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Technology Demonstration and Commercialization

EPACT specifically directs DOE to conduct demonstration and commercialization programs on coal-based technologies (Title XIII, Section 1301; see Appendix A, this volume). DOE's CCT program constitutes the major effort in this area, although relevant activities are also being conducted under the Office of FE's R&D program for coal. The CCT program constitutes a major government-funded effort and provides some useful insights into the role of DOE in facilitating the transition of advanced coal-based technologies from demonstration into the commercial sector. Under the Clinton administration, there is a strong emphasis on accelerating the commercial deployment of new technologies and on developing markets for U.S. technologies both domestically and overseas. In this context the committee has been asked to make recommendations pertaining to EPACT Section 1301(c), subparagraphs c(3), c(4), and c(5) (see Appendix B, this volume). As discussed in Chapter 1, these subparagraphs relate to the requirement for current FE RDD&C programs and the CCT program to deliver commercial technologies by 2010. Recommendations made by the Clean Coal Technology Coalition (CCTC) and the National Coal Council (NCC) for the future of the CCT program are reviewed below. The committee's conclusions and recommendations are given in Chapter 10.

COMMERCIALIZATION ISSUES

The steps required to commercialize any new technology differ greatly, but the fact that coal is a solid substance introduces a significant technical risk into the technology scale-up process. The difficulty of extrapolating the processing of solids from laboratory through pilot scale to commercial scale is widely recognized. Piloting even at a 1,000 ton/day scale cannot completely ensure the same results at 10,000 ton/day. This differs from processing gases or liquids, where extrapolation from laboratory to full commercial scale in a single step is now commonly practiced, based on an in-depth understanding of the chemical engineering parameters governing such operations. For example, a 14,000 bbl/day commercial Mobil fixed-bed methanol-to-gasoline plant was designed and built based on a 4 bbl/day laboratory unit (Bibby et al., 1988). The difficulty of scale-up when processing solids, such as coal, increases with increasing complexity of the process. Systems that require multiple sequential or tightly integrated solids reactors are at a distinct disadvantage; simplicity is at a premium for solids processing, and this extends to the many auxiliary steps required for the demonstration of a complete coal-fired power generation system. Thus, in scaling-up coal technologies, notably for power generation, there is a need for prudent stepwise increases in capacity from laboratory to pilot plant to demonstration scale. The complexity of power generation systems implies that commercialization is particularly expensive.

The objective of the DOE demonstration and commercialization effort is to enhance the process whereby a developing technology is demonstrated at the commercial scale such that it is regarded as commercially available by the ultimate user. In most instances this requires the mitigation or elimination of the additional technological and economic risks that the user associates with the adoption of a new as compared to a proven technology. In the power generation area, the investor-owned utility cannot generally assume the risk of a new technology, faced with a possible loss of return on investment from the rate-making authority if the technology does not perform as expected and requires modification.

It is an accepted principle for advancing new technology to commercial maturity that the first-of-a-kind commercial plant is significantly higher in cost to build than subsequent plants and does not provide adequate information on all operating, maintenance, and cost issues. A new technology is not considered mature and commercially demonstrated until two to five applications of the technology have been installed, as illustrated by the generic capital cost learning curve shown in Figure 8-1. The issue for DOE is how to enhance the installation of additional applications of early demonstrations.

CLEAN COAL TECHNOLOGY PROGRAM

The CCT program is a technology development effort jointly funded by government and industry in which advanced coal-based technologies are being demonstrated at a scale large enough for the marketplace to judge their commercial potential. A unique feature of the program is that industry plays a major role in defining the demonstration project and in ensuring eventual commercialization. It is intended that once the program is complete the private sector should be able to make use of the technologies developed in the commercial arena without further government support. The industrial partner in each CCT project is required to contribute at least 50 percent of the total cost, indicating the extent of their commitment to develop a technology with a real commercial potential. The patent rights for inventions developed during the demonstration program are normally granted to the industrial participant, thereby preserving the incentives for subsequent commercialization. Five competitive solicitation cycles (CCT Rounds I through V) have been conducted, resulting in 45 active demonstration projects encompassing total public and private investments of $6.9 billion, of which DOE is providing $2.4 billion (34 percent) and private and other sources are providing $4.5 billion (66 percent). Currently authorized funding by solicitation round for the CCT program is given in Chapter 1. From CCT Round III onward, industrial program participants have been required to commercialize technologies in the United States on a best-effort, nondiscriminatory basis, although they cannot be forced to license technologies to their competitors. A summary of CCT activities is provided in Table 8-1. Additional information on demonstration projects in the CCT program is provided in Appendix F.

ADVANCED POWER SYSTEMS DEMONSTRATION PROJECTS

DOE's technology goals for the Advanced Power System demonstration projects were given earlier in Chapter 7 (Tables 7-1, 7-2, and 7-4). Many of the technologies being demonstrated in the CCT program are the same as those being targeted in the FE R&D program. As a result, a number of the CCT demonstrations are also being considered demonstrations under the FE R&D program, notably, first- and second-generation PFBC, first- and second-generation IGCC, IGFC, and mild gasification technology demonstrations. Of the 45 active CCT demonstration projects, 18 are scheduled for completion, 11 will be in operation, and the remaining 16 were in design and construction by the end of FY 1994.

Advanced Emission Control Systems

Of the 45 active CCT demonstration projects, 19 involve advanced emission control systems technologies aimed at the cleanup of SO_2, NO_x, and particulates (see Chapter 7, Table 7-8). The 19 projects require an obligation of $672 million (approximately 15 percent of the program funding), of which the private sector has contributed approximately 58 percent. The demonstrations apply to 3,250 MW of generating capacity (units from 5 to 605 MW in size). These activities are expected to have a relatively short-term payoff and result in commercially available technologies for compliance with the acid rain precursor provisions of the Clean Air Act. The technologies being developed also offer significant export potential.

Integrated Gasification Combined Cycle

A key component for new power generation systems in the near- to mid-term periods (through 2020) will likely be the gas turbine. The fundamental thermodynamic advantage of a heat engine with a 1260 °C (2300 °F) (and rising) inlet temperature over the typical steam turbine with a 540 °C (1000 °F) inlet is very great and the main reason thermal efficiencies in excess of 50 percent are possible.

In the foreseeable future, gas turbine capacity is anticipated to be in the range of 100 to 300 MW, including a combined steam generation cycle. This will require gasification systems that use between 1,000 and 3,000 tons/day of coal. The series of new gasification systems being demonstrated under the CCT program can be expected to achieve these levels, although most still fall in the lower end of the range. IGCC units being demonstrated under the CCT program (see Table 6-3) have capacities of 65 to 480 MW (total capacity of 1,343 MW), and all are scheduled for completion between 1995 and 2000. Thermal efficiencies are predicted to reach 45 percent, with SO_2, NO_x, and particulate emissions well below New Source Performance Standards (NSPS) levels. A discussion of the gasification technologies being demonstrated under the CCT program is given in Chapter 6.

Pressurized Fluidized-Bed Combustion

Another new technology being demonstrated is PFBC. Two first-generation PFBC demonstrations, sized at 70 and 80 MW, are part of the CCT program, as is a 95-MW second-generation PFBC demonstration unit. PFBC technology has the potential to achieve 50 percent thermal efficiencies but only if hot gas cleanup systems can be improved and used in conjunction with advanced turbines (see Chapter 7). PFBC has a very compact footprint that makes it a viable technology for repowering existing generating units.

Direct-Fired Systems

The technology for direct firing of coal in a gas turbine or diesel engine has been developed through the proof-of-concept phase under the FE R&D program. In addition, a dual stationary coal-fired diesel engine with a combined rating of 14 MW will be demonstrated in Round V of the program. This activity is not scheduled to receive any further funding under the FE R&D program.

Indirectly-Fired Systems

The FE R&D program has supported this technology through two programs: EFCC (externally fired combined-cycle) and HIPPS. A demonstration of EFCC technology at the 47-MW level is planned for Round V of the CCT program. Continuation of development work on HIPPS is proposed for FY 1995, with a goal of achieving 47 percent thermal efficiency (DOE, 1994b). If the HIPPS technology is to advance to the demonstration phase, the components that will be demonstrated in the CCT EFCC project must prove to be commercially viable. Thus, demonstration of HIPPS technology must await the outcome and economic evaluations of the EFCC demonstration.

Advanced Pulverized Coal Systems

As noted in Chapter 7, the FE R&D program is supporting the development of the low-emission boiler system with the goal of demonstrating a 42 percent efficient system with emissions one-half to one-third of the NSPS by the year 2000. For FY 1995, the FE R&D program has requested $7.6 million to continue engineering development and subsystem testing of this technology.

Fuel Cells

Development and demonstration of fuel cell technology have been transferred from the coal component of the FE R&D program to the gas component, on the basis that technology demonstration and commercialization will likely be accelerated using gas rather than coal. An IGCC demonstration selected in CCT Round V will utilize a portion of the clean coal gas to fuel a 2.5-MW molten carbonate fuel cell.

FUTURE DIRECTIONS

Additional CCT Solicitations

Section 1321 of EPACT requires DOE to conduct additional solicitations for the development of cost-effective, higher-efficiency, low-emission coal utilization technologies for commercialization by 2010. Recommendations for the future of the CCT program have been made by two groups, the CCTC and the NCC.

The CCTC, representing the coal, utility, manufacturing, design, and construction industries and states, advocates the demonstration of clean coal technologies and has made recommendations to DOE regarding the future of the CCT program (CCTC, 1993). The CCTC seeks to ensure that technologies demonstrated in whole or in part through the existing CCT program are also commercially deployed and thereby made ready for "commercial application" as required by Section 1301 of EPACT. The CCTC's specific position regarding Sections 1301 c(3) and c(4) is as follows:

- While continuing to support the completion of the projects already selected in the current CCT program, the program would be modified to address commercial deployment by reducing the financial risks associated with the use of the technologies.
- The program would operate basically as it does now but would cost share only certain cost differentials when compared to a conventional technology. The DOE's cost share of the "risk gap" would be significantly less than the current 50 percent. Specifically, DOE support for commercial demonstration plants would be determined using a risk-based formula to make a given CCT cost competitive with conventional technologies.

With regard to Section 1301 c(5), the CCTC would keep the same program elements and management structure in place, with a revised focus on cost sharing the financial risk. The proposed risk-based formula for determining cost sharing would address both capital cost risk and operating cost risk. As these risks decrease in subsequent demonstrations, so would the cost-shared DOE support, resulting in eventual commercial acceptance with no cost sharing. Timing of this future program must build on the first-of-a-kind projects and result in commercial acceptance to meet repowering and new capacity requirements from 2005 onward.

The NCC, a federal advisory committee to the Secretary of Energy, has, at the request of the Secretary, made recommendations regarding the future direction of the CCT program (NCC, 1994). The NCC has recommended that no more solicitations be issued under the current CCT program. The NCC further recommends that the Secretary foster the establishment of a new federal-level CCT incentive program to stimulate initial and sustainable commercial deployment of CCT. The recommended CCT incentive program would provide approximately $1.1 billion of capital incentives and $0.3 billion in operating incentives over the 15-year period from 1995 to 2010. The incentives would offset 10 to 15 percent of the capital risk and help offset operating risks associated with first-of-a-kind and early commercial units. The incentive would be based on a percentage of the capital and operating cost risk differential between the CCT and conventional technology. For example, if the risk differential between a 400-MW IGCC project and conventional pulverized coal with FGD plant is $360 million, the federal incentive for the project would be $54 million or 15 percent of the differential.

International CCT Initiative

Section 1332 of EPACT (Innovative Clean Coal Technology Transfer program) proposes the development of a joint DOE/Agency for International Development clean coal technology program to encourage exports of U.S. technologies that allow more efficient, cost-effective, and environmentally acceptable use of coal resources. FY 1995 funding has been requested to implement an international initiative for "showcase" demonstration projects in clean coal technologies in China and Eastern Europe. Specifically, DOE has proposed that China receive approximately $50 million for an IGCC demonstration plant, and $25 million in support is proposed for power plant refurbishment in Eastern Europe. DOE expects these funds to be available from projects that were selected in the first five rounds of the CCT program but have or will in the future drop out of the program.

The first priority for the existing CCT program, mandated by Congress in Section 1301 of EPACT, is to conduct a research, development, and demonstration program that will result in CCT technologies that are ready for commercial use by 2010. Thus, in the view of the committee, the impact on the existing CCT program of using CCT program funds to support technology demonstrations in a foreign country requires careful examination. Funding of CCT technology in foreign countries in lieu of domestic demonstrations runs a risk of delivering little if any technology advancement, export opportunities, or lasting U.S. jobs. It is entirely possible that the demonstrations will provide a basis for a foreign country to copy the technology and provide subsequent installations itself.

A further question raised by the committee concerns the suitability of IGCC technology to meet China's major increases in demand for electricity and significant environmental problems. Commercially available pulverized coal plants with modern flue gas cleanup technology may be more cost effective and beneficial (see Chapter 3). Supporting funding for commercially available technology, including retrofit technologies for environmental control, could come from the traditional sources of overseas aid, without impacting the existing CCT program or the FE R&D program budget.

ADVANCED FUEL SYSTEMS DEMONSTRATION PROJECTS

As noted in Chapter 2, the objective of the Advanced Fuel Systems program is to develop systems that can produce coal-derived transportation fuels, chemicals, and other products at costs competitive with oil-derived products. At the present time, the prices of coal-derived liquid fuels are significantly greater than of those derived from petroleum or natural gas. Oil prices are not expected to rise sufficiently in the near future to change this situation. As a result, there is currently minimal private sector support for developing and demonstrating technologies for the conversion of coal to fuels at a commercial scale. One exception is in mild gasification technology. The FE R&D program has sponsored a process development unit for mild gasification (the Illinois Mild Gasification Facility) that is supported by 20 percent private sector investment. In addition, the CCT ENCOAL Mild Coal Gasification project aims to demonstrate the production of both a solid and a liquid fuel from coal. This approach has been attempted many times in the past and has not been successful (Probstein and Hicks, 1982), principally because 50 to 70 percent of the feed coal remains as a low-volatile-content char that must be used as a fuel or feedstock. Pyrolysis as a source of liquid fuels has been commercially practiced only under wartime conditions in Germany between 1935 and 1945 based on the Lurgi sweep gas carbonization process. Current efforts have focused on using the char as a boiler fuel or in the production of form coke. The characteristics of the char and the resulting price paid for it have prevented this approach from being economical. DOE has no further plans to use the Illinois Mild Gasification Facility following completion of ongoing development activities. No additional funding for the facility has been requested for FY 1995.

A stand-alone facility for producing finished liquid fuels from coal must necessarily be large to achieve economies of scale and will thus be very expensive. As discussed in Chapter 6, recent systems studies have projected equivalent crude prices of $30 to $35/bbl for stand-alone production of high-quality gasoline and distillate fuels. This cost, combined with the uncertainty in crude oil prices over the operating life of the liquefaction plant, are strong disincentives for demonstration and commercialization projects. However, coproduct systems combining F-T (Fischer-Tropsch) synthesis of coal liquids and electric power generation have the potential to reduce the equivalent crude cost of coal liquids by approximately $5 to $7/bbl (see Chapter 6, Gray, 1994; Tam et al., 1993).[1]

The above results, together with oil price projections for 2010 (EIA, 1994), indicate that demonstration and early deployment of liquefaction technology in coproduct systems may become economically attractive within the mid term (2006–2020), that is, in approximately the same timeframe as installation of advanced IGCC power generation facilities. Nevertheless, the price projections from the studies assume "*n*th plant" costs. As for advanced power generation technologies, first-of-a-kind or pioneer plant demonstrations are likely to be significantly more expensive than fully commercial systems. Thus, the committee anticipates that some federal cost sharing of early demonstration plants, similar to that in the CCT program, will be necessary to stimulate industry participation, and ultimate adoption, of coproduct systems to produce coal liquids and electric power.

FINDINGS

1. Demonstration of advanced coal-based technologies at a commercial scale, as in the FE R&D and CCT programs, is an important step in the development of commercially available technologies. The demonstrations being supported by the FE R&D and CCT programs appear,

[1]In the studies cited the economic return on electric power production was assumed to be consistent, with the savings applied to the liquid products.

for the most part, to be well directed toward advancing power generation technologies that have the potential to meet relevant goals for thermal efficiency, environmental control, and reduced costs.

2. The program components and management of the current CCT program have demonstrated the ability to conduct a successful demonstration program, as evidenced by the involvement and financial support of the private sector.

3. The commercial acceptance of new power generation technologies will be impeded by the remaining financial risk associated with second- and third-of-a-kind demonstration projects.

