Review of DOE's Vision 21 Research and Development Program

PHASE I

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

REVIEW OF DOE'S VISION 21 RESEARCH AND DEVELOPMENT PROGRAM—PHASE I

Committee to Review DOE's Vision 21 R&D Program—Phase I

Board on Energy and Environmental Systems
Division on Engineering and Physical Sciences

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OF THE NATIONAL ACADEMIES

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The committee expresses its thanks to the following individuals: Donald Bonk, NETL; Anthony V. Cugini, National Energy Technology Laboratory (NETL); Thomas J. Feeley, NETL; E.P. Ted Foster, Air Products and Chemicals, Inc.; Stephen Gehl, Electric Power Research Institute; Hossein Ghezel, FuelCell Energy; Larry Grimes, National Coal Council; Robert Horton, ChevronTexaco Worldwide Power & Gasification, Inc.; Abbie W. Layne, NETL; John L. Marion, Alstom Power, Inc.; John McDaniel, Tampa Electric Company; Robert R. Romanosky, NETL; John A. Ruether, NETL; Randall E. Rush, Southern Company Services, Inc.; Lawrence A. Ruth, NETL; Gary Stiegel, NETL; Mark C. Williams, NETL; and John C. Winslow, NETL. (See Appendix B for a list of their presentations.) The committee wishes to especially thank Larry Ruth and Carl Bauer, National Energy Technology Laboratory, for their presentations and discussions with the committee and their diligence in responding to the many requests for information by the committee.

Finally, the chairman wishes to recognize the committee members and the staff of the Board on Energy and Environmental Systems of the NRC for their hard work in organizing and planning committee meetings and their individual efforts in gathering information and writing sections of the report.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Richard Balzhiser, NAE,
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Neville Holt, Electric Power Research Institute,
John B. O'Sullivan, consultant,
Jack Siegel, Energy Resources International,
Dale R. Simbeck, SFA Pacific, Inc., and
Douglas Todd, Process Power Plants, LLC.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by David Morrison, U.S. Nuclear Regulatory Commission (retired). Appointed by the National Research Council, he was responsible for making sure that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

James J. Markowsky, *Chair*
Committee to Review DOE's Vision 21
R&D Program—Phase I

Contents

Executive Summary

The Vision 21 Program is a relatively new research and development (R&D) program. It is funded through the U.S. Department of Energy's (DOE's) Office of Fossil Energy and its National Energy Technology Laboratory (NETL). The *Vision 21 Program Plan* anticipates that Vision 21 facilities will be able to convert fossil fuels (e.g., coal, natural gas, and petroleum coke) into electricity, process heat, fuels, and/or chemicals cost effectively, with very high efficiency and very low emissions, including of the greenhouse gas carbon dioxide (CO_2) (DOE, 1999a). Planning for the program began to take shape in 1998 and 1999. Since then, workshops have been held, proposals for projects have been funded, and roadmaps have been developed for each of the key technologies considered to be part of the Vision 21 effort. Vision 21 is focused on the development of advanced technologies that would be ready for deployment in 2015.

Vision 21 as it currently stands is not per se a line item in the Office of Fossil Energy budget but, rather, a collection of projects that contribute to the technologies required for Vision 21 energy plants. Vision 21 management estimates that about \$50 million was expended in fiscal year (FY) 2002 on Vision 21 projects and activities. These projects have come about not only as a result of a Vision 21 solicitation by DOE/NETL but also as an outgrowth of ongoing R&D activities in the traditional Office of Fossil Energy coal and power systems program. Ongoing activities that are oriented to achieving revolutionary rather than evolutionary improvements in performance and cost and that share common objectives with Vision 21 are considered to be part of the Vision 21 Program and activities. Thus, Vision 21 activities must be coordinated across a suite of activities in DOE and NETL programs contained in the Office of Fossil Energy's R&D programs on coal and power systems. This coordination is partially achieved through a matrix management structure at NETL, and the responsibility for managing Vision 21 is vested in a small steering committee.

The goals of Vision 21 are extremely challenging and ambitious. As noted in the *Vision 21 Technology Roadmap*, if the program meets its goals, Vision 21 plants would essentially eliminate many of the environmental concerns traditionally associated with the conversion of fossil fuels into electricity and transportation fuels or chemicals (NETL, 2001). Given the importance of fossil fuels, and especially coal, to the economies of the United States and other countries and the need to utilize fossil fuels in an efficient and environmentally acceptable manner, the development of the technologies in the Vision 21 Program is a high priority.

This report contains the results of the second National Research Council (NRC) review of the Vision 21 R&D Program. The first review of the program was conducted by the NRC Committee on R&D Opportunities for Advanced Fossil-fueled Energy Complexes. It resulted in the report *Vision 21, Fossil Fuel Options for the Future*, which was published in the spring of 2000 (NRC, 2000). At that time, the Vision 21 Program was in an embryonic stage, having been initiated by DOE in 1998-1999. The NRC report contained a number of recommendations for DOE to consider as it moved forward with its program; DOE's responses to many of these recommendations are considered in Chapter 3. Now, 2 years after the first review, DOE's Deputy Assistant Secretary for Coal and Power Systems requested that the NRC again review progress and activities in the Vision 21 Program. In response, the NRC formed the Committee to Review DOE's Vision 21 R&D Program—Phase I. Most of the members of this committee also served on the committee that wrote the earlier report (see Appendix A for committee biographical information).

The present report is organized into three chapters. Chapter 1 introduces the Vision 21 Program and presents background information. Chapter 2 presents strategic recommendations for the program as a whole. Chapter 3 focuses on the individual technologies. This Executive Summary brings forward from Chapter 2 three major issues that the committee believes are of the highest priority from a programwide strategic standpoint—namely, what the focus of the program should be, how it should be empowered to accomplish its goals, and what analytic capabilities it should have to evaluate technological approaches for reaching its goals. At the same time, it reiterates the five most important of the nine recommendations in that chapter. Also, based on the premise that some of the technologies in Chapter 3 are more essential than others to realizing Vision 21 goals, the committee selected five high-priority recommendations from that chapter and reiterates them here in the Executive Summary.

STRATEGIC ASSESSMENT

The *Vision 21 Technology Roadmap* was the outcome of a workshop in August 2000 that attempted to identify barriers to the successful development of each of the technologies under investigation in Vision 21 and to create a strategy for overcoming them (NETL, 2001). Vision 21 envisions the development of technology modules selected and configured to produce the desired power, process heat, or fuel and chemical products from the feedstocks, which would include fossil fuels and, when appropriate, opportunity feedstocks (e.g., biomass, municipal waste). These technology modules will be based on the advanced technologies under development in the program, which are identified in the technology roadmap as (1) gasification, (2) gas purification, (3) gas separation, (4) fuel cells, (5) turbines, (6) environmental control, (7) sensors and controls, (8) materials, (9) computational modeling and virtual simulation, (10) systems analysis and systems integration, (11) synthesis gas conversion to fuels and chemicals, and (12) combustion and high-temperature heat exchange.

The *Vision 21 Program Plan* anticipates a variety of possible energy plant configurations processing a variety of fossil and waste fuels and producing a varied slate of products to meet specific market needs. In most cases, the primary or only product will be electricity, but other products such as transportation fuels, chemicals, synthesis gas (syngas), hydrogen, and steam might also be produced depending on location and market factors. The use of fossil fuels as a possible pathway to producing hydrogen is also in keeping with the growing interest of DOE in supporting the development of technologies for hydrogen production and use. Vision 21 energy plants will have challenging performance targets for efficiency of fuel-to-electricity generation, conversion of feedstocks to fuels, environmental emissions, and cost (see Chapter 1).[1] The targets for emissions include a 40 to 50 percent reduction in CO_2 emissions by efficiency improvement and essentially a 100 percent reduction if the CO_2 is separated and sequestered, preventing its release to the atmosphere.

Vision 21 Program Focus

Vision 21 was originally conceived as, and to a large extent remains, a very broad and inclusive program. It addresses all fossil fuels, as well as opportunity feedstocks, the conversion of these resources into secondary fuels as well as electricity, the use of both steam and gas cycles, a wide range of scales, and plants designed with and without sequestration-ready greenhouse gases. Given the ambitious and challenging goals, targets, and time scales of the Vision 21 Program and the financial resources available, the committee believes the program's

[1]For example, fuel-to-electricity conversion efficiency of 60 percent for coal-based systems (based on the higher heating value of the fuel) and 75 percent for natural-gas-based systems (based on the lower heating value (LHV)). For a fuels-only plant producing hydrogen or liquid transportation fuel, 75 percent feedstock utilization efficiency (LHV) is the target.

chances of success will be improved and the program will be strengthened if it becomes more sharply focused.

Recommendation. The Vision 21 Program should continue to sharpen its focus. It should focus on the development of cost-competitive, coal-fueled systems for electricity production on a large scale (200-500 MW) using gasification-based technologies that produce sequestration-ready carbon dioxide and near-zero emissions of conventional pollutants.

Program Management and Budget

Currently, responsibility for managing Vision 21 on a day-to-day basis is vested in a small steering committee (called the Vision 21 team) drawn from DOE and NETL staff and headed by the Vision 21 program manager. The program manager interacts informally with the NETL program and project managers who control the funding and have oversight responsibility for individual Vision 21 projects. The current management structure thus relies on a process of cooperation and consensus. Because the ultimate responsibility for ensuring the effectiveness of Vision 21 lies with the senior management of DOE/NETL, the Vision 21 Program lacks the level of control and accountability at the program level seen in successful R&D programs. The committee considers that the present management structure is weak and that a more rigorous, integrated program management structure is needed to accomplish the ambitious goals of the Vision 21 Program, with leadership by a program manager who has overall authority and responsibility for meeting the goals of the program.

Recommendation. A more rigorous management structure is needed to accomplish the ambitious goals of the Vision 21 Program. The Vision 21 program manager should be provided with the budget and overall responsibility and authority needed to manage the program, including appropriate staff responsible for program planning, implementation, and evaluation.

Currently, the Vision 21 Program does not have an identifiable budget of its own. DOE/NETL estimates that roughly $50 million of the current (FY 2002) funding is devoted to Vision 21 activities, approximately one fourth of the Office of Fossil Energy's R&D budget. Vision 21 management projects that to achieve current Vision 21 goals would require that the Vision 21 budget grow by roughly an order of magnitude over the next 5 years. The committee agrees that there is the potential for large imbalances between future program requirements and future funding levels. The committee also believes that the current Vision 21 goals will not be reached if the Vision 21 Program continues to be supported at the present level of funding. Its goals would have to be modified and its projects prioritized. Rigorous assessment requires the formulation of several alternative schedules for achieving Vision 21 Program goals matched to alternative budget scenarios. This should lead to a convincing argument for the appropriate size of the program.

Recommendation. The U.S. Department of Energy (DOE) and the National Energy Technology Laboratory (NETL) should estimate the budget required to support the current Vision 21 Program goals and should reconcile these estimates with various funding scenarios. DOE/NETL should also estimate and articulate the benefit (or cost) to the United States of achieving (or failing to achieve) Vision 21 goals.

Analytical Capabilities

More than any previous program within DOE's Office of Fossil Energy, Vision 21 requires a strong component of systems integration and analysis to set goals and priorities. For Vision 21 to lead to systems that can compete in the marketplace, the advanced technologies being developed within NETL's current program structure (e.g., gasifiers, turbines, fuel cells) must be successfully integrated at a commercial scale. Many integration issues—for example, the integration of fuel cells with gas turbines—remain unresolved.

Currently, systems analysis and integration activities are handled piecemeal, mainly by external organizations performing independently as DOE contractors. The DOE Vision 21 team appears not to have sufficient internal engineering capabilities to model, analyze, and evaluate the potential of alternative Vision 21 plant configurations. Nor does DOE/NETL currently have access to all of the proprietary models and databases developed and used by its contractors for process development and systems evaluation.

Systems integration and engineering analysis should play a far more prominent role in the Vision 21 Program and management structure than is currently the case. The key planning decisions, such as decisions about priorities and funding levels for the various component technologies, should stem from careful and systematic analyses of alternative options and their likelihood of success.

Recommendation. The U.S. Department of Energy and the National Energy Technology Laboratory should create an independent systems analysis group for the Vision 21 Program, colocated with the program leadership and responsible for systems integration and engineering analysis. This group should provide an independent view of the promise and value of various projects and technologies from the perspective of Vision 21. It should develop the in-house ability to use credible engineering performance and cost models for all major plant components; to configure and analyze alternative Vision 21 plant designs; and to evaluate the reliability, availability, and maintainability of alternative designs. By continually refining its process flow sheets and iterating with Vision 21 project teams, the group should identify key technical bottlenecks and integration issues.

It should draw on its in-house technical expertise and modeling capabilities to provide assistance, advice, and R&D guidance to the DOE program leadership and Vision 21 project teams.

Effective management and monitoring of progress in the technology development programs is important to the productive utilization of limited resources and to the overall success of the program. Enhanced systems analysis and integration can also help to assess trade-offs and to establish correct performance goals for different technologies. The Vision 21 Program leadership has developed a technology roadmap that lays out plans and timetables for achieving Vision 21 goals. Currently, however, many of the goals and milestones of Vision 21 describe end points more than a decade from now. Such long-term milestones have limited programmatic value.

Recommendation. The Vision 21 Program leadership should develop detailed intermediate milestones in the context of an overall technology roadmap. The milestones should have high technical content and specified costs. Responsibility within the Vision 21 Program for creating these interim milestones and for designing the programs to reach them should be clearly assigned. Moreover, formal processes should be established that lead to independent technical audit and evaluation of the programs.

TECHNOLOGY DEVELOPMENT

Fuel-flexible gasification systems convert carbon-containing feedstocks (coal, petroleum coke, residual oil, wastes, biomass, etc.) by reacting them with oxygen at elevated pressure and temperature to produce synthesis gas (syngas, a mixture of carbon monoxide and hydrogen). After cleaning to meet the requirements for subsequent processing, the syngas can be converted into electricity by combined-cycle (gas turbine together with a steam turbine), fuel cell, or gas turbine–fuel cell hybrid power plants at high energy conversion efficiencies. These are the combinations of coal-conversion technology and energy-conversion technology most likely to have the potential to achieve the 60 percent (based on higher heating value, HHV) efficiency target of the Vision 21 Program. When it is reacted with steam in a gasification plant system, syngas can also be converted into a mixture of hydrogen and CO_2 at relatively low cost compared with a combustion system. This mixture can then be separated into essentially pure streams of hydrogen for fuel or chemical use and CO_2 that can be sequestered (NRC, 2000).

The Vision 21 Program has a number of advanced technologies under development that are necessary to meet the challenging goals of the program. Chapter 3 contains the committee's assessment of progress, barriers, critical issues, and recommendations for each technology area; further details about the technologies and background can also be found in the committee's first report (NRC, 2000). The following are the highest-priority technology-related findings and recommendations identified by the committee. They pertain to gasification, gas purification, turbines, and fuel cells.

Gasification

Finding. Under current conditions in the United States, heavy-oil- and coke-fueled integrated gasification combined-cycle (IGCC) plants, as well as gasification plants for the production of hydrogen and other chemical feedstocks, are economically viable today because the feedstocks have near-zero or negative value. However, commercial-scale coal gasification-based power plants are not currently competitive with natural gas combined-cycle power plants at today's relative natural gas and coal prices, nor are they projected to be so by 2015 without significant capital cost reductions. Even if the projected cost of these plants reaches the required levels, investors need confidence that these plants will run as designed, with availability levels in excess of 90 percent. The only way to achieve this is to build additional plants incorporating the necessary lower cost improvements and to allow extended periods for start-up so the improved technologies can mature sufficiently to meet their goals. The pace of development and demonstration appears to be too slow to meet the goal of having coal gasification technology qualified for the placement of commercial orders by 2015.

Recommendation. The U.S. Department of Energy should work cooperatively with industry on technology development programs to lower the cost and improve the reliability of the first few commercial-scale Vision 21 plants. The Clean Coal Power Initiative (CCPI), recently authorized by Congress, is an example of the kind of program that can provide support for the construction of high-risk, early commercial plants. These plants should demonstrate and perfect the technology that will make coal gasification-based power plants suitable for deployment on normal commercial terms.

Finding. The U.S. Department of Energy development programs for Vision 21 technologies for gas cleanup, fuel cells, and power production with advanced gas turbines do not currently include adequate testing of these technologies on actual coal-derived synthesis gas (syngas). The most effective way to accomplish the required testing is to install slipstream units in existing coal-fueled gasification plants so that the needed performance data can be collected. This is not being done.

Recommendation. The U.S. Department of Energy is encouraged to set up programs for the installation and operation of slipstream units to obtain data needed from commercial-scale gasification plants.

Gas Purification

Finding. The objectives of the gas purification program are not stated quantitatively or with the required cost targets, and the milestones are insufficiently detailed to permit intermediate assessments of progress towards goals.

Recommendation. The objectives and milestones for the gas purification program need to be more rigorously defined and stated and the responsibility for accomplishing each milestone assigned clearly to a performing organization. Intermediate milestones with a higher technical content and specific cost targets also need to be incorporated into future review processes and into ongoing assessments of progress. Cost-benefit analyses and cost targets need to be incorporated into the planning and execution of these programs.

Turbines

Finding. In response to current industry needs, the U.S. Department of Energy's High Efficiency Engine Technology (HEET) program is focused on natural gas as a fuel to both gas turbines and gas turbine–fuel cell hybrids. Additional information and data are required to develop cost-effective, reliable, emission-compliant systems for power generation in Vision 21 gasification-based plants.

Recommendation. Additional commitments should be made to develop, design, and test large-scale turbine and fuel cell power systems that can function successfully on both synthesis gas (syngas) and hydrogen, including the development of sophisticated thermal cycles involving intercooling, reheat, humidification, and recuperation. Improvements in current natural-gas-fueled power generation systems should be incorporated to the extent appropriate in syngas- and hydrogen-fueled Vision 21 power plants. The U.S. Department of Energy is encouraged to set up programs for the installation of test articles (including vanes, blades, and other high-temperature components) as well as for the installation and operation of slipstream units to obtain the needed data from commercial-scale gasification plants.

