Conf-9410125--1

DOE/METC/C-95/7175

Repowering Flexibility of Coal-Based Advanced Power Systems

Authors:
Rita A. Bajura (DOE/METC)
Thomas F. Bechtel (DOE/METC)
Dale K. Schmidt (DOE/METC)
John G. Wimer (DOE/METC)

Conference Title:
13th Electric Power Research Institute Conference on Gasification Power Plants

Conference Location:
San Francisco, California

Conference Dates:
October 18 - 21, 1994

Conference Sponsor:
Electric Power Research Institute

REPOWERING FLEXIBILITY OF COAL-BASED ADVANCED POWER SYSTEMS

R. A. Bajura
T. F. Bechtel
D. K. Schmidt, J. G. Wimer
Morgantown Energy Technology Center
U.S. Department of Energy
Morgantown, WV 26507-0880

Introduction

The Department of Energy's (DOE's) Morgantown Energy Technology Center (METC) helps enhance the economic competitiveness, environmental quality, and national well-being of the U.S. by developing advanced power-generation systems. The potential market for advanced power-generation systems is large. In the U.S., electric demand is estimated to grow at about 1 percent per year through the year 2010.

The total power generation market also includes new-capacity as well as replacement of existing power plants as they age. Thus, the market for power systems over the next 15 years is estimated to be about 279,000 megawatts (MW), but could range from as much as 484,000 MW to as little as 153,000 MW. These predictions are summarized in Table 1. Over the next 15 years, the replacement market is potentially much larger than the expansion market because of the large base of aging power plants in the U.S.

Table 1. Future Power Markets, 1995 to 2010 (in gigawatts)

Market	Mid	High	Low
New Capacity	206	342	117
Repowering Capacity	73	142	36
Grand Totals	279	484	153

Currently, more than half the electricity in the U.S. comes from coal, and this will probably continue at least through 2010, because coal is low cost and readily available. The success of the Clean Coal Technology (CCT) program enhances the attractiveness of coal as a fuel for power generation.

The METC Power Systems business sector consists of six systems (or products) that can help meet future power market needs: integrated gasification combined cycle (IGCC), pressurized fluidized-bed combustion (PFBC), externally fired combined cycle (EFCC), advanced turbine systems (ATS), fuel cell (FC), and integrated gasification fuel cell (IGFC). These advanced power generation products must be clean (approach 1/10 of New Source Performance Standards), highly efficient (50 percent or more), and low cost ($1,000 to $1,200 per kilowatt [kW] for coal-based systems), and they must have the flexibility to handle different coals or natural gas. (See Table 2.) METC focuses research on enabling technologies, especially those that couple technologies with several products, thus maximizing investment. (See Figure 1.)

Table 2. Power System Goals -- 2010

System	$/kW	HHV Efficiency
IGCC	1050	52
2nd Gen. PFBC	1000	52
EFCC	1200	52
ATS	45	58
FC-natural gas	1000	60
IGFC	1200	55

Advanced Power Systems

	Advanced Gasifier	Hot Gas Cleanup	Advanced Furnace/Heat Exchanger	Advanced Turbine System	Fuel Gas Cleanup
PFBC	■	■		■	
IGCC	■	■		■	
EFCC			■	■	■
IGFC	■	■			

Figure 1. Elements Common to Advanced Systems and Technologies

Product Impact of Advanced Turbine Systems (ATS)

A significant initiative undertaken 2 years ago is the ATS program, which is jointly sponsored by the DOE's Office of Fossil Energy and Office of Energy Efficiency and Renewable Energy. The objectives are to develop ultra-high efficiency, environmentally superior, and cost-competitive gas turbine systems for base-load natural-gas-fired applications in utility and industrial markets. Figure 2 shows the efficiency impact of ATS technologies on different advanced power products, illustrating again the DOE strategy of supporting the development of systems and technologies with the greatest payback potential.

Significant changes in turbine design are required to achieve ultra-high efficiencies. Potential changes include higher firing temperatures, cycle modifications, the use of ceramics and high-temperature materials, and advanced blade cooling techniques. Firing temperatures that are 90 to 150 °C (200 to 300 °F) higher than state-of-the-art turbine systems are needed to achieve required efficiencies. Possible cycle modifications include intercooling, chemical and thermal recuperation, massive moisture injection, and using reheat combustors. Changes in combustor design, such as hot wall ceramics or staged combustion, are needed to meet environmental requirements, including nitrogen oxides (NO_X) emissions in the single digit parts-per-million range.

The ATS program is a cooperative effort. A steering committee that includes representatives from the Electric Power Research Institute (EPRI), the Gas Research Institute, and the Environmental Protection Agency in addition to the DOE offices is chartered to ensure that ATS-developed products meet the specific regional needs of industry.

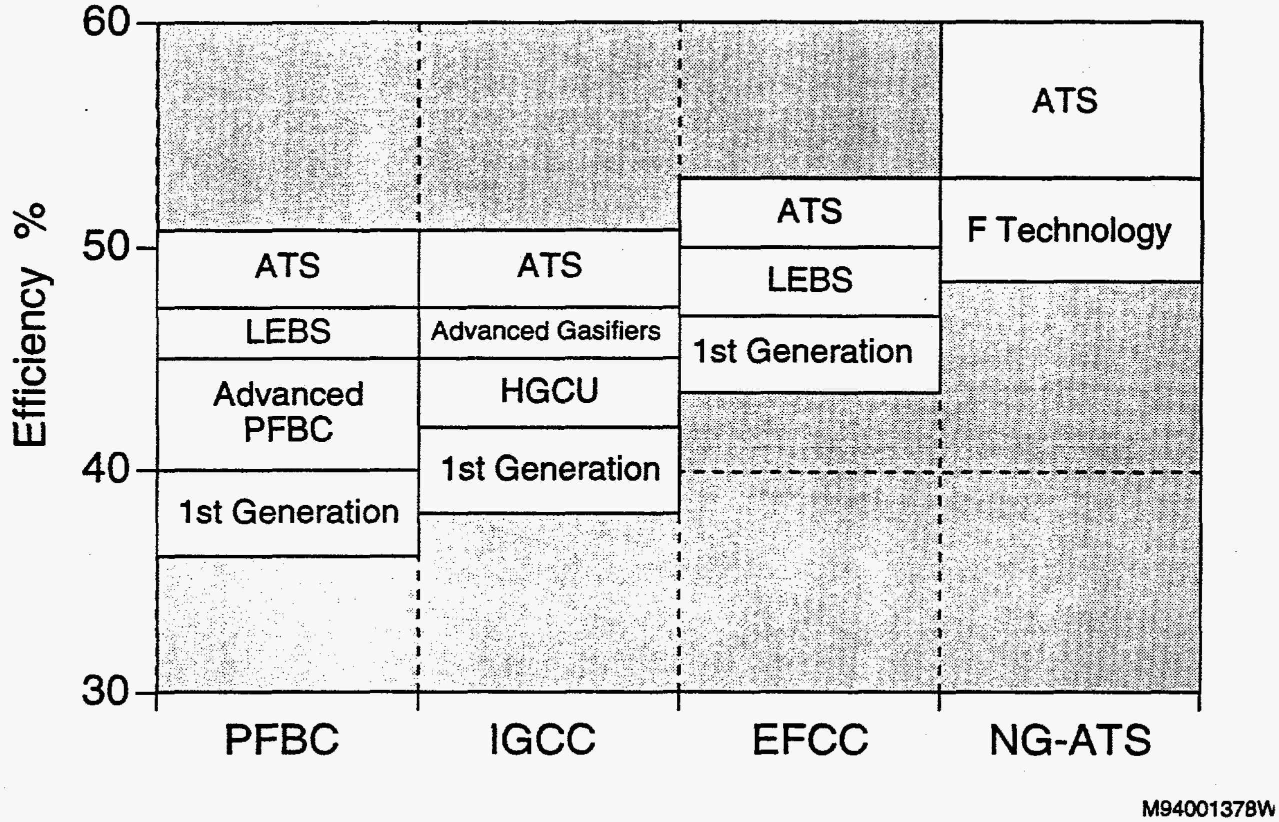

Figure 2. Advanced Gas-Turbine Impact on Other Technologies

Major development in the ATS Program is led by U.S. turbine developers under cost-shared contracts with DOE. Six systems studies were conducted by different turbine manufacturers to develop their advanced concepts. A total of $10.6 million of awards were made in 1993 to General Electric, Westinghouse, Solar Turbines, and Allison for conceptual design development of their ATS. Negotiations continue with a fifth vendor.