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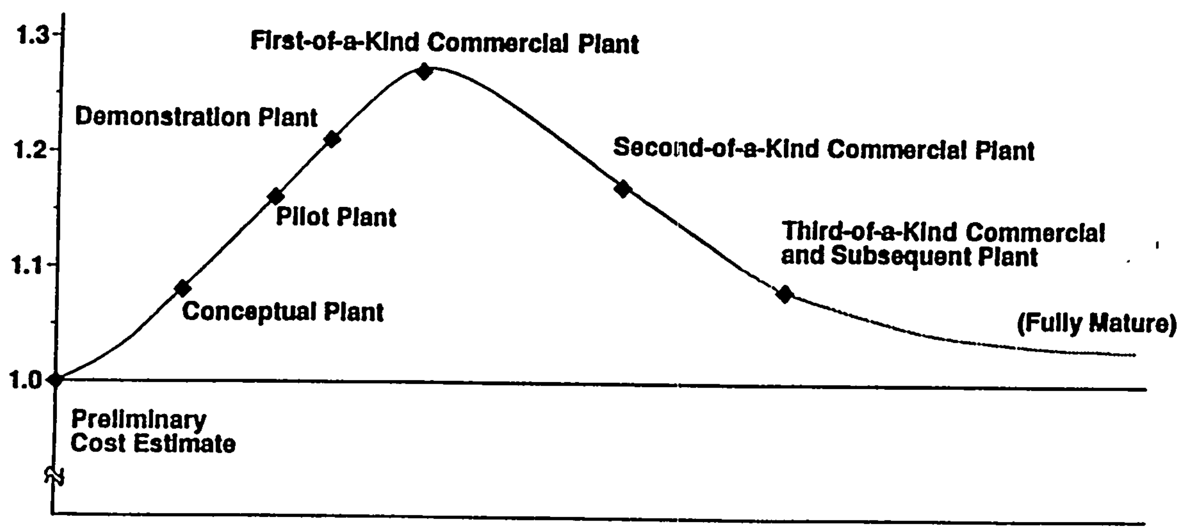

Figure 8-1 Capital cost learning curve.

Table 8-1 Summary of CCT Activities

Round	Principal Goals	Number of Proposals Submitted	Number of Projects Selected; Current Status
I	Demonstrate feasibility of clean coal technologies for future commercial applications	51[a]	9 plus 14 alternates; 1 complete, 8 ongoing, including 3 alternates
II	Demonstrate technologies: • Capable of being commercialized in 1990s • More cost effective than current technologies • Capable of achieving significant reduction of SO_2 and NO_x emissions from existing facilities	55	16; 4 withdrawn, 12 ongoing
III	Demonstrate technologies capable of: • Being commercialized in 1990s • Achieving significant reductions in emissions of SO_2 and/or NO_x from existing facilities • Providing for future energy needs in environmentally acceptable manner	48	13; all ongoing
IV	Demonstrate technologies capable of: • Retrofitting, repowering, or replacing existing facilities while achieving significant reductions in SO_2 and/or NO_x emissions • Providing for future energy needs in environmentally acceptable manner	33	9; 2 withdrawn, 7 ongoing
V	Advance efficiency and environmental performance of coal-using technologies applicable to new or existing facilities	24	5; pending final approval

[a]The majority of the proposals were for four technologies: coal preparation (10), coal gasification (10), atmospheric fluidized-bed combustion (9), and flue gas cleanup (7).

Source: DOE (1994a).

9

Advanced Research Programs

The present chapter provides a brief overview of the organization and budgets for the DOE's Office of FE advanced research programs relating to coal. The DOE and committee perspectives on the role of advanced research for coal-based technologies are then presented. The chapter concludes with a brief discussion of opportunities for advanced research in three areas: combustion and gasification, coal conversion and catalysis, and materials. It is not the intention of the committee to provide a comprehensive list of research opportunities for coal-based technologies but rather to highlight key areas. The specific research opportunities discussed were identified by the committee on the basis of its review and analysis of current DOE programs (Chapters 5 through 7), and particular importance was accorded activities unique to coal technologies. In each case the proposed research is directed toward meeting, and ultimately exceeding, DOE's targets for advanced coal-based power systems and the production of clean fuels from coal.

PROGRAM ORGANIZATION AND BUDGETS

The advanced research programs within the DOE FE coal R&D program consist of a set of cross-cutting programs within the AR&TD (Advanced Research and Technology Development) budget category and a set of technology-specific programs falling under the general category of Advanced Research and Energy Technology (AR&ET), formerly known as Advanced Research. The AR&ET technology-specific programs fall within the Advanced Clean Fuels and Advanced Clean/Efficient Power Systems budget categories (see Table 2-1). This program organization responds to a directive from Congress stating that, for ease of budget presentation and receiving testimony, advanced research directly related to a specific coal area should be presented both in the budget and in testimony as part of the total program for that specific technology area, rather than as part of the AR&TD budget category.

The AR&TD program includes both research and nonresearch portions. The Technology Crosscut activities within AR&TD (see Chapter 2) include all nonresearch areas, namely, Environmental Activities, Technical and Economic Analyses, International Program Support, and Coal Technology Export, as well as two advanced research areas, specifically, Instrumentation and Diagnosis and Bioprocessing of Coal. For the purposes of the present discussion, the nonresearch portion of the AR&TD program will not be considered, and corresponding budget data are not included in Tables 9-1 and 9-2.

Table 9-1 presents the funding history of advanced research programs on coal since 1988. The 1995 budget request represents the DOE and administration proposal to Congress. When these budget numbers are expressed in constant dollars, it can be seen that there was a decrease of approximately 30 percent in the advanced research budget between FY 1988 and FY 1994, with an additional decrease of approximately 25 percent from the FY 1994 level proposed for FY 1995.

A more detailed comparison between the FY 1994 enacted appropriation and the 1995 congressional request is shown in Table 9-2, which also shows in more detail the advanced research activities funded under AR&TD and AR&ET. Major budget reductions are proposed in FY 1995 for the programs in materials (25 percent), components (50 percent), and, most notably, coal liquefaction (85 percent). It is proposed that the FY 1994 budget of $5.2 million for coal liquefaction be reduced to $0.8 million in FY 1995.

THE ROLE OF ADVANCED RESEARCH

DOE Perspective

A perspective on the mission, vision, and goals of the FE advanced research activities is provided in a recent document from DOE (1994b). The role of advanced research within the FE program is "to stimulate, nurture, and advance *critical enabling science and technologies* for fossil energy systems." A series of advanced research goals, strategies, and success indicators have been selected to support relevant DOE business lines and the core Office of FE business lines of clean fuel systems and clean/efficient power systems (see Chapter 2) and to directly reflect customer and stakeholder expectations. The goals are as follows:

1. Provide the core competencies in the critical enabling science and technologies that enable the Office of FE business lines to succeed in their missions.
2. Through feasibility testing, identify and nurture innovative concepts for advancing the technology and removing barriers to achieving the Office of FE's business line goals.
3. Provide the fundamental data, information, materials, and tools required by the U.S. fossil energy industry to bring advanced fossil energy systems to commercial fruition.
4. Improve the environmental performance of fossil energy systems by performing research that significantly increases system efficiencies, provides advanced environmental control systems, and shifts from waste management to pollution prevention/waste minimization.

The Committee's Perspective

Based on its analysis of likely future trends in coal use and ongoing DOE coal programs, the committee observed that the use of coal for power generation is confronting an increasingly demanding set of requirements. Following many years of gradual improvement of pulverized coal-steam turbine baseload power systems, with limited add-ons for emissions control, there is a need for greatly enhanced technology for emission control, for improved efficiency, and for improvements in the overall economics of power generation. Similarly, during the time periods considered in this study it is probable that liquid and gaseous fuels manufactured from coal will be needed. Improvements in the cost and efficiency of manufacturing processes will depend on further advances in the chemistry and engineering related to coal use.

In light of the continuing needs for advances beyond the 2010 targets defined for the power systems and fuels programs (Chapter 2) and the goals defined in DOE's Strategic Plan (DOE, 1994a), the committee identified a critical role for DOE advanced research programs on coal. Such programs have the potential to exploit the extensive opportunities for improved coal technology while compensating for the decline in industrial and non-DOE government support for long-range research on coal. The optimum role for DOE differs from one advanced research area to another but is largely determined by technology needs and their degree of specificity to coal-based systems and by complementary research activities in industry and government organizations outside DOE. The following discussions of some major research areas address opportunities for DOE advanced research programs to contribute to the development of coal technologies. The research areas discussed are combustion and gasification, coal conversion and catalysis, and materials.

COMBUSTION AND GASIFICATION

Research on oxidation of fuels to provide useful energy with acceptable emissions is the subject of a large international activity. Much current work relates to gas-phase reactions and to soot formation and oxidation (see, for example, The Combustion Institute, in press). However, coal combustion research falls outside these areas because of the large amount of char formed by the pyrolysis step and because of the ash content of coal. Problems directly related to coal—such as emissions, waste products, and char oxidation efficiency—are receiving far less attention than problems relating to other fuels. Much of the recent advanced research on coal-related combustion issues, notably the interaction with coal ash and the final stages of oxidation, has been conducted in the United States, principally under DOE and, to a lesser extent, National Science Foundation sponsorship. The committee noted that, in the absence of research needs and funding from other sources, DOE support is important to achieve progress in quantitative understanding of coal-related combustion and gasification issues and to identify innovative concepts for further investigation.

While still a promising area for research, gas-phase chemistry of NO_x formation and destruction and of the oxidation of carbon monoxide (CO) and hydrocarbons, has advanced to the point where simplified gas kinetic models can be used in conjunction with primitive turbulence modeling as a semiquantitative design and development tool for low-emission furnaces and gas turbine combustors. However, in the case of coal, the early release of gas-phase hydrogen cyanide introduces NO_x production pathways not yet quantitatively explored. Moreover, promising research opportunities still exist, including implementation of more sophisticated models. In contrast, the understanding and quantitative treatment of carbon kinetics, taking into account catalytic and physical interactions with ash and graphitization of carbon as the oxidation process proceeds, is at a relatively primitive stage. Since future innovations in coal gasifier and combustor design will depend, to a considerable extent, on quantitative understanding of the interaction between pyrolysis, carbon oxidation, and emissions, the committee noted that DOE's advanced research program for coal needs to address this issue.

The final stage of carbon oxidation is of special interest because of the observed reduction of reactivity at high conversion rates (Davis et al., in press). The long reaction times and high temperatures required for high carbon conversion will increase thermal NO_x formation in the presence of excess air. The interactions involved are complex, and improved quantitative understanding of the evolution of carbon reactivity and its interaction with the physical and catalytic properties of the coal ash is needed for choice of optimum levels of carbon oxidation.

Two major advanced research opportunities were identified by the committee as a basis for improving high-performance gasification systems. In low-temperature and countercurrent fixed-bed gasification processes, escape of fuel nitrogen as ammonia can occur, resulting in the formation of additional NO_x on combustion if not removed. Quantitative treatment of this problem is needed for improvement of these processes. For low-temperature gasification processes where high carbon conversion is needed, catalysis of carbon gasification by ash constituents, such as calcium, or by added catalysts remains a promising area related to future advances in gasification efficiency.

COAL CONVERSION AND CATALYSIS

The complexity of coal structure and chemistry has important implications for conversion technologies and catalysis. Coals are inhomogeneous on the macroscopic, microscopic, and molecular levels. They are insoluble, opaque, macromolecular systems composed of a mixture of organic and inorganic constituents. While knowledge of coal's physical and chemical structures remains rudimentary, knowledge and understanding of coal reactivity are even more limited. Most of the available tools for determining chemical structure are designed to work with systems of pure compounds and either do not work when applied to coals or become much more complex in their application. The efficacy of solid catalysts when used with solid coals decreases very significantly compared to their effectiveness in fluid systems. Opportunities exist to develop entirely new catalysts that will contact coals and effect desired reactions. The committee identified a role for DOE in supporting advanced research on coal conversion and catalysis to ensure the cleanest and most efficient utilization of coal, consistent with the goals of the advanced fuels and power systems programs, and to compensate for the absence of significant industrial research in this field.

In reviewing current DOE coal advanced research programs, the committee particularly noted the decline in efforts devoted to coal liquefaction technology. Given the likely growth in importance of coal liquids in the mid and long term, as described in the committee's strategic planning scenarios (see Chapter 4), the committee identified coal liquefaction as an important area for advanced research within the DOE coal program. Industrial transformations of fossil fuels are catalytic, and the creation of new and improved catalysts and better reactors to use those catalysts has been a central thrust of fuel chemistry for almost a century. The use of catalytic chemistry with coals presents unique and difficult problems. Since coal is a solid, it cannot move around into contact with a catalyst surface. Thus, the use of immobile solid catalysts typical of oil and gas processing is not possible with coal. It is necessary either to render the coal fluid, to use catalysts of extraordinarily high dispersion, or to use catalysts that are themselves mobile fluids. All three approaches have been used with some success, and there has been a fairly continuous improvement in catalysts used. Further enhancements can be anticipated based on a mix of applied and fundamental studies on topics such as highly dispersed catalysts, diffusion in coals and coal-catalyst contacting, and effective mobile catalysts. Both lower-temperature catalysts and more selective chemistries have the potential to reduce costs.

Research opportunities can be conveniently divided into two major categories: improvements in current processing chemistry and technology and liquefaction processes based on new chemistries. Possible improvements in chemistry and technology (see also Chapter 6) include:

- low-pressure reaction at 2.17 MPa (300 psig) or less;
- use of low-cost subbituminous coal or lignite, especially deposits having high hydrogen-to-carbon ratios;
- removal of coal oxygen as carbon dioxide;
- complete conversion to liquids with boiling points below 540 °C (1000 °F);
- improved selectivity to minimize production of hydrogen, water, and hydrocarbon gases;
- coproduction of high-value chemical and other nonfuel products; and
- direct use of gas from IGCC systems equipped with hot gas cleanup for F-T synthesis and to produce hydrogen for direct liquefaction.

For direct liquefaction, existing processes require cold gas cleanup, shifting to convert carbon monoxide and water to hydrogen and CO_2, and scrubbing to remove CO_2. There would be significant energy and capital cost savings if the hot gasifier gas could be used without cooling and further processing. Water/gas shift activity in the catalyst system used would be desirable; however, currently available catalysts are not sufficiently sulfur resistant. The use of hot gasifier product for F-T synthesis would require new catalysts capable of carrying out the reaction in the presence of the sulfur concentrations and traces of heavy metals remaining after hot gas cleanup. More active or selective sulfur-tolerant catalysts could markedly improve both direct liquefaction and the upgrading of coal liquids.

Alternative process chemistries of potential interest include

- coprocessing based on alkylation or transalkylation chemistry rather than hydrogenation,
- oxidative depolymerization to oxygenate fuels, and
- new depolymerization chemistry followed by fixed-bed catalytic upgrading.

The DOE AR&TD budget for bioprocessing of coal was $1.9 million in FY 1994, and the same funding has been proposed for FY 1995. The main thrusts of the bioprocessing program in recent years have been to explore and apply recent advances in biotechnology to convert coal to liquid fuels and to improve the environmental acceptability of advanced power systems. Activities have included characterization of the metabolic features of bacteria found to remove organic sulfur, mineral matter, and metals from coal and investigation of mechanisms for bioconversion of coal. Most experts in the field now agree that biotechnology is best suited for the manufacture of high-value-added products and is least well suited for the production of very large amounts of low-value-added materials, as in the case of coal processing. Thus, current and proposed future DOE coal program efforts in biotechnology will focus on cleanup of sulfur- and nitrogen-containing compounds in combustion gases, rather than on coal desulfurization and demineralization. The committee notes that, although there are possible opportunities for biological cleanup of flue gas (NO_x and SO_2 removal), significant technological difficulties remain because of the relatively long processing times and large volumes of gas to be treated.

MATERIALS

General Comments

R&D aimed at developing high-performance materials designed to operate in hostile environments is a very large and active area of endeavor worldwide. Given the limited resources of DOE's coal advanced research program in materials, the committee identified a need for this program to focus on key materials development issues for coal-based technologies while leveraging more generic materials developments from other programs.

The preceding review of DOE's coal R&D programs given in chapters 5 through 7 has been used by the committee as a basis for identifying opportunities in materials research specific to coal-based technologies. Three areas have been selected for emphasis and are discussed below: advanced gas turbines; high-temperature, high-pressure heat exchangers; and inorganic membranes. The present discussion is not intended to provide an exhaustive list of materials research opportunities relevant to the coal program but rather to highlight key materials-based enabling technologies critical to the success of DOE programs in advanced clean fuels and advanced power systems.

Advanced Gas Turbines

Many of the advanced coal-based power generation technologies currently being developed incorporate gas turbines (e.g., IGCC, advanced PFBC, direct coal-fired gas turbines, and IFC [indirectly fired cycles]). Thus, gas turbines constitute a key component in advanced coal-based power generation technologies.

The ATS (advanced turbine systems) program, funded under the natural gas component of the FE R&D program budget, aims to develop advanced land-based turbines for natural gas systems but adaptable to coal- or biomass-derived fuels. The systems efficiency target using natural gas is greater than 60 percent based on lower heating value (approximately 55 percent HHV equivalent). Many generic materials issues,[1] such as increased temperature capability and extended operating lifetime, are being addressed in the ATS program by DOE and industry

[1]See NRC (1986) for an assessment of materials needs for large land-based gas turbines.

participants, and related developments for natural-gas-fired turbines should be broadly applicable to turbines using coal-derived fuels. The committee recommends that activities in the FE coal R&D program focus on materials issues specific to the use of coal-derived fuels in advanced turbines.

All attempts to date to direct fire gas turbines with coal have resulted in significant ash deposition and corrosion of hot gas path components as a result of the aggressive chemical nature of the products of coal combustion (LaHaye and Bary, 1994). The development of turbine materials capable of surviving the hostile environment of direct coal-fired systems represents a major challenge. In the case of gasification-based systems, the environmental constraints imposed on the turbine materials are less demanding than in the case of direct coal firing but more severe than in a natural-gas-fired system. Coal gasification produces a raw syngas consisting mainly of carbon monoxide and hydrogen but with substantial quantities of CO_2 and water; minor quantities of hydrogen sulfide, ammonia, and hydrogen chloride; and a few parts per million of alkali metals (NRC, 1986). While unprocessed natural gas can contain large amounts of hydrogen sulfide, pipeline natural gas contains no hydrogen sulfide and a sulfur weight fraction of only 0.000007 (DeLuchi, 1993).

