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PETCreview

Pittsburgh Energy Technology Center
Office of Fossil Energy
U.S. Department of Energy

Combustion 2000

**Liquid
Transportation
Fuels from Coal
Part 2: Indirect
Liquefaction**

**A Computer
Expert System
to Reduce Power
Plant Emissions**

**PETC's Flow
Analysis
Laboratory
Assists Artificial
Heart Research**

Office of Fossil Energy
U.S. Department of Energy

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On the Cover: A view of Georgia Power's Plant Hammond located in Coosa, Georgia, where the DOE Clean Coal Technology Program is demonstrating three advanced combustion techniques to reduce nitrogen oxides emissions. See Highlight on page 40. Photographed for DOE by R.C. Krieder.

MASTER

FROM THE DIRECTOR

As I mentioned in the last issue, the U.S. Department of Energy recently released the first edition of the National Energy Strategy. This strategy is meant to lay the foundation for a more efficient, less vulnerable, and environmentally sustainable energy future. It highlights four major goals:

- Increasing energy and economic efficiency
- Securing future energy supplies
- Enhancing environmental quality
- Fortifying foundations through fundamental science and engineering research education and technology transfer

Sun W. Chun

I am pleased to say that the work we perform and manage at PETC strongly supports these goals and that we have already made major contributions in all of these areas. In this issue of the *PETC Review*, we present four articles on projects that are excellent examples of work related directly to each of the major goals.

The "Combustion 2000" article describes an exciting new program that is designed to achieve dramatic improvements in the efficiency and environmental performance of future coal-fired power plants, while maintaining electricity costs at or below current levels. The two major parts of the Combustion 2000 program are the engineering development of a "Low-Emission Boiler System," which applies relatively near-term technology to lower sulfur dioxide and nitrogen oxides emissions, and the "High-Performance Power System," which uses advanced technology for significant efficiency increases. Industry has responded to our solicitations requesting proposals for both parts of the program and will undertake the challenge of developing these improved power systems by forming teams with the necessary skills and commitment to make this program a success.

The matter of securing the nation's energy future was introduced in the last issue of the *PETC Review* with the first of a two-part article on "Liquid Transportation Fuels from Coal." We take that subject up again in this issue to discuss indirect liquefaction and the nation's ability to produce transportation fuels from coal. As some of our readers may know, indirect liquefaction is the only coal conversion technology that can produce performance enhancing additives (e.g., alcohols) for gasoline to increase octane ratings and to reduce automobile emissions. Indirect liquefaction is also a particularly good route for producing high-cetane diesel fuels.

On the environmental front, a new and very promising approach to choosing the "correct" cleaned coal for a utility's boiler is being developed. A Coal Quality Expert computer program will, through a series of logic questions, help utilities pick the most economical coals to achieve required emissions levels. The Coal Quality Expert System will use data from an extensive series of test burns of coals cleaned by different means and to different degrees.

Finally, we offer the article "PETC's Flow Analysis Laboratory Assists Artificial Heart Research." Using equipment that is normally employed to study coal flow to instead study the flow of blood in artificial hearts, this project is one of the finest examples of technology transfer at work. The results of these studies may eventually help sustain human lives.

We continuously strive to fund research that would enhance both the efficiency of fossil energy technologies and the dependability of future energy supplies, while providing for better environmental quality and reduced energy costs. In addition, we try to transfer and apply technologies to all areas of science and research. We are excited about the future and the possibilities open to us in the field of fossil energy; we will continue to share the results of those efforts with you as they develop.

COMBUSTION 2000

Coal is this country's largest and most valuable energy resource, comprising over 75% of our proven energy reserves. These reserves are the energy equivalent to about 2 trillion barrels of crude oil, more than double the world's known oil reserves. If we can use coal to reduce our dependence on imported oil, the United States can move toward greater energy self-sufficiency, energy security, and economic stability. For this to happen, environmental problems associated with greater use of coal need to be addressed. This is the driving force behind Combustion 2000.

The U.S. Electricity Supply

Electric utilities consume nearly 800 million tons of coal per year or about 85% of the coal used in the United States. About 55% of all the electricity generated in the United States is produced from coal. To maintain and increase coal's future role in the production of electric power, new combustion and emissions control technologies that offer low emissions, high efficiency, and a high degree of reliability are required. These technologies must cost no more than those of the conventional technologies in use today.

Although many electric utilities now have excess generating capacity, this situation is expected to change during the coming decade. The construction of new power plants has, for various economic and political reasons, been less than expected and is not keeping pace with increasing electricity demand. New plant construction will eventually have to increase significantly, probably during the late 1990s and early 21st century, to keep up with demand.

According to the Energy Information Administration, the net effect of retiring aging power plants and of adding new plants that are now under construction or that are planned to come on line by the mid-1990s will be to raise operable capacity to about 700 GW. This increase in capacity is equivalent to an annual growth of about 0.5%. However, during this

period of slow growth in net supply, electricity demand is expected to grow by about 3%, a figure comparable to the projected rate of overall economic growth. A load growth of 3% represents a need for 20,000 MW per year of new capacity—the equivalent of building twenty 1,000-MW plants each year. Therefore, by 1995, moderate growth in electricity demand and low growth in generating capacity will cause excess capacity to disappear. By the year 2000, significant shortfalls are projected between power demand and generating capacity.

Emissions regulations are expected to sharply tighten over the next decade as a result of continuing concern over acid rain, air toxics (e.g., metals and polycyclic aromatic hydrocarbons), global climate change, ozone pollution, and solid waste disposal. Therefore, new power plant capacity will be needed at a time when increased pressures may come to bear on power producers to lower the emissions of sulfur dioxide (SO₂), nitrogen oxides (NO_x), and, perhaps, air toxics and carbon dioxide (CO₂). Systems to burn coal more cleanly and economically must become available within the next decade to ensure that coal will continue to be a fuel of choice for electric power generation. If these systems can be provided, the United States will be able to realize the benefits of using its most abundant energy resource.

Enter Combustion 2000

Early in 1989, a task group was organized at PETC to lay the foundation for a new program that would address the needs of clean coal technology for the first decade of the 21st century and beyond. This new program, called Combustion 2000, aims to develop the technology base that directly addresses the major threats to the continued use of coal for electric power generation. The specific goals of the program are to (1) dramatically improve the environmental performance of future coal-fired power plants and (2) significantly increase the efficiency of coal-fired power production. These goals will be achieved by conducting two parallel and complementary activities: (1) development of a Low-Emission Boiler System and (2) development of a High-Performance Power System.

Low-Emission Boiler System

The Low-Emission Boiler System (LEBS) will use relatively near-term technology to develop a power plant that has dramatically lower SO₂, NO_x, and particulate emissions than do today's plants and that will also keep the cost of electricity comparable to that of conventional technology (e.g., a pulverized coal boiler with electrostatic precipitator and wet limestone scrubber). Recent technological advances have been made in the combustion and flue gas cleanup areas. Examples of combustion technologies that are becoming available include combustion modifications for minimizing NO_x emissions such as staged air, staged fuel (reburning), and improved high-efficiency, low-NO_x burners; and slagging and vortex combustors capable of rejecting a significant fraction of the ash before it enters the boiler.

Some of these advances are the result of scientific research conducted over the past 20 years. For example, applications of research on the chemistry of nitrogen compounds during combustion are appearing in full-scale, coal-fired utility plants. This research indicates that advanced combustion controls alone should be

capable of limiting NO_x emissions to 0.2 lb NO₂/10⁶ Btu in new coal-fired utility boilers. This compares with a current U.S. New Source Performance Standard (NSPS) of 0.6 lb NO₂/10⁶ Btu for bituminous coal. In some Western European countries, NO_x emissions standards have already been reduced to the range of 0.2 lb NO₂/10⁶ Btu. Fairly expensive flue gas cleanup systems dedicated to NO_x control are the only technically viable options presently available for meeting such stringent NO_x emissions standards. By focusing on advanced combustion controls, the LEBS program offers a much lower cost alternative for extensive reductions in NO_x emissions.

Slagging combustors, similar to the type originally developed under DOE sponsorship in the mid-1970s for magnetohydrodynamics (MHD) applications, have been demonstrated on industrial boilers. In addition to high carbon conversion efficiency, slagging combustors have been shown to achieve low NO_x emissions and coal ash removals of up to 90% upstream of the boiler. This high ash rejection can result in improved boiler tube environments that, in turn, could lead to tighter tube spacings, improved heat exchange, smaller boiler size, and lower cost. The vitrified ash produced by slagging combustors is also a more environmentally benign waste product because the metals incorporated in this form of ash are not expected to be leachable.

Emerging Flue Gas Cleanup Technologies. The Combustion 2000 Task Group reviewed over 20 flue gas cleanup technologies that are now under development. Among the more promising candidates for the Low-Emission Boiler System are advanced limestone scrubbing (e.g., forced oxidation, with or without an adipic acid additive), NOXSO (see *PETC Review*, Issue 2), Tung flue gas desulfurization, and WSA-SNOX. These four technologies are discussed below.

- Forced oxidation limestone scrubbing enhanced with an adipic acid additive, already in use in Europe, represents an improvement to commercial wet scrubbers.

It produces a gypsum by-product that may be sold for profit or disposed of safely and inexpensively in a landfill.

- The NOXSO process is a dry flue gas treatment process capable of removing both SO_2 and NO_x . These species are removed from the flue gas as the gas passes through a fluidized bed of solid adsorbent at 120°C . Spent sorbent is regenerated by heating to desorb NO_x and treating it with a reducing gas, which yields a mixture of SO_2 and H_2S that is then converted to elemental sulfur in a Claus reactor. The NO_x stream is recycled to the boiler where it dissociates to nitrogen and oxygen. The NOXSO process generates little waste by maximizing production of salable products. A 5-MWe proof-of-concept test is underway at Ohio Edison's Toronto Station, and a 100-MWe demonstration is in the design phase under the Clean Coal Technology Program.

- The Tung process is a highly efficient regenerable wet scrubbing process that can remove 98% of the SO_2 . It is similar to the commercial sodium-based Wellman-Lord scrubber; however, the bisulfite solution is regenerated by extraction with an aqueous amine. SO_2 is steam-stripped from the relatively small volume of amine solution, which requires only a fraction of the energy that would have been needed to steam-strip SO_2 from the aqueous bisulfite solution itself. Installation and testing of the Tung process on a 3-MWe flue gas slipstream at Niagara-Mohawk Power Company's Dunkirk Station, scheduled for 1992, will demonstrate this process on a coal-generated flue gas.

- In the WSA-SNOX process, SO_2 is catalytically oxidized to SO_3 and recovered as concentrated sulfuric acid in an air-cooled, falling-film condenser made of glass. No raw materials are used, and no waste products or wastewater are generated. A WSA-SNOX demonstration project was selected for funding under Round 2 of the Clean Coal Technology Program.

(a) Conventional Coal-Fired Rankine Cycle for Power Generation

Figure 1. (a) Conventional (above) and (b) High-Performance (right) Power Systems.

Candidates for increasing the removal of particulate matter from flue gas are advanced electrostatic precipitators and improved fabric filters. Either emerging technology is capable of removing more of the fine particulates (under 10 microns) that are present in flue gas from coal-fired plants. Because many metal species and complex organic substances are adsorbed onto the surfaces of fine, respirable particulates, increasing the removal of fine particles will also reduce the emission of potentially harmful substances into the atmosphere.

Another important objective of the Low-Emission Boiler System is increased thermal efficiency. It is anticipated that efficiency improvements (to a level of between 38 and 42%) brought about by creatively integrating boiler, combustor, and flue gas systems will help offset the costs of advanced components. These improvements can come about through improved steam conditions attainable by using better heat exchange materials; greater low-temperature heat recovery from flue gases, and higher temperature flue gas desulfurization. The latter can eliminate the need for reheating stack gases to achieve acceptable plume buoyancy.

Modular design will also be emphasized, wherever appropriate.