Research, Development, and Demonstration (RD&D) Status

IGCC, PFBC, EFCC, and IGFC power systems are being evaluated at 19 technology integration sites across the U.S. (See Figure 3.) These sites effectively meld Government and private monies for building and operating these research, development, and demonstration (RD&D) facilities. Research and development (R&D) projects typically are 80 percent public-funded, and CCT demonstration projects have a maximum 50-percent public funding. IGCC is being evaluated at seven CCT locations and four R&D facilities. PFBC will be demonstrated at four CCT sites with related R&D at three test facilities. For both EFCC and IGFC, there is one CCT and one R&D site. Planned operating periods for the projects are shown in Figure 4.

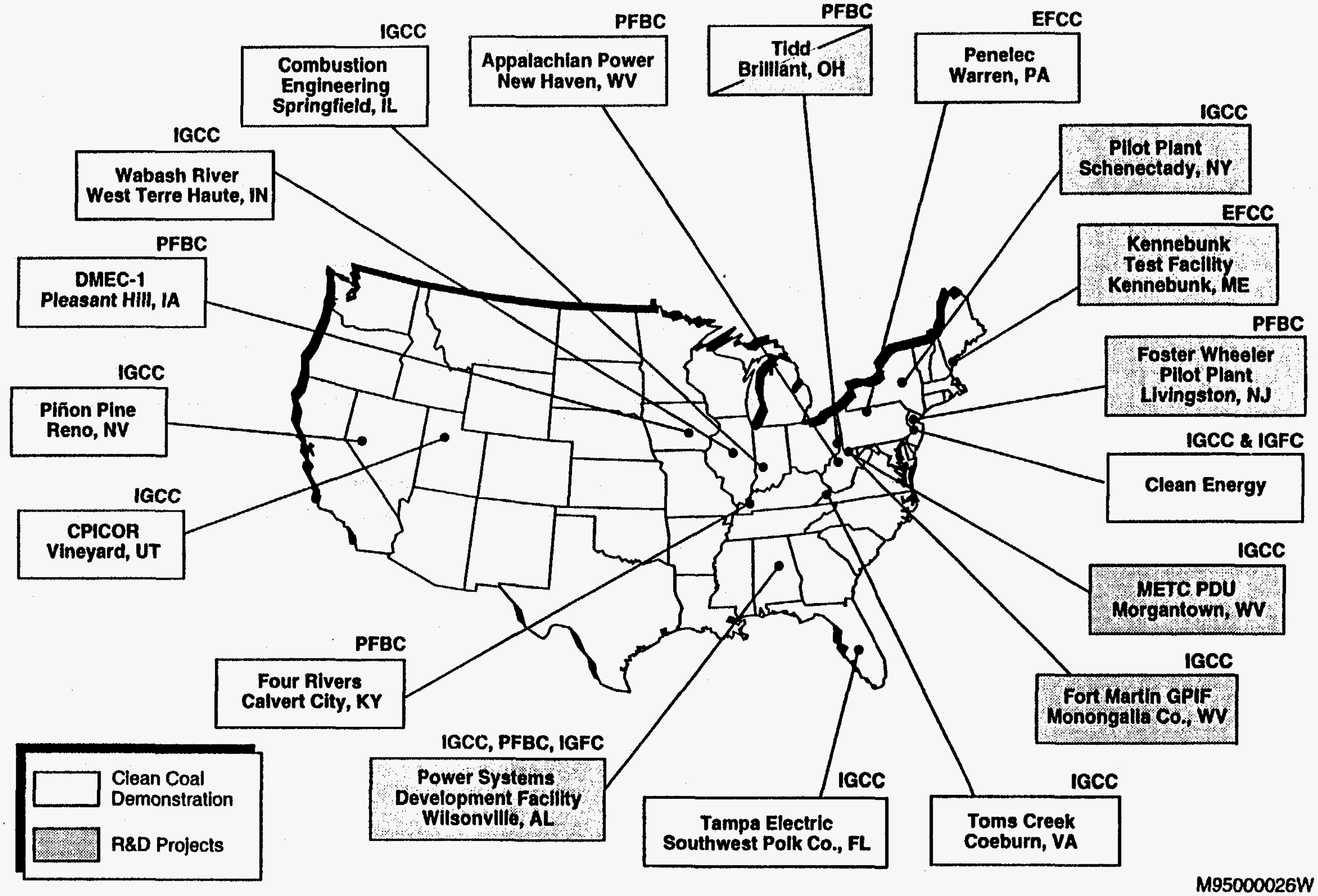

Figure 3. Locations of METC's Advanced Power-Systems Clean-Coal Projects

Project	Sponsor	Feature	Size	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Combustion Engineering IGCC	Combustion Engineering	Repower 25 MW ST	65 MW										
Tampa Electric IGCC	Tampa Electric	Greenfield	250 MW										
Wabash River IGCC	Destec/ PSI	Repower 104 MW ST	262 MW										
Piñon Pine IGCC	Sierra Pacific	New Plant Existing Site	95 MW										
Toms Creek IGCC	TAMCO	Greenfield	55 MW										
Clean Energy	Clean Energy Genco	Repower 200 MW ST	477 MW										
CPICOR IGCC	Centerior Energy	New Plant @ Steel Mill	Hot Metal + 250 MW										
Tidd PFBC	American Electric Power	Repower Demonstration	79 MW										
PFBC Utility Demonstration	American Electric Power	Greenfield	350 MW										
DMEC-1 PFBC	Midwest Power	Repower Demonstration	180 MW										
Four Rivers 2nd Generation CPFBC	Four Rivers Energy Partners	Greenfield Cogeneration	70 MW										
Penelec EFCC	Penelec	Repower 25 MW	100 MW										
Tidd Filter/PFBC	Ohio Power	Hot Filter	10 MW										
Pilot Plant PFBC	Foster Wheeler	Pilot Plant	1.5 MW										
METC PDU/IGCC	METC	Hot Gas Desulfurization	2 MW equiv.										
Fort Martin GPIF/IGCC	METC	Advanced Gasifier	15 MW equiv.										
Kennebunk EFCC	Hague	Ceramic Heat Exchange	1 MW equiv.										
Pilot Plant IGCC	General Electric	Hot Gas Cleanup	2 MW equiv.										
Wilsonville IGCC	Southern Company	Adv. Sys. Integration	5 MW equiv.										

M95000027W

Figure 4. RD&D Projects Operating Periods

The seven IGCC-CCT projects are (1) Combustion Engineering Repowering Project, (2) Tampa Electric Polk County Project, (3) Wabash River Repowering Project, (4) Piñon Pine Project, (5) Toms Creek IGCC Project, (6) CPICOR IGCC/COREX® Project, and (7) Clean Energy Project. They are each briefly described below.

Combustion Engineering (CE) Repowering Project. The Combustion Engineering Repowering Project is designed to repower a 25-megawatt electric (MWe) steam turbine. The IGCC system is based on CE's dry-feed, air-blown, entrained-flow pressurized gasifier and a moving-bed hot gas cleanup system.

Tampa Electric Polk County Project. The Tampa Electric Project will demonstrate the greenfield application of a 250-MWe IGCC system based on the Texaco oxygen-blown entrained-flow gasification technology. A moving-bed hot gas cleanup system will be operated in a partial flow, parallel gas stream. Environmental permitting is complete and construction recently began.

Wabash River Repowering Project. The Wabash River Coal Gasification Repowering Project is a joint venture of Destec Energy, Inc., and PSI Energy, Inc. (PSI). The objective is to demonstrate the commercial application of an IGCC system to repower one of six existing units at PSI's Wabash River Generating Station in West Terre Haute, Indiana. The coal-fired boiler will be replaced by a gasifier island to convert coal to clean fuel gas. The station's refurbished steam turbine will be arranged in a combined-cycle power island configuration, with the addition of a gas turbine and heat recovery steam generator to generate a combined total of 262 MWe. Construction is around 50 percent complete with operation planned for August 1995.

Piñon Pine IGCC Power Project. The Piñon Pine Power Project is a 95-MWe IGCC facility to be built at Sierra Pacific Power Company's Tracy Power Station near Reno, Nevada. The facility will demonstrate an IGCC system utilizing the air-blown KRW agglomerating ash fluidized-bed gasifier, hot gas cleanup for particulate removal and desulfurization, and a power island that includes the first commercial use of the General Electric MS6001FA gas turbine. Construction is scheduled to begin in February 1995.

Toms Creek IGCC Project. The Toms Creek IGCC Demonstration Project is being undertaken by TAMCO Power Partners, a partnership formed by Tampella Power Corporation and Coastal Power Production Company. As originally conceived, the project will be a greenfield facility located in Coeburn, Virginia, at the Virginia Iron, Coal and Coke Company's Toms Creek Mine. The project will demonstrate a 55-MWe IGCC system based on the Tampella U-Gas® fluidized-bed gasification technology, high-temperature particulate control, and fluid-bed desulfurization using mixed metal oxides.

