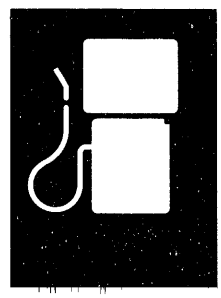
Advanced Fuel Systems

Development of systems that can produce coal-derived transportation fuels, chemicals, and other products, at costs competitive with oil-derived products, is an important part of the clean coal technologies RD&D program. Several different approaches have been undertaken to provide a diversity of products and to enable the integration of coal-based fuels into the U.S. fuel supply and distribution system.

Direct Liquefaction is the catalytic conversion of coal into light hydrocarbon liquids, by reaction with hydrogen at elevated temperatures and pressures in the presence of a coal-based hydroaromatic solvent. The resulting "synthetic crude oil" can be processed into transportation fuels and chemicals using the existing petroleum-refining infrastructure.

The Direct Coal Liquefaction Systems program focuses on the development of advanced processes for the production of coal-derived liquids at high conversion efficiency, with superior environmental performance, and at low capital and operating costs. The objective is to develop systems that can produce liquid transportation fuels and chemicals from coal at a cost competitive with that of equivalent petroleum-derived products.



Direct Liquefaction RD&D Program Description

The Direct Coal Liquefaction Systems program is a time-phased research and development effort to develop cost-effective and environmentally acceptable technologies for the production of transportation fuels from coal.

The Direct Coal Liquefaction Process

Direct liquefaction converts coal directly to distillate liquids in a single step without going through an intermediate gaseous state as does indirect liquefaction. As a result, the process has a relatively high thermal efficiency of between 60 and 70 percent, and a high product yield.

Direct liquefaction breaks the large, complex components of coal into smaller compounds that form liquids with properties similar to petroleum. Hydrogen is added to the coal during liquefaction, raising the hydrogen-to-carbon ratio of the coal-based liquids to a level comparable to petroleum products.

Environmental requirements are met by existing proof-of-concept (POC) systems, which produce distillates that have a lower sulfur and mineral content than petroleum does. The liquids produced can be upgraded using conventional petroleum-refining technologies to produce gasoline, diesel fuel, jet fuel, and other liquid transportation fuels, along with by-product chemicals. The gasoline derived from coal is comparable to petroleum-based gasoline, and meets the aromatic content limits of the Clean Air Act Amendments of 1990. Although products from this technology meet current fuel specifications, additional work is needed to improve the economics of producing and refining coal liquids.

Program Elements

The Direct Liquefaction program covers all aspects of technology development, from basic and exploratory research, through a 3-tons-per-day POC unit. In all, the program has five elements. The three research and development program elements are:

- Catalytic two-stage liquefaction process development.
- Coal/Oil coprocessing process development.
- Advanced liquefaction concepts process development.

The two additional demonstration-related program elements are:

- POC-scale demonstration.
- Commercial-scale demonstration.

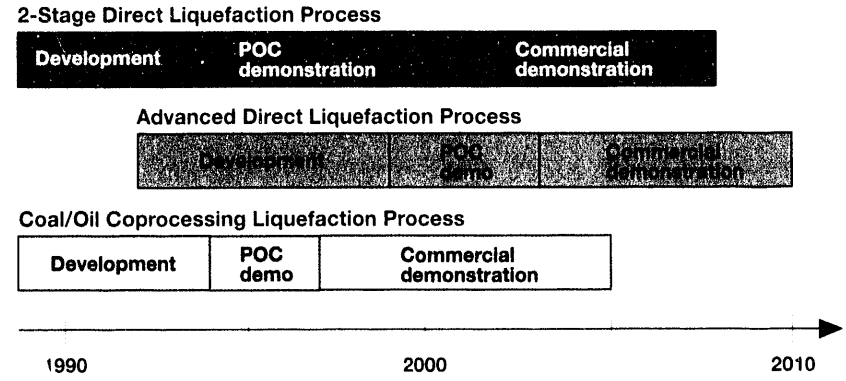
The process development program elements involve small-scale research and development, plus engineering, economic, and environmental analyses. POC demonstrations will take place at the 3-tons-per-day scale, and subsequent demonstrations will take place at a commercial scale.

In addition to these five program elements, the Direct Liquefaction program is also supported by cross-cutting activities in a number of other areas. These include:

- Fuels Base Research
- Coal Preparation
- Hydrogen/Synthesis Gas production
- Waste Management

The Direct Liquefaction program focuses on process improvements required for making this technology cost-competitive with petroleum-based fuels technologies. The goal is to develop coal-based technologies, by the next decade, that can provide an all-distillate product slate at a cost of $25 per barrel.

Development Cycle

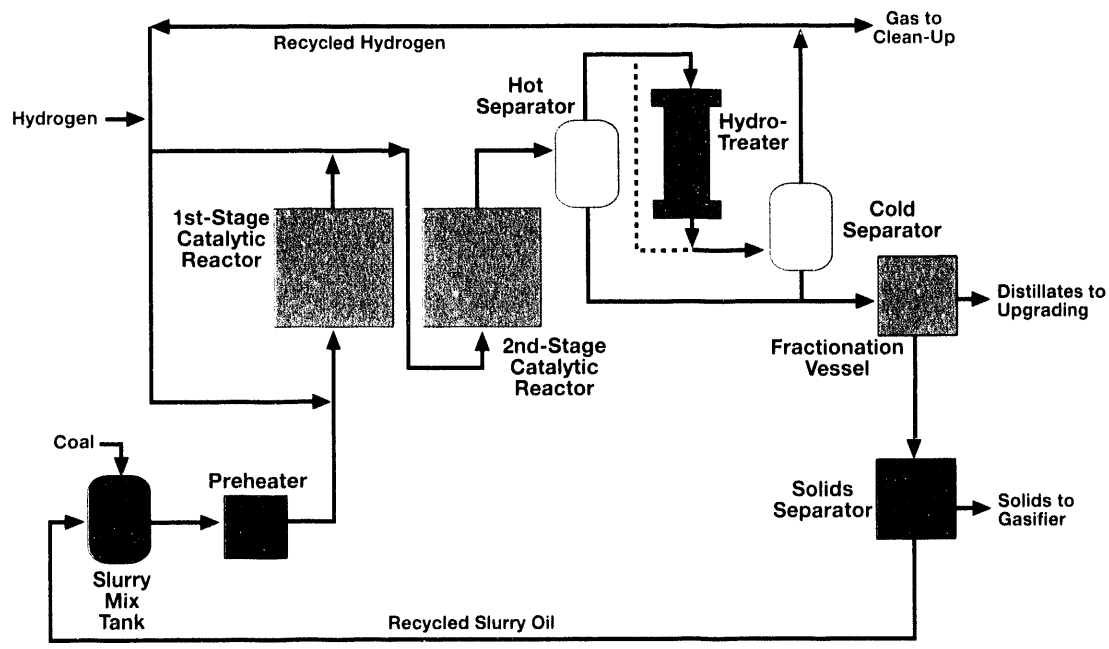


➤ Direct liquefaction processes for production of liquid fuels from coal are currently under development, and may be ready for commercial-scale demonstrations in the next decade. Development comprises R&D efforts at laboratory-, bench-, and POC-levels.

RD&D Program Goals

Direct Liquefaction Systems	Baseline Process	Advanced Process
[illegible]	$33	$25
[illegible]	3.5 - 4.0	4.0 - 4.5
[illegible]	benign	benign

System Components



▲ Direct liquefaction breaks the large, complex molecules of coal into liquids with properties similar to petroleum. In this process, the coal is first slurried with coal-derived oil, preheated, then passed through two ebullating-bed reactors, both operated at high temperatures and pressures, and both containing catalyst pellets suspended in a hydrogen/slurry stream. Hydrogen is added to the coal during liquefaction to raise the hydrogen-to-carbon ratio of the coal-based liquids to a level comparable to petroleum products.

Direct Liquefaction Program Activities

There are three major areas of interrelated, sequenced direct liquefaction RD&D activity: catalytic two-stage liquefaction, coprocessing, and advanced liquefaction concepts. Each of these research areas is evaluated and controlled through the POC demonstration stage by additional engineering, economic, and environmental analyses that provide guidance for further research and process integration. The objective of these analyses is to determine optimum design configurations, process conditions, and product slates, to meet the program's economic and environmental goals. Projects which are technically successful are screened through an economic evaluation prior to scale-up to the next level of R&D, to ensure their benefits to the overall plant design.

Catalytic Two-Stage Liquefaction Process Development

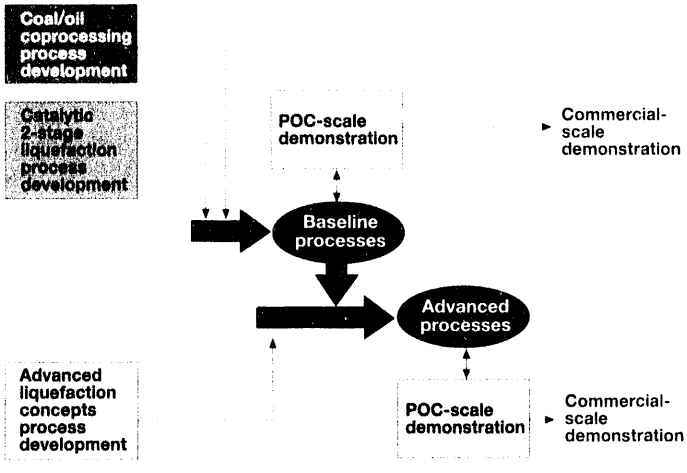
One of the principal focuses of the Direct Liquefaction program is the development of the catalytic two-stage liquefaction process. The products of this two-stage process are refinery-compatible distillates, which can be further processed, using normal refining procedures, into a variety of transportation fuels.

Activities in this program element include laboratory- and bench-scale R&D aimed at demonstrating optimal ebullating-bed reactor system performance for bituminous and subbituminous coals. The major components of this effort are testing commercially available supported catalysts, developing scale-up data for a commercial design, demonstrating improved hydrogen utilization, and verifying improved process conditions and configurations developed during bench-scale research.

Coal/Oil Coprocessing Process Development

Coprocessing involves the simultaneous conversion of coal and a heavy petroleum residuum, and is likely to account for the first production of coal-based transportation fuels in existing petroleum refineries. Activities in this program element include the optimization of reactor and process configurations, single-stage and two-stage processing, enlargement of a feedstock compatibility database, and further definition of process operations.

Program Elements Interaction



◄ Many elements are needed to bring about the early commercialization of two-stage direct coal liquefaction technology, and coal/oil coprocessing is likely to introduce coal earliest into refineries. Advanced research in crosscutting technologies is crucial to early commercialization of direct liquefaction technology. POC-scale testing confirms laboratory- and bench-scale developments, and provides design data for a commercial-scale demonstration, which is expected to follow closely.

Advanced Liquefaction Concepts Process Development

This third element focuses on the improvement of liquefaction technology through novel concepts and catalysts that have the potential to increase process efficiency and selectivity. Liquefaction chemistry is a subelement of this activity. To further the identification and development of new process concepts, five contractors were chosen in 1991 to pursue laboratory-scale research. The most promising concepts will be tested at the bench-scale level, and further verification will then be conducted at POC-scale.

Other crosscutting research activities related to advanced liquefaction concepts include preconversion processing to improve coal reactivity and hydrogen utilization, improved oxygen and mineral removal to reduce regressive reactions, coal cleaning to improve liquid yields and process operation, and bottoms processing to determine efficient ways to remove mineral matter and unreacted coal.

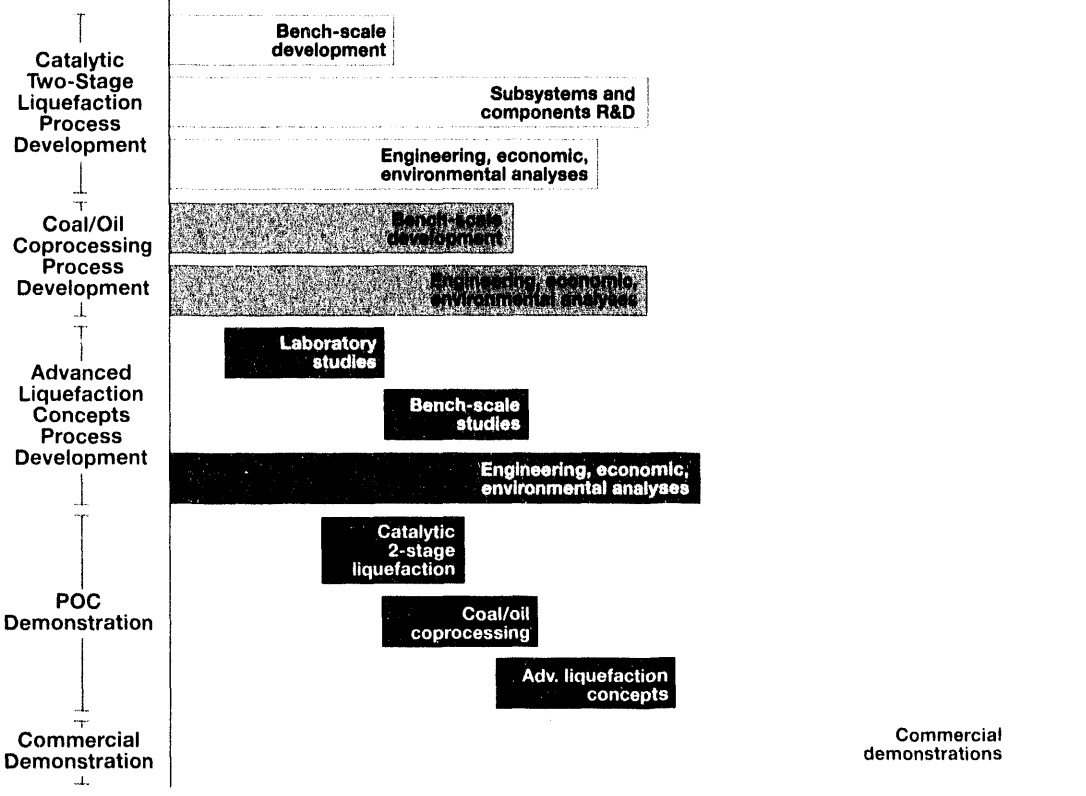
Proof-of-Concept Demonstration

At the Process Development Unit (PDU) facility in Lawrenceville, New Jersey, the two-stage ebullating-bed reactor system will be used to conduct POC testing to improve the economics of the most promising developments of the three process development program elements: catalytic two-stage liquefaction, coal/oil coprocessing, and advanced liquefaction concepts. The 3-tons-per-day facility has the flexibility to test improved configurations and equipment on a larger scale, in order to demonstrate operability, create products for upgrading and end-use studies, and provide engineering data for commercial scale-up design.

Commercial-Scale Demonstration

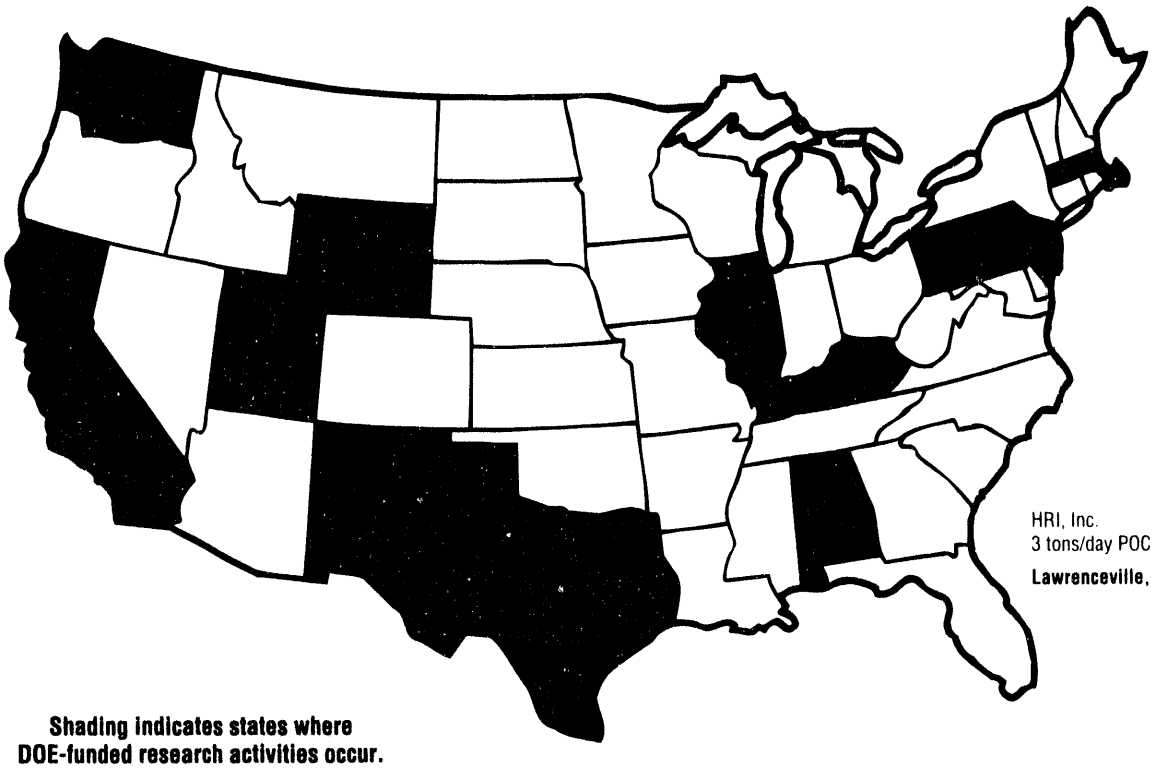
This program element focuses on the design, construction, start-up, and operation of commercial-scale demonstration facilities for direct coal liquefaction processes currently under development. Such large-scale demonstration, if eventually undertaken, would be selected by competitive procurement, and would have at least a 50 percent cost-share from an industrial partner or consortium. These large-scale demonstrations would serve to provide verification of the design and scale-up basis, prove long-term operability of process components, and allow more accurate engineering, environmental, and economic evaluations of the technologies.

