW. Next generation utility-scale turbines are rated at nearly 400 MW in combined-cycle applications.

Gas turbines produce high quality heat that can be used to generate steam for CHP and combined-cycle applications, significantly enhancing efficiency. They accommodate a variety of gases including those derived from gasification of coal, biomass, and hydrocarbon wastes. However, pollutant emissions, primarily nitrogen oxides, are a concern particularly as turbine inlet temperatures are increased to improve efficiency.

Currently, industrial-scale simple cycle machines have efficiencies around 30 percent. The industrial-scale portion of the ATS Program, addressed here, seeks to improve on that efficiency by 15 percent. Additional objectives are 10 percent reduction in the cost of electricity, enhanced fuel flexibility, less than 10 ppm nitrogen oxides and 25 ppm carbon monoxide without post-combustion controls, and reliability-availability-maintainability-durability equal to or better than current systems.

In the near term, gas turbines with efficiencies of 40 to 43 percent will be available as a result of the ATS efforts. Under the ATS Program, the Allison Engine Company took the approach of increasing inlet temperature to 2,400 ºF, increasing the pressure ratio to 30:1, and using staged lean premix fuel injection and catalytic combustion. Plans are to introduce these features in an existing product line. Solar Turbines, Inc. is using a modest inlet temperature of 2,200 ºF and pressure ratio of 9:1, and is incorporating a high efficiency recuperator. These features are to be incorporated in the 4.2-MWe Solar Mercury™ 50 and introduced into the market in 2000.

The ATS Program includes two supporting activities. One addresses critical materials and manufacturing issues, with the objective of hastening the incorporation of new materials and components in gas turbines. Work includes development of thermal barrier coatings and advanced casting techniques for single crystal turbine components, and is being carried out by industry with assistance from national laboratories and universities. The other supporting activity, the Advanced Gas Turbine Systems Research (AGTSR) Program, is an effort to establish a scientific foundation for a next-century gas turbine. The South Carolina Institute for Energy Studies is coordinating the AGSTR Program, a consortium of more than 97 universities in 37 states formed to advance the fundamental knowledge base in gas turbines requisite to continued improvement.

As for future activities, the advanced turbine systems will become the platforms for the fuel cell/turbine hybrids. And the advanced high-temperature materials and supporting processes emerging from successful research will be integrated over time into ATS components and subsystems to enhance efficiency and performance.

Fuel Cell/Turbine Hybrids

Performance Targets

Efficiency (LHV):
70% by 2010
80% by 2015

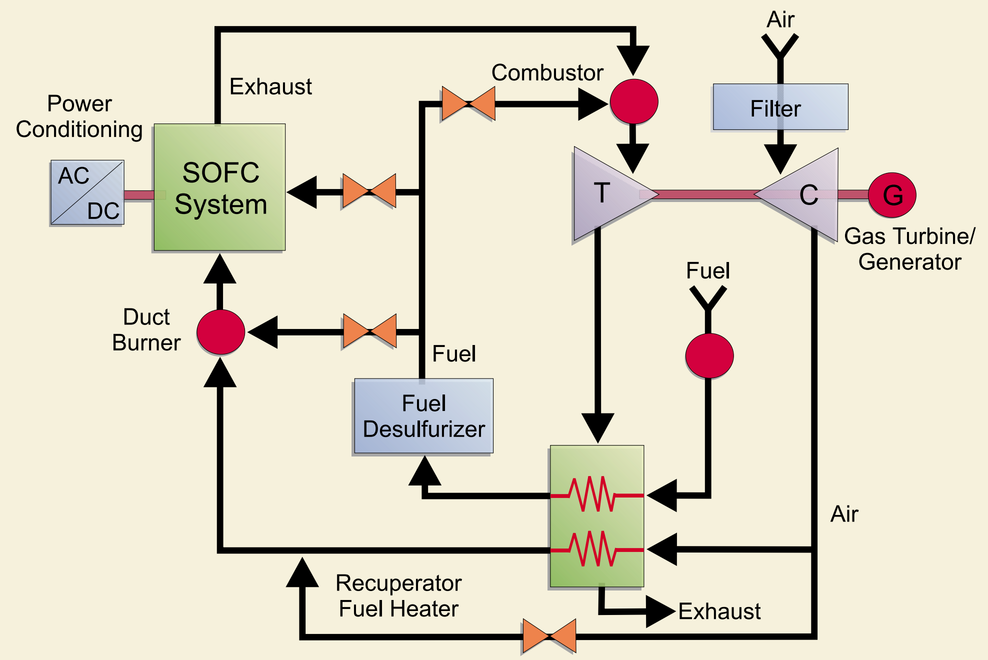
System studies to date indicate that fuel cell/turbine hybrids could realize a 25 percent increase in efficiency and 25 percent reduction in cost for a comparably sized fuel cell. The synergy realized by fuel cell/turbine hybrids derives primarily from using the rejected thermal energy and combustion of residual fuel from a fuel cell in driving the gas turbine. This leveraging of the thermal energy makes the high-temperature MCFCs and SOFCs ideal candidates for hybrid systems. Use of a recuperator contributes to thermal efficiency by transferring heat from the gas turbine exhaust to the fuel and air used in the system.

Exploratory research on fuel cell/turbine hybrids is underway in partnership with the National Fuel Cell Research Center at the University of California at Irvine and at NETL. The experimental work involves evaluation of a 75-kW turbine operating in combination with a simulated fuel cell. The particular focus is on dynamic operating conditions (startup, shutdown, load following, and upsets) and the associated controls. The objective is to establish: (1) key operating parameters and their interrelationships, (2) a range of safe operating conditions, and (3) a database and dynamic modeling tools to support further development.

Also supporting hybrid system development is a fully instrumented NETL Low-Btu Combustion Studies Facility. Fuel cell anode gases can be simulated for combustor design studies.

In an attempt to develop an early-entry hybrid system, five teams of fuel cell and turbine manufacturers have been engaged to conduct conceptual feasibility studies on fuel cell/turbine systems. The teams are predominately composed of the high-temperature MCFC and SOFC fuel cell manufacturers and the turbine manufacturers participating in the DOE's ATS program. The goal is to develop hybrid systems with efficiencies greater than 70 percent for market entry by 2010. As hybrid system capability increases, efficiencies of 80 percent are expected by 2015 along with designs for integration into Vision 21 Plants.

Example of Fuel Cell/Turbine Hybrid System



Courtesy of Siemens-Westinghouse

Advanced Gas Engines

Performance Targets

Size: <5 MW

Efficiency: 50% LHV

NO_x Emissions: <5 ppm

Year: 2010

Reciprocating engines, or piston-driven internal combustion engines, are a widespread and well-known technology. These engines offer low capital cost, easy startup, proven reliability, good load-following characteristics, and heat recovery potential. Incorporation of exhaust catalysts and better combustion design and control significantly reduced pollutant emissions over the past several years.

With the greatest distributed generation growth occurring in the under-5-MW market, reciprocating engines have become the fastest selling distributed generation technology in the world today. Of the reciprocating engines, spark ignition natural gas-fired units have increased their percent of market share by over 150 percent from 1995–1997. The reason for increased popularity stems from low initial installed costs, low operating costs, and low environmental impact.

Natural gas-fired reciprocating engine capacities typically range from 0.5–5 MW. The highest efficiencies achieved for these engines, which occur in the mid-range of 1–2 MW, are 38–40 percent for domestic engines and as high as 44 percent for some European engines.

A recent Advanced Stationary, Reciprocating, Natural Gas Engine Workshop concluded that a research and development initiative is warranted to enhance the cost and performance of spark ignition natural gas-fired engines in the less-than-5-MW market. Goals identified include:

Reciprocating engine at University of Alaska, Fairbanks

NETL in-house reciprocating engine research

- Increasing efficiency 15–20 percent,
- Reducing NO_x emission levels,
- Reducing total hydrocarbon emission levels,
- Reducing hazardous air pollutants,
- Reducing cost of electricity, and
- Maintaining durability and reliability levels.

Participation in the workshop included a consortium of four engine manufacturers and several engine component suppliers, as well as a strong university contingent that identified potential future academic partnerships.

The impetus for continuing growth in engine use is the anticipated rapid expansion of distributed generation domestically and internationally, and the preference for reciprocating engines in the less-than-5-MW market. Domestically, realizing performance goals will alleviate potential strain on natural gas supplies and essentially eliminate pollutant emission concerns. Internationally, improved cost and performance will provide U.S. engine manufacturers a strong market position.

As with the other gas-based distributed generation systems, reciprocating engine technology is adaptable to other gases such as landfill gas and propane, and gases derived from gasification of coal, biomass, and municipal, forestry, and refinery wastes.

Program Success

While 175 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 Department of Energy in partnership with the New York Power Authority installed a 200-kW PAFC in Central Park to provide electricity to 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. The government provided about one-third of the project cost under a Department of Defense-funded program administered by the Department of Energy. The program is designed to accelerate introduction of fuel cells and develop a U.S. manufacturing capability.

PAFC units (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 nearby location in Times Square in New York City.

Photo courtesy of ONSI Corporation

Fuels

Expanding Clean Fuel and Feedstock Resources

INTRODUCTION

CLEAN FUELS FOR A SECURE FUTURE

The need for liquid fuels is forecast to be a critical element of this Nation's energy future in the 21st century. The C&PS Fuels Program seeks to ensure the development and demonstration of economically competitive, efficient, environmentally responsible coal-based technologies that produce ultra-clean transportation fuels, utility and boiler fuels, chemicals, and carbon products for metallurgical and industrial applications.

PROGRAM AREAS

- TRANSPORTATION FUELS AND CHEMICALS
- SOLID FUELS AND FEEDSTOCKS
- ADVANCED FUELS RESEARCH

The Fuels Program is driven by three preeminent challenges: (1) improve the environment, (2) strengthen the economy, and (3) enhance our energy security.

In 1996, the transportation sector was responsible for 80 percent of the carbon monoxide, 50 percent of the nitrogen oxides, and 40 percent of the volatile organic compounds of the total man-made air emissions in the United States. Moreover, transportation accounts for approximately 470 million metric tons (MMT) of carbon emissions, or 32% of total U.S. carbon emissions. The Energy Information Administration (EIA) projects that by 2020, total carbon emissions in the U.S. will increase to 1,960 MMT under business-as-usual assumptions with transportation accounting for 690 MMT, or 35% of total U.S. carbon emissions. There is a host of potential regulatory actions that could require major additional reductions in energy-related emissions during the next decade, and some are expected to be very expensive if compliance must depend on conventional fuels. 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.