CPICOR IGCC/COREX® Project. The CPICOR project objective will demonstrate an industrial process to produce both power and iron based on the COREX® process. In the COREX® process developed by Deutsche Voest-Alpine Industrieanlagenbau GmbH, iron oxide ore is charged into a reduction shaft furnace. The furnace also receives reducing gas from a melter-gasifier located below it. The melter-gasifier is charged with coal and oxygen, which react to produce the reducing gas and also provide sufficient heat to melt the iron produced in the reduction furnace. In the furnace, the iron oxide ore reacts with the reducing gas to produce direct-reduced iron. The significant amount of energy that remains is most efficiently used for power production in a gas-fired combined-cycle system. The project team has announced a project development agreement with Geneva Steel of Vineyard, Utah. Upon approval by DOE, the plant would be integrated into the existing Geneva mill in Vineyard, Utah, to produce 250 MWe of power and 3,000 tons/day of liquid iron.

Clean Energy Project. The Clean Energy Demonstration Project, proposed by Clean Energy Partners Limited Partnership (CEP), will feature an advanced, commercial-scale, 477-MWe IGCC system configured to repower a 200-MWe steam turbine and a 1.25-MWe coal gas fueled molten carbonate fuel cell (MCFC). CEP consists of Clean Energy Genco, Inc., (an affiliate of Duke Energy Corp.); Makowski Clean Energy Investors, Inc., (an affiliate of J. Makowski Company); British Gas Americas, Inc., (an affiliate of BG Holdings, Inc.); and an affiliate of General Electric Company. Clean Energy Genco, Inc., is the managing general partner of the CEP. The MCFC portion of the project will be executed under a subcontract with Fuel Cell Engineering, a subsidiary of Energy Research Corporation. The project will demonstrate four objectives: (1) Scaleup of the British Gas/Lurgi gasifier to commercial size; (2) integration of major processes and equipment within the IGCC system; (3) operation of a 1.25-MWe MCFC with coal gas; and (4) construction and operation of an advanced coal-fired power plant by an Independent Power Producer under commercial terms and conditions. A negotiated Cooperative Agreement was recently provided for Congressional approval.

Four PFBC projects are also in DOE's CCT Program: (1) Tidd PFBC Plant, (2) DMEC-1 Limited Partnership Circulation PFBC Project, (3) Utility PFBC Demonstration Project, and (4) Four Rivers Energy Modernization Project.

The Tidd PFBC project is the first operational turbine-based CCT project and is an extremely successful example of the anticipated results that will accrue from all of the IGCC, PFBC, and EFCC demonstration projects. The Tidd PFBC has now operated over 9,500 hours at various operating conditions, including full load. Adding the operating hours that each of Tidd's sister plants have accumulated in Sweden and Spain, there are approximately 50,000 hours of experience on first-generation PFBC technology.

Of the four PFBC projects in the CCT program, three different PFBC suppliers are represented. These technologies will confirm the environmental performance, cost, reliability, and maintainability of bubbling bed, circulating, and advanced PFBCs. The utility demonstration project will scale up PFBC technology to a 340-MWe size plant that is more common in the utility industry. The Four Rivers Project utilizes advanced PFBC technology that has evolved from pilot-plant testing in the DOE R&D program to integrated operation at the Power Systems Development Facility (PSDF), which is being done in conjunction with EPRI.

There is one EFCC project in the CCT Program, a project with the Pennsylvania Electric Company (Penelec). The Penelec project, currently in design phase, will demonstrate a 65-MWe EFCC system. This project relies on technology that has also evolved from the R&D program funded by DOE and a consortium of 18 participants made up of utilities, State agencies, utility groups, and industrial members including international representation and representation by EPRI.

A number of the major R&D projects are key components of the developmental path for IGCC, PFBC, and EFCC products. These R&D projects include (1) Power Systems Development Facility (PSDF), (2) Fort Martin Gasifier Product Improvement Facility (GPIF), (3) Morgantown Energy Technology Center (METC) Hot Gas Desulfurization Process Development Facility (PDU), (4) General Electric Environmental Systems, Inc., (GEESI) Pilot Plant, (5) Foster Wheeler (FW) Pilot Plant, (6) Tidd Filter, and (7) Kennebunk Test Facility. These are briefly described below.

Power Systems Development Facility (PSDF). The PSDF facility will be located at the Southern Company's Clean Coal Research Center near Wilsonville, Alabama. Participants in this cost-shared RD&D project include DOE, Southern Company Services, Foster Wheeler, American Electric Power, M.W. Kellogg, Westinghouse, Southern Research Institute, GM-Allison, Alabama Power Company, Southern Electric International, and EPRI. Startup is scheduled for the third quarter of 1995.

The PSDF will be used to solve systems integration issues and to develop product improvements in several of DOE's power systems. The PSDF will contain five separate modules, an advanced PFBC, a transport reactor gasifier, several hot gas particle control devices (PCD), a combustion gas turbine, and a fuel cell test skid provided by EPRI. The PSDF modular design maximizes the flexibility of the facility.

The advanced gasifier module uses M.W. Kellogg's transport reactor technology. The module will provide for parametric testing of the PCDs over a wide range of operating temperatures, gas velocities, and particulate loadings. The transport reactor is sized to process nominally 2 tons/hr of coal to deliver 1,000 actual cubic feet per minute (acfm) of particulate laden gas to the PCD inlet over the temperature range of 1,000 to 1,800 °F at 184 to 283 psia. Two PCDs will be tested alternately on the transport reactor.

Plans are currently being made to integrate a 100-kW MCFC Test Skid at the facility.

Fort Martin Gasifier Product Improvement Facility (GPIF). A team consisting of Jacobs Sirrine Engineers, Inc., Riley Stoker Corporation, and PSI PowerServ, is designing and will construct the facility. The gasifier concept is based on PyGas, a patented air-blown gasification process. The facility will be located at Monongahela Power Company's Fort Martin station near Morgantown, West Virginia. Monongahela Power Company is an operating subsidiary of the Allegheny Power Service Systems.

The overall goal of the GPIF is to improve IGCC technology and reduce cost. The gasifier is an air-blown hybrid concept that combines an entrained-bed pyrolyzer within a fixed-bed of char, which gasifies the carbon. The gasifier will be capable of operating with highly caking eastern coals. The modest off-gas temperature from the gasifier (1,500 °F), together with contaminant removal within the gasifier, are projected to lead to significant cost reduction and efficiency improvement for IGCC systems. The plant will operate at pressures ranging from 200 pounds per square inch actual (psia) to 600 psia and will be designed to process up to 150 tons/day of high-swelling bituminous coal. Detailed design is underway with ground-breaking scheduled for early 1995.

Morgantown Energy Technology Center (METC) Hot Gas Desulfurization Process Development Facility (PDU). METC has been developing advanced hot gas cleanup sorbents for IGCC advanced power systems, providing experimental support to the DOE contractor efforts and to CCT participants. Current process development activities include the Fluid-Bed Hot Gas Desulfurization (HGD) Process Development Unit (PDU) project. This project is designed to provide data on concept feasibility, process performance, engineering problems, and scaleup. Construction has begun on the 150,000 standard cubic feet per hour Fluid-Bed HGD PDU and the syngas generator that will supply fuel gas to the PDU.

General Electric Environmental Systems, Inc. (GEESI), Pilot Plant. GEESI is developing a moving-bed, high-temperature desulfurization system at their corporate R&D center in Schenectady, New York. A fixed-bed, air-blown gasifier capable of processing about 1,800 pounds per hour of bituminous coal supplies fuel gas to a desulfurization system at a pressure of 20 atm and a nominal temperature of 1,000 °F and to a turbine simulator. H_2S is removed from the fuel gas in the counterflow absorber, which contains up to 3,000 pounds of a mixed-metal oxide sorbent. An external sorbent regeneration loop produces an off-stream of sulfur dioxide suitable as feed stream to a sulfuric acid plant. Over 400 hours of testing have been completed in the 3-MWe scale unit to investigate the performance and durability of mixed-metal oxide sorbents. The most recent pilot plant tests have been conducted with Z-Sorb, a proprietary sorbent available from Phillips Petroleum Company. Favorable results with Z-Sorb have been observed.

Gas turbine components are also being tested to measure combustor performance on low-Btu gas, assess the effect of impurities in the fuel gas on deposition/corrosion in the gas turbine hot flue gas path, and measure the level of trace impurities in the exhaust. To minimize undesirable sorbent-chloride reactions, the fuel gas hydrogen chloride level must be reduced. To achieve this target, a chloride control subsystem has been installed and tested to control levels entering the desulfurizer unit. This work directly supports the systems being designed for Tampa Electric and Combustion Engineering projects in the CCT Program.