Major Activities and Milestones



➤ The principal goal of the Direct Coal Liquefaction program is to facilitate the commercialization of coal-derived transportation fuels which meet environmental standards and are cost-competitive with petroleum-derived fuels. Environmental requirements are already met by existing POC systems, which produce distillates that have a lower sulfur and mineral content than petroleum does. Meeting the goal of cost competitiveness will require further process improvements. The Direct Liquefaction program focuses primarily on these improvements, with the goal of developing, by the early 2000s, a system that will provide all-distillate fuels for $25 per barrel.

Major Demonstrations and Activities



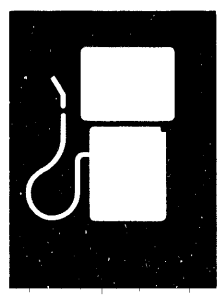
HRI, Inc.
3 tons/day POC Facility
Lawrenceville, New Jersey

Shading indicates states where DOE-funded research activities occur.

DOE-funded research activity is also taking place in Alberta, Canada.

Indirect liquefaction is the catalytic conversion of coal-derived synthesis gas, at moderate temperature and pressure, into liquid fuels such as methanol, gasoline, and diesel fuel, and octane enhancers such as methyl tertiary-butyl ether (MTBE).

The Indirect Coal Liquefaction Systems program focuses on the development of advanced processes for the production of coal-derived fuels and chemicals that have high conversion efficiency, superior environmental performance, and low capital and operating costs. The objective is to develop systems that can produce liquid transportation fuels and chemicals from coal at a cost competitive with equivalent petroleum-based products. The indirect liquefaction technologies currently under development have been shown to convert coal into fuels that comply with the future air quality standards mandated by the Clean Air Act Amendments of 1990.



Indirect Liquefaction RD&D Program Description

The Indirect Coal Liquefaction Systems program is a time-phased research program to develop cost-effective and environmentally acceptable technologies for the production of transportation fuels, fuel additives, and high-value chemicals from coal.

The Indirect Coal Liquefaction Process

Indirect coal liquefaction 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 by the use of various reactors, catalysts, and operating conditions 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.

The hydrocarbon fuels have no aromatic or sulfur compounds and exhibit very low toxicity. Both these and the oxygenated fuels are environmentally superior and will comply with the future air quality standards mandated by the Clean Air Act Amendments of 1990.

Program Elements

The Indirect Coal Liquefaction program covers all aspects of technology development, from basic and exploratory research through precommercial demonstration units. Six program elements have been defined. The three major program elements are the development of technologies for hydrocarbon fuel production, for oxygenated fuel production, and for high-value chemicals production. Important additional program elements, driven largely by the three major elements, include advanced research, proof-of-concept (POC) testing of promising technologies, and ultimately, the commercial demonstration of economically viable processes.

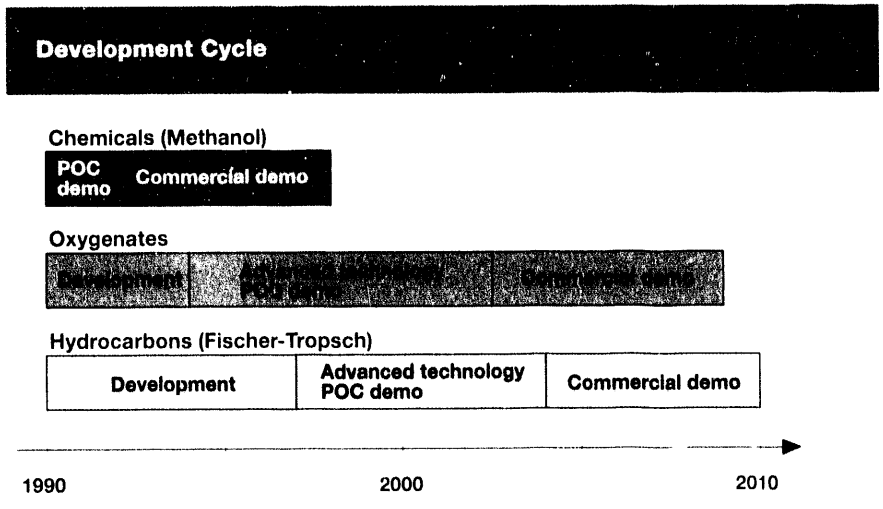
Specific activities within each of the major program elements are very similar. The work associated with each area focuses on improving catalyst activity, selectivity, and life; enhancing the yield and quality of the products; improving reactor performance; and reducing production costs.

Program Goals

With the achievement of these activities, the following specific program goals can be accomplished:

- The production of gasoline and diesel fuels that are competitive with fuels produced from petroleum, costing $25 per barrel.
- The production of high-quality hydrocarbon fuels that meet or exceed the requirements of the 1990 Clean Air Act Amendments.
- The production of isobutanol from coal at a price competitive with conventional sources. (It is expected to cost $1.26 per gallon in 1995.)
- The production of methyl tertiary-butyl ether from coal at a price competitive with conventional sources. (It is expected to cost about $1.30 per gallon in 1995.)

Development Cycle



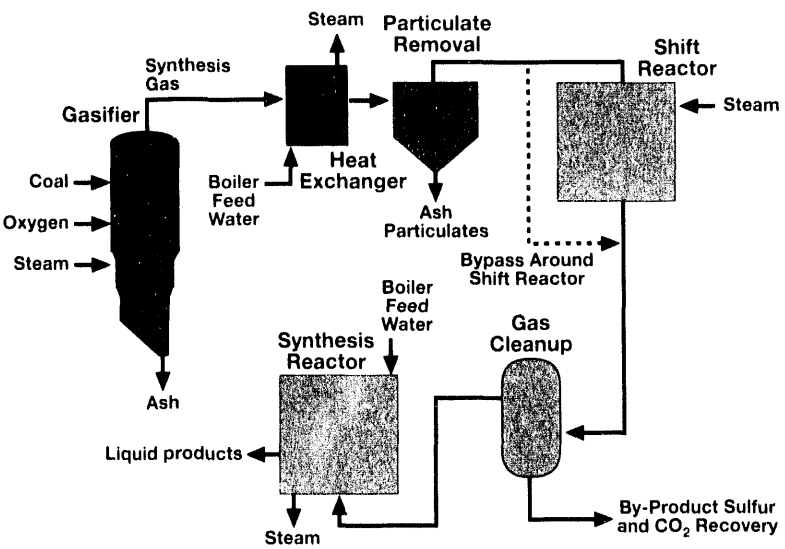
➤ Currently, the development of indirect liquefaction processes for chemicals production is nearing commercial-scale demonstration. Although several POC demonstrations of indirect liquefaction technologies are currently in progress, the development of advanced technologies may lead to additional POC demonstrations late in this decade. Commercial-scale demonstrations would then follow early in the next decade.

RD&D Program Goals

Indirect Liquefaction Systems	Present Technology	Advanced Technology
[illegible]	$30	$25
[illegible]	55%	60%
[illegible]	to meet 1995 CAAA regulations	to exceed 2000 CAAA regulations
[illegible]	benign	benign

CAAA=Clean Air Act Amendments

System Components



➤ Indirect coal liquefaction technologies convert coal into liquid fuels and chemicals in two sequential stages. First, coal is gasified using oxygen and steam to generate a gas containing mostly carbon monoxide and hydrogen. This is known as synthesis gas. Then the synthesis gas is cleaned of impurities and converted into a variety of products, including hydrocarbon fuels, oxygenated compounds, and premium chemicals, by employing various reactors, catalysts, and operating conditions. Different products result depending on the catalyst and conditions employed.

Indirect Liquefaction Program Activities

The Indirect Coal Liquefaction program elements encompass the identification and progressive development of promising new ideas for technology evolution, from bench-scale to large-scale POC testing, as appropriate. Second- and third-generation technologies, such as bioconversion, are expected to be products of this process.

Hydrocarbon Fuels Technology Development

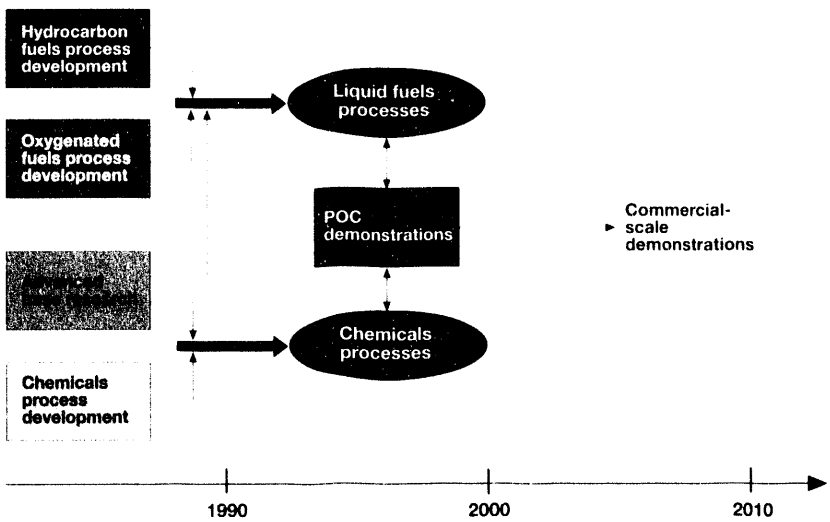
This program element is concerned with the development of coal-derived transportation fuels for use either alone, or in blends with commercial petroleum-based transportation fuels. Of particular importance is the ability of the final products to meet or exceed existing and future regulations for automotive emissions.

Development activities on process technologies include work on both catalysts and slurry reactors to improve their performance. In the case of slurry reactors, emphasis is also given to establishing an engineering data base for the scale-up and design of a commercial reactor. Development work on iron and cobalt catalysts involves the preparation and evaluation of new, improved formulations (for Fischer-Tropsch synthesis). The emphasis is on achieving higher levels of activity, selectivity, and stability, while also reducing the cost of commercial operations. The development of catalyst/wax separation techniques is also an important research focus for the successful development of slurry phase reactors. All promising catalysts and other technological developments will be evaluated in DOE's Alternative Fuels Development Unit at LaPorte, Texas.

Oxygenated Fuels Technology Development

The activities in this program element are similar to the RD&D activities described for the hydrocarbon fuels program element. However, since the focus is oxygenated compounds, the research content differs. Process development activities are focused on improving technologies for alcohol and ether synthesis. While catalyst development activities for oxygenates synthesis have the same general goals as for hydrocarbon synthesis, different types of catalysts, such as copper-based and ruthenium-based catalysts, are being evaluated. Of particular interest is research on poison-tolerant catalysts and the development of novel synthesis routes to fuels. DOE's Alternative Fuels Development Unit will also be used to evaluate promising technologies and/or process improvements.

Program Elements Interaction



◄ Base research and process development activities will lead to the development of advanced indirect liquefaction processes for fuels and chemicals production. Commercial-scale demonstration of the liquid-phase methanol production via indirect liquefaction is part of DOE's Clean Coal Technology program. Additional commercial-scale demonstrations of indirect liquefaction processes are expected early in the next decade.

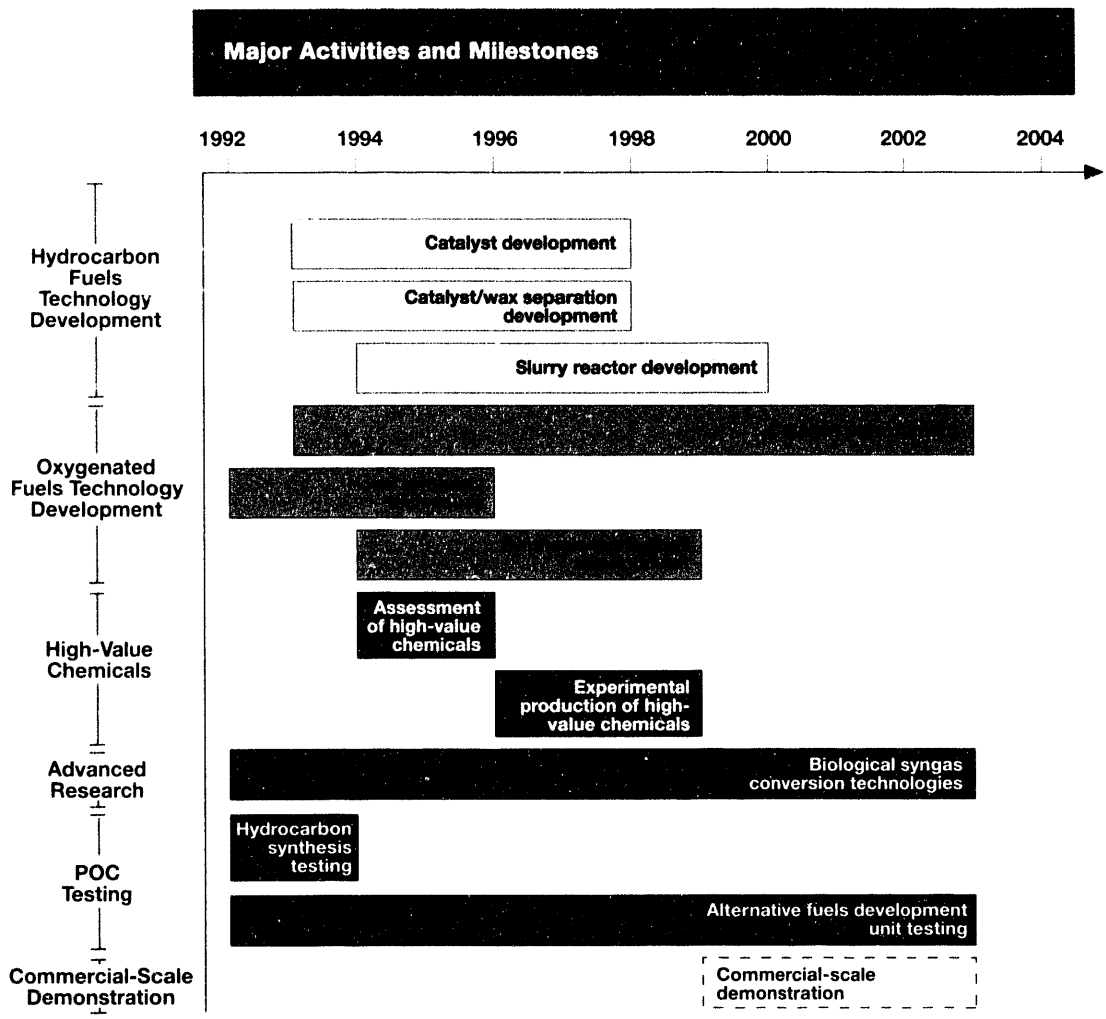
High-Value Chemical Development

Synthesis gas, as well as primary products from the synthesis gas conversion process, offer a myriad of opportunities for the production of high-value chemicals. The manufacture of dimethyl ether (DME) from synthesis gas has already been demonstrated at DOE's Alternative Fuels Development Unit. The processing of dimethyl ether, with or without synthesis gas present, has been shown to yield high-value chemicals and chemical intermediates. Process modifications and improved catalysts are being explored for the production of these and other valuable chemicals and intermediates.

Advanced Research on Indirect Coal Liquefaction

The advanced research program is focusing on novel biological synthesis gas conversion technologies for the production of fuels and chemicals, technologies that have potential for major breakthroughs. Such improved technologies may lead to substantially reduced product costs or high-quality products. The feasibility of an integrated two-stage synthesis gas fermentation process for producing a mixture of alcohols is being explored.

Sulfur-tolerant bacteria are also being developed in an attempt to reduce the cost of sulfur removal from synthesis gas prior to its conversion to alcohols. Promising technologies resulting from this work must undergo a preliminary economic assessment, and will then be further developed under the appropriate major program element.



➤ Commercialization of advanced indirect liquefaction processes is the overall objective of the Indirect Liquefaction Systems program. This is expected to follow operation of large-scale commercial demonstration plants for individual technologies, funded at least 50 percent by private industry. DOE-sponsored applied research and process development that concentrate on reactor design, process chemistry, and kinetics, as well as catalyst development, will bring new technologies to the point of commercial demonstration.

Proof-of-Concept Testing

At DOE's Alternative Fuels Development Unit, the slurry bubble column reactor has been used to conduct POC testing. This testing is designed to improve the economics of hydrocarbon fuel, oxygenated fuel, and gas conversion technologies for high-value chemicals synthesis. This reactor is especially appropriate for use with coal-derived synthesis gas: it is simple to construct, has high productivity, and offers very efficient heat transfer capabilities.

Recent work at the facility has successfully demonstrated the use of slurry reactors to synthesize hydrocarbons. This type of reactor, used to produce methanol, will be demonstrated in DOE's Clean Coal Program. Future runs will focus on the synthesis of higher alcohols, ethers, and additional hydrocarbon fuels.