The EIA also predicts that, by 2020, U.S. petroleum imports (already representing over 50% of consumption) will rise to 65% and increase our negative balance of payments. Currently, the U.S. 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 substantially 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 whose production will eventually peak and decline in the face of continually increasing demand. It cannot be known when this peak in production will occur with any degree of certainty. 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.

For the long-term, the wisest policy is to depend on a balanced mixture of energy sources including gas, coal, biomass, opportunity fuels, wastes, and oil. Without new and better technology, the ability to lower emissions will be limited and the costs of energy will increase.

A key emphasis in transportation fuels development is the production of high-quality, clean-burning diesel fuels from both natural gas and coal. The Solid Fuels and Feedstocks program area examines the environmental and economic benefits of blending biomass and waste feedstocks with coal, develops tailored feedstocks for making premium carbon products, and provides the means to remove trace contaminants from coal. Through Vision 21, advanced technologies 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.

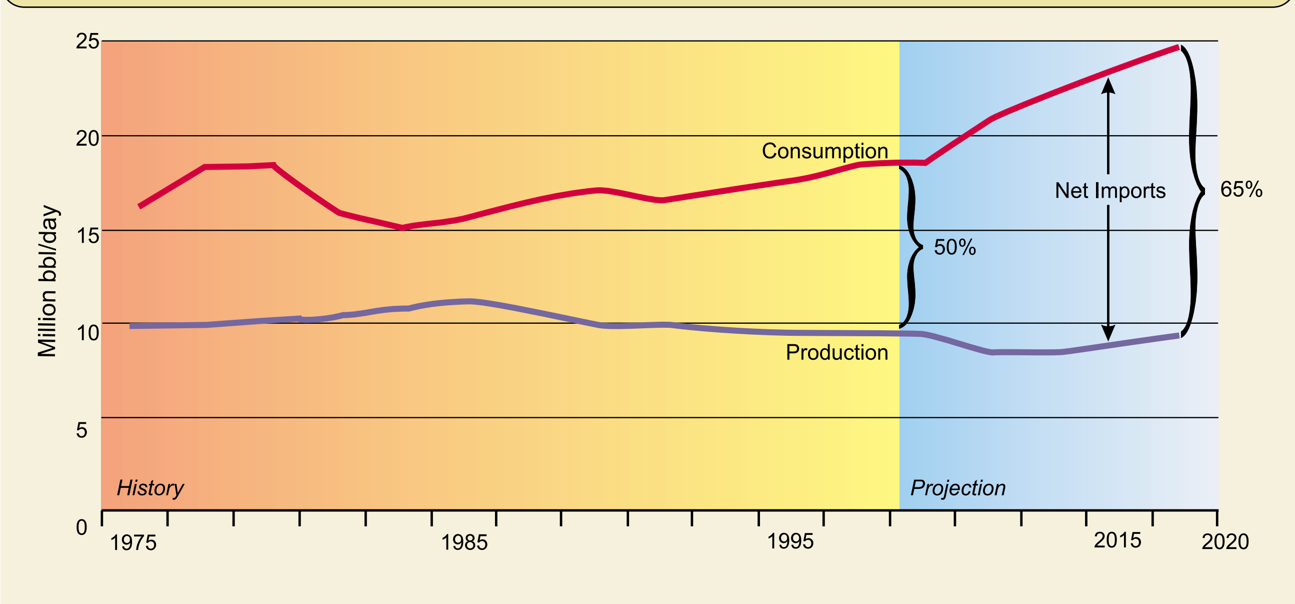
The Program

The C&PS Fuels Program response to these environmental, energy security, and economic challenges 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 domestic resources. Specifically, research is focused on developing ultra-clean transportation fuels, feedstocks for power generation that will help to lower emissions, and carbon high-value products. Technology development in these R&D areas will ensure coal's continued role in the Nation's energy future.

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 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 "grand challenges" associated with Vision 21. The Solid Fuels and Feedstocks program area involves coal preparation, potential HAPs precursor removal, carbon products development, and carbon recovery.

Research is focused on developing ultra-clean transportation fuels for high-efficiency vehicles and light- and heavy- duty trucks.

EIA – Projected U.S. Crude Oil Production and Consumption



Benefits

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, chemical, and power through coproduction.

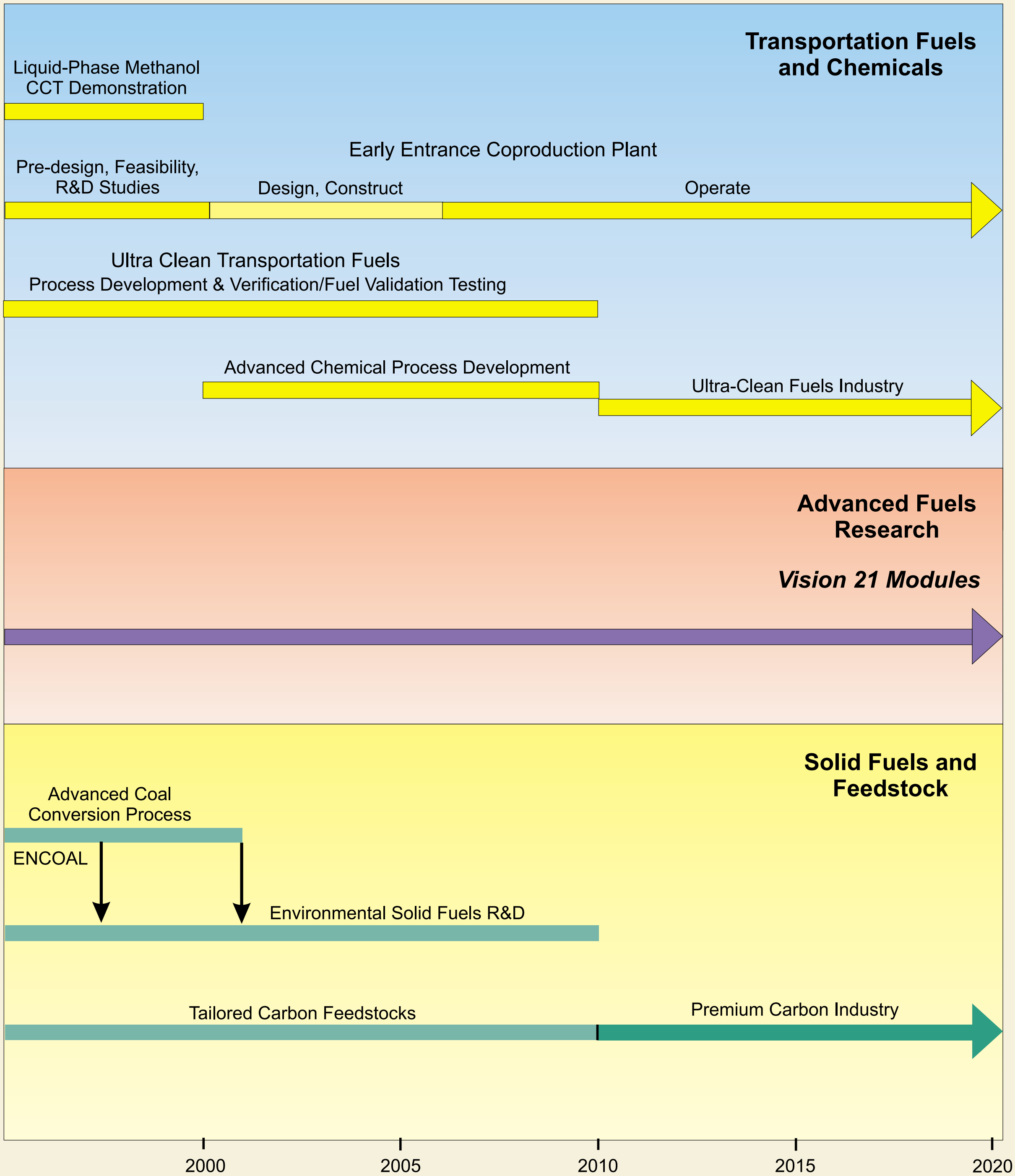
Supplier Benefits

- Boosts processing efficiencies of fuels development 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.

National Benefits

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

Roadmap


Transportation Fuels and Chemicals
Liquid-Phase Methanol CCT Demonstration
Early Entrance Coproduction Plant
Pre-design, Feasibility, R&D Studies
Design, Construct
Operate
Ultra Clean Transportation Fuels
Process Development & Verification/Fuel Validation Testing
Advanced Chemical Process Development
Ultra-Clean Fuels Industry
Advanced Fuels Research
Vision 21 Modules
Solid Fuels and Feedstock
Advanced Coal Conversion Process
ENCOAL
Environmental Solid Fuels R&D
Tailored Carbon Feedstocks
Premium Carbon Industry
2000
2005
2010
2015
2020

DRIVERS

- EPA standards will require cleaner burning transportation fuels in order to reduce urban air pollution, including carbon monoxide, nitrogen oxides, volatile organic compounds, and particulates.
- 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 demand for petroleum in non-industrialized countries will nearly double, and the U.S. will be importing nearly 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 negative balance of payments and the potential for supply disruptions with the attendant economic dislocations.
- 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 environment.

GOALS

- Transportation Fuels and Chemicals

  – 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.
- Solid Fuels and Feedstocks

  – 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.
- Advanced Fuels Research

  – 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

- Transportation Fuels and Chemicals
  – Complete demonstration of Liquid-Phase Methanol Clean Coal Technology Demonstration Project. (2001)
  – 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 demonstrates the feasibility of producing some combination of power, fuels, and chemicals from coal. (2007)
  – Establish fuel industry/government consortiums to identify needs of transportation industry; continue support/participation in engine/vehicle development efforts.
- Solid Fuels and Feedstock
  – Complete demonstration of Advanced Coal Conversion Process Clean Coal Technology Project. (2001)
  – 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 use of coal.
- Advanced Fuels Research
  – Conduct research and early development of improved innovative concepts for Vision 21 modules to produce transportation fuels, chemicals, and carbon products with high efficiency, improved environmental performance, and reduced CO_2 production.