Foster Wheeler Second-Generation PFBC Development. DOE's advanced PFBC development is embodied in a cost-shared contract with the Foster Wheeler Development Corporation to commercialize a PFBC system with at least 45 percent efficiency. The ongoing testing at Foster Wheeler's Livingston pilot plant is intended to quantify the environmental performance and operability of the partial-gasifier carbonizer and the circulating PFBC. A related activity is the refinement of Westinghouse's Multi-Annular Swirl Burner (MASB), which Foster Wheeler chose as the burner concept that would meet the unique requirements for boosting the temperature of a PFBC gas turbine.

Tidd Ceramic Filter Slipstream. To further DOE's goal of allowing PFBC vendors to mate their boilers to any commercially available gas turbine, a major evaluation of ceramic filters is underway at the Tidd PFBC. American Electric Power is passing one seventh of the hot pressurized gas produced by their PFBC through the largest U.S.-built ceramic filter system. Westinghouse has provided the filter system which includes the internal mounting assembly, auxiliary equipment, and the first set of filters that will be evaluated. The filter internals consists of three clusters with each cluster supporting 128 silicon carbide candle filters on three plenum levels. The project goals are to test integrated hot gas filter test modules, evaluate long-term performance and reliability in a PFBC environment, determine long-term operating and maintenance requirements, and evaluate the responsiveness of selected ceramic filters during normal, transient, and upset commercial-PFBC operating conditions. To date, over 3,500 hours of operation have been accumulated on this facility demonstrating the long-term performance and reliability of the Westinghouse system.

Kennebunk Test Facility. This project in Kennebunk, Maine, is being lead by Hague International and is principally responsible for the development of the EFCC. This R&D program integrates a pulverized coal burning low-NO_X burner with a ceramic and metallic heat exchanger system and a gas turbine. The R&D work at this facility will lead directly to the scaled-up Penelec EFCC Demonstration Project in the CCT Program.

Importance of Repowering Flexibility

Much has been written about the complex and changing character of the electric utility industry. Many diverse forces and trends evolve from national policy, regional requirements, and site specific environmental, technical, and economic factors (Bechtel 1994; Hewson 1994; Salvador, Bajura, and Mahajan 1994; Simbeck, Vejtasa, and Karp 1994; Wolk and Holt 1994).

Most forecasters agree that the predominant market in the U.S. for advanced coal-based power systems for the next 5 to 15 years will be in repowering applications.

About 40 percent of existing coal power plants are already over 25 years of age and as these units continue to age, net dependable generating capacities will likely decline; forced outage rates will increase; and thermal efficiencies will drop. Repowering can reverse these trends and supply incremental capacity, improving unit availability, and increased operating efficiency.

Other reasons for utilities to repower existing fossil stations with more efficient advanced power systems are to obtain unit life extension, increase generating capacity, improve unit efficiency resulting in fuel savings and improved dispatch, lower systems emissions, increase fuel flexibility, maximize use of existing system generation assets such as an already permitted site with an in-place transmission system, and the ability to continue use of a local fuel source.

Utility needs vary dramatically, therefore, repowering choices must be flexible enough to offer a full range of performance choices. METC's strategy for advanced power generation has been to assist industry in developing and demonstrating a range of technologies such that power producers can make trade-off evaluations and choose the system that best meets specific repowering needs.

The combinations of IGCC, PFBC, EFCC, and CAFBC provide capacity changes from zero to an increase of 150 percent. For emissions reduction, choices that provide greater reductions typically require a greater capital investment. Environmental performance must be a trade-off against these costs and other regulatory considerations. It may be advisable to exceed the sulfur or nitrogen removal limits for compliance regulations in one plant in order to earn allowance credits that can be used elsewhere or sold. The following example illustrates potential repowering configurations, including estimates of the important variables.

A Typical Candidate for Repowering

The coal-fired steam-turbine power plant is the nation's most common system for electric power generation, accounting for over 40 percent of the nation's capacity in 1992 (Energy Information Administration 1994). Since many of these plants are over 30 years old, they represent a large market for repowering. Figure 5 illustrates a 1960s vintage unit. This 10 MPa/538 °C/538°C (1,450 psig/1,000 °F/1,000 °F) reheat coal-fired steam-cycle system may be considered a typical candidate for repowering. Pulverized coal and air are combusted in a water-tube boiler to produce high-temperature, high-pressure steam. The steam is

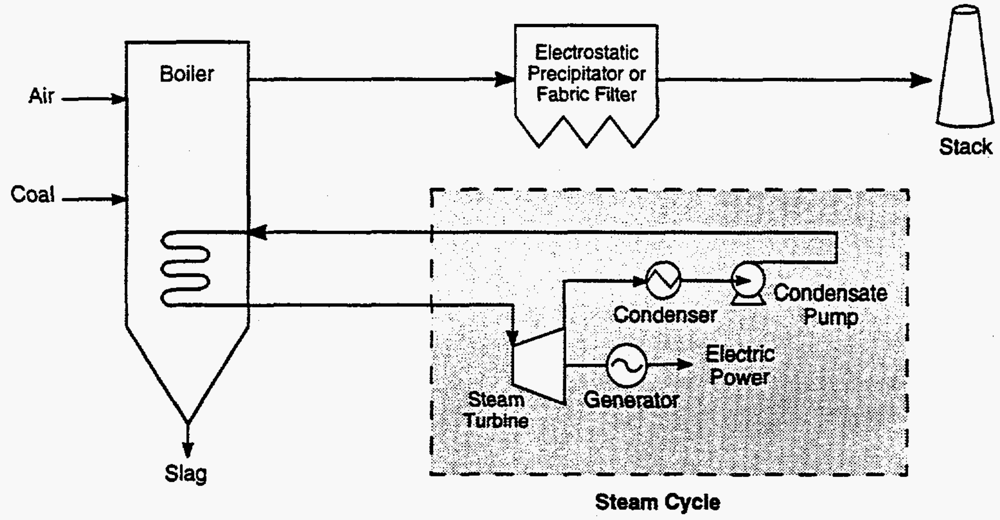

Figure 5. A Typical Candidate for Repowering

expanded through a steam turbine to generate 100 MW (gross) of electric power. Hot combustion gases exit the top of the boiler and ash is removed from the bottom. An electrostatic precipitator removes particulates from the boiler exhaust gas before the exhaust is discharged through the stack. The plant has no devices to control emissions of sulfur dioxide (SO_2) or NO_X. Most coal-fired steam turbine power plants are composed of multiple power trains similar to the one illustrated in Figure 5.

METC Power Systems products offer many repowering options for the candidate system. In the following section, several such options are described and compared. All these options utilize, to the extent possible, existing coal unloading and stacking equipment and existing buildings and structures. The 100-MW steam cycle, along with its electrical generating and power conditioning hardware, is also retained in each option, although it is refurbished and upgraded to 105 MW (gross).

Projected performances for all options are based on METC's expectations for matured ("fifth plant") technologies fueled with eastern U.S. coals that have heating values of 11,000 to 12,500 Btu/lb and sulfur contents of 2 to 3 percent. CAFBC is already mature, and plans to repower with this technology could be made now. By 1996 to 1998, first-generation PFBC and oxygen-blown IGCC systems will have been demonstrated at a level sufficient for commercial plans to be made to repower with these technologies by the year 2000. By 1999 to 2002, EFCC and second-generation PFBC systems will have been demonstrated at a level sufficient for commercial plans to be made to repower with these technologies by the year 2003. The availability of a gas turbine for each option is assumed, although turbines of the exact size selected may not actually exist. The IGCC option assumes the use of a "G-technology" gas turbine, since these turbines are designed for IGCC systems and will soon be available. Time frames for commercialization are illustrated in Figure 6.