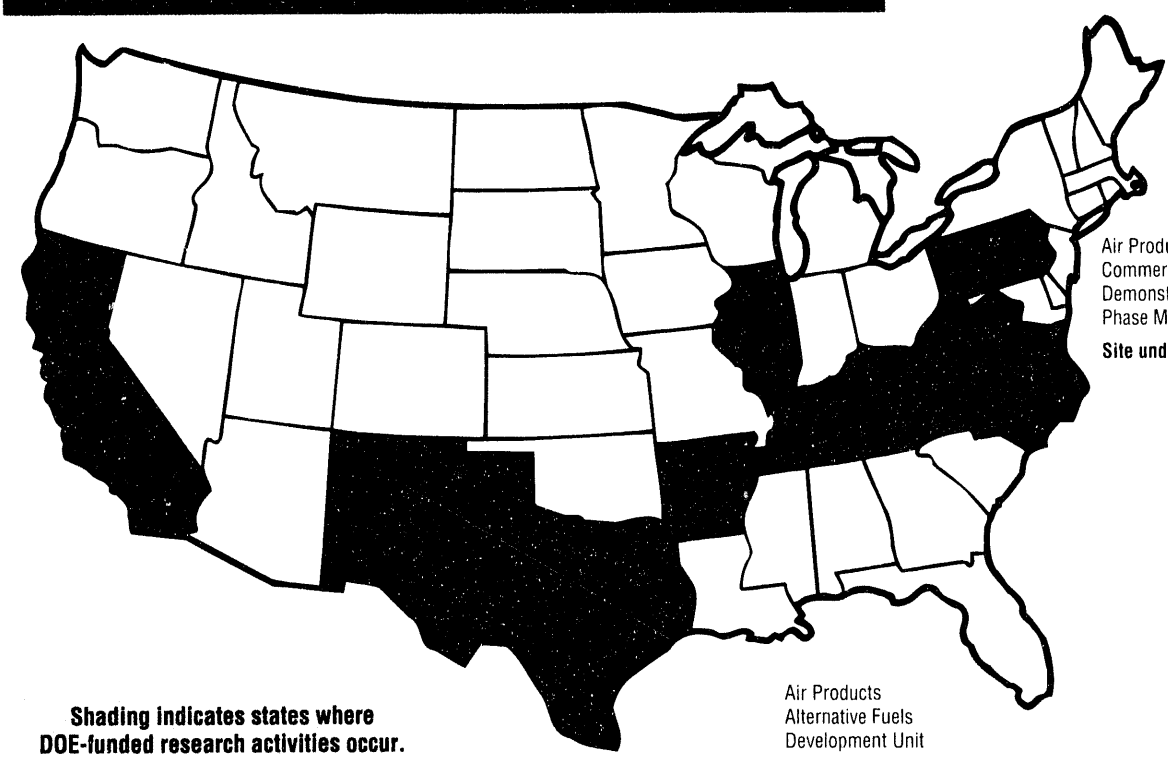
Commercial-Scale Demonstration

This program element focuses on the design, construction, start-up, and operation of a commercial-scale demonstration facility for an indirect coal liquefaction technology being developed under DOE sponsorship. This large-scale demonstration plant would be selected by competitive procurement, and would have at least a 50 percent cost-share from an industrial partner or consortium.

Private Sector Participation

In all development activities of the program elements described, private-sector participation will be sought to expedite the eventual commercialization of the technologies. Of particular importance are the formation of industry/government consortiums for each new technology and cooperative evaluation at DOE's Alternative Fuels Development Unit. After successful demonstration at POC-scale, the technologies will be ready for commercial demonstration.

Major Demonstrations and Activities

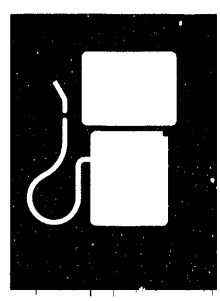


Shading indicates states where DOE-funded research activities occur.

Hydrogen and Synthesis Gas Systems

Hydrogen and synthesis gas can be produced by gasification of coal, and are important feedstocks for the production of fuels and chemicals through indirect and direct coal liquefaction. Production of hydrogen now constitutes about one-quarter of the total cost of making fuels by direct liquefaction; similarly, production of synthesis gas now constitutes about two-thirds of the total cost for making fuels and chemicals by indirect liquefaction. Hydrogen is also expected to eventually become an important fuel in its own right, for use in fuel cells to produce electricity, and for direct use as a gaseous transportation fuel.

The Hydrogen/Synthesis Gas program focuses on the development of new, environmentally superior, affordable technologies for production of hydrogen and synthesis gas from coal. The objective is to improve the commercial viability of liquid fuels produced from coal, by providing less expensive sources of hydrogen and synthesis gas than will be available in the future from natural gas feedstocks.



Hydrogen/Synthesis Gas RD&D Program Description

Hydrogen and synthesis gas are intermediate products of coal gasification.

Synthesis Gas

Synthesis gas, a mixture of hydrogen and carbon monoxide, is an important intermediate product in the manufacture of liquid fuels and chemicals, and results from the reaction of coal, oxygen, and steam in a coal gasifier. Once produced, synthesis gas can be processed ("shifted") to produce gaseous feedstocks with custom ratios of hydrogen to carbon monoxide, for specific fuels production processes.

Hydrogen

Hydrogen, in addition to being a constituent of synthesis gas, is a valuable chemical feedstock and fuel in its own right, which can be produced by further shifting of, and separation from, synthesis gas.

Hydrogen/Synthesis Gas Production

Hydrogen and synthesis gas are now normally produced by steam reforming of natural gas, which is currently the least costly route. Although a few commercial applications involving coal-derived synthesis gas already exist, it is the development of advanced, lower-cost coal-based systems for the production of hydrogen/synthesis gas, combined with the expected gradual rise in natural gas prices, which will eventually make coal the preferred route.

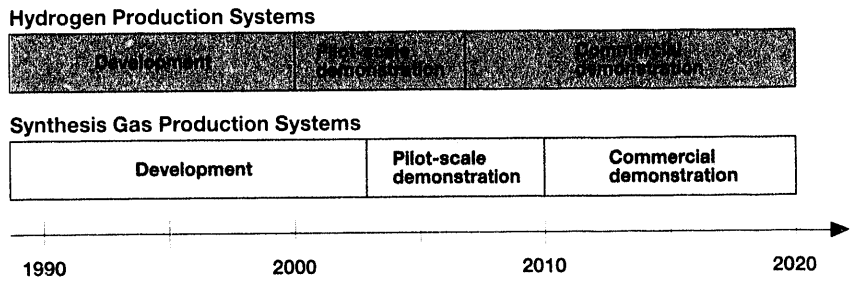
Program Goals

The objective of the Hydrogen/Synthesis Gas program is to develop and commercialize new coal-based technologies that will in the future have cost advantages over their natural-gas-based counterparts.

The costs of liquid fuels that result from coal liquefaction processes are greatly dependent on the costs of producing hydrogen or synthesis gas. Production of hydrogen now constitutes about one-quarter the total cost of making fuels by direct liquefaction; similarly, production of synthesis gas currently constitutes about two-thirds the total cost of making fuels and chemicals by indirect liquefaction. Future competitiveness of coal-based liquid fuels versus their petroleum-based counterparts may therefore depend on the development of coal-based systems that dramatically lower the cost of production of hydrogen and synthesis gas.

Development Cycle

➤Development of advanced processes for low-cost production of hydrogen and synthesis gas from coal may lead to proof-of-concept (POC) demonstrations in the next decade and commercial introduction by the year 2010.



Hydrogen/Synthesis Gas Systems

There are four major Hydrogen/Synthesis Gas program elements:

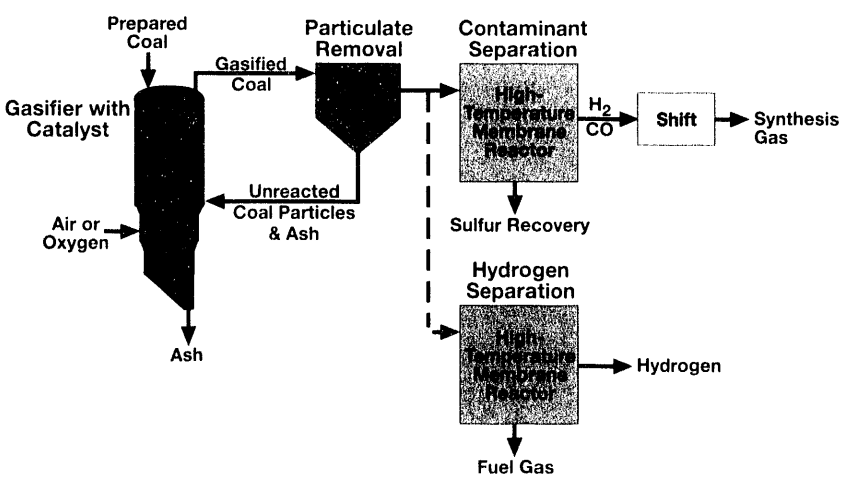
- Advanced gasification technology development.
- Gas separations technology development.
- Systems integration and support studies.
- Pilot- and commercial-scale demonstrations.

Each of these program elements represents a necessary step for eventual commercial acceptance of coal-based hydrogen and synthesis gas as a replacement for natural-gas-based production of these fuels. Gas separations technology, systems integration, and economic and technical support studies will initially lead to improved processes that are technically viable, but may still not be economically competitive. Future advances in coal gasification technology and associated systems integration and optimization can lead to large-scale demonstrations of advanced, lower cost processes.

RD&D Program Goals

Hydrogen/Synthesis Gas Systems	
[illegible]	at least 10% lower than natural-gas-based systems at time of commercialization (by 2010)
[illegible]	to meet all environmental regulations
[illegible]	benign or saleable

System Components



▲ Systems for the production of hydrogen or synthesis gas consist of a gasifier which converts coal or coal-derived material into a mixture of gases. A catalyst is used to increase the hydrogen concentration in the gases. After removal of particles of incompletely reacted coal or ash, the gas is separated in high-temperature membrane reactors to provide pure hydrogen or a synthesis gas free of contaminants.

Hydrogen/Synthesis Gas Program Activities

The Hydrogen/Synthesis Gas Systems program has a number of specific activities under way that will advance the individual program elements.

Advanced Gasification Technology Development

This program element focuses on identification and development of advanced gasification processes capable of producing synthesis gas with a relatively high hydrogen content, and with comparatively low carbon dioxide generation. Included in this program element is Technology Base Research for the development of biological coal gasification processes, and development of new catalysts for use in steam gasification of coal.

Gas Separations Technology Development

Activities in this program element center on development of several different highly selective gas separation membranes capable of operating at elevated temperatures and pressures characteristic of coal gasification product gas. These advanced membranes will be of great technical and economic benefit because they will allow:

- Hydrogen separation from synthesis gas.
- Carbon dioxide separation from synthesis gas.
- Efficient removal of hydrogen sulfide, ammonia, and other contaminants.

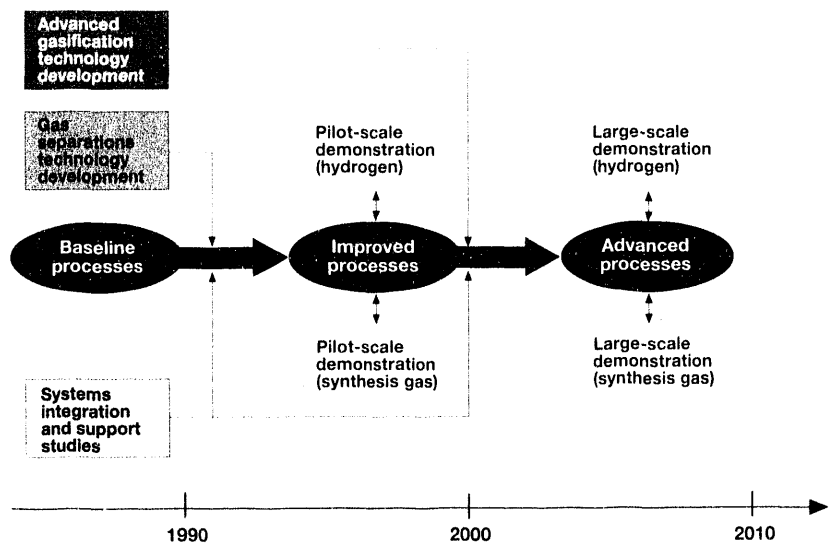
Systems Integration and Support Studies

This program element focuses on the integration of gasifier and gas separations technology using computer models, at the relatively small process research unit (PRU) scale of development. A series of market studies and technical and economic analyses will also be conducted, in order to identify optimum system configurations. Small-scale component testing is also a part of this program element.

Pilot- and Commercial-Scale Demonstrations

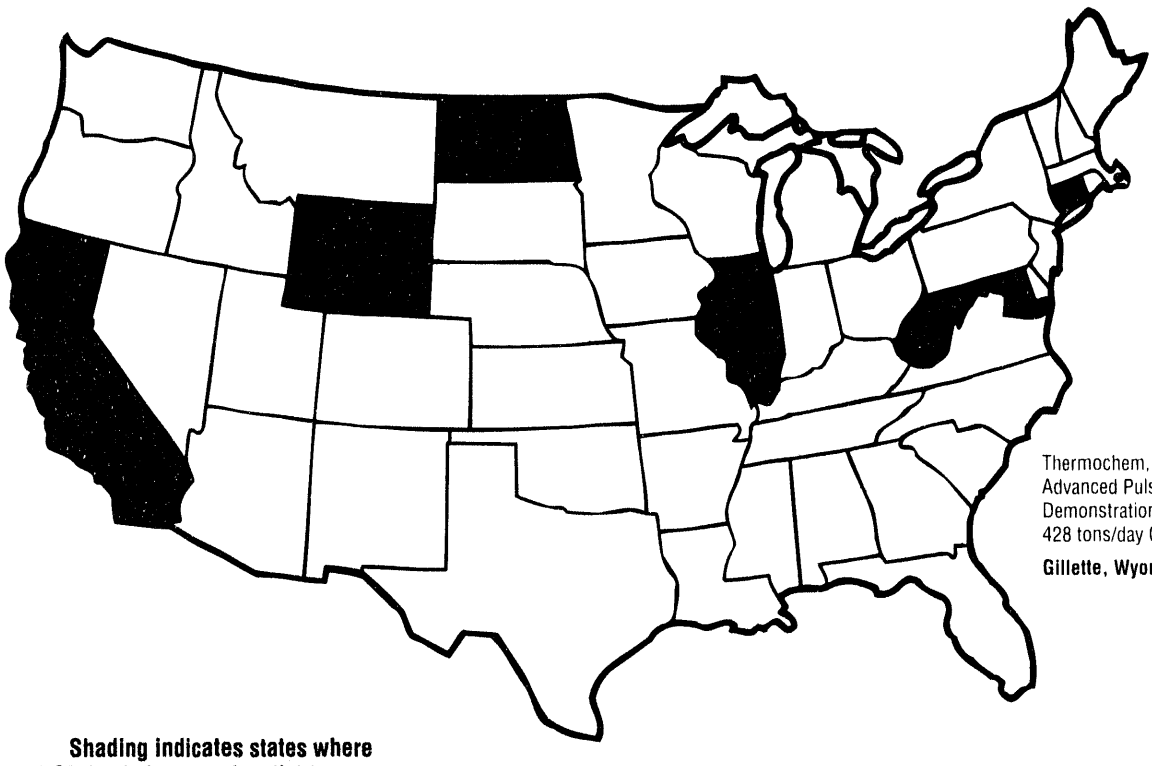
This program element includes design, construction, and operation of both pilot-scale and commercial-scale demonstrations of advanced coal-based processes for the production of hydrogen and synthesis gas. Where appropriate, pilot-scale facilities might be incorporated cost-effectively into more comprehensive DOE installations, such as a slipstream at an already existing Clean Coal IGCC Demonstration or another similar large-scale facility. Commercial-scale demonstrations could also be part of future, broader demonstrations of coal liquefaction technologies. Such demonstration plants would be selected by competitive procurement, and would have at least a 50 percent cost-share from an industrial partner or consortium.

Program Elements Interaction



◄ "Baseline" processes for production of synthesis gas from coal have seen commercial application in the 1980s and earlier. Systems integration, support studies, and advances in gas separations technology will lead to improved, but not yet fully optimized, coal-based processes for the production of hydrogen and synthesis gas. Future advances in gasification technology (including biogasification) and associated system integration/optimization studies may lead to advanced cost-competitive processes, which after successful large-scale demonstrations will result in commercial introduction by the year 2010.

Major Research Activities

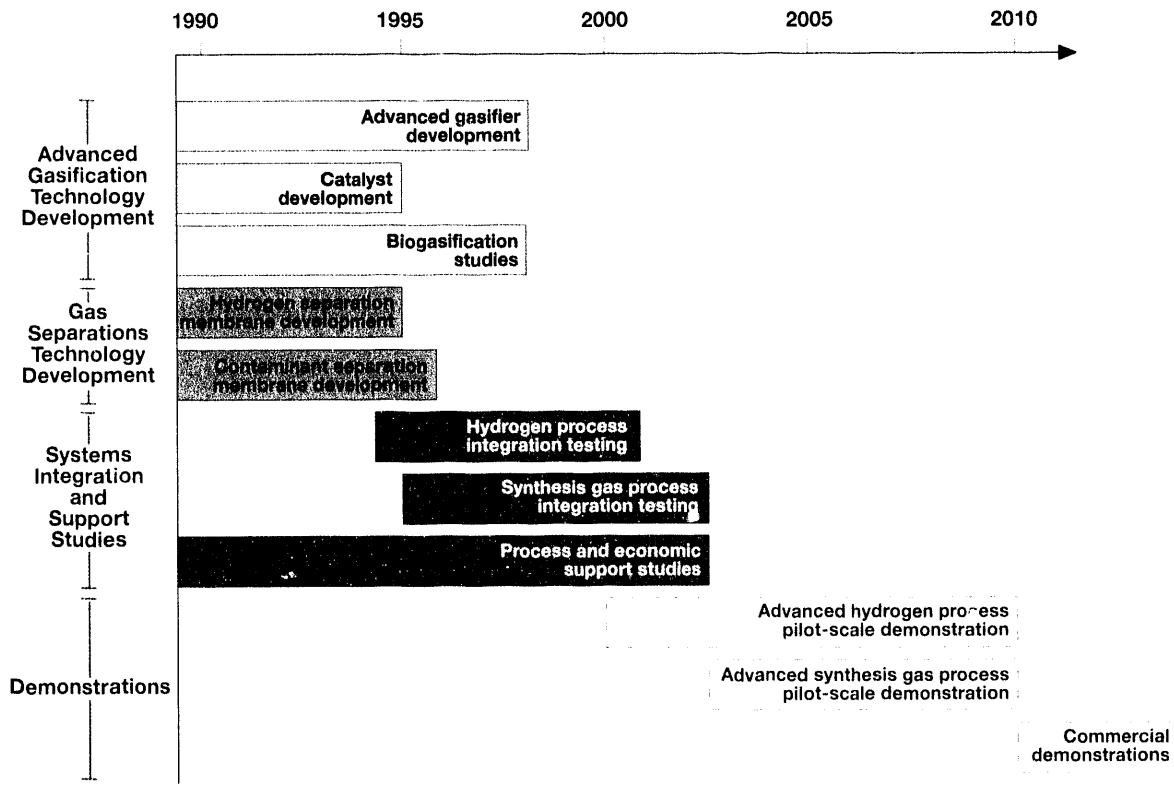


Thermochem, Inc.
Advanced Pulse Gasification
Demonstration
428 tons/day Clean Coal Demonstration
Gillette, Wyoming

Shading indicates states where DOE-funded research activities occur.