Measures of Success

- 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 meet EPA Tier II Standards (i.e., 0.07g/mi NO_x, 0.01g/mi PM). (2008)
- To deploy commercially-scaleable, fully integrated coproduction plants that demonstrate the technical, economic, and environmental benefits of producing multiple products from gasification-based technology. (2007)
- To increase output of U.S. finished carbon products industry by 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; meet requirements and schedules of advanced vehicle development program for clean fuels. (2020)

PROGRAM AREAS

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. The 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 infrastructure; (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. In addition, advanced chemical processes are being developed that lead to greater process efficiencies and lower capital costs.

The base program area research efforts address key technical issues associated with making premium fuels and chemicals, and provides the foundation upon which to pursue initiatives such as the Liquid-Phase Methanol™ Project currently being demonstrated in the Clean Coal Technology 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.

Projects within the base program areas currently emphasize:

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.

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

Systems Engineering

- Extensive life cycle analyses to identify those areas of fuel conversion processing that offer the best opportunities for CO_2 mitigation.

Concurrently, R&D is underway on novel methods to reduce production of greenhouse gases through process improvements and utilization 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.

Technology Status and Direction. With current technology, the cost of producing coal-derived fuels in stand-alone plants would be about $30 per barrel crude oil equivalent (COE). The cost can be reduced to the $21 per barrel COE target by coproduction of liquid fuels and electric power. Novel three-phase slurry reactor technology is being developed to cost-effectively produce premium fuels, an excellent diesel fuel-blending feedstock, or high-value chemicals using syngas produced from natural gas, petroleum coke, refinery waste, and/or coal. Because of the interest in production of high-quality diesel fuel through the Fischer-Tropsch process, DOE's Office of Transportation Technologies is an important partner with the Office of Fossil Energy in developing fuels and transportation systems.

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

Ultra-Clean Transportation Fuels Initiative

It is important to coordinate and integrate FE activities that have clean fuels development as their goal, in the most efficient and cost-effective manner. Therefore, FE's petroleum processing, natural gas-to-liquids, and coal-based transportation fuels activities have partnered to form a comprehensive, well-coordinated Ultra-Clean Transportation Fuels Initiative (UCTFI) for producing fuels for ultra-low emission vehicles. This integrated FE activity has the common goal of promoting the production of ultra-clean fuels from a diversity of resources. This 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 DOE Energy Efficiency's Office of Transportation Technologies provided the basis for DOE EE-FE collaboration on a major solicitation that was issued in February 2000. This UCTFI encompasses three R&D areas that will be pursued over five years.

The core part of UCTFI is directed toward systems-oriented R&D projects that lead to the production of sufficient quantities of fuel to validate performance and emissions. Fuels testing will be done in collaboration with DOE Energy Efficiency's Office of Transportation Technologies. The second focus area is on development of advanced unit operations/processes for producing ultra-clean transportation fuels. The third area emphasizes the development of new and innovative emission control systems. 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 emission requirements;
- Be compatible with the existing liquid fuels infrastructure;
- Enable vehicle efficiencies to be significantly increased, with concomitantly reduced CO_2 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, etc. are coproduced in one facility from various feedstocks. This initiative is part of a joint effort with the Gasification Technologies program. In these studies, teams will 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. These activities will help industry teams refine their strategies, reduce technical risk, and define economic and environmental requirements.

In Fiscal Year 1999, three projects were chosen for negotiation and two project awards were made. Texaco Natural Gas, Inc. and its team will combine its gasification technology with Rentech Fischer-Tropsch technology to produce high-quality transportation fuels and chemicals from a coal and petcoke. The Dynegy Power Corporation team will evaluate producing power and chemicals from a plant that processes coal and non-coal feedstocks. A third project, Waste Management and Processors, Inc. and its team including Sasol Technology Ltd. and Texaco Global Gas and Power, will assess the economics and feasibility of a plant that converts coal residue into premium transportation fuels and power.

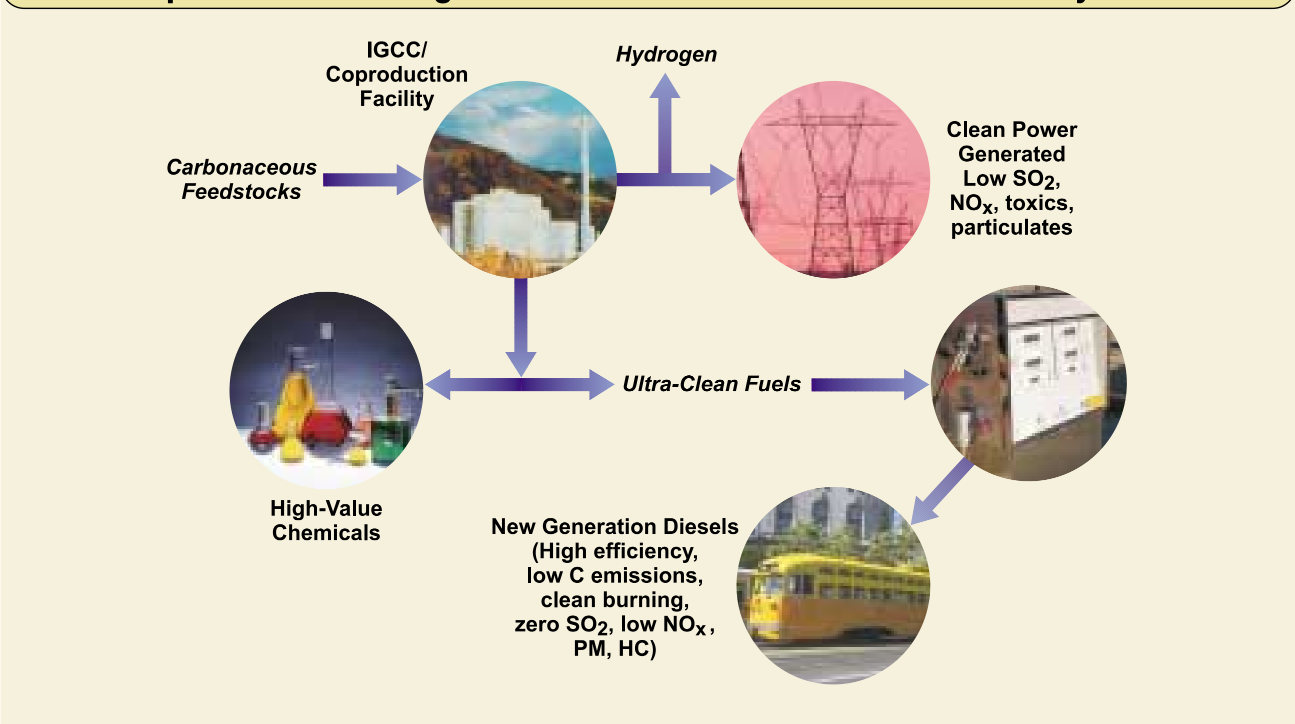
Systems Engineering and Analysis

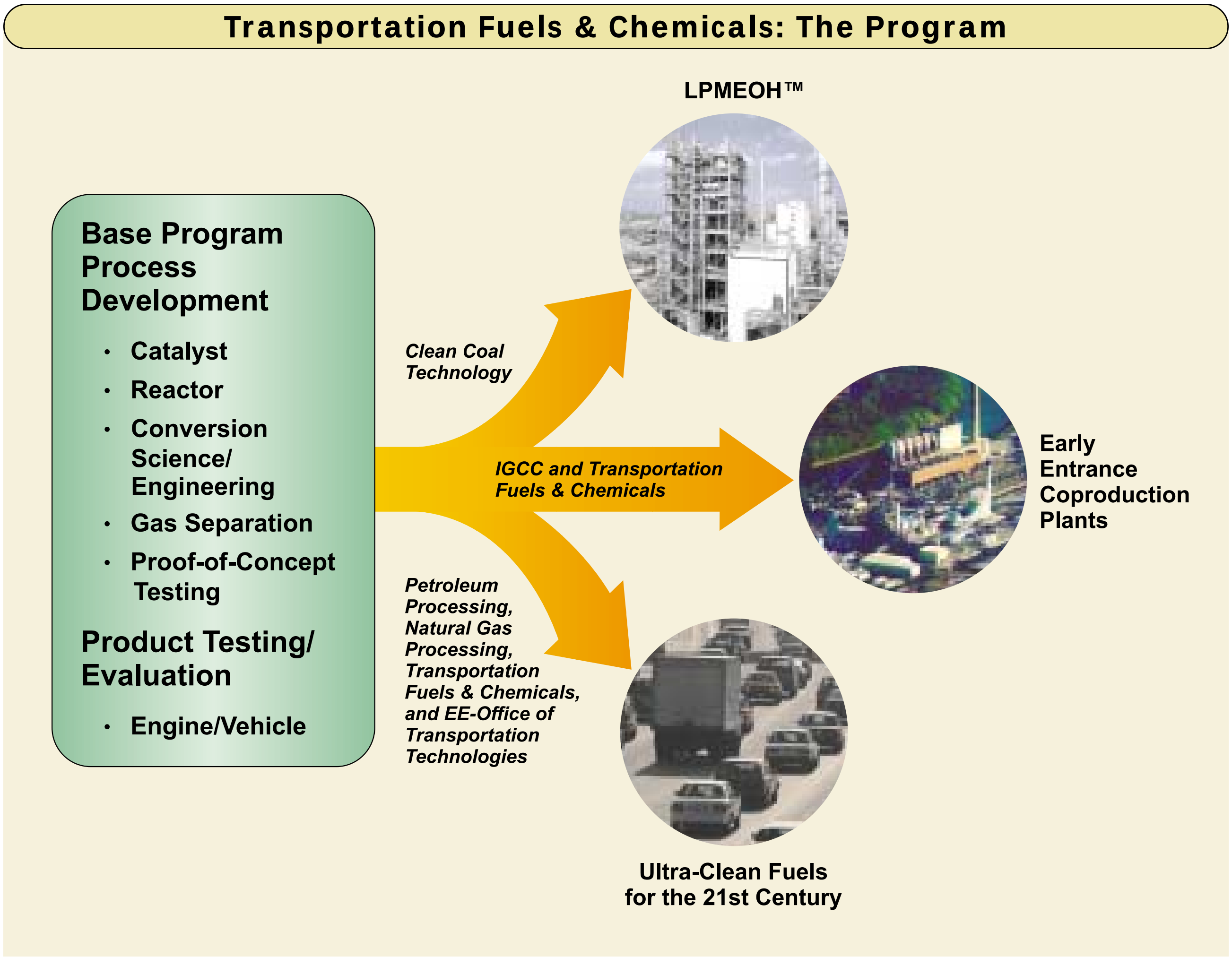
Engineering and economic analysis are needed to define and prioritize future R&D initiatives to support commercialization activities, both domestic and international. A major emphasis is on performing life-cycle environmental analysis on CO_2 and analysis of configurations that can significantly reduce manufacturing costs.