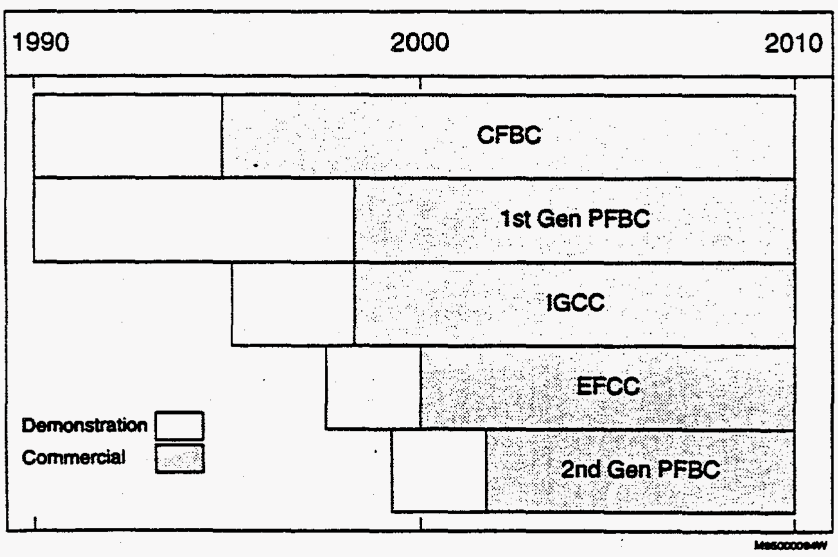

Figure 6. Time Frame of Repowering Options

Repowering Options

CAFBC Technology

Figure 7 illustrates the candidate system repowered with Circulating Atmospheric Fluidized Bed Combustion (CAFBC) technology. Crushed coal and pulverized limestone are fed into the CAFBC boiler. In the bottom of the boiler, hot, high-pressure air fluidizes and entrains a bed of particles that are mostly spent limestone, ash, and calcium sulfate. Combustion and desulfurization both take place in the fluidized bed. The sorbent reacts with SO_2 gas in the bed to form calcium sulfate, a dry, granular bed-ash material that is easily disposed of and may be used as a by-product. Combustion temperatures are controlled between 843 and 899 °C (1,550 and 1,650 °F), which is the most efficient range for desulfurization. In addition, these relatively low combustion temperatures limit NO_X formation. At various levels of the boiler, additional streams of air complete the combustion of fuel in stages. Staged combustion also helps to suppress NO_X formation. Steam is generated in the boiler's waterwalls. Dry, spent ash is removed from the boiler bottom. Large particles that become elutriated in the combustion gas are captured in cyclones and recirculated back to the combustor. This continuous circulation of coal char and sorbent particles is the novel feature of CAFBC technology. It helps to control boiler temperature and improves mixing, which extends the contact time of solids and gases, thus promoting coal utilization and sulfur capture. Heat is recovered from the hot flue gas to generate steam in the economizer and superheaters and to preheat air that is supplied to the boiler. Finally, the cooled flue gas passes through fabric filters before exiting the stack. Steam generated in the boiler, economizer, and superheaters is expanded through the refurbished steam turbine to generate 105 MW (gross) of electric power.

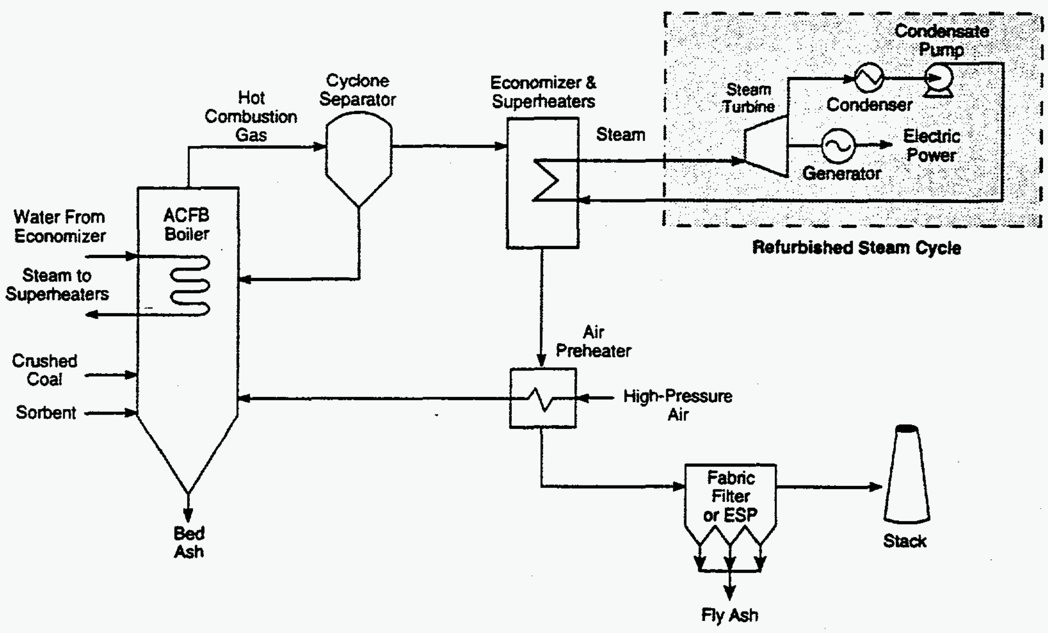

Figure 7. Repowering With CAFBC Technology

First-Generation PFBC Technology
Figure 8 illustrates the candidate system repowered with first-generation PFBC technology. Inside the PFBC boiler, high-pressure air from the turbine compressor fluidizes a bed of sorbent, coal-water fuel paste, and coal ash. The sorbent reacts with SO_2 gas in the bed to form calcium sulfate, a dry, granular bed-ash material that is easily disposed of and may be used as a by-product. A relatively low bed temperature limits the formation of NO_X. Cyclones remove entrained ash particles from the boiler's hot exhaust before the exhaust is expanded through a gas turbine to produce 24 MW of electric power. The hot gas turbine exhaust is used to heat boiler feedwater in an economizer. Particulates are removed from the cooled gas before it exhausts through the stack. From the economizer, feedwater is supplied to the boiler's in-bed tubes to generate superheated steam. The steam is expanded through the refurbished steam turbine to produce 105 MW, resulting in a gross plant capacity of 129 MW.

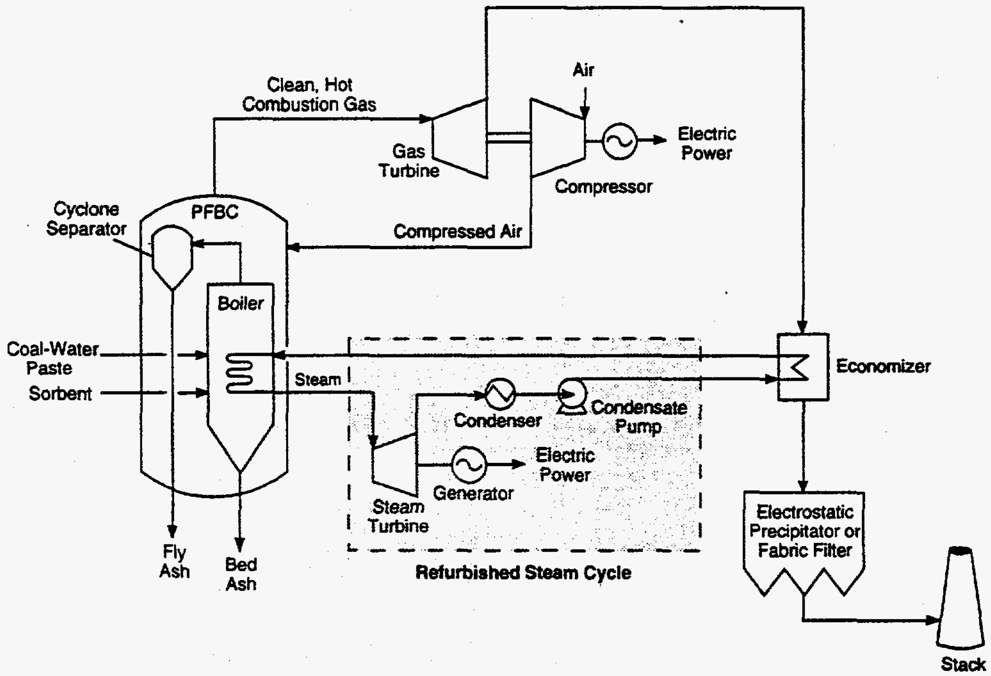

Figure 8. Repowering With First-Generation PFBC Technology

IGCC Technology
Figure 9 illustrates the candidate system repowered with oxygen-blown IGCC technology. Oxygen and a coal-water slurry are fed to the gasification vessel where they are partially combusted to produce a hot, raw, medium-Btu gas. Most of the coal's non-carbon material is melted and flows out of the gasifier to form slag, a non-leaching glassy material. High pressure steam is generated as the hot, raw, fuel gas passes through a cooler before being cleaned to a level acceptable to the gas turbine. Particulates are removed from the fuel gas

and recycled to the gasifier. During further cooling, other impurities, such as ammonia and carbon dioxide, are removed and treated. Next, an acid gas removal system captures over 98 percent of the sulfur in the fuel gas. The clean syngas is preheated before being combusted in a "G-technology" gas turbine, producing 210 MW of electric power. Heat from the gas turbine exhaust is captured in an HRSG. Steam produced by the HRSG and the coal gas cooler is then expanded through the refurbished steam turbine, generating 105 MW, resulting in a gross plant capacity of 315 MW.