Fuel Cells

Finding. The *Vision 21 Roadmap* for fuel cell technology identifies performance and cost goals for the various components of a high-temperature fuel cell energy system. The roadmap also lists the barriers to reaching each of these goals. The Vision 21 fuel cell program includes four fuel cell plants as its main milestones. The overall Vision 21 programs in gasification, gas processing and separation, gas turbines, materials, modeling, systems computations, etc., have elements that may pertain to fuel cell energy systems.

Recommendation. The U.S. Department of Energy National Energy Technology Laboratory Vision 21 fuel cell program plan and schedule should incorporate milestones in addition to the current four milestones, each of which represents the construction and operation of a high-temperature fuel cell power-generation plant. The additional milestones should deal with (1) removal of significant barriers to program success identified in the fuel cell roadmap and (2) accomplishment of significant steps in preparation for plant construction and operation, including developments, tests, designs, and evaluations of performance and costs for both the demonstration plant and the projected commercial plant. To the extent possible, the milestones should include quantitative measures as criteria for successful achievement, such as overall capital and operating costs of the projected commercial plant.

1

Introduction

The Vision 21 Program is a relatively new research and development (R&D) program, which is funded through the U.S. Department of Energy's (DOE's) Office of Fossil Energy and its National Energy Technology Laboratory (NETL). Planning for the program began in 1998-1999, and a workshop was held in August 2000 to develop technology roadmaps for each of the key technologies. Currently, the Vision 21 Program per se is not a line item in the Office of Fossil Energy budget but is a collection of projects and activities that contribute to the technologies required for advanced Vision 21 energy plants. The program is focused on the development of advanced technologies for deployment beginning in 2015. Vision 21 facilities would be able to convert fossil fuels (e.g., coal, natural gas, and petroleum coke) into electricity, fuels, and/or chemicals with very high efficiency and very low emissions, including of the greenhouse gas CO_2. With the dominance of fossil fuels in powering the U.S. economy, especially that of coal in the electricity sector, and their projected growth in the United States and worldwide, the need for technologies that utilize fossil fuels in an efficient and environmentally friendly manner is a high priority. As noted in the *Vision 21 Technology Roadmap*, if the program meets its goals, it will essentially remove many of the environmental concerns traditionally associated with the use of fossil fuels for producing electricity and transportation fuels or chemicals (NETL, 2001). The use of fossil fuels as a possible pathway to producing hydrogen is also in keeping with the growing interest of DOE in supporting the development of technologies for hydrogen production and use.

This report contains the results of the second National Research Council (NRC) review of the Vision 21 R&D Program. The first review of the program was conducted by the NRC Committee on R&D Opportunities for Advanced

Fossil-Fueled Energy Complexes, which resulted in the report *Vision 21, Fossil Fuel Options for the Future*, published in the spring of 2000 (NRC, 2000). At that time the Vision 21 Program was in a relatively embryonic stage, having been initiated by DOE in 1998-1999. The NRC report contained a number of recommendations for DOE to consider as it moved forward with its program; DOE's responses to many of these recommendations are considered in Chapter 3. Now, 2 years after the first review, DOE's Deputy Assistant Secretary for Coal and Power Systems requested that the NRC review progress and activities in the Vision 21 Program. In response, the NRC formed the Committee to Review DOE's Vision 21 R&D Program—Phase I. Most of its members also served on the committee that wrote the earlier report (see Appendix A for committee biographical information). Many details of the program were covered in that report and will not be repeated here. It is anticipated that the committee will conduct reviews of the Vision 21 Program on a regular basis.

As noted in *DOE's Vision 21 Program Plan* and the *Vision 21 Technology Roadmap*, Vision 21 is a new initiative for developing the technologies necessary for ultraclean, fossil-fuel-based energy plants that will be ready for deployment in 2015 (DOE, 1999a; NETL, 2001). It is envisioned that technology modules will be selected and configured to produce the desired products from the feedstocks (e.g., coal, natural gas, petroleum coke and, where appropriate, opportunity feedstocks such as refinery wastes or biomass) (NETL, 2001). The key technologies under development are identified in the *Vision 21 Technology Roadmap* and reviewed here in Chapter 3:

- Gasification,
- Gas purification,
- Gas separation,
- Fuel cells,
- Turbines,
- Environmental control,
- Controls and sensors,
- Materials,
- Modeling, simulation, and analysis,[1]
- Synthesis gas conversion to fuels and chemicals, and
- Advanced coal combustion.[2]

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[1]The *Vision 21 Technology Roadmap* breaks out two areas: (1) computational modeling and virtual simulation and (2) systems analysis and integration, which the committee has combined into one area for the purposes of this report.

[2]The *Vision 21 Technology Roadmap* identifies the area as combustion and high-temperature heat exchange; the committee has chosen to focus on advanced coal combustion.

For example, coal (along with other feedstocks) might be gasified to create synthesis gas (syngas, a mixture of carbon monoxide (CO) and hydrogen (H_2)); H_2 might be separated from the syngas for use in fuels cells to generate electricity; fuels and/or chemicals might also be synthesized from the syngas; and waste heat from the fuel cell might be used to produce electricity using steam turbines. It is envisioned by DOE that once technology modules are developed, vendors will be able to combine advanced technologies in configurations tailored to meet specific market needs. To support this integration effort, DOE is developing a modeling and simulation capability intended to reduce the risks and costs of building Vision 21 plants. While DOE also acknowledges the importance of demonstration projects to confirm component and system capabilities, the Vision 21 Program does not include funds to carry out large-scale demonstrations. Such projects would have to be funded and implemented outside the Vision 21 Program.

GOALS AND TARGETS

As noted above, the ultimate goal of Vision 21 is to create ultraclean, fossil-fuel-based energy plants with high efficiency. It is also anticipated that most of these plants will be sequestration ready, i.e., the CO_2 resulting from the fossil fuel conversion will be available for capture and sequestration. (At the current time, the activities related to sequestration science and engineering, e.g., geologic or ocean disposal, are carried on in a separate DOE program.) Specifically, the Vision 21 energy plant performance targets are as follows (NETL, 2001):

- *Efficiency for electricity generation:* 60 percent for coal-based systems (based on higher heating value (HHV)); 75 percent for natural-gas-based systems (based on lower heating value (LHV) or 68 percent based on HHV). These efficiencies exclude consideration of the energy required for CO_2 capture.
- *Efficiency for a fuels-only plant:* 75 percent feedstock utilization efficiency (LHV) when producing fuels such as H_2 or liquid transportation fuels alone from coal. These efficiencies exclude consideration of the energy required for CO_2 capture.
- *Environmental:* atmospheric release of
  - — Less than 0.01 lb/million British thermal units (MMBtu) sulfur and nitrogen oxides; less than 0.005 lb/MMBtu particulate matter;
  - — Less than one-half of the emission rates for organic compounds listed in the *Utility HAPS Report* (EPA, 1998);[3]
  - — Less than l lb/trillion Btu mercury; and
  - — 40-50 percent reduction of CO_2 emissions by efficiency improvement, essentially 100 percent reduction with sequestration.

[3]HAP, hazardous air pollutant.

- *Costs:* aggressive targets for capital and operating costs and for reliability, availability, and maintenance. Products of Vision 21 plants must be cost-competitive with other energy systems having comparable environmental performance, including specific carbon emissions.
- *Timing:* major benefits from improved technologies begin by 2005. Designs for most Vision 21 subsystems and modules available by 2012; Vision 21 commercial plant designs available by 2015.

Vision 21 plants will probably be large, stand-alone central station facilities or integrated with industrial or commercial operations. The *Vision 21 Technology Roadmap* also notes that small, distributed power generation is not considered to be part of Vision 21, although spin-off technologies from Vision 21 may be applicable to distributed generation, and Vision 21 plants could be designed as an integral part of a distributed power concept (NETL, 2001).

MANAGEMENT APPROACH AND BUDGET

Planning for the Vision 21 Program and associated activities takes place at workshops that involve the Office of Fossil Energy and the NETL, other DOE offices, the national laboratories, state and local governments, universities, and private industry. Working relationships are being created with a number of organizations outside DOE and NETL. According to the *Vision 21 Technology Roadmap*, NETL also plans to issue a series of competitive solicitations, create consortia, and develop cooperative research and development agreements (CRADAs) and other agreements (NETL, 2001). An initial Vision 21 solicitation was issued on September 30, 1999, resulting in three rounds of awards comprising 15 new projects.[4] Additional projects have resulted from other solicitations in various technology product areas in the Office of Fossil Energy.

The Vision 21 Program contains projects arising not only from the solicitation noted above, but also from ongoing activities in the traditional R&D program areas in the Office of Fossil Energy. Ongoing activities that are oriented toward achieving revolutionary rather than evolutionary improvements in performance and cost and that share common objectives with Vision 21 are considered to be part of Vision 21 activities. Vision 21 projects must contribute to the technology base needed to design Vision 21 energy plants. Thus, the Vision 21 Program per se is not a line item in the Office of Fossil Energy budget but rather a collection of projects that contribute to the technologies required to realize Vision 21 energy plants, and the program must be coordinated across the suite of activities in DOE/NETL programs contained in the Office of Fossil Energy's R&D programs on coal and power systems. This coordination is partially achieved through a matrix

[4]L. Ruth, NETL, "Vision 21—Overview," Presentation to the committee on May 20, 2002.

management structure at NETL. The Vision 21 team works with NETL product managers, DOE's Office of Fossil Energy headquarters, industry, universities, and others to provide coordination for the program. The estimated budget for Vision 21 activities was about $50 million for FY 2002; the FY 2003 request to Congress is estimated to have been about $65 million.[5]

STATEMENT OF TASK

The statement of task for the committee was as follows:

> The NRC committee appointed to conduct this study will review the Vision-21 program on an annual basis. It will receive presentations from DOE on progress in the program, R&D directions and initiatives that are being taken, DOE's strategy for the deployment of technologies coming from Vision 21 (including special attention to coal-intensive developing countries where the market is likely to be), and plans for further efforts. Depending on the extent to which the DOE carbon sequestration program is connected to Vision 21 efforts, the committee may also review progress on sequestration and associated costs. Based on its review, the committee will write a short report with recommendations, as appropriate, that it believes will help DOE to meet the ambitious and challenging goals in the Vision-21 program. The committee's continued involvement could provide periodic guidance to DOE that would sharpen Vision 21 efforts and hasten the realization of its goals.
>
> It is also envisioned that DOE may ask the committee from time to time to address additional tasks related to the Vision 21 program. If so, a statement of task would have to be developed between the NRC and DOE, and additional funding necessary to undertake the additional task will be requested from DOE.

The latter part of the statement of task was not considered during this review, since DOE did not ask the committee to address additional tasks.

The committee held two meetings. The first entailed a series of presentations by program managers on the various aspects of the Vision 21 Program, as well as some presentations from technical experts working in the private sector. The second listened to additional presentations, as necessary (see Appendix B). The committee also formulated a set of written questions about the Vision 21 Program to DOE and NETL staff as another means of collecting information, as well as reviewing the technical literature: NETL staff provided written answers to the committee's questions. The committee also worked in closed sessions at its meetings to formulate its conclusions and recommendations and to draft its report.

ORGANIZATION OF THE REPORT

Chapter 1 provides a brief background to the Vision 21 Program and the purpose of the current review and study; the reader is urged to consult the previ-

[5]Ibid.

ous committee report, as well as DOE documents, for further details (DOE, 1999a, b, c; DOE, 2002b; NETL, 2001; NRC, 2000). Chapter 2 presents the committee's key strategic recommendations for the Vision 21 Program as a whole. In it, the committee has tried to keep its recommendations to a minimum to focus the attention of DOE and NETL on key critical issues. Finally, Chapter 3 addresses each of the technology areas under development in the Vision 21 Program. Those familiar with the committee report issued in 2000 will note that at that time, Vision 21 distinguished between "enabling" technologies and "supporting" technologies, a distinction that has been removed from the program and is not reflected in the current report. The appendixes present committee members' biographical information (Appendix A) and activities of the committee to collect information (Appendix B).

2

Strategic Assessment of the Vision 21 Program

This chapter presents nine Vision 21 programwide recommendations that the committee believes to be critical to the success of the Vision 21 Program. Chapter 3 presents the committee's recommendations in specific Vision 21 Program areas.

Vision 21 has ambitious goals. It represents an important strategic effort by the U.S. Department of Energy (DOE) to develop substantially improved technology that will allow fossil fuels to be used for the production of electricity, chemicals, and fuels with near-zero environmental emissions and with efficient utilization of energy resources. There has been notable progress since the program's inception. The Vision 21 Program needs to evolve further, largely along lines already identified.

The committee's nine recommendations address the focus of the Vision 21 Program; linkages to neighboring programs in DOE's Office of Fossil Energy program but outside the Vision 21 Program; management structure; budget; in-house engineering modeling; linkages to demonstrations; linkages to the basic research community and programs abroad; and program evaluation.

PROGRAM FOCUS

The Vision 21 Program was originally conceived as, and to a large extent remains, a very broad and inclusive program. Vision 21 addresses a variety of fossil fuel and other energy sources, including coal, natural gas, combustible wastes, and bio-products; the conversion of these resources into convenience fuels, chemicals, heat, and electricity; the use of steam cycles and gas cycles for power generation; a wide range of plant scales, ranging from small, distributed systems to large central-station facilities; and the design of plants with and without the readiness to sequester greenhouse gases. This comprehensive scope was adopted at the outset in order to involve a broad constituency in the definition of Vision 21 goals and activities. Over the past 2 years, the Vision 21 Program has begun to narrow its scope and focus on coal relative to other energy sources, on electricity relative to other secondary products, and on gasification and gas turbine cycles relative to direct combustion and steam cycles. The committee strongly endorses these developments. The performance, cost, and environmental goals that have now been established for Vision 21 plants argue strongly for a focus on gasification-based systems, as discussed in the committee's previous report (NRC, 2000) and elaborated in this report, in Chapter 3. A primary focus on coal-based technologies and electric power generation is also appropriate given the importance of domestic coal resources now and in the foreseeable future. A primary focus on electricity production is also warranted, given the dominant role of electricity in domestic uses of coal, and given the competition from petroleum and natural gas as sources of synthetic fuels and chemicals. However, the opportunities for coproduction of chemicals, fuels, and electricity from coal via advanced technologies should continue to be included in Vision 21.

The committee believes that the Vision 21 Program will be strengthened substantially by continuing to sharpen its focus. In particular, the committee believes the program should focus on large-scale facilities—200-500 megawatts (MW)—and on designs that produce sequestration-ready CO_2 as well as near-zero emissions of conventional pollutants. This sharper focus will allow the Vision 21 Program to concentrate on the most cost-competitive coal-based options, to achieve tight program management, to plan for phased commercialization, to monitor progress closely, and to optimize its use of limited financial and human resources. Systems that capture carbon (in the sense that they produce sequestration-ready CO_2) are important as well, given the widely recognized importance of reducing greenhouse gases and the R&D challenges in achieving the long-term Vision 21 goals for CO_2 emissions. DOE already plays a leading role in the U.S. carbon sequestration program, and Vision 21 is the logical home for the separation and capture dimensions of this research, given its long time horizon and globally significant consequences.

Finally, as elaborated in the next section of this report, the committee emphasizes that a more sharply focused Vision 21 Program requires strong complementary programs outside Vision 21, several of which have long histories and considerable momentum. Indeed, Vision 21 cannot succeed without continued support for the many excellent programs elsewhere in DOE's Office of Fossil Energy, with which Vision 21 interacts.

Recommendation. The Vision 21 Program should continue to sharpen its focus. It should focus on the development of cost-competitive, coal-fueled systems for electricity production on a large scale (200-500 MW) using gasification-based technologies that produce sequestration-ready carbon dioxide and near-zero emissions of conventional pollutants.

LINKAGES TO DOE'S FOSSIL ENERGY R&D OUTSIDE VISION 21

The Vision 21 Program is only one part of the overall R&D program of DOE's Office of Fossil Energy. Many of the programs in that office are understood to lie outside Vision 21 but are nonetheless closely related and complementary. By design, Vision 21 is aimed at developing a commercial design that can be deployed in the marketplace after 2015. In the period before 2015, the advanced coal combustion program and other non-Vision 21 programs should lead to coal-based electric generating options with significantly improved environmental and operating performance. Both Vision 21 and the advanced coal combustion program benefit from the exchange of knowledge, concepts, and practical experience acquired in the two programs.

Further examples of symbiotic relationships are programs addressing the environmental demands on today's fleet of coal plants; materials research (such as materials for high-temperature and high-pressure steam cycles that also have applications to gasifiers); and the storage or sequestration of CO_2 after it leaves the plant gate. If the committee's recommendation of a sharpened focus for the Vision 21 Program is accepted, further areas will be understood to lie outside the Vision 21 boundary, including advanced technology for distributed power and for natural gas turbines or advanced combustion and advanced steam conditions for utility power plants. Vision 21 should be managed in ways that encourage cross-fertilization across various DOE programs. The stronger the neighboring programs outside Vision 21, the greater the likelihood of success in achieving Vision 21 goals.

Recommendation. The Vision 21 Program, with its long time horizon, requires strong companion programs with short-term and medium-term objectives to support it and to provide a two-way flow of technical insight. The committee recommends that the leadership of Vision 21 remain dedicated to this cross-fertilization, closely monitoring the research conducted elsewhere in the Office of Fossil Energy, incorporating the results of that research into Vision 21, and, where appropriate, bringing the insights gained within the Vision 21 Program to bear on work in neighboring areas.

PROGRAM MANAGEMENT

Responsibility for managing the Vision 21 Program on a day-to-day basis is vested in a small steering committee (called the Vision 21 team) drawn from DOE and National Energy Technology Laboratory (NETL) staff and headed by the Vision 21 program manager. The program manager interacts informally with the NETL program and project managers who control the funding and oversee individual Vision 21 projects. The current management structure thus relies on a process of cooperation and consensus, and ultimate responsibility for ensuring the effectiveness of Vision 21 lies with the senior management of DOE and NETL. This means that the Vision 21 Program lacks the control and accountability at the program level seen in successful R&D programs.