Major Activities and Milestones

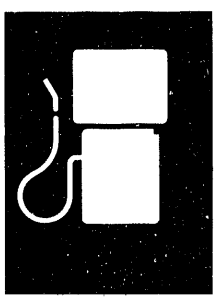
➤ Commercialization of advanced processes for the production of hydrogen and synthesis gas is a long-term goal of the Hydrogen/Synthesis Gas Systems program. Process improvements in gasification and gas separations technology are necessary for development of these advanced processes. Small-scale integration studies and testing of system components would precede proposed pilot-scale testing of fully integrated systems, and proposed commercial-scale demonstrations (funded at least 50 percent by an industrial partner) could occur as part of more comprehensive demonstrations of coal liquefaction technologies.



Mild Gasification Systems

Mild gasification is the conversion of coal by low-temperature pyrolysis and subsequent second-stage processing to a variety of value-added solid, liquid, and gaseous products. In a mild gasification process, coal is converted into useful products for several different market sectors.

The Mild Gasification Systems program focuses on development of advanced integrated processes for the production of coal-derived fuels, chemicals, and other industrial products at high conversion efficiency, with superior environmental performance, and at low capital and operating costs. The objective is to develop systems that can produce an array of useful coal-derived products at a cost which is competitive with alternative methods of manufacturing these products.



Mild Gasification RD&D Program Description

Mild gasification is based on coal pyrolysis technology. Mild gasification systems are simple, relatively low-cost systems for producing a broad spectrum of useful, environmentally acceptable, and economical products via coal pyrolysis. The process results in three types of primary products: gases (5-10 percent), liquids (10-30 percent), and solid char (50-70 percent). These distributions can vary greatly, depending on specific pyrolysis process conditions and the type of coal being utilized.

These primary or raw products can then be further upgraded using second-stage processes to create a variety of value-added products for different market sectors. Char can be processed to produce form coke, carbon black, activated carbon, and specialty fuels. Mild gasification liquids can be fractionated or catalytically cracked, or they can undergo hydrotreating to produce chemical feedstocks, carbon electrodes, octane enhancers, diesel fuel blenders, pitch, and road binders. Primary gaseous products will most frequently be consumed by the process to generate heat for pyrolysis, although separation of byproducts such as ammonia from the primary gaseous product stream is possible.

There are currently two classifications of mild gasification technology:

- First-Generation Mild Gasification Systems, which upgrade lower rank coal to a high-quality utility boiler fuel while also producing liquid fuel.
- Advanced Mild Gasification Systems, which produce a much broader spectrum of value-added fuels, chemicals, and industrial products.

Program Goals

Currently, the Mild Gasification Systems program has two primary objectives:

- To demonstrate at commercial-scale a first-generation Mild Gasification System by the year 1995.
- To develop a commercially viable Advanced Mild Gasification System by the year 2000.

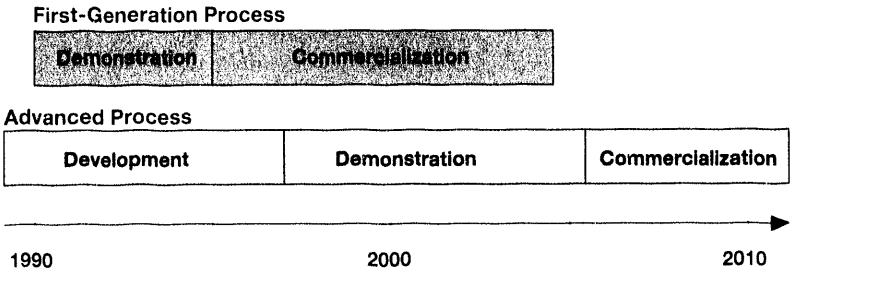
A first-generation Mild Gasification System, the ENCOAL Mild Gasification Project is part of the DOE Clean Coal Technology program and is expected to complete commercial-scale demonstration by the year 1995. Advanced mild gasification systems are the primary focus of the DOE development efforts described here.

The major Mild Gasification Systems program elements include:

- Process research unit (PRU) studies for advanced mild gasification systems.
- Support studies and activities.
- Advanced mild gasification process proof-of-concept (POC) demonstration, at process demonstration unit- or pilot-scale.
- Commercial-scale demonstration of advanced mild gasification systems.

Each of these program elements represents a necessary step towards the eventual commercialization of advanced mild gasification technology. Support studies, including process modeling and product characterization, and small-scale process development have led to a viable advanced mild gasification process. Successful pilot-scale demonstration of this process may lead to a large-scale demonstration that will attract commercial interest.

Development Cycle

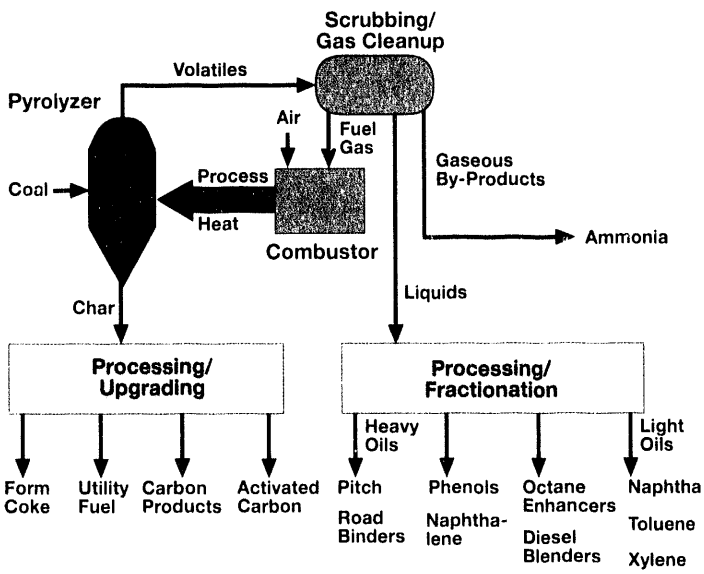


➤ Currently, first-generation mild gasification systems are at the commercial demonstration stage of development. These systems, typified by the ENCOAL Clean Coal Technology demonstration project, upgrade lower-rank coal to a high-quality utility boiler fuel while also producing liquid fuel products. Development of advanced mild gasification systems may lead to demonstration and eventual commercialization of processes that produce a much broader spectrum of value-added fuels, chemicals, and industrial products from coal.

RD&D Program Goals

Mild Gasification Systems	
[illegible]	to meet all environmental regulations
[illegible] solid wastes	benign
[illegible] quality standards	as good as equivalent products currently available
[illegible] costs	up to 10% less than alternative means of creating equivalent products

System Components



▲ Mild gasification is a less costly, coal-based alternative to traditional petroleum-based means of producing liquid and solid fuels and other non-fuel products. The coal is first fed into a pyrolyzer reactor where liquids, solids, and various volatiles are produced.

Char, the major product, can be further processed (blended, briquetted, and carbonized) to produce a series of valuable end-products, such as form coke, utility fuel, and activated carbon. The volatiles are condensed to produce liquids, which become feedstocks for the production of high-value chemicals and fuels, through various process operations such as fractional distillation and hydrotreating. Noncondensible fuel gas is generally used to produce process heat for the pyrolyzer. Typical products from mild gasification include pitch, heavy oils, middle oils, and light oils. When further refined, these can lead to various transportation fuels, octane enhancers, and road binders.

Mild Gasification Program Activities

The Mild Gasification Systems program has a number of specific activities under way that will advance the individual program elements.

Process Research Unit Studies

In 1987, four contractor teams were chosen to develop four different mild gasification concepts at the 100-pound-per-hour process research unit (PRU) scale. Each of these teams included process developers, coal producers, process engineers, and product end-users. This realistic, multidisciplinary approach assures a successful blending of process and product viewpoints, from research to the commercial market.

Product groups have been chosen, as well as the technologies and coals to develop each of the products. PRU-sized reactors have been designed, built, and operated, and the various products have been tested at small scale. Several teams also designed 0.5- to 1-ton-per-hour PDUs, based on these small-scale results. Three of the PRU projects were successfully completed in 1992, and the remaining project will be completed in 1993.

Support Studies

A variety of support studies are being carried out at DOE research facilities, national laboratories, universities, and private industry. These studies include:

- Modeling of the mild gasification processes.
- Development of key technologies needed in the processes.
- Separation and characterization methods for the solid and liquid products.
- Development of upgrading and product testing.
- Technical and economic assessments of the processes under development.

The support studies are expected to continue through 1998; some have received funding from the Advanced Research program.

POC Pilot-Scale Demonstration

This program element includes design, construction, and operation of an advanced mild gasification process, which may be demonstrated at the 1-ton-per-hour scale. The intent is to:

- Demonstrate integrated operation of the process.
- Collect data for the design of a possible future commercial-scale demonstration plant.
- Prepare a detailed design of such a demonstration plant.
- Produce sufficiently large amounts of products for subsequent upgrading and testing.
- Develop technical and economic information and plans for eventual commercialization of the process.

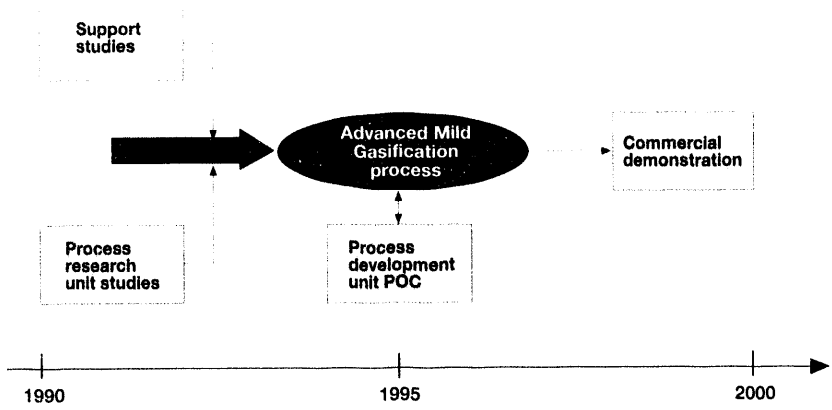
An industrial team, which is headed by the Kerr-McGee corporation and will be responsible for design, construction, and operation of this PDU, was selected in 1992. Activities in this program element may be completed by 1997.

Commercial-Scale Demonstration

One DOE-supported, first-generation mild gasification commercial-scale demonstration is currently in progress, the ENCOAL Mild Gasification Project, which is part of the DOE Clean Coal Technology program.

This program element focuses on the design, construction, start-up, and operation of an advanced mild gasification commercial-scale facility. Such a demonstration plant would be selected by competitive procurement, and would have at least a 50 percent cost-share from an industrial partner or consortium.

Program Elements Interaction

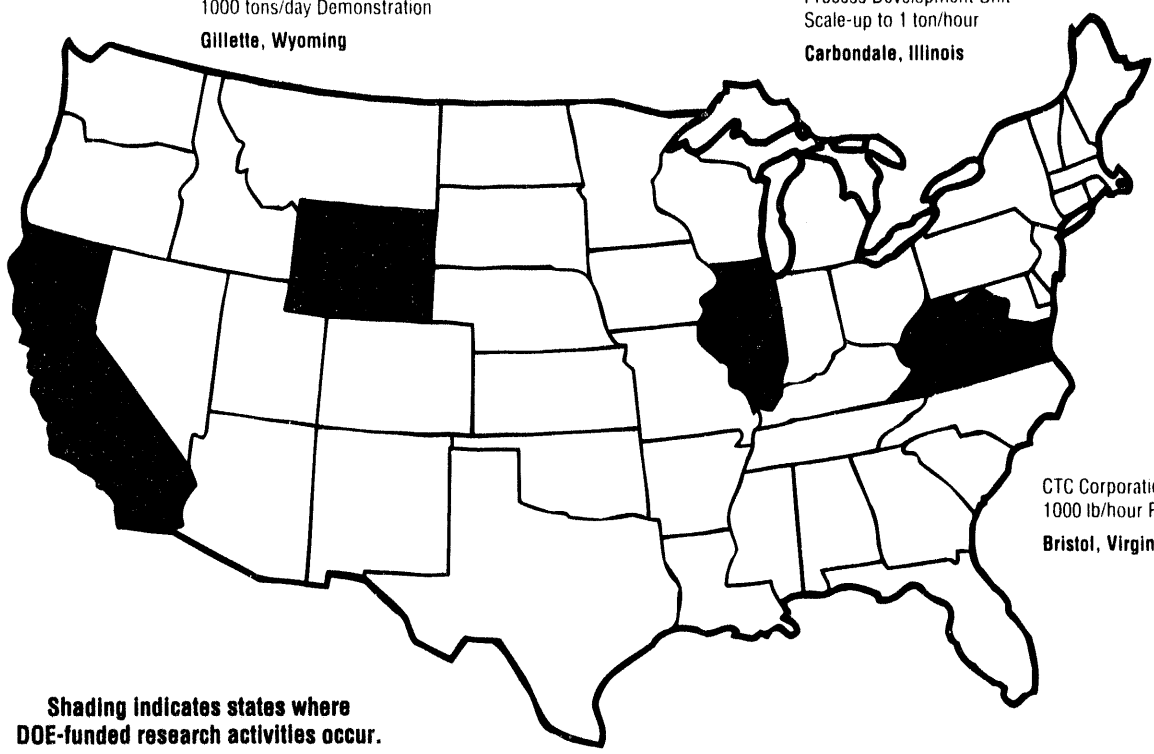


◄ Process modeling, product characterization and other support studies, as well as process development at the PRU-scale, have led to the development of advanced mild gasification processes. One or more of these processes will have a POC demonstration at pilot-plant-scale, which will pave the way toward eventual commercial-scale demonstrations.

Major Demonstrations and Activities

ENCOAL
Mild Gasification Project
Liquid/solid products from coal
1000 tons/day Demonstration
Gillette, Wyoming

Kerr-McGee
Process Development Unit
Scale-up to 1 ton/hour
Carbondale, Illinois

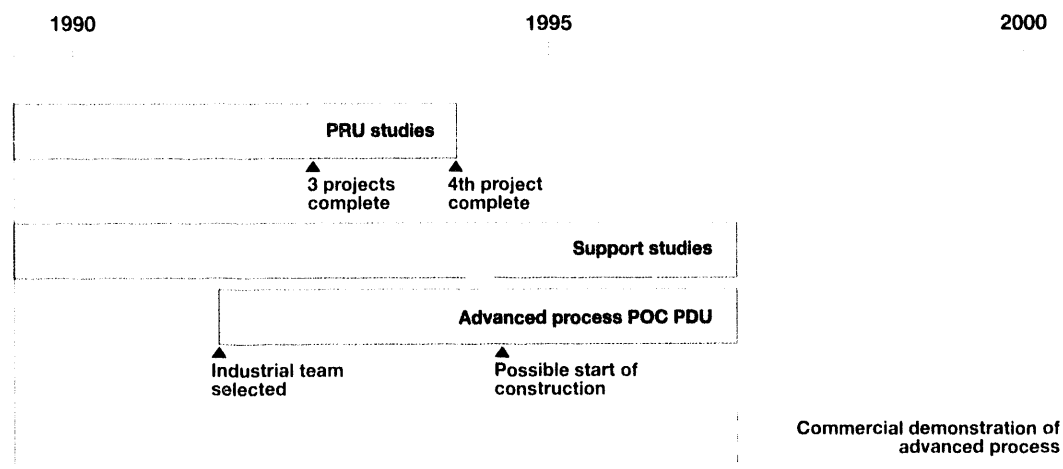


CTC Corporation
1000 lb/hour POC Facility
Bristol, Virginia

Shading indicates states where DOE-funded research activities occur.

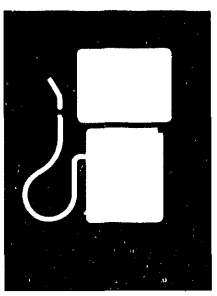
Major Activities and Milestones

➤ Commercialization of an advanced mild gasification process is the overall objective of the Mild Gasification Systems program, and would follow operation of a large-scale demonstration plant funded at least 50 percent by an industrial partner. DOE-sponsored research and development activities to bring such an advanced process to the point of demonstration include small-scale process development plus process modeling studies and environmental/economic characterization of possible products of the process. A pilot-scale demonstration is also required as proof-of-concept.



Base Research for Advanced Fuel Systems: A Crosscutting Program

The Base Research program advances the scientific and technical knowledge base required for significant improvements in the cost and performance of coal-fueled systems. The objective of the Base Research for Advanced Fuel Systems program is specifically to develop novel process concepts, and to achieve improvements in critical science and technologies that will enable solutions to the problems of converting heavy hydrocarbons to liquid transportation fuels.



AFS Base Research RD&D Program Description

Base Research for Advanced Fuel Systems (AFS) is an integral part of the overall R&D program for liquid transportation fuels, and supports all of the various systems under development in those areas where generic problems or barriers are common.