The Low-Emission Boiler System will attempt to rethink coal-fired boiler design while using the new technologies that are now becoming available through research and development. Environmental control will be integrated with combustion, heat transfer, and all of the other aspects of boiler design. The new power system will outperform conventional plants; however, it will resemble today's plants sufficiently to make it readily acceptable by the electric utility industry.

High-Performance Power System

The second project to be conducted in parallel as part of the Combustion 2000 program may be among the most challenging efforts to be undertaken by DOE's Office of Fossil Energy. Designated the High-Performance Power System (HIPPS), the system would use advanced technology to produce electricity from coal with an overall thermal efficiency of 47% or higher. This compares to an efficiency of about 35% for today's conventional plants. In addition, because

it is targeted for commercial use somewhat later, the environmental performance goals for HIPPS are more stringent than those for the Low-Emission Boiler System. Emissions of SO_2 , NO_x , and particulates would be lower; and, because of the higher efficiency, emissions of CO_2 will be reduced significantly by between 25 and 30 percent. Thus, HIPPS directly addresses concerns over CO_2 , which has been associated with global climate change. Flue gas desulfurization wastes will be virtually eliminated by using cleanup processes that generate usable by-products. Equally important, the above performance will be achieved while aiming to reduce electricity costs by 10% compared with current systems.

Technology Candidates. A number of high-performance combined-cycle systems are already under development with DOE sponsorship, including (1) combined-cycle gasification—fuel cell, (2) combined-cycle gasification—gas turbine, (3) direct-fired gas turbine combined cycle, and (4) MHD combined cycle technologies. PETC has conducted studies to determine if there are other potentially attractive systems whose

Figure 2. Artist's conception of High-Temperature Advanced Furnace (HITAF). In this design, the water wall would be used to superheat steam for the steam cycle.

development should be supported. A leading candidate is a combined-cycle system that uses a gas turbine driven by a working fluid separately heated in a novel high-temperature advanced furnace (HITAF). A supplementary clean fuel can be used to boost the temperature of the working fluid in order to take advantage of high-temperature, high-efficiency gas turbines. Energy in the gas turbine exhaust is used to run a steam cycle. As with other high-performance systems, the new HIPPS can provide high thermal efficiency and reduced emissions of CO_2 .

The technological risk associated with HIPPS is relatively low. Other than advanced flue gas cleanup technology needed to achieve very low emissions, the only technology step-out is the

HITAF. Another advantage of HIPPS is that the power system will be much more like the facilities in use today than are some of the other advanced systems. Neither a gasifier nor a system to clean the hot gasification products (flue gas) is required. A simplified schematic of HIPPS is shown in Figure 1(b). Also, Figure 1(a) is a diagram of the coal-fired Rankine cycle, the type of cycle used by conventional power plants. The required turbines needed for HIPPS are already commercially available. Moreover, features are built into HIPPS that make this system evolutionary (i.e., a version of this system using coal and natural gas co-firing can even be built today using available high-temperature furnace technology). If there is a need to use natural gas for more valuable applications, the amount of gas used would

be reduced as advances are made in high-temperature furnace technology.

An artist's conception of what the furnace might look like is shown in Figure 2. The purpose of the furnace is to heat the clean working fluid—air—to prescribed turbine inlet temperatures. As in a boiler, the furnace will contain a radiant and a convective section (see *PETC Review*, Issue 2, "Combustion Primer" for more information). However, because the heat transfer surfaces will be at a higher temperature than in a boiler, the combustion process and heat transfer system must be closely controlled and matched. Engineering analyses have shown significant improvements in thermal efficiency for this HITAF concept (see Figure 3).

The design of the heat transfer surface may be quite unlike that used in conventional boilers or furnaces. The heat transfer materials will be under low stress because they will contain working fluid under the relatively low pressures (about 150-200 psi) of the turbine inlet. The use of heat transfer geometries other than tubes is a strong possibility. This could be a big advantage because advanced alloys or ceramics will need

to be used for some portion of the heat transfer surface. Fabrication of these advanced materials into heat transfer components need not be limited to the conventional shapes used for boilers.

NO_x emissions will be sharply reduced by regulating the rate of fuel and air addition into the furnace and by controlling the temperature profile of the combustion products. There is also the likelihood of significantly reducing SO₂ emissions by injecting a sorbent into the controlled-temperature furnace. Emissions controls will need to be well integrated with the combustion and heat transfer processes.

Program Approach

Table 1 summarizes the relationship of the Low-Emission Boiler System and the HIPPS projects with respect to the timing for commercial readiness; efficiency, emissions, and cost of electricity objectives; and key design features. Significant systems development efforts will be required for both the Low-

Figure 3. High-Performance Power System efficiency.

	<i>Low-Emission Boiler System (LEBS)</i>	<i>High-Performance Power System (HIPPS)</i>
Timing	Design base for initial <i>commercial plants</i> available by 2000.	Design base for <i>proof-of-concept plant</i> available by 1999; commercial readiness by 2004.
Thermal Efficiency	Uses an advanced version of a conventional steam power plant cycle to achieve efficiencies of 38-42%.	Uses an indirectly heated gas-turbine combined cycle that requires the development of a high-temperature advanced furnace (HITAF) to achieve efficiencies of 47% or higher.
Emissions Controls Technologies	Utilizes emissions controls technologies now in advanced development or demonstration to achieve SO ₂ , NO _x , and particulate emissions of 1/3, 1/3, and 1/2, respectively, of the current New Source Performance Standards (NSPS).	Utilizes similar, but more refined, versions of the emissions controls technologies used by LEBS to achieve SO ₂ , NO _x , and particulate emissions of 1/4 of the current NSPS (may also use "breakthrough" technologies, if available).
Process Improvements	Utilizes emerging improvements in pulverized coal (PC)-fired furnace design to reduce costs.	Utilizes a new PC-fired HITAF to achieve high performance and to reduce costs.
Target Cost	Cost of electricity target no higher than current coal-fired plant designed to meet NSPS.	Cost of electricity target 10% below that of current coal-fired plant designed to meet NSPS.

Table 1. Comparison of LEBS and HIPPS.

Emission Boiler System and the HIPPS. The new power plants will be designed from the ground up with advanced technologies in mind. All major plant subsystems (e.g., coal preparation and feeding, combustion, heat transfer, emissions controls, ash management, waste disposal, and power cycle configuration) will be totally integrated.

The Low-Emission Boiler System Program will have four phases:

- Systems analysis/R&D plan formulation and component definition/ preliminary commercial generating unit design
- Engineering development/subsystem testing
- Proof-of-concept (POC) plant design
- POC plant construction/operations

Systems analysis will include concept development and R&D planning for the entire program. System design assessments will be made periodically to evaluate the progress of the

work. The engineering development phase of the program will include component development and testing of the plant subsystems on a relatively small scale—about 3 to 5 MWe. Sufficient time will be allowed for engineering development so that major technical issues are resolved before proceeding with the POC plant, which would have a rating of at least 20 MWe. The POC testing and evaluation, which is to be completed in Fiscal Year 2000, will serve as the design basis for a commercial-scale plant.

Development of the Low-Emission Boiler System will require expertise in a broad range of technical areas (e.g., boiler design, combustion, and flue gas cleanup). Therefore, teaming of contractors was encouraged to ensure that this expertise will be available. The use of interdisciplinary teams is consistent with the systems approach and will promote communication among contractors to solve the problems that are certain to arise. Each team will be given responsibility for developing the

full system. Equally important, the team members will be allowed to retain a proprietary position in the technology that is developed and will be required to cost-share in the overall development. This feature will motivate post-program commercialization, which is a key project objective.

A solicitation that covered the entire four-phase Low-Emission Boiler System program was issued on December 3, 1990, and closed on April 1, 1991. Multiple awards are expected by December 1991. Program evaluation with probable down selection to fewer teams will occur after Phases I and III. The anticipated program schedule is shown in Figure 4.

Development of the HIPPS includes three phases: (I) concept definition and preliminary R&D; (II) engineering development and testing/prototype plant design; and (III) construction, operation, and evaluation of a commercial prototype plant. The three-phase program will culminate in testing of a 40- to 80-MWe commercial prototype in 2001. The major activities for Phase I are systems analysis; engineering analysis; preliminary experimental work; design of a commercial-scale generating plant; and formulation of an engineering research, development, and test plan for

Phase II. The engineering development phase includes furnace development, flue gas cleanup process testing, component and subsystem integration, and system control. A major part of engineering development will be to design, construct, operate, and evaluate a high-temperature furnace with a capacity in the range of 50 million Btu/hr.

Development responsibility for HIPPS (as with the Low-Emission Boiler) lies within the Office of Fossil Energy's Advanced Combustion Technology Program. To ensure overall program success, complementary research will be conducted in the Flue Gas Cleanup and Coal Preparation Programs, as well as in Advanced Combustion Technology. Flue Gas Cleanup will focus on advanced SO₂ and particulate matter control. Supporting research in Coal Preparation will focus on removal of selective mineral species from the coal. For example, the advanced alloys and/or ceramics to be used in the HITAF may be attacked by certain inorganic constituents (e.g., alkali-metal compounds) present in the coal ash. If so, then a reasonable approach would be to selectively remove these from the coal before combustion. Supporting research in Advanced Combustion would include studies on NO_x control, ash management and, perhaps, in situ sulfur control.

Figure 4. Program schedule, Low-Emission Boiler System.

Figure 5. Program schedule, High-Performance Power System.

The program will also include extensive research on advanced materials suitable for high-temperature heat exchange. As in the Low-Emission Boiler System, it will probably be advantageous to use a type of combustor (e.g., slagging or vortex) that provides significant ash rejection (removal) upstream of the heat exchange surface. Reduced ash levels may provide an improved environment for the heat transfer surface and can result in potentially higher reliability and lower costs. The findings of current research on capturing sulfur within the combustion chamber suggest that, within the development time for the HIPPS, techniques for substantial sulfur capture will be available. If so, then the flue gas scrubbing step could function more as a "polishing" operation, resulting in potentially lower costs for sulfur control.

A Program Research and Development Announcement (PRDA) for Phase I of the HIPPS Program was issued on September 19, 1990, and closed on December 19, 1990. Selection of three U.S. industry teams was announced to the public on June 12, 1991. The teams are:

- Foster Wheeler Development Corporation, Livingston, New Jersey
 - Bechtel Corporation
 - Research-Cottrell

- TRW, Inc.
- AiResearch Division of Allied-Signal Corporation
- United Technologies Research Center, East Hartford, Connecticut
 - UTC Turbo Power and Marine
 - Bechtel Corporation
 - Power Technology International (a consortium of PSI Technology Company and Reaction Engineering International)
 - Oak Ridge National Laboratory
 - University of North Dakota Energy and Environmental Research Center
- Westinghouse Electric Corporation, Orlando, Florida
 - Babcock and Wilcox Company
 - Fluidyne Engineering Corporation
 - Allison Division of General Motors
 - Allegheny Power System
 - Sei-Tec, Inc.
 - ERC, Inc.

Awards for Phase I will be made late in Fiscal Year 1991. Phase II will be initiated with a competitive solicitation in 1993. There will be a phase transition evaluation for down selection after

Phase II. No separate solicitation will be issued for Phase III. An anticipated project schedule is shown in Figure 5.

Summary

The Combustion 2000 program will help advance direct coal utilization technology into the 21st century. The Low-Emission Boiler System rethinks coal-fired boiler design for minimum emissions at the lowest possible cost and applies emerging combustion and flue gas cleanup system technologies. The HIPPS program is a comprehensive R&D effort that offers significant efficiency and environmental benefits. While higher in technical risk than LEBS, the HIPPS program is designed to be significantly lower in technical risk than other high efficiency systems being developed, and will yield an operating plant that will closely resemble today's power plants. Most importantly, the HIPPS will increase efficiency by at least one-third compared with today's plants. Combustion 2000 promises to be a challenging and exciting undertaking and one that will have a strong positive effect on both the environmental quality and energy security of this nation.