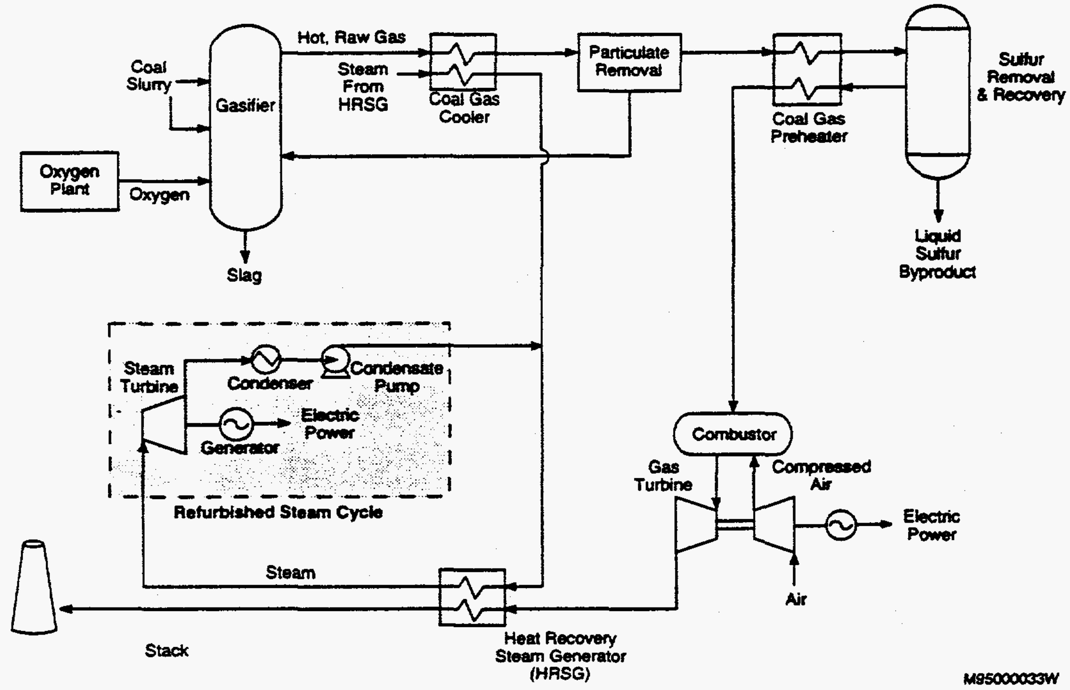

Figure 9. Repowering With IGCC Technology

EFCC Technology

Figure 10 illustrates the candidate system repowered with EFCC technology. Pulverized coal and air are supplied to a low-NO_X coal combustor. Heat from the staged combustion generates steam in the combustor's waterwall tubes. Hot combustion gas is exhausted from the combustor and enters a slag screen, where ash particles are captured as they impact an array of ceramic rods. The hot combustion gas then passes through a ceramic heat exchanger, transferring heat to the clean, pressurized air that is discharged from the compressor section of the gas turbine. This clean, hot, pressurized air is then expanded through the gas turbine, producing 48 MW of electric power.

In this way, costly turbine components are not exposed to the corrosive and abrasive substances in the combustor exhaust gas. Instead, clean air is heated in the ceramic heat exchanger by the hot combustion exhaust gas and is expanded through the turbine.

Combustion gas discharged from the ceramic heat exchanger enters the heat recovery steam generator (HRSG), where a portion of its remaining sensible heat is used to generate steam. Finally, the combustion gas passes through a flue gas desulfurization (FGD) vessel for SO_2 removal and a fabric filter for particulate removal before being exhausted through the stack. Steam produced in the combustor and the HRSG is expanded in the refurbished steam turbine, producing 105 MW, resulting in a gross plant capacity of 153 MW.

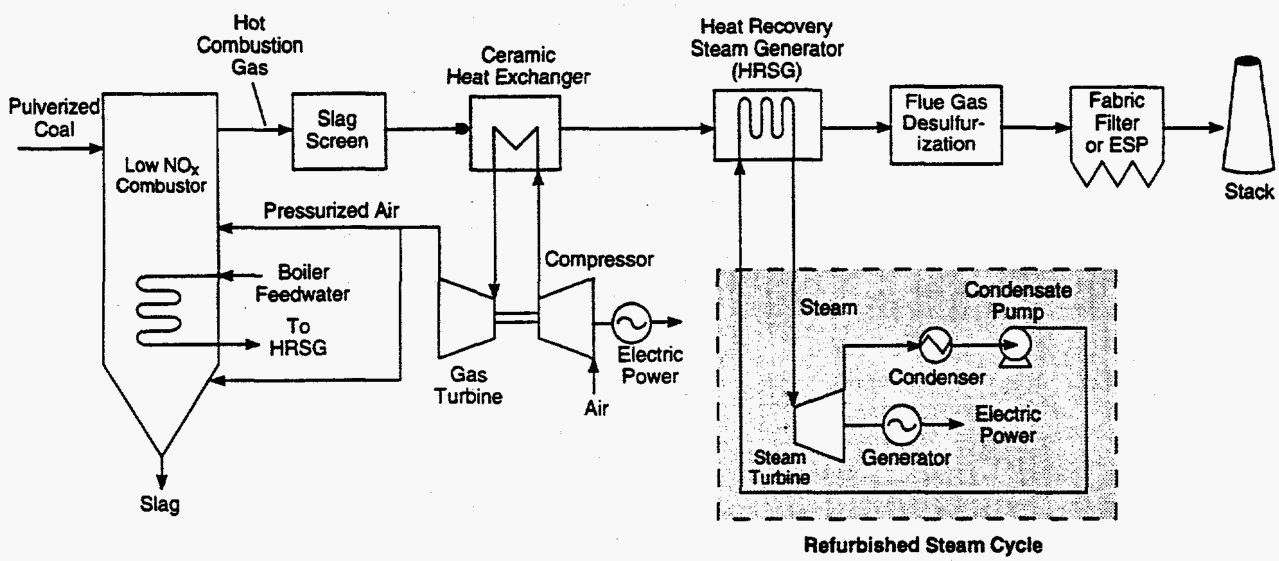

Figure 10. Repowering With EFCC Technology

Second-Generation PFBC Technology

Figure 11 illustrates the candidate system repowered with second-generation PFBC technology. Crushed coal, crushed sorbent and pressurized air are supplied to the carbonizer, which produces a low-Btu fuel gas and char. Coal char and spent sorbent are withdrawn from the carbonizer bed and supplied to the PFBC boiler, along with pressurized air. Particulates that are removed from the carbonizer fuel gas are also recycled to the PFBC boiler. The clean fuel gas is then supplied to the topping combustor. The PFBC boiler burns the carbonizer char, producing steam in its fluid-bed heat exchanger. SO_2 gas released during combustion and captured as calcium sulfide in the carbonizer's spent sorbent are converted to calcium sulfate. Bed material that becomes entrained in the boiler exhaust is captured by a cyclone and is recirculated through the fluid-bed heat exchanger to the boiler. The clean, hot, flue gas is used to burn the fuel gas in the topping combustor. Hot gas exiting the topping combustor is expanded through a modified gas turbine, generating 75 MW of electric power. Pressurized air from the gas turbine compressor is supplied to the carbonizer and PFBC boiler. The gas turbine exhaust is used to heat boiler feedwater and produce steam in the

HRSG being exhausted through the stack. Steam from the HRSG is superheated in the boiler's fluid-bed heat exchanger before being expanded through the refurbished steam turbine to produce 105 MW, resulting in a gross plant capacity of 180 MW.