The major issue associated with the use of coal-derived gas in advanced turbines is the effect of contaminants, notably sulfur and alkali metals, on turbine performance (operating temperature and lifetime). Possible penalties in the overall efficiency of gasification-based systems can be anticipated based on the need to operate at lower temperatures to reduce the corrosive effects of contaminants in the coal-derived gas. Corrosion is also likely to severely reduce the lifetime of the turbine components. The ability of hot gas cleanup systems to reduce contaminants to levels acceptable for high-temperature advanced turbines has not yet been demonstrated. Reverting to cold gas cleanup would involve an efficiency penalty of one to three percentage points.

From a materials perspective, the critical issue for coal gas-fired systems is the extent to which corrosion-resistant turbine blade materials and coatings can increase the environmental tolerance of advanced turbines, thereby reducing (or eliminating) the need for gas cleanup and possible associated efficiency penalties. Allowable levels of contaminants depend on engine design and turbine pressures and temperatures, but the corrosion problem is likely to be the most severe for the first-stage blades that are exposed to the highest temperatures and the full concentration of impurities in the gas stream (Bernstein and Allen, 1992).

Given the increased likelihood of environmental attack, evaluation of candidate material systems for coal-fueled turbine systems is necessary, with an accompanying search for better materials. The superalloys currently used for turbine blades are generally protected from high-temperature oxidation and corrosion attack by a variety of coatings. Formation on the coating surface of reaction products—specifically, adherent alumina or chromia scales—retards subsequent reaction between the coating and the environment. A recent review of high-temperature coatings for combustion turbine blades (Bernstein and Allen, 1992) addresses coating requirements for protection from different types of environmental attack.

Since fuel type is probably the most important variable influencing the choice of a coating, the use of gas derived from coal gasification is likely to have a significant impact on the choice of turbine blade coatings. The complex chemical reactions that occur at high temperatures, and the susceptibility of these reactions to small chemical changes in the coating and gaseous environment, suggest that significant effort will be necessary to develop and evaluate coatings for turbines used in coal gasification-based power systems. There are a large number of commercial coatings available, and a number of different application methods that influence the coating behavior, but there is no one coating that is resistant to all types of high-temperature attack. It has been suggested that in systems using coal-derived fuel, coatings on advanced superalloys and the alloys themselves will need to form chromia rather than alumina scales for increased corrosion resistance (Bannister et al., 1994). In the case of the substrate (blade) materials, this constraint may limit the availability of suitable high-strength alloys.

Recently, the use of thermal barrier coatings (TBCs) has proven extremely useful in extending the temperature capabilities of existing superalloys. TBCs are ceramic coatings applied over metal substrates to insulate them from high temperatures. They consist of a layer of stabilized zirconium oxide that is 0.12 to 0.38 mm (0.005 to 0.015 inches) thick applied over a bond coat composed of an oxidation-resistant metal coating. Although TBCs themselves are expected to be only minimally corroded by the more aggressive environment in coal-fueled turbines, both the substrate and the bond coat may be adversely affected.

The development of alternative turbine materials with higher-temperature capability than existing superalloys—notably monolithic ceramics and ceramic matrix composites—is being addressed in the ATS program. The potential improvements in high-temperature corrosion resistance of ceramic materials compared to state-of-the-art superalloys is of interest for turbines using coal-derived fuels.

Heat Exchangers

In terms of materials behavior, the critical requirements for the ceramic heat exchanger for EFCC power generation systems (see Chapter 7) are

- to maximize operating temperatures for the proposed duty cycle, notably combinations of high temperature and pressure;
- to resist fouling and alkali corrosion, with emphasis on the latter for low-rank coals; and
- to avoid catastrophic failure.

Although advanced ceramics offer excellent high-temperature properties, such as high strength, corrosion and erosion resistance, and refractoriness, they are subject to brittle fracture due to critical flaws. High-velocity fragments from a failed ceramic tube have the potential to initiate rapid sequential failure of the array of ceramic tubes in the heat exchanger. The current proprietary tube design permits "graceful" rather than catastrophic failure.

Advanced structural ceramics with increased temperature capability and improved toughness are under development in a number of government/industry programs, including the ATS program (see above), the Integrated High-Performance Turbine Energy Technology program, including the U.S. Air Force, Navy, Army, Advanced Research Projects Agency, and the National Aeronautics and Space Administration (NASA), and the NASA Enabling Propulsion Materials program. Materials developed in these and other programs for high-temperature gas turbine applications may offer the higher operating temperatures and improved brittle fracture characteristics required for the ceramic heat exchanger in EFCC power generation systems. Since the proposed ceramic heat exchanger involves no moving parts, it is significantly less susceptible to deterioration from ash deposition or corrosion than are rotating components in the gas path of a turbine (LaHaye and Bary, 1994). However, the ash deposition and corrosion problems encountered using pulverized coal and the high-pressure cycles encountered in EFCC applications are unlikely to be addressed in materials development programs that are not targeted at coal-based technologies. In the view of the committee, the DOE coal materials program should focus on such issues specific to coal-based systems.

Current materials development and testing of the ceramic heat exchanger for EFCC systems is being conducted by Hague International (Orozco and Vandervort, 1993; Vandervort et al., 1993; Orozco, 1993; LaHaye and Bary, 1994). Activities are focusing on pressure and environmental testing. Over 2 million hours of successful operation of low-pressure ceramic heat exchanger units in corrosive high-temperature industrial environments has already been demonstrated. A series of tests is planned to demonstrate that a complete ceramic heat exchanger can contain pressures up to 1.21 Mpa (175 psia), endure at least 100 hours of operation under static and dynamic loadings, and meet thermal performance requirements. During these tests, the combustor will be fired with natural gas for operational simplicity. Subsequent testing with a coal-fired combustor will verify the ability of the slag screen to protect the ceramic heat exchanger from coal ash.

Ceramic materials demonstrate superior corrosion resistance compared to conventional metals and superalloys but can be severely degraded by alkali metals in coal combustion products. In particular, nonoxide ceramics such as silicon carbide (SiC) corrode in an oxidizing environment. The corrosion process is affected by the material processing technique, grain size, and impurity content. Hague International has conducted a series of corrosion tests on 46-cm (18-inch) long, 2.5-cm (1-inch) diameter tubular coupons of candidate heat exchanger materials, notably, an alumina matrix composite, reaction-bonded SiC, mullite (orthorhombic aluminum silicate, $Al_6Si_2O_{13}$), and monolithic alumina (Al_2O_3). Preliminary results indicate that mullite shows the highest temperature capability and good corrosion resistance. After 300 hours at 1090 °C (2000 °F) with brief excursions to 1480 °C (2700 °F), little corrosion was observed.

Despite performance enhancements in advanced ceramics, a temperature limit of approximately 1090 °C (2000 °F) currently exists for ceramic heat exchanger materials. A report published in the late 1980s (OTA, 1988) noted that federal government support has been necessary to accelerate development of the ceramic materials and system technology for heat exchangers, despite projected economic and performance advantages. Material manufacturers and end users have considered the technical risks too high to invest their own funds in systems development and implementation.

Membranes

Membranes play a key role in the production of fossil-fuel-based products that meet composition standards for engine and combustor performance and provide environmental compliance through the removal of pollutant molecules (NRC, 1993). Possible applications of membranes to coal-based systems include the separation of hydrogen from coal gas streams and of impurities such as hydrogen sulfide (H_2S), ammonia (NH_3), SO_2, NO_x, and trace metal compounds from coal conversion (e.g., gasification) and combustion (flue gas) streams. Such separations can account for a major fraction of the investment and operating cost for coal-based systems. A particularly important application for advanced clean/efficient power systems is the cleanup of coal gasification streams to drive advanced turbines. As discussed above, the ability of hot gas cleanup systems to reduce the contaminants to levels acceptable for high-temperature advanced turbines remains to be demonstrated. Another possible application of membranes is for the separation of methane from very dilute coalbed methane streams (see Chapter 5).

Low-temperature polymer membrane technology is fairly well developed and is useful for liquid-liquid, liquid-gas, and gas-gas separations (DOE, 1992). However, polymer membranes are limited to relatively low temperatures (less than 250 °C [480 °F]) and are subject to chemical and abrasive attack, particularly in the aggressive environments encountered in coal-based systems. Inorganic (ceramic) membranes have the potential to operate at the high temperatures required for advanced power generation systems (e.g., 815 °C [1500 °F] for removal of hot gas particulates from advanced PFBC and IGCC systems) and to provide significantly enhanced corrosion and erosion resistance compared to polymer membranes. Other expected advantages of advanced inorganic membranes include high permeability (1,000 to 10,000 times organic membrane permeability) and high selectivity (DOE, 1993).

In materials terms, refractory behavior and resistance to environmental attack depend on a suitable choice of ceramic material and associated fabrication process. Possible problems can be anticipated in coal-based systems due to reaction of candidate ceramic membrane materials—such as alumina, zirconia, and silica—with gas stream components, notably SO_2 and alkali metals, at temperatures in the range of 540 °C to 1090 °C (1000 °F to 2000 °F). The presence of steam is likely to accelerate the degradation process. Requirements for high separation efficiency impose further materials constraints in terms of pore size distribution and mean pore size in the membrane. A high degree of control during membrane fabrication is necessary to achieve the desired microstructural features. Ceramic membranes consist of a porous support a few millimeters thick, a porous intermediate layer 10 to 100 microns thick with pore diameters in the range of 0.05 to 0.5 microns,[2] and the separation layer with a thickness of 1 to 5 microns (Burggraaf et al., 1989). Generally, the separation layer must have pore diameters less than 10 nm for effective separation of gaseous components by diffusion (Krishnan et al., 1993); in some cases a mean pore size of 2.5 nm may be necessary.[3]

Current commercially available membranes do not meet all performance requirements for cleanup of coal-gas and flue gas streams, although several manufacturers produce inorganic membranes for micro- and ultrafiltration applications, and some of these have pore diameters less than 10 nm and are capable of separating gaseous components. However, extensive membrane technology has been developed over the past 40 years for nuclear gaseous diffusion applications, and alumina and zirconia membranes have been used for the separation of uranium hexafluoride (UF_6) isotopes for the nuclear industry since 1950 (Krishnan et al., 1993). Current

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[2]One micron = 10^{-6} m.

[3]One nm = 10^{-9} m.

DOE programs to develop ceramic membranes for coal-based applications are attempting to leverage this existing knowledge base. Investigators at the Oak Ridge Gaseous Diffusion Plant have produced alumina (ceramic) membranes with pore radii as small as 70 nm. Membrane separation tests have demonstrated a capability to separate hydrogen from gas mixtures (DOE, 1992).

Membrane material research opportunities specific to coal-based systems involve primarily the development of inorganic membranes for separation of coal-derived products and impurities at elevated temperature and in corrosive environments. Improvements can be anticipated in the selectivity and separation efficiency based on enhanced understanding of the relationship between pore structure and the physical chemistry of molecular separations (NRC, 1993). Opportunities also exist for the development of membranes with improved resistance to the environments characteristic of coal-based systems, such that operating lifetimes can be extended. Given the likely increase in concerns over greenhouse gas emissions, the investigation and demonstration of cost-effective separation of methane from very dilute coalbed methane streams using membrane techniques also merit some attention.

FINDINGS

Future innovations in coal gasifier and combustor design will depend largely on an improved quantitative understanding of the interactions between coal ash, carbon oxidation, and emissions. The committee identified this topic as being of importance for DOE's coal-related advanced research activities, given its relevance to improved coal-based systems for power generation and fuel production.

Advanced research on coal liquefaction has the potential to achieve significant cost savings, either through improvements in current processing chemistry and technology or through processes based on new chemistries. There is currently very little industrial research on coal liquefaction; most activities are funded by DOE.

The operating environment in a coal-gas-fired turbine is more corrosive than that in a natural-gas-fired turbine, due primarily to the presence of sulfur and alkali metals. Evaluation of existing and emerging turbine material systems is needed to determine their suitability for advanced coal gasification-based power generation systems. This evaluation will require appropriate test rigs and methods for accelerated long-term testing in corrosive environments. Subsequent materials development will likely be necessary to optimize substrate and coating materials. The need for improved corrosion-resistant turbine materials is dependent on the ability of hot gas cleanup systems to reduce contaminant levels in coal-derived gas to acceptable levels for advanced gas turbines. The more successful the hot gas cleanup, the less demanding are the materials requirements, and vice versa.

The performance of high-temperature, high-pressure heat exchangers for EFCC power generation systems is currently limited by the properties of available materials. In particular, the maximum operating temperature of approximately 1090 °C [2000 °F] would not provide efficiencies significantly higher than state-of-the-art pulverized coal systems. The corrosive environment resulting from coal combustion imposes additional severe demands on materials. The ability to reach operating temperatures of 1370 °C to 1425 °C (2500 °F to

2600 °F)—corresponding to the inlet temperatures of future advanced gas turbines—represents a major materials challenge and is far from the current state of the art.

Inorganic membranes with high separation efficiencies and long-term resistance to high-temperature corrosive environments have the potential to improve the economics of power generation from coal, particularly for systems using advanced turbines. Materials development is required to improve the separation efficiency of ceramic membranes used for hot gas and flue gas cleanup. Improvements in durability at elevated temperatures in corrosive environments are also needed. Additional research opportunities exist to investigate membrane separation of methane from very dilute coalbed methane streams.

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Table 9-1 Trends in Advanced Research Budgets (millions of current dollars)

Area	FY 1988	FY 1989	FY 1990	FY 1991	FY 1992	FY 1993	FY 1994	FY 1995 (request)
AR&TD (research)	21.1	20.2	21.2	22.9	23.0	20.4	22.6	19.8
AR&ET (fuels)	6.1	6.9	6.8	8.1	7.1	7.4	5.2	0.8
AR&ET (power systems)	8.1	7.4	7.1	8.2	7.3	2.9	2.1	1.8
Total[a]	35.3 (41.1)	34.5 (38.5)	35.1 (37.5)	39.2 (40.3)	37.4 (37.4)	30.7 (29.9)	29.9 (28.4)	22.4 (20.7)

[a]Figures in parentheses represent total budget in constant 1992 dollars.
Source: Personal communication from David Beecy, U.S. DOE, to Jill Wilson, National Research Council, July 20, 1994.

Table 9-2 Advanced Research Budgets for FY 1994 and FY 1995 (millions of current dollars)

Area	FY 1994 (enacted)	FY 1995 (requested)
AR&TD		
Coal Utilization Science	3.1	3.1
Materials	8.9	6.9
Components	1.7	0.9
Bioprocessing of Coal	1.9	1.9
University and National Laboratory Coal Research plus University Coal Research	5.0	5.0
HBCUs,[a] Education, and Training	1.0	1.0
Instrumentation and Diagnostics	1.0	1.0
Subtotal (AR&TD)	**22.6**	**19.8**
AR&ET		
Advanced Clean Fuels Research		
Coal Liquefaction	5.2	0.8
Advanced Clean/Efficient Power Systems		
Combustion Systems	0.5	0.4
Control Technology and Coal Preparation	1.1	1.0
Surface Coal Gasification	0.5	0.4
Subtotal (AR&ET)	**7.3**	**2.6**
TOTAL	**29.9**	**22.4**

[a]Historically black colleges and universities.
Source: DOE (1994c).

PART III

RECOMMENDATIONS FOR DOE'S FUTURE COAL PROGRAM

10

Conclusions and Recommendations

This chapter synthesizes the discussions and findings of Part II (chapters 5–9) in the context of the committee's charge and the strategic planning framework and background presented in Part I (chapters 1–4). For each topic discussed in chapters 4 through 9, conclusions and recommendations are offered below.[1] The cross-cutting systems analysis area not explicitly covered in chapters 4 through 9 is addressed separately. In the final section of the chapter, the committee's conclusions and recommendations are interpreted in the context of the individual sections of the EPACT that relate to coal (see Chapter 1 and Appendix B).

STRATEGIC PLANNING FOR COAL

In Chapter 4 a strategic planning framework was established to assess planning for coal-related RDD&C. The framework is based on projected scenarios for future energy demand and markets for coal technologies, taking into account likely future environmental requirements, competing energy sources, institutional issues, international activities, and other factors affecting the demand for coal. In the committee's view, the overall objective of DOE's coal program should be to provide the basis for technological solutions to likely future demands, as reflected in the scenarios. The committee defined three planning horizons—near-term (1995–2005), mid-term (2006–2020), and long-term (2021–2040) periods—for which the scenarios were formulated and requirements for coal were outlined. Based on its analysis, the committee concluded that coal will continue to be a major energy source in the U.S. economy over all planning horizons considered and that a sustained program of RDD&C for coal technologies is important for the economic, environmental, and security interests of the United States.

The strategic planning framework identified two priority areas for the DOE coal program: (1) conversion of coal to electricity, representing the principal market for coal for all planning periods, but particularly in the mid- to long-term periods; and (2) conversion of coal to liquid and low- and medium-Btu gaseous fuels, in the mid to long term. EPACT requirements for coal use emphasize the need for high efficiency, low environmental impacts, and competitive costs. These needs are generally consistent with DOE's objectives for coal RDD&C, as defined in the

[1]Asterisks (*) identify the most important recommendations.

most recent planning documents (DOE, 1993a, 1994a). The DOE planning horizon, however, currently extends only to 2010. Specific objectives have been formulated for that period for advanced power systems and advanced fuel systems. These objectives are discussed below in the sections on electric power generation and clean fuels from coal.