Lawrence A. Ruth is Director of the Coal Utilization Division at PETC. He manages DOE's Advanced Combustion Technology and Alternative Fuels Utilization Programs as well as Advanced Research programs dealing with coal preparation, combustion, and emissions control. He joined PETC in 1988 after 16 years in private industry, with Exxon Research and Engineering Company and Energy and Environmental Research Corporation. Most of his experience involves combustion and fuels technology, including control of combustion-generated emissions, heat transfer, and fluidized bed processing. He has over 50 publications and papers. Dr. Ruth has a Ph.D. in chemical engineering from the City University of New York, and bachelor's and master's degrees in chemical engineering from City College of New York.

LIQUID TRANSPORTATION FUELS FROM COAL

Part 2: Indirect Liquefaction

In the last issue of the PETC Review, we discussed the U.S. Department of Energy's (DOE's) rationale for seeking alternative sources of liquid transportation fuels (see sidebar) and described the direct coal liquefaction research and development (R&D) program. In this article, we examine the history as well as current and future research activities for DOE's Indirect Liquefaction Program.

Our focus will be on the use of indirect liquefaction for the production of hydrocarbon fuels. We also briefly review our R&D activities for producing oxygen-containing fuels and fuel components.

Using today's best available direct liquefaction technology, a high-quality synthetic crude oil can be produced from coal. This product would be competitive with crude oil (West Texas Intermediate) priced at between \$35 and \$40 per barrel. The per-barrel costs of producing liquids using indirect liquefaction are considerably higher. However, the products of indirect liquefaction

resemble petroleum products that have already been refined and are ready for use. Consequently, indirect liquefaction products carry a higher value, which is not easily measured in terms of crude oil equivalent prices. At present, our best estimates indicate that product costs, from either direct or indirect liquefaction, are nearly equal when measured on a crude oil-equivalent basis. Most importantly, the very different product slates produced by indirect liquefaction are complementary to those obtained using direct liquefaction. For example, an indirect liquefaction plant can be designed to produce a high-quality diesel fuel, and direct liquefaction yields a product that is best suited for the manufacture of a high-quality gasoline. Using another catalyst and reactor design, an indirect liquefaction plant can be configured to produce high value oxygenates that can be used to enhance gasoline performance and improve air quality by lowering vehicle emissions. Primarily because of product slate diversity, DOE's Coal Liquefaction R&D Program continues to investigate both direct and indirect methods of producing liquid fuels from coal.

The average daily consumption of petroleum products in this country is about 17 million barrels per day. Almost half of this petroleum is now imported, and about two-thirds of the total petroleum consumed is used for transportation fuels. The continuing availability of these liquid fuels is very important to the energy supply situation and economy in the United States. Since the early 1970s imports of petroleum have periodically been jeopardized by worldwide political uncertainties. For this reason, DOE has continually emphasized the importance of R&D for developing alternative sources of liquid fuels that would be suitable for use as transportation fuels. Technology for producing liquid fuels from coal has been available since the 1930s, and coal is the United States' most abundant energy supply source. Therefore, much of the R&D work performed by DOE has centered on coal-derived alternative fuels.

Figure 1. Indirect liquefaction of coal.

Indirect Liquefaction Process Description

In indirect liquefaction (see Figure 1), coal is fed to a gasifier, where it is partially burned at high temperatures under moderate pressures in the presence of oxygen and steam. This partial combustion of the coal generates a gas consisting mainly of carbon monoxide (CO) and hydrogen (H₂).

This gas mixture is commonly referred to as "synthesis" gas. In a second step, these gases are cooled and cleaned of particulates. In conventional indirect liquefaction processes, the gases are next sent to a shift reactor in which the H₂/CO ratio is adjusted to that of the final desired liquid fuel. In advanced indirect liquefaction processes, the shift reactor can be eliminated, thereby considerably reducing production costs, as discussed below. After being cleaned of impurities (e.g., carbon dioxide and hydrogen sulfide), the synthesis gas is sent to a

synthesis reactor and converted to liquid products. The products obtained from the process depend on the temperature, pressure, and catalyst in the synthesis reactor as well as the design of the reactor. Typical products include hydrocarbons (e.g., diesel fuel, jet fuel and paraffin wax) and oxygenates (compounds that contain oxygen atoms), such as methanol, higher alcohols, or ethers. Oxygenates may be used as transportation fuels or additives that make gasoline burn more cleanly. If specification-grade fuels or marketable chemicals are desired, the mixture of products must be separated.

History of Indirect Liquefaction

The conversion of synthesis gas to hydrocarbons—the basis of the indirect liquefaction process—was first demonstrated in

Configuration	Sasol		Advanced Gasifier		Advanced Gasifier + Advanced Reactor
Gasifier	Lurgi	Lurgi	Shell	Shell	Shell
F-T Reactor	Fluid Bed	Fixed Bed	Fluid Bed	Fixed Bed	Slurry Phase
Overall Thermal Efficiency, %	44	44	55	53	59
Required Product Selling Price, \$/barrel	59	55	51	48	42

Table 1. Improvements in indirect coal liquefaction – estimates based on using Wyoming subbituminous coal.

Germany in 1902 by Sabatier and Senderens. Using a nickel catalyst, they showed that CO could be hydrogenated to produce ethylene. Soon after, scientists in Germany demonstrated the conversion of synthesis gas to hydrocarbons and oxygenates over a cobalt catalyst at high pressures. In the 1920s, Franz Fischer and Hans Tropsch used an iron catalyst at normal pressure to produce mainly oxygenated compounds. The process became the basis for much of the following research and is known as Fischer-Tropsch (F-T) synthesis.

After World War II and with the advent of the Cold War, concerns were raised regarding the strategic importance of liquid fuels and the difficulty of assuring access to Middle East oil. In response, the Department of the Interior (DOI) proposed a crash program to produce liquid fuels from coal as well as oil shale. As part of this program, DOI's Bureau of Mines (BOM) constructed a liquefaction facility in Louisiana, Missouri, using an Army surplus ammonia-synthesis plant as the site for both direct liquefaction and F-T indirect liquefaction units. These two units were designed to produce 200 and 100 barrels per day, respectively, of liquid products. However, with abundant supplies of very-low-priced Middle East crude oil, the United States soon lost interest in producing liquid fuels from coal, and the plant was closed in 1953.

Full-scale commercial production using indirect liquefaction of coal has occurred only in the Republic of South Africa. In 1955, a South African firm, Sasol, Ltd., further developed F-T technology by constructing and commissioning an indirect liquefaction plant, known as Sasol I. This facility is still operating today and uses an iron-based catalyst. Research at Sasol continued for the next 20 years and resulted in numerous improvements to the operation. After the oil embargo in 1973 and under increasing economic isolation resulting from its apartheid policies, the South African government subsidized Sasol's construction of two new plants—Sasol II and III. These two plants were commissioned in 1980 and 1983, respectively. The combined annual production capacity of all three Sasol facilities is 50 million barrels of liquid products. Their combined output provides much of South Africa's liquid transportation fuels.

Coal is not the only feedstock for indirect liquefaction processes. Natural gas can be reacted with steam to yield synthesis gas, which can be subsequently converted to liquid products. In the early 1950s, an F-T plant operating on natural gas was built by the Cythage Hydrocol Company in Brownsville, Texas. This facility employed reactor technology developed by Hydrocarbon Research, Inc., a company that continues to play a significant role

In our on-going R&D program. This plant only operated for a brief time because of increased U.S. demand for natural gas and low prices for petroleum fuels. More recently, industry has shown increased interest in using indirect liquefaction processes based on natural gas. Throughout the world, there exist abundant supplies of low-cost natural gas that exceed the demands of local markets. Indirect liquefaction technology offers the means of converting these remote natural gas resources to liquid products that can be economically transported to meet international market needs. For example, the Mobil Corporation has constructed a commercial indirect liquefaction plant in New Zealand. This plant, which began operations in 1985, has a total product capacity of 14,500 barrels of gasoline per day. Natural gas is first converted to synthesis gas, which is subsequently converted to methanol and then gasoline. Technology to convert synthesis gas to methanol has long been available. What made the New Zealand plant possible was Mobil's development in the 1970s of a process to convert methanol to gasoline using a new catalyst. Recognizing that this approach is also appropriate for coal-based processes, a portion of Mobil's overall development effort was funded by the Department of Energy.

Goals of the DOE Indirect Coal Liquefaction Program

The Coal Liquefaction R&D Program, as a whole, is directed at meeting National Energy Strategy goals to "reduce the cost, investment risks, and environmental impacts of producing liquid fuels from coal." Although F-T synthesis for indirect liquefaction has been demonstrated in large commercial-scale plants in South Africa, the technology used there is inefficient, and the estimated product cost is not low enough to be commercially competitive with petroleum products without the aid of government subsidies. If a similar plant, including the Lurgi gasifiers used in Sasol II and III, were built in the United States, the required selling price of the product would be about \$55 to \$59 per

barrel (see Table 1), and the overall thermal efficiency of the process would be low, about 44%. Therefore, one of the major goals of the Indirect Liquefaction R&D Program is to find and develop process improvements that will lower the cost of liquid products to a level that is competitive with transportation fuels derived from petroleum. Engineering analyses indicate that a goal of producing liquid products for \$30 or less per barrel (crude oil equivalent) is not unrealistic and may be reached in the near future.

Inherent to reaching this cost goal is a major improvement in the thermal efficiency of indirect liquefaction. Such an efficiency improvement would not only reduce local environmental impacts associated with liquids production but would also yield significantly lower emissions of carbon dioxide, which has been associated with global climate change. Another important environmental objective of the indirect liquefaction program is the production of alternate transportation fuels that show superior emissions performance upon combustion. For example, the diesel fuel produced via F-T synthesis has been shown to substantially reduce hydrocarbon, CO, and particulate emissions, as compared with conventional diesel oil. Our work in developing indirect liquefaction processes for production of oxygenates is very much motivated by their ability to reduce pollutant emissions.

Oxygenates

The term oxygenates refers primarily to either alcohols or ethers. As additives in transportation fuels, particularly gasoline, these materials increase octane ratings and reduce pollutant emissions. The use of oxygenates in transportation fuels is likely to increase as refiners and automobile manufacturers struggle to achieve the reduced vehicle emissions goals required by the 1990 amendments to the Clean Air Act. Current petroleum-based commercial technologies for oxygenates yield nearly pure compounds at costs significantly higher than petroleum. In addition, use of large amounts of a

Gasifier	Shell	Lurgi
Composition Dry, Vol%		
H ₂	30	50
CO	66	25
CO ₂	3	10
CH ₄ + Higher Hydrocarbons	—	15
Inerts	1	—
H ₂ /CO Molecular (Volume) Ratio	0.45	2
Net Efficiency to Synthesis Gas, %	78-80	61

Table 2. Composition of synthesis gas from Shell and Lurgi gasifiers operating on Western U.S. coals. Net efficiency includes thermal losses in reforming methane to synthesis gas.

single compound in gasoline skews the performance characteristics of the fuel and can result in operating difficulties in internal combustion engines. Indirect liquefaction can produce mixtures of alcohols and/or ethers, which may be less expensive than pure compounds and which may be used in higher concentrations in the fuel without sacrificing the operating efficiency of the vehicle. For these reasons, the oxygenates research being conducted under the Indirect Coal Liquefaction Program is focused on unique new routes to fuel components that may be more economical and more technically desirable than those available with petroleum-based technology.

Some of the current research work on oxygenates was reported on at the Liquefaction Contractors' Review Meeting held in Pittsburgh, Pennsylvania, September 3-5, 1991: "Synthesis of Octane Enhancers During Slurry-Phase Fischer-Tropsch," "High Octane Ether from Synthesis Gas Derived Alcohols," and "Development and Demonstration of a One-Step Slurry-Phase Process for the Co-Production of Dimethyl Ether and Methanol." In a later issue, we will discuss our R&D activities directed at the production of oxygenated transportation fuels.