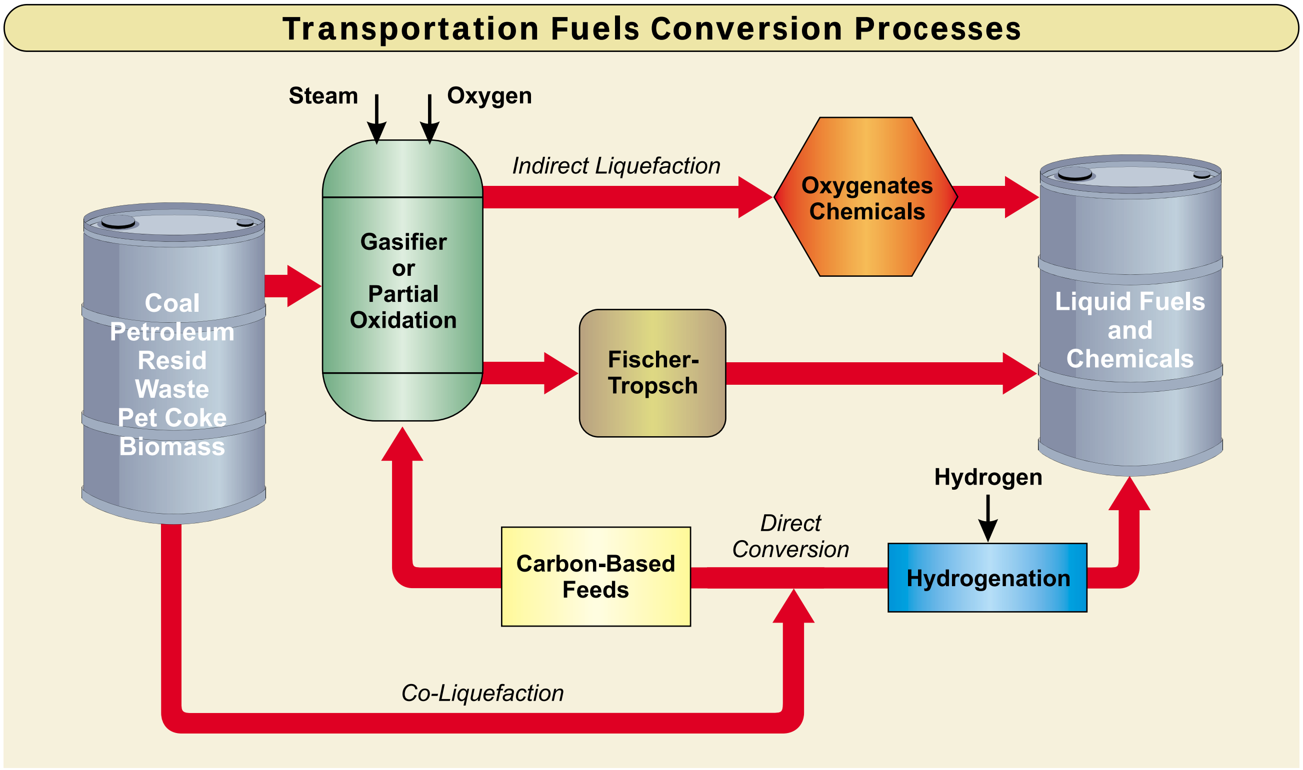
Proof-of-Concept Testing

Proof-of-Concept (POC) evaluations to produce Fischer-Tropsch and other premium, high performance fuels will provide optimum processing strategies and sufficient quantities of materials for engine and vehicle tests. All coal-fuels R&D, which culminates in POC activities and fuel testing, is focused on developing fuels that assist the transportation sector in meeting its future emission requirements. To this end, partnerships have been created with other federal organizations and their stakeholders to facilitate commercial deployment of these advanced, ultra-clean fuels.

Coproduction Integrated into a Power/Fuels/End-Use System




Transportation Fuels & Chemicals: The Program
LPMEOH™
Base Program Process Development
Catalyst
Reactor
Conversion Science/ Engineering
Gas Separation
Proof-of-Concept Testing
Product Testing/ Evaluation
Engine/Vehicle
Clean Coal Technology
IGCC and Transportation Fuels & Chemicals
Early Entrance Coproduction Plants
Petroleum Processing, Natural Gas Processing, Transportation Fuels & Chemicals, and EE-Office of Transportation Technologies
Ultra-Clean Fuels for the 21st Century


Transportation Fuels Conversion Processes
Steam
Oxygen
Indirect Liquefaction
Oxygenates Chemicals
Coal Petroleum Resid Waste Pet Coke Biomass
Gasifier or Partial Oxidation
Fischer-Tropsch
Liquid Fuels and Chemicals
Hydrogen
Direct Conversion
Carbon-Based Feeds
Hydrogenation
Co-Liquefaction

Novel R&D in Coal Conversion

Computation chemistry techniques will be used to more efficiently develop kinetic models of coal conversion processes, which will greatly reduce the laboratory R&D needed to effect process improvements. In addition, R&D will examine innovative hydrogen production technologies that have the potential to provide for both sequestration of CO_2 and significant reductions in manufacturing costs.

SOLID FUELS AND FEEDSTOCKS

The objectives of the Solid Fuels and Feedstocks program area are to: (1) develop and verify innovative processing, handling, and transportation technologies that would 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. These technologies would yield a wide range of products that are economically competitive with and result in less environmental impact than competing fuels or products.

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 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 and in combination with biomass, rubber, plastics, industrial residues, municipal solid wastes, and other solid wastes. Feedstocks are based on solid fuels that can be converted to high-value carbon-containing products.

Clean Coal Technology Program

Two Clean Coal Technology 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 (LFC®) process successfully completed operations 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 (PDF®) and more than 121,000 barrels of coal derived liquid (CDL®). 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

Rosebud SynCoal Partnership's Advanced Coal Conversion Process for upgrading low-rank subbituminous and lignite coals.

8-year contract to supply a high-energy-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 1999, the ACCP facility had processed over 2.3 million tons of raw coal to produce over 1.5 million tons of Syncoal®.

Environmental Solid Fuels

Research in this area is developing innovative methods for recovering useable fuels from materials that otherwise would be discarded at coal cleaning plants or utility power stations. Projects address the estimated 2 to 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, under development is a method for removing mercury from coal before it is burned, 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 proof-of-concept (POC)-scale testing of a selective agglomeration process that uses a new mixing device (tubular processor); pilot-scale testing of an electrostatic separation process for dry, fine-size coal; and POC-scale testing of an advanced flotation control system.

The Solid Fuels and Feedstocks Program investigates making premium carbon products from coal, such as high-quality graphite electrodes. (Courtesy of the Carbide/Graphite Group, Inc., Pittsburgh, PA.)

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 and cooperation with a broad-based, utility-sector consortium for coal utilization.

Tailored Carbon Feedstocks

Premium carbon feedstocks and products are being developed by an industry-led, cost-shared consortium that will develop, demonstrate, and commercialize technologies for non-fuel uses of coal, 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
- Materials for heat-resistant applications.

Advanced Fuels Research

The goal for the Advanced 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 objectives are 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.

Advanced Fuels Research encompasses research activities that develop fossil-resource technology for transportation fuels, chemicals, and carbon and industrial product markets. These technologies must not only provide increased energy security by using domestic resources in an environmentally benign manner, but they also must be consistent with global climate change strategy, which might require complete control of the carbon cycle. The research centers on developing, over the longer term, significantly improved and innovative technologies that produce economically competitive fuels with minimal environmental impact and with reduced by-product CO_2 production. Examples of such technologies include: (1) innovative, less severe, 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 increased environmental performance and with less CO_2; (3) computational methods to improve catalyst development and experimental evaluation; and (4) bioprocessing systems that produce liquid transportation fuels with less CO_2 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.

Program Success

Fuels Research at LaPorte, Texas Plant

As the research progresses in the base 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 fifteen 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.

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

Carbon Sequestration

Addressing Global Climate Change

INTRODUCTION

Fossil fuels will remain the mainstay of energy production well into the 21st century. Availability of these fuels to provide clean, affordable energy is essential for the prosperity and security of the United States. However, increased concentrations of carbon dioxide (CO_2) due to carbon emissions are expected unless energy systems reduce the carbon emissions to the atmosphere.

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 brings to the energy mix.

The President's Committee of Advisors on Science and Technology (PCAST) underscored the importance of carbon sequestration in its report "Federal Energy Research and Development for the Challenges of the Twenty First Century." PCAST recommended increasing the U.S. Department of Energy's (DOE's) R&D for carbon sequestration. Specifically, the report stated: " A much larger science-based CO_2 sequestration program should be developed. The aim should be to provide a science-based assessment of the prospects and costs of CO_2 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 joint Office of Fossil Energy and Office of Science April 1999 draft report "Carbon Sequestration: State of the Science" subsequently has assessed ". . . key areas for research and development (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."

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 U.S. trillions of dollars. Further, achieving a mid-point stabilization scenario (e.g., 550 ppm CO_2) 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.

PROGRAM AREAS

- **CO_2 Separation and Capture**
- **Sequestration of CO_2 in Geologic Formations**
- **Ocean Sequestration**
- **Carbon Sequestration in Terrestrial Ecosystems**
- **Advanced Concepts**
- **Modeling and Assessments**

The program portfolio covers the entire carbon sequestration "life cycle" of capture, separation, transportation, and storage or reuse, as well as research needs for the two other major energy related greenhouse gases of concern, methane (CH_4) and nitrous oxides (N_2O). Specifically, the program has six elements:

- Cost effective CO_2 capture and separation processes.
- CO_2 sequestration in geological formations including oil and gas reservoirs, unmineable coal seams, and deep saline reservoirs.
- Direct injection of CO_2 into the deep ocean and 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.