Recommendation. A more rigorous management structure is needed to accomplish the ambitious goals of the Vision 21 Program. The Vision 21 program manager should be provided with the budget and overall responsibility and authority needed to manage the program, including appropriate staff responsible for program planning, implementation, and evaluation.

BUDGET

The Vision 21 Program does not have an identifiable budget of its own. DOE estimates that roughly $50 million of the current (FY 2002) funding (approximately one fourth of the Office of Fossil Energy R&D budget) is devoted to Vision 21 activities. DOE also projects that to achieve current Vision 21 Program goals the Vision 21 budget would have to grow by roughly an order of magnitude over the next 5 years. The committee agrees that there is a potential for large imbalances between future program requirements and future funding. It also believes that Vision 21 goals will not be reached if the program continues to be funded at the present level, in which case its goals would have to be modified and its projects prioritized. Rigorous assessment requires the formulation of several alternative schedules for achieving Vision 21 Program goals, matched to alternative budget scenarios. This exercise should lead to a convincing argument for funding the Vision 21 Program at an appropriate level.

Recommendation. The U.S. Department of Energy (DOE) and the National Energy Technology Laboratory (NETL) should estimate the budget required to support the current Vision 21 Program goals and should reconcile these estimates with various funding scenarios. DOE/NETL should also estimate and articulate the benefit (or cost) to the United States of achieving (or failing to achieve) Vision 21 goals.

SYSTEMS INTEGRATION AND ANALYSIS

More than any previous program within the DOE's Office of Fossil Energy, Vision 21 requires a strong component of systems integration and analysis in order to set goals and priorities. For Vision 21 to lead to systems that can compete in the marketplace, the advanced technologies being developed within NETL's current programs structure (e.g., gasifiers, turbines, fuel cells) must be successfully integrated with one another at the commercial scale. Many integration issues remain unresolved—for example, the effective integration of fuel cells and gas turbines.

Currently, systems analysis and integration activities are handled piecemeal, mainly by external organizations performing independently as DOE contractors. The DOE Vision 21 team appears not to have sufficient internal engineering capability to model, analyze, and evaluate alternative Vision 21 plant configurations. Nor does DOE/NETL currently have access to many of the proprietary models and databases developed and used by its contractors for process development and systems evaluation. The committee recognizes that the development of an in-house capability for independently evaluating alternative systems in support of Vision 21 Program planning and prioritization is not a simple or straightforward task and will require additional resources and time. Nonetheless, it is critical to the overall Vision 21 Program effort, especially in light of the budget issues discussed earlier.

Systems integration and engineering analysis should play a far more prominent role in the Vision 21 Program and management structure than is currently the case. The key planning decisions, such as decisions about priorities and funding levels for the various component technologies, should stem from careful and systematic analyses of alternative options, the likely benefits, and the likelihood of success.

Recommendation. The U.S. Department of Energy and the National Energy Technology Laboratory should create an independent systems analysis group for the Vision 21 Program, colocated with the program leadership and responsible for systems integration and engineering analysis. This group should provide an independent view of the promise and value of various projects and technologies from the perspective of Vision 21. It should develop the in-house ability to use credible engineering performance and cost models for all major plant components; to configure and analyze alternative Vision 21 plant designs; and to evaluate the reliability, availability, and maintainability of alternative designs. By continually refining its process flowsheets and iterating with Vision 21 project teams, the systems analysis group should identify key technical bottlenecks and integration issues. It should draw on its in-house technical expertise and modeling capabilities to provide assistance, advice, and R&D guidance to the DOE program leadership and Vision 21 project teams.

LINKAGES TO LARGE-SCALE DEMONSTRATIONS

The federal government has embarked on several new programs aimed at encouraging the early phases of deployment of large, coal-based, central generating plants with improved performance and reduced emissions and costs. These programs provide financial support for first-of-a-kind demonstrations and financial and other incentives for subsequent early commercial applications. They complement the Vision 21 Program. The programs offer an effective path to the first full-scale Vision 21 plant. They create an opportunity for Vision 21 to test components and systems directly at an early stage and to gain early information about actual costs and technical hurdles.

These new programs are being developed based on a model of the path to commercial deployment. In this model (1) first-of-a-kind plants entail incremental costs related to the technical risks of emerging technologies, and these costs exceed the cost of the best available alternative; (2) as the second, third, fourth, etc. plants are built, more becomes known about their design, construction, and operation, and unit costs decrease; and (3) when the technology has been deployed in sufficient numbers, the plants outperform their competitors.

Recommendation. The leadership of the Vision 21 Program must work with industry to develop a commercialization strategy that takes advantage of the nation's current and emerging demonstration programs. Vision 21 must find ways to involve developers and users of Vision 21 technologies with these demonstrations. Equally important, Vision 21 must be a force for the inclusion of strong research programs within the federal demonstration programs, in order to accelerate the commercial application of Vision 21 technologies.

LINKAGES TO BASIC RESEARCH AND INTERNATIONAL ACTIVITIES

In its 2000 report, the committee recommended that "the U.S. Department of Energy (DOE) should develop mechanisms to link the Vision 21 Program with other basic science and engineering research programs in and beyond DOE. DOE should also coordinate the domestic and international commercialization and deployment of Vision 21 technologies" (NRC, 2000, p. 5). Over the past 2 years, linkages to the basic research community have been established in a few areas. However, the Vision 21 Program has had only minimal involvement with programs of research and commercialization in other countries.

Recommendation. The committee reiterates its earlier recommendation that much more should be done within the Vision 21 Program to involve the basic research community and gain commitments from it in order to acquire state-of-the-art fundamental concepts. Furthermore, much more should be done within Vision 21 to leverage technology developments and commercial opportunities elsewhere in the world.

EVALUATING PROGRESS

The Vision 21 Program leadership has developed a technology roadmap that lays out plans and milestones for achieving Vision 21 goals. Currently, however, many of the plans and milestones of Vision 21 describe end points more than a decade from now. Such long-term milestones have limited programmatic value.

Recommendation. The Vision 21 Program leadership should develop detailed intermediate milestones in the context of an overall technology roadmap. These milestones should have high technical content and specified costs. Responsibility within Vision 21 for creating these interim milestones and for designing the programs to reach them should be clearly assigned. Moreover, formal processes should be established that lead to independent technical audit and evaluation of the programs.

The Vision 21 Program has advanced from the inception and definition stage to the productive phase, where the measurement of progress and an assessment of the soundness of the guiding principles should be the basis for prioritizing projects. This is also a phase where the proliferation of projects in an environment of limited resources will require that projects be selected for termination with the rigor provided by careful engineering analysis and state-of-the-art chemical and engineering knowledge.

The descriptions of the programs and their milestones in Vision 21 lacked the level of detail required to judge progress. This will become increasingly critical to the effectiveness of future reviews, whether conducted by the National Academies or by other expert groups for DOE, as the Vision 21 Program progresses and evolves. With careful attention to conflict of interest, it will be important for DOE and NETL to bring industry experience and expertise to bear on external reviews of Vision 21 Program activities.

Recommendation. The U.S. Department of Energy and its National Energy Technology Laboratory should enable future reviews of the Vision 21 Program that examine in considerably more detail the technical content of each project. Such reviews should provide sufficient technical detail and bring to bear sufficient engineering analysis to answer the following questions about each project and subprogram:

1. Does the project lie along a critical path and provide an economic incentive to make a significant difference?
2. Is the approach taken (i.e., the guiding principles) novel? Does it use knowledge that comes from state-of-the-art and sound scientific and engineering principles? How does it compare with competing technologies, and how is benchmarking rigorously and routinely carried out?
3. Are the projects tapping the leading intellects and centers of excellence in each area?
4. What are the technical and intellectual barriers, and are they being addressed specifically by strategies taken or proposed?
5. How are the targets and milestones set within the context of complete engineering analyses of an *overall* Vision 21 plant? Are the milestones frequent and detailed enough to be useful to judge progress?

In such reviews, mechanisms should be put in place to protect intellectual property through the filing of patents and through a limited number of non-disclosure agreements, but the exchange of required information should not be otherwise restricted in a way that might protect inappropriate or poorly conceived approaches from scrutiny.

3

Vision 21 Technologies

INTRODUCTION

This chapter reviews the technology areas under development in the Vision 21 Program and identified in the *Vision 21 Technology Roadmap* (NETL, 2001). The areas addressed are gasification; gas purification; gas separations; fuel cells; turbines; environmental control technology; sensors and controls; materials; modeling, simulation and analysis; synthesis gas (syngas) conversion to fuels and chemicals; and advanced coal combustion. Each section of this chapter contains (1) a brief introduction to the technology and its importance to the Vision 21 Program; (2) milestones and goals for the technology; (3) progress, significant accomplishments, and current status in the technology area; (4) responses to recommendations from the committee's 2000 report; (5) issues of concern and remaining barriers to technology development; and (6) findings and recommendations. Further detail and background on the technologies can be found in the committee's 2000 report, in the *Vision 21 Program Plan* and in the *Vision 21 Technology Roadmap* (NRC, 2000; DOE, 1999a; NETL, 2001).

GASIFICATION

Introduction

Fuel-flexible gasification systems convert carbon-containing feedstocks (coal, petroleum coke, residual oil, wastes, biomass, etc.) by reacting them with oxygen, usually at 95 percent purity and elevated pressure and temperature, to produce syngas, a mixture of carbon monoxide and hydrogen. Steam can be injected to adjust the ratio of hydrogen to carbon monoxide in the syngas and/or as a temperature moderator. As produced, this gas contains impurities, which can be stripped out using well-developed refinery gas cleanup having very high demonstrated removal rates (Meyers, 1997). Shifting from direct coal combustion in air to gasification in oxygen can become more attractive and more cost-effective as emissions regulations are further tightened. After cleaning to meet the requirements for subsequent processing, the syngas can be converted into electricity by combined cycle technology (gas turbine plus steam turbine), fuel cells, or gas turbine plus fuel cell hybrid power plants at high energy conversion efficiencies. These are the most likely combinations of coal-conversion technology and energy-conversion technology with the potential to achieve the 60 percent higher heating value (HHV) efficiency target of the Vision 21 Program. By reaction with additional steam downstream of the gasification reactor, syngas can also be converted into a mixture of hydrogen and CO_2. This mixture can then be separated into essentially pure streams of hydrogen for fuel or chemical use and CO_2 that can be sequestered (NRC, 2000).

Other approaches to coal gasification have been developed that utilize air instead of high-purity oxygen. The potential reward for using air is avoidance of the cost of an air separation plant to produce oxygen and the energy consumed in the plant's operation. These cost-saving factors are offset by the large amount of nitrogen introduced into the system, which increases the size and energy costs associated with cleanup of the relatively dilute syngas stream. The presence of nitrogen also increases the cost of separating CO_2 from the syngas as part of a sequestration scheme. As a result, air-blown gasification is not considered to be compatible with sequestration systems. One of the most important advantages of oxygen-blown coal gasification technology relative to coal combustion technologies that use air, as well as coal gasification technologies that use air, is that it is compatible with the need for relatively low-cost CO_2 separation required for CO_2 sequestration.

Gasification plants that process feed materials with very low or negative cost, such as petroleum coke and residual oil, can be commercially justified today for various combinations of hydrogen, by-product steam, and power production. Coal gasification for hydrogen production for chemical manufacturing is also widely practiced. More than 160 gasification plants worldwide are in operation producing the equivalent of 50,000 megawatts (thermal) (MW_t) of syngas (Simbeck, 2002).

Four coal-fueled integrated gasification combined cycle (IGCC) single-train demonstration power plants with outputs greater than 250 MW have been built since 1995, two in Europe and two in the United States. Each of these plants was built with a significant subsidy as part of a government-sponsored program. As expected, each of the plants has taken 3 to 5 years to approach the upper range of availability, 70-80 percent, that was predicted when they were designed.

The cost of these plants was between $1,400 and $2,000/kW.[1] Experience gained from the operation of these demonstration plants, as well as from the design, construction, and operation of coke and residual-oil-fired gasification plants can be used to reduce costs to the range $1,200 to $1,500/kW (NRC, 2000). However, to be competitive with natural-gas-fueled, combined-cycle units after 2015 at natural gas prices of $3.50-$4.00/MMBtu, the investment for a mature plant of this type will have to be reduced to less than $800/kW (overnight basis for engineering, procurement, and construction costs only) in an IGCC configuration that can achieve 45 percent (HHV) efficiency (DeLallo et al., 1998; EPRI, 1999) and to less than $1,000-$1,100/kW in an integrated gasification combined cycle/fuel cell (IGCCFC) configuration that can achieve 60 percent efficiency (HHV) (neither configuration includes the losses associated with CO_2 capture) (NRC, 2000). In addition, recent surveys of the market for gasification technologies indicate that plant owners will require 90 percent availability for power production plants and 97 percent availability for chemical production plants (DOE, 2002a).

Meeting the 2015 goal of the Vision 21 Program—having competitive IGCC plant designs available for implementation on normal commercial terms—will require the development of new technology to meet the investment cost, efficiency, and availability requirements of the market. Improvements in all five sections of the IGCC plant—feed solids handling, air separation, gasification, gas cleanup, and power generation—will be necessary.

Milestones and Goals

The current goals of the gasification program are as follows:

- Fuel flexibility up to 10 percent (large units) and 30 percent (small units) of fuel other than coal (biomass, waste products, etc.);
- Improved gasifier performance: greater than 95 percent availability, greater than 82 percent cold gas efficiency;
- Gasifier cost target of $150/kW (includes syngas cooling and auxiliary but not air separation); syngas cost target of $2.50/MMBtu (at a coal cost of $1.25/MMBtu);
- More efficient, more reliable, lower cost feed system to operate at up to 70 atmospheres; and
- Novel gasifier concepts that do not require oxygen but utilize instead internal sources of heat, e.g., residual heat produced by a high-temperature fuel cell.[2]

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[1]Throughout this report, capital costs include only the costs of plant equipment and installation, except as noted.

[2]G.J. Stiegel, NETL, "Gasification," Presentation to the committee on May 20, 2002.

The current milestones for the gasification program are as follows:

- Test prototype gasifiers at pilot scale (2005)
  - — Transport reactor and partial gasifier module at the Power Systems Development Facility (PSDF);
- Test pilot-scale novel gasifier that does not require oxygen separation (2005)
  - — General Electric–Energy and Environmental Research fuel-flexible gasification-combustion technology;
- Commercial deployment of advanced fuel-flexible gasifiers (2008); and
- Commercially ready gasifier designs that meet Vision 21 requirements (2010).

Progress, Significant Accomplishments, and Current Status

DOE-sponsored programs are under way to develop technology to meet each of the listed objectives and milestones, as follows:

- A novel high-pressure feed system has been designed for introducing low-cost, waste solids into the second stage of the 250-MW Wabash River gasifier. Implementation is uncertain in view of the lack of funds for capital improvements at the plant.
- In the area of improving gasifier availability, laboratory work has identified a new refractory that has the potential for significantly improved refractory life. Much work is required to further develop this material and then confirm its performance in a full-scale gasifier. New approaches to sensors and data-processing systems that can accurately measure temperatures in the gasifier between 2000°F and 3000°F and survive for extended periods of time are ready for testing in full-scale systems.
- A design optimization study has indicated that capital cost reductions of 20 percent and a reduction in the overall IGCC commercial plant project timetable (design and construction) from 57 months to 46 months are possible.
- Preliminary experimental work has identified a sorbent that decomposes in the gasifier to supply oxygen directly to the coal for gasification.
- Significant progress has been made in demonstrating that the transport-reactor gasifier at the large pilot-scale PSDF can achieve greater than 95 percent carbon conversion when operating on air and Powder River Basin coal. Initial experiments in this gasifier with oxygen in place of air achieved 90-94 percent carbon conversion. This is a major step forward in the development of this potentially lower cost gasification system. Further experiments are planned to determine if higher conversion levels can be achieved. Higher conversion levels in oxygen-blown systems are required

for compatible, low-cost integration with CO_2 separation systems. Tests with bituminous coals using both air and oxygen are planned to determine their performance in the transport reactor system.

Achievement of the two pilot-scale gasification milestones by 2005 appears to be feasible. However, the milestones for commercial deployment of advanced fuel-flexible gasifiers by 2008 and for commercially ready gasifier designs that meet Vision 21 requirements by 2010 appear too optimistic in view of the current state of technology development coupled with the time it takes to prove the commercial readiness of key components. Among the improved components that are needed for commercially viable Vision 21 plants are single-train gasifiers with capacities of 400-500 MW, 400-500 MW syngas-fueled combined cycles, low-cost oxygen separation plants, improved refractories, and improved diagnostic instrumentation. Progress in a number of these areas that can contribute to lowering plant capital cost requirements is discussed elsewhere in the report.

Response to Recommendations from the Committee's 2000 Report

The committee recommended as follows:

Recommendation. The Vision 21 Program should encourage industry-led demonstrations of new technologies. The Vision 21 commercial designs and cost estimates will be of great value if they can be validated against existing data-bases and component demonstrations, which would encourage deployment by industry.

One of the important actions taken by Congress was to authorize DOE to launch the Clean Coal Power Initiative (CCPI) program, which is described as follows by DOE (2002b):

> The CCPI is a cost-shared partnership between the government and industry to demonstrate advanced coal-based, power generation technologies. The goal is to accelerate commercial deployment of advanced technologies to ensure the United States has clean, reliable, and affordable electricity. This ten-year initiative will be tentatively funded at a total Federal cost share estimated at $2 billion with a matching cost share of at least 50%.

CCPI provides a mechanism for subsidizing demonstrations of improved IGCC technologies in full-size plants. Two proven methods of validating the potential usefulness of improved technology are to test components in operating IGCC plants so that those components are exposed to realistic environments and to test processes in slipstream units at existing large coal-gasification plants. DOE should be encouraged to carry out these kinds of test programs in commercial-scale facilities.