DOE Research in Fischer-Tropsch Technology

A major advance in our ability to produce liquid fuels using indirect coal liquefaction has already occurred. New, more efficient coal gasifiers for synthesis gas production have been developed and demonstrated. These include the Dow, Texaco, and Shell gasifiers. The availability of these improved gasifiers plays a major part in improving process economics because up to 80% of the total cost of an indirect liquefaction process is involved in preparing synthesis gas. A comparison of the thermal efficiency of the Shell gasifier with that of the Lurgi gasifier used at Sasol is given in Table 2. Besides being more thermally efficient, these advanced gasifiers require substantially less overall plant capital investment than do the Lurgi gasifiers. As shown in Table 1, product costs from F-T synthesis are reduced from \$55-59 to \$48-51 per barrel when Lurgi gasifiers are replaced with high-efficiency gasifiers, in this case the Shell, while using the same fluid-bed or fixed-bed type reactors found in the Sasol plants.

All three of the more efficient, advanced gasifiers mentioned above (Dow, Texaco, Shell) are

operating at or near commercial scale in facilities in the United States and Europe. The newer gasifiers, however, have an inherent drawback when used as the first step for indirect coal liquefaction: Typically (see Table 2), they produce a gas with a lower proportion of hydrogen than the gas from a Lurgi gasifier. Indirect liquefaction synthesis reactors available today are unable to accept a low H_2 -to-CO gas. This means that the gas composition must be modified (before F-T synthesis) by additional and expensive catalytic processing in the shift reactor. This problem also raises an opportunity for R&D that can significantly lower total production costs; namely, the development of an advanced synthesis reactor that can use the low H_2 -to-CO synthesis gas directly.

Earlier DOE-sponsored work in methanol synthesis technology showed that slurry-phase catalytic reactors could be effectively used to convert low hydrogen synthesis gas into liquid fuels. Systems engineering analyses performed for DOE have shown that development of slurry-

phase reactor technology for F-T synthesis would allow the catalytic shift reactor to be completely eliminated (see Figure 1), improve overall process thermal efficiency and yield lower cost transportation fuels, as summarized in the right-most column in Table 1. Therefore, the DOE R&D program for Fischer-Tropsch indirect liquefaction is focused primarily on the development of slurry-phase reactor technology.

There are three main elements to this effort:

- Development of the reactor itself
- Development of catalyst-wax separation technology
- Development of effective catalysts for use in slurry-phase reactors

To understand the rationale for the research efforts in these areas, it is first necessary to understand the slurry-phase reactor and its unique characteristics and to contrast those to the more conventional fixed-bed reactor (see Figure 2).

Figure 2. Reactors used for Fischer-Tropsch synthesis (schematic diagram).

Advanced Reactors

The conversion of synthesis gas to liquids is an exothermic reaction (i.e., considerable heat is given off), and this heat must be removed. In a typical fixed-bed synthesis reactor, the catalyst is packed into about 10,000 one-inch tubes, and the synthesis gas is sent through this array of tubes. The tubes are water-cooled, and much of the heat given off by the reactor is captured as process steam. However, heat transfer within the packed tubes is poor, and if a low H_2 -to-CO synthesis gas were used, carbon would be deposited on the catalyst surfaces, resulting in severe catalyst deactivation and loss of operability.

In contrast to the fixed-bed reactor, the slurry-phase reactor is relatively simple. Basically, a finely divided catalyst is suspended in a liquid. For F-T synthesis, this liquid is a waxy portion of the product. The reactant gases are bubbled through the catalyst slurry and react on the surface of the catalyst to produce the desired product. The use of finely divided catalysts ensures high rates of reaction that result in a large amount of product per unit of reactor volume per unit of time. The presence of the liquid and the turbulence caused by the gas flow allow the effective removal of heat from the surface of the catalyst. Therefore, higher rates of reaction and greater conversion can be achieved.

In the slurry-phase reactor, the gas flow keeps the catalyst slurry well mixed. The heat given off by the reaction is recovered as steam through a heat exchanger embedded in the reactor volume. Moreover, the total heat exchanger tube area is only a small fraction of the tube area of a fixed-bed reactor for F-T synthesis. This excellent ability to remove the heat given off by the exothermic reaction prevents carbon from being deposited on catalyst surfaces, thereby reducing catalyst deactivation when low H_2 -to-CO synthesis gas is used. These are the advantages of slurry-phase reactors.

The major uncertainty about using slurry-phase reactors for F-T synthesis involves fluid flow and heat transfer characteristics in the reactor. DOE's slurry-phase reactor research effort will obtain hydrodynamics, heat transfer, and mass

transfer data needed to properly design slurry-phase reactors. This will be accomplished by issuing a solicitation for gathering operational data that covers a range of experimental reactor sizes. In addition, a methodology for designing a slurry-phase reactor will be developed, and a consistent set of correlations for all design parameters will be produced.

Optimization of slurry-phase reactor operation may require a number of process modifications, including changes in (1) reactor configuration to improve mixing, heat transfer, or vapor-liquid separation of the products; (2) catalyst particle size distribution or surface properties to reduce settling or to increase the concentration of catalyst within the reactor; and (3) the liquid composition in the reactor to allow for higher gas velocity or better heat transfer.

Catalyst/Wax Separation

Slurry-phase reactors used for F-T synthesis produce product wax inside the reactor. To maintain the proper slurry level inside the reactor, the wax must be continuously removed. At the same time, to prevent catalyst loss, an efficient method for separating the catalyst from the wax after removal from the reactor is essential. The wax can be readily processed (hydrocracked) into premium-quality diesel fuel if it is relatively free from catalyst. The diesel fuel produced has been shown to substantially reduce hydrocarbon, CO, and particulate engine emissions compared with conventional diesel fuel.

In early fiscal year 1992, DOE will issue a solicitation for development of new or improved technologies to separate the catalyst from the product wax. The solicitation will cover two phases: (1) basic laboratory research to develop the technology, demonstrate performance, and obtain sufficient data to perform an initial design and cost estimate and (2) construction of a unit and performance of additional engineering evaluations in an integrated bench-scale unit.

Catalysts

Catalyst research is primarily concerned with developing catalysts for slurry-phase reactors

Metal	Relative Cost
Iron	1
Cobalt	230
Nickel	350
Ruthenium	31,000
Rhodium	570,000

Table 3. Relative cost of catalyst metals

that have enhanced activity, improved selectivity (i.e., ability to produce the desired product), good stability (i.e., long life), and tolerance for poisons that could deactivate the catalyst. Numerous metals have been evaluated as catalysts for F-T synthesis. Table 3 displays the relative cost of these metals.

As shown, iron is by far the least expensive metal for use as a catalyst. The use of cobalt, however, may be justified because of its higher activity and improved selectivity to make hydrocarbons. Although the cost of nickel is about the same as cobalt, it produces too much methane to warrant further investigation. Finally, the high cost of ruthenium and rhodium and their lack of availability are obstacles for their commercial use.

Table 4 shows the target performance criteria that have been established for evaluating and comparing catalysts. Synthesis gas conversion should be high, and selectivity to light hydrocarbon gases should be low to eliminate the need to reform the gases to H_2 and CO, which

is costly and would decrease efficiency. High catalyst activity and catalyst loadings are required in slurry-phase reactors for maximum productivity, and this will result in reduced capital costs.

There are several types of iron catalysts but the most active are those manufactured by precipitation of iron salts. Therefore, the Indirect Liquefaction Program has focused on preparation and use of precipitated iron catalysts. The steps required to prepare these catalysts are listed in Table 5. The point of this table is that each of the eight steps in the process has several process variables that can be controlled. Each variable can have a major impact on the properties of the catalyst (activity, stability, selectivity, and slurry behavior). The role of each of these variables must be understood to produce the best possible catalyst.

Two major contracts are currently in place for catalyst development—one with the University of Kentucky and its teammate United Catalyst, Inc., and the other with UOP, Inc. Two catalysts from the UOP contract were recently evaluated in a slurry-phase reactor for extended periods of time. Both catalysts were extremely stable—the first was tested for over 2,000 hours; the second was more than twice as active and almost achieved all of the performance criteria listed in Table 4. Because of their higher activity, DOE also plans to develop cobalt-based catalysts. A solicitation was issued in Fiscal Year 1991, and awards will be made in early Fiscal Year 1992.

Table 4. Desired performance criteria for slurry-phase reactor catalysts.

- High catalyst activity (i.e., high conversion—about 88%—of synthesis gas to products).
- Good catalyst stability and tolerance for poisons that can deactivate a catalyst— $\leq 1\%$ deactivation of the catalyst per week for 2 weeks.
- High selectivity to desired products and $\leq 4\%$ light hydrocarbon gases (methane and ethane) in products.
- Ability to use low (0.5 to 1.0) hydrogen feed gas from new, more efficient gasifiers.
- Ability to operate slurry reactor with high loadings ($\geq 20\%$) of solid catalyst in slurry phase.

1. Precipitate an iron oxide/oxyhydroxide gel containing a copper promoter.
2. Filter to separate the precipitate from the solution.
3. Dry the filter cake.
4. Crush the filter cake to the required particle size.
5. Impregnate the powdered filter cake with a potassium-based promoter.
6. Calcine the material promoted with potassium.
7. Grind and size to produce the final catalyst particle size (between 10 and 50 microns).
8. Establish pretreatment reaction conditions for attaining desired catalytic activity and selectivity.

Table 5. Steps for preparing a precipitated iron catalyst

Major Research Facilities

Two major facilities will support the development and engineering efforts of the indirect liquefaction program. Laboratory results will first be tested under integrated operating conditions in the Indirect Liquefaction Bench-Scale Unit (BSU), now under design. Processes that show favorable technical and economic potential will be further tested at the Alternate Fuels Development Unit on a larger scale that will obtain performance data relevant to industry.

Indirect Liquefaction Bench-Scale Unit

At this time, DOE has neither a cost-effective BSU available to collect the needed slurry-phase reactor data discussed above nor an appropriate unit to test the catalyst-wax separation technology. Therefore, a BSU for the Indirect Coal Liquefaction Program is being built at PETC. The M.W. Kellogg Company is designing and installing the facility; completion is scheduled for Fall 1993.

The indirect liquefaction BSU will consist of two parallel trains, each with a capacity of about one barrel per day of liquid products. One train will be dedicated to the synthesis of oxygenated products, and the second train will be dedicated to F-T synthesis. Each train will have both a slurry-phase and a fixed-bed reactor available for

operation. The BSU will be able to operate over a wide range of process conditions. The composition of the feed gas (including impurities such as hydrogen sulfide, carbon dioxide, etc.) will also be variable over a wide range to simulate any gasifier product composition.

The Indirect Liquefaction BSU will be used to develop slurry reactor design information, prove operability of the catalyst-wax separation unit, and test the best catalyst or catalysts developed in the program. As such, the Indirect Liquefaction BSU will serve as the program's key facility for technology development, evaluation and transfer, forming a bridge between laboratory work on new process concepts and larger scale proof-of-concept testing. The integrated operating data developed at the BSU will provide the basis for technical and economic analyses of total process concepts. Advanced slurry-phase Fischer-Tropsch synthesis technologies that pass muster will be moved to proof-of-concept testing at the Alternate Fuels Development Unit.

The BSU for indirect liquefaction technology development complements the direct liquefaction BSU that will also be sited at PETC (*PETC Review*, March 1991). In addition to supporting programmatic goals of the DOE Coal Liquefaction R&D Program, both BSU's will also be made available for conducting industry-proprietary R&D. By providing industry with access to first-class test facilities, we hope to further encourage private-sector investment in direct and indirect liquefaction R&D. This is yet another example of DOE's

commitment to stimulating technology development and transfer through cooperative efforts with industry.

Alternate Fuels Development Unit

The Alternate Fuels Development Unit is located outside Houston, Texas, in La Porte. This facility is operated by Air Products and Chemicals, Inc., and is adjacent to their commercial plant for producing hydrogen and carbon monoxide. A synthesis gas feed from this commercial plant is used to simulate a coal-derived synthesis gas. The reactor components installed at the Alternate Fuels Development Unit are at a scale sufficient to provide design data for commercial indirect liquefaction plants. The nominal production rate is 35 barrels per day; however, in many cases this rate has been significantly exceeded. Over the past few years, the Alternate Fuels Development Unit provided proof-of-concept testing for the successful development of the slurry-phase methanol reactor, which is now scheduled for commercial demonstration under DOE's Clean Coal Technology Program. Most recently, proof-of-concept testing was successfully completed on a new process for efficiently converting synthesis

gas into a mixture of dimethyl ether and methanol, for use as an environmentally superior automotive fuel or fuel additive.