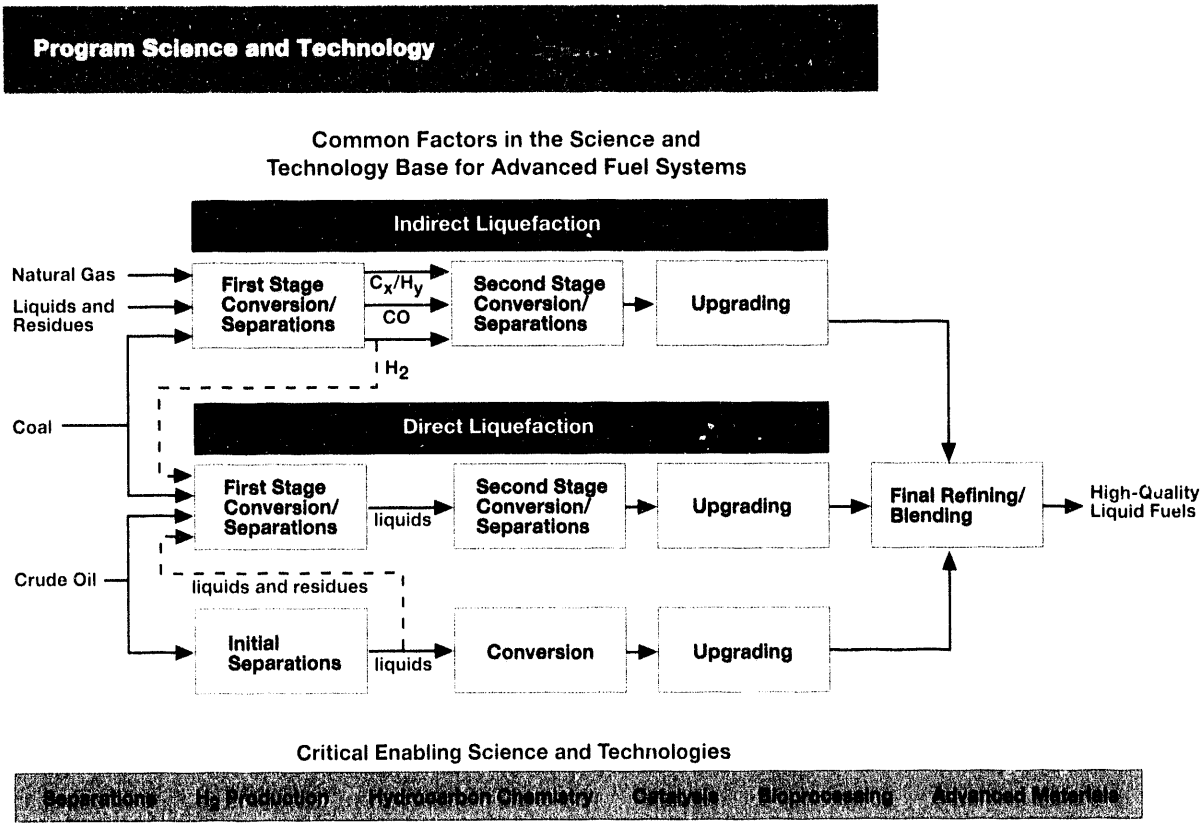
Program activities cover four major topics:

- Novel liquefaction and gasification process concepts.
- The fundamental chemistry of reactions in coal and coal-derived materials.
- Advanced catalysis for coal liquefaction and gasification.
- Technology for selective separation of gases from liquid-gas mixtures.

Many benefits are expected from this research. New classes of coal conversion catalysts with enhanced activity will be developed. Coal-derived liquids will then be available at significantly lower cost and with improved environmental acceptability.

New analytical technology will be developed for predicting the successful conversion of coal to liquid fuels. New biological approaches will be developed for the conversion of coal under low-severity conditions, which will have less environmental impact than current methods. Research on production and management of process hydrogen will also produce new approaches that could greatly reduce the cost of this key reactant, which is a large part of the total cost of coal-derived liquid fuels. Research on coal gasification chemistry and novel catalytic approaches can lead to more economical processes for producing synthesis gas (CO/H_2) for indirect coal liquefaction.

Program Science and Technology



▲ The Base Research for Advanced Fuel Systems program is an integral part of the overall R&D program for liquid transportation fuels, and supports all of the systems under development wherever generic problems or barriers exist, and common factors apply. Program activities focus on improving the basic understanding of coal gasification and liquefaction processes, and on exploring advanced new-generation liquid fuel processing approaches.

AFS Base Research Program Activities

Activities are focused on improving the basic understanding of coal gasification and liquefaction processes, and on exploring advanced new-generation processing approaches for producing liquid fuel substitutes for petroleum-derived gasoline, other petroleum distillates, and oxygenated fuel constituents.

There are three categories of activity:

- Direct Coal Liquefaction Advanced Research
- Indirect Coal Liquefaction Advanced Research
- Coal Gasification Advanced Research.

Direct Coal Liquefaction Advanced Research

The principal objective of this research element is to identify and test novel advanced concepts for the conversion of coal to liquid fuels. A second objective is to develop fundamental data that will provide improved understanding of coal liquefaction processes.

Activities are centered on identifying process concepts and advanced catalysts that will lead to processes that are less capital-intensive, can be performed under less severe operating conditions, are more selective, and make better use of hydrogen.

The major activities are:

Novel Concepts

Emphasis will be placed on those approaches to coal liquefaction that have the potential for substantially improving process efficiency and selectivity at reduced cost. These will include chemical and low-temperature treatment to enhance reactivity; liquefaction of beneficiated coal; advanced biological and biomimetic methods for liquefaction, upgrading of coal-derived liquids, and recovery of metals from spent catalysts; and the reduction of process-derived carbon dioxide emissions by means of novel approaches for the production of hydrogen.

Fundamental Research

Activities will be aimed at correlation of coal structure with liquefaction reactivi[illegible]nversion chemistry, and re[illegible]ction studies; advanc[illegible]pectrometric and nuclear [illegible]etic resonance methods for elucidating the composition of coal and coal liquids; and the chemistry of coal-heavy oil coprocessing and residuum conversion.

Advanced Catalysts

Research includes methods for the preparation and testing of fine-particle-size iron-based catalysts for use in the first stage of a direct liquefaction process, and of supported catalysts for use in the second stage of a direct liquefaction process, or for conversion of coal-derived liquids to reformulated gasoline that will meet the requirements of the Clean Air Act Amendments of 1990.

Indirect Coal Liquefaction Advanced Research

Activities are focused on identifying indirect liquefaction process concepts and advanced catalysts that will lead to processes that are less capital-intensive.

The major activities are:

Novel Concepts

Research will be conducted on novel approaches to indirect liquefaction that will significantly improve process operability and selectivity, reduce process severity, and provide greater efficiency in the production and use of hydrogen. This will include biotransformation of synthesis gas into ethanol, novel approaches to partial oxidation of coal and residual materials, and chemical and biological approaches to extracting hydrogen from water.

Advanced Catalysts

Finding new catalysts that will be more active and selective, and that will have greater resistance to deactivation, is the object of this program activity. It includes catalysts for the transformation of high molecular weight waxes from F-T processes into high octane fuels, the search for environmentally acceptable oxygenate gasoline components, catalysts with improved physical stability for slurry-phase indirect liquefaction, and exploration of the use of fine-particle-size, sulfur-tolerant, disposable catalysts for the conversion of synthesis gas into hydrocarbons and oxygenates.

Gasification Advanced Research

This program element supports fundamental and exploratory research to advance coal gasification technology by increasing the efficiency, reducing the costs, and enhancing the environmental acceptance of gasification systems. Research is focused on the chemistry of coal reactions and the separation of gaseous products from coal-derived gas mixtures. Gas produced from coal can be used to generate electricity, or to produce a synthesis gas for further processing to liquid fuels and chemicals. However, to achieve this potential, significant technical advances must be made to make coal gasification more cost-competitive and environmentally acceptable.

The major activities are:

Reaction Chemistry

All areas of gasification reactions are investigated: pyrolysis, devolatization, reaction mechanisms and rates, intermediate and transient reactions, ash and slag formation, development of predictive models, and the use of gasification catalysts. Biological gasification is also a part of this program, using microorganisms to convert coal and coal-derived products to synthetic natural gas and useful by-products.

Separation Science and Technology

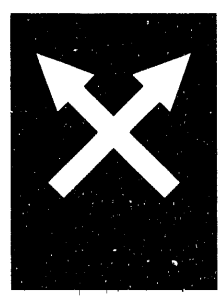
This research activity is concerned with the separation of selective gases from gaseous mixtures, and from mixtures of gases and liquids. It involves ceramic membranes, liquid ion-exchange membranes, membrane support methods, high-temperature sorbents, and electrochemical separation techniques.

Crosscutting Technology Programs

Many clean coal technologies under development by DOE are relevant to both advanced power and advanced fuel systems. Progress in these technologies, known as "crosscutting" technologies, can yield improvements in the efficiency, environmental performance, and life cycle costs of virtually all of the systems under development. There are four different program areas: coal preparation, alternative fuels utilization, flue gas cleanup, and waste management.

Coal preparation is the precombustion cleaning of coal to produce a more marketable product. This improvement is achieved by reducing the undesirable components present in run-of-mine coal, and thereby enhancing the overall quality, uniformity, and desirability of the coal produced.

The Coal Preparation program focuses on developing coal-cleaning processes for use with the advanced power systems under development. The objective is to help advanced power systems comply with, or improve on, the requirements of the Clean Air Act and its 1990 Amendments. Since this is a crosscutting program, Coal Preparation technology advances will have an impact on several of the power systems under development.



Coal Preparation RD&D Program Description

Coal preparation technology can be divided into two main categories: conventional coal preparation and advanced coal preparation.

Conventional Coal Preparation

Conventional coal preparation, now in wide commercial use, is a two-step process of physical preparation and physical cleaning. Physical preparation involves the mechanical crushing, grinding, and sizing of coal, which improves coal handling characteristics and enhances the coal's response to subsequent cleaning treatments. Physical cleaning involves the use of various processes to remove the ash, moisture, and sulfur components from coal. These cleaning methods take advantage of the physical and physicochemical property differences between coal particles and coal impurities to cause their separation.

Some processes — such as those used for jigs, tables, dense-medium vessels, and cyclones — exploit specific gravity differences to separate impurities. Other cleaning methods rely on surface chemistry variations. Froth flotation technology, which is in widespread use, and oil agglomeration, which has been used in a few commercial installations, both use this approach.

Advanced Coal Preparation

Advanced coal preparation research is geared to improving upon the current state-of-the-art techniques to achieve an even greater separation of impurities and to further reduce cleaning costs. Intended for a marketplace in which regulatory incentives require a much cleaner burning coal, these improved technologies employ an array of advanced cleaning methods. In addition to improvements to the physical, physicochemical, and chemical methods currently being used, biological processes based upon microbial and enzymatic techniques may also prove feasible.

The Coal Preparation program has four major RD&D activity categories:

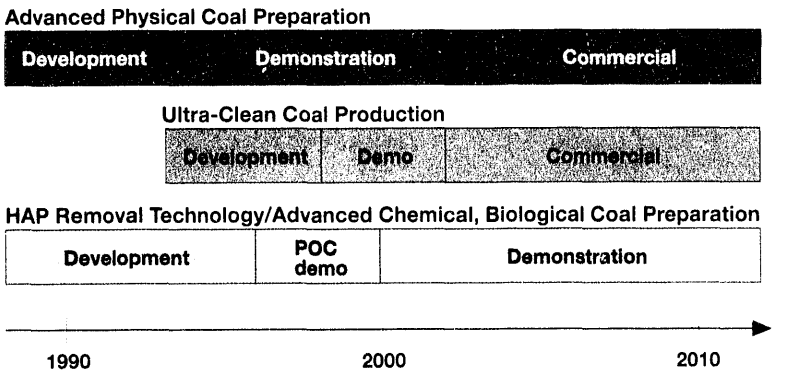
Compliance Technology

The primary focus of this research activity is the development of advanced coal-cleaning processes capable of significantly reducing the pyritic sulfur content of coal, while also achieving high Btu recoveries. Designed to help advanced power systems comply with the acid rain control requirements of the Clean Air Act Amendments of 1990, these advanced processes will also be helpful in removing the trace element precursors to hazardous air pollutants (HAPs).

High-Efficiency Preparation

High-Efficiency Preparation focuses on the accumulation of a technology base for the development of more efficient and cheaper ways to improve, handle, and market coal fines. Intended to facilitate compliance with the Clean Air Act Amendments of 1990, High-Efficiency Preparation projects will enable today's coal preparation facilities to evolve towards achieving the removal of increased amounts of pyritic sulfur from coal.

Development Cycle



➤ **The Coal Preparation program is developing a set of near- and long-term technologies for use with existing and future coal-fueled power plants. Advanced physical techniques for removing acid rain precursors will be developed by 1994; an engineering design base for producing ultra-clean coal by physical means will be established by 1998; and initial investigation into the precombustion removal of selected trace elements will be completed by 1997.**

Premium Fuel Development

Building upon the work of the Compliance Technology program, this research element will focus exclusively on the development of coal-based feedstocks for advanced pulverized coal systems. The goal is the development of cleaned-coal-based fuels for use in advanced power systems and for sale in premium fuel markets.

Technology Base Activities

These activities invoive the investigation of novel coal preparation techniques that have the potential to be either more efficient or cheaper than the more conventional methods being developed in the other activity categories.

RD&D Program Goals

	Coal Preparation	
Acid Rain Control	Pyritic sulfur rejection	85%
	Btu recovery	85%
	Fuel cost	$2.20 per million Btu
	Timeframe	POC by 1994
Precombustion Removal of HAP Precursors	HAP rejections	≥ regs for specific HAP
	Fuel cost	$2.20 per million Btu
	Timeframe	POC by 2000
Premium Fuel Development	Sulfur	0.6 lb per million Btu
	Ash	1.5 lb per million Btu
	Fuel cost	$2.50 per million Btu
	Timeframe	POC by 1998

HAP=Hazardous Air Pollutant

Program Elements Interaction

Coal Preparation Program Contributions to Advanced Power Systems

	Compliance Technology	High-Efficiency Preparation	Premium Fuel Development	Technology Base Activities
APC (LEBS)	■	■	■	■
IFC (HIPPS)	■	■	■	■
DCFHE	■	■	■	■
PFBC				
MHD		■		
IGCC		■		
IGFC		■		

➤ Advanced Coal Preparation technology is used to pretreat coal before combustion to remove acid rain precursors and related hazardous air pollutants, and to produce a feedstock suitable for most advanced coal-fired systems. The coal preparation system involves grinding the coal, separating the impurities by beneficiation, formulating the clean coal into a transportable, usable product, and disposing of the wastes. Program activities to develop this technology consist of compliance technology, high-efficiency preparation, premium fuel development, and technology base activities.

Advanced Coal Preparation technology can be effectively integrated into advanced power-generating systems at the time those systems are developed.

Coal Preparation Program Activities

Coal Preparation program activities for Compliance Technology, High-Efficiency Preparation, Premium Fuel Development, and Technology Base Activities currently extend through the end of FY 1998.

Compliance Technology

Three proof-of-concept (POC) contracts have been awarded to demonstrate the ability of three different advanced physical coal-cleaning techniques to reduce SO_2 emissions cost-effectively. POC-scale testing by ICF Kaiser Engineers will focus on advanced flotation technology. Southern Company Services has completed POC-scale testing of selective agglomeration, and Coal Technology Corporation will test advanced cycloning.

In addition, development work on a coal preparation process flowsheet simulator is under way at Aspen Technology. This simulator will be applicable to all three advanced coal-cleaning processes.

Bench-scale R&D is also planned for a number of novel precombustion concepts to remove HAP precursors. POC-scale testing and evaluation will be conducted on the most promising technologies for HAP precursor reduction.

High-Efficiency Preparation

Bench-scale projects have begun on a number of emerging technologies with promising prospects, including:

- Development of hardware and software for on-line control of froth flotation columns.
- Evaluation and enhancement of the synergism between froth flotation and multigravity separation.
- Development of a micronized magnetite process for improving the quality of fine coal.

Proposals received in response to a 1992 solicitation for POC-scale High-Efficiency Preparation projects are currently being evaluated, and approximately four of these proposals will be chosen for award sometime in 1993.

Premium Fuel Development

Major activities focus on the development of technologies that aid in the production of coal-based premium fuels for advanced pulverized coal systems. Promising concepts such as advanced column froth flotation and selective agglomeration will be subjected to bench-scale studies, design and engineering development, and the construction, testing, and evaluation of a process development unit (PDU), under a contract with AMAX Research and Development Center.

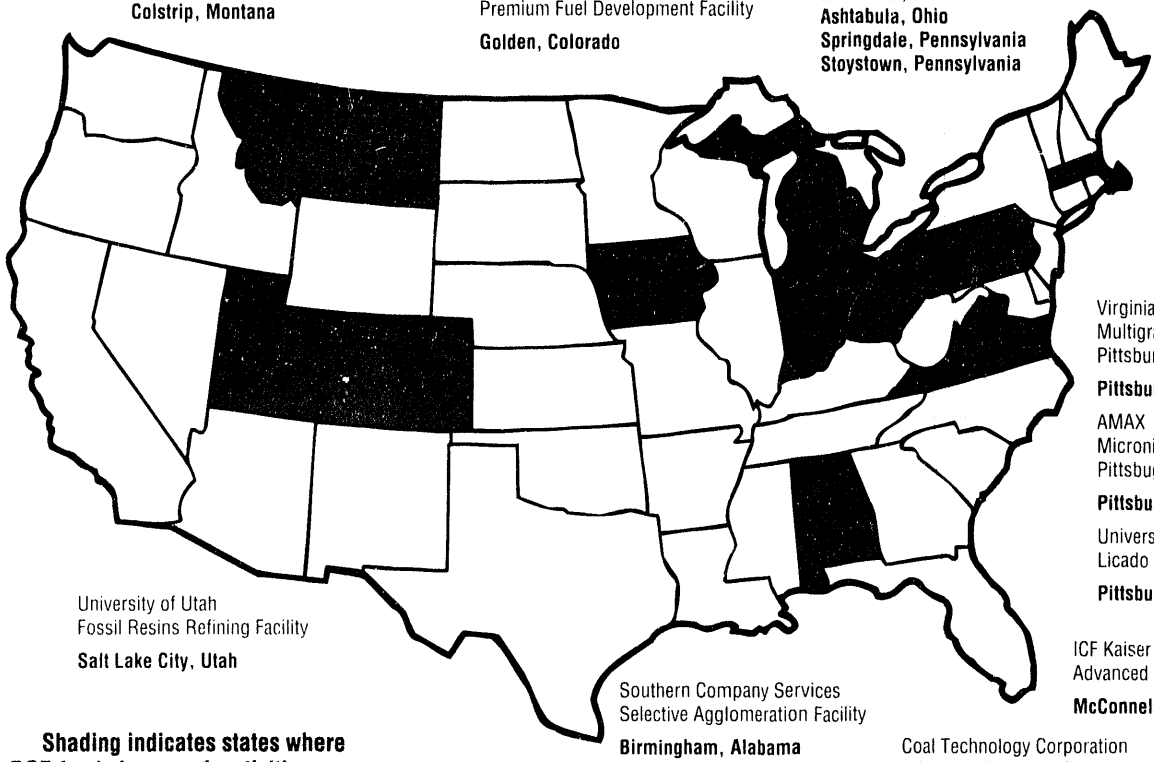
Later efforts may involve the engineering development of chemical and biological advanced coal-cleaning processes. These processes offer the potential to meet even tighter specifications for ultra-clean coals to be used as feedstocks for advanced pulverized coal systems.