BENEFITS

CUSTOMER BENEFITS

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

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.
- Expands business opportunities for power producers by adding a commodity to the product slate.

NATIONAL BENEFITS

- Results in an estimated cumulative benefit to the U.S. economy of $2.7 trillion through 2050.
- Provides for energy security by enabling use of vast domestic coal resources, which are expected to provide 50 percent of the electricity produced well into the 21st century.
- Allows continued economic growth by stabilizing energy costs.

The Program

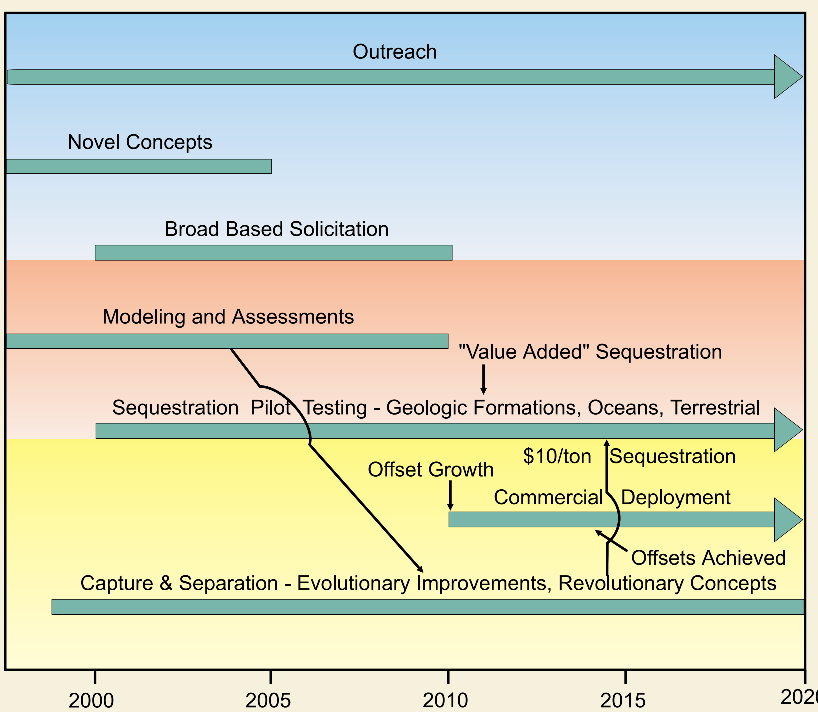
The program goal is to reduce by 2015 the cost of carbon sequestration to $10 or less per net ton of carbon emissions avoided. A program designed to achieve this goal encompasses R&D on a diverse portfolio of sequestration technologies. These technologies offer the best chance of success, both in reducing risks and ultimate cost to the nation, under a carbon constrained future. Since the 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. In collaboration with DOE's Office of Science, the report "Carbon Sequestration: State of the Science" identifies the five major areas of R&D needs that serve as the basis for the program. The significant industry participation essential for all phases of the program is achieved through workshops, advisory panels, competitive awards and cost shared partnerships. 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. For example, a competitive solicitation was issued in FY1998 and resulted in the selection of 12 innovative novel concepts for the control of atmospheric emissions of CO_2, methane and nitrous oxide. In May 1999 six of the most promising concepts were selected for further study.

Modeling and assessments provide the capabilities to evaluate technology options in a total systems context, considering costs and impacts over the full product cycle. Further, the societal and environmental effects are analyzed to provide a basis for assessing trade-offs between local environmental impacts and global impacts.

In the mid-term, sequestration pilot testing will develop options for direct and indirect sequestration. The direct options involve the capture of CO_2 at the power plant before it enters the atmosphere coupled with "value-added" sequestration, such as using CO_2 in enhanced oil recovery (EOR) operation and in methane production from deep unmineable coal seams. "Indirect" sequestration involves research on means of integrating fossil fuel production and use with terrestrial sequestration and enhanced ocean storage of carbon.

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.

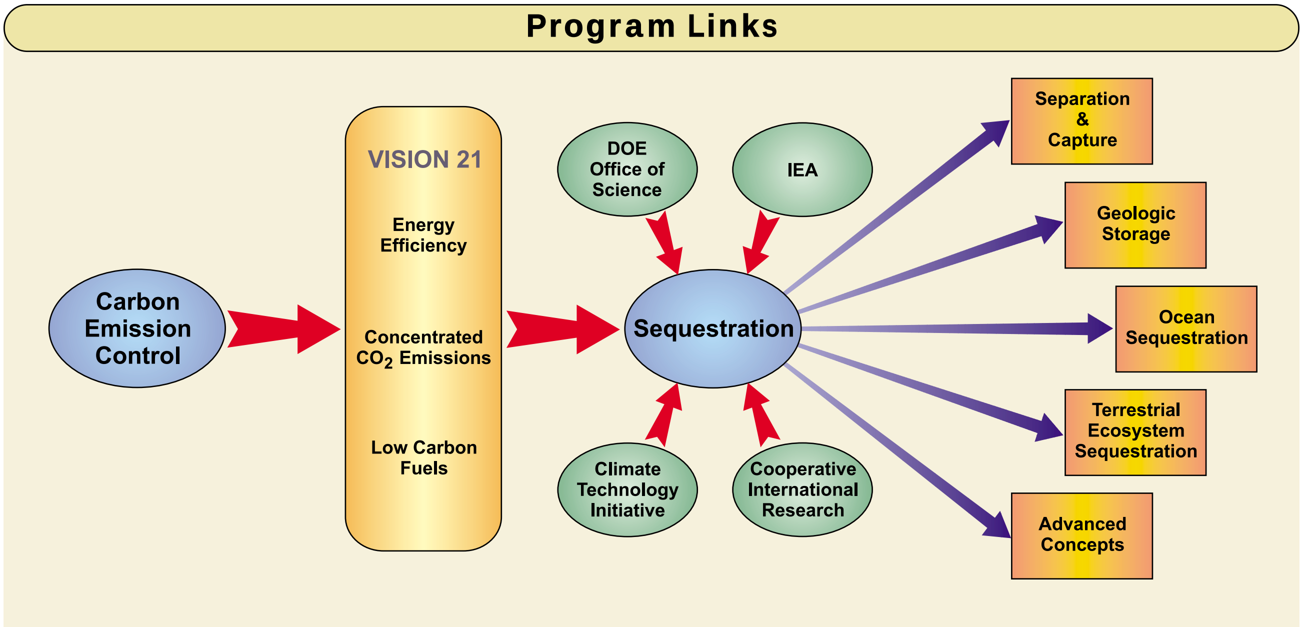
Roadmap



LINK TO VISION 21 AND OTHER PROGRAMS

The CO_2 Sequestration Program is one of three carbon emission control options being addressed under the Coal and Power System Program. The other two options: 1) improving the efficiency of energy use and 2) reduction of the carbon content of fuels are being addressed under the Central Power Systems, Distributed Generation and the Fuel Programs. Under the Vision 21 strategic concept, the systems and modules produce a relatively pure stream of CO_2 that is amenable to capture and sequestration. The development of advanced CO_2 separation technologies under the sequestration program will produce systems that are compatible with the process conditions envisioned for the Vision 21 advanced energy systems. Further, "value added" techniques such as the EOR technologies and coal bed methane extraction are being pursued under Fossil Energy's Oil and Gas RD&D programs.

Moreover, the program supports collaborative efforts with other DOE organizations such as the Office of Science. Continual collaborative activities and workshops are essential to keep all stakeholder groups — industry, end-user, non-profit organizations, academia, national laboratories, the environmental community, and governments — appraised of new developments and to maintain dialogue on the merits of carbon sequestration. International collaboration also is key to developing technology options for mitigating global emissions of greenhouse gases. Program interactions include work with international research groups such as the International Energy Agency (IEA) Greenhouse Gas R&D Programme, and the Climate Technology Initiative (CTI) of the Framework Convention on Climate Change (FCCC). Significant cost sharing and technology transfer to the U.S. are possible through international agreements. These agreements include: cooperative research among the U.S., Japan, and Norway on deep ocean storage of CO_2; and the U.S. and Canadian project on CO_2 sequestration in deep, unmineable coal seams accompanied by coal bed methane production.



DRIVERS

- Availability of clean affordable energy is essential for the prosperity and security of the U.S. and the World in the 21st century.
- 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 and environmental limits on nuclear and renewable alternatives.
- Emissions of CO_2 into the atmosphere is inherent to the use of fossil energy resources for electricity generation, transportation, industrial heat and power and building systems.
- Increased concentrations of CO_2 in the atmosphere due to carbon emissions are expected unless energy systems reduce the 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.
- While much uncertainty is associated with the relationship between CO_2 emissions from energy systems and other human activity and climate change, it is possible that deep cuts in CO_2 emissions will be required over the next 50 to 100 years.

GOALS

- 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.
- 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 CO_2, beginning in 2025.

Strategies

- Pursue evolutionary improvements in existing CO_2 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 CO_2 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 CO_2.
- 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 CO_2 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 — appraised of new developments and maintain an open dialogue on the merits of carbon sequestration.

Measures of Success

- 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 CO_2 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.

Program Areas

Carbon Sequestration Targets

Offsets in growth of greenhouse gases:
— Technologies by 2015
— 1/2 required reduction by 2015

Cost: $10/ton avoided cost

Based on the report "Carbon Sequestration: State of the Science", the R&D activities are structured around five basic pathways to long-term carbon sequestration.

- Separation and capture,
- Sequestration of CO_2 in geologic formations,
- Ocean sequestration,
- Carbon sequestration in terrestrial ecosystems (soils and vegetation), and
- Advanced concepts (chemical, biological and other approaches).

These five pathways are supported by the modeling and assessments program activity.