A preliminary F-T synthesis run is planned at DOE's Alternate Fuels Development Unit in early-to-mid 1992. The run will provide baseline data with which researchers can measure the progress of various projects, verify the scalability of results from laboratory-scale to a large-scale slurry reactor, define programmatic research needs, and produce products for use in other research programs. The run is being co-sponsored by several industrial organizations.

Future Liquefaction Topics

Within DOE, the Coal Liquefaction Program is a key component of the Department's overall strategy to secure our nation's energy future. Both the direct and indirect liquefaction programs are focused on producing transportation fuels at lower costs and reduced environmental impacts. In future issues of the *PETC Review*, we will discuss our R&D efforts in oxygenates and in advanced concepts to integrate liquefaction with technology for electric power generation.

Gary J. Stiegel is Program Coordinator for Indirect Liquefaction within the Office of Project Management. Gary received his bachelor's and master's degrees in chemical engineering and an MBA from the University of Pittsburgh. Before joining PETC in 1976, he was employed by Union Carbide Corporation. At PETC, Gary has served as a project manager for direct liquefaction programs and for a joint USAF/DOE jet fuels program. He also spent approximately 10 years in various facets of direct coal liquefaction research and development where he served as chief of the Reaction Engineering Branch. Gary is a registered professional engineer in Pennsylvania and is the co-author of several papers on reaction engineering and catalysis for direct coal liquefaction.

A COMPUTER EXPERT SYSTEM TO REDUCE POWER PLANT EMISSIONS

The Coal Quality Expert computer system is designed to give utilities a new and powerful tool that will quickly and economically predict the total cost impact of coal quality on boiler performance, maintenance, operational costs, and emissions. Integrating more than 20 computer models into one workstation, the Coal Quality Expert will evaluate numerous options, as specified by the user, to determine the least expensive emission control strategy for a given plant. The U.S. Department of Energy (DOE) selected this \$17.4 million project in Round 1 of the Clean Coal Technology Program. This project is performed jointly by CQ, Inc. (a wholly owned subsidiary of the Electric Power Research Institute [EPRI] located in Homer City, Pennsylvania); ABB-Combustion Engineering in Windsor, Connecticut; and others.

The Coal Quality Expert is designed to predict the economic, operational, and environmental benefits of using commercially achievable cleaned coals and will, therefore, enable coal-burning utilities to select the best-quality coals for their boilers. The project consists of two major activities: (1) testing and data gathering, which involve optimization of coal quality for combustion in different types of coal-burning utility boilers and (2) developing an expert system computer program that can emulate human reasoning in a specified area of knowledge.

A major focus of this project is extensive data-gathering and analysis to validate models currently in use and to develop and evaluate the new models that will constitute the Coal Quality

Expert. Project members are collecting samples of the project's various coals at mines, commercial cleaning plants, and at the project's six host power plants. A total of 26 coals are being characterized, cleaned, and tested in bench- and pilot-scale combustion chambers to determine their combustion characteristics. A total of 12 coals (baseline and improved quality) will be field-tested in full-scale electric utility boilers at six sites. Through testing at all three scales (bench through full), the project is able to isolate key variables and determine how these variables affect full-scale operations.

This is one of the largest efforts ever attempted to link pre-combustion, combustion, and post-combustion technologies to solve power plant emission problems. Over 20 companies from

around the country, including software developers, testing laboratories, and utilities, will participate in this project.

Figure 1 shows the major components of the Coal Quality Expert System. All of these models are integrated into a single tool to enable planners and engineers to examine the cost and effects of coal quality on each facet of power generation from the mine to the stack. The Coal Quality Expert System will guide users to the appropriate components of the system with a series of questions or specific menu options. Users may only need to use one or two components for some analyses; other efforts may require the integration of many model results.

The foundation for the Coal Quality Expert is EPRI's Coal Quality Impact Model (CQIM). This model assesses the impacts of coal quality on

plant performance and operating costs. Already used by 75 utilities, the CQIM features detailed equipment modules for all systems that are directly affected by coal quality. All performance factors are translated into specific costs, allowing direct comparisons of alternative coal supplies. More than 20 other software models and data bases (including a flue gas desulfurization model, a coal cleaning cost model, a transportation model, and a new plant construction model) will be integrated with CQIM to form the Coal Quality Expert. Within the project, responsibility for software development and integration rests with Black and Veatch.

CQ's Homer City Coal Laboratory and the University of North Dakota Energy and Environmental Research Center in Grand Forks are now analyzing the test coals. The ABB

Figure 1. Coal Quality Expert system: Abbreviated schematic.

Figure 2. Constructing a data base from test results.

Combustion Engineering's Test Facility in Windsor, Connecticut; the Babcock & Wilcox (B&W) Research Center in Alliance, Ohio; and the University of North Dakota Energy and Environmental Research Center are performing the bench- and pilot-scale combustion tests on these coals (see Figure 2).

Six full-scale field tests are being conducted in all major types of boilers. Electric Power Technologies (EPT) of Menlo Park, California, will lead a team of contractors who will measure

power plant performance using the test coals. Data from these 30-day test burns will help to determine the impacts of changes in coal quality (by cleaning, switching, or blending) on plant performance and emissions. This test program is now in progress. The designated plant sites are:

- Alabama Power Company's Gaston Plant in Wilsonville, Alabama
- Mississippi Power Company's Watson Plant in Gulfport, Mississippi

- Northern States Power Company's King Plant in Oak Park Heights, Minnesota
- Public Service Company of Oklahoma's Northeastern Plant in Oologah, Oklahoma
- Pennsylvania Electric Company/New York State Electric & Gas Corporation's Homer City Plant in Homer City, Pennsylvania
- Duquesne Light Company's Cheswick Plant in Springdale, Pennsylvania

During field testing, project teams collect coal samples and take measurements at the pulverizers, the boiler, the fans, the precipitators, and the flue gas ducts. The field test data collected will be used to correlate coal characteristics with combustion behavior. The goal is to determine engineering correlations that will accurately predict how a particular coal will burn in a designated unit. This will reduce future needs for full-scale test burns, which can cost more than \$1 million each. The fireside advisor software in the Coal Quality Expert will provide guidelines for determining which tests to apply and a step-by-step procedure for conducting test burns to avoid unnecessary, expensive testing.

The test data generated will be used to develop and validate the Coal Quality Expert models that will predict the performance of commercially available cleaned coals with regard to site-specific total plant performance. The computer models will provide specific information on slagging and fouling, precipitator performance, flue gas particulate removal, nitrogen oxides (NO_x) formation, sulfur dioxide (SO₂) emissions, flue gas desulfurization performance, and pulverizer wear.

So far, two field tests have been conducted. The first was performed between August and December 1990 at Public Service Company of Oklahoma's, Northeastern Station, Unit 4. The test involved two types of coal (Wyoming's Upper Middle and Lower Wyodak seams and Oklahoma's Crowborg seam) normally used at the plant and three different blends of those coals. The purpose of the test was to determine slagging characteristics of the blended coals. Test results indicated that a blend of 90% Wyoming and 10% Oklahoma coal showed more superior ash deposition characteristics than did Wyoming coal alone. The second field test was conducted from October 9 to November 10, 1990, at Mississippi Power Company's Watson Plant Unit 4 in Gulfport, Mississippi. The operational impacts of blends of several coals (Illinois No. 2, No. 3, No. 5, and No. 5A; and Western Kentucky No. 11) normally used at the plant were evaluated to assist in planning future coal procurement, as well as to develop data required for the Coal Quality Expert.

The Coal Quality Expert will predict the effects of a particular coal on each facet of power generation—from the mines to the stack. The expert system will evaluate numerous options (including various qualities of coal, available transportation methods, and alternative emissions control strategies) to determine the most cost-effective coal and the least expensive emissions control strategy for a given plant. This software will enable power station operators to select the right quality coal to produce the lowest cost electricity and yet remain within emission limits.

During the performance of this project, which is scheduled for completion in February 1994, individual computer models will be completed and made commercially available to industry. The entire Coal Quality Expert system will be commercially available at project completion. For further information about these models, please contact:

Mr. Clark Harrison • CQ, Inc. • 1 Quality Center
Homer City, PA 15748-0280 • Phone: (412) 479-6016

Individual computer models will be made commercially available (see sidebar for details) as they are developed. The first of these models, the Acid Rain Advisor, will be ready for use in late 1991. This model deals with compliance options for addressing the acid rain provisions of the recently amended Clean Air Act. Specifically, this Act provides utilities with allowances for SO_2 emissions. These allowances can be traded between power plants and between utility systems. This allows tradeoffs to be made regarding use of scrubbers, fuel cleaning, fuel switching, and other approaches as compliance options. Overall, the Acid Rain Advisor will provide a utility with a powerful tool for evaluating possible options at individual plants at the overall system level and for considering trading emissions allowances with other utilities.

The Coal Quality Expert will include cost estimating models for new and retrofit coal cleaning processes, power production equipment, and emissions control systems. When the Coal Quality Expert is complete in 1994, users will be able to develop the most economical emissions control strategies, identify fuel options based on overall plant economics, and evaluate alternative power plant designs.

The Coal Quality Expert promises to be a powerful source of coal quality information. Users will be able to evaluate the total cost impacts of different coals and coal qualities on power plant performance and emissions. With the Coal Quality Expert, utilities and industry will be able to hold down the costs of generating electricity at coal-fired plants while protecting the environment.

Consistent with the intent of the National Energy Strategy, implementation of projects like the Coal Quality Expert and the other projects in the Clean Coal Technology Program will allow us to use coal, America's most plentiful energy resource, as one of the cleanest and most economical sources of electrical power. As the models become available, we will keep you informed in the "Update" section of the *PETC Review*, and we will continue to provide additional articles describing the research and results of the Clean Coal Technology Program.

Robert J. Evans joined DOE as a Project Manager for the Office of Clean Coal Technology in January 1989 and is overseeing three projects: Coal Quality Expert, WSA-SNOX (Wet Gas Sulfuric Acid- SO_2 and NO_x reduction), and LIFAC (Limestone Injection into the Furnace with calcium oxide Activation). Bob received a civil engineering degree from Geneva College. In subsequent years, he earned a mechanical engineering degree and master's degrees in civil and mining engineering from the University of Pittsburgh. Before assuming his current position, Bob worked for 4 years at the U.S. Bureau of Mines as a project manager in the Advanced Mining Systems Division. While working previously for DOE, Bob served as a project engineer in the Coal Liquefaction Division and as a branch chief for Coal Mine Development and Production.

UPDATE

United States Clean Coal Technology Exported to Poland

(Issue 2, September 1990)

In addition to providing retrofit technologies for removing sulfur dioxide (SO_2) from current power plant emissions in Poland, the United States Agency for International Development (through DOE/PETC) is providing assistance in helping the Polish people to develop cleaner methods for burning their indigenous coals in small boilers and home heating systems. In Krakow, there are nearly 3,000 small boilers totaling 300 MW(t) and 200,000 home heating stoves that burn coal. This past June, PETC initiated an assessment of existing practices and equipment and will investigate several simple methods to reduce emissions, primarily organics and particulates. With the help of Brookhaven National Laboratory and Biuro Rozwoju Krakow (the Province of Krakow's planning agency), pilot tests will be conducted on district boilers and home stoves. Data collected from these tests will be combined with engineering analyses to provide a coordinated data base for determining equipment and strategies that will be effective in reducing pollution. This project will involve the use of U.S. technology, and it is expected that alliances will be formed to foster business ventures between U.S. and Polish firms.

Dr. Krzysztof Görlich, shown standing next to an elaborately decorated flue for one of the 200,000 home heating stoves in Krakow, Poland, is a member of the U.S./Poland Bilateral Steering Committee and Krakow City Council. He has been appointed by both the Province and City of Krakow to monitor environmental facets of various programs, including the DOE/PETC Clean Coal Technology project.