Conclusions

1. DOE's strategic planning objectives for coal technology RDD&C currently extend only through the year 2010, even though coal will continue to be a major source of energy well beyond that period.

2. The most important strategic objectives for coal RDD&C programs are to support the development of (a) advanced coal-based electric power systems that are considerably more efficient and cleaner than current commercial systems and which will be needed beginning in the near to mid term; and (b) advanced coal-based fuel and coproduct systems that can be used to replace conventional oil and gas in the mid- to long-term periods.

Recommendations[2]

1. *The planning horizon for DOE coal RDD&C programs should extend beyond the agency's current planning horizon of 2010. The committee recommends the use of three time periods for strategic planning: near term (1995–2005), mid term (2006–2020), and long term (2021–2040). The main objective of DOE's coal program in all periods should be to provide the basis for technological solutions to likely future demands in a way that is robust and flexible.

COAL PREPARATION, COAL-LIQUID MIXTURES, AND COALBED METHANE RECOVERY

Coal preparation—or cleaning—is a widely used commercial process for removing mineral matter from as-mined coal to produce a higher-quality product. Current physical cleaning processes are used primarily to reduce the ash content of as-delivered coal, although some sulfur reduction (typically 20 to 30 percent) is also achievable in coals with high pyrite content. Because coal is an abundant and relatively low cost fuel, the incremental cost of coal cleaning is a major factor limiting the degree of impurity reductions that are economically feasible.

DOE research in recent years has focused on advanced processes to clean fine coal fractions to achieve a relatively low ash, low-sulfur product suitable primarily for premium applications, such as the production of coal-liquid mixtures that can be substituted for petroleum-based fuels. More recently, attention has also focused on the potential for coal cleaning to

[2]Asterisks (*) identify the most important recommendations.

remove trace species as a means of reducing power plant emissions of air toxics. A series of RD&D goals has been defined (DOE, 1993a).

Coal-liquid mixtures or slurries—primarily coal-oil and coal-water fuels—are another commercial technology that allows coal to be substituted for liquid fuels in combustion applications. R&D in this area peaked during the late 1970s and early 1980s when oil prices were high and coal-based substitutes were attractive. Commercial interest waned, however, as oil prices declined and oil price projections remained stable. Nonetheless, DOE has continued to fund basic and applied research related to CWSs (coal-water slurries), primarily at universities.

Finally, interest in recovery of coalbed methane has been stimulated by concern about greenhouse gases and EPACT requirements. Methane recovery technology for high methane concentrations is commercially available, and recovery is practiced by the gas and coal mining industries where local conditions justify the investment. However, systems for the capture and use of dilute coalbed methane streams, which are found in many coal mining operations, are not sufficiently mature for commercial implementation. As noted in Chapter 3, increased efforts will likely be needed to reduce coalbed methane released from underground mining, in accordance with the Climate Change Action Plan (Clinton and Gore, 1993). The research challenge is to economically recover coalbed methane from very dilute gas streams.

Conclusions

1. Coal preparation is a highly developed, commercially available technology that is widely used in the coal industry but that offers only limited opportunities for R&D to significantly lower the cost of advanced coal preparation processes. Continued research with extensive industry participation should achieve further improvements in existing and emerging technologies.

2. There may be opportunities through sustained fundamental research on cleaning processes to improve the environmental acceptability of coal.

3. Given the mature status of technologies for the production and use of coal-liquid mixtures and the very limited market for these mixtures, no further development by DOE appears necessary.

4. Although the collection and use of concentrated coalbed methane streams are not widely practiced in the coal mining industry, relevant technologies are available for commercial application.

5. Additional reductions in emissions of coalbed methane could be achieved through the development of technologies for the capture and use, or destruction, of dilute coalbed methane streams.

Recommendations

1. Strategic planning goals for the performance and cost of coal cleaning processes should define clearly the supporting role of coal preparation in DOE's programs in advanced power generation and fuels production, thereby focusing R&D activities.
2. DOE should phase out program activities related to coal-liquid mixtures.
3. DOE should implement a technology R&D program that addresses the control and use of dilute coalbed methane gas streams in response to EPACT requirements.

ELECTRIC POWER GENERATION

Power Generation Systems

The availability of high-performance gas turbines and low-cost natural gas has resulted in the use of natural-gas-fired combustion turbines for many recently installed power generation facilities. As discussed in chapters 3 and 4, decreasing availability and higher costs for natural gas in the next decade and beyond are expected to result in a resurgence of construction and repowering of coal-based power generation facilities, with requirements for greatly improved emission controls and higher efficiency. Substantial improvements over past practices are technically possible. A large fraction of DOE RDD&C on power generation is devoted to systems designed to meet anticipated emission control and efficiency requirements.

The advanced coal-based power generation systems under development with DOE funding can be divided into three groups based on projected efficiency:[3]

- Group 1—approximately 40 percent efficiency—includes the low-emission boiler system (LEBS), first-generation PFBC (PFBC-1), and first-generation IGCC (IGCC-1).
- Group 2—approximately 45 percent efficiency—includes EFCC, second-generation PFBC (PFBC-2), and second-generation IGCC (IGCC-2).
- Group 3—50 to 60 percent or greater efficiency—includes HIPPS, improved second-generation PFBC (improved PFBC-2), integrated gasification advanced-cycle (IGAC), and IGFC.

Important features of these systems are summarized in Table 10-1. Information on state-of-the-art commercial pulverized coal systems is included in the table as a baseline. Current DOE funding levels for these various technologies were summarized in Chapters 2 and 7.

Efficiency and Cost Targets

As shown in Table 10-1, DOE's efficiency goals for advanced power systems rise to 60 percent for the year 2010 (best current new plant levels are about 38 percent for the United States and 42 percent worldwide). In the DOE plan the highest efficiencies are expected to be

[3]For definitions of thermal efficiency, see Glossary.

achieved with IGFC technology (DOE, 1993a). A number of other systems are projected to achieve efficiencies of 45 to 55 percent using advanced combustion and gasification-based approaches and high-performance gas turbines. A major objective of the DOE plan is to achieve these higher efficiencies at an overall cost of electricity that is 10 to 20 percent lower than that of today's coal-fired power plants while also meeting more stringent environmental requirements (see Table 10-2).[4]

In the view of the committee, the DOE efficiency goals, especially for the later years, are quite optimistic. For example, the efficiency goals of 55 percent for systems using 1290 °C (2350 °F) gas turbine topping cycles exceed the performance capabilities of about 50 percent efficiency for current combined-cycle systems using natural gas. While turbine improvements are expected to raise the efficiency on natural gas to about 57 percent (see Chapter 7), coal gasification and gas cleanup energy losses will decrease efficiency by five to 10 efficiency points when using the gasification systems being demonstrated in the CCT program (see Chapter 6). Thus, substantial reduction of gasification-related losses is needed to achieve the DOE target system efficiency with IGCC. As noted in Chapter 7, the hybrid second-generation pressurized fluidized-bed combustion system, which gasifies only part of the coal, is estimated to have a potential for approximately four percentage points higher efficiency than IGCC systems where all the coal is gasified (Maude, 1993). Conceivably, this system could achieve the DOE efficiency goal; however, substantial technical hurdles remain to be overcome. Similar comments apply to the 60 percent efficiency goal for IGFC systems.

The goal of 10 to 20 percent reduction in the cost of power, concurrent with significant efficiency increases and emissions reductions, may be especially difficult to realize. For example, roughly 30 percent of the cost of electricity today for a new coal-fired plant represents the cost of fuel (EPRI, 1993). Thus, reducing fuel requirements by one-third by raising plant efficiency from about 40 to 60 percent would lower the overall electricity cost by about 10 percent, which is DOE's minimum cost reduction objective. A smaller efficiency gain would yield still smaller cost savings. These estimates assume that the nonfuel costs—principally the initial capital cost—remain constant. DOE targets show lower capital costs for advanced technologies than current commercial systems. More likely, the capital cost of more efficient combined-cycle systems will exceed that of the simpler, less demanding technologies now in use (Merrow et al., 1981). Higher capital and operating costs would mean that overall reductions in the cost of electricity would be difficult or impossible to achieve.

While projections of the cost and performance of new technologies are subject to great uncertainty (Frey et al., 1994), comparison of systems and options should be done on a common and clearly stated basis to provide valuable guidance for investment in RDD&C (see below, Systems Analysis and Strategy Studies). Such comparative studies are extremely valuable for assessing the validity of program goals and for communication of results.

A more realistic cost goal for the DOE advanced power systems program might be to achieve efficiency improvements at an overall electricity cost comparable to that for new coal plants today. For the future U.S. market, some cost premium could even be acceptable if justified by the improved environmental performance and reduced externality costs associated with advanced technologies. Indeed, future environmental regulations may well require such

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[4]Identical to Table 2-3.

higher performance, creating new incentives for investment in higher-efficiency systems. To be competitive overseas, advanced technologies would require the lowest possible capital costs consistent with the environmental and other requirements of specific foreign markets. In short, despite DOE's current planning estimates, it remains to be seen whether high performance and smaller investment costs are in fact compatible objectives.

Group 1 Systems

Group 1 power generation systems generally make use of commercially available components and technologies, such as supercritical boilers, gasifiers, and cold gas cleanup systems. Only limited use of first-generation PFBC and IGCC systems is expected in the United States. Demonstration programs for these technologies are under way both in the United States and abroad, and the main incentive to continue the domestic activity is to develop a foundation for second- and third-generation systems. On the other hand, the LEBS technology program outlined by DOE (1993a) does not appear to offer opportunities for development of a substantially more efficient, lower- emission system. Only if LEBS achieves a significantly lower cost than existing systems with comparable performance would its development be justified for near-term markets.

Assuming that Group 1 performance and cost objectives can be met, the market for Group 1 technologies will probably be limited to near-term installations where there is no economic penalty for carbon dioxide (CO_2) emissions. Although the committee's baseline scenarios assume no such penalties for the near term (1995–2005), it envisions new regulations or penalties aimed at forcing CO_2 reductions during the mid-term period (2006–2020). Technologies in Group 1, with their limited efficiency improvements over existing plants, would be at a disadvantage relative to the newer Group 2 systems emerging in the mid-term period. The "less demanding" scenario discussed in Chapter 4 assumes that economic penalties on CO_2 emissions might not be imposed for the foreseeable future. This might well be the case in developing countries such as China, and Group 1 technologies might therefore be of potential export interest.

Group 2 and 3 Systems

In contrast to Group 1 systems, technologies in groups 2 and 3 are judged by the committee to have greater potential to meet future power generation and associated environmental requirements: all technologies in these two groups make use of advanced components to achieve higher efficiencies and lower emissions. Major questions of system integration and reliability will need to be addressed, and early pioneer installations could serve as a basis for improved systems.

The riskiest components appear to be the high-temperature heat exchanger and furnace required for the indirectly fired systems, and the hot gas cleanup systems for the advanced PFBC and gasification-based systems. It is not established that high-temperature gas turbines can tolerate the chlorine and alkali metals that may be present in FBC (fluidized-bed combustion) products or the sulfur and particulates in the gasifier products of IGCC systems. Although hot gas cleanup is a component of advanced IGCC systems, cold gas cleanup could still allow the technology to succeed, if at a lower efficiency. In this sense, IGCC is a somewhat less risky technology than PFBC.

The 1370 °C to 1425 °C (2500 °F to 2600 °F) gas turbine required for Group 3 systems is within the state of the art for aviation systems but is still under development for electric power generation systems and will require demonstration and testing. The IGCC-2 and IGAC systems with an advanced gas turbine may not be significantly more expensive than first-generation systems if the turbine development effort is successful.

As noted previously, integrated gasification fuel cell systems offer the highest efficiencies and emission controls. Systems using molten carbonate or solid oxide fuel cells incorporate a steam bottoming cycle to maximize efficiency. Molten carbonate and solid oxide fuel cells operate at high temperatures (650 °C [1200 °F] and 980 °C [1800 °F], respectively). Since the maximum voltage produced by a fuel cell decreases with increasing temperature, the higher-temperature solid oxide fuel cell produces a smaller fraction of the total system power. However, the potentially lower costs of the solid oxide fuel cell provide incentives for continued research on these systems. The potential market for fuel cell technologies is quite large, especially for distributed power generation. However, fuel cell systems may still not be cost competitive with gas turbine systems without environmental incentives for higher efficiencies.

Gas turbine and fuel cell activities are currently funded under the natural gas portion of DOE's FE R&D program. However, gas turbines and fuel cells could be used with coal-derived gas, with the addition of gasification and gas cleanup facilities. The principal operating difference between natural gas and coal-derived fuel gas in these applications relates to the contaminants in coal-derived gas. Cold gas cleanup is capable of removing contaminants to a negligible level; however, there is an efficiency penalty of about two percentage points, along with the production of liquid waste streams that must be treated, adding to system complexity and cost. Hot gas cleanup is potentially more efficient but at the expense of less complete removal of contaminants, especially volatilized species that are not captured in current hot gas cleanup designs.

The requirements for cleanup of coal-derived fuel gas are expected to differ for fuel cell and gas turbine systems. System optimization will be required and needs to be established as part of the DOE coal program. For the molten carbonate fuel cell, ammonia, hydrogen sulfide, chlorine compounds, trace metals, and particulates would interact with the electrodes and with the carbonate electrolyte, necessitating electrolyte replacement and disposal of resulting water-soluble solid waste. For high-temperature gas turbines, damage to the blades is of greatest concern, and a discussion of research aimed at mitigating this concern can be found in Chapter 9 (Advanced Research Programs). Degradation caused by contaminants would limit maximum turbine inlet temperature, thereby limiting attainable system efficiency.

Thus, for fuel cell systems, the major development challenge is to reduce both fuel cell costs and balance-of-plant costs. For gas turbines, the major goal is to maximize turbine inlet temperature. Increasing turbine inlet temperature from the current maximum of 1290 °C (2350 °F), beyond the 1370 °C to 1425 °C (2500 °F to 2600 °F) proposed for integrated gasification advanced-cycle systems, to the 1540 °C to 1650 °C (2800 °F to 3000 °F) used in high-performance turbines would bring system efficiencies to a level approaching that expected for molten carbonate fuel cells. These major development goals for fuel cells and gas turbines apply to systems fueled with either natural gas or coal-generated gas. No special considerations for coal-derived fuel gas appear necessary at this time, beyond those described above for the coal program.

To use coal, both fuel cell and gas turbine systems depend on coal gasification technology; both can accept methane and light hydrocarbons in the fuel gas. As discussed in Chapter 6, coal gasification results in a loss of five to 10 percentage points in overall power generation efficiency compared to natural gas. Development of maximally efficient gasification technology is thus essential for future high-efficiency utilization of coal for both fuel cell and gas turbine systems.

Magnetohydrodynamics

The use of topping cycles—as in fuel cells, gas turbines, and MHD generators—to achieve efficiencies higher than those attainable in the simple steam Rankine cycle (approximately 42 percent) has been adopted worldwide and is the major focus of the ongoing DOE program on advanced technologies for electricity generation. Advances in gas turbine and fuel cell technologies have essentially closed the original efficiency gap that stimulated a large worldwide effort on MHD during the 1960s and 1970s. Over the past decade, this MHD effort has been greatly reduced. Within the DOE FE Advanced Clean/Efficient Power Systems Program, no further funds are allocated for MHD, except for closeout of the proof-of-concept study. EPACT Section 1311 recommends (and the committee concurs) that an integrated documentation of the results of the extensive proof-of-concept work should be prepared, to capture the "lessons learned" and to establish a reference point for any possible development of MHD systems in the future.

Emissions Control Technologies

Environmental control requirements for coal-based power plants are expected to become increasingly stringent in response to more demanding federal, state, and local requirements. In the near term, new control requirements for nitrogen oxides (NO_x) and air toxics are anticipated, along with new ambient standards for fine particulates. Over the longer term, significant reductions in CO_2 and solid wastes may be needed.

Targets

DOE's strategic objectives for conventional air pollutants (SO_2, NO_x, and particulates) express future goals relative to the 1979 federal New Source Performance Standards (NSPS) for coal-fired power plants (see Table 10-2). These emissions goals apply to advanced power systems in Groups 2 and 3. DOE's goals for 2000 and 2005 can already be met or exceeded by technology in commercial use today, although cost reduction remains an important objective.

Because environmental control requirements show a strong tendency to become more stringent, and because DOE's emissions goals for the next decade already are being achieved with modern technology (see Chapter 3), it is not clear to the committee that the DOE goals will be adequate to meet all necessary environmental standards for coal plants a decade or more from now. The 2010 target of 1/10 NSPS represents a relatively demanding level of emissions reduction but one that should be achievable by a number of coal-based systems much sooner than 2010 (although not all advanced systems may be able to meet the objective readily for all pollutants). Whether DOE's emission goals will be adequate to meet regional and local environmental quality constraints—which tend to be the most demanding—cannot be foreseen.

Emissions control requirements for hazardous air pollutants (air toxics) have yet to be defined by the EPA (U.S. Environmental Protection Agency). The most likely need in this area will be for control of volatile species, such as mercury, which escape collection in existing gas cleaning systems. Studies are in progress to assess baseline emission levels for current and advanced technologies.