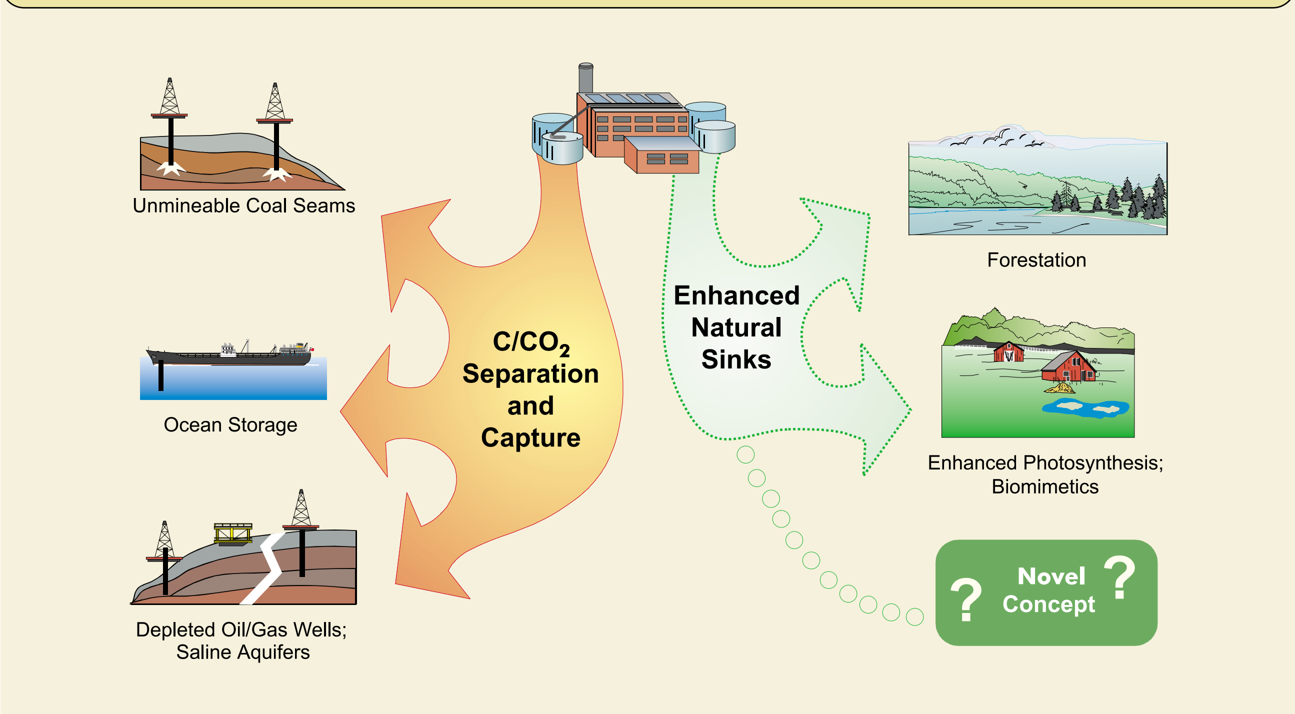
Separation and Capture

Before CO_2 gas can be sequestered from point sources, it must be captured as a relatively pure gas. CO_2 is routinely separated and captured as a by-product from industrial processes such as synthetic ammonia production, H_2 production, and limestone calcination. However, existing capture technologies are not cost-effective when considered in the context of CO_2 sequestration. Carbon dioxide capture is generally estimated to represent three-fourths of the total cost of a carbon capture, storage, transport, and sequestration system. The program area will pursue evolutionary improvements in existing CO_2 capture systems and also explore revolutionary new capture and sequestration concepts. The most likely options currently identifiable for CO_2 separation and capture include the following:

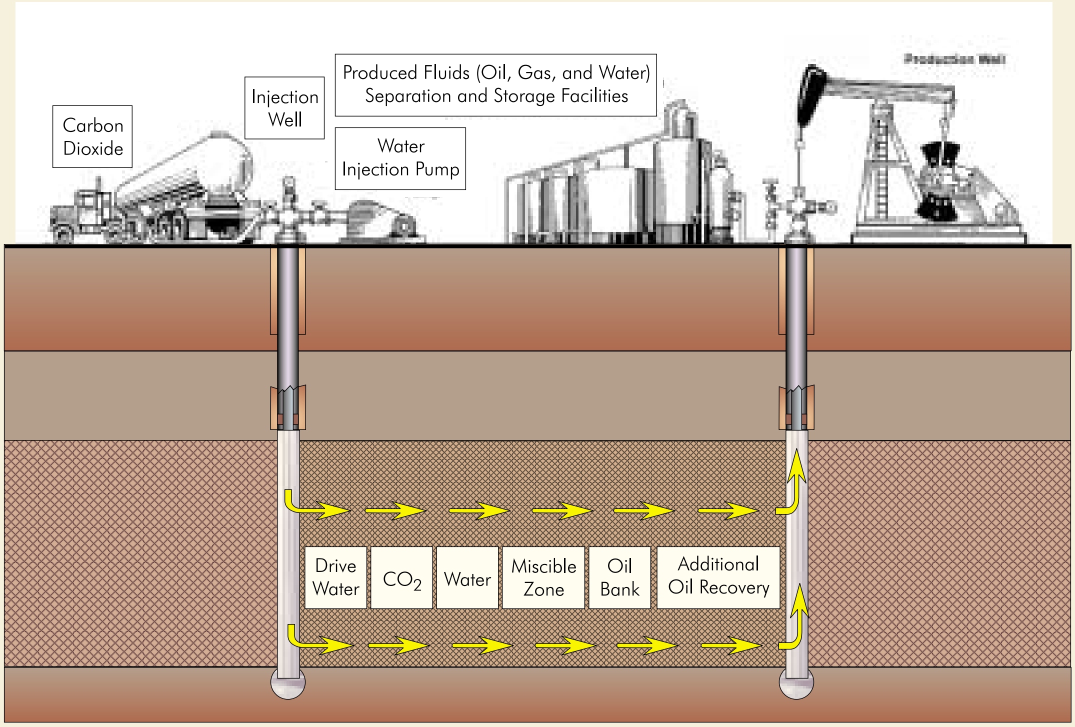
- Absorption (chemical and physical)
- Adsorption (physical and chemical)
- Low-temperature distillation
- Gas separation membranes
- Mineralization and biomineralization

Opportunities for significant cost reductions exist since very little R&D has been devoted to CO_2 capture and separation technologies. Several innovative schemes have been proposed that could significantly reduce CO_2 capture costs, compared to conventional processes. "One box" concepts that combine CO_2 capture with deduction of criteria-pollutant emissions are concepts to be explored.

Sequestration Sinks



EOR Application



Sequestration of CO_2 in Geologic Formations

CO_2 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 CO_2 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 CO_2 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 revenues from recovered oil/gas. In an EOR application, the integrity of the CO_2 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 CO_2 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) is to depressurize the bed, usually by pumping water out of the reservoir. An alternative approach is to inject carbon dioxide gas into the bed. Tests have shown that CO_2 is roughly twice as adsorbing on coal as methane, giving it the potential to efficiently displace methane and remain sequestered in the bed. CO_2 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 CO_2 sequestration in coal beds is that many of the large unmineable coal seams are near electricity-generation facilities that are large point sources of CO_2 gas. Thus, limited pipeline transport of CO_2 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 CO_2 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 United States is large, making them a viable long-term solution. It has been estimated that deep saline formations in the United States could potentially store up to 500 billion tonnes of CO_2 . Second, most existing large CO_2 point sources are within easy access to a saline formation injection point, and therefore sequestration in saline formations is compatible with a strategy of transforming 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 CO_2 storage in saline formations is a key component of this program element. Determining that CO_2 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 CO_2 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 tonnes per year of recovered CO_2 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 CO_2 geological sequestration facility in the world.

Ocean Sequestration

CO_2 is soluble in ocean water, and through natural processes the oceans both absorb and emit huge amounts of CO_2 into the atmosphere.

It is widely believed that the oceans will eventually absorb most of the CO_2 in the atmosphere above the pre-industrial level of 288 ppm. However, the kinetics of ocean uptake are unacceptably slow, causing a peak in atmospheric CO_2 concentration of several hundred years. The program will explore options for speeding up the natural processes by which the oceans absorb CO_2 and for injecting CO_2 directly into the deep ocean.

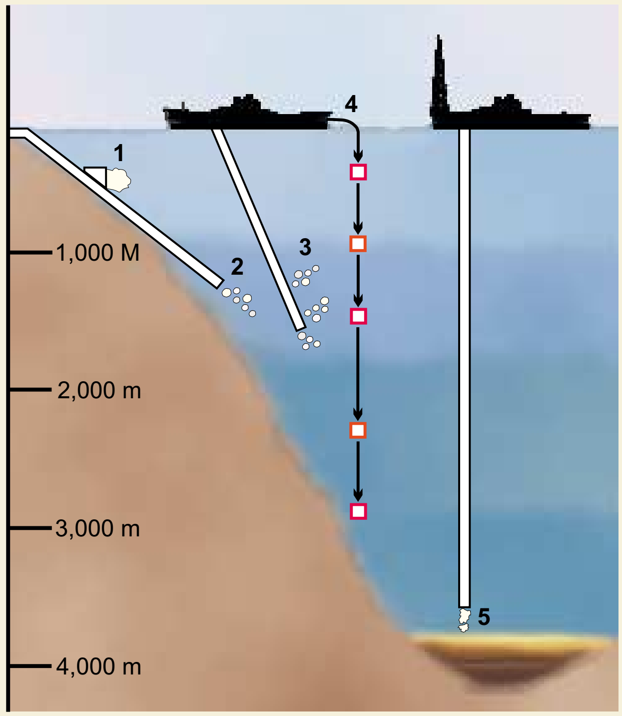
One approach to enhancing the rate of CO_2 absorption in the ocean involves adding combinations of micronutrients and macronutrients to those ocean surface waters deficient in such nutrients. The objective is to stimulate the growth of phytoplankton, which are expected to consume greater amounts of carbon dioxide. When carbon is thus removed from the ocean surface waters, it is ultimately replaced by CO_2 drawn from the atmosphere. The extent to which the carbon from this increased biological activity is sequestered is unknown at this point.

Technology exists for the direct injection of CO_2 into deep areas of the ocean; however, the knowledge 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 CO_2 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 CO_2 on the pH of ocean water.

Carbon Sequestration in Terrestrial Ecosystems (soils and vegetation)

Enhancing the natural processes that remove CO_2 from the atmosphere is thought to be one of the most cost-effective means of reducing atmospheric levels of CO_2, and forestation and deforestation abatement efforts are already under way. 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. This program area is

Ocean Disposal of CO_2



Dissolution
1 — Dense Plume
2 — Droplet Plume

Dispersion
3 — Towed Pipe
4 — Dry Ice

Isolation
5 — CO_2 Lake

being conducted in collaboration with the DOE Office of Science, and the U.S. Forest Service of the U.S. Department of Agriculture.