Recommendation. The U.S. DOE should pursue both revolutionary and evolutionary approaches to the development of gasification systems to achieve its performance and cost targets. Because the gasification sections of IGCC and IGCCFC plants contain many highly integrated gasification components (coal handling, oxygen production, gasification, gas cleaning, heat exchange) significant cost reductions in all sections will be necessary to meet the overall Vision 21 goal. The key areas in other sections of the plant targeted for R&D focus are oxygen production, hydrogen separation, carbon dioxide capture and high-temperature fuel cells.

In most cases DOE responded appropriately to the committee's recommendation in 2000 to pursue both revolutionary and evolutionary improvements in all the sections of a gasification-based power plant. R&D programs have been initiated that relate to the gasification section, oxygen production, hydrogen separation, CO_2 capture, and high-temperature fuel cells.

Issues of Concern and Remaining Barriers

Broad market acceptance of coal gasification as measured by a significant number of new orders for gasification-based power plants in the years after 2015 will require commercial-scale experience to provide the appropriate design bases that can be replicated. At this time, only the 250-MW Tampa Electric Polk power station and the Wabash River coal gasification project, which utilize modern Texaco and E-Gas entrained gasification technologies, respectively, for power production, are in operation in the United States. Because they need to generate power at competitive costs, both plants operate extensively on blends of coal and lower cost petroleum coke or on coke alone. The Great Plains Coal Gasification plant in North Dakota uses the older, more costly fixed-bed Lurgi gasification technology for the production of synthetic natural gas. The transport reactor system under development at the PSDF has demonstrated significant potential for the air-blown and oxygen gasification of low-cost subbituminous Powder River Basin Coal. Its applicability to the conversion of bituminous coal is being evaluated experimentally at this time.

Unfortunately none of these systems provides an adequate basis for competitive future IGCC power plants with the potential for low-cost CO_2 capture to meet Vision 21 goals. Significant scale-up to 400- to 500-MW single-train size and operating improvement to overall IGCC plant availability of greater than 90 percent are both required if IGCC plants are to reach the cost goal of $800/kW (overnight basis for engineering, procurement, and construction costs only) with coal at $1.25/MMBtu so that they will be competitive with natural gas combined-cycle plants fueled with $3.50-$4.00/MMBtu natural gas.

Substantial operating experience with full-scale (400-500 MW), single-train gasification power plants with greater than 90 percent availability is needed to provide investors with the confidence they need to make investments with the same degree of risk as other types of power plants. Achieving that reliability requires the reliability growth normally experienced with building a number of plants over a number of years. Permitting, design, and construction of power plants of this size normally require 5-8 years. The first few plants of a series are likely to take 3-5 years to achieve the reliability and performance required for commercialization. The CPPI program is the only program currently in place to provide subsidies for these kinds of plants. The total of $2 billion over the next 10 years is sufficient to provide for 50 percent funding of several full-scale plants. However, sufficient operating experience is unlikely to be achieved by 2015 to support competitive designs.

DOE has recognized the following critical barriers to competitive IGCC power generation and has R&D programs in place to resolve the issues associated with each one:

- Transport reactor scale-up and oxygen blowing,
- Cost and reliability of advanced gasifiers,
- Syngas cooling materials, operability, and cost,
- Solids transport and removal,
- Dry gasifier feedstock capability, variability, cost,
- Availability greater than 90 percent,
- Risk reduction management, and
- CO_2 capture compatibility.

Findings and Recommendations

Finding. Under current conditions in the United States, heavy-oil- and coke-fueled integrated gasification combined-cycle (IGCC) plants, as well as gasification plants for the production of hydrogen and other chemical feedstocks, are economically viable today because the feedstocks for these plants have near-zero or negative value. However, commercial-scale coal-gasification-based power plants are not currently competitive with natural gas combined-cycle power plants at today's relative natural gas and coal prices, nor are they projected to be so by 2015 without significant capital cost reductions. Even if the projected cost of these plants reaches the required levels, investors need confidence that these plants will run as designed, with availability levels in excess of 90 percent. The only way to achieve this is to build additional plants incorporating the necessary lower cost improvements and to allow extended periods for start-up so the improved technologies can mature sufficiently to meet their goals. The pace of development and demonstration appears to be too slow to meet the goal of having coal gasification technology qualified for the placement of commercial orders by 2015.

Recommendation. The U.S. Department of Energy should cooperate with industry on technology development programs to lower the cost and improve the reliability of the first few commercial-scale Vision 21 plants. The Clean Coal Power Initiative (CCPI), recently authorized by Congress, is an example of the kind of program that can provide support for the construction of high-risk, early commercial plants. These plants should demonstrate and perfect the technology that will make coal gasification-based power plants suitable for deployment on normal commercial terms.

Finding. Experimental work, sponsored by DOE, is under way to further develop and evaluate air-blown coal gasification as a potentially lower cost approach to power production in competition with conventional coal combustion and oxygen-blown coal gasification. Because the product gas is diluted with nitrogen, air-blown gasification is not considered appropriate for making syngas for subsequent chemical production. However, this technology may in fact find a market for power production in the nearer term (pre-Vision 21) regulatory situation, which is presumed to not include CO_2 emission capture requirements.

Recommendation. The U.S. Department of Energy should continue to fund air-blown gasification R&D, but outside the Vision 21 Program, because it is not compatible with the CO_2 sequestration-ready requirements that the committee is recommending for a more focused Vision 21 Program.

Finding. The U.S. Department of Energy development programs for Vision 21 technologies for gas cleanup, fuel cells, and power production with advanced gas turbines do not currently include adequate testing of these technologies on actual coal-derived synthesis gas (syngas). The most effective way to accomplish the required testing is to install slipstream units in existing coal-fueled gasification plants so that the needed performance data can be collected. This is not being done at this time. One example of a slipstream project is a 2-MW molten carbonate fuel cell that has been scheduled for installation at the Wabash River IGCC in the third quarter of 2003.

Recommendation. The U.S. Department of Energy is encouraged to set up programs for the installation and operation of slipstream units to obtain data needed from commercial-scale gasification plants.

GAS PURIFICATION

Introduction

Gas purification can help achieve the stated objectives of the Vision 21 Program, namely, the elimination of air emissions, an increase in energy efficiency, and in a decrease in the cost of using coal to produce electricity, fuels, and chemicals. The predominant contribution of this part of the Vision 21 Program is in the removal of contaminants from process streams to prevent their eventual release or damage to downstream components. Originally, the program appeared to include a wide range of filters and contaminant removal strategies applicable at very high temperatures. The committee's 2000 report recommended a shift to the mid-temperature range (300°-700°F), which is most relevant to gasification processes, and the required changes appear to have been incorporated into the most recent activities, although significant components addressing hot gas filters remain in the program (NRC, 2000). The program has greatly increased its emphasis on the removal of hydrogen sulfide (H_2S) and CO_2, consistent with the overall Vision 21 evolution toward a coal gasification strategy within a carbon-constrained energy environment.

Milestones and Goals

The objectives of the Vision 21 gas purification program are these:[3]

- Near-zero environmental emissions from gasification-based processes and
- Reduce synthesis gas contaminant levels to protect downstream components
  - — Mid-temperature operation (300°-700°F) is emphasized;
  - — Contaminants of concern include both gas-phase contaminants and particulates at Vision 21 concentration levels.

The milestones for the Vision 21 gas purification program are these (DOE, 1999a):

- Complete pilot-scale testing of subsystem components (e.g., sulfur control, particulate control, trace contaminant control) (2002);
- Test prototypes of integrated gas-cleaning systems (2004); and
- Complete design basis of commercial-scale gas purification system (2010).

A number of things are not clear from these milestones or from Stiegel[4] and DOE (1999a): the implementation time frame, the intermediate milestones, or the guiding principles that would permit an assessment of progress and likelihood of success throughout the course of this program. It is also unclear which specific activities would be required for success and which performing organizations would be responsible for each specific milestone.

[3]G.J. Stiegel, NETL, "Gas Purification," Presentation to the committee on May 20, 2002.
[4]G.J. Stiegel, NETL, "Gas Purification," Presentation to the committee on May 20, 2002.

Progress, Significant Accomplishments, and Current Status

The current program includes NETL activities addressing the development of selective sulfur sorbents and sulfur oxidation processes, as well as the operation of a facility for the development and demonstration of gas cleanup technologies. A program led by Research Triangle Institute (RTI) is exploring removal strategies involving sorbents and membranes for H_2S, CO_2, ammonia (NH_3), and hydrogen chloride (HCl). Siemens Westinghouse leads a project that aims to develop two-stage processes for H_2S and HCl removal to parts per billion (ppb) levels.

The NETL Gas Process Development Unit has been certified for operation and will start evaluations of sorbents and process configurations shortly. In-house NETL research appears to have led to packed-bed adsorbents that decrease H_2S concentrations to less than 1 ppm at moderate temperatures. It is stated that this is a significant improvement over commercial processes, which lead to 60-80 ppm at 25 percent higher costs. The properties of these materials in fluid and transport bed systems are currently being explored. It is not clear, however, whether the systems are compared with sulfur removal processes at higher temperatures, since low- and medium-temperature adsorbents capable of sulfur removal to less than 1 ppm are routinely used to purify synthesis gas in refining, gas conversion, and methanol synthesis. The committee was informed (after requesting some clarification) that the new materials are regenerable, in contrast with those used in available technologies for deep sulfur removal. In view of the thermodynamic requirements for strong adsorption (for removal of sulfur to 1 ppm), the guiding principles and mechanism by which regeneration occurs completely and with high energy efficiency need to be carefully examined before significant outlays for additional research. NETL research activities have also led to a selective H_2S oxidation process, which could bring significant reductions in the costs associated with synthesis gas cleanup.

The RTI-led project has also developed a selective H_2S oxidation process, although it is unclear what "developed" means in this context and as used throughout the descriptions of various Vision 21 projects. A comparison of the RTI-led project and the NETL project is not possible in the absence of additional details (or even a common basis of comparison).[5] Clearly, such a comparison and the systematic exchange of information between the RTI and NETL oxidation projects would minimize any duplication of effort and exploit the likely synergies between the two projects.

Response to Recommendations from the Committee's 2000 Report

The committee report (NRC, 2000) recommended that the time frame for development of contaminant removal technology be extended to match the imple-

[5]G.J. Stiegel, NETL, "Gas Purification," Presentation to the committee on May 20, 2002.

mentation milestones of the gasification processes envisioned in the Vision 21 Program. That report also recommended that medium-temperature removal schemes be preferred to removal schemes at high temperatures, in view of the recommended increased emphasis on gasification relative to combustion research. These two recommendations have been reflected within the emerging program, although some residual activities in hot gas filtering remain in the Vision 21 Program. The cost analyses carried out for some of the technologies also reflect the recommendations of the committee. Less visible in the current program is any closer integration with science-based initiatives within and outside DOE or any attempt at the rational or theory-guided design of materials, which were included as general recommendations in the earlier committee report.

Issues of Concern and Remaining Barriers

Several issues are apparent from the emerging gas purification programs. The current emphasis on H_2S may well have orphaned the required concurrent efforts in CO_2, HCl, and NH_3 removal, and it is unclear if or how these last-named three have been accommodated within parallel efforts in DOE's environmental control program and the materials program, or how any exchange of information is taking place, or how technical synergies among purification, separations, materials, and environmental control areas are being encouraged and exploited. The depth and rigor of the economic analyses is not apparent from the information made available, and the comparisons among the various approaches under development and between each approach and existing commercial processes are not treated consistently.

The 2002 milestone (complete pilot-scale testing of subsystem components, e.g., sulfur control, particulate control, trace contaminant control) does not seem realistic in view of the limited progress to date. Finally, the extension of fixed-bed materials to transport or fluid-bed systems remains uncertain as does the path by which models and experiments will be used to assess the likelihood of success and to guide the design of new materials that meet the proposed performance and cost requirements.

Findings and Recommendations

Finding. The objectives of the gas purification program are not stated quantitatively or with the required cost targets, and the milestones are insufficiently detailed to permit intermediate assessments of progress towards goals.

Recommendation. The objectives and milestones need to be more rigorously defined and stated and the responsibility for accomplishing each milestone assigned clearly to a performing organization. Intermediate milestones with a higher technical content and specific cost targets also need to be incorporated into future review processes and into ongoing assessments of progress. Cost-benefit analyses and cost targets need to be incorporated into the planning and execution of these programs.

Finding. The current emphasis on hydrogen sulfide (H_2S) adsorption and oxidation is appropriate, but it leaves research on removal strategies for other impurities with insufficient emphasis and support. The methodology used to determine the appropriate balance among efforts aimed at the removal of specific impurities is not clear. Many of the activities in gas purification seem unconnected to closely related research in other subprograms and in research activities, such as in materials, separations, surface chemistry, and catalysis, supported by the Office of Science and the National Science Foundation.

Recommendation. The Vision 21 Program should balance the current effort in H_2S with more visible activities in the removal of CO_2, HCl, and NH_3, after appropriate and rigorous engineering analysis of the trade-offs and process requirements. It should couple these efforts with those currently under way in the separations and environmental controls areas. These activities should be more closely connected to those sponsored by the gas separations, materials, and environmental controls subprograms in Vision 21 and possibly include a consolidation of these three subprograms into a single one with a more fundamental emphasis on the extraction of specific molecules from complex streams at medium temperatures.

Recommendation. The Vision 21 Program should conduct a specific engineering analysis of the proposed and on-going Vision 21 oxidation approaches to sulfur removal to more precisely assess performance, cost and economics of these approaches.

Finding. The activities within the purification program share fundamental principles associated with the chemical and structural properties of porous solids and their surfaces. This is an area where rapid scientific progress has occurred and where rigorous theory is emerging as an essential tool for the design and synthesis of new materials. These tools are not being used effectively or systematically within the current program.

Recommendation. A panel of technical experts should assess the state of adsorption technology, identify the fundamental materials barriers (chemical and structural) to improvements, and recommend more fundamental and theory-guided research activities to supplement the existing exploratory program. These activities should be carried out as part of a crosscutting effort in adsorption, which should include efforts in the gas separations, environmental controls, and materials subprograms.

Finding. The gasification-based emphasis in the Vision 21 Program has created intellectual and technological connections among the areas currently structured separately as subprograms in gas purification, gas separations, and environmental controls. The programs are defined predominately on the basis of where and for what reason a stream is "purified," yet they share common intellectual components and chemistries based on catalysis, adsorption, and transport.

Recommendation. The gas purification, gas separations, and environmental controls subprograms should be immediately merged into a single subprogram. A rigorous engineering analysis should be carried out to examine where in the process the removal or extraction of certain molecules should occur—e.g., oxygen (O_2) purity vs. CO_2 capture; H_2S or mercury (Hg) removal after gasification or SO_x or Hg removal after combustion; NO_x removal via catalysis/adsorption or NO_x avoidance via catalytic combustion, and so on. This would exploit the common intellectual basis of the processes and allow their integration in a less fragmented manner.

GAS SEPARATIONS

Introduction

The stated objectives and focus of the Vision 21 Program are the elimination of air emissions, an increase in energy efficiency, and a decrease in the cost associated with the use of coal to produce electricity, fuels, and chemicals. Gas separations enable some of the critical technologies required to achieve these objectives. Air enrichment is required for high-efficiency gasification processes, and it will become increasingly essential as concentrated CO_2 effluent streams become more valuable in a carbon-constrained environment with viable sequestration options. Fuel cells are essential components in many approaches designed to eliminate emissions, minimize CO_2 emissions, and remove the intrinsic second-law inefficiencies of conventional Carnot cycles for power generation. In some scenarios, pure hydrogen (H_2) streams are required for power generation using fuel cells, and the availability of such streams will require significant advances in the extraction of H_2 from the synthesis gas streams produced in coal and biomass gasification. The current program focuses narrowly on ceramic and metal-ceramic composite membranes, which, if successfully developed and implemented, will make it possible to generate pure O_2 and H_2 streams. Also, the sequestration of CO_2 in carbon-constrained energy scenarios will require cost-effective methods for the concentration and separation of CO_2 from effluent streams. The current program includes one component that examines the feasibility of CO_2 hydrate formation and the enabling mechanisms for the efficient and selective extraction of CO_2 from these effluent streams.

Milestones and Goals

The objectives of the Vision 21 gas separation program are these:[6]

- Produce 99.5-percent pure O_2 using membranes or other advanced technologies at an energy consumption of less than 100 kWh/ton O_2 and a cost of \$10-\$12/ton O_2;
- Produce 99 percent pure H_2 using dense ceramic membranes or other advanced technologies at a cost of less than \$4/MMBtu, and
- Develop technology for separating CO_2 from syngas or H_2 (e.g., CO_2 hydrates or hydrogen separation membranes) at a cost of less than \$10/ton CO_2).

The stated milestones of the Vision 21 gas separation program are these:[7]

- Test a prototype air separation module integrated with a gas turbine (2006);
- Develop a technology base for commercial hydrogen separation membranes (2006);
- First commercial membrane oxygen separation plants (2008); and
- First commercial membrane hydrogen plants for power and fuels processing (2010).

No intermediate or more detailed milestones are stated,[8] nor is it clear which of the several concurrent programs is supposed to achieve each of these milestones. The CO_2 part of the program does not seem to have stated milestones.

Progress, Significant Accomplishments, and Current Status

The current program includes two projects in O_2 separation led independently by Praxair and Air Products that predate the Vision 21 Program. Both projects appear to be making satisfactory progress towards the long-term performance targets. The differences and/or synergies between the two projects and any possible complementarity in the two approaches remain disappointingly uncertain, and the two efforts appear to duplicate many activities and tasks. The

[6]G.J. Stiegel, NETL, “Gas Separation,” Presentation to the committee on May 20, 2002.
[7]Ibid.
[8]Ibid.

performance targets for flux, stability, integrity of metal-ceramic seals, and commercial viability have been exceeded. Yet, the expected cost reductions remain modest relative to the overall cost reductions required for implementing the gasification-based power generation processes envisioned within the program. This suggests that the performance targets have not been sufficiently aggressive in the context of the Vision 21 strategy to focus on systems that "achieve leapfrog improvements in performance and costs" (DOE, 1999a). The concurrent programs in O_2 separation appear to be at a sufficiently advanced state of development that a technology incorporating any synergies between the two projects can and should be chosen and that the promise of the technology would drive industry-led implementation even without DOE funding. While the progress and improvements have been significant,[9] the likelihood and impact of future advances remain uncertain, as do the mechanisms for seeking such improvements from research activities within and outside the current DOE-funded projects.