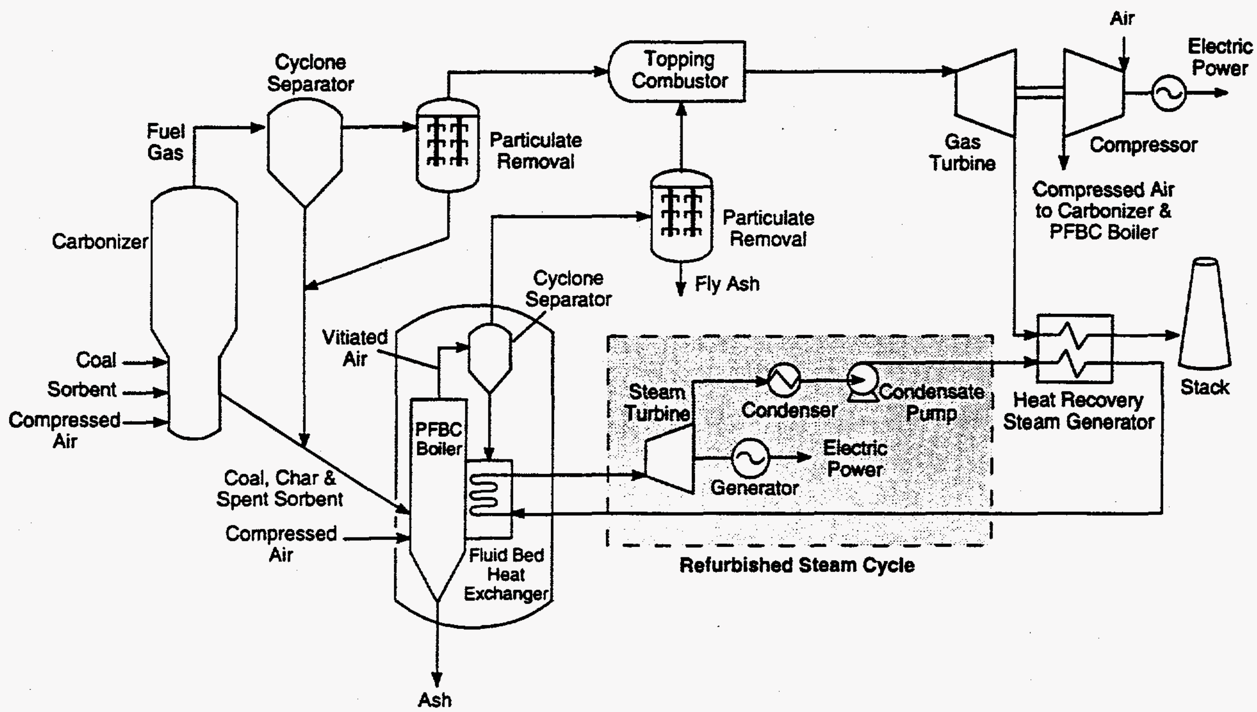

Figure 11. Repowering With Second-Generation PFBC Technology

Comparing the Options

Table 3 summarizes how repowering with each technology option impacts the performance of the typical plant. These impacts include increased generating capacity and increased efficiency. Environmental performance is also enhanced by repowering, since emissions of CO_2, SO_2, and NO_X are all reduced. The cost of achieving these improvements is also tabulated for each repowering option.

Total Repowered Plant Cost and Capacity Addition

The total cost of repowering is critical in deciding how or if to repower. Figure 12 illustrates the flexibility in total cost of repowering offered by METC's advanced, coal-based technologies. CAFBC is the least-cost option, largely because it adds little capacity to the existing plant. The other options, all of which add gas turbines of different sizes, are more costly since they increase the existing plant's generating capacity substantially. If additional capacity is desired, however, these options are competitive on a $/kW basis, as shown by

Table 3. Repowering a Typical Power Plant With Advanced, Coal-Based Systems

	Typical Candidate	CAFBC	1st Gen. PFBC	IGCC	EFCC	2nd Gen. PFBC
Steam Turbine, MW (gross)	100	105	105	105	105	105
Gas Turbine, MW (gross)	N/A	N/A	24	210	48	75
Gross Power, MW	100	105	129	315	153	180
Capacity Addition, MW (gross)	N/A	5	29	215	53	80
Efficiency (HHV)	30.2%	33.4%	37.3%	42.1%	36.6%	41.8%
Sulfur Dioxide, lb/MMBtu	3	0.4	0.2	0.02	0.1	0.2
Nitrogen Oxides, lb/MMBtu	0.8	0.2	0.3	0.08	0.25	0.3
Carbon Dioxide Reduction, lb/MWhr	N/A	229	454	676	418	663
Sulfur Dioxide Reduction, lb/MWhr	N/A	29.8	32.1	33.7	33.0	32.3
Nitrogen Oxide Reduction, lb/MWhr	N/A	7.00	6.29	8.39	6.71	6.59
Repowered Total Plant Cost, $ Millions	N/A	112 - 133	155 - 181	268 - 394	176 - 222	160 - 214
Repowered Total Plant Cost, $/kW	N/A	1070 - 1270	1100 - 1400	850 - 1250	1150 - 1450	890 - 1190

Figure 13. METC's advanced, coal-based technologies allow the capacity of the repowered plant to be increased from zero to 200 percent at capacity costs as small as 850 $/kW.

Efficiency

Two common motives for repowering are decreasing an existing plant's cost of electricity or reducing its emissions. The efficiency of a repowered plant has a significant impact on both. METC's advanced, coal-based technologies offer net efficiency gains of 3.2 to 11.9 percentage points over the typical plant. The systems for which a gas turbine generates the largest portion of the total power are also the most efficient. However, as shown by Figure 14, these systems also have a higher total repowered plant cost, since they add more capacity.

Emissions

By increasing an existing plant's efficiency through repowering, a corresponding reduction in CO_2 emissions is attained since less fuel is consumed to generate a given amount of electrical power. This is evident by noting the similarity of Figure 14, which shows each option's efficiency, to Figure 15, which shows each option's reduction of CO_2 emissions. The systems with the highest CO_2 reductions have the highest efficiencies--and the highest total repowered plant costs.

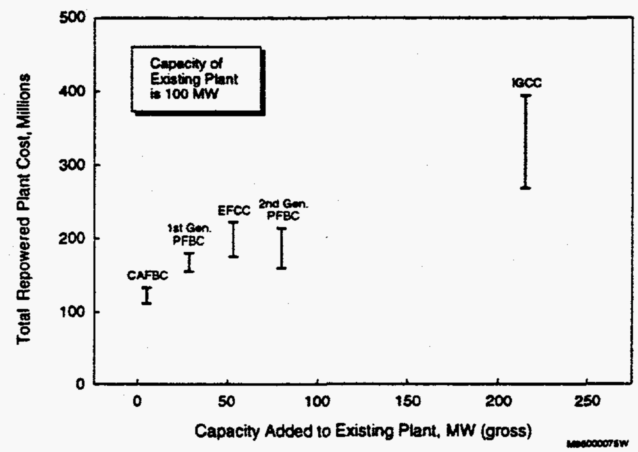

Figure 12. Repowering Flexibility - Adding Capacity

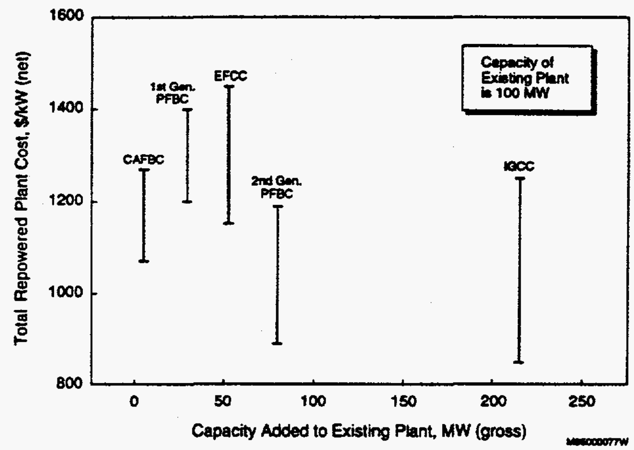

Figure 13. Repowering Flexibility - Capacity Cost

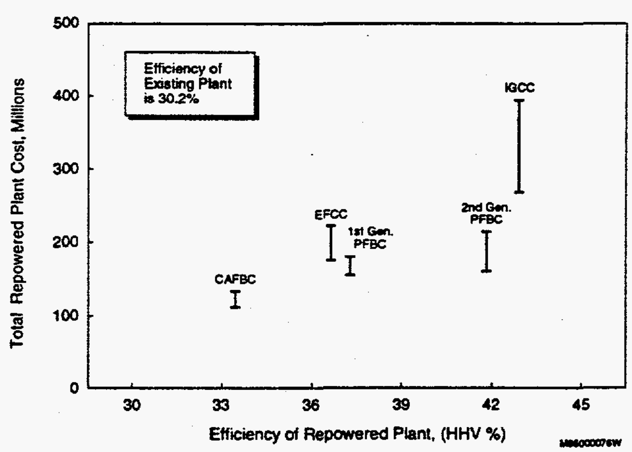

Figure 14. Repowering Flexibility - Plant Efficiency

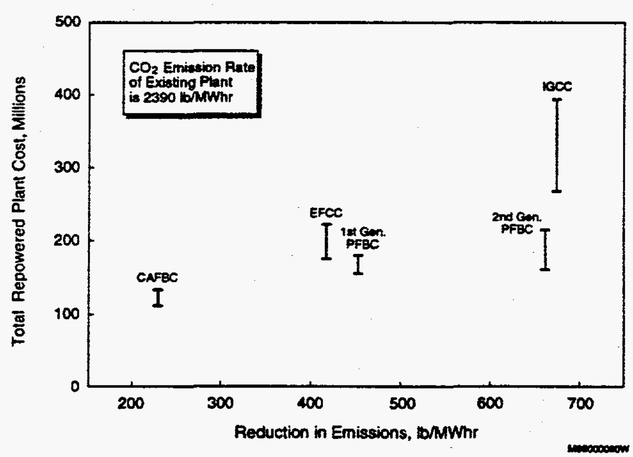

Figure 15. Repowering Flexibility - Reduction of CO_2 Emissions

Increasing an existing plant's efficiency results in corresponding reductions in emissions of SO_2 and NO_X on a weight of emissions per killowatt hour-basis. However, the SO_2 and NO_X emission-control systems in advanced repowering technologies offer far greater reductions than those in a plant where these emissions are not controlled. METC's advanced, coal-based technologies have SO_2 emissions that range from 0.4 pounds per million British thermal units (lb/MMBtu) to as little as 0.02 lb/MMBtu. As shown in Figure 16, the systems offering the greatest reductions in SO_2 are also those that add the most capacity, resulting in higher total repowered plant costs. On a $/kW basis, however, the least expensive systems (IGCC and second-generation PFBC) offer the greatest SO_2 reductions. NO_X emissions for the advanced technologies range from 0.3 lb/MMBtu to as little as 0.08 lb/MMBtu. Figure 17 shows that reductions in NO_X emissions are not, in general, correlated to the total repowered plant cost.