Boiler Manufacturer Chosen for U.S./Italy Superclean Coal-Water Slurry Demonstration

(Issue 2, September 1990)

As we reported in Issue 2 of the *PETC Review*, a boiler manufacturer had been selected in a project to demonstrate that superclean (about 1% ash content) coal-water slurries produced from U.S. coals can be burned in boilers designed for oil, without sacrificing efficiency or harming the environment. Since that report, a 15 million-Btu-per-hour Keeler boiler has been installed in a new building at the East Campus heating plant on the grounds of Pennsylvania State University. The boiler is large enough to heat dormitories for 3,000 students. The demonstration began in July using Brookville seam coal from Perry Brothers Coal Company in Sharon, Pennsylvania. The coal is cleaned near the mine; shipped to KVS in Danville, Pennsylvania, for coal-water fuel preparation; and then trucked to the University. The study will conclude in December 1991. In addition to providing information about retrofitting oil-designed boilers to coal-water fuels, the data will also provide important guidance on how to design boilers for use with these coal-based fuels.

PETC'S FLOW ANALYSIS LABORATORY ASSISTS ARTIFICIAL HEART RESEARCH

"A preeminent example of the benefits of creative technology transfer. Not only is DOE's research investment enhancing our energy security, but that same investment offers an opportunity for the medical community for research that can literally save lives."

*James D. Watkins
Secretary of Energy*

In the past 10 years, a cardiothoracic surgery team led by heart transplant surgeon Dr. Bartley Griffith at Presbyterian-University Hospital in Pittsburgh has performed several state-of-the-art procedures: a heart-lung transplant in 1982, a heterotopic heart transplant (a process in which the original heart is left in place and an additional heart is transplanted into the body that acts as a left ventricular assist device) in 1984, and a double lung transplant in 1988. In 1985, they became the second team to use the Jarvik total artificial heart (TAH) as a bridge to cardiac transplantation. In the last 6 years, 20 patients have been supported by the Jarvik TAH and 25 patients by another heart pump, the Novacor Left Ventricular Assist Device (LVAD). This makes Pittsburgh's local heart transplant center one of the world's most active and the world leader in the use of the Novacor LVAD.

The cardiothoracic surgery team is part of an extensive artificial heart research program at

the University of Pittsburgh's Presbyterian-University Hospital. One of their main research objectives is to improve the hemodynamics, or blood flow behavior, in artificial heart pumps in an effort to increase patient survival rates and lengthen their tolerance to the artificial heart implants. In October 1990, medical researchers led by Dr. Harvey Borovetz, Director of Bioengineering for the Artificial Heart Program, asked PETC to assist his team in their study of hemodynamics in artificial heart pumps.

Advanced diagnostic equipment developed by PETC researchers to study flow fields in coal utilization processes is now being applied to study hemodynamics of artificial heart pumps. The studies are being performed in PETC's Flow Analysis Laboratory by a team of researchers from PETC, Presbyterian-University Hospital, and two artificial heart pump companies. Under this program, the two heart pumps that will be studied are the Novacor LVAD and the Nimbus AxiPump.

The Novacor Left Ventricular Assist Device

One of the major problems facing patients with terminal heart disease is the availability of donor hearts for transplant. Each year an estimated 30,000 patients are in need of a transplant, but only about 2,000 acceptable donor hearts are made available. As a result, many patients who are candidates for transplant surgery do not survive until a donor heart becomes available.

The medical community is attempting to bridge the time gap between heart failure and cardiac transplant with the use of artificial heart pumps.

Today, emphasis is being directed toward using devices that assist an ailing heart instead of

replacing it with a total artificial heart such as the Jarvik-7. One of these devices is a Left Ventricular Assist Device (LVAD) developed by Novacor, a Division of Baxter Healthcare (see Figures 1 and 2). The success rate with the Novacor LVAD is very encouraging — more than 70% of the Novacor LVAD implant patients at Presbyterian-University Hospital have been kept alive until a donor heart was found.

The shortage of donor organs and the requirement for a good "match" between donor and recipient is now significantly increasing the length of time an LVAD implant must be used. At the time this article was written, a patient at Presbyterian-University Hospital had been kept alive with the Novacor LVAD for more than 300 days. Over these extended periods of contact between the patient's blood and the artificial surfaces within the LVAD, even subtle

Figure 1. Arrangement of the Novacor LVAD in the human body: as shown, the LVAD is powered by internal batteries and an external strap-on battery pack and is controlled by an implanted miniature computer. Figure courtesy of Novacor, a Division of Baxter Healthcare.

Figure 2. Novacor LVAD set up in PETC's Flow Analysis Facility. Note that transparent housings have been added to visualize flow around the inlet and outlet valves.

blood/device interactions may be of clinical importance. For example, it is well known that thrombosis, or blood clotting, can occur on artificial surfaces. If clots dislodge into the blood stream, they may be transported to vital organs resulting in neurologic or other medical complications.

The interactions between blood and artificial surfaces are a function of patient-dependent hematologic factors and the behavior of blood flow near the surfaces. Recent developments in laser-based flow imaging techniques at PETC have, for the first time, made possible detailed measurements of flow on surfaces within the Novacor LVAD. These developments allow the Flow Analysis Laboratory to assist the University of Pittsburgh and Novacor with the increasingly complex analysis of blood flow dynamics and its relationship to clinical LVAD management. This cooperative research contributes to the continuing effort to optimize device performance and the goal of improving the quality of life for cardiac transplant candidates.

This project is being performed under a Cooperative Research and Development Agreement (CRADA) which is just one of many DOE mechanisms to promote America's economic security by creating and transferring vital technologies. Defined by Congress in the Technology Transfer Act of 1986, CRADAs enable PETC to engage in collaborative projects with industry, academia, and other research institutions that are willing to contribute resources toward common programs and projects.

CRADAs enable industry partners to access PETC's unique facilities, equipment, and expertise quickly and easily. Many combinations of joint resources are possible. Partners can provide people, money, or equipment as their share. PETC can provide people, equipment, and facilities; however, PETC cannot provide any funds to its CRADA partners.

This CRADA with the University of Pittsburgh is just one of several that PETC has initiated over the past several years. PETC and the Pennsylvania Energy Development Authority completed a project on the research needs of the anthracite coal industry. Bonmol Corporation drew on PETC's expertise in flue gas cleanup sorbents for its project, and AMAX Coal Industries collaborated on a project that investigated the reconstitution of coal fines. Presently, PETC is working with the American Society for Testing and Materials, BO Technical Developments, and Consolidation Coal under separate similar arrangements.

If you would like information about PETC's ongoing research activities or about the opportunities for forming a CRADA, contact Ms. Kay Downey, Technology Transfer Officer, at (412) 892-6029.

The Nimbus AxiPump

Another implantable heart device being studied at PETC is the axial flow pump, developed by Nimbus Inc. and known as the AxiPump (Figure 3). This is a revolutionary miniature LVAD consisting of a small turbine the size of a penlight battery (see Figure 4). One of the many advantages of its small size is the reduced surface area in contact with blood. Another unique feature of the AxiPump is that, rather than being pulsatile like the human heart, it is a continuous flow device. An AxiPump patient with a very weak heart would have no significant pulse or systolic/diastolic blood pressure. According to Presbyterian-University Hospital medical researchers, this device could significantly reduce the demand for donor hearts and has the potential to save up to 30,000 lives per year.

For the AxiPump to work properly, the shear stresses imposed on blood must be kept within a narrow range. Excessive shear stresses can damage blood cells, while very low shear stresses tend to promote blood clotting. The flow velocities and resulting shear stresses in the AxiPump are being measured in the Flow Analysis Laboratory using high-speed photography and pulsed laser imaging techniques.

Figure 3. Location of the Nimbus AxiPump between the left ventricle and the thoracic aorta. Figure courtesy of Nimbus Inc.

Figure 4. The rotary turbine of the Nimbus AxiPump.

This is a formidable task because flow fields must be measured across a millimeter gap between turbine blades that are spinning at 12,000 revolutions per minute.

PETC's Flow Analysis Facility

To study "multiphase" fluid dynamics in coal utilization processes, researchers have developed a state-of-the-art Flow Analysis Laboratory (see Figure 5). This lab features a wind tunnel designed to simulate flow fields in coal utilization processes. Sophisticated flow diagnostic equipment is used to measure flow fields in the wind tunnel. This flow diagnostic equipment includes a pulsed laser imaging (PLI) system and a laser Doppler velocimeter (LDV). The PLI system, which was designed and developed at PETC over the past 5 years, uses digital photography to map flow fields. This system employs a pulsed copper-vapor laser as a special strobe light to illuminate multiple-exposure digital photographs of particle motion in a flow field. The digital photographs are analyzed to extract quantitative flow information using a computer workstation with parallel processing capabilities. PETC researchers have published several articles describing the design and application of PLI systems.

One of the main applications of the Flow Analysis Laboratory is the analysis of flow fields that occur in heat-exchanger tube banks of coal-fired boilers. Figure 6 shows a picture of simulated streamline motion over a steam tube in the wind tunnel. These flow fields govern the heat transfer and ash deposition processes in heat-exchanger tube banks. The Flow Analysis Laboratory has also been used to analyze the behavior of sprays used in flue-gas desulfurization systems and flow fields in coal cleaning experiments that measure the trajectories of charged particles subjected to electromagnetic fields.

Medicine and Coal Research Meet

Under the terms of the CRADA, PETC and medical researchers from the University of

Figure 5. A view of the PETC Flow Analysis Laboratory.

Figure 6. Simulated streamline motion over a steam tube in the wind tunnel.

Pittsburgh's Presbyterian-University Hospital, Novacor, and Nimbus will work as a team to analyze flow behavior in the Novacor LVAD and the Nimbus AxIPump. A flow loop that uses a Jarvik-7 artificial heart to simulate the human heart and circulatory system has been set up in the Flow Analysis Laboratory. The Novacor LVAD is connected to the Jarvik-7 to simulate the real flow conditions in an implant patient (see Figure 7). The PLI and LDV systems, which are usually directed into the wind tunnel, are being applied to the LVADs.

One of the more interesting techniques being employed by PETC researchers to see fluid motion close to the pump surfaces involves the use of fluorescent particles. With the PLI technique, particles that are visible when illuminated with laser light are added to a fluid. They allow the fluid motion to be seen, and they also mimic the motion of blood cells and platelets. However, the particles cannot be seen very close to a pump surface because of the intense glare of laser light reflected from the surface. To see the particle motion near the valve surface, special fluorescent particles are

Figure 7.
The Jarvik-7 and
Novacor LVAD set up
in the Flow Analysis
Laboratory.

Figure 8a. The pericardial trileaflet outflow valve of the Novacor LVAD (a magnified view).

Figure 8b. Fluorescent particle motion around the pericardial valve of a Novacor LVAD.

used. When the fluid is illuminated with monochromatic (single color) laser light, the fluorescent particles are excited and subsequently emit light of a different color. A special light filter is placed in front of the camera lens. This filter blocks the wavelength of the laser light reflected off the valve surfaces. The camera only sees colors that are different than that of the laser light—including colors emitted by the fluorescent particles. Figure 8a shows the pericardial trileaflet outflow valve of the Novacor LVAD, and Figure 8b shows the fluorescent particle motion around the outflow valve. Because thrombosis is known to occur on the valve surfaces, the particle motion on the valve surface is of particular interest.

PETC researchers hope to gain from the vast experience of the medical community in designing pumps to handle fluids with strong coagulative properties. This could help energy researchers with the design of pumps, reactors, and other equipment for handling liquefied coal products and coal slurries, which also have strong coagulative properties.

"We are extremely excited about the opportunity to make these clinically relevant measurements in the state-of-the-art PETC facility. We believe that the information we obtain will guide the design of current and future heart pumps."