The current program in the separation of H_2/CO_2 mixtures includes three approaches: extraction of H_2 via ceramic membranes at high temperatures, and low-temperature extraction of CO_2 via either hydrate formation or selective diffusion through polymeric membranes. In the H_2-membrane approach, some increases in flux have been attained by the use of thin films and composites, but their cost and practical implementation remain unclear, especially at the high temperatures of the envisioned applications. CO_2 removal via the hydrate formation project appears to have remained at the conceptual stage, but even so the results so far suggest significant promise, the implications of which must be experimentally demonstrated. The polymeric membrane project has just been initiated and appears to have no tangible accomplishments, well-defined milestones, or clearly articulated strategy.

Significant barriers remain in all of these projects. They arise predominately from the untested large-scale implementation of ceramic membranes and from the high level and great variety of impurities in $H_2/CO_2/CO$ streams derived from synthesis gas.

Response to Recommendations from the Committee's 2000 Report

The 2000 committee report recommended the rapid evaluation of the CO_2 hydrate approach in anticipation of a greater emphasis on CO_2 removal from shifted synthesis gas streams: The current program reflects changes in response to this recommendation (NRC, 2000). However, the assessment and the conclusions still require significant refinement and a higher level of detail and rigor.

The committee also recommended continued support of oxygen transport membranes with the objective of choosing the most effective technology in the near future. The Vision 21 Program has followed this recommendation, and the

[9]Ibid.

demonstrated advances bode well for the ultimate implementation of ceramic membranes for air purification. The thermodynamic infeasibility of generating H_2 from water using proton conductors (pointed out during the committee meetings with DOE program managers in 2000) has been recognized by DOE, and that the program had at one time been proposed (DOE, 1999a) no longer appears in the Vision 21 Program.

The committee's 2000 report suggested that research activities in general be better coordinated with fundamental research activities led by DOE's Office of Science and the National Science Foundation (NRC, 2000, pp. 24-25). This suggestion does not appear to have been followed in the gas separation area, even though these funding organizations provide significant support in the areas of ceramic materials, polymer films, and surface science of potential adsorbents.

Finally, the committee's recommendation to conduct an independent economic assessment of the hydrogen membrane technology appears to have led to the definition of some targets, but the details and rigor of the assessment and the likelihood that the current hurdles can be overcome within the proposed milestones remain unclear. It is also unclear whether the economic assessment evaluated recent advances in the hydrogen membrane technology area outside the narrowly focused programs currently funded by DOE.

Issues of Concern and Remaining Barriers

It appears that the Vision 21 Program in O_2 separation will reach commercial viability within the next 6-7 years but will lead to relatively modest cost reductions compared with those required to achieve the cost target for systems generating power via gasification-based routes. The costs and time scales of the two concurrent projects and the apparent lack of synergy between them is of great concern, especially in view of limited budgets and the need to increase the emphasis on H_2/CO_2 separations. The H_2 ceramic membrane project appears to be too narrowly focused and to duplicate some of the efforts already made in solving related problems for ceramic materials, and the configurations useful for O_2 transport are similar in composition, module design, and transport mechanism to those used for H_2 transport. In both O_2 and H_2 ceramic membranes, the variable concentration and identity of the many impurities in process streams continue to raise significant concerns about the durability of these membrane systems, especially the H_2 membranes, which must operate at higher temperatures and under more aggressive chemical environments, or when O_2 transport membranes are more closely coupled to the gasifier in an effort to exploit chemical potential gradients to increase O_2 fluxes and decrease compression costs.

In addition, the exclusive emphasis on ceramic membrane separations allows for very limited purity-cost trade-offs, because of the very high H_2 and O_2 purity that makes these membranes attractive. It is unclear, however, that such purities are either required or cost-effective in gasification-based processes. Yet, adsorption or absorption processes with lower product purity but considerably higher purity-cost elasticity are not being actively pursued as part of the program, and the purity-cost trade-offs have not been examined by rigorous engineering analysis.

Findings and Recommendations

Finding. The milestones for the gas separations program are not sufficiently detailed to permit intermediate rigorous assessments of the likelihood of success in any one area, and some of the targets are not sufficiently aggressive compared with the leapfrog technologies encouraged by Vision 21. The lack of technical details and of clearly described guiding principles makes these assessments not just difficult but impossible, and the milestones less useful than required. The current state and expected progress are not benchmarked rigorously against recent advances in the open and patent literature, and they appear to be measured only internally against targets and expectations.

Recommendation. The Vision 21 Program in gas separations should continue to include strategies for separating O_2 from air, but with a continuous evolution toward the more challenging task of extracting H_2 or CO_2 from shifted synthesis gas streams. More aggressive and detailed intermediate milestones and a better description of the guiding strategies for future advances should be incorporated into all future technical and committee reviews of these programs. Competitive surveillance of outside activities in ceramic membranes should become an integral part of this program (and all other Vision 21 subprograms) in order to measure the progress of Vision 21.

Finding. The two concurrent programs in O_2 separations duplicate efforts with few synergies, and they seem ill advised at this stage of development and in light of the unmet demand for effort in other areas. The programmatic connections between the Vision 21 Program using pressure-driven O_2 separation and parallel development efforts using concentration gradients in synthesis gas generation from natural gas are unclear; yet, materials, mechanical and chemical issues, and manufacturing technologies are nearly identical in the two approaches. The two O_2 separation projects within the Vision 21 Program do not appear to be connected in any way with the H_2 membrane program, with which they share many common technical issues and barriers, or for that matter with each other. In addition, no connections are apparent among these ceramic membrane programs and the materials program in Vision 21, or with very significant materials programs funded by the Office of Science and by the National Science Foundation, all of which have significant components dealing with ceramic materials and with the surface properties of potential adsorbents.

Recommendation. A detailed technical review should be conducted of the ceramic membrane programs in O_2 and H_2 separation using outside experts. The objective would be to select one of the two current programs for subsequent demonstration and implementation and to incorporate all of the existing intellectual property and knowledge into this remaining program. The funds made available by this consolidation would be redirected for the development of new membrane materials for H_2 transport (integrating it more closely with the materials program and with the remaining development program in O_2 transport membranes) and for more fundamental studies of capture strategies for CO_2.

Finding. The economic promise of CO_2 hydrates as a separation technology is supported by the economic assessment carried out, but the technical feasibility and the thermodynamic and kinetic barriers remain largely unexplored. In addition, the rigor of the engineering and thermodynamic analyses remain unclear, as do the guiding principles that would make this the most attractive of the myriad available absorbers with a wide range of binding energies.

Recommendation. An independent technical review should be conducted in the general area of CO_2 separations, with emphasis on the common thermodynamic and dynamic issues that limit the commercial viability of all these technologies. Specifically, an assessment should be made of any fundamental advantages of hydrates over other "adsorbents," which may form complexes with CO_2 binding kinetics and thermodynamics similar to those of CO_2 hydrate complexes.

Finding. The impact of the O_2 (and H_2) purity on the economics of the gasification-based processes being developed as part of Vision 21 does not appear to have been considered through any detailed engineering analysis. Thus, the potential consequences of the inelastic purity-cost trade-offs of membrane systems and more flexible processes remain unexplored.

Recommendation. A rigorous engineering analysis of the impact of O_2 (and H_2) purity on overall plant economics should be carried out and alternative processes not based on dense ceramic membranes (e.g., adsorption, absorption, porous membranes) should be considered as more effective sources of less enriched O_2 (and H_2) streams.

Finding. The gasification-based emphasis in Vision 21 has created intellectual and technological connections among the areas currently structured as gas purification, gas separations, and environmental controls. These areas are currently structured as separate programs, defined predominately on the basis of where and for what reason a stream is "purified." Yet, they share intellectual components and chemistries based on catalysis, adsorption, and transport.

Recommendation. The gas purification, gas separations, and environmental controls subprograms should be immediately merged into a single subprogram. A rigorous engineering analysis should be carried out to answer critical questions about the point in the process where certain molecules should be removed or extracted (e.g., O_2 purity vs. CO_2 capture; H_2S or Hg removal after gasification or SO_x or Hg removal after combustion; NO_x removal via catalysis/adsorption or NO_x avoidance via catalytic combustion, and so on). This will exploit the common intellectual basis of the required processes and allow their integration into the process in a less fragmented manner.

Finding. H_2 separation remains the most challenging area scientifically. It is the most critical separations hurdle in any gasification scenario that uses H_2, and the one where progress has been most disappointing and that is most in need of fundamental research. There is a need to stimulate such research—in, for example, DOE's Office of Science and at the National Science Foundation (NSF)—on the fundamental issues that will be critical to meeting the Vision 21 separations challenges.

Recommendation. The H_2 separation program should shift its priorities, as befits its longer range and greater difficulty, toward experimental and theoretical research of a more fundamental nature. This shift in Vision 21-funded research projects should occur concurrently with an efficient and direct integration with materials and separation programs in NSF and the DOE Office of Science. This recommendation for stronger fundamental programs and closer integration with these federal agencies appears throughout this report in the context of many subprograms. It is most critical in the H_2 separations area because of the area's level of difficulty, its importance in H_2-dependent gasification scenarios, and the limited progress made throughout many years of DOE-sponsored research.

FUEL CELLS

Introduction

Fuel cells convert the chemical energy in a fuel directly to electrical energy at high efficiency. High-temperature fuel cells, including molten carbonate and solid oxide systems, are capable of using mixtures of hydrogen, carbon monoxide, and methane as fuel. Because of their high conversion efficiency, fuel cells can be used in conjunction with coal-gasification and gas-turbine systems to produce power at overall efficiency levels that can meet, and perhaps significantly exceed, the Vision 21 Program goal of 60 percent (HHV) for coal and 75 percent (LHV) for natural gas—equivalent to 68 percent (HHV).

However, current high-temperature fuel cell systems have modest capacities; the largest system ever built, which was used for natural gas, had a capacity of only about 2 MW. Recent development programs have focused on small, natural-gas-fueled units that could meet the needs of a potential distributed power-generation market. Experimental work to date on coal-derived gas has been in laboratory or slipstream units, with the largest experiments at a scale of 20 kW. The costs of current units, which are still manufactured in small development facilities, are far higher than the cost requirements of the distributed power-generation market, which in turn are higher than the more stringent cost requirements of the central station market. Cost reduction is the greatest challenge to the development of fuel cells for central station coal gasification-fueled units. Other unresolved issues are associated with operation in conjunction with gasification and gas-turbine systems, which must ultimately be demonstrated in large-scale units.

Goals

Two of the stated goals of the Vision 21 Program are to achieve 60 percent efficiency (HHV) for coal-fired power-generating systems and 75 percent efficiency (LHV) for natural-gas-fired generating systems. Meeting both goals will require that high-temperature fuel cells be combined with gas turbines in hybrid systems. To meet these two overarching Vision 21 goals, the fuel cell program has divided its activities into two areas.

The first, to develop fuel cell-turbine hybrids, covers the natural gas fuel cell program for 21st century fuel cell-gas turbine hybrids (DOE, 1999a, 1999b, 1999c) and is focused on reducing emissions of carbon dioxide, oxides of sulfur (SO_x), and oxides of nitrogen (NO_x). The expressed goals are as follows:

- Near-term efficiency of 60 percent (LHV) (FY 2003),
- Mid-term efficiency of 70 percent (LHV) (FY 2010),
- Long-term efficiency of 75 percent (LHV) (FY 2010),
- Capacities of between 1 and 10 MW, and
- Projected commercial cost of less than $1,700/kW.

The current program calls for work to be carried out by established developers of high-temperature fuel cells. FuelCell Energy is working on molten carbonate, and Siemens-Westinghouse on solid oxide fuel cell systems. Both developers are focusing on systems with capacities of 250 kW to 5 MW for distributed power generation or cogeneration. Both developers have demonstrated hybrid fuel cell-gas turbine systems of about 250 kW.

DOE/NETL has established outside the Vision 21 Program a new fuel cell program, the Solid State Energy Conversion Alliance (SECA). The goal of this program is to establish by 2010 a number of commercial solid oxide fuel-cell-based products with capacities of 5 to 10 kW and overall system costs of $400/kW or less based on a total market for such products of about 50,000 units/year. Contracts are under way with four industrial organizations, each of which will develop, design, fabricate, and market a product based on solid oxide fuel cell technology. Additional contracts are contemplated, with other organizations developing additional products or new technology benefiting one or more of the product developers.

The outcome of this SECA program is expected to be lower costs for solid oxide fuel cells based on expanded cell production and more interest on the part of industry in solid oxide technology due to profitable commercial applications.

The goal of the Vision 21 fuel cell program is the development of large-scale (i.e., greater than 30-MW capacity), high-temperature fuel cell power systems with the following characteristics:

- A system cost of ≤$400/kW and a cell cost of ≤$200/kW,
- An operating life of 80,000 hours,
- "Improved" performance relating to efficiency, power density, tolerance for contaminants, and
- Fuel flexibility, ability to use coal gas, biomass, petroleum distillates, and residues.

Progress, Significant Accomplishments, and Current Status

The DOE/NETL continuing program in fuel cells recently fabricated and demonstrated two approximately 250-kW, natural-gas-fired, hybrid fuel cell-gas turbine power generation plants, one employing molten carbonate cells, the other solid oxide cells. The efficiencies of these systems, about 53 percent (LHV), has fallen significantly short of the target 60 to 70 percent (LHV) because the design and operating characteristics (capacity, compressor pressure ratio, expander inlet temperature) of the available gas microturbines has not been integrated effectively with the fuel cell generator characteristics.

The program also now includes four SECA projects, each conducted by an industrial firm and directed at commercializing a complete 5- to 10-kW solid oxide power generation unit for a specific market application—a mobile, premium, or military power source. Products are to be available in 4 years, and their cost is to be reduced from $1,400/kW to $400/kW or less by 2011. The primary goal of the SECA program is to reduce the high production cost of fuel cell power systems, now perceived to be the most significant barrier to commercialization of the technology. The secondary goal is to develop markets for solid oxide fuel cell systems and to provide a base of industrial support for the continued development of high-temperature fuel cell technology. Proposals have been sought and received from developers of technology considered to be of interest to the industrial organizations producing the SECA products. The development of lower cost fuel cell fabrication technologies was not considered one of the areas of interest.

Four current fuel cell projects are listed by DOE/NETL in the current Vision 21 Program:

- The design and cost estimate for a 40-MW hybrid molten carbonate fuel cell power system;
- An investigation of a system combining a solid oxide fuel cell power system with a ceramic membrane O_2 transport system used to complete the combustion of the spent fuel, avoiding dilution of the CO_2 product with N_2; CO_2 capture is thus simplified;
- The development and fabrication of a 3- to 5-kW planar solid oxide fuel cell system coupled with a supercharger-derived gas turbine. This is a SECA program;
- A scale-up and cost estimate of the fuel cell technologies included in the SECA program from 5 or 10 kW to 250 kW.

Main Integration Issues

Coal gasification and fuel-gas cleaning will be required for central station power systems. The gasification technology will have to be adapted and integrated into the overall fuel cell power system. Attaining high overall efficiencies in power generation will require that the heat rejected from the fuel cell operation provide enough heat for fuel reforming or gasification. The feed gas to the fuel cell will have to be cleaned to protect the cells from sulfur compounds, heavy metals, and particulates in the coal gasification effluent.

The Vision 21 gasification program includes work on coal gasification processes directed at reducing the gasification temperature, which could allow reject heat from fuel cell operation to be used in the gasification process. But further consideration is needed to explore the use of heat from cell operation in coal gasification.

Gas Turbines

The Vision 21 gas turbine program includes turbines for large-scale hybrid fuel cell power systems. In such systems the gas turbine will generate about 1/5 of the total power output. But the capacity of such turbines, their technical features, and their operating characteristics are not defined in the turbine program as outlined. Nor has a technical or programmatic approach to the development of gas turbines suitable for fuel cell power systems been specified. A fundamental problem for such development appears to be the inflexibility of the operating characteristics of both the gas turbine and the fuel cell generator and the inherent mismatch between them. For example, fuel cell efficiency increases as the load is decreased while gas turbine efficiency decreases significantly.

Micro gas turbines from Capstone and Ingersoll-Rand have been incorporated in the two DOE/NETL hybrid fuel cell systems tested to date. These turbines, along with heat exchangers for regenerative air heating, were designed for small-scale, natural-gas-fired, distributed power generation. They have not proved optimal in these fuel cell systems because of the mismatch in operating conditions. And the overall system efficiencies have fallen significantly short of DOE/NETL target values. Suitable gas turbines could not be identified for a 1.0-MW tubular solid oxide fuel cell power system in an Environmental Protection Agency (EPA) laboratory building.

Further definition and development is required in the Vision 21 Program regarding gas turbine requirements for hybrid fuel cell power systems.

Heat Exchangers

Low-cost, reliable equipment for heat exchange is essential in all fuel cell power systems for fuel and air preheat, heat removal from the cells, and heat recovery. Hybrid fuel cell–gas turbine systems need an exchanger for regenerative air heating from the turbine expander exhaust gases. Regenerative air heaters will be required with top temperatures of 1400°F to 1600°F at pressure differences of 2 to 4 atmospheres. No indication of such heat exchanger development appears in the Vision 21 program material. Apparently such development is left for the fuel cell and gas turbine developers.

The lack of effective, economic exchangers may severely limit the efficiencies achieved in hybrid fuel cell power systems. Further consideration should be given to the need for exchanger development in the Vision 21 gas turbine program.

Materials

Special materials will be required for the production of fuel cell components, such as the electrolyte, electrodes, cell supports, current collectors and interconnects, cell stacks and/or arrays, ducts, and manifolds. Low-cost manufacturing techniques will also be required for the production of fuel cell stacks, bundles, and arrays. The development of these fuel cell materials and the associated production techniques should logically be included in the Vision 21 fuel cell program.