In the mid- to long-term periods a critical environmental issue for coal use is likely to be the need to reduce emissions of CO_2 and other greenhouse gases. The committee concurs with DOE's primary strategy of reducing coal-related CO_2 emissions by improving the energy efficiency of new power generating plants. The CO_2 benefits of advanced technologies should be compared to the best commercial technologies currently available, which are more efficient than average U.S. plants (Table 10-3). The reductions actually achieved in the U.S. economy will depend on the rate of penetration of the advanced technology.

The DOE program plan includes the cross-cutting area of control technology, whose general goal is to achieve "ultra-low" emissions beyond the goals for 2010 (DOE, 1993a). No specific targets are set. However, the historical evidence (Appendix D) shows a strong trend toward requiring emissions from new coal plants to be reduced to the maximum extent achievable, within reasonable constraints on economic cost. Ideally, a risk-cost-benefit analysis would serve as the basis for determining environmental control regulations; discussion of this topic is beyond the scope of the present study. A possible vision for longer-term environmental R&D goals is to benchmark emissions of air pollutants from coal plants relative to cleaner but more costly competing fuels, particularly natural gas. With the exception of CO_2 content, it is feasible to match the quality of natural gas by cleanup of coal-derived gas. Since natural gas will continue to be used, a consistent set of requirements for coal-derived gas and natural gas may be appropriate. To the extent that such a goal for ultra-low emissions can be achieved, the environmental acceptability of coal relative to competing energy sources will be enhanced. The long-term challenge for the DOE program, then, would be to develop systems that achieve targeted emissions reductions from coal plants at reasonable cost. If this long-term goal can be achieved, the primary environmental concern remaining for coal-based systems, aside from CO_2 emissions, will be solid wastes.

The increasing cost and decreasing availability of landfill disposal options, particularly near urban and suburban population centers, will require increased attention to waste minimization, recycle, and reuse methods. In the committee's opinion, DOE's goal of reducing solid wastes from advanced pulverized-coal systems by half appears to be reasonable for near- to mid-term technologies (DOE, 1993a). More ambitious goals than the targeted 50 percent waste utilization from advanced power systems by 2010 are appropriate for the long term, when higher waste disposal costs will provide greater incentives for waste reduction at the source.

Technology Development Needs

A number of technologies now being demonstrated in the CCT program offer potentially lower emissions control costs in the near term for conventional air pollutants, for both new and retrofit plants. The most challenging problem for DOE is to achieve reliable and cost-effective emissions control using hot gas cleanup for advanced power systems. The most critical need is for high-temperature, high-pressure particulate removal. This technology is essential for the advanced PFBC systems; it is one way to achieve higher efficiencies with advanced IGCC systems. Hot gas desulfurization technology similarly remains to be developed for advanced IGCC systems. While current hot gas cleanup devices achieve very low levels of SO_2 and particulate emissions, to date neither hot gas particulate removal nor hot gas desulfurization systems have approached the durability and reliability requirements needed for a commercial system. Furthermore, current hot gas cleanup systems do not control volatile air toxics or nitrogen oxides (NO_x). DOE remains optimistic that these critical problems will be solved through continued R&D. Nonetheless, the promise of advanced PFBC and the potential efficiency gains of IGCC and IGFC systems will not be realized until significant progress is demonstrated. For gasification-based systems, existing or improved cold gas cleanup systems can meet anticipated environmental requirements but at an efficiency penalty of about two percentage points.

To achieve larger or more rapid reductions in CO_2 emissions than can be achieved by improving the thermal efficiency of coal-based power plants, technological options for the removal and storage of CO_2 from conventional and advanced power systems could also be needed. The current DOE plan provides for such a contingency, in its objective of demonstrating by 2010 the capability to reduce and sequester CO_2 emissions by about 80 percent at a cost premium of not more than 20 percent (DOE, 1993a). Given the current state of technology in this area, the most pressing need is for research related to CO_2 storage.

One of the most demanding long-term technical challenges for the DOE coal program is the reduction or elimination of solid wastes—a major environmental concern—through innovative and cost-effective recycle and reuse options, perhaps as part of an integrated "coal refinery."[5] At present, DOE has only a relatively small program ($2.4 million per year) in solid waste management. At least one of DOE's advanced coal technologies—the second-generation PFBC system—generates more solid waste than today's best commercial plants meeting stringent standards for SO_2 removal (98 percent or more). This underscores the need to find effective solutions that will allow coal to compete environmentally with alternative fuels for power generation.

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[5]The term "coal refinery" is understood as a system consisting of one or more individual processes integrated so as to allow coal to be processed into two or more products supplying two or more markets.

Conclusions

Power Generation Systems

1. DOE's selection of efficiency, emissions, and cost as key attributes of advanced coal-based technology is appropriate for strategic planning. However, its specific efficiency and cost objectives for advanced power systems appear to be overly optimistic given the current state of technology. On the other hand, DOE's power plant emission goals appear to be insufficiently challenging relative to the capabilities of current commercial technology and the environmental demands expected on future coal use.

2. The market for Group 1 systems (LEBS, PFBC-1, and IGCC-1, with approximately 40 to 42 percent efficiency) will probably be small in the United States. The overseas market may offer the best opportunities for commercialization. In particular, because LEBS offers comparatively small potential to evolve to a significantly higher performance system, it will be attractive only if it achieves a significant cost reduction relative to current commercial systems with comparable performance.

3. For group 2 and 3 systems with 45 to 60 percent targeted efficiency, new technological achievements are required to achieve the goals defined by DOE, including development of high-temperature gas turbines, high-temperature heat exchangers, hot gas cleanup systems, and advanced fuel cells.

4. Overall, gasification-based systems offer the lowest risk and highest potential for lower emissions and higher efficiency than current technology, but cost expectations need to be more clearly defined.

5. System optimization cost and market studies are needed to define the roles and relative merits of the systems now being funded.

6. While most of the DOE gas turbine program is funded under the DOE natural gas budget, the future of many of the high-efficiency options for efficient coal use depends on firing these same turbines with gas from coal gasification or pressurized fluidized-bed combustion.

7. The gas turbine program under the DOE coal budget is appropriately focused on assessing the problem of trace material contamination (e.g., alkali metals) and possible solutions, such as special turbine materials, especially when hot gas cleanup is used.

8. The integrated gasification fuel cell system offers the highest efficiency and lowest emissions of power generation systems under development within the DOE program. However, high fuel cell cost may be a significant barrier to widespread use, and a carefully documented projection of the potential for cost reduction is needed to establish program priorities.

9. The highest efficiency for IGFC systems will be obtained with hot gas cleanup; however, the requirements for contaminant removal need to be established.

10. The molten carbonate fuel cell offers the most promise among the current fuel cell options for IGFC power generation systems.

11. Overall, current DOE priorities as reflected in the FY 1994 budget authorization and the FY 1995 budget request for advanced power systems—including the fuel cell and gas turbine components of the natural gas program—are consistent with the committee's view of priorities across different power generating options.

Emissions Control Technologies

12. Overall, DOE can make an important contribution to reducing the costs and improving the performance of emissions control technologies by careful selection of critical problems for research in conjunction with industry.

13. Hot gas particulate cleanup is an especially critical technology at this time, since it will be an essential element in the success of high-performance PFBC and could improve the efficiency of gasification-based systems.

14. Hot gas cleanup for sulfur removal is another critical development needed for advanced PFBC systems where high-efficiency sulfur removal still needs to be demonstrated at acceptable reagent stoichiometries. There would also be efficiency benefits for advanced IGCC systems.

15. A thorough understanding is needed of options for the control of hazardous air pollutants, especially volatile air toxics, such as mercury and chlorine, across the set of advanced combustion and gasification-based technologies.

16. NO_x control measures meeting DOE's performance targets for advanced power systems with hot gas cleanup and high-temperature turbines remain to be fully specified and demonstrated. Selective catalytic reduction or other add-on technologies could well be required in addition to the combustion-based NO_x controls now envisioned.

17. Solid waste reduction is needed for all coal-based systems. Waste minimization, by-product recovery, and reuse options will become increasingly important and merit additional attention.

18. Currently, the primary focus of DOE's coal R&D to reduce CO_2 emissions is improving power plant efficiency. Should future policy measures require an accelerated rate of CO_2 reductions, additional measures to remove and dispose of CO_2 from gas streams, to avoid CO_2 emissions to the atmosphere, could also be warranted.

Recommendations[6]

Power Generation Systems

1. DOE's quantitative performance and cost objectives for advanced power systems should be reviewed in light of the committee's discussion and conclusions. In particular, a more realistic goal for advanced power systems would be to achieve significant efficiency improvements at an overall cost comparable to new plants today. For environmental R&D goals, an alternative long-term vision is to benchmark air emissions from coal plants relative to cleaner but more costly competing fuels, particularly natural gas. The long-term challenge would be to achieve greater emissions reductions economically while substantially reducing solid wastes.

2. Further development of LEBS should be predicated on at least 50 percent cost sharing with industry to demonstrate its potential to reduce costs below those of current systems with comparable performance.

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[6]Asterisks (*) identify the most important recommendations.

3. *Future investment of DOE resources in first-generation systems should be based on realistic market expectations and value as an entry into new technology with high growth potential. At least 50 percent industry cost sharing should be required to demonstrate private sector confidence in these technologies.

4. *Second- and third-generation gasification-based systems should be given the highest priority for new plant applications. Work on all the advanced systems should focus on acquiring the cost, emissions control, and efficiency information needed to select the most promising systems for further development. The limitations of critical components, such as heat exchangers, turbines, and fuel cells, and the timing and probability of technological successes should be taken into account. This process should begin before FY 1996 and should include a rigorous comparative study of the design options.

5. The DOE coal program should focus on assessing and solving turbine life problems related to coal-generated trace materials. If limitations caused by trace components are identified, research on special control technologies and on alternative materials resistant to the effects of contaminants should be undertaken.

6. DOE should identify research priorities specific to the use of coal-derived gas in fuel cells, such as the effect of contaminants on fuel cell performance and emissions.

Emissions Control Technologies[7]

7. *A critical assessment of hot gas cleanup systems for advanced IGCC and PFBC should be undertaken immediately to determine the likely costs and the ability to meet, in the next three to five years, all requirements for future high-temperature (>1260 °C [>2300 °F]) turbine operation and environmental acceptability.

8. Research on control of volatile air toxics for advanced power systems should be initiated, with a priority on those substances that remain in a gaseous phase at typical exhaust gas temperatures (generally >95 °C [>200 °F]). Assessments of current capabilities to control other hazardous air pollutants should also be undertaken.

9. Research should be continued on innovative approaches for less costly and more effective control of sulfur and nitrogen emissions in both retrofit and new plant applications.

10. Reduction of solid waste emissions from coal use processes should be given a higher priority in the DOE research program, with emphasis on innovative and lower-cost by-product recovery and reuse. An evaluation of by-product disposal and reuse options and costs should be conducted for all DOE-funded coal programs.

11. In addition to emphasis on efficiency improvements, continued R&D on the most promising retrofit measures for CO_2 capture and disposal is appropriate.

[7]Asterisks (*) identify the most important recommendations.

CLEAN FUELS AND SPECIALTY PRODUCTS FROM COAL

Clean gases and liquid products derived from coal have the potential for substantial future use. At present, natural gas and refined petroleum are much less costly than comparable products from coal. However, both of these resources are expected to become more costly (EIA, 1994).

DOE's primary strategic objective for advanced fuel systems is to demonstrate by 2010 advanced concepts for producing liquid fuels and other products from coal that can compete with products produced from petroleum, when petroleum prices are $25/bbl (1991 dollars) or greater.[8] At this price, coal-derived liquids may become competitive with nonconventional oil sources, such as tar sands and shale, and may also compete with the higher worldwide oil prices projected for the mid to long term.

It is likely that national efforts to reduce CO_2 emissions, as well as other environmental legislation and regulatory actions, could lead to increased emphasis on improved efficiency for technologies that convert coal to gaseous and liquid fuels. However, the cost of coal alone is too low to justify large additional investments for efficiency improvement. To date, DOE has not adopted environmental emission goals for coal liquefaction process plants, as it has for electric power plants. Future plants will likely have to meet air, land, and water emission requirements that are more stringent than those in place today, which could increase the overall cost of coal conversion processes relative to processes that use oil or gas.

Coal Gasification

The conversion of coal to cleaned gas with current technology incurs a loss of the inherent useful energy in the coal of approximately 20 percent, corresponding to an efficiency loss of 10 percentage points in IGCC systems using coal-derived gas (see Chapter 6). This loss can be largely attributed to temperature cycling and increased energy requirements for compression. Commercial high-temperature, oxygen-blown, entrained-flow systems with cold gas cleanup would have a loss of around 13 percentage points. The committee believes that further improvements in gasification technology are quite feasible and that cooperative programs with industry could help identify opportunities to improve both fluidized-bed and moving fixed-bed systems, leading to increased efficiency of advanced power generation systems.

For coproduct systems producing clean fuels and electricity, requirements for maximizing system efficiency are much alike. However, air-blown systems would be at a disadvantage. If oxygen systems are used, minimized oxygen consumption is important, and low-temperature gasification with methane production would require less heat and therefore less oxygen. Catalytic fluidized-bed systems offer potential for this application and have been studied in the past, but no currently active programs have been identified by the committee.

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[8]The committee notes that DOE's costing method employs assumptions common among electric utilities but not among oil companies. In particular, the interest rates assumed in amortizing the capital cost of a liquefaction plant are based on a lower assumed risk and therefore lower rates of return than are commonly used by the petroleum industry (see Chapter 2 and Glossary). This difference in required rate of return will result in higher costs compared to DOE estimates (DOE, 1993b).

The ongoing CCT program includes demonstration of six commercial gasification technologies. In addition, the proposed FY 1995 FE coal R&D program budget for Advanced Clean/Efficient Power Systems includes significant funding for construction of an advanced air-blown, moving fixed-bed gasifier, which has the potential to meet the IGCC-2 efficiency goal of 45 percent and minimize production of coal tar. However, since air rather than oxygen is used, this system would not be well suited for the production of clean fuels requiring hydrogen or syngas. A significant reduction in the DOE budget for advanced gasification research has been proposed for FY 1995 (see Chapter 6), despite the needs and research opportunities for improved gasification efficiency for both power generation and clean fuels production.

Products from Coal-Derived Gas

Hydrogen Production

Production of pure hydrogen from fossil fuels involves oxidation and separation, together with conversion of CO and water to H_2 and CO_2 by the water-gas shift reaction. This set of processes is quite mature but is being improved by competing catalyst manufacturers and developers of hydrogen production technology, with ammonia manufacture a main outlet. Apart from advanced research on separation processes, there appears to be minimal need for DOE participation developing processes for manufacture of merchant hydrogen.

Production of pure hydrogen is expensive and a major consumer of energy. Clean fuels production processes that conserve hydrogen and involve in situ conversion of CO and water to H_2 provide important gains in efficiency and cost reduction through heat integration and provide a preferred option for synthetic fuels manufacture.

Synthetic Natural Gas Production

While the current low cost of natural gas makes synthetic natural gas (SNG) uneconomical, there have been important advances in synthesis processes from industrial and government-funded R&D that allow use of the low H_2/CO ratios from advanced gasifiers, increased tolerance for sulfur, and improved design of reactors for the highly exothermic methanation reaction. Processes for direct production of methane by coal pyrolysis and low-temperature catalytic gasification followed by cryogenic separation offer additional pathways.

It has been estimated (COGARN, 1987) that these newer technologies can reduce the cost of stand-alone SNG production by approximately 25 percent. However, the resulting cost will still be higher than projections by the EIA (Energy Information Administration) for natural gas wellhead prices of about $3.50/thousand cubic feet or less in 2010. Thus, development of an economic incentive for large single-product plants is not expected before the late mid- or long-term periods (2020–2040). The DOE coal program does not include major programs devoted to catalytic SNG synthesis. This seems appropriate in view of the long time horizon and the excellent capabilities outside DOE. Advanced low-temperature gasification processes, however, ultimately have the potential to increase efficiency and reduce the cost of manufacturing SNG, liquid fuels, and chemicals.

Separating the methane formed directly in gasification processes by pyrolysis and by reactions in low-temperature gasification can be achieved cryogenically or by diffusion. The latter requires advances in high-temperature selective diffusion membranes.

Methanol from Syngas

Methanol has been an important commodity for many years, with uses in the chemical industry and as a solvent. It can be used neat as a motor fuel and, with the requirement for inclusion of oxygenates in gasoline, its use in preparing oxygenated components by reaction with olefins has grown rapidly. Manufacture of methanol from coal is currently more expensive than manufacture from natural gas.

Methanol is made by the catalytic conversion of syngas at about 250 °C (480 °F) at 60 to 100 atmospheres pressure. Both coal and natural gas can be used as syngas sources. The current commercial processes use a fixed-bed catalytic reactor in a gas recycle loop. A wide range of mechanical designs are used to control the heat released from the reaction. New developments in methanol technology include fluidized-bed methanol synthesis and use of a liquid-phase slurry reactor for methanol synthesis. The slurry technology offers improved control of temperatures; it was developed in LaPorte, Texas, in a joint DOE/industry program.

There is relatively little industrial R&D activity on processes using syngas with low H_2/CO ratios and the sulfur concentrations achievable with hot gas desulfurization. For use of coal, such a process could be less costly and more efficient than current technology and could be integrated advantageously with electricity generation in a coproduct system.