Dr. Harvey Borovetz

Harvey S. Borovetz, Ph.D., is Professor of Surgery in the School of Medicine of the University of Pittsburgh and Director of Bio-engineering for the Artificial Heart Program at Presbyterian-University Hospital. Dr. Borovetz obtained his M.S. and Ph.D. degrees in Bio-engineering from Carnegie Mellon University. Upon completion of his Ph.D. in 1976, Dr. Borovetz joined the faculty of the Department of Surgery, University of Pittsburgh where he remains today. He also holds an appointment as Senior Lecturer of Engineering in Medicine at Carnegie Mellon University. Dr. Borovetz's other ongoing projects include a study of the role of hemodynamics in the development of arteriosclerosis and development of an intravascular membrane blood oxygenator.

Frank Shaffer is the Principal Investigator responsible for the development of the Flow Analysis Laboratory and its Pulsed Laser Imaging equipment. Frank obtained his bachelor's and master's degrees in Mechanical Engineering from West Virginia University. While working on his M.S. degree, he developed instrumentation for flow measurements in recirculating fluidized beds at the National Science Foundation Fluid-Particle Research Center in Morgantown. After graduating in 1986, Frank joined PETC as a research engineer in the Coal Combustion Division where he has continued research in multiphase flows and particulate deposition. He has published extensively and given numerous presentations in the United States and abroad on these research subjects.

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FOCUS ON

Curt M. White

Dr. Curt Marshall White, leader of PETC's Analytical Research Group, received the 1991 W.S. Jackman Medallion of Distinction on June 1 during a ceremony held at California University of Pennsylvania. The Medallion, first established and granted in 1983, is named in honor of Wilbur Samuel Jackman, a professor, author, and administrator of the University, who graduated from California

in 1877. Professor Jackman was known internationally as the "Father of elementary education science." The award is given by the California Alumni Association to graduates of the University who have gained national and/or international recognition in their professions and have distinguished both themselves and their alma mater. Another recipient of this award was PETC's own Herb Rotcofsky.

Dr. White received a B.A. in Chemistry from California State College (the predecessor of California University of Pennsylvania), an M.S. in Chemistry from the University of North Dakota, and a Ph.D. in Chemistry from Duquesne University. He has extensive experience in gas chromatography, combined gas chromatography-mass spectrometry, and organic analytical chemistry of fuels. His research interests include defining the

nature and chemistry of sulfur in coal; studying the physical, chemical, and thermodynamic properties of coal liquefaction products; and developing new analytical methods for fuel analysis. Further interests involve the analytical applications of mass spectrometry and capillary gas chromatography. His recent research has focused on the chemistry of the chloromethane/zeolite reaction as a means to form gasoline from natural gas.

Dr. White is the author of over 50 publications concerned with fossil fuel chemistry and geochemistry. He has published four books, most recently an edited volume entitled *The Geochemistry of Sulfur in Fossil Fuels*. Dr. White is also the Physics/Fossil Fuels topical editor of *Polycyclic Aromatic Compounds: An International and Interdisciplinary Journal* and is a member of the editorial boards of *Energy & Fuels* and *The Journal of High-Resolution Chromatography*.

Dr. White is an Adjunct Associate Professor of Environmental Chemistry in the Graduate School of Public Health at the University of Pittsburgh. He has been at PETC for the past 17 years, contributing steadily to the understanding of the organic geochemistry of coals and the environmental aspects of fossil fuel processing.

HIGHLIGHTS

Coal Preparation Process Research Facility Completed

PETC's Coal Preparation Process Research Facility (CPPRF) has been completed and is currently undergoing shakedown testing. This state-of-the-art, continuous bench-scale facility will accommodate a wide variety of advanced fine-coal cleaning and handling processes, circuits, and equipment for testing of 100 to 500 pounds per hour of feed coal. The CPPRF is comprised of three areas that can be operated independently or in series for flexibility: (1) a permanent conventional precleaning circuit, (2) a permanent three-stage grinding (comminution) circuit, and (3) an open, emerging technology area for short-term incorporation of other modules or equipment on a sequential or concurrent basis. The use of this continuous, bench-scale facility will offer a critical link in the scale-up between applied research in the laboratory and proof-of-concept or demonstration testing.

PETC has identified activities in advanced coal beneficiation technology development to be conducted in the CPPRF in Fiscal Year 1992. These activities will be of four general types: (1) outside contracts resulting from competitive DOE solicitations; (2) Cooperative Research and Development Agreements (CRADAs) with industry and other private-sector groups; (3) scale-up of bench-scale processes developed at PETC; and (4) bulk preparation of specification coals for other coal utilization technologies. For example, PETC is currently running a solicitation for continuous, bench-scale testing in the CPPRF of high-efficiency coal preparation equipment/technologies for fine coal. Contract awards will be made in 1992.

Raw coal (up to 150 mm in size) will be received outside the CPPRF and reduced to 6 mm x 0 top size in a four-roll crusher. It will then be conveyed into the CPPRF and stored in one of the two 5-ton feed storage bins for use in the different circuits. The conventional precleaning circuit can process up to 1.25 tons of coal per hour. First, the 0.6 mm x 0 fine coal is removed via wet screening, and the remaining 6 mm x 0.6 mm coal is sent to either one or two stages of cleaning using 150-mm diameter dense-medium cyclones. The cleaned coal and/or fines can be (1) used in the emerging technology area, (2) shipped without additional processing, or (3) first comminuted in a three-stage circuit capable of handling 100 to 500 pounds of coal per hour. The three-stage circuit includes a hammermill and two wet-grinding ball mills and is capable of grinding the coal to as fine as 0.02 mm top size. A state-of-the-art computer control system will be used to configure, operate, and monitor 24 distinct flowsheet configurations, requiring a minimum of manpower.

This facility will be a national resource for coal preparation research and development that will result in extensive interactions with major industrial concerns through cooperative agreements.

Model of new Coal Preparation Process Research Facility

Advanced Wall-Fired Low-NO_x Combustion Demonstration Achieves Preliminary AOFA Test Results

Three advanced combustion techniques to reduce nitrogen oxides (NO_x) emissions are being demonstrated on a 500-MWe wall-fired boiler under the U.S. Department of Energy's Clean Coal Technology Program at Georgia Power's Plant Hammond. The primary objective of the project is to demonstrate the NO_x reduction effectiveness of Advanced Overfire Air (AOFA), Low-NO_x Burners (LNB), and the combination

NO_x Emission preliminary test results

of these technologies under short-term controlled and long-term utility load dispatch conditions. The project involves four test evaluations: baseline, AOFA, LNB, and LNB with AOFA. After establishing baseline performance, each technology will be evaluated for NO_x reduction effectiveness and its impact on boiler operation.

Baseline tests of the non-modified boiler and AOFA testing have been completed. LNBs (24) have recently been installed, and data collection began in June. Preliminary results indicate that the most important variables that affect NO_x reduction are boiler load and excess oxygen levels. For

AOFA, depending upon load, the long-term preliminary test results produced a statistically reliable data set that indicates about 20% reduction in NO_x.

AOFA test results also indicate increased carbon levels in the ash after combustion. In some cases, two-fold increases were observed. Southern Company Services (Southern Company's engineering and service company and the industrial manager for this project) is in the process of trying to understand the reason(s) for the increased carbon levels and the impact they may have on operations.

AOFA incorporates separate (from the wind box) injection ports and duct configurations that are designed to provide increased secondary air penetration. The AOFA system, designed by Foster Wheeler, provides increased penetration velocities, relative to standard AOFA systems, by supplying secondary air from completely separate aerodynamically designed ducts located above the existing burner wind box.

The Foster Wheeler designed LNBs installed for this demonstration control fuel and air mixing to preclude the formation of NO_x. This is accomplished by regulating the initial fuel-to-air mixture, velocities, and turbulence to create a fuel-rich flame core and by controlling the rate at which additional air, required to complete combustion, is mixed with flame solids and gases to maintain a deficiency in oxygen.

The Electric Power Research Institute is participating in this project with DOE and Southern Company Services. Consistent with the goals of the National Energy Strategy, this demonstration is a joint government and industry partnership that is designed to encourage the use of U.S. domestic coals in an environmentally responsible manner.

Microcel Microbubble Column Flotation

A microbubble column flotation technology called Microcel[®] (recently licensed to ICF Kaiser Engineers of Pittsburgh, Pennsylvania) removes mineral matter, including pyrite, from coal by passing very fine air bubbles up through a slurry of coal mineral matter and water in a column. The coal particles, which are hydrophobic, attach to the air bubbles and are carried up to the surface as a froth. At the same time, the hydrophilic mineral particles remain in the water and flow out the bottom of the column. A counter-current flow of water enters the top of the column and washes entrained mineral-matter particles from the froth.

Early development of this advanced flotation technology began at PETC, and subsequent work was done at Virginia Polytechnic Institute (VPI) and State University, with support from PETC, and under the direction of Professor Roe-Hoan Yoon, director of VPI's Center for Coal and Minerals Processing. The license to Kaiser Engineers is a major step in bringing this technology to commercial readiness.

A prototype commercial-scale column is currently undergoing testing at Shell Mining Company's coal preparation plant in Naugatuck, West Virginia. The 8-foot diameter, 27-foot-high column processes about 16 tons per hour of minus-100-mesh, high-ash, low-solids-concentration fine coal slurry reject material from the plant's classifying cyclones. Because this material was difficult to clean using conventional froth flotation processing, it was previously discarded, resulting in lost energy values and the accumulation of solid wastes. The Microcel[®] system has been successful in achieving more than 65% Btu (energy) recovery from this material, while reducing the ash content of the product coal to 10 - 12%.

DOE Selects Clean Coal IV Proposals

On September 10, 1991, DOE's Acting Assistant Secretary for Fossil Energy, Linda G. Stuntz, announced the selection of nine projects for negotiations in Round IV of the Clean Coal Technology Program. Three Integrated Gasification Combined Cycle (IGCC) technology projects will be managed by the Morgantown Energy Technology Center. Two precombustion cleaning, two post-combustion cleaning, and two combustion technology projects will be managed by PETC. The total Round IV proposed project cost is \$1.5 billion of which DOE's share is \$567 million.

PETC's assignments include projects by:

- Union Carbide Corporation to demonstrate a 75-MWe regenerable, amine-based flue gas desulfurization system at the Alcoa Generating Corporation Warrick Power Plant near Newburgh, Indiana.
- New York State Electric & Gas Corporation to demonstrate the "S-H-U" flue gas desulfurization process at the Milliken Station in Lansing, New York. The process uses a formic acid-enhanced, wet limestone scrubber technology that claims a 98% SO₂ removal rate. The project will also test the NO_x OUT injection process for NO_x control, and a heat pipe air heater system to optimize thermal efficiency.
- Custom Coals International to demonstrate an advanced physical coal cleaning technology and its integration with coal/sorbent reconstitution techniques to produce a self-scrubbing fuel that emits less than 1.2 lb of SO₂ per million Btu. The fuel will be manufactured at Duquesne Light's coal cleaning facility, and tests of the product will be conducted at their Cheswick Plant and at Richmond Power and Light's Whitewater Valley station.
- ThermoChem, Inc., to demonstrate the operation of a pulse combustor in an application for steam gasification of coal at a Weyerhaeuser Paper Mill in Springfield, Oregon.
- Cordero Mining Company to demonstrate the Carbontech Syncoal Process to upgrade high-moisture, low-sulfur, low-rank coals. This two-stage, hot oil/hot air, coal drying process will be demonstrated at the Cordero Mine near Gillette, Wyoming.
- Tennessee Valley Authority to demonstrate the reduction of NO_x emissions by the retrofit of coal reburning to a pulverized coal wall-fired boiler on an existing 175 MWe, wall-fired unit at TVA's Shawnee Fossil Plant near Paducah, Kentucky. The reburn fuel will be used at micronized size, about 80% below 325 mesh.

There are now 42 active projects in the Clean Coal Technology Program approaching a total value of \$4.6 billion of which DOE's share is about \$1.7 billion.

Southern Company Services to Test Selective Catalytic Reduction Technology

In this \$15.6-million effort, Southern Company Services, Inc., the U.S. Department of Energy, and the Electric Power Research Institute (EPRI) will test Selective Catalytic Reduction (SCR) technology on Gulf Power Company's Plant Crist Unit No. 5 located near Pensacola, Florida. This project will demonstrate the applicability of the SCR technology to significantly reduce nitrogen oxides (NO_x) emissions from power plants using flue gas that contains high- and low-ash loadings derived from the combustion of high-sulfur U.S. coals. SCR process capabilities (NO_x removal catalyst performance, operating conditions, catalyst life, etc.) and process economics will be assessed.