The request for proposals to the core program supporting the SECA fuel cell systems developers excluded materials and fabrication process development save for the production of low-cost materials for current fuel cell production techniques.

Two projects in the Vision 21 materials program—oxide-dispersion-strengthened (ODS) tubing for high-temperature exchangers at Specialty Metals and Oak

Ridge National Laboratory (ORNL) and electrolyte materials at Pacific Northwest National Laboratory (PNNL)—appear directly applicable to the fuel cell program. It is not clear how these projects currently interact with the primary elements of the program.

Computerized Simulations

DOE has selected computerized simulation as a possible means for facilitating the development of Vision 21 technologies (i.e., for assessing alternatives, determining optimal configurations, and reducing the costs of demonstrations). DOE has used the ASPEN computerized material and energy balance program to model the performance—primarily capacity but also the efficiency of various fuel cell systems based on their configurations and operating conditions as represented by a flow diagram.

The Vision 21 fuel cell program has initiated a project at the National Fuel Cell Research Center (NFCRC) to model and optimize the various natural-gas- and coal-fired power system configurations, most of which incorporate solid oxide fuel cells. It is not clear to what extent models of the plant components used and/or developed in this program will be made available for use by the public. In any case, additional simulation capabilities are needed in the development of Vision 21 fuel cell power systems to do the following:

- Relate system reliability and maintainability to the design of the fuel cell stack and auxiliary equipment as well as to the overall configuration of the plant as indicated in its overall flow diagram;
- Explore the operability (start-up, load follow, and shutdown) and controllability of the generation or cogeneration plant and evaluate diagnostic procedures required for its safe, automatic, unattended operation;
- Study and evaluate various manufacturing techniques for the production of fuel cell stacks; and
- Represent the overall fuel cell plant layout and design in three-dimensional space in enough detail to estimate overall plant space requirements and costs.

Power Conditioning

Another technology important to a fuel cell power system is power conditioning, converting the direct current output of fuel cells to alternating current, maintaining the desired output voltage, and matching the power generated by the fuel cells with the load. Reducing the cost of fuel cell power systems will require the development of affordable power conditioning systems, perhaps integrated with the computerized instrumentation and control system.

The Vision 21 fuel cell program is relying on other DOE and Department of

Defense (DOD) programs and procurements to provide low-cost power conditioning systems of adequate performance and capacity.

Proposed Program Plan, Milestones, and Schedule

Elements of the DOE/NETL Vision 21 fuel cell program plan are found in the *Vision 21 Program Plan* (DOE, 1999a), the *Vision 21 Technology Roadmap* (NETL, 2001), and the DOE presentation to the committee.[10] This presentation identified the construction and operation of four demonstration plants as the major milestones of the program:

- A hybrid fuel cell-gas turbine power plant of about 1 MW (2006),
- A fuel cell power plant integrated with a coal gas fuel processor (2006),
- A 60-70 percent (LHV) efficient hybrid fuel cell-gas turbine fired by natural gas (2010), and
- A 30-MW hybrid fuel cell power system integrated with a coal gasifier (2015).

In general, these plants expand on those proposed in the *Vision 21 Program Plan* of April 1999 (DOE, 1999a). The integration of coal processing with fuel cell generation has been added. A second large-scale, coal-fired hybrid plant has been added as an overall culmination of the Vision 21 fuel cell program.

It would appear that those elements of the Vision 21 fuel cell program identified in the April 1999 plan as "Develop 21st Century Fuel Cell" have been incorporated in the SECA effort. Four to six industrial organizations will initiate efforts to produce low-cost, small-scale commercial fuel cell systems of 5-10 kW capacity. They will be aided in their efforts by a number of other organizations—universities, research centers, national laboratories, etc.—in areas the industrial organizations identify as important to their work. This arrangement is expected to produce the improvements in cell performance and cost required by Vision 21 fuel cell systems. The milestones and schedules for SECA are essentially commercial fuel cell systems with an overall cost in 2004 of $1,400/kW, declining to $1,000/kW in 2007 and $400/kW in 2010.

The *Vision 21 Technology Roadmap* for fuel cell systems covers the following (NETL, 2001):

- The status and objectives for performance and cost associated with various elements of a fuel cell system in the following categories:
  - The fuel cell generator—materials, cell and stack fabrication; manifolding, support, and housing, etc.;

[10] M. Williams, NETL, "Program Overview of the Vision 21 Fuel Cells Program," Presentation to the committee on May 20, 2002.

  — The fuel preparation and processing equipment;
  — Balance of plant equipment—piping, heat removal and recovery, gas and steam turbines, operation and control. The gas turbine roadmap includes turbines for hybrid fuel cell-gas turbine systems; and
  — Power recovery and conditioning equipment—wiring, dc-ac conversion.
- The perceived barriers between the status and objectives for each of the elements identified in the categories above; and
- The status of these barriers and the approach to minimizing their effect in three time periods, namely, 0 to 5, 5 to 10, and 10 to 15 years.

This roadmap was prepared in a workshop attended by representatives of fuel cell experts from industry, universities, and the government, including the national laboratories.

It is not clear how this roadmap can or will be used in guiding the journey to the Vision 21 goal of designs for large-scale, commercial, natural-gas- and coal-fired fuel cell generation and cogeneration systems in 2015. In general, the map gives no indication of technical approaches to overcome the barriers to performance and cost improvement. It appears to offer administrative measures—for example, design something, develop this, leverage that, demonstrate something else. How this advice fits in the DOE/NETL mode of defining and contracting research, development, and demonstration is not clear.

It appears that the DOE/NETL Vision 21 fuel cell program has chosen to define demonstration products or plants that will serve as milestones for the overall program. The industrial contractors for these products or plants will identify areas for supporting research and development. They will conduct such, subcontract it to outside organizations, or recommend that DOE/NETL include it in procurements contracted primarily to universities, national laboratories, and private research and development organizations.

Information is not readily available on the allocation of funding in various other DOE/NETL programs—including those in gasification, gas cleaning, and gas turbine programs—that apply to the Vision 21 fuel cell program. The adequacy of efforts in the three areas is difficult to assess without some knowledge of this funding.

Discussion

DOE/NETL has an effective fuel cell program that has demonstrated significant progress in technology development. It has focused on high-temperature molten carbonate and solid oxide fuel cells and on a single developer of each of these cell types. Both developers have successfully demonstrated natural-gas-fueled power systems, both fuel cell based and hybrid fuel cell/gas turbine based, of 200 kW or larger. DOE/NETL has now launched a program, SECA, to reduce the cost of solid oxide fuel cell systems having a capacity of 5 to 10 kW and to commercialize their production and application.

An apparent application for larger, high-temperature fuel cell systems, perhaps 2 to 20 MW in capacity, is natural-gas-fired distributed power generation or cogeneration systems. It would appear advantageous for the DOE/NETL fuel cell program to develop and demonstrate a flexible, integrated cogeneration system capable of supplying power, heat in the form of steam, and cooling based on an absorption refrigeration cycle acting as a heat pump. Such a system might readily attain an energy efficiency of 80 percent.

The committee has recommended that the DOE/NETL Vision 21 Program focus on coal-based, utility-scale (200-500 MW) power generation having minimal environmental impact, including CO_2 emissions (see Chapter 2). The committee's specific findings and recommendations for the Vision 21 fuel cell program are consistent with this general recommendation. It should be clearly understood, however, that these recommendations are meant to extend the fuel cell program rather than replace the directions and goals of fuel cell programs currently under way on natural-gas-fired distributed-generation or cogeneration systems.

Response to Recommendations from the Committee's 2000 Report

The following comments pertain to the DOE/NETL response to the recommendations on the fuel cell program from the committee's 2000 report on the Vision 21 program (NRC, 2000). Essentially, the two recommendations from the 2000 report can be summarized as follows: The Vision 21 fuel cell program should focus on reducing the capital costs and enhancing the performance of fuel cell systems in large-scale power generation (or cogeneration) plants. Funding for this program should be specified and provided.

The DOE/NETL points out that A.D. Little has studied the scale-up of fuel cell units under development in the SECA program from 5-10 kW to 250 kW. This study considered the piping and manifolding required for paralleling between 25 and 50 of the SECA units and the scale-up of the balance of plant components. Scale-up to multi-megawatt fuel cell generators may well involve significant modification of cell dimensions and stacking or bundling arrangements, as well as manifolding and piping. Further and more detailed scale-up studies considering both generator performance and cost are recommended by the committee.

DOE also said that the National Fuel Cell Research Center is performing screening analyses of both natural-gas- and coal-fired cycles, including optimization, part-load performance, temperature sensitivities, and costs. An independent review of the preliminary results would be useful for setting the direction of the Vision 21 fuel cell program.

Findings and Recommendations

Finding. The four DOE/NETL projects that currently make up the Vision 21 fuel cell program address a scattering of Vision 21 concerns: the scale-up of Solid State Energy Conversion Alliance (SECA) fuel cell technologies to 250 kW and the molten carbonate fuel cell system to 30 MW; the adaptation of the high-temperature fuel cell systems to yield spent fuel streams suitable for CO_2 capture; and the further development of a planar solid oxide fuel-cell power system to 3-5 kW.

Recommendation. Other fuel cell projects should be added to Vision 21's proposed program of demonstration plant design, fabrication, and operation, to address the scale-up of high-temperature fuel cell generator systems to 200-500 MW. While fuel cells are modular components, it seems likely that such an increase in capacity might well involve significant changes from current practice in several respects:

- Cell dimensions,
- Sealing and manifolding for reactants and products,
- Heat removal and insulation arrangements,
- Support, containment, and piping, and
- Manufacturing processes and installation and maintenance procedures.

In pursuit of such additional projects, the following factors are important considerations:

- The integration of high-temperature fuel cells with the processing and use of coal-, biomass-, and waste-derived fuels, especially the restrictions that molten carbonate and solid oxide fuel cells may place on the "cleanliness," pressure, and temperature of the fuel gas; and
- The design of flexible high-temperature fuel cell power generator modules that might be more readily fabricated and integrated with a variety of other components to satisfy a broad variety of applications.

Finding. To meet efficiency and cost goals, Vision 21 utility-scale, coal-fired fuel cell power plants will require the integration of the fuel cells with coal gasification, fuel gas cleaning, and heat removal and recovery systems that produce additional electrical energy either through a gas turbine operating in a regenerative Brayton cycle or a steam generator and steam turbine operating in a Rankine cycle. The capacity of such a power plant must be sufficiently large, 200-500 MW or greater, so that the lower cost and greater availability of coal compared with the higher cost of natural gas as fuel will outweigh the capital cost of the coal processing systems.

High-temperature fuel cells, molten carbonate or solid oxide, are the only cells whose reject heat can be used in coal gasification or power generation through thermal cycles such as the Brayton or Rankine cycles. Also, such cells have an additional advantage: The oxygen is transferred into the fuel gas through the electrolyte, so the combustion products, CO_2 and water, are formed free of nitrogen. The CO_2 can be readily concentrated by condensation of the water and thus prepared for sequestration.

Recommendation. Analytical and experimental studies should be performed to identify means for integrating the coal gasification and fuel gas cleaning processes with fuel cell power generation. Such studies, perhaps slipstream tests at existing gasification facilities, should be carried out to verify that the clean fuel gas product meets the requirements of both the cells and the environment in terms of contaminants (H_2S, COS, NH_3, alkalis, heavy metals, and particulates) and of their combustion products, the emissions from the plant. Plant design and evaluation studies should propose and evaluate means for making effective use of the reject heat from the fuel cells. The studies should also investigate with which technical features, on what scale, and under which economic and environmental conditions (including CO_2 capture and water conservation) coal gasification, gas cleaning, and fuel-cell-based power generation might be economically competitive with conventional coal- or natural-gas-fired generation. Such studies should be useful in determining the technical course of the Vision 21 fuel cell, coal gasification, and gas turbine programs and in justifying their funding.

Finding. The DOE/NETL fuel cell program has produced two hybrid fuel cell-gas turbine power systems of approximately 250 kW, one based on molten carbonate and the other on solid oxide fuel cells. Three, possibly four, additional hybrid systems are included in the program plan and schedule. The attractiveness of such plants lies in their potential for high efficiencies when converting from fuel to electric power, perhaps 75 percent (LHV) or higher for natural-gas-fired plants. But the problem is the difficulty in matching fuel cell and gas turbine components to provide an overall plant that meets the power needs of a particular application. Gas turbines are relatively inflexible in operation; their development for a particular application is in general a costly and lengthy process. Their operating characteristics do not match well those of fuel cells. All of these difficulties are confirmed by the fact that the efficiency of hybrid systems to date, about 53 percent (LHV), has fallen far short of target values, 75 percent (LHV), and has only incrementally increased the efficiency of the fuel cell system itself, about 47 percent (LHV). (The DOE/NETL fuel cell program outside Vision 21 might be emphasizing distributed cogeneration systems based on high-temperature fuel cells as a means for attaining high overall energy efficiencies, in the range of 80 to 85 percent (LHV).)

Recommendation. The DOE/NETL fuel cell program inside Vision 21 should further analyze and evaluate the performance and economics of a hybrid fuel cell-gas turbine system for large-scale, coal-fired power plants of 200-500 MW. The characteristics of the gas turbine required for such a plant should be determined, and any research and development required to achieve this turbine should be outlined, with a schedule and cost estimate.

Finding. *The Vision 21 Roadmap* for fuel cell technology identifies performance and cost goals for the various components of a high-temperature fuel cell energy system. The Roadmap also lists the barriers to reaching each of these goals. The Vision 21 fuel cell program includes four fuel cell plants as its main milestones. The overall Vision 21 programs in gasification, gas processing and separation, gas turbines, materials, modeling, systems computations, etc., have elements that may pertain to fuel cell energy systems.

Recommendation. The U.S. Department of Energy National Energy Technology Laboratory Vision 21 fuel cell program plan and schedule should incorporate milestones in addition to the current four milestones, each of which represents the construction and operation of a high-temperature fuel cell power generation plant. These additional milestones should deal with (1) removal of significant barriers to program success identified in the fuel cell roadmap and (2) accomplishment of significant steps in preparation for plant construction and operation, including developments, tests, designs, and evaluations of performance and costs for both the demonstration plant and the projected commercial plant. To the extent possible, the milestones should include quantitative measures as criteria for successful achievement, such as overall capital and operating costs of the projected commercial plant.

Finding. Many of the technical hurdles associated with membrane fabrication, sealing, manifolding, and module design and integration are common to both the ceramic membrane program and the solid oxide fuel cell program, but there is no evidence of any integration between the two programs.

Recommendation. Vision 21 should find mechanisms for sharing knowledge between the ceramic membrane and solid oxide fuel cell programs in order to leverage the funding and expertise available in the two areas.

TURBINES

Introduction

Combustion turbines are Brayton-cycle machines that produce electricity from gaseous or liquid fuels with thermodynamic efficiencies determined approximately by the firing temperature of the machine and the exit temperature of the exhaust gases. Firing temperatures in modern gas turbines are approximately 2500°F, and temperatures of 2700°F are anticipated soon. The development of high-temperature materials, intricate blade-cooling systems, and thermal barrier coatings has contributed to current high efficiencies of approximately 56-58 percent (LHV). The large-scale (400 to 500 MW) 60 percent (LHV) efficient, 60-Hz combined-cycle machines developed under DOE's Advanced Turbine System (ATS) program by Westinghouse Electric (now Siemens-Westinghouse) and by General Electric Company (GE) are now projected to be field tested on natural gas in 2003 and 2004 (or later), respectively. The 50-Hz version of the GE machine will be tested in Great Britain beginning in late 2002. These dates are later than projected by this committee in its 2000 report (NRC, 2000).

Combined-cycle power plants produce electricity from clean coal-derived synthesis gas (syngas) in gasification-based power plants in operation today. These units generally are based on mid-1990s technologies with 2500°F firing temperatures and gross power outputs of 300-400 MW. Combined-cycle power plants will be the power generation technology of choice in early gasification-based Vision 21 plants and may be used in conjunction with fuel cells in later gasification-based Vision 21 plants.

Over the past 2 years, DOE has transitioned from the ATS program, which was focused on product development (primarily the ATS machines), to the high efficiency engine technology (HEET) program, which focuses on technology infusion in natural gas combustion, materials and structures, sensors and controls, monitoring, and hybrid fuel cell-turbine systems. This change has been in response to requests from both Congress and the power industry to emphasize improving the reliability, availability, and maintainability (RAM) of current units and reducing current life-cycle costs rather than future fuel flexibility.

DOE has identified a number of HEET programs that are critical to the success of the Vision 21 Program, including the following:[11]

- ATS-derived combined-cycle improvements for coal gas applications;
- Combustor designs capable of less than 0.01 lb NO_x/MMBtu emission using catalytic combustion, trapped vortex design, and advanced after-treatment;
- New materials for improved performance and durability;
- Sensors and monitoring of conditions for improved operations and system life management; and
- Design that gives turbines the flexibility they need to be used in hybrid applications.

[11] A. Layne, NETL, "High-Efficiency Engines and Turbines," Presentation to the committee on May 20, 2002.

Milestones and Goals

The current goals of the turbine program are these:

- Fuel-flexible turbine systems capable of overall system efficiencies of 60 percent (HHV) using coal-derived gas;
- Turbines for large-scale fuel cell-turbine hybrid systems capable of overall system efficiencies of 80 percent (LHV) using natural gas;
- Turbines with NO_x emissions of less than 0.01 lb/MMBtu;
- Hydrogen and natural gas/oxygen (in place of air) turbines; and
- Combustion turbine costs of $135/kW; for combined-cycle systems, total combustion turbine plus steam turbine cost of $270-300/kW.

The current milestones for the turbine program that are related to the Vision 21 Program are these:

- Completion of the hydrogen and natural gas/oxygen turbine concept studies (2004),
- Demonstration of integrated fuel cell-turbine hybrid at 1 MW scale (2005),
- High-efficiency (3000°F firing temperature) turbines available (2008), and
- Field testing of fuel-flexible advanced turbine with coal gas (2010).