Technology Base Activities

Research is being conducted to study the scientific underpinning of some of the processes currently under development, and to assess, at lab-scale, technologies that have strong potential to become the coal-cleaning methods of the future.

➤ The major activities of the Coal Preparation program have been structured and integrated to promote the commercialization of advanced technologies in the next decade. Milestones have been developed to allow flexibility with respect to possible regulatory changes. The focus is on developing control technology for acid rain precursors that could be deployed in the near-term to assist industry in complying with the 1990 Clean Air Act Amendments. A further goal is to develop physical beneficiation methods that will provide a technology base for producing ultra-clean coal that could serve as a feedstock to APC systems. Technology Base Research activities are critical to the success of these efforts.

Major Demonstrations and Activities



Advanced Coal Conversion Process
Demonstration Project
Rosebud Syn Coal Partnership
45 tons/hour Clean Coal Demonstration
Colstrip, Montana

AMAX
Premium Fuel Development Facility
Golden, Colorado

Custom Coals International
Clean Coal Demonstration
Self-Scrubbing Coal Project
Richmond, Indiana
Ashtabula, Ohio
Springdale, Pennsylvania
Stoystown, Pennsylvania

Virginia Polytechnic Institute
Multigravity Separator/Microcel
Pittsburgh Energy Tech. Center
Pittsburgh, Pennsylvania

AMAX
Micronized Magnetite Process
Pittsbugh Energy Tech. Center
Pittsburgh, Pennsylvania

University of Pittsburgh
Licado Process Development
Pittsburgh, Pennsylvania

University of Utah
Fossil Resins Refining Facility
Salt Lake City, Utah

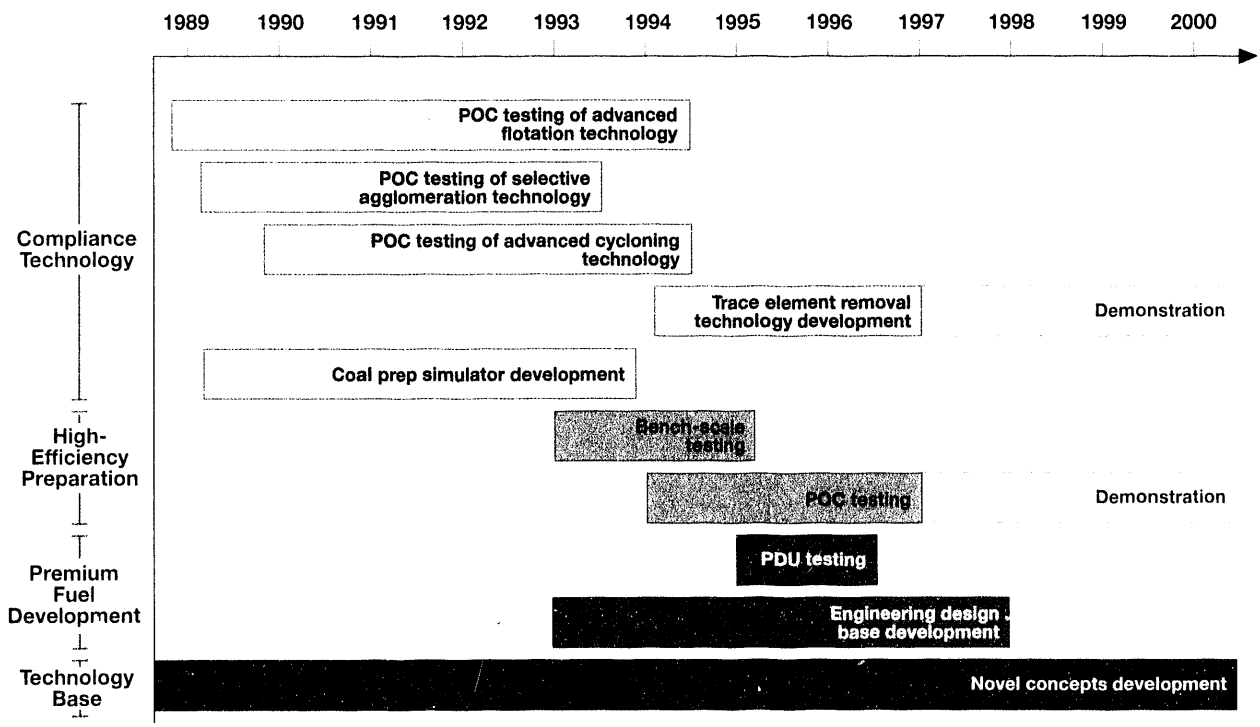
ICF Kaiser
Advanced Flotation Facility
McConnelsville, Ohio

Southern Company Services
Selective Agglomeration Facility
Birmingham, Alabama

Coal Technology Corporation
Advanced Cycloning Facility
Bristol, Virginia

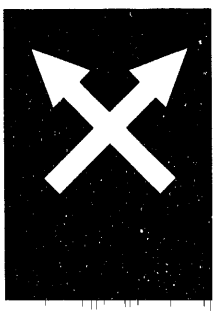
Shading indicates states where DOE-funded research activities occur.

Major Activities and Milestones



The Alternative Fuels Utilization (AFU) program consists of fuel technology research and development. It is a crosscutting program in that it impacts several of the advanced coal-fired power systems under development, and its purpose is to ensure the efficient performance of the heart of these systems — the combustor. Much of the technology developed is expected to apply to conventional coal-fired plants, also providing near-term benefits to the power industry.

The AFU program is structured to make successive, ongoing, technical contributions to other DOE programs, and it is also coordinated with the efforts of commercial developers. Fuel producers, hardware designers, manufacturers, utilities, and other end-users are all partners in facilitating the final goal — the development of commercially competitive alternative fuel systems.



AFU RD&D Program Description

The Alternative Fuels Utilization program addresses the development and utilization of coal-water fuels, and solid coal fuels, such as ultra-fine coal and pelletized coal. The broad objective of the program is to develop fuel technologies that will allow advanced coal-fired power systems to attain their projected thermal and environmental performance at the lowest possible cost. The program is directed at providing fuel development support for both utility and nonutility power systems.

Program Elements

The four elements included in the program are:

Fuel Formulation

Fuel formulation covers all the processes involved in the conversion of coal-based raw materials into new fuel forms.

Fuel Characterization

This aspect of the program is concerned with the evaluation of the properties of different fuel forms.

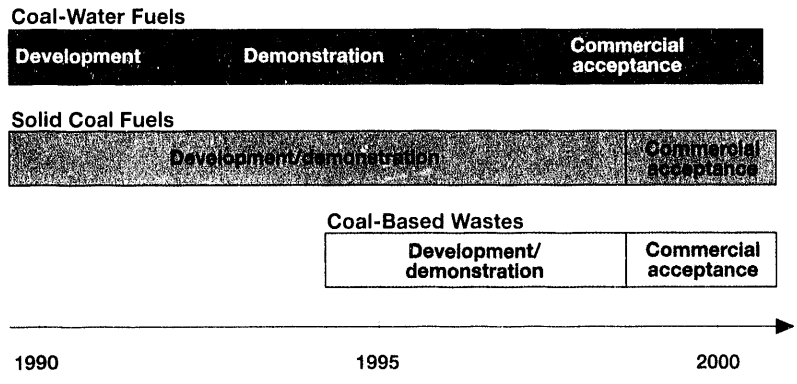
Fuel Logistics

This program element involves the development of new methods and equipment for the storage, transportation, and handling of fuels.

Fuel Utilization

This program element involves conducting tests of each end-use system to establish the acceptability of fuel forms.

Development Cycle



➤ The Alternative Fuels Utilization program complements and supports coal combustion technology for existing and future coal-fueled power plants.

RD&D Program Goals

Alternative Fuels Utilization

Formulation/Characterization	Provide coal-based fuels to meet user specifications.
	Develop coal-based fuels as clean alternatives to oil.
	Convert coal and hydrocarbon wastes into fuels.
Logistics	Maximize use of conventional equipment.
	Minimize maintenance requirements.
Utilization	Provide potential users with detailed information on fuel acceptability.
Cost	Make costs competitive with costs of fuels currently in use.

Program Elements Interaction

➤ The AFU program supports many of the power systems being developed by DOE, and each element contributes to the success of these programs. Fuel formulation defines the processes for converting coal-based raw materials into a fuel form compatible with the end-use system. Fuel characterization describes the properties of the fuel form in order to determine its compatibility with the end-use system. Fuel logistics defines the equipment needed for the transport, storage, and handling of the fuel form. Fuel utilization establishes the acceptability of the fuel form by testing it in the e- -use system, or a simulation of this sys-.

Alternative Fuels Utilization Program Contributions to Advanced Power Systems

	Fuel Formulation R&D	Fuel Characterization	Fuel Logistics	Fuel Utilization R&D
APC	■	■	■	■
IFC	■	■	■	■
DCFHE	■	■	■	■
PFBC				
MHD	■	■	■	■
IGCC				
IGFC				

AFU Program Activities

The major activities of the AFU program are:

Fuel Formulation

The focus of the fuel formulation effort is to produce fuels prepared from coal, or a combination of coal and other materials, which can meet the specifications of an individual power system. A small industrial plant, for instance, may have severe fuel storage constraints coupled with stringent local emissions-control regulations, requiring use of a clean, easily handled fuel.

Activities occur in two stages:

Evaluation

Evaluation of the compatibility of candidate fuel materials and fuel forms with the end-use system.

Formulation

Formulation of carefully selected fuel forms.

The fuel materials available are of many types:

- Coal, as it comes from the mine, or cleaned.
- Coal fines.
- Chars.
- Solid and liquid residues formed as the by-products of coal cleaning and conversion processes.

Fuel forms are also varied:

- Solid, as in powders, granules, and pellets.
- Slurry, as in coal suspended in water.

Fuel Characterization

Once specifications have been established for specific systems, the physical, chemical, and combustion characteristics of a fuel must be measured.

Some of the important properties of fuels to be considered include:

- Ash level and composition, including potential pollutants and toxic metals.
- Handling properties.
- Reactivity.
- Tendency of the fuel to erode, corrode, slag, and foul the combustion system.

Activities occur in two steps:

- Development of the standardized analyses, tests, and qualification and evaluation procedures required by a specific application. This is to determine fuel specifications, and to allow several alternative fuels to be given comparable evaluation.
- Characterization, or evaluation, of the fuel. This may be accomplished in a laboratory, or by tests in a pilot plant. Should the fuel be judged unsatisfactory in any one characteristic, the fuel will be reformulated or a new fuel will be developed.

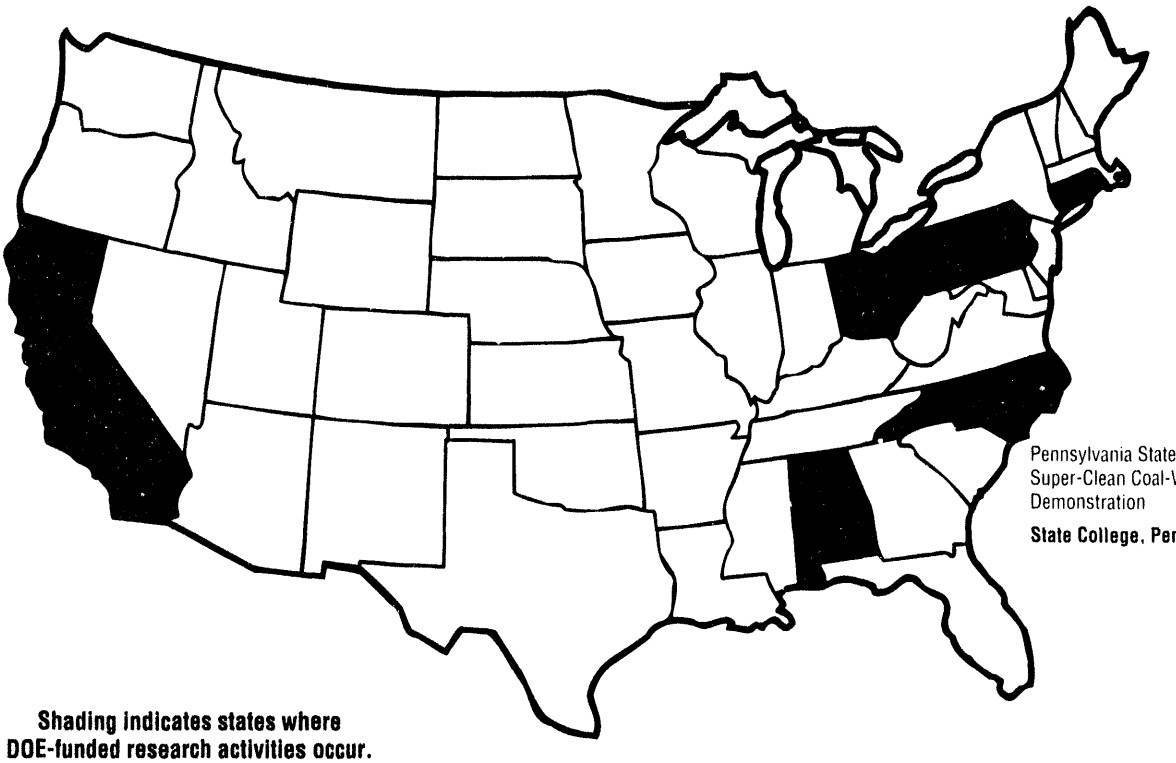
Fuel Logistics

Commercial equipment must be tested, or new equipment designed for the transportation, storage, and handling of new fuels, to ensure sufficient safety and convenience to the user. The availability of commercial equipment is investigated first, and it may sometimes be modified for use. Components commonly designed or modified for new fuels include site storage containers, pumps, valves, metering devices, fuel atomizers, burners, and safety equipment.

Fuel Utilization

The acceptability of a fuel is determined by its long-term performance in full-scale systems. Starting with a pilot project under well-instrumented and carefully chosen operating conditions, testing then progresses through successively larger scale projects, to culminate in long-duration site demonstration tests that are run under conditions that closely parallel those the end-user would encounter.

Major Demonstrations and Activities

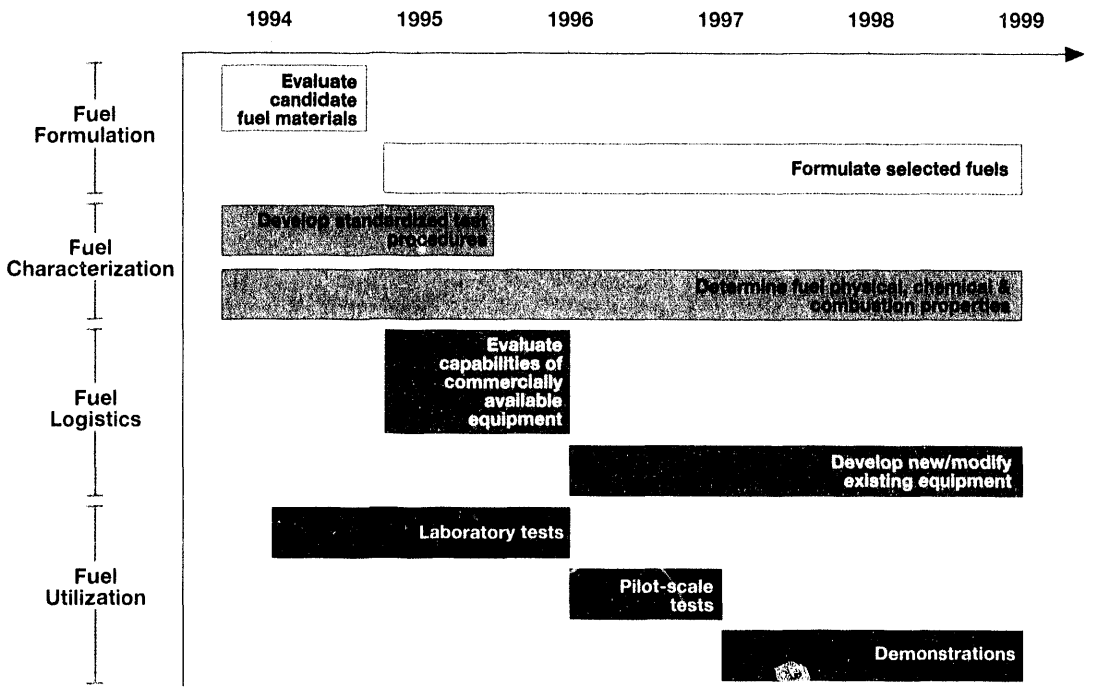


Pennsylvania State University
Super-Clean Coal-Water Slurry
Demonstration

State College, Pennsylvania

Shading indicates states where DOE-funded research activities occur.

Major Activities and Milestones



➤Milestones have been developed to guide the AFU program towards full support of new coal utilization technologies development. The AFU program is an ongoing effort as it supports many of the coal utilization systems currently under development as well as those of the future. The timing of input from each of the activities shown is coordinated with that of advanced power systems such as APC, IFC, DCFHE, and MHD.

Flue Gas Cleanup Systems Program

Flue Gas Cleanup is the cleaning of gas produced by coal combustion prior to its discharge into the atmosphere. Undesirable species present at significant levels in untreated flue gas can include sulfur dioxide (SO_2), nitrogen oxides (NOx), airborne particulates, and air toxic species. Carbon dioxide (CO_2), implicated in global warming scenarios, is also present in large quantities in coal combustion gas.

The Flue Gas Cleanup Systems program focuses on the development and demonstration of cost-effective new emissions-control technologies to support the needs of both existing and future coal-fueled power plants. The objective is to help advanced power systems comply with, or improve on, the Clean Air Act and its 1990 amendments. Since this is a crosscutting program, Flue Gas Cleanup Systems technology advances will have an impact on several of the advanced coal-fueled power systems under development.