Liquid Hydrocarbons from Syngas (Fischer-Tropsch Synthesis)

While gasoline hydrocarbons can be manufactured from methanol by the Mobil methanol-to-gasoline process, production by F-T (Fischer-Tropsch) synthesis is currently favored for new overseas facilities when low-cost gas is available. F-T synthesis can produce premium-quality diesel and jet fuel with minimum processing. Gasoline is also produced but requires more extensive upgrading to meet octane number specification. DOE has been active in applying the slurry reactor technique to this process. The ability of this process to handle high-molecular-weight wax and to use the low H_2/CO ratio gas from coal without the need for shifting to a higher ratio is important. Limited DOE development work is being conducted in LaPorte, Texas, in cooperation with industry groups.

Recent DOE-sponsored systems and cost studies (Gray, 1994; Tam et al., 1993) using the DOE financing basis (see Chapter 2 and Glossary) have projected equivalent crude prices of $30 to $35/bbl for stand-alone production of high-quality gasoline and distillate fuels (diesel, aviation). When production of F-T liquids was combined with gasification-based power generation, the equivalent crude cost was reduced by $5 to $7/bbl, bringing it closer to the EIA reference case projected price for crude oil of $28/bbl in 2010 (EIA, 1994). Thus, the studies indicate the possibility of coal-based fuels production in the mid-term period (2006–2020), which is about the same period as major construction of gasification-based power generation facilities.

Further cost reductions can be anticipated by continued systems studies; however, critical examination of the premium fuel credit should be included. Opportunities for cost reductions by research include optimization of once-through processes and development of catalyst systems compatible with sulfur levels attainable using hot gas cleanup.

Products from Direct Liquefaction and Pyrolysis of Coal

Direct Coal Liquefaction by Hydrogenation

Following the oil embargo of 1973, direct liquefaction was the subject of intensive R&D, both industry and DOE funded. Since then, the drop in oil prices has led to abandonment of all large-scale development and drastic reductions in both industrial and DOE research activities. The products of direct liquefaction can be refined to produce highly aromatic high-octane gasoline and high-quality diesel fuel. Jet fuels and heating oil can also be produced. A design, systems, and cost analysis based on results from DOE's advanced liquefaction R&D facility in Wilsonville, Alabama, projected an equivalent crude price based on utility financing of approximately $33/bbl using Illinois No. 6 coal (DOE, 1993b). Use of lower-cost western coal might reduce the cost to approximately $30/bbl. There is optimism at DOE and among some industry groups that with continued R&D and systems analyses the DOE goal of $25/bbl (1991 dollars) for liquids from coal can be reached.

The aforementioned estimate based on Wilsonville data concerned dedicated coal liquefaction plants. Coproduction of liquids and electricity with advanced gasification systems can be expected to reduce costs. The reduction would likely be significant but probably less than the $5 to $7/bbl estimated for F-T liquefaction. Coprocessing of coal with residual fuel or tar in oil refineries has been studied by both industry and DOE.

While use of coal introduces both coal and ash handling requirements, improved process performance and continued low cost of coal are expected to revive commercial interest in the mid-term period (2006–2020) if oil prices follow EIA projections (EIA, 1994). Several research areas offer promise for reducing the cost and improving the efficiency of direct liquefaction by hydrogenation: use of raw coal gasifier product with a catalyst capable of in situ shifting of CO to H_2, removal of the oxygen in coal as CO_2 rather than water, use of a low-pressure reactor, and minimized production of light hydrocarbons.

Direct Coal Liquefaction by Pyrolysis

Controlled heating of coal in pyrolysis can produce modest yields of liquids. The heat of pyrolysis is small, and, if the char product can be used without cooling, high thermal efficiencies can be achieved. The pyrolysis liquids are low in hydrogen and high in oxygen compared to petroleum residuum or bitumen but could be coprocessed with bitumen or fed to a direct coal liquefaction unit. Their tendency to polymerize on storage limits their use as a supplementary fuel for power generation without further processing.

While probably of lower value to a refinery than bitumen, it seems possible that coproduction with gasification could make pyrolysis liquids competitive with tar in the same period as deployment of advanced power generation systems. DOE studied coproduction of pyrolysis char and coke (mild gasification) and began construction of demonstration facilities, but no further funding has been requested in the FY 1995 budget. A CCT demonstration of this technology using low-sulfur western coal is under way; the plan is to market pyrolysis liquids as power plant fuel oil and to burn the coke.

Coal Refineries and Coproduct Systems

The energy industries are mostly specialized, oriented to a narrow range of products and markets. Electric utilities supply electricity along with some steam to local users; oil refineries supply liquid fuels along with some petrochemical feedstocks; and gas suppliers collect, purify, and transmit natural gas to end users. Government regulations differ for these areas, and separate specialty business units have been established to deal with these separate regulatory systems. As discussed in Chapter 2, this regulatory environment has been changing to make it more attractive for groups outside the traditional utilities to generate and sell electric power.

The concept of a coal refinery, analogous to an oil refinery, has been discussed for many years, but the availability of low-cost petroleum has provided a disincentive to implement the coal refinery concept. More recently, EPACT directed DOE to examine the potential of coal refineries, and a report has been published (DOE, 1991). Screening studies by the Mitre Corporation (Gray, 1994) identified major synergies between advanced power generation based on gasification and production of clean fuels and chemicals. The preceding discussion identified several examples of cost and energy savings from the manufacture of a variety of products from coal gasification. The available data (Gray, 1994; Tam et al., 1993) indicate an equivalent crude cost of $5 to $7/bbl less for a combination of F-T synthesis and electric power generation than for stand-alone plants for liquids production. In these estimates the economic return on electric power production was held constant and the savings were applied to the liquid coproducts.

There are many other product combinations besides coal liquids and electric power, and quantitative studies can provide essential strategic guidance for both R&D and identification of optimized combinations of electric power, fuels, and chemical products. The incentives for coproduction by refineries, chemical plants, or independent producers of clean gas and other products will vary widely with location and the organizations involved. Cooperation with potential users is important to the success of such strategic planning studies.

The funding for DOE programs to produce clean liquid fuels from coal has declined significantly in recent years (see Chapter 6). The discussion above has indicated the possibility of introducing liquid fuels from coal at about the same time as new IGCC-based electric power generation facilities might be constructed. The timely availability of appropriate demonstrated technology will depend on initiating programs to investigate opportunities and develop coproduct systems as soon as possible.

Conclusions

1. Gasification plays a critical role as the first and most costly step in the production of electric power by combined-cycle systems and in the production of clean gaseous and liquid fuels and chemical products.

2. Gasification options exist that offer potentially greater efficiencies than currently available commercial systems. Among the relatively unexploited options, low-temperature fluidized-bed gasification systems, with the possible use of catalysts, appear to be the most versatile for providing the entire array of future products from coal. A few examples of such systems are in development, but the committee believes there are additional opportunities for further development.

3. The current DOE gasification program is devoted almost entirely to gasifier technology for power generation. However, gasification efficiency improvements are also needed to produce clean gaseous and liquid fuels. The proposed FY 1995 budget reductions are not consistent with this need.

4. Materials research leading to membrane diffusion techniques for recovering a by-product hydrogen stream is a major opportunity for DOE coal research relating to the production of pure hydrogen from coal-derived gas.

5. Production of SNG from coal is not expected to be of importance until late in the long term.

6. The major opportunity to improve thermal efficiency and cost in SNG production is in the gasification step.

7. High-efficiency oxygen-blown gasifiers developed for combined-cycle power generation would also be applicable to use in SNG manufacture.

8. For large single-product plants, direct coal liquefaction offers a 5 to 10 percent higher efficiency with correspondingly less CO_2 production than coal-based F-T syntheses, with production of methanol falling between these two limits. Similarly, the cost of producing a slate of refined transportation fuels by direct liquefaction is potentially lower than for the coal-based F-T synthesis gas-based fuels.

9. An estimate of the petroleum crude oil prices at which the products from a large direct liquefaction plant meeting current refined fuel specifications could compete is around $30/bbl using western coal and utility financing. For F-T liquids the equivalent crude oil price would be approximately $5/bbl higher (i.e., $35/bbl), with methanol production about the same as direct liquefaction. With typical oil industry financing, the equivalent crude prices would be on the order of $5 to $10/bbl higher.

10. Recent cost estimates for coproduction of coal liquids and electric power indicate that coal liquids might compete with petroleum at $25/bbl or less, with the possibility of coal-derived liquid fuel production at about the same time as installation of advanced IGCC power generation facilities.

11. Continued research in conversion chemistry and process optimization have the potential to reduce the cost of coal liquids from large liquefaction plants to the DOE goal of $25/bbl (1991 dollars).

12. There is little need, at this time, for large pilot plant or demonstration programs, but a bench-scale and small pilot plant program is needed to evaluate promising leads and provide focus for laboratory-scale research in direct liquefaction.

13. Advances and maintenance of core competencies in direct coal liquefaction technology in the United States depend increasingly on DOE activities, since R&D on direct coal liquefaction has dwindled to a very low level in industry.

14. Continued reductions in funding will cause a major degradation in the effectiveness of the DOE coal liquefaction program. This trend places the nation's long-term coal liquefaction option at risk because government support has become critical in sustaining U.S. competency in this area.

Recommendations[9]

1. *An expanded DOE role should be established to ensure the timely availability of the most efficient and economic gasification systems for future uses of coal in power generation and in the production of clean gases and liquids.

2. A research program should be established to improve the efficiency of gasification systems suitable for clean fuels production. The DOE program for improvement of gasifier efficiency also should include systems that produce methane directly and are applicable to both SNG and power generation.

3. No direct program on SNG manufacture is recommended.

4. *DOE's R&D program for coal liquefaction technologies should be continued at least at the FY 1994 level, with the goals of decreasing the cost of coal liquids and increasing overall efficiency.

5. Within DOE's coal liquefaction program, the effects of efficiency and other improvements on reducing CO_2 production should be considered.

6. Within the DOE program on coal liquefaction, highest priority should be given to direct coal liquefaction research, concentrating on fundamental coal chemistry and innovative process development.

7. DOE sponsorship of small pilot plant facilities should be continued to test and improve liquefaction technologies, but larger pilot plants should not be built in the near term without significant private sector participation.

8. *An assessment of strategies and opportunities for coproduction of premium liquid fuels and gasification-based power should be an important component in planning a program for the introduction of liquid fuels from coal.

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[9]Asterisks (*) identify the most important recommendations.

SYSTEMS ANALYSIS AND STRATEGY STUDIES

One critical activity identified by the committee that is not highlighted in DOE's current planning documents is systems analysis. This activity is essential to assessing coal R&D needs and priorities and to strategic planning. Given the expanding number of process options for advanced power generation, fuels production, and environmental controls, which designs are the most promising to pursue? How should complex processes be configured to achieve optimal results? How should individual components be designed to maximize performance and minimize cost? How do advanced process concepts compare to currently commercial technology and to each other? What are the most promising markets for advanced technologies, and what are the greatest technical risks? How do the various technical and economic uncertainties for new process designs affect projections of performance and cost, and how can targeted R&D best reduce critical uncertainties? A well-designed systems analysis program should be able to address such questions.

The DOE Fossil Energy program already has in place a significant systems and engineering analysis activity at both its Morgantown Energy Technology Center (METC) and its Pittsburgh Energy Technology Center (PETC) and additional capabilities at DOE headquarters in Washington. Each of these offices is involved in analysis and evaluation of processes and programs within selected areas of DOE activity. Analytical approaches of varying sophistication are employed for process analysis and evaluation, often with reliance on outside contractors in addition to in-house staff.

A preliminary look at DOE's ongoing activity in systems analysis indicates a significant amount of activity spread among METC, PETC, and headquarters. A major shortcoming, however, appears to be a lack of systematic assumptions and design premises within and across the full suite of DOE's advanced energy conversion and environmental control research programs. Rather, it appears that different parts of the DOE organization, working with a variety of different contractors, employ different assumptions and approaches—circumstances that preclude rigorous comparisons or evaluations of technologies in a given category (e.g., advanced power systems or advanced fuel systems).

Communicating the results of analyses to interest groups within and outside DOE is another important contribution of systems studies (see, for example, NRC, 1992), a contribution that could be greatly improved by consistency and clarity in the assumptions and methods used for analysis. Similarly, greater efforts to incorporate feedback from industrial and other stakeholders, coupled with timely and systematic publication of results, are also needed. A more coherent approach to systems analysis could be of real value for strategic R&D planning.

Of substantial value are the advanced analytical and computer-based methods for analysis, synthesis, and design of complex processes that DOE has begun to develop in recent years. For example, new methods to address technical and economic uncertainties are especially critical to characterize advanced processes and designs properly at the early stages of development. Characterization and analysis of uncertainties are also critical to identifying robust system designs, risks, potential markets, and key problem areas that should be targeted for research to reduce technological risks. While DOE has supported the development of advanced modeling approaches for systems analysis and design and is beginning to adopt some of these methods for

R&D management, more rapid implementation of a rigorous systems analysis methodology could be of significant value for long-term strategic planning.

Conclusions

1. The growth in opportunities to use coal to produce electricity, fuels, chemicals, and coproducts calls for expanding and strengthening DOE's Office of FE systems analysis activity, which plays a critical role in coal-related RDD&C and strategic planning.

Recommendations[10]

1. *An expanded and more prominent role for systems analysis is recommended in developing RDD&C strategies for the DOE coal program. This activity should establish a clearly stated and consistent set of criteria, assumptions, and design premises that can be applied to all technologies in a given category, to facilitate rigorous comparisons. Advanced methods of analysis, design, and risk evaluation should be adopted, and extensive interaction with the user community—notably U.S. industry—and active dissemination of major study results and methods should be pursued.

TECHNOLOGY DEMONSTRATION AND COMMERCIALIZATION

An important goal for the DOE coal program, as specified by EPACT, is to accelerate the development and commercial introduction of new technologies related to coal use. A major additional objective is to increase the competitiveness of U.S. firms engaged in supplying equipment and advanced technology to the power-generating industry at home and abroad. Before commercialization, large-scale demonstration is generally necessary to provide credible evidence of improved performance and practicability. These demonstrations are expensive and are generally cost shared by DOE and industry. The DOE role can vary from operating and managing a cost-shared facility to cofunding a program located at an industrial site and managed by the industrial partner.

The demonstration programs under DOE's FE R&D budget are generally of the first type, while the CCT demonstration projects are generally of the second type, with DOE operating only as a cofunding agency. The annual budget for FE coal R&D demonstration programs is approximately $150 million/year; additional funding for demonstrations of fuel cells and advanced turbines is included in the Office of FE's natural gas budget.[11] The CCT program will expend about $6.9 billion over 14 years on 45 programs, with industry contributing more than two-thirds of the total funding. The major CCT effort is expected to result in commercial

[10]Asterisks (*) identify the most important recommendations.

[11]For FY 1994, $74 million; for FY 1995 (request), $113 million.

applications, and, while most of the activities are not yet completed, most of the programs seem to be well chosen, based on the level of private support. Significant future use of these technologies will depend on a follow-up commercialization program that alleviates concerns about costs and reliability of advanced technologies (see Chapter 8). The extent of DOE involvement necessary to stimulate private sector investment in such a program requires further assessment, taking into account any social costs resulting from delay in the implementation of advanced coal-based systems.

At the request of the Secretary of Energy, the National Coal Council recently completed a study of commercialization opportunities and recommended a strategy for overcoming the barrier of the high costs and risks involved in using "pioneer technologies." It was recommended that approximately $1.4 billion be provided over 15 years (1995–2010) to provide about 10 to 15 percent of total capital and to help offset operating risks for the first plant after the demonstration plant, with a decreasing amount for the next three to five installations. Cost sharing would be for a percentage of that part of the commercial application that represents technical and economic risks not present in commercially available technology. This initiative would be in addition to the DOE FE R&D and CCT programs for technology demonstration.

Conclusions

1. Adequate technology demonstration and commercialization programs are essential for timely commercial application of new coal use technologies.

2. The timely introduction of clean coal technologies will depend on further demonstrations of a few pioneer installations beyond the CCT program to allay concerns about costs and reliability; some federal participation will be necessary to stimulate private sector investment.

3. Cost sharing of the risk differential between pioneer plants and commercially available technologies will accelerate the commercial acceptance of many of the new coal-based technologies.

Recommendations[12]

1. *Support of the current CCT program should be continued and the ongoing program completed. While no further solicitations are planned under the existing CCT program, the FE coal R&D program should continue to cofund demonstrations of selected Group 2 and Group 3 advanced clean coal technologies beyond those currently being demonstrated by the CCT program.

2. Any uncommitted funds from the CCT program should continue to be spent on activities related to the domestic use of clean coal technologies.

[12]Asterisks (*) identify the most important recommendations.

3. *An incentive program should be developed and implemented that would offset the capital and operating cost risks associated with early commercial applications of technologies previously demonstrated at a commercial scale.

4. Management of an incentive program by DOE should be the same as that of the current CCT program. The elements should be the same, except that cost sharing applies only to the risk components and not the total project costs. Because the solicitation, negotiation, design, construction, and demonstration phases can take five to seven years, multiple solicitations in several fiscal years should be conducted near the end of the demonstrations of the current 45 projects.

ADVANCED RESEARCH PROGRAMS

The principal aims of the DOE coal advanced research program are to pursue technology goals and exploratory research opportunities while maintaining a balance between revolutionary research and evolutionary engineering development programs. In conducting a strategic assessment of the DOE coal advanced research activities, the committee did not aim to provide a comprehensive list of research opportunities. However, some critical areas for coal-related research were identified during the committee's review of current programs. These include research on combustion and gasification, materials, and coal conversion and catalysis, as discussed in Chapter 9. In identifying these areas the committee accorded special importance to research areas unlikely to be addressed outside the FE coal R&D program. For example, the study of coal chemistry and catalytic reactions is not supported to a significant extent outside DOE's FE coal R&D program. The committee supports the DOE view, outlined in the recent FE advanced research strategic plan (DOE, 1994b), that advanced research activities within the coal program should be directed toward meeting the strategic objectives defined for advanced clean/efficient power systems and clean fuel systems. In line with the committee's earlier recommendation to modify coal RDD&C strategic planning horizons, the committee believes that the advanced research program should devote more effort to mid- and long-term requirements than is now the case.