Progress, Significant Accomplishments, and Current Status

The committee took note of the following:

- The 60 percent (LHV) efficient gas turbines developed for natural gas under the ATS program are not available for commercial order in 2002, as had been anticipated in the committee's 2000 report. The Siemens-Westinghouse machine is scheduled to go into operation at a Lakeland, Florida, site in 2003. Initial operation of the 60-Hz GE machine, originally scheduled for a Scriba, New York, site in 2004, is likely to be delayed as a result of the cancellation of that project by the plant owner.
- Significant progress has been made in demonstrating that hybrid gas turbine-fuel cell power plants can produce attractive efficiencies when fueled with natural gas. More than 4,700 hours have been accumulated at 52 percent (LHV) efficiency with a unit of 300-400 kW capacity that combines a Fuel Cell Energy molten carbonate fuel cell stack and a Capstone microturbine. Over 1,000 hours were accumulated at 53 percent efficiency with a 300-kW capacity unit that combines a Siemens-Westinghouse solid oxide fuel cell and a Northern Research microturbine. It should be noted that neither the gas turbines nor the fuel cells used in

these tests had been optimized for this application. All of the components had been designed for other functions. Hybrid systems are discussed in more detail in the section of this chapter that addresses fuel cells.

- Programs are under way to develop improved materials and manufacturing technologies for turbine blades.
- Computational modeling is being applied to improve turbine efficiency and emissions performance.

It is likely that the turbine concept studies will be completed and the 1-MW hybrid power plant will be demonstrated as scheduled. However, large-scale 3000°F turbines are unlikely to be available by 2008 because of the time and funding needed to develop relatively large ceramic components for these machines. Field testing of a full-scale, advanced, fuel-flexible turbine with coal-derived syngas before 2010 is also considered unlikely because there are currently no commitments to appropriate development programs for those machines.

Response to Recommendations from the Committee's 2000 Report

The recommendation from the committee's 2000 report was as follows (NRC, 2000):

> **Recommendation.** The U.S. Department of Energy should look further ahead into the 21st century in formulating its Vision 21 plans. The ATS machines that are now proposed as the core of the Vision 21 program will be approaching the end of their model life cycle in 2015 and are likely to be supplanted in the marketplace by machines with higher efficiencies (either through higher firing temperatures or more sophisticated thermal integration cycles). To optimize its research, development and demonstration (RD&D) program, DOE must understand how these products will affect the efficiency and economic performance of Vision 21 technologies. Finally, from a research standpoint, more emphasis should be placed on those cycles that result in hydrogen as the gas turbine fuel rather than syngas to identify if any unique components will have to be developed.

Comparative systems studies are being performed by NETL, Reaction Engineering, and the NFCRC. Projects are also under way to improve hydrogen combustion, and there is coordination with the hydrogen program at DOE's Office of Energy Efficiency and Renewable Energy (EERE).

Issues of Concern and Remaining Barriers

DOE has implemented a large program to improve the performance of existing natural-gas-fueled gas turbine power plants by reducing their life-cycle costs and improving their reliability. Improved materials, sensors, and diagnostics are the main thrust of this program, which is very likely to be of use in future Vision 21 plants fueled with natural gas. However, the applicability of the outcomes of this work to syngas- and hydrogen-based Vision 21 plants is not as certain. A parallel but certainly smaller-scale program is required to accumulate the data necessary to determine if these improved systems will be of value in syngas- and hydrogen-fueled systems or whether modified or alternative systems must be developed.

While the Westinghouse Electric (now Siemens-Westinghouse) ATS machine was designed to accommodate syngas, the GE H machine was not. A significant amount of reengineering of the GE machine will be required to qualify it for operation on syngas. In addition, better combinations of cooling systems and metal properties—that is, combinations that would allow syngas firing temperatures to be as high as natural gas firing temperatures—have the potential to improve system efficiency and should be investigated. It is also necessary to collect data that will allow development of a quantitative relationship between the level of trace contaminants in syngas and damage to metals and ceramics at high temperatures.

GE is reportedly willing to offer commercial guarantees on the use of hydrogen as a fuel in its current GE 7FA+ machines. Earlier versions of this same model currently operate with syngas at the Wabash River and Polk IGCC plants. The main challenge is to determine a mechanism for qualifying the next-generation, large (400 to 500 MW) H machines for service on either syngas or hydrogen. Obviously a plant owner will want to take advantages of the economies of scale that would result from a single-train plant. However, there is a considerable risk in using a machine that has never before been run on a particular fuel in a new plant.

Hybrid gas turbine plants are being developed at this time for natural gas. There is likely to be a considerable amount of design and development work that must be done to optimally integrate a unit of this type into a gasification-based power plant.

NO_x emission control systems for syngas operation of ATS machines are likely to be required to achieve NO_x emissions levels of 3-9 ppm or less. Current methods used to reduce NO_x emissions to the 10-25 ppm level required in current IGCC plants include diluting syngas by injecting nitrogen or saturating the syngas with evaporated water. These methods are relatively expensive. The most commonly used technology to achieve lower NO_x emissions in natural-gas-fired combined-cycle systems is selective catalytic reduction (SCR). However, it is likely that the use of SCR technology in Vision 21 IGCC plants will require that sulfur compounds in the syngas be reduced to less than 15 ppm (equivalent to 2-3 ppm in the product gas entering the heat recovery steam generators (HRSG)) to avoid the possibility of ammonium sulfate deposition in the narrow spaces between the finned tubes in the HRSG section of the combined-cycle plant. These deposits are formed when the sulfur compounds in the syngas fed to the gas turbine react with the excess ammonia emitted from the SCR system. These deposits will reduce the reliability of the combined-cycle system and increase downtime. Achievement of those very low sulfur levels will require the development of improved COS hydrolysis to convert a greater fraction of the

COS in the syngas to H_2S. Conventional H_2S removal systems, which are very effective at removing H_2S to the needed levels, cannot remove sufficient amounts of COS from the syngas to achieve the desired sulfur level.

The other candidates for achieving very low NO_x emissions are combustion modifications and catalytic combustion, or some combination thereof.

Findings and Recommendations

Finding. In response to current industry needs, the DOE High Efficiency Engine Technology (HEET) program is focused on natural gas as a fuel to both gas turbines and gas turbine-fuel cell hybrids. Additional information and data are required to develop cost-effective, reliable, emission-compliant systems for power generation in Vision 21 gasification-based plants.

Recommendation. Additional commitments should be made to develop, design, and test large-scale turbine and fuel-cell power systems that can function successfully on both syngas and hydrogen, including the development of sophisticated thermal cycles involving intercooling, reheat, humidification, and recuperation. Improvements in current natural-gas-fueled power generation systems should be incorporated to the extent appropriate in syngas- and hydrogen-fueled Vision 21 power plants. DOE is encouraged to set up programs for the installation of test articles (including vanes, blades, and other high-temperature components) as well as for the installation and operation of slipstream units to obtain the needed data from commercial-scale gasification plants.

Finding. The route to successful, reliable operation of the 400- to 500-MW H series turbines in combined cycles using either syngas or hydrogen has not been established.

Recommendation. The U.S. Department of Energy (DOE) is encouraged to work with gas turbine vendors and potential gasification plant investors on an approach to qualifying the 400-500 MW H series machines that is acceptable to the market and will lead to commercial acceptance of these machines for integrated gasification combined cycle (IGCC) plants.

Finding. Emissions of nitrogen oxides (NO_x) from integrated gasification combined-cycle (IGCC) power plants are likely to be limited to 3-9 ppm in the future. The application of currently available NO_x emission control technologies for syngas-fueled combustion is not cost effective for this higher level of control.

Recommendation. Research and development on catalytic combustion and other means of modifying combustion is needed to identify potentially cost-effective systems for controlling NO_x emissions from syngas-fired, combined-cycle power plants.

Finding. The use of oxygen in place of air to fire hydrogen in integrated gasification combined cycle (IGCC) plant combined cycles has been proposed as a method of reducing NO_x emissions. Diluents will be needed to reduce the adiabatic flame temperature in the combustion zone.

Recommendation. System studies should be used to determine if the use of oxygen and hydrogen in a turbine to reduce NO_x emissions is economically viable.

ENVIRONMENTAL CONTROL TECHNOLOGY

Introduction

The primary aim of the Vision 21 Program is elimination of environmental impacts from the use of coal to produce electricity, fuels, and chemicals. Emissions to the air are controlled in Vision 21 technologies by improved efficiency and emission control technology. Emission control technology development within the DOE is found in three different program areas: coal and environmental systems, gasification, and sequestration. The coal and environmental systems area is divided into two programs: (1) Innovations for Existing Plants (IEP), which focuses on pulverized coal and fluidized-bed combustion systems for existing and new power plants and (2) Vision 21, which focuses on gasification-based systems for new power plants. IEP has been aimed at reducing the emissions of conventional pollutants such as sulfur dioxide (SO_2), NO_x, and particulate matter, but more emphasis is now being given to controlling hazardous emissions such as trace metals, acid gases, and organics. In the gasification area the focus is on syngas cleanup rather than post-syngas combustion releases to the ambient air. Syngas cleanup is discussed more fully in the section on gas purification. The sequestration program deals with the capture, separation, and reuse or disposal of CO_2 emissions. Capture and separation of CO_2 are discussed in the section on gas separation. The disposal of CO_2 is not addressed in this review of the Vision 21 R&D program.

Goals and Milestones

The emission control goal of the Vision 21 Program (gasification-based system focus) is as follows: Remove environmental concerns (i.e., achieve near-zero emissions) associated with the use of fossil fuels (coal, gas) for producing electricity and, where appropriate, clean transportation fuels (including hydrogen).[12] Vision 21 energy plant performance targets are as follows (NETL, 2001):

- Atmospheric releases
  - Less than 0.01 lb/MMBtu sulfur and nitrogen oxides,
  - Less than 0.005 lb/MMBtu particulate matter,
  - Less than 1.0 lb/trillion Btu mercury, and
  - Less than 50 percent of the organic emission rates listed in *Utility HAPS Report* (EPA, 1998)[13]
- CO_2 emission reduction
  - 40-50 percent by efficiency improvement, and
  - Essentially 100 percent reduction with sequestration

The coal and environmental systems program has a number of near-term milestones, which may have relevance to gas purification and environmental controls for Vision 21 plants:

- By December 2002 Phase I field testing of sorbent injection technology will be completed at four commercial coal-fired power plants to achieve 50-70 percent mercury (Hg) control.
- By December 2002 a targeted solicitation will be issued for Phase II field testing of advanced Hg control technologies.
- By March 2003 a targeted solicitation for gasification-based Hg control capable of operating at moderate temperatures (300°F to 700°F).
- By June 2003 complete the slipstream testing of an advanced hybrid particulate collector.

One long-term goal will be to develop lower cost technology for controlling Hg and other trace metals from pulverized coal and gasification units.

Progress, Significant Accomplishments, and Current Status

Progress has been made in controlling emissions of NO_x, particulates, and Hg. Preliminary studies of O_2-enhanced combustion show a 30 percent improvement in NO_x reduction compared with ultra-low-NO_x burners. The fundamental understanding of O_2-enhanced combustion establishes baseline performance and supports the development of O_2 separation technology for Vision 21 plants. A slipstream test of an advanced particle precharger and separator system has achieved a 99.9+ percent capture of primary particulate, which is very close to

[12] T.J. Feeley, NETL, "Innovations for Existing Plants (IEP) Program," Presentation to the committee on May 20, 2002.

[13] HAP, hazardous air pollutant.

the Vision 21 performance target and a 90 percent Hg removal by injecting modest amounts of an activated carbon. DOE believes that development of this advanced particulate control system has proceeded far enough to warrant full-scale testing. Under the program, a first-of-a-kind field testing of Hg control using sorbent injection achieved over 70 percent Hg removal. Such field tests provide a basic understanding of the operating parameters that affect sorbent performance and should support the development of novel approaches for control of Hg and other hazardous air emissions from Vision 21 gasification plants. R&D has been expanded under the program to include by-products and residues from combustion systems that are similar to those that will be produced by Vision 21 systems.

The environmental control program has made progress in eliminating the emissions of NO_x, particulate matter, and Hg from combustion systems. Particulate control levels are very near to the Vision 21 target. NO_x and Hg control levels are continuing to decline and appear to be on a track to achieve the specified goals. The efforts to control Hg from gasification systems is in its early stages, but a significant effort is being implemented. High levels of Hg removal are being achieved for at least one gasifier configuration in commercial operation today (DOE, 2002c). Since acid gases are soluble and heavy metals should be captured by high-efficiency particulate control, it appears that the targets for these constituents also have the potential to be met.

R&D related to organics does not appear to be part of the program at this time. A significant number of by-product projects have been implemented and it is too early to comment on the potential for those projects to lead to elimination of waste streams.

Response to Recommendations from the Committee's 2000 Report

In its 2000 report, the committee recommended that specific goals for eliminating environmental pollutants from Vision 21 plants be defined, including the goal of near-zero emissions (NRC, 2000). The committee recognized that specific goals also need to be established for CO_2. The Vision 21 Program has been assigned specific emission control goals, including a goal for CO_2.

The committee recommended that plants should be designed to periodically process wastes such as spent catalysts, saturated absorbents, contaminated solvents, and water-treatment sludge. The Vision 21 Program has been expanded to include R&D for eliminating or reusing the by-products and residues from advanced power systems.

The committee recommended that in keeping with its proclaimed industrial ecology approach, DOE should examine the overall Vision 21 goal of "eliminating environmental concerns." There is, however, no indication that DOE has done this.

Issues of Concern and Remaining Barriers

It appears to the committee that the Vision 21 Program has a reasonable chance to achieve the pollution control goals for most of the pollutants it has targeted. However, it may be over optimistic to think that a commercial design can achieve essentially 100 percent control of CO_2 and 100 percent utilization of any by-products or residues in a cost-competitive manner.

Gas purification and environmental control for a Vision 21 plant are inherently intertwined. Near-zero emission levels from a Vision 21 plant may be desirable from one or both of the following standpoints: making the syngas an acceptable fuel for a gas turbine or fuel cell or meeting an environmental standard. Similarly, lessons learned in the development of pollutant controls for existing or new combustion plants will in all likelihood contribute to the development of advanced pollutant control for Vision 21 plants and vice versa. For this reason the gas purification and environmental control programs should work very closely. DOE may want to consider combining the programs to ensure that the knowledge gained in one application is shared in others. A substantial cross flow of information must occur in these two programs to increase the probability that near-zero emissions will be achieved.

Findings and Recommendations

Finding. The Vision 21 Program has established specific quantitative goals for near-zero emissions from the systems that will make up a plant for generating electricity, fuels, or chemicals. Except for CO_2 and by-product utilization, those goals appear to the committee to be achievable. The R&D efforts for hazardous air pollutants are addressing Hg, but it is not evident that other trace metals, acid gases, or organics are being addressed.

Recommendation. The Vision 21 Program for emission control should continue the development of controls for sulfur compounds, NO_x, particulate matter, and Hg. In addition, the program should assess other hazardous emissions from Vision 21 systems and, if warranted, implement R&D to achieve the specified near-zero emission levels for those pollutants. In cooperation with the gas purification and gas separation programs, the environmental control technology program should periodically address what R&D might be required to fully achieve the CO_2-reduction goal. The Vision 21 Program should continue to fully implement a program that addresses utilization of by-products and residues.

Finding. The goals and milestones for syngas gas purification and environmental control for combustion systems and Vision 21 systems are inherently intertwined. New knowledge gained in one program will in all likelihood lead to advancement and new knowledge in the other. Transfer of experience and research results between the two programs will greatly enhance the achievement of goals in both programs.

Recommendation. The gas purification, gas separation, and environmental controls subprograms should be merged immediately into a single subprogram. A rigorous engineering analysis should be carried out to answer critical questions about the point in the process where the removal or extraction of certain molecules should occur (e.g., O_2 purity vs. CO_2 capture; H_2S or Hg removal after gasification or SO_x or Hg removal after combustion; NO_x removal via catalysis/adsorption or NO_x avoidance via catalytic combustion). Such an analysis would exploit the common intellectual basis of the required processes and allow their integration into the overall process in a less fragmented manner.

SENSORS AND CONTROLS

Introduction

The stated objectives and focus of the Vision 21 Program are to lower significantly the emissions of pollutants, improve the overall efficiency, and make the capital and operating costs competitive with those of natural-gas-fed power generation systems. Innovative sensors and controls could improve plant efficiency by enabling better utilization of the raw materials and could lower the capital cost on a per unit product basis by increasing plant availability. In some cases, new generations of sensors and controls will be needed before an enabling technology can be implemented—for example, several controls will be needed for the operation of hydrogen-fed gas turbines and fuel cells.

Currently, there are seven sensors and controls projects related to the Vision 21 Program. Most of them are in the advanced materials portfolio of the NETL Advanced Research program. The April 2001 workshop[14] on sensors and controls technology helped to identify some of the relevant needs in the Vision 21 Program but failed to attract stakeholders involved in the operation of the existing gasification demonstration plants. It is also not clear if there is sufficient funding to undertake the R&D efforts suggested in the workshop.

The Vision 21 Program will benefit from a strong sensor and controls R&D program. The Materials Program of the NETL Advanced Research program is the appropriate group in which to carry out the sensors and controls projects. However, the Materials Program should work closely with the System Analysis Group to focus and prioritize project funding by quantifying the potential impacts of advanced sensors and controls.

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[14]NETL's Office of Coal and Environmental Systems, Sensors and Controls Workshop, April 17-18, 2001, Sacramento, California. Proceedings available online at <http://www.netl.doe.gov/coalpower/advancedresearch>.

Goals and Milestones

DOE envisions that the advanced materials program will develop advanced sensors and control systems for the Vision 21 plants.[15] The Instrumentation, Sensors, and Control Systems Program strategies are as follows:

- Develop technology suited for harsh conditions,
- Screen and accept development risk,
- Maintain involvement of stakeholders, including developers and users,
- Take a whole systems approach,
- Capitalize on technology deployment skills, and
- Direct recent advances in sensor technology toward Vision 21 applications.

Two technology roadmaps have been developed for sensors and controls technology. According to these roadmaps, the innovative sensors and control technologies will be demonstrated in about 10 to 15 years from now. No detailed milestones were given.