In the SCR system, controlled amounts of ammonia are mixed with the combustion gases produced from coal combustion. The mixture then passes through a reaction chamber, containing catalyst, built alongside the boiler. The catalyst promotes the reaction of NO_x with ammonia to form harmless molecular nitrogen and water. The SCR facility will consist of three 2.5-MWe-equivalent SCR reactors, six 0.20-MWe-equivalent SCR reactors, and associated equipment for operations, maintenance, and testing. The testing will be conducted on a flue gas slip stream taken from Unit No. 5.

This project will test various catalysts of different shapes and chemical compositions. Three U.S. catalyst suppliers (Engelhard, Grace, and Norton), two European suppliers (Haldor Topsoe and Siemens), and two Japanese suppliers (Hitachi Zosen and Nippon Shokubai) have been chosen to supply catalysts for this Clean Coal Technology Program demonstration project.

The project's preliminary design phase is complete, and the detailed engineering phase has begun. If successful, this project will demonstrate that SCR can achieve approximately an 80% reduction of NO_x emissions from utility boilers firing high-sulfur, U.S. coals with acceptable catalyst deactivation rates. This technology, which is being tested on a tangentially fired boiler during this demonstration, could be retrofitted onto other types of boilers, including cyclone-fired boilers—a type of boiler that is particularly prone to high NO_x emissions and that cannot be easily retrofitted with other developing NO_x control technologies.

DOE is providing \$7.5 million, or 48%, of the project's total cost. EPRI is contributing \$2.0 million, and Southern Company Services, Inc., is providing more than \$6.0 million. The project is scheduled to be completed by mid-1994.

RD&D AWARDS

Research, Development, and Demonstration (RD & D) Awards are awarded by PETC as (1) grants to universities, (2) contracts to corporations, or (3) clean coal cooperative agreements with industry. They support key scientific and engineering projects identified by PETC as vital to the nation's energy interest. For reports resulting from these contracts, please contact either:

<p>(1) for DOE employees and its contractors
 Office of Scientific & Technical Information
 P.O. Box 62
 Oak Ridge, TN 37831
 (615) 576-8401</p> | <p>(2) the general public
 National Technical Information Service
 U.S. Department of Commerce
 5285 Port Royal Road
 Springfield, VA 22161
 (703) 487-4650</p> |
|--|---|

Please be aware that there are fees connected with these services.

Date of Award	Awardee	Project/Contract Number
<i>Liquid Fuels</i>		
01/15/91	University of Arkansas Fayetteville, AR	High Pressure Syngas Fermentation AC22-91PC91028
02/08/91	Universal Fuel Development Association Grand Forks, ND	Fine Particle Catalysis for Coal Liquefaction AC22-91PC90048
03/15/91	UOP Inc. Corporate Research Center Des Plaines, IL	Development of a Catalyst for Conversion of Syngas Derived Materials to Isobutylene AC22-91PC90042
04/02/91	Advanced Fuel Research East Hartford, CT	Dual Role of Oxygen Functions in Coal Pretreatment and Liquefaction: Crosslinking and Cleavage Reactions AC22-91PC91026
05/16/91	M. W. Kellogg Co. Houston, TX	Design of Generic Coal Conversion Facility AC22-91PC89854
05/21/91	Amoco Oil Co. Naperville, IL	Selective Catalytic Cracking of Fischer-Tropsch Liquid to High Value Transportation Fuels AC22-91PC90057

Date of Award	Awardee	Project/Contract Number
06/27/91	Union Carbide Corp. Charleston, WV	Heterogeneous Catalytic Process for Alcohol Fuels from Syngas AC22-91PC90046
<i>Environmental Control Technology</i>		
05/23/91	Consolidation Coal Co. Research Division Pittsburgh, PA	Advanced In-Duct Injection for SO ₂ Control AC22-91PC90360
06/04/91	Southern Research Institute Birmingham, AL	A Novel Carbon-Based Process for Flue Gas Cleanup AC22-91PC91345
06/06/91	Southern Research Institute Birmingham, AL	Fundamental Mechanisms in Flue Gas Conditioning AC22-91PC90365

Small Business Innovation Research (SBIR) Program

DOE's SBIR program was developed to implement the Small Business Innovation Development Act of 1982. The objective of the program is to strengthen the role of small, innovative firms in areas of research and development that are federally funded. This research and development, in turn, will serve as a base for technological innovation while at the same time meeting agency needs.

In 1990, under Phase I of the SBIR program, 170 projects were funded (out of 1,172 grant applications submitted) at about \$50,000 each for preliminary feasibility studies. The firms receiving these Phase I awards were eligible to submit applications to continue their work in 1991 under Phase II of the program, which is the principal research and development phase. A list of some of the applications recommended for Fiscal Year 1991 Phase II awards is given below. These Phase II awards will average about \$495,000 for a two-year period.

For a complete list of the 65 applications recommended for Fiscal Year 1991 Phase II awards, contact Dr. Samuel Barish, SBIR Program Manager, U.S. Department of Energy, ER-16, Washington, DC 20545. The Department expects to issue the next SBIR solicitation in the fall of 1991. If you wish to be on the list to receive the next program solicitation, submit your request to Dr. Barish at the above address or call 301-353-3054.

ADA Technologies, Inc.; Englewood, Colorado; *Development of a Multi-Gas Process for Hot-Gas-Stream Cleanup Systems.*

Advanced Processing Technologies, Inc.; Salt Lake City, Utah; *Advanced Design of an Air-Sparged Hydrocyclone System for Fine Coal Flotation.*

Advanced Fuel Research, Inc.; East Hartford, Connecticut; *Mild Gasification in Transport Reactors.*

Bend Research, Inc.; Bend, Oregon; *Development of a Novel Process for the Separation of Nitrogen from Natural Gas Using a Nitrogen Solvent.*

CeraMem Corporation; Waltham, Massachusetts; *A Novel Filter Shape for Flue Gas Cleanup.*

CoraMem Corporation; Waltham, Massachusetts; *High Temperature Ceramic Filter Development.*

Chang Yul Cha and Associates; Laramie, Wyoming; *Development of an Advanced Process for Simultaneous Removal of Sulfur Oxides and Nitrogen Oxides from Flue Gas by an Electromagnetic Method.*

Chromex, Inc.; Albuquerque, New Mexico; *Development of a Multiple Input Spectrometer for Process Monitoring Applications.*

Eltron Research, Inc.; Aurora, Illinois; *Perovskite Solid Electrolytes for Intermediate Temperature Fuel Cells.*

Giner, Inc.; Waltham, Massachusetts; *Development of a Flue Gas Desulfurization Process Using a Novel Regenerative Hydrogen Bromide System.*

Membrane Technology & Research, Inc.; Menlo Park, California; *Ultrathin Metal Membranes.*

Northwest Fuel Development, Inc.; Portland, Oregon; *Gas Turbines for Combustion of Natural Gas in Mine Ventilation Air.*

Pacific Creative Research; San Diego, California; *Chemical Coal Cleaning at Low Caustic/Coal Ratios.*

Peak Instruments, Inc.; Pennington, New Jersey; *An Efficient X-Ray Wavelength Spectrometer for Improved Elemental Analysis on Electron Microscopes.*

Southwest Sciences, Inc.; Santa Fe, New Mexico; *A Novel Mass Spectrometer for Combustion Studies.*

Star*Tek Inc.; Las Vegas, Nevada; *Reservoir-Specific Data Correlation and Transfer Methodology.*

TDA Research, Inc.; Wheat Ridge, Colorado; *High Temperature Hydrogen Sulfide Removal.*

PUBLICATIONS AND PRESENTATIONS

Coal Preparation

Sulfur and Ash Reduction Potential and Selected Chemical and Physical Properties of U.S. Coals, Volume II—Central Region.

Cavallaro, J.A., Deurbrouck, A.W., Killmeyer, R.P., Jacobsen, P.S., and Fuchs, W.
USDOE/Pittsburgh Energy Technology Center,
DOE/PETC/TR-91/1, October 1990.

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WORKSHOP NOTES

PETC recently co-hosted discussions between United States and Soviet Union energy experts in the first exchange in the field of energy to follow pledges of technical cooperation as a result of the G-7 meeting in London and the summit in Moscow. Sponsored by DOE, under an agreement reached with the Soviet Union in July 1990, the "U.S./U.S.S.R. Workshop on Fossil Energy Technology and Industry" focused on coal, oil, and natural gas technologies.

Mikhail Shchadov (left), Soviet Minister of the Ministry of the Coal Industry, was impressed with the surface mine production at the R&F Coal Company in Cadiz, Ohio. Jack Cox, President of R&F (pictured in background), provided extensive details of R&F's spoil-side dragline used at this mine site. Environmental controls and reclamation practices were of great interest to the Soviet delegation.

The workshop began in Morgantown, West Virginia, on July 31, and discussions moved to Pittsburgh on August 1-2. The 8-day series of meetings included technical discussions and tours of U.S. energy research and production facilities by 17 of the Soviet Union's top energy officials. Led by Rantik Margulov, First Deputy Chairman of the State Fuels and Energy Commission (SFEC) of the U.S.S.R. Cabinet of Ministers, the Soviet delegation consisted of representatives from the Soviet Central Authority, the Republics, and local enterprises.

The workshop concluded on August 7 when a record of the meeting was signed by Margulov and the head of the United States delegation, DOE Deputy Secretary W. Henson Moore. The record committed the U.S. and the Soviet Union to exchange information on energy policy and directions and world energy issues. In addition, the workshop met a second important objective — it established a commitment between government and private-sector officials in the United States and their counterparts in the U.S.S.R. to hold technology exchanges to advance efficient and environmentally safe developments in the fossil energy field.

Seven specific measures were spelled out, including the establishment of a technical group to review the status of magnetohydrodynamics (MHD) technology and to develop recommendations for cooperation in the field. Another measure

called for the organization of a technical working group composed of government and industry representatives. This working group will hold a workshop on Clean Coal Technology research, development, and demonstration efforts in both countries and will determine the nature and scope of any cooperative activities.

Because the United States and the U.S.S.R. are the world's second and third largest coal producers, respectively (China is the world's largest coal producer), the new agreement will play a key role in the global energy future. Coal is emerging as the Soviet Union's primary source of energy, and the Energy Information Administration has indicated that world coal use will grow by 30% in the next 20 years. In fact, demand for advanced coal-burning equipment alone could reach \$50 billion by the year 2000. The workshop has created the opportunity for U.S. industry to explore new markets in the Soviet Union.

The SFEC will correspond with DOE to recommend dates, topics, and sites for a visit by U.S. delegates to the U.S.S.R. later in 1991. The U.S. delegation will consist of representatives from the government and the private sector.

CALENDAR OF UPCOMING EVENTS

December 3-6, 1991

1991 SO₂ Control Symposium

Co-sponsors: EPRI & U.S. EPA

Grand Hyatt Washington, Washington, DC

Contact: C. J. Drummond (412) 892-4889

April 28 - May 1, 1992

**17th International Conference on
Coal Utilization & Slurry Technologies**

Co-sponsor: Coal & Slurry Technology Association

Sheraton Sand Key, Clearwater, Florida

Contact: L. A. Ruth (412) 892-4461

May 4-7, 1992

**3rd International Symposium on the
Biological Processing of Coal**

Co-sponsor: EPRI

Sheraton Sand Key, Clearwater, Florida

Contact: G. Olson (412) 892-6294

July 26-31, 1992

**Coal Preparation, Utilization, and
Environmental Control Conference**

Westin William Penn, Pittsburgh, Pennsylvania

Contact: R. E. Hucko (412) 892-6133

September 22-24, 1992

Liquefaction Contractors' Review

Westin William Penn, Pittsburgh, Pennsylvania

Contact: G. V. McGurl (412) 892-4462

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