The advanced research budget declined by about 30 percent in real terms between FY 1988 and FY 1994, with an additional decrease of approximately 25 percent proposed for FY 1995. Comparing the FY 1994 enacted appropriation and the FY 1995 budget request indicates that major reductions are proposed in coal liquefaction (84 percent), components (50 percent), and materials (25 percent). The reductions in funding for coal liquefaction, when combined with a proposed 36 percent reduction in funding for liquefaction programs outside the advanced research program, are of special concern, given the prospects for producing coal liquids in the mid to long term.[13]

In Chapters 6 and 7 the committee identified ample opportunities for major contributions to fuels and power generation programs from advanced research. However, DOE's budget reductions for advanced research are not commensurate with the requirements for advancement

[13]For a more detailed discussion of advanced research budgets, see Chapter 9.

of coal technology, notably the increasing needs for lower-cost, more efficient, and more environmentally acceptable use of coal.

Conclusions

1. There are increased needs and opportunities for advanced research directly related to achieving cost reduction and improved performance goals for advanced power systems and fuels production.

2. The recent trend in decreasing support for coal-related advanced research activities is not commensurate with the expanding needs to support DOE's mission.

Recommendations[14]

1. *Increased resources should be devoted to advanced research activities to support DOE's strategic objectives for coal, with emphasis on needs identified for mid- and long-term improvements in efficiency, emissions reduction, and cost for both power generation and fuels production.

THE ENERGY POLICY ACT OF 1992 (EPACT)

In this section the committee's conclusions and recommendations are interpreted in the context of the individual sections of EPACT that relate to coal (see Chapter 1 and Appendix B).

There is considerable overlap between the different coal-related sections of EPACT. For example, Section 1301 requires DOE to establish RDD&C programs on coal-based power generation technologies. One of the technologies addressed by DOE in this context is MHD, which is also addressed specifically in Section 1311. Similarly, issues relating to the cost-competitive conversion of coal to fuels are addressed in Sections 1301, 1305, 1309, and 1312.

In addition, there is very wide variation in the scope of different EPACT provisions. Section 1301 addresses the whole range of coal-based technologies, whereas other sections focus on very specific aspects of coal utilization, such as coal-fired diesel engines or low-rank coal R&D.

For these reasons of overlap and disparity of scope, the committee chose to develop and organize its conclusions and recommendations on the basis of strategic planning scenarios (Chapter 4) rather than by the individual sections of EPACT. The committee's approach has the advantage of providing a robust framework that can readily be adapted to respond to changes in the scenarios.

Table 10-4 summarizes the major EPACT provisions relating to coal, key features of relevant DOE programs, and the committee's comments and ratings in terms of priority for DOE. In assessing priorities for DOE activities, the committee used the criteria developed in Chapter 4. Prime considerations were the timing and goals of the program in light of the

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[14]Asterisks (*) identify the most important recommendations.

scenarios developed by the committee; the potential for technological success; likely markets; the potential for controlling, reducing, or eliminating environmentally important wastes; and the need for DOE participation, given the current development status of the technology, and other industrial and federal programs. For example, if technologies are already available commercially, the committee generally recommended a low priority in this area for DOE activities. Similarly, if there is currently extensive R&D activity in the private sector, the committee recommended that DOE leverage this effort.

The committee concluded that DOE has responded to some degree to all the sections of EPACT addressed in the study. However, the extent of the response varies widely. In the case of power generation systems, addressed primarily in EPACT Section 1301, the DOE Advanced Clean/Efficient Power Systems program is very responsive to the EPACT requirements to "ensure a reliable electricity supply" while complying with environmental regulations and controlling emissions (see Chapter 7). The committee endorses DOE's approach to the development of advanced coal-based power generation technologies, given the likely need for new, clean, efficient coal-based power generation capacity in the mid to long term (2006 through 2040). The committee's recommendations for priorities in developing the possible technology options are presented earlier in this chapter (under "Power Generation Systems").

The need to commercialize coal-based technologies, preferably by 2010, is addressed in EPACT sections 1301 and 1321. The committee concluded that DOE's CCT program represents an excellent start in the area of commercializing advanced power generation technologies, but, as noted above, plans need to be developed by DOE for activities beyond the conclusion of current CCT activities.

In contrast to DOE's generally adequate response to the sections of EPACT addressing power generation, its activities in coal liquefaction fall short of EPACT requirements, the committee concluded. As noted in Chapters 6 and 9, there was a significant reduction in funding of coal liquefaction activities between FY 1993 and FY 1994, and a significant further reduction is proposed for FY 1995. Given the likely growth in demand for coal liquids over the mid- to long-term periods (see Chapter 4) and the decline in industry-supported liquefaction research, the priority that EPACT gives to DOE liquefaction activities appears to be well founded.

Coproduction of electricity and other products, such as coal liquids, also is accorded relatively high importance by EPACT (sections 1304, 1305, and 1312), but it does not represent a major element of DOE's current program. Given the likely future growth in the use of coal for clean fuels and specialty products and the potential for economically attractive manufacture based on coproduction (see Chapter 6), the committee considers increased DOE effort in assessing coproduct systems or "coal refineries," in keeping with EPACT requirements, to be appropriate.

EPACT Section 1307 requires DOE to assess the feasibility of establishing a national clearinghouse for the exchange and dissemination of information on coal-related technology. The committee noted that means already exist to disseminate DOE reports on coal technologies to interested parties. Thus, any clearinghouse activity should be broader in scope and should involve participants from inside and outside DOE. However, the committee considered that the need for such an activity should be established by a market survey of potential users prior to significant investment of resources.

In comparing all the activities within DOE's current coal program and those mandated by EPACT, the committee noted a significant discrepancy in priorities. The current DOE program focuses on relatively near term activities, notably the development, demonstration, and commercialization of coal-based power generation systems by 2010, at the expense of longer-term research programs. Such longer-term programs would position the United States to respond to future energy scenarios in which coal assumes increasing importance for uses other than power generation. In contrast to the DOE approach, the coal-related provisions of EPACT endorse the development of a longer-term, more balanced spectrum of coal-based technologies. The committee's recommendation that strategic planning for coal should address requirements for periods to the middle of the next century is more consistent with the EPACT approach than with DOE's current priorities.

Conclusions

1. The current DOE program is appropriate and responsive to EPACT sections related to coal-based electric power generation.
2. EPACT places significant emphasis on programs related to the expansion of coal use for manufacture of liquid and gaseous fuels and specialty products.
3. The DOE program covering uses of coal beyond power generation has decreased in recent years.
4. The need for a national clearinghouse to exchange and disseminate data on coal technologies has not yet been established.

Recommendations[15]

1. There should be increased DOE support of fundamental and applied research aimed at longer-term uses of coal (2006–2040) to balance decreased industry research, guarantee the maintenance of U.S. technological expertise in this area, and position the United States to respond to future energy needs.
2. *Within the DOE coal program there should be an increasing emphasis on the production of clean fuels and other carbon-based products over time.
3. No further action should be taken to establish a national clearinghouse until a need has been established based on a market survey of potential users.

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[15]Asterisks (*) identify the most important recommendations.

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Table 10-1 Advanced Coal-Based Power Systems Supported by DOE

Technology (target year for commercial design)	Design Efficiency (percent)	Coal Conversion Components	Power Generation Components	Particulate Control System	SO_2 Control System	NO_x Control System
New pulverized coal (commercial baseline)	38-42	Supercritical boiler	3,500 to 4,500 psi steam turbine	ESP or fabric filter	Wet lime or limestone FGD	Low NO_x burners + SCR
GROUP 1 SYSTEMS						
LEBS (2000)	42	Supercritical boiler	4,500 psi steam turbine	Advanced flue gas cleanup + combustion controls[a]		
PFBC-1 (2003)	~40	Bubbling and circulating bed PFBC units	1,800 psi steam turbine + gas turbine	Cyclones + fabric filter	In-bed limestone or dolomite	Combustion controls
IGCC-1 (1997)	~40	O_2-blown entrained-bed gasifiers	2350°F gas turbine +HRSG/turbine	Cold gas quenching	Cold gas H_2S absorption	Cold gas cleanup + steam injection
GROUP 2 SYSTEMS						
EFCC (1997)	45	Slagging combustor + 2300°F heat exchanger	2350°F gas turbine + HRSG/turbine	Fabric filter	Wet FGD	Combustion controls (+ SCR if needed)
PFBC-2 (2005)	45	Circulating PFBC + coal pyrolyzer	2350°F gas turbine + 2,400 psi steam turbine	Hot gas filtration	In-bed limestone or dolomite	Combustion controls (+ SCR if needed)
IGCC-2 (2002)	45	Oxygen- or air-blown fluidized-bed gasifier	2350°F or 2500+°F gas turbine + HRSG/turbine	Hot gas filtration	Hot gas desulfurization + in-bed limestone (optional)	Combustion controls (+ SCR if needed)

Technology (target year for commercial design)	Design Efficiency (percent)	Coal Conversion Components	Power Generation Components	Particulate Control System	SO_2 Control System	NO_x Control System
<u>GROUP 3 SYSTEMS</u>						
HIPPS (2003)	50	High-temperature advanced furnace	2500 °F gas turbine + HRSG/turbine (+ auxiliary fuel if needed)	Advanced flue gas cleanup system + in-furnace controls[a]		
Improved PFBC-2 (2010)	≥50	Circulating PFBC + coal pyrolyzer	2600 °F turbine + 4,500 psi steam turbine	Hot gas filtration	In-bed limestone or dolomite	Combustion controls (+ SCR if needed)
IGAC (2010)	≥50	Oxygen- or air-blown fluidized-bed gasifier	2600 °F gas turbine (humidified)	Hot gas filtration	Hot gas desulfurization + in-bed limestone (optional)	Combustion controls (+ SCR if needed)
IGFC (2010)	≥60	Oxygen- or air-blown fluidized-bed gasifier	Molten carbonate fuel cell (1200 °F) +HRSG/turbine	Hot gas filtration	Hot gas desulfurization + in-bed limestone (optional)	Combustion controls (+ SCR if needed)

HRSG, heat recovery steam generator.
ESP, electrostatic precipitator.
FGD, flue gas desulfurization.
SCR, selective catalytic reduction.
[a]Final system not yet selected.

Table 10-2 Strategic Objectives of the DOE Advanced Power Systems Program

Objective	Period 2000	2005	2010	2015
Efficiency (percent)	42	47	55	60
Emissions (NSPS)[a]	1/3	1/4	1/10	1/10
Cost of energy	10-20 percent lower than currently available pulverized coal technology			

[a]NSPS, New Source Performance Standards. Current federal standards apply to emissions of sulfur dioxide, oxides of nitrogen, and particulates from coal-based steam generators.
Source: DOE (1993a).

Table 10-3 Potential CO_2 Reductions for Advanced Power Systems Relative to Current Coal-Fired Power Plants (percent)[a,b]

Basis for Comparison; Efficiency	Period 2000	2005	2010	2015
Average U.S. plant; 33%	21	30	40	45
New U.S. plants; 38%	10	19	31	37
New plants worldwide; 42%	0	11	24	30

[a]The numbers in this table show the percent reduction in CO_2 from replacing an existing power plant of the indicated efficiency with a more efficient advanced plant that meets the DOE goals in Table 10-2. See Table 10-2 for assumed efficiency improvements for advanced coal technology in each time period.
[b]A widely used computer model developed by DOE's Battelle Pacific Northwest Laboratories was run to estimate the long-term impacts of meeting DOE's cost and efficiency objectives. The model estimated an overall reduction of about 19 percent in coal use and CO_2 emissions from power generation in the year 2050 from introducing DOE's more advanced and lower-cost power systems in the United States, relative to a base case with a much smaller rate of efficiency improvement. These results, of course, depend on a host of other model assumptions and projections besides meeting DOE technology goals. The results are presented simply to indicate that a 30 to 40 percent reduction in CO_2 emissions from new plants does not translate into a comparable reduction in overall CO_2 emissions even after 35 years.

Table 10-4 EPACT Requirements and DOE Coal Program Compared[a]

EPACT Requirements	Key Features of DOE Program Activities	Committee Rating and Comments
TITLE XIII—COAL Subtitle A—Research, Development, Demonstration, and Commercial Application		
<u>Section 1301: Coal Research, Development, Demonstration, and Commercial Application Programs</u>		
•Conduct RDD&C programs on coal-based technologies to: - ensure reliable electricity supply - comply with environmental regulations - control emissions - achieve cost-competitive conversion of coal to transportation fuels - demonstrate conversion of coal to synthetic fuels - ensure timely commercial application of coal technologies with improved efficiency and emissions control - ensure availability of technologies for commercial use by 2010	•Advanced clean/efficient power systems: - advanced pulverized coal-fired power plant, including low-emission boiler systems - indirect-fired cycle - integrated gasification combined-cycle - pressurized fluidized-bed - advanced research and environmental technology (AR&ET), including hot gas and flue gas cleanup - magnetohydrodynamics (MHD)	*High priority for DOE—adequate level of effort* (see text for discussion and priorities) See below, also under Section 1301, Advanced Research, for comments on AR&ET. See Section 1311 for comments on MHD program.

[a]This summary of DOE program activities is based on planning documents provided by DOE's Office of Fossil Energy, the DOE FY 1994 budget, the FY 1995 congressional budget request, and presentations to the committee by DOE staff (see Appendix F).

Table 10-4 EPACT Requirements and DOE Coal Program Compared (Continued)

EPACT Requirements	Key Features of DOE Program Activities	Committee Rating and Comments
	•Advanced clean fuels (see also Section 1312): - direct liquefaction - indirect liquefaction - coal preparation - AR&ET	*High priority for DOE—additional effort recommended* •Focused program on high-efficiency gasification needed •Increased emphasis on liquefaction recommended (see Section 1312) •Continue current limited effort in coal preparation.
	•Advanced research (Advanced Research and Technology Demonstration, plus specific technologies for fuels and power systems), with major activities including: - coal utilization science - materials and components - university/national laboratory coal research - coal liquefaction	*High priority for DOE—additional effort recommended* •The balance between short- and long-term activities within the FE coal R&D program should be reassessed, based on strategic planning extending beyond 2010. (See text for discussion.)
	•Clean Coal Technology (CCT) demonstration projects	*High priority for DOE—adequate level of effort* •Commercial acceptance of clean coal technologies may not occur in the proposed period without further cost sharing of technical and financial risk.

EPACT Requirements	Key Features of DOE Program Activities	Committee Rating and Comments
Section 1302: Coal-Fired Diesel Engines		
•Conduct RDD&C program for utilization of coal-derived liquid or gaseous fuels, including ultra-clean CWSs (coal-water slurries) in diesel engines.	•See Section 1301 for gaseous and liquid fuels. •Coal-fired diesel program (Direct Coal-Fired Heat Engines activity) was completed in FY 1993. •Coal-fired diesel engine to be demonstrated in CCT-V.	*Low priority for DOE—inactive* •Coal-derived liquids and gaseous fuels do not differ significantly from conventional diesel fuels; no separate DOE-funded study required. •DOE program on coal-fired diesels has been carried through to an appropriate level; no justification for further activity because of unfavorable economics and potentially insurmountable environmental issues.
Section 1303: Clean Coal, Waste-to-Energy		
•Conduct RDD&C program for use of solid waste combined with coal as fuel source for clean coal combustion technologies: - tires and coal in fluidized-bed combustion units - combined gasification of coal and municipal sludge using IGCC - fuel pellets - waste methane	•Under DOE contract, Riley Research conducted tests in circulating atmospheric fluidized bed on cofiring of coal with de-inking paper sludge and high-Btu ash. •DOE sponsored pilot-scale work on cofiring of coal and infectious hospital waste; subsequent demonstration in Lebanon, Pennsylvania, will involve 50 percent DOE cost share. •DOE has assessed technical and economic feasibility of direct liquefaction of coal with hydrocarbon- or paper-based wastes to produce premium transportation fuels; follow-up program proposed.	*Adequate level of DOE effort* •Gasification system approach best addressed by private sector •Minimal DOE participation required for hospital waste program. No major R&D issues to be addressed; requires additional stack cleanup. Waste methane—see Section 1306

Table 10-4 EPACT Requirements and DOE Coal Program Compared (Continued)

EPACT Requirements	Key Features of DOE Program Activities	Committee Rating and Comments
<u>Section 1304: Nonfuel Use of Coal</u>[b]		
•Plan and carry out RDD&C program for nonfuel use of coal, including: - production of coke and other carbon-based products, chemicals, and chemical feedstocks from coal - chemicals from synthesis gas - utilization of wastes from coal (see Section 1308) •Above program should include assessment of economic feasibility of coproduction, refining, and utilization of coal-based products (see Section 1305)	•Syngas production activity supports concept development for coproduction of coal-derived fuels and chemicals in conjunction with electric power (see Section 1312, indirect liquefaction).	•See Section 1312
	•Mild gasification/coal refinery activities address production of coke and chemical intermediates (see also Sections 1305 and 1312).	*Low priority for DOE* •Decreasing market for coke •CCT program on mild gasification adequate (see Section 1305)
	•DOE supporting Carbon Products Consortium in development of coal-based alternative feedstocks and establishment of links with industry. No further funding requested for FY 1995.	*Low priority for DOE*
<u>Section 1305: Coal Refinery Program</u>		
•Conduct RDD&C program for coal refining technologies for high-sulfur coals, low-sulfur coals, subbituminous coals, and lignites to produce transportation fuels, compliance boiler fuels, fuel additives, lubricants, and chemical feedstocks, alone or with power generation.	•Coal refinery activity included under advanced clean fuels research (Section 1312) addresses coproduction of electricity and coal liquids.	*High priority for DOE* •Worthwhile concept; systems assessments have indicated promising areas, especially coproduction of syngas liquids with electricity. •Further assessments needed to identify and exploit opportunities.
	•Mild gasification is part of ongoing CCT program.	*Low priority for DOE* •Adequately covered by CCT program.