Flue Gas Cleanup RD&D Program Description

The Flue Gas Cleanup program is structured to address the specific requirements of the Clean Air Act Amendments of 1990 and the Rio Treaty of 1992 concerning global warming, by means of the development and demonstration of new high-efficiency emissions-control technologies. The goal is to provide the electric utilities with technology options that will enable them to comply with environmental regulations, at costs that will keep coal systems competitive in both domestic and foreign markets.

Program Goals

The primary intent of the Flue Gas Cleanup program is threefold:

- To develop extremely high-efficiency emissions-control technologies to reduce SO_2, NOx, and particulate emissions to less than one-tenth of current New Source Performance Standards (NSPS) levels.
- To mitigate the risks associated with air toxics emissions.
- To determine the technical and economic feasibility of postcombustion options for CO_2 control.

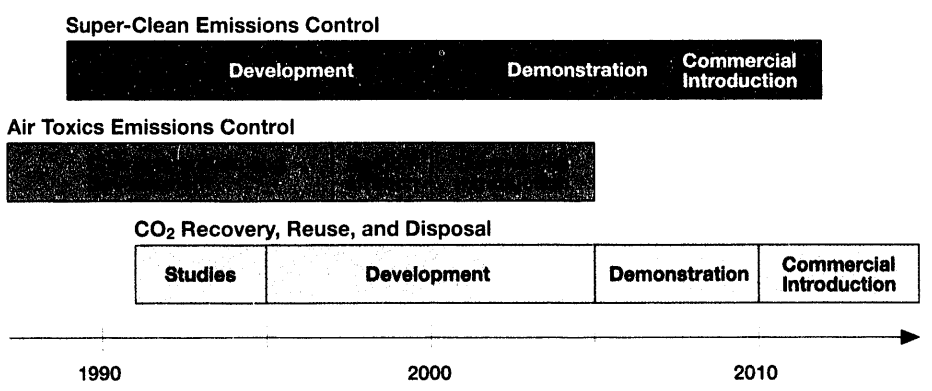
The technologies developed within this program must minimize parasitic power consumption, or add to the power being generated, if possible. To minimize waste disposal requirements, the technologies also must produce usable by-products. The Flue Gas Cleanup program is structured to address anticipated environmental requirements for the commercial deployment of coal-based power systems after the year 2000.

The Flue Gas Cleanup program has three major program elements:

Super-Clean Emissions Control

This program element focuses on the development of super-clean emissions-control technologies for present and future coal-based power systems. Its objective is to provide emissions-control technologies that reduce SO_2, NOx, and particulates to one-tenth the level required by the NSPS without high-volume solid waste generation.

Development Cycle



➤ The Flue Gas Cleanup program provides for the development of advanced control technology for near-term needs, such as control technology for air toxics emissions, and long-term control technologies for advanced power systems beyond 2010.

Air Toxics Emissions Control

This program element will characterize the specific air toxics associated with coal-based power systems as appropriate, and develop control technologies.

Carbon Dioxide Recovery, Reuse, and Disposal

This element will develop control technologies for CO_2 collection, reuse, and/or disposal. Its purpose is to provide an array of technology options that can be successfully demonstrated to capture and substantially postpone the reentry of CO_2 into the atmosphere, without adding more than 20 percent to the cost of electricity.

RD&D Program Goals

Flue Gas Cleanup	
	1/10
	1/10
	1/10
	90% to > 99%, depending on substance
	0.4 lb CO_2 per kW-hour; 80% recovery/sequester of CO_2 produced

NSPS=New Source Performance Standards

Program Elements Interaction

Flue Gas Program Contributions to Advanced Power Systems

	Super-Clean Emissions Control	Air Toxics Emissions Control	CO_2 Recovery, Reuse, and Disposal
LEBS	■	■	■
IFC	■	■	■
DCFHE	■	■	■
PFBC			■
MHD		■	■
IGCC			■
IGFC			■

➤ Advanced Flue Gas Cleanup systems for SO_2, CO_2, NOx, and particulate controls can be effectively integrated into advanced power-generating systems at the time that those systems are developed.

Flue Gas Cleanup Program Activities

Research and development activities in the Flue Gas Cleanup program begin with small laboratory experiments and continue through proof-of-concept (POC) testing at the 1 MWe to 12 MWe scale. The technologies are then ready for demonstration, either in a facility that is integrated with one of the advanced power systems under development, or separately at an existing power plant.

The specific tasks of the three major program elements can be summarized as follows:

Super-Clean Emissions Control

Activities in this program element are focused on three areas:

- Development of high-performance flue gas cleanup systems capable of removing 99 percent of the SO_2 and 95 percent of the NOx from flue gas. These advanced systems should be developed through the POC stage by the year 2000 and be demonstrated at full scale by 2006.
- Development of new control methods to limit emissions of fine particulates to 0.002 pounds per million Btu. Full-scale testing of the most promising control technologies for coal-based advanced power systems will be completed by 1998.
- Identification and development of coal-based systems with NOx reduction sufficient to operate in ozone nonattainment areas. Development through the POC stage will be accomplished by 1997.

Air Toxics Emissions Control

This program element will pursue parallel characterization studies on the emissions of existing and advanced power systems, and will identify potential air toxics emissions. Control strategies will then be developed for specific hazardous substances. This element will be closely integrated with the advanced power system programs of the DOE.

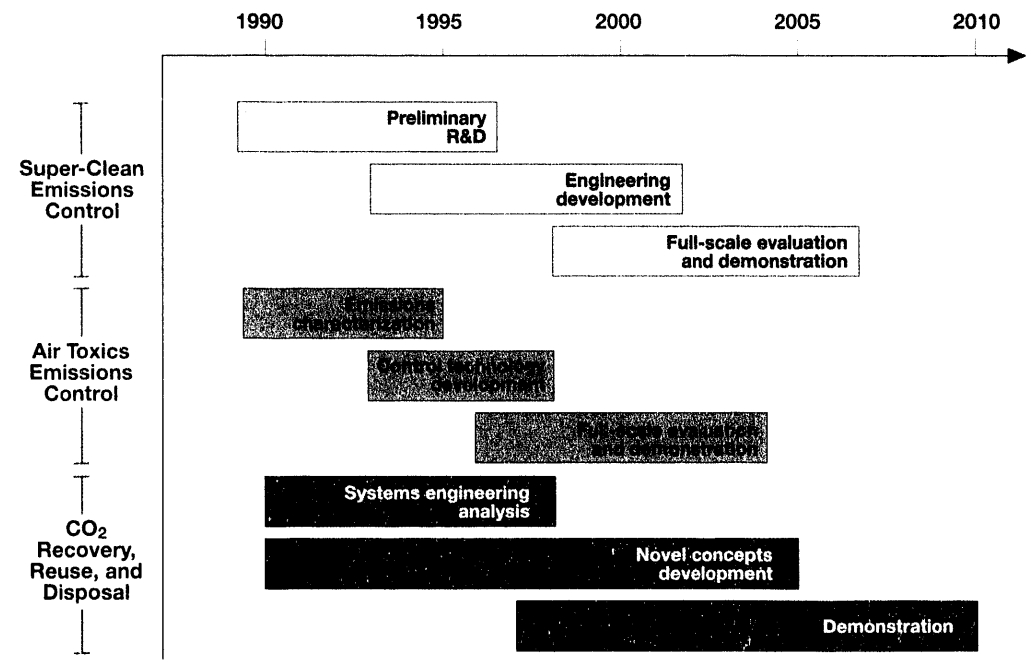
Advanced Research

The Air Toxics Emissions Control element is supported by research activities conducted by the Advanced Research and Technology program. Specifically, studies of the transformations of trace elements that occur during the coal combustion process are being conducted to provide insight into the types of technology required for control of air toxics emissions.

Carbon Dioxide Recovery, Reuse, and/or Disposal

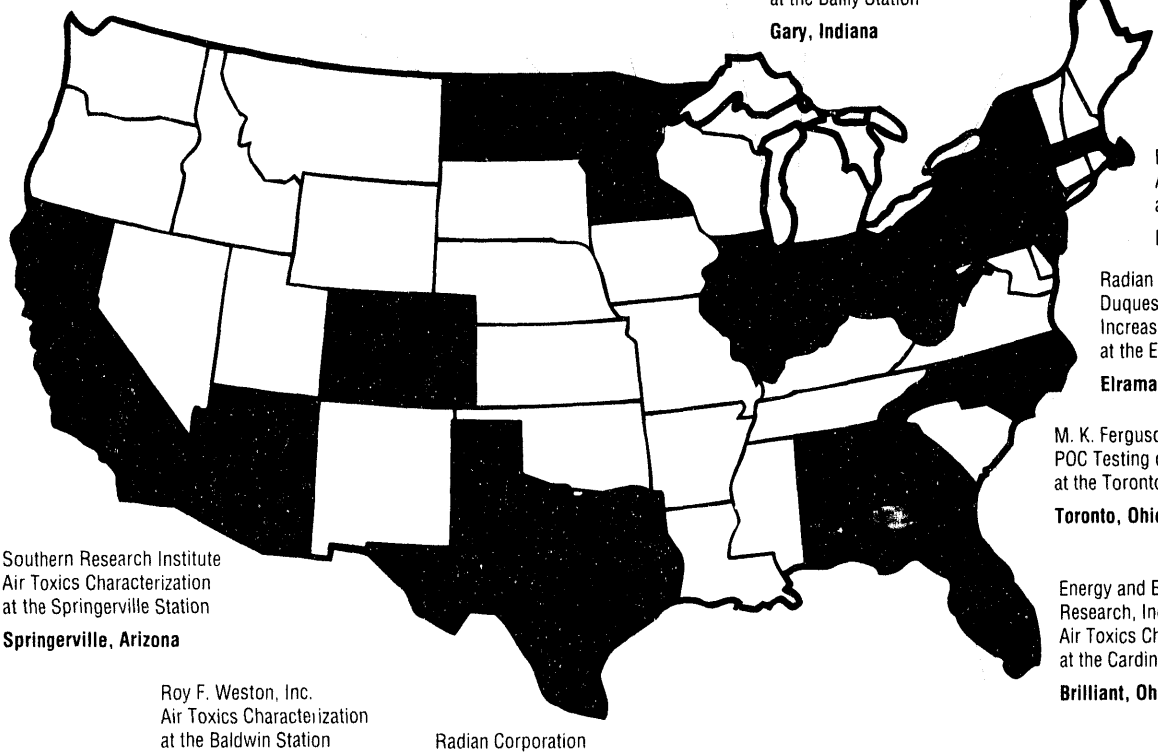
Technologies capable of meeting performance objectives will be developed through the POC stage by 2005 and subsequently demonstrated at full scale by 2010. Program activities will include extensive analysis of concepts, engineering analyses, and the development and demonstration of novel approaches to the capture, reuse, and disposal of CO_2.

Major Activities and Milestones



◄ The major activities of the Flue Gas Cleanup program have been structured and integrated to provide for the commercialization of advanced control technologies by 2010. Milestones have been developed to allow flexibility in control technology development for regulatory changes.

Major Demonstrations and Activities



Electric Power Research Institute
High Sulfur Test Center

Radian Corporation
New York State Electric and Gas
Increased Scrubber Efficiency
at the Kintigh Station

Somerset, New York

Roy F. Weston, Inc.
Air Toxics Characterization
at the Clay Boswell Station

Cohasset, Minnesota

Battelle Memorial Institute
Air Toxics Characterization
at the Coal Creek Station

Underwood, North Dakota

Radian Corporation
Hoosier Energy
Increased Scrubber Efficiency
at the Merom Station

Sullivan, Indiana

Radian Corporation
Public Services of Indiana
Increased Scrubber Efficiency
at the Gibson Station

Owensville, Indiana

Southern Research Institute
Air Toxics Characterization
at the Bailly Station

Gary, Indiana

Allied Signal Corp.
POC Testing of the SOXAL
Process at the Dunkirk Station

Raycon
POC Testing of the Tung
Process at the Dunkirk Station

Dunkirk, New York

Battelle Memorial Institute
Air Toxics Characterization
at the Niles Station

Niles, Ohio

Radian Corporation
Duquesne Light Co.
Increased Scrubber Efficiency
at the Elrama Station

Elrama, Pennsylvania

M. K. Ferguson Co.
POC Testing of the NOXSO Process
at the Toronto Station

Toronto, Ohio

Southern Research Institute
Air Toxics Characterization
at the Springerville Station

Springerville, Arizona

Energy and Environmental
Research, Inc.
Air Toxics Characterization
at the Cardinal Station

Brilliant, Ohio

Roy F. Weston, Inc.
Air Toxics Characterization
at the Baldwin Station

Baldwin, Illinois

Radian Corporation
Southwestern Electric Power Co.
Increased Scrubber Efficiency
at the Pirkey Station

Hallsville, Texas

Radian Corporation
Air Toxics Characterization
at Plant Yates

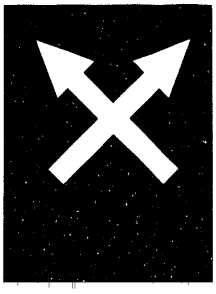
Newnan, Georgia

Radian Corporation
Tampa Electric Co.
Increased Scrubber Efficiency
at the Big Bend Station

Apollo Beach, Florida

Shading indicates states where DOE-funded research activities occur.

The Waste Management program focuses on the development of methods for the efficient and environmentally sound management of the waste produced by advanced power systems. In meeting stringent air emission regulations, these systems often transform gaseous emissions into solid or liquid waste products. These waste products must then be used or disposed of in ways that conform with regulatory statutes dealing with the protection of land, surface water, and groundwater resources. The diversity of the advanced power generation technologies under development and the differences in their waste products require a variety of options. As a crosscutting program, the Waste Management program will therefore have an impact on all of the advanced coal-fueled power systems under development.



Waste Management RD&D Program Description

The Waste Management program is focused on the waste products being formed by the advanced power generation technologies currently under development in both public and private sectors.

These waste products must be managed in a way that ensures compliance with regulatory statutes such as the Clean Water Act, the Safe Drinking Water Act, the Resource Conservation and Recovery Act, and the National Energy Policy Act. The Waste Management program will make sure that technology is available to achieve this compliance.

Program Goals

A major goal of the program is to establish that solid waste from advanced fossil energy technologies is not a roadblock to their commercialization. Specific targets include:

- Achievement of 50 percent utilization of solid waste from advanced fossil energy technologies in commercial markets.
- Identification of cost-competitive, high-volume uses for advanced coal combustion wastes.
- Utilization of advanced coal combustion by-product materials to stabilize, remediate, and reclaim contaminated grounds.

In general, waste technologies can be classified as:

- Disposal technologies, for dealing economically and efficiently with waste materials.
- Utilization technologies, for recycling the waste materials instead of disposing of them.

Disposal Technology

This program element involves the placement of waste products in permanent repositories. Although waste utilization is preferable to disposal, market conditions or the characteristics of the waste may preclude recycling. Therefore, environmentally sound and economical disposal technology must be available as the minimum requirement for commercialization of advanced power systems to proceed. All methods must provide:

- Suitable methods for cost-effective removal of the residue from the producing facility.
- Design features at the repository that prevent the release of potentially harmful chemical species into the environment.

Disposal technology development is currently focused on the characterization of the wastes produced by clean coal technologies. This study has moved from the laboratory to the field to examine how individual waste materials interact with the environment.

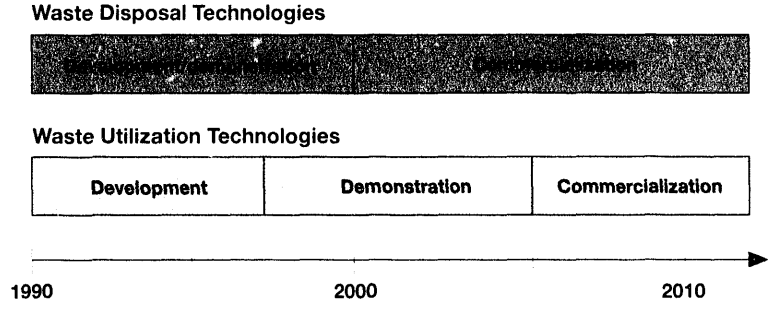
Utilization Technology

Utilization of waste products is desirable because it not only eliminates the need to find suitable storage for wastes, but also creates a new resource material, while conserving natural resources. Utilization technologies involve:

- The use of wastes to replace existing materials in commercial products.
- The use of the waste materials to create new products.

The use of waste materials must be not only environmentally protective, but also cost-competitive with other, more conventional materials.

Development Cycle



➤ The Waste Management program provides for the development of advanced waste disposal and utilization technologies for use with existing and future coal-fueled power plants.

RD&D Program Goals

Waste Management	
[redacted]	Commercial and regulatory acceptance by 2010 of methods for environmentally benign and economically competitive disposal of solid wastes from advanced power systems.
	Completion of chemical, physical, and regulatory characterization of waste products produced by developing advanced pulverized coal technologies.
[redacted]	50% utilization by 2010 of solid wastes from advanced pulverized coal technologies in commercial markets.
	Established usage of alkaline coal by-products for environmentally protective mine remediation.
	Commercial acceptance of products manufactured from advanced pulverized coal by-products.

Program Elements Interaction

Waste Management Program Contributions to Advanced Power Systems

	Waste Characterization	Waste Disposal R&D	Waste Utilization Technology Development
LEBS	■	■	■
IFC	■	■	■
DCFHE	■	■	■
PFBC	■	■	■
MHD	■	■	■
IGCC	■	■	■
IGFC	■	■	■

➤ Waste management of solid process wastes can be effectively integrated into all advanced power generating systems at the time that those systems are developed.

Waste Management Program Activities

The activities of the Waste Management program can be divided into three areas: the characterization of wastes, disposal studies in the field, and the development of utilization technologies.

Waste Characterization

This includes all the projects involved in the collection and subsequent physical, chemical, mineralogical, and regulatory analysis of residues. Such projects develop a comprehensive understanding of the nature of each waste material, necessary in order to predict how it will interact with the environment, or to assess its utilization potential.