Advanced Concepts (Chemical, Biological, and Other Approaches)

Recycling or reuse of CO_2 from energy systems would be an attractive alternative to storage of CO_2. The goal of this program area is to reduce the cost and energy required to chemically and/or biologically convert CO_2 into either commercial products that are inert and long-lived or stable solid compounds.

Two promising chemical pathways are magnesium carbonate and CO_2 clathrate, an ice-like material. Both provide quantum increases in volume density compared to gaseous CO_2. 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 CO_2 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 CO_2 and do not incur costs for separation, capture, and compression of CO_2 gas. This program area will seek to develop novel and advanced concepts for capture, reuse, and storage of CO_2 from energy production and utilization systems based on, but not limited to:

- Biological systems
- Advanced catalysts for CO_2 or CO conversion
- Novel solvents, sorbents, membranes and thin films for gas separation
- Engineered photosynthesis systems
- Non-photosynthetic mechanisms for CO_2 fixation (methanogenesis and acetogenesis)
- Ways for genetic manipulation of agricultural and trees to enhance CO_2 sequestering potential
- Advanced decarbonization systems Biomimetic systems

Modeling and Assessments

Better assessments of the costs, risks, and the potential of carbon sequestration technology are essential to develop technological options for greenhouse gas mitigation. Sound assessment capabilities are required to evaluate technological option 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.

EMERGING CONCEPTS

In May 1999, DOE selected six promising concepts for further study from a group of 12 projects competitively selected the previous year. Drawn from 62 proposals, the 12 projects subsequently underwent preliminary feasibility studies.

The six selected projects were extended for 22 months with additional federal funding, permitting larger scale experimentation and more extensive technical and economic assessments. At the end of this second phase, DOE plans to select projects for a final 30-month phase designed to prove engineering feasibility, which will include a pilot- and large-scale testing program.

The six projects chosen by DOE to enter a second phase of development are:

- **Battelle Memorial Institute, Columbus, Ohio**, to evaluate geologic and geochemical processes that could be used to sequester carbon dioxide into deep aquifers that have no known use;
- **Institute for Environmental Management Inc., Palo Alto, California**, working with the California Energy Commission and Yolo County, California, to demonstrate a way to capture methane, a very potent greenhouse gas, from landfills;
- **McDermott Technologies Inc., Alliance, Ohio**, to examine the potential for large-scale carbon dioxide transportation and deep-ocean sequestration;
- **Research Triangle Institute, Research Triangle Park, North Carolina**, to develop an inorganic, palladium-based membrane that would separate hydrogen and concentrated carbon dioxide from hydrocarbon fuels;
- **TDA Research Inc., Wheat Ridge, Colorado**, to study a novel carbon dioxide separation system for a power plant that uses iron- and copper-based sorbents;
- **University of Texas at Austin, Austin, Texas**, to identify optimal saline water-bearing formations in the U.S. for carbon dioxide disposal.

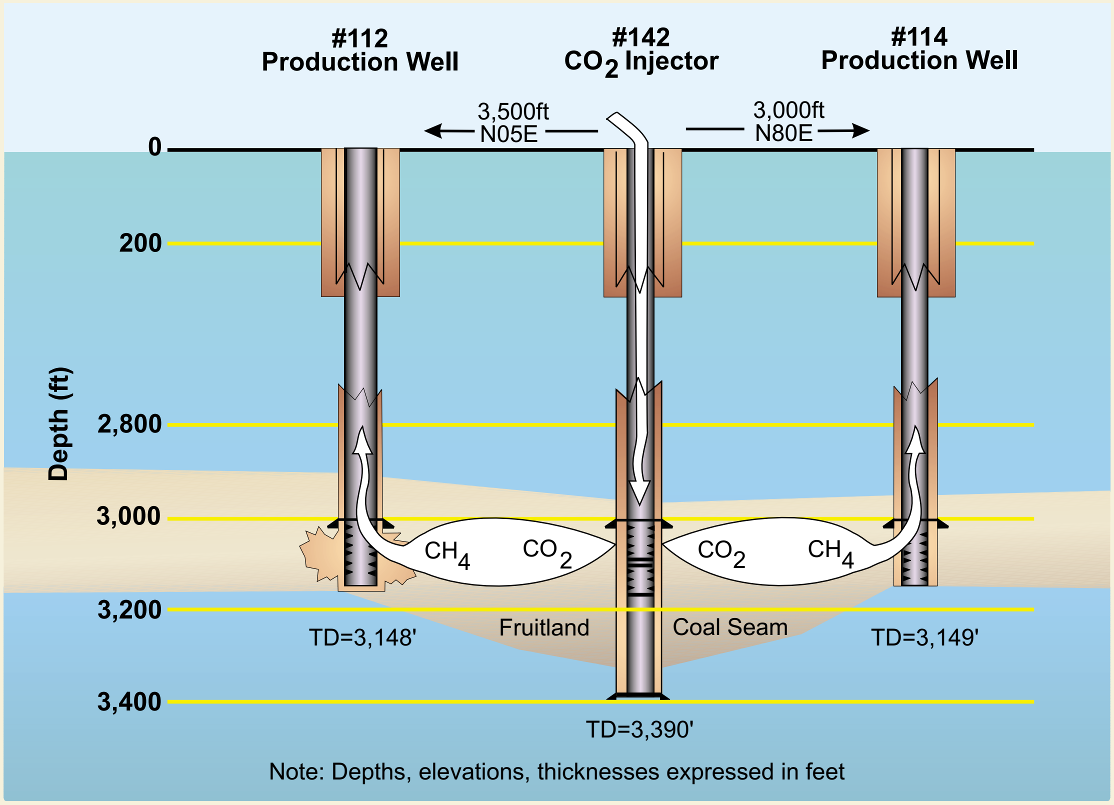
Program Success

Coal Seam Formations

In the United States, estimated coal resources to a depth of 6,000 feet total nearly six trillion tons. Some 90 percent of this amount is considered economically unminable with current technology as either too thin, too deep, or unsafe. These unavailable coal deposits represent a widely dispersed potential option for CO_2 storage, with many of the coals potentially producing methane for commercial use.

For the past 25 years, DOE and its predecessor agencies have been facilitating the evolving recognition and development of coalbed methane resources and technologies. The concept of using injected CO_2 to enhance coalbed methane production is already being field-tested by industry. Much of the data gathered from these tests is proprietary; however, unpublished information supports the retention of the CO_2 in coalbeds. Since 1996, Burlington Resources, a major producer of coalbed methane, has conducted a commercial pilot test for CO_2 injection to enhance coalbed methane recovery. As a spin-off, the pilot sequesters CO_2 as part of its routine operation. Burlington's pilot is located within the northern San Juan basin, in New Mexico, which is the most successful coalbed methane development in the world.

Burlington's Allison Unit



Source: Advanced Resources International

A depiction of a Vision 21 plant and its components as integrated into an existing urban context (namely Roosevelt Island in New York City). Within this plant construct, emissions of carbon dioxide would be dramatically reduced because of higher plant efficiencies. The plant design would also include the option for capturing and sequestering carbon dioxide. Thus, the plant could produce zero emissions — essentially decoupling the use of carbon-based fuels from the production of greenhouse gases.

Advanced Research

Opening New Frontiers in Power

Introduction

The Advanced Research Program supports Vision 21 and is an integral part of the Central Systems, Distributed Generation, and CO_2 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.

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 United States and abroad. Improvement of the energy infrastructure, which includes 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 systems, and coal-based fuel systems with greatly reduced or no net emissions of CO_2. This second set of activities addresses the full spectrum of fossil utilization research and development, technology transfer, outreach, and private sector partnerships.

The Advanced Research Program is charged with coordinating and directing research that will lead the technological developments of the C&PS program. This is accomplished by identifying and nurturing innovative concepts, and with the aid of the basic research community, advancing the technology to achieve FE's program goals. The Advanced Research Program facilitates the transition of research to the appropriate program areas for development and marketing. With the export of U.S. coal and power systems technology abroad, the Advanced Research Program promotes the national goals of energy and environmental security, and increases the opportunity for U.S. technology use in the global marketplace.

Program Areas

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

Benefits

Customer Benefits

- Ensures continued economic well-being for U.S. citizens by reducing energy costs resulting from advanced technologies.
- Improves the U.S. economy and increases the number of high-skill jobs for Americans by increasing international technology export.

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.
- Enables the production of advanced, high-efficiency power systems that better utilize domestic fossil fuel resources through development of advanced coal research.

National Benefits

- Provides Americans with a dependable domestic source of power by maintaining coal as the primary source of energy for electricity production.
- Mitigates the global environmental impact of the increased fossil fuel use by overcoming the obstacles to using clean fossil-powered systems.
- 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.

Drivers

- Climate change initiatives will likely require serious 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.
- With deregulation, the utility industry is consolidating and keeping older plants on line to remain economically competitive. The question of how this will affect availability, reliability of electric supply, and the deployment of advanced technologies will probably remain unanswered for some time.
- The existing stock of US 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 deamnd due to population and economic growth.
- 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.
- 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, it could be the fuel of choice of electric utilities and independent power producers to satisfy future electric demand.
- U.S. dependence on imported oil and gas continues to grow. By 2015, imported oil is expected to amount to 61% of consumption, and imports of gas to 14% of consumption.

Goals

- Overall, to deliver the scientific understanding and technological innovations that are critical to the success of C&PS programs as well as FE and DOE missions.
- Leverage research opportunities through science partnerships and pursue international science collaborations.
- Generate fundamentally-based 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 having no negative inpact on the environment.
- Promote strong relationships between DOE and the academic community through research activities directed toward advancements in advanced power systems.
- Support Fossil Energy in developing collaborative technical activities with international performers in the coal and advanced power system area.