[b]The committee notes that DOE programs responding to Section 1304 include fuel and nonfuel uses of coal.

Table 10-4 EPACT Requirements and DOE Coal Program Compared (Continued)

EPACT Requirements	Key Features of DOE Program Activities	Committee Rating and Comments
<u>Section 1306: Coalbed Methane Recovery</u>		
•Conduct a study of barriers and environmental safety aspects. •Disseminate information to public on state-of-the-art technologies. •Conduct coalbed methane demonstration and commercial application program	•Previous DOE program ended in 1993. •Clinton administration's Climate Change Action Plan (CCAP) establishes new initiatives to reduce methane emissions from all major sources, including coal mines (Clinton and Gore, 1993). •DOE FY 1994 budget request for $300K for coalbed methane activities was not approved; FY 1995 budget request covers coalbed methane recovery under natural gas program. •CCAP requires DOE and EPA to create Coalbed Methane Outreach program—currently no activity due to lack of funding. •CCAP requires expansion of DOE RD&D programs for methane recovery from coal mining; interaction with stakeholders initiated in 1993 continues.	<u>Low methane concentration (<1.0%)</u> *Moderate priority for DOE* •There are possible low-level R&D activities investigating separation and combustion processes for dilute methane. <u>Higher methane concentrations</u> *Low priority for DOE* •Existing commercial technology adequate but in limited use.
<u>Section 1307: Metallurgical Coal Development</u>		
•Establish RDD&C program for use of metallurgical coal as: - a boiler fuel - an ingredient in steel manufacture - source of coalbed methane	•DOE not currently conducting any research specific to metallurgical coal development. •Information on gas content in 16 U.S. coal basins available in METC database. •Commercial technology exists to burn metallurgical coal as boiler fuel or use in steelmaking.	*Low priority for DOE—inactive* •No new technology needed to burn as boiler fuel. •Activities relating to metallurgical coal as a source of coalbed methane should be included in Section 1306 programs.

Table 10-4 EPACT Requirements and DOE Coal Program Compared (Continued)

EPACT Requirements	Key Features of DOE Program Activities	Committee Rating and Comments
Section 1308: Utilization of Coal Wastes		
•Establish RDD&C program for utilization of coal wastes from mining and processing, including as a boiler fuel.	•AR&ET program on waste management includes examination of technical and economic aspects of waste utilization technology	*Low priority for DOE—inactive* •Technology is commercial—possible limited DOE role in economic and technical assessment. •Application of past DOE work on fluidized-bed combustion now being handled by industry.
Section 1309: Underground Coal Gasification		
•Conduct RDD&C program for in situ conversion of coal to an easily transportable gaseous fuel.	•DOE program ended in FY 1991. Sufficient technical, operational, and environmental parameters developed to allow industry to make necessary decisions regarding commercialization.	*Low priority for DOE—inactive* •In agreement with current DOE assessment that underground gasification will not result in a competitive gaseous fuel.
Section 1310: Low-Rank Coal Research and Development		
•Pursue R&D program to expand use of low-rank coals in high-value-added carbon products, fuel cells, coal-water fuels, distillates, and other niche market applications.	•Research effort on low-rank coals sponsored by DOE at University of North Dakota Energy and Environmental Research Center (UNDEERC). •Consortium being formed under UNDEERC leadership to demonstrate production of low-rank coal water fuels from Alaskan coals.	*No special effort required aimed at low-rank coals* •Low-rank coals are included in general coal utilization program (Section 1301) and represent one end of a continuum of materials.

EPACT Requirements	Key Features of DOE Program Activities	Committee Rating and Comments
Section 1311: Magnetohydrodynamics (MHD)		
•Carry out RDD&C program to determine adequacy of engineering and design information completed to date under DOE sponsorship. •Issue solicitations to fulfill above objective.	•Conducting proof-of-concept program closeout •No solicitations issued	*Documentation and cleanup activities—high priority for DOE* •Need for thorough documentation of past work: current plans for this activity insufficient. *MHD system development—low priority for DOE* •MHD does not appear to offer significant advantages over other advanced high-efficiency systems. •Next step in development involves very expensive demonstration program, since technical risk cannot be broken down.
Section 1312: Oil Substitution Through Coal Liquefaction[c]		
•Conduct RDD&C program to develop economically and environmentally acceptable advanced technologies for oil substitution through coal liquefaction. Program goals are to include: - improved resource selection and product quality - increased net yield - increased overall thermal efficiency - reduced capital and operating costs	•Direct liquefaction, including advanced liquefaction processes, coprocessing with waste materials, and innovative process concepts	*High priority for DOE* •DOE should maintain an active program since industry activity in this area is declining. •Innovative approaches should be encouraged. •Large pilot and demonstration plants not required at this time.

[c]See also committee ratings and comments on advanced clean fuels research under Section 1301.

Table 10-4 EPACT Requirements and DOE Coal Program Compared (Continued)

EPACT Requirements	Key Features of DOE Program Activities	Committee Rating and Comments
	•Indirect liquefaction, including Fischer-Tropsch chemistry, catalyst development, reactor design, oxygenate catalyst research, syngas, and low-cost hydrogen production	*High priority for DOE* •Opportunities for coproduction with electricity (see Section 1305). •Need coordination with active industry programs for natural gas conversion; DOE should focus on applying this technology to coal.
	•Mild gasification/coal refinery activity, including systems for coproducts (overlap with Section 1305)	•See Section 1305
TITLE XIII—COAL Subtitle B—Clean Coal Technology Program		
Section 1321: Additional Clean Coal Technology Solicitations		
•Conduct additional solicitations for development of cost-effective, higher-efficiency, low-emission coal utilization technologies, with emphasis on need for commercialization by 2010.	•In response to request from Secretary for Energy, the National Coal Council prepared a report (NCC, 1994) addressing future directions for the CCT program. •DOE report, *Clean Coal Technology—Completing the Mission*, released 05/06/94 (DOE, 1994c). •No additional solicitations issued beyond CCT-V. •Proposed diversion of CCT funds to overseas demonstration projects.	*High priority for DOE—future action requires consideration* (see text for discussion) •Emphasis should be on deployment of technologies developed and demonstrated in earlier rounds. •Commercial acceptance of CCT technologies may require further cost sharing of technical and financial risk.

Table 10-4 EPACT Requirements and DOE Coal Program Compared (Continued)

EPACT Requirements	Key Features of DOE Program Activities	Committee Rating and Comments
TITLE XIII—COAL Subtitle C—Other Coal Provisions		
Section 1332: Innovative Clean Coal Technology Transfer Program		
•Develop joint DOE/Agency for International Development clean coal technology transfer program to encourage exports of U.S. technologies that allow more efficient, cost-effective, and environmentally acceptable use of coal resources.	•Solicitations for China and Eastern Europe "showcase" projects to be outlined in FY 1994. •Public meeting on Clean Coal International Technology Transfer Program held February 1994. •NCC report (see Section 1321) includes advice on conducting international technology transfer effort.	*Low priority for DOE compared to domestic program* •Current funds probably insufficient to meet requirements of Sections 1321 and 1332. •Priority should be given to Section 1321 requirements emphasizing CCT deployment in domestic market.
Section 1336: Coal Fuel Mixtures		
•Prepare a report on technical and economic feasibility, development status, market potential, and commercialization barriers to combining coal with other materials, such as oil and water fuel mixtures.	•Coal preparation program (Advanced Clean Fuels Research) includes superclean coal water slurry (SCCWS) project (formerly part of Alternative Fuels Program).	*Low priority for DOE—previous assessments adequate* •Technologies for this very specialized market have been effectively commercialized and utilized.
Section 1337: National Clearinghouse		
•Assess feasibility of establishing national clearinghouse for exchange and dissemination of information on technology relating to coal and coal-derived fuels.	•No current DOE activities; DOE is awaiting recommendations from National Research Council.	•Need for national clearinghouse should be established by market survey of potential users. •Any activity should involve participants from inside and outside DOE. •External committee should assess feasibility of concept and make recommendations for implementation.

Table 10-4 EPACT Requirements and DOE Coal Program Compared (Continued)

EPACT Requirements	Key Features of DOE Program Activities	Committee Rating and Comments
TITLE XX—GENERAL PROVISIONS; REDUCTION OF OIL VULNERABILITY Subtitle A—Oil and Gas Supply Enhancement		
Section 2013: Natural Gas Supply		
•Conduct five-year program to increase recoverable natural gas resource base by more intensive recovery from discovered conventional resources; extraction from unconventional sources; surface gasification of coal; and recovery of methane from biofuels.	•METC Surface Coal Gasification Program involves R&D on new concepts development and refinement of existing systems.	*Methanation aspect of SNG production—low priority for DOE* *Gasification—high priority for DOE* (see Section 1301)
Conduct five-year program on cofiring of natural gas with coal in utility and large industrial boilers.	•Cofiring of natural gas with coal addressed in CCT program.	*Low priority for DOE—appropriate level of effort* •Established technology for pulverized coal •CCT program activity adequate.

Appendix A

Project Description
Strategic Assessment of DOE's Coal Program

For Public Release
August 18, 1993

NATIONAL ACADEMY OF SCIENCES-NATIONAL RESEARCH COUNCIL
COMMISSION ON ENGINEERING AND TECHNICAL SYSTEMS
ENERGY ENGINEERING BOARD

STRATEGIC ASSESSMENT OF
THE DEPARTMENT OF ENERGY'S COAL PROGRAM

INTRODUCTION:

The Energy Policy Act of 1992 (EPACT) gives certain responsibilities to the Secretary of Energy pertaining to DOE's coal program. EPACT further requires the Secretary to submit reports to the Congress on the program, including a plan for Research, Development, Demonstration, and Commercial Application (RDD&C) to meet the objectives defined in Title XIII, Section 1301. Other sections in Subtitle A identify specific technologies or areas that the U.S. Department of Energy should address under this RDD&C program. In addition to Subtitle A, Subtitles B and C in Title XIII and Subtitle A in Title XX, also identify other coal-related activities in the areas outlined below for implementation by the DOE.

TITLE XIII COAL

Subtitle A: Research, Development, Demonstration, and Commercial Application:

- -- Section 1301: RDD&C Program on Coal Conversion and Utilization Technologies;
- -- Section 1302: Coal-fired Diesel Engines;
- -- Section 1303: Clean Coal, Waste-to Energy;
- -- Section 1304: Nonfuel Use of Coal;

- -- Section 1305: Coal Refinery Program;
- -- Section 1306: Coalbed Methane Recovery
- -- Section 1307: Metallurgical Coal Development;
- -- Section 1308: Utilization of Coal Wastes;
- -- Section 1309: Underground Coal Gasification;
- -- Section 1310: Low Rank Coal Research and Development;
- -- Section 1311: Magnetohydrodynamics;
- -- Section 1312: Oil Substitution Through Coal Liquefaction.

Subtitle B (Clean Coal Technology Program):

- -- Section 1321: Additional Clean Coal Technology Solicitations

Subtitle C: Other Coal Provisions:

- -- Section 1332: Innovative Clean Coal Technology Transfer Program;
- -- Section 1336: Coal Fuel Mixtures;
- -- Section 1337: National Clearinghouse.

TITLE XX GENERAL PROVISIONS; REDUCTION OF OIL VULNERABILITY

Subtitle A: Oil and Gas Supply Enhancement:

- -- Section 2013: Natural Gas Supply
  - -- Subsections dealing with surface gasification of coal, and cofiring of natural gas and coal.

Section 1301 requires that the Secretary of Energy submit a report to the Congress to achieve the objectives defined in this section, including "ensuring reliable electricity supply, complying with applicable environmental requirements, achieving cost-competitive production and demonstration of liquid and gaseous fuels from coal, and ensuring the timely commercial application of cost-effective coal technologies." In particular, subparagraphs c(1) to c(5) of Section 1301 call for this report to include the following information:

- -- Subparagraph c(1): A detailed description of ongoing RDD&C activities regarding coal-based technologies undertaken by DOE, other Federal or State government departments or agencies and, to the extent such information is publicly available, other public or private organizations in the United States and other countries.
- -- Subparagraph c(2): A listing and analysis of current Federal and State government regulatory and financial incentives that could further the goals of the programs established under Subtitle A.
- -- Subparagraph c(3): Recommendations regarding the manner in which any ongoing coal-based demonstration and commercial application program might be modified and extended to ensure the timely demonstrations of advanced coal-based technologies.
- -- Subparagraph c(4): Recommendations, if any, regarding the manner in which the cost sharing demonstrations conducted pursuant to the Clean Coal Program established by

Public Law 98-473 might be modified and extended in order to ensure the timely demonstration of advanced coal-based technologies.

-- Subparagraph c(5): A detailed plan for conducting the research, development, demonstration, and commercial application programs to achieve the goals and objectives defined in Section 1301.

The DOE has been conducting coal RD&D programs for many years. These programs have addressed, or are addressing, some of the areas identified in EPACT. The Office of Fossil Energy's coal programs are described in the document entitled "Coal Strategic Plan" and in the Administration's budget request for fiscal year (FY) 1994. Beginning in FY 1994, the Office of Fossil Energy will begin to update its "Coal Strategic Plan," and formulate the RDD&C plan required by Section 1301. As part of this process, the Office of Fossil Energy is seeking the advice and recommendations of the National Research Council regarding strategy and priorities in its coal program.

PROPOSED ACTIVITY:

The Energy Engineering Board (EEB) will establish a committee to review DOE's current coal program, and selected sections of EPACT relating to coal, and develop recommendations to update the "Coal Strategic Plan." The committee will include about 10 members from disciplines pertinent to the proposed effort. Expertise will be sought in areas such as coal science, conversion of coal to gaseous and liquid fuels, especially coal gasification, coal-based electricity generation, chemical engineering, energy engineering, environmental control technologies, energy economics, and strategic planning for R&D. The committee will provide independent scientific and technical advice consistent with the strategic assessment requested by the DOE targeted at the planning cycle beginning with FY 1996. In the process of nominating the committee and during the course of the study, as appropriate, the EEB will consult with other NRC units including the Board on Earth Sciences and Resources and the Board on Chemical Sciences and Technology. The committee will be subject to the usual NRC bias and conflict of interest procedures.

The committee will:

- Review the DOE coal program including the current version of the "Coal Strategic Plan" and additional details contained in the Administration's budget requests for FY 1994 and 1995, as appropriate.
- Review the sections identified above in EPACT, especially Section 1301, and the status of the DOE coal program vis-a-vis the provisions in the EPACT and coal related R&D in organizations outside DOE.
- Recommend objectives (including performance and schedule) that ought to be emphasized for those areas in EPACT that are not in the current DOE coal program.

- Make recommendations pertaining to Section 1301 (c), especially subparagraphs c(3), c(4), and c(5):
  - -- As part of this task, DOE's Office of Fossil Energy will provide the committee early in the study with the Office's own, strategically focused descriptions of its ongoing research, development, demonstration, and commercial application activities, and the listing and analysis of current government regulatory and financial incentives described in subparagraphs c(1) and c(2), respectively. The Office will also provide for the committee's consideration its evaluations of requirements in several areas related to EPACT provisions (e.g., nonfuel uses of coal, coal refining).
- Identify priorities for DOE's future coal program areas based on the foregoing reviews and recommendations and the assumption that the outyear budgets (to be appropriated) for the DOE coal program remain at the FY 1994 level (in real terms).
- Prepare a report that would include, in broad strategic terms, the emphasis and priorities that DOE ought to consider in updating its "Coal Strategic Plan" and responding to the EPACT.

The committee will have an initial orientation and planning meeting to set the terms of reference for the study. The Office of Fossil Energy will brief the committee on its expectations of the study, on its Coal Strategic Plan, coal-related provision in EPACT, the current DOE coal program, and preliminary strategies and plans for new initiatives.

The committee will invite a number of outside experts to brief it at its second meeting. The objective of this meeting will be to solicit information and opinion from a variety of sources in industry, universities, national laboratories and, as appropriate, other public and private sector organizations that have an interest in the DOE coal program. The meeting will be directed at a critical assessment of the current DOE coal program and areas in EPACT identified above for which the DOE is seeking programmatic objectives and priorities.

The committee will hold additional deliberative meetings to formulate its conclusions and recommendations and prepare its report.

It is anticipated that the study will begin about August 1, 1993, and the committee's report would be available by July 31, 1994.

ANTICIPATED RESULTS:

The study will result in a final report to the Department of Energy responsive to the charge outlined in this proposal. The committee's report will be subject to NRC review procedures and be made available to the public without restrictions. The report will be prepared in sufficient quantity to ensure adequate distribution.