Waste Disposal R&D

This research investigates the interaction of waste materials with the environment. Typically, test cells containing waste materials are monitored extensively for an extended period of time. Specific objectives include:

- Determining the leaching behavior of a broad spectrum of wastes.
- Identifying technologies, such as self-cementation, that can be used to improve the environmental performance of waste repositories.

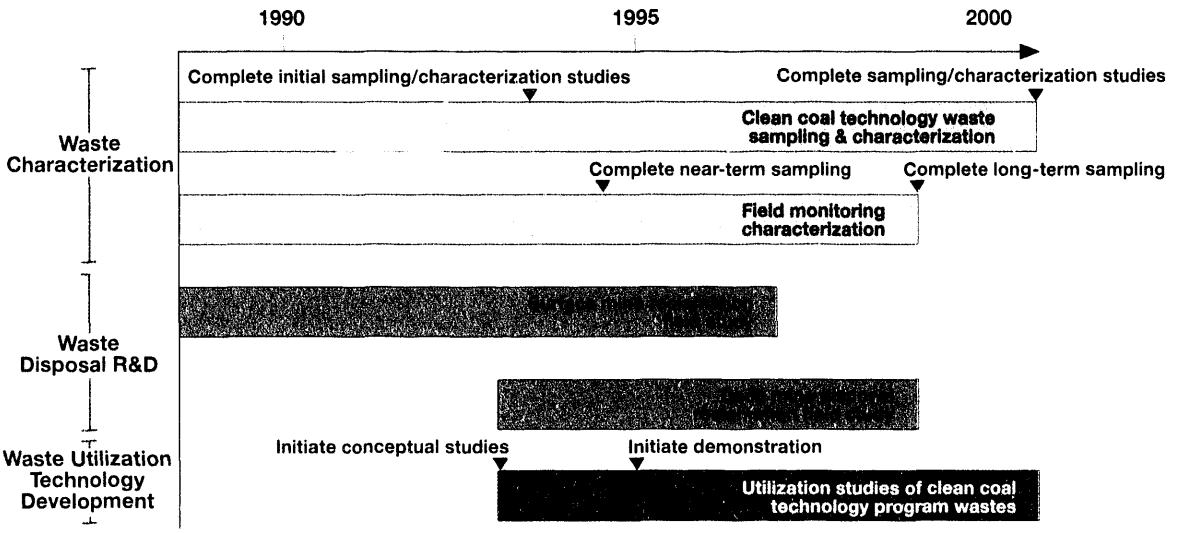
The studies will provide information needed by utilities and regulators to determine the design of disposal facilities. The results from the field studies will be correlated with laboratory studies and existing geohydrological models to predict engineering and environmental performance of full-scale waste disposal.

Waste Utilization Technology Development

This program element focuses on developing technologies that could divert large quantities of waste materials from nonproductive disposal. Economic as well as technical issues are examined in determining feasibility, and industrial support is being pursued to increase the likelihood of successful commercialization.

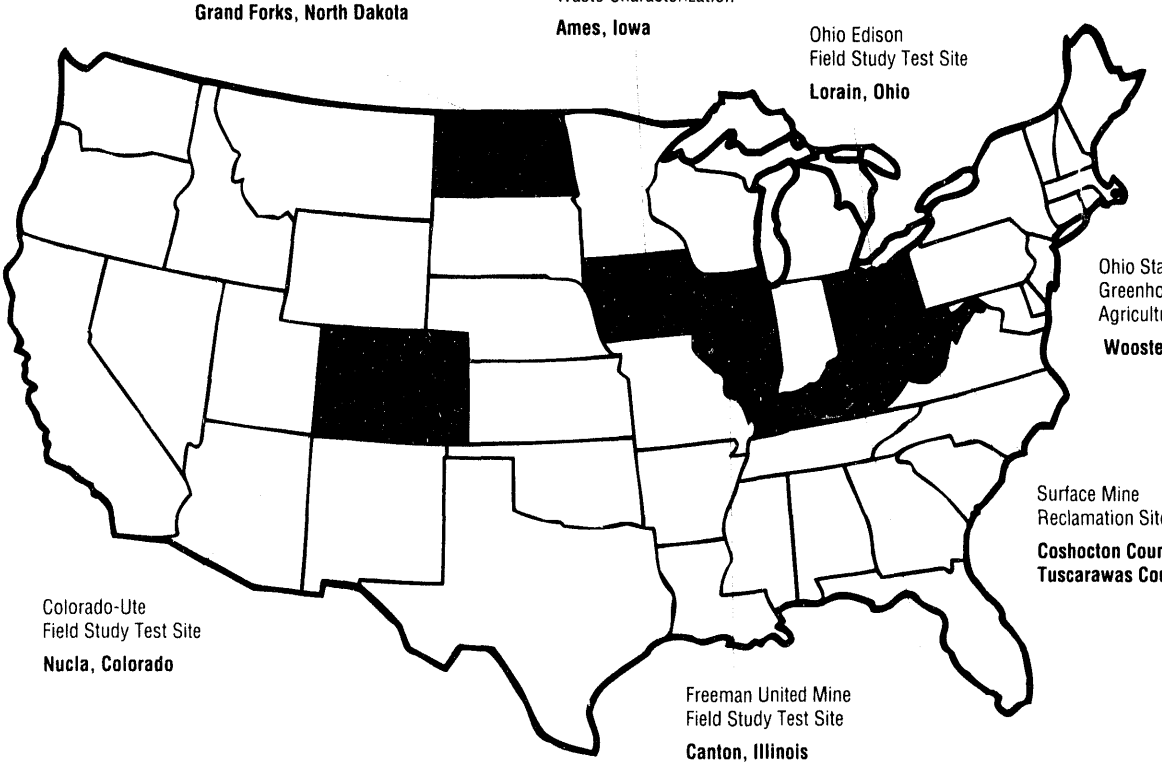
Utilization technology efforts center on inexpensive, low-technology processes which have the potential for using large quantities of residues. There are already many examples of successful waste product recycling, such as the use of fly ash in concrete, and desulfurization gypsum in wallboard. The best uses are generally considered to be found in construction, agriculture, mine reclamation, and soil stabilization.

Major Activities and Milestones



▲ The major activities of the Waste Management program have been structured and integrated to promote the commercialization and widespread use of advanced waste management and utilization technologies in the next decade. Milestones have been developed to allow flexibility with respect to possible regulatory changes.

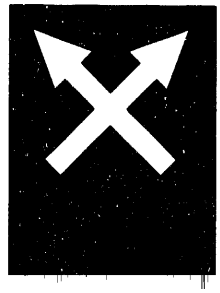
Major Demonstrations and Activities



Shading indicates states where DOE-funded research activities occur.

The Base Research Crosscutting Technology program supports multiple technologies. Its major objective is to pursue applied research and technology transfer in critical enabling science and technology areas that crosscut multiple fossil energy technologies. It aims to strengthen the U.S. knowledge base and infrastructure, enhance economic and environmental acceptability of domestic fossil fuels, and strengthen the international competitiveness of the U.S. fossil fuel industry.

Partnerships with national laboratories, industry, and academia play an important role in the work of this research program. They link the applied research efforts on fossil fuels science at the nation's universities with technological innovations in industry.



Crosscutting Base Research RD&D Program Description

Within the Coal Advanced Research and Technology Development (AR&TD) program, there are several crosscutting research programs. These programs are aimed at developing the means to overcome technological barriers to the realization of power systems' goals, and to increase the scientific and technological knowledge base required to understand the mechanisms controlling these systems. The programs have application to all fossil fuel technologies: coal, petroleum, and natural gas.

Each of the program elements makes a specific contribution of critical data. The three major programs are:

- Advanced Materials Research
- Coal Bioprocessing Research
- University Coal Research.

A fourth program, the Small Business Innovation Research (SBIR) program, receives 1.5 percent of the Fossil Energy (FE) extramural RD&D budget. Under this program, competitive grants are made to small businesses for research projects which crosscut all fossil energy technology areas.

Advanced Materials Research

This program aims at the development of a technology base in advanced materials synthesis and processing, conducted by exploratory research of new materials, ideas, and concepts that have the potential to improve significantly the performance or cost of existing fossil systems, or to enable the development of new systems and capabilities.

Some of the products under development are tough ceramic structural composites, high-temperature corrosion-resistant structural alloys, and new materials which provide specific new performance functions.

Coal Bioprocessing Research

This program element is focused on ways to apply biotechnologies to improve the performance and environmental acceptability of coal utilization and conversion. Research investigates the fundamental chemistry, biochemistry, microbiology, and engineering of coal bioprocessing, focusing on the bioconversion of coal and coal-derived gases, liquids, and wastes, and on bioprocess engineering.

University Coal Research

This research is focused on improving the knowledge base in fundamental and innovative coal science and technology research, and on training fossil fuel scientists and engineers in relevant disciplines.

Other Base Research

Other projects include research to develop the basic information required to design efficient and cost-effective solids transport systems; development of novel components to improve the durability and reliability of fossil energy systems; and instrumentation and diagnostics to measure and control energy conversion system processes.

Advanced Materials Research

Research Areas	Research Subtopics
Functional Materials	Inorganic membranes Catalysis support materials Solid-state electrolyte systems materials Ceramic filters Carbon molecular sieves
Structural Ceramics	Structural ceramic composites Nanocluster ceramics
Structural Alloys	Advanced austenitic alloys Iron aluminides Advanced coatings and claddings Ultra-high-temperature alloys

➤ The focus of the Advanced Materials Research element is on resolving problems in physical and chemical environments that are beyond the limits of current materials. New, advanced materials are expected to deliver increased system efficiency, durability, and operability, as well as to reduce costs. A further goal is the development of new materials for new systems concepts.

Crosscutting Base Research Program Activities

The activities of each element of the Crosscutting Base Research program are as follows:

Advanced Materials Research

Activities in this area address the development of functional materials to provide new systems capabilities, the development of new structural ceramics and alloys, methods of minimizing the effects of corrosion, and technology development and transfer.

Functional Materials

Functional materials are being developed for new systems capabilities. These include solid-state electrolytes for energy conversion, gas separators, and reactors; inorganic membranes for gas, liquid, and solid separations; catalyst supports for more effective catalytic systems; carbon molecular sieves for gas separations; and ceramic filters for hot gas cleanup.

Structural Ceramics

Research is being conducted on ceramic composites and nanocluster ceramics to provide tough ceramics for very high temperature, harsh environments.

New Structural Alloys

Advanced austenitic alloys, iron aluminides, ultra-high-temperature intermetallic alloys, and advanced coatings that will resist erosion and corrosion better are being developed.

Corrosion

Research in this area concentrates on the fundamental mechanisms that lead to degradation of materials in the highly corrosive environments characteristic of coal conversion and utilization environments.

Technology Development and Transfer

This sector of research monitors fossil materials needs and any advances in materials science. It supports jointly funded projects which improve the pace and effectiveness of technology transfer to industry.

Coal Bioprocessing Research

Biological processing of fossil fuels is in an embryonic state. Research efforts to date have focused on obtaining and characterizing biocatalysts that perform as desired, not on understanding the unique biochemistries involved. FE bioprocessing activities focus on three areas: bioconversion of coal to fuel constituents, removal of pollutants from combustion gases, and bioprocess engineering studies.

Conversion of Coal to Fuel Constituents

Research in this area includes methods for biocatalysis in non-aqueous systems, depolymerization of coal with microorganisms, and upgrading of coal liquids to transportation fuels.

Removal of Gaseous Pollutants

Differing methods of removing SO_2 and NOx from coal-derived combustion gases are being explored.

Bioprocess Engineering Studies

This research evaluates engineering parameters that influence the operation of bioprocessing reactors. It also investigates new reactor concepts.

Coal Bioprocessing Research

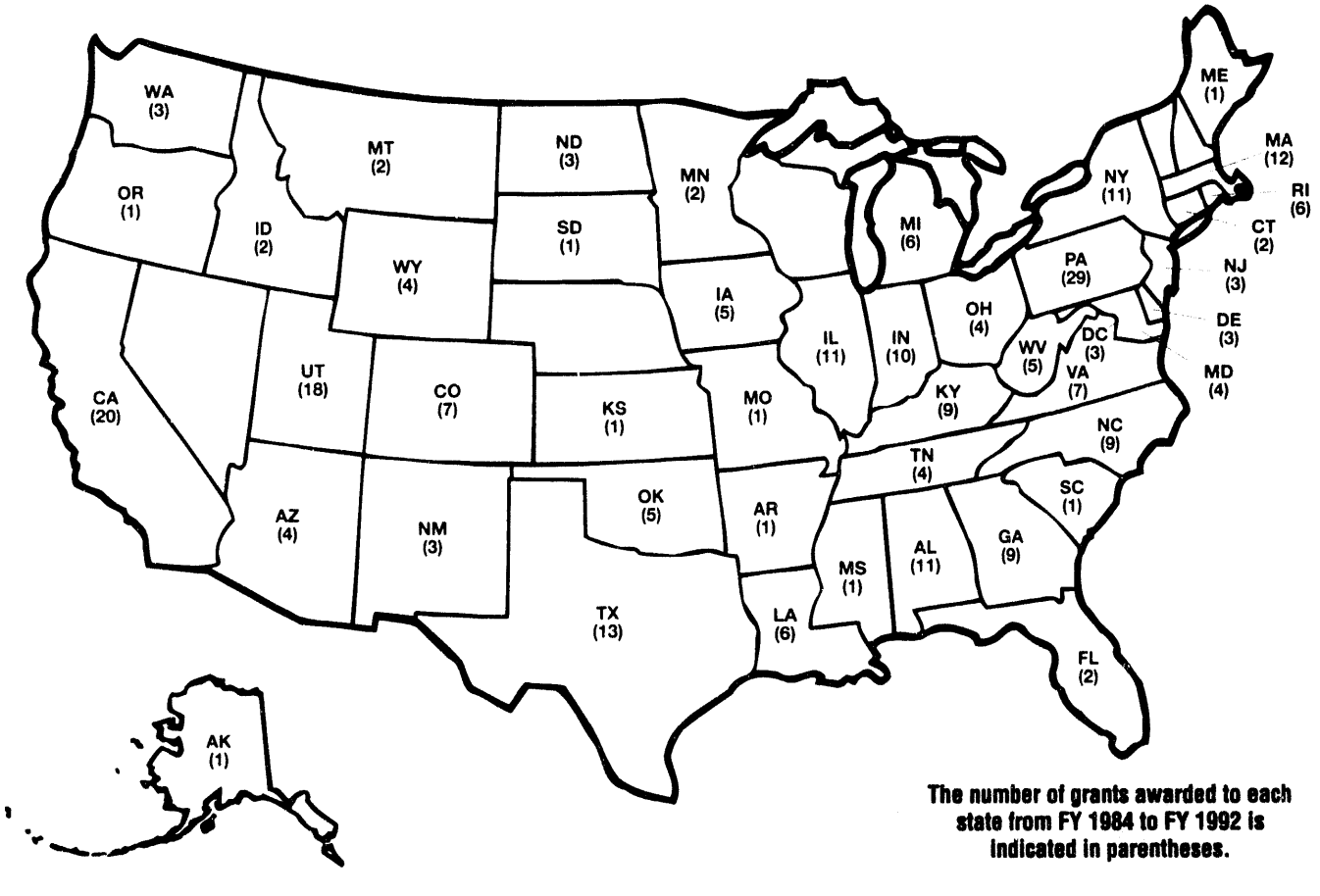
Research Areas	Research Subtopics
Bioconversion of Coal	Coal solubilization Use of biocatalysts in non-aqueous systems Conversion of synthesis gas to oxygenates
Pollution and Waste Management	Removal of pollutants from gas streams Decontamination of solid wastes from coal and petroleum processing
Bioprocess Engineering	Reactor development and testing Mathematical modeling of bioreactors

➤ Coal Bioprocessing Research is dedicated to the discovery and development of improved methods for conversion and utilization of coal and coal-derived materials, including effluents and waste products, through the use of biological or biomimetic systems.

University Coal Research

The goal of this program is to encourage United States universities to conduct applied research in coal science. This research is purposely broad in scope, since it is expected that each project will make a contribution to the overall understanding of the chemical and physical processes involved in the conversion and utilization of coal. The University Coal Research program provides funds for such projects, in support of the FE strategic goals of environmentally acceptable power generation options and secure liquid fuel options. Approximately 25-30 grants for meritorious coal research are awarded each year. A pilot project also promotes collaborative research between university and industry teams.

Participants in FE University Coal Research Program



The number of grants awarded to each state from FY 1984 to FY 1992 is indicated in parentheses.

Glossary of Terms

AFU	Alternative Fuels Utilization
AFS	Advanced Fuel Systems
APC	Advanced Pulverized Coal
APS	Advanced Power Systems
CAAA	Clean Air Act Amendments
CGEN	Coal-Fired Cogeneration
CO_2	carbon dioxide
COE	cost of electricity
CRADA	Cooperative Research and Development Agreement
DCFD	Direct Coal-Fired Diesels
DCFGT	Direct Coal-Fired Gas Turbines
DCFHE	Direct Coal-Fired Heat Engines
EFCC	Externally Fired Combined Cycle
FE	fossil energy
GPIF	Gasification Product Improvement Facility
HAP	hazardous air pollutant
HIPPS	High Performance Power System
HITAF	high-temperature advanced furnace
IFC	Indirectly Fired Cycle
IGAC	Integrated Gasification Advanced Cycle
IGCC	Integrated Gasification Combined Cycle
IGFC	Integrated Gasification Fuel Cell
kW	kilowatt
LEBS	Low Emission Boiler System
MCFC	Molten Carbonate Fuel Cells
METC	Morgantown Energy Technology Center
MGS	Mild Gasification System
MHD	Magnetohydrodynamics
MWe	megawatt
NOx	nitrogen oxide
NSPS	New Source Performance Standards
PAFC	Phosphoric Acid Fuel Cell
PC	pulverized coal
PDU	process development unit
PETC	Pittsburgh Energy Technology Center
PFBC	Pressurized Fluidized-Bed Combustion
POC	proof-of-concept
PRU	process research unit
SOFC	Solid Oxide Fuel Cell
SO_2	sulfur dioxide