Strategies

Vision 21 is the guiding principle that defines the activities of the Advanced Research program by setting priorities for the next century. Many elements of what must be contained in the Vision 21 concept already exist and are part of the C&PS technology portfolio. Some of the strategies for achieving Vision 21 through the Advanced Research Program include:

- Identify next generation of advanced fuel and power systems that can operate at greater efficiencies and at an economic cost that is lower than for the present state-of-the art.
- Support the research necessary to graduate new technologies to the development stage.
- Initiate research that is likely to lead to entirely new technology areas.
- Provide sustained support to fund high-risk work in anticipation of technological advances or as key experiments that facilitate development of breakthrough technologies.
- Develop an effective Center of Excellence for Advanced Research at NETL.
- Search opportunities for power systems in targeted countries.

Measures of Success

- Make available high-temperature corrosive, erosive-resistant materials to increase the durability and extend the operating envelope of advanced power systems.
- Facilitate both new international market entries and expansion in existing markets for U.S. energy-related technologies, services, and energy resources.
- Award approximately 20 research grants annually to provide the fundamental research and novel approaches to successfully develop advanced power systems and clean fuels for transportation.
- Explore novel aspects of fuels and their production from coal and other energy resources in combination with coal.

Link to Vision 21

The Vision 21 concept defines the activities of FE's Advanced Research Program by setting priorities for the 21st century. The research thrusts of FE's Advanced Research activities 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 criteria pollutants, and with sequestration, having no net emissions of CO_2. 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, a 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 FE Advanced Research Program. Though not meant to be an exhaustive list of critical research needs to achieve Vision 21, these needs include:

- Lower-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
- Approaches to effectively capture and sequester CO_2

The Advanced Research Program is directly related to the other programs within C&PS. Advanced Research is key to innovation and progression in its commercial program areas because it: (1) supports the research necessary to graduate new technologies to the development stage, and (2) initiates 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.

Vision 21 energy plant of the future.

Center of Excellence for Advanced Research – Energy Plants of the Future
(Computational Energy Science)

Strategy

Conduct computational research on advanced energy plants to provide:

- Insight into the complex interaction of physical and chemical systems involved.
- Direction to experimental research that addresses key technical barriers.

Activities

- Modeling sub-elements in energy conversion devices.
- Combining sub-element models to describe the steady state operation and dynamics of a complete energy conversion device.
- Integrating devices into a model of an overall energy plant.
- Developing a manufacturing model to aid in commercialization of materials and devices produced from the research.

Benefits

- More rapid and efficient scale-up of new processes.
- Reduced need for large, expensive experimental units.
- Reduced operational risks at commercialization.
- Experiments and tests conducted for model validation.

Program Areas

Materials and Advanced Metallurgical Research

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 advanced fossil energy systems. 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. The program area funds exploratory research designed to develop new materials that have the potential to improve the performance or reduce the cost of existing fossil fuel technologies. Also funded is the development of materials for new systems and capabilities.

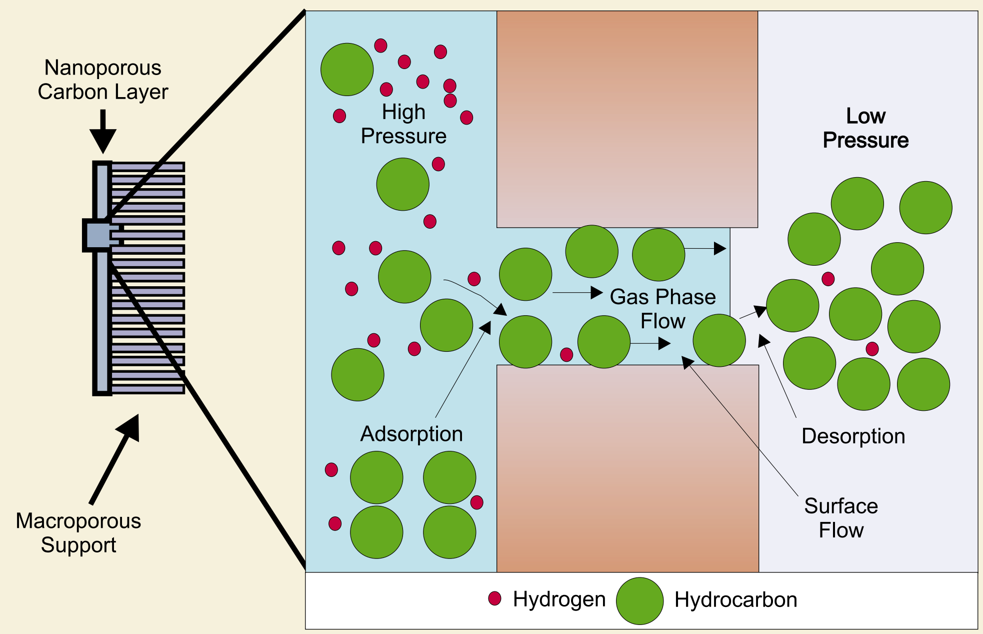
New materials and components are being developed under the Materials and Advanced Metallurgical Research program area to address the special needs of Vision 21. The ceramic materials required for novel membrane applications (including low-cost oxygen separation and hydrogen separation) and special alloys 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 this program area. FE's materials research program area includes the Advanced Research Materials Program at Oak Ridge National Laboratory and the Advanced Metallurgical Research Program at Albany, Oregon, as well as related activities within the Office of Science and Technology at NETL.

Bioprocessing

This program area sponsors research into the biology, biochemistry, microbiology, and bioengineering technologies. Activities are focused on developing the bioprocesses capable of fostering innovative uses for coal and its by-products, developing alternative fuels, identifying biomass sources of 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. An example of current projects in bioprocessing include investigation of marine mechanisms of CO_2 sequestration, and sequestration effects on marine ecology to further the sequestration goals of Vision 21.

Selective Flow Membranes



Strength Through Science

The following state-of-the-art virtual demonstration capabilities being performed by the Advanced Research Program strengthen the scientific base of design and demonstration tools.

3-D Visualization. 3-D solid model, compatible with 2-D drawing, allowing interactive Virtual Reality (Semi-immersive or Immersive).

Information System. 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 System. Internet capabilities will allow collaboration between a geographically separated work team.

CAD/CAE. Will provide engineering drawings (schematic diagrams, P&IDs, loop diagrams, termination drawing, structural) to generate reports with total integrity with 3-D model.

Process Simulation. Process optimization, economic valuation, component sizing, sensitivity analysis are integrated with visualization, CAD, and other components of the virtual demo, utilizing a unit operations library physical properties database.

Control Systems. Tightly coupled Vision 21 systems will require sophisticated transients control strategies for normal operation, load following, start up/shut down, and safety.

Mechanistic Modeling. Models are physics-based. Included are Computational Fluid Dynamics (including single/multi-phase, heat transfer, chemical reactions, radiation), Finite Element Structural simulation, material simulation, and event-based simulation.

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 (CUS) program area.

This program area supports research that develops technologies for clean, efficient power generation from coal and other fossil fuels. Experimental research and theoretical investigations are conducted to address technological barriers, and novel processes are developed to overcome the barriers.

The CUS program area continues to be heavily involved in modeling efforts, and is developing advanced designs and visualization software necessary to design, evaluate, and optimize the performance of next generation power systems. Research activities are integrated among industry alliances, National laboratories, and the university community including (1) advanced concept and system studies of an analytical, computational or experimental nature for testing novel concepts or evaluating promising power systems components, configurations or integrated issues; (2) visualization capability that utilizes immersive, interactive, and distributed visualization technology in the design of next generation power plants; (3) mechanistic model development of versatile, reliable models, based on the fundamental laws of science for the performance of power production processes; and (4) the development of system tools for integrated use of information technology in power plant design.

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

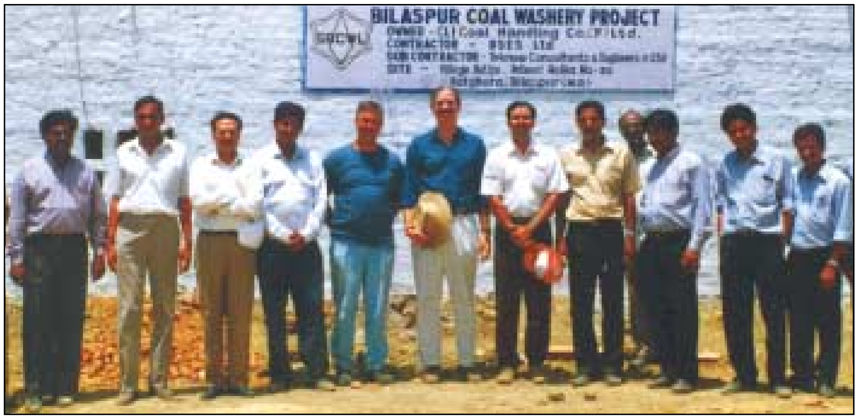
This program area was established to provide a mechanism for cooperative research between historically black institutions and other minority institutions with U.S. industries and federal agencies. This program area strives to support the education of scientists and engineers, and sponsors research in support of the Office of Fossil Energy's product lines. The Historically Black Colleges and Universities/Other Minority Institutions program area has emphasized improving the environmental compatibilities of advanced coal, oil, gas, and environmental technology concepts.

Small Business Innovation Research/Small Business Technology Transfer

Small businesses have historically played a key role in introducing revolutionary innovations which have lead to competitive advantages in world markets. FE's Small Business Innovation Research/ Small Business Technology Transfer program area makes competitive grants to small businesses for fossil-related technology research projects that interest small businesses while advancing the mission of FE. Research supports FE goals of obtaining clean fuels and energy from fossil resources.

International/Coal Technology Export

Worldwide, the demand for power is increasing exponentially. The foreign market for electric power systems has been estimated at nearly $180 billion by 2030. 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 Bilaspur Coal Washery Project in the state of Madhya Pradesh is India's first private commercial coal washery for electric power generation.

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 Commission for Europe Clean Coal Technology Initiative, and the World Energy Council.
- ***Maximize export opportunities.*** The U.S. is the world leader in the development of clean fossil-powered technologies. The International program area works to ensure that U.S. 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 pursuing export opportunities. Such barriers include 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 international border systems. FE 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-power systems, bilateral efforts are ongoing in seven regions: Africa, Eastern Europe, the Pacific Rim, Russia and the Newly Independent States, South Asia and Near East, Western Europe, and 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.

Program Successes

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 iron aluminide alloy. The application of this alloy as a filter 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 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, the 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, with about $15 million of the total brought to NETL for direct implementation.

One of the 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% ash in the 2.5-million-ton-per-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.

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.