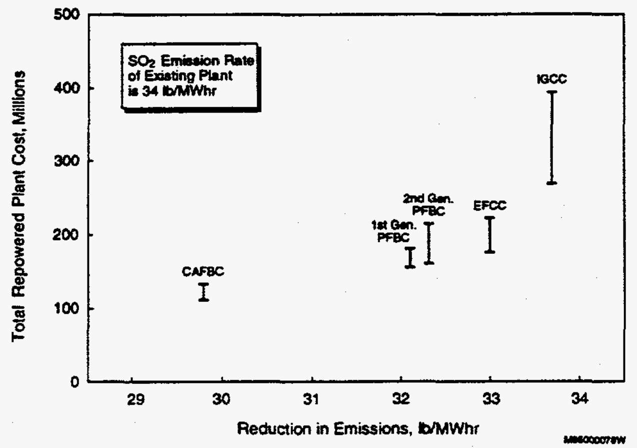

Figure 16. Repowering Flexibility - Reduction of SO_2 Emissions

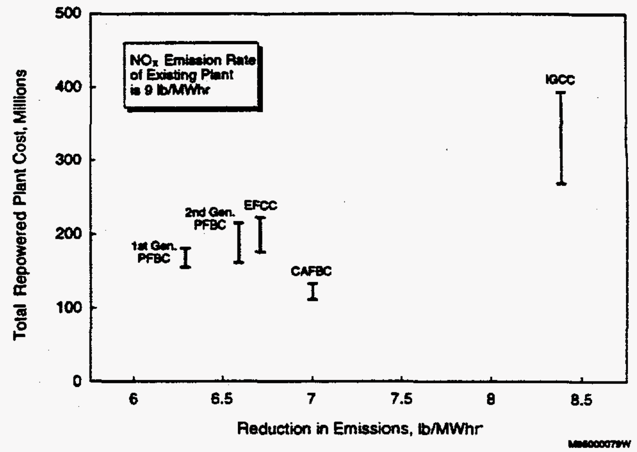

Figure 17. Repowering Flexibility - Reduction of NO_X Emissions

Conclusion

Most repowering situations focus on reuse of the existing steam cycle, site auxiliary systems, and support facilities. These areas can account for 20 to 55 percent of the greenfield capital costs depending upon the technology selected and the existing equipment compatibility. Of the METC power systems repowering options, technologies offering higher efficiency and best environmental performance require greatest total investment coincident with greatest capacity addition. However, these more efficient systems appear to be the most economical on a dollar per kilowatt basis.

Advanced power systems RD&D results of the past year have been significant. CCT demonstrations at all project stages have been progressing rapidly. Six of these twelve CCT advanced power systems projects are repowering demonstrations. Of these repowering projects, the TIDD PFBC plant accumulated over 9,500 hours of operation to date and more than 3,500 hours with hot particulate filter operation on a slipstream. The Wabash River IGCC, at around fifty percent construction complete, is to go into operation in August 1995. Cooperative Agreement negotiations were completed for the Clean Energy IGCC and the Penelec EFCC projects, selected in the last CCT solicitation.

R&D has focused in areas critical to maximizing results of the CCT demonstrations that will lead to improvements in the power systems products as commercial deployment evolves. Key R&D facilities are in-place for proving system advances, such as hot gas cleanup.

A completed CCT demonstration power system project is the Nucla CFB Project. From 1988 to 1991, the Nucla 110 MWe CFB accumulated over 15,700 hours of coal-fired operation. As a result, Pyropower Corporation was able to save almost 3 years in establishing a commercial line of ACFB units sold with warranty in sizes ranging up to 400 MWe.

The advanced power systems that METC continues to promote are power systems that get rid of two of the three major power plant components that limit performance of existing plants. You won't find METC working on better pulverized coal boilers, better steam turbines, or better scrubbers. Instead, the METC advanced power systems will make use of available steam turbines in combination with gas turbines that break the 40 percent efficiency barrier in a cost effective way; offer reliable base load dispatch and maximum fuel flexibility.

METC will also be working on fuel cells, the ultra-clean, ultra-efficient, quiet, direct conversion machine that eliminates the concept of a working fluid. We need your leadership in making sure the product focus is correct, the development cycle timing is appropriate, and that the job we do is complete enough that your application risks are acceptable. The "new DOE" is more than open to your feedback; it will assertively seek it and will commit to reflect it in our actions. Unless our customers succeed, we have no reason for being.

References

Bechtel, T.F., 1994. The Role of Advanced Technology in the Future of the Power Generation Industry. p. 3-11 in *Proceedings of the Coal-Fired Power Systems 94--Advances in IGCC and PFBC Review Meeting*. H.M. McDaniel, R.K. Staubly, and V.K. Venkataraman, eds. DOE/METC-94/1008, Vol. 1, NTIS/DE94012252.

Brdar, R.D., and G.F. Friggens, 1994. Taking Steps Forward--The EGCC Demos. Presented at the Eleventh Annual International Pittsburgh Coal Conference, Pittsburgh, Pennsylvania, September 1994.

Energy Information Administration, 1994. p. 66 in *Annual Energy Outlook 1994*. DOE/EIA-0383(94). Springfield, VA: National Technical Information Service.

Hewson, 1994. Potential Role of Fluid Bed Combustion Technologies for Utility Repowering. Presented at the EPRI Fluidized Bed Combustion for Power Generation Conference, Atlanta, Georgia, May 17.

McDaniel, H.M., R.K. Staubly, and V.K. Venkataraman, eds, 1994. *Proceedings of the Coal-Fired Power Systems 94--Advances in IGCC and PFBC Review Meeting*. DOE/METC-94/1008, Vol. 1, NTIS/DE94012252; DOE/METC-94/1008, Vol. 2, NTIS/DE94012253.

Robertson, A., et al. 1989. *Second Generation Pressurized Fluidized Bed Combustion Plant.* Report to the U.S. Department of Energy, Morgantown Energy Technology Center, Contract DE-AC21-86MC21023.

Rubow, L.N., et al., 1992. *Clean Coal Reference Plants: Atmospheric CFB.* Springfield, VA: National Technical Information Service, NTIS/DE93000251.

Rubow, L.N., et al., 1992. *Clean Coal Reference Plants: Pressurized Fluid Bed Combustor.* Report to the U.S. Department of Energy, Morgantown Energy Technology Center, Contract DE-AC21-89MC25177.

Salvador, L.A., R.A. Bajura, and K. Mahajan, 1994. The Role of Clean Coal Technologies in Post-2000 Power Generation. Presented at the 56th Annual American Power Conference, Chicago, Illinois, March 25-27.

Simbeck, D.R., S. Vejtasa, and A. Karp, 1994. Overview of the Independent Power Producer (IPP) Market for Advanced Coal-Fired Systems. p. 48-57 in *Proceedings of the Coal-Fired Power Systems 94--Advances in IGCC and PFBC Review Meeting*. H.M. McDaniel, R.K. Staubly, and V.K. Venkataraman, eds. DOE/METC-94/1008, Vol. 1, NTIS/DE94012252.

Staubly, R.K., R.A. Dennis, and D.C. Cicero, 1994. Overview of METC's Gas Stream Cleanup Program. Presented at the Eleventh Annual International Pittsburgh Coal Conference, Pittsburgh, Pennsylvania, September 1994.

U.S. Department of Energy, 1994. Clean Coal Technology Demonstration Program, Program Update 1993. U.S. Department of Energy, DOE/FE-0299P.

Wolk, R.H., and N.A. Holt, 1994. Overview of Global Utility Market for Advanced Coal Fired Systems. p. 27-47 in *Proceedings of the Coal-Fired Power Systems 94--Advances in IGCC and PFBC Review Meeting*. H.M. McDaniel, R.K. Staubly, and V.K. Venkataraman, eds. DOE/METC-94/1008, Vol. 1, NTIS/DE94012252.