Progress, Significant Accomplishments, and Current Status

The workshop held in April 2001 provided good inputs for a list of needs for various Vision 21 enabling technologies, and a solicitation (de-ps26-02nt41432-3) for industry procurement related to sensors and controls sciences was released in 2002. It is not clear if any specific research has been initiated, nor has an award been announced from the recent solicitation. The current program consists of five projects on sensors, one project on diagnostic tools, and one project on controls. The total funding for the seven projects is about $2 million. Most of them were initiated before the inception of the Vision 21 Program.

The five sensor projects are related to the detection of flue gas constituents, in situ gas measurement in high-temperature environments, the measurement of solid flow velocity, the detection of ultratrace levels of mercury, and the measurement of the temperature in a gasifier reactor chamber. The design and fabrication of these sensors are at various stages. The five projects will be completed on or before 2003.

An online interfacial diagnostic tool is used in the manufacturing of membrane electrode assemblies (MEAs) for the proton exchange membrane (PEM) fuel cell. The tool has been successfully used to evaluate various fabrication methods for the MEAs. This project will be completed in 2002.

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[15] R. Romansky, NETL, "Advanced Research Vision 21 Sensors and Controls Program," Presentation to the committee on May 20, 2002.

Response to Recommendations from the Committee's 2000 Report

The committee's earlier report recommended the initiation of a sensors and controls R&D program because of their significant potential impacts on the Vision 21 Program. The recommendation was included in the section on advanced materials (NRC, 2000).

DOE has done a good job of establishing a critical mass with scientists from the existing Advanced Materials Program. The April 2001 workshop also brought many good ideas and identified some key issues and opportunities in sensors and controls.

Issues of Concern and Barriers Remaining

The current sensors and controls projects will not be able to meet the Vision 21 goals even if they are successfully implemented. For one thing, the lists of sensors and controls needs developed at the April 2001 workshop are incomplete. The lists do not include enhancement of the enabling technologies, such as hydrogen-fed gas turbines, fuel cells, and gasification.

The current R&D programs for sensors and controls lack inputs and participation from key stakeholders in the gasification demonstration plants and developers of Vision 21 enabling technologies. There is no systematic approach to quantifying the potential benefits of any sensors and controls projects in the Vision 21 Program. Another major hurdle in bringing these stakeholders to the Vision 21 Program is the delicate balance between the need for public disclosure and the need for protecting sensitive operation and maintenance (O&M) data and know-how.

Findings and Recommendations

Finding. The sensors and controls program is positioned correctly within the National Energy Technology Laboratory's (NETL) Advanced Research program. Some of the critical needs of the program have been identified, but the milestones are not sufficiently detailed to permit interim rigorous assessments of the likelihood of success in any one area.

Finding. The current project portfolio was developed before the Vision 21 Program was proposed. It is inadequate for the needs identified in the April 2001 Vision 21 workshop. The ChevronTexaco project on the measurement of gasifier reactor chamber temperature is the only project that could have a significant impact on the operation of the gasifier.

Finding. Few participants at the April 2001 Vision 21 workshop were involved in the operation of the Vision 21 gasification demonstration plants or the development of the enabling technologies. A thorough understanding of the operation and maintenance of Vision 21 plants is essential in the focus and prioritization of the sensors and controls projects.

Recommendation. The Vision 21 Program in sensors and controls should continue the strategies it laid out for meeting the technical needs identified at the April 2001 Vision 21 workshop. A systems analysis approach to quantifying the potential impacts of these sensors and controls projects on operation and maintenance (O&M) costs and plant capital cost should be used in the selection of future projects. More slipstream demonstration projects should be implemented in existing gasification demonstration plants.

MATERIALS

Introduction

The commercial viability of Vision 21 technologies will be highly dependent on the development of cost-effective advanced materials for oxygen separation membranes, gasifiers, high-temperature heat exchangers, high-temperature refractory, hydrogen separation membranes, seals and electrodes for fuel cells, thermal barrier coatings, blades and gas flow path for turbines, and ultra-high-temperature and high-pressure materials for advanced power generation. The challenge this presents is even more severe when coal rather than natural gas is the feedstock. As a result, the success of the Vision 21 Program will depend directly on the timely development, demonstration, and commercialization of advanced, cost-competitive, reliable materials and high-temperature corrosion-resistant coatings for the critical components within the various technologies. The information collected by the committee on the materials program was largely gathered from presentations to the committee at its meetings[16] as well as written answers from NETL in response to committee questions.[17]

Goals and Milestones

DOE has developed a roadmap that aligns the materials R&D program with the overall goals of Vision 21. This was accomplished by having the materials R&D elements (joining, materials design, modeling, mechanical properties, material characterization, synthesis and processing/fabrication, and corrosion/erosion studies) aligned with the materials technologies (coatings/protection materials,

[16]Romansky, NETL, "Advanced Research Vision 21 Materials Program," Presentation to the committee on May 20, 2002.
[17]L. Ruth, NETL, written answers to questions from the committee, July 12, 2002.

new alloys, functional materials, ultra-high-performance materials, and ultra-supercritical materials), which are then applied to the corresponding key component technologies (turbine blades/rotors/pipes, casting, membranes, hot-gas filters, refractory castables/bricks, seals, and absorbents). This approach is viewed as critical, in that the entire materials program is driven by the performance requirements of the components and their design.

The overall goals of the DOE materials program are as follows:

- Apply new alloys for use as structural materials that can withstand severe environmental conditions in Vision 21 plants; applications include gas turbine airfoils and combustor components, high-temperature heat exchangers, such as tubing for steam superheaters and reheaters, and air preheaters.
- Apply ultra-high-performance materials for applications in the 1800°-3100°F range, including high-efficiency turbine components and gasification systems.
- Apply coatings, including both metallic and ceramic materials, that would protect underlying structural components against corrosion.
- Develop and apply functional materials, including alloys and ceramics, for use as gas filters to remove particulates to levels required for gas turbines and other sensitive equipment; gas separation membranes; catalysts for fuel synthesis and other reactions; and fuel cell electrodes.

The major milestones for the technologies for Vision 21 are as follows:

- Test structural ceramics composites for turbines combustors (2005).
- Develop single-crystal alloy composition to allow Vision 21 turbines to perform as required (2005).
- Test a prototype air separation module integrated with a gas turbine (2006).
- Develop technology base for a commercial hydrogen separation membrane (2006).
- Achieve commercial readiness for improved hot gas filter material (2008).
- Bring on stream the first commercial oxygen membrane separation plant (2008).
- Bring on stream the first commercial hydrogen membrane plant for power and fuel processing (2010).
- Demonstrate turbine blade/vane in-field repair technique (2010).
- Demonstrate 1400°F capabilities for steam superheaters and for reheaters in operating plants (2010).
- Bring advanced single-crystal turbine blades into commercial service (2010).

- Demonstrate turbine components required for advanced applications, e.g., hydrogen turbine (2010).
- Test advanced high-temperature refractory in gasification and combustion systems (2010) and in commercial systems (2013).

Progress, Significant Accomplishments, and Current Status

To meet these goals, DOE has set up a materials roadmap that aligns material technologies with critical components of the various Vision 21 technologies. The following summarizes progress and significant accomplishments in the five materials technologies.

Coatings and Protection of Materials

The nine projects in the coatings area will be carried out by eight organizations representing national laboratories, universities, and industry. The coatings portfolio entails work in five areas, along with the completion dates:

- Weld-overlay techniques for intermetallics—work is ongoing, with completion in 2004;
- Extended lifetime metallic coatings—completion in 2005;
- Slurry-based mullite coating—completion in mid-2006;
- Metallic coatings for power generation—completion in 2007; and
- Corrosion protection at ultra-high temperatures—completion in 2009.

Work is under way in weld-overlay techniques for intermetallics. It will be followed by work on extended-lifetime metallic coatings, which is scheduled to begin in 2003.

New Alloys

Eight projects account for the activity in the area and will be carried out by national laboratories, universities, and industry. The alloys portfolio entails work in the following areas:

- Oxide-dispersion-strengthened (ODS) alloys for heat exchangers—work is ongoing, with completion anticipated in 2003;
- Advanced austenitic alloys—completion in 2004;
- High-creep-strength alloys—completion mid-2004;
- Weldable intermetallics—completion in 2005;
- Advanced ferritic alloys—completion in 2007; and
- Advanced ODS alloys—completion in mid-2007.

Current projects involve work in ODS alloys for heat exchangers, advanced austenitic alloys, and high-creep-strength alloys.

Functional Materials

Thirteen projects make up the activities in functional materials and will be accomplished primarily by national laboratories and universities. The functional materials portfolio entails work in the following areas: separation membranes, seals, hot gas filters, and support materials. In gas separation, the milestones are to (1) test a prototype air separation module by 2006 and (2) develop the technology base for a commercial hydrogen separation membrane by 2006. In the filter area, the milestone is to test prototypes of hot gas filters in 2004. The other projects are scheduled to support their respective component milestones. Five projects were either under way or had been completed in the functional materials area. Significant accomplishments include these:

- Commercialization of an iron aluminide filter with a temperature capability of about 800°C. An ODS variant of this filter could achieve use temperatures of greater than 1000°C;
- Progress in developing reliable high-temperature seals associated with the use of solid-state electrolytes in fuel cells. This involves the development of oxidant-resistant brazes for joints in devices using solid-state electrolytes;
- Progress in developing a state-of-the-art technique for thin-film processing (including sintering) using a novel plasma infrared heating technology. This has the potential for dramatic reductions in the processing cost for dense thin-film devices such as the electrolyte for a solid oxide fuel cell; and
- Development of a novel temperature sensor that can last up to 18 times longer than current thermocouple sensors.

Ultra-High-Performance Materials

Eight projects will make up the development in this area and will be performed predominately by the national laboratories and universities. The portfolio entails the following activities:

- Vapor-liquid-solid (VLS) process for silicon carbide (SiC) fibrils work is ongoing—completion in 2003;
- Advanced refractories—completion in 2005;
- Mo-Si alloy based on Mo_5Si_3—completion scheduled by 2007; and
- Intermetallic reinforced Cr alloys—completion in 2008.

Progress has been made in the development of a Mo-Si-B alloy system that is functional at over 1400°C. Major accomplishments over the last 2 years include a confirmation of the ability to accurately predict properties of this alloy by modeling based on first principles. Significant accomplishments include understanding the oxidation behavior of this material, the development of alloy and processing modifications to improve the oxidation response of the alloy, and improvement in the fracture toughness of the alloy to the point where it will probably be used in, for example, hot path components of turbines. In the advanced refractory area, a phosphate-modified high-chrome brick refractory has been developed that enhanced resistance to slag penetration. Field testing is planned.

Ultra-Supercritical Materials

This is a development program that has all the major steam generator vendors participating and support from the Electric Power Research Institute (EPRI), the metals industry and associated organizations, and Oak Ridge National Laboratory (ORNL). Alloys evaluated and/or developed in the program will have applications to advanced coal technologies and will provide more efficient steam cycles for Vision 21 plants. The goal of the program is to develop an alloy that can withstand steam conditions of 1400°F and 5,300 psi. The milestones for this development are as follows: (1) develop 1400°F materials by 2007; (2) develop the American Society of Mechanical Engineers (ASME) code for the 1400°F material by 2008; (3) demonstrate at commercial scale by 2010; (4) continue to pursue cost reduction and fabrication enhancements through 2015. Work is under way to develop cost-effective materials that can withstand 1400°F.

Response to Recommendations from the Committee's 2000 Report

There was only one overall recommendation, which summarized seven individual recommendations based on findings that appeared in the section "Overall Assessment of the Vision 21 Program" of the committee's 2000 report (NRC, 2000). DOE has essentially adopted and has action plans for all of the recommendations that were based on the findings in the materials section of the 2000 report. The main finding in the materials section was that the commercial success of the Vision 21 Program will depend largely on the successful development and demonstration of cost-effective coatings and structural materials, membranes, ceramics, and catalytic materials for Vision 21 systems and components. The recommendation for this finding was that the materials program should be based on the cost and performance goals for Vision 21 technologies and should be coordinated to meet those goals.

In response to these recommendations, DOE developed a materials roadmap to coordinate technology component requirements with materials development. Now, ORNL and NETL are coordinating their materials development with other federal and DOE materials development programs. In addition, numerous projects and activities have been initiated or planned to respond to the needs of materials development. Although this was an excellent first step and significant progress appears to have been made, the materials roadmap needs to incorporate intermediate milestones that would identify the actual time frames for selection of the specific cost-effective materials that are needed for the following:

- Oxygen separation membranes,
- Gasifiers,
- High-temperature heat exchangers,
- High-temperature refractory for gasifiers,
- Hydrogen separation membranes,
- Seals and electrodes for fuel cells,
- Thermal barrier coatings, and
- Blades and gas flow paths for gas turbines.

Since the committee's last review (made in connection with the 2000 report), the advanced materials research program has been organized and focused, as was recommended in the earlier report. The program generally reflects those recommendations by the committee; missing, however, are the specific material requirements of the various technology components for Vision 21 and time frames for their development.

Issues of Concern and Barriers Remaining

The following is a list of concerns and potential barriers for specific technology areas:

- Coal gasification—develop longer life feed nozzles and demonstrate longer life refractory;
- Gas separation—develop reliable and cost-effective membranes, develop materials resistant to trace contaminants, and improve the CO_2/H_2 separation membrane efficiency.
- Gas turbines—develop new high-temperature materials for improved performance and durability, develop sensors and condition monitors for improved operations and system life, and develop an advanced turbine that can operate on synthesis gas.
- Fuel cells—develop cost-effective materials and a manufacturing process for solid oxide fuel cells (SOFC), and explore the complexity of the piping needed to connect the numerous fuel cell stacks that would make up a typical central power generating station for 200 to 500 megawatt electric (MW_e).
- Materials and cost—overcome the additional materials and cost chal-

lenges posed by using coal rather than natural gas and by the operating conditions for the Vision 21 technologies. The funding needs of the materials program have to be weighed against the potential impact of advanced materials on the commercial viability of Vision 21 technologies.

Findings and Recommendations

Finding. The various projects for materials and coatings have end dates that are now coordinated with the materials and coating selection requirements for the various Vision 21 technology components.

Recommendation. Specific time lines and intermediate and final milestones should be developed for the material and coating selections for various Vision 21 technology components.

Finding. Material and coating requirements need to be identified for the use of synthesis gas (syngas) in the advanced high-temperature gas turbine.

Recommendation. A closer working relationship between the Vision 21 advanced materials program activities and the component technology areas needs to be developed in order to identify materials and coating issues and develop an action plan.

Finding. NSF and DOE's Basic Energy Sciences (BES) have programs that address a wide variety of fundamental materials research, but to date there is no connection with NETL's Advanced Materials Program.

Recommendation. NETL should begin a dialog with NSF and BES to coordinate their respective material development programs, so as to minimize duplication, leverage the resources of the respective organizations, and expedite the development of advanced materials and coatings for Vision 21 technologies.

Finding. The current expenditure level, if maintained over the next 5 years, may not be adequate to achieve the materials required to meet the Vision 21 technology component goals.

Recommendation. The funding over the next 5 years should be reexamined to learn if it can meet the requirements for advanced materials and coatings.

MODELING, SIMULATION, AND ANALYSIS

Introduction

One of the guiding principles of the Vision 21 Program is that the system synergies realizable from combining several advanced technologies will lead to viable economics for clean coal technology. In order to make a credible case for industry to commit to commercialization and to partnerships with companies outside their traditional areas of business, it will be essential to build and validate robust models of system design, performance, and costs.

The ability to create and defend credible engineering models and cost estimates of Vision 21 plants should be considered one of the most important products of the Vision 21 Program. In many ways, it is this capability that delivers the detailed and actionable "vision" of Vision 21.

Computational modeling and simulation consist of two general project areas, which DOE calls (1) simulation and modeling and (2) systems analysis and integration.

Program Goals

The following are the goals of the Vision 21 Program as defined in presentations to the committee. The objectives of the Vision 21 simulation and modeling activity are as follows:

- Develop science-based computational tools and apply them to simulate clean, highly efficient energy plants of the future;
- Develop a virtual simulation capability that predicts:
  — Interactions of turbines, fuel cells, combustors, environmental control systems and other major components;
  — Dynamic responses of an entire energy plant; and
  — A virtual environment in which to visit and explore future Vision 21 plants.

The objectives of the Vision 21 systems analysis activity are as following:

- Identify and evaluate concepts for Vision 21 plant subsystems and components;
- Select "reference" plants for detailed study; and
- Identify technology gaps and an R&D strategy to fill gaps.

The objectives of the Vision 21 systems integration activity are as follows:

- Obtain feedback on systems integration experience from operating IGCC and fuel cell-turbine hybrid plants;
- Conduct a series of systems integration workshops to identify and clarify issues;
- Identify systems integration issues for reference plants (e.g., module compatibility);
- Resolve systems integration issues and provide input to the R&D strategy where necessary;
- Identify, address, and resolve issues relating to subsystem and plant dynamics and control; and
- Identify, address, and resolve industrial ecology issues.

The Vision 21 milestones for what NETL calls its Computational Modeling and Virtual Simulation activities are as follows:

- Identify reference plants for further study (2002);
- Identify additional reference plants (2004);
- Develop analyses of reference plant concepts (2005);
- Make methodology available to identify and analyze systems integration (2005);
- Complete system integration analyses of reference plants (2006);
- Complete industrial ecology assessment for reference plants (2006);
- Make available technology base for Vision 21 plant modules (2012); and
- Make available technology base for complete plants (2015).

Current Status and Significant Accomplishments

There have been several important accomplishments in simulation and modeling activities since the beginning of the Vision 21 Program. The National Fuel Cell Research Center (NFCRC) has been selected as a contractor for defining Vision 21 reference plants that could meet the objectives of Vision 21. Five high-performance, coal-based systems have been identified, and preliminary analysis of each of the concepts has begun.

NETL has prepared several analyses of individual novel power processes and integrated systems that will be useful in many parts of the Vision 21 Program.

Vision 21 simulation workshops have been held, and research contracts have been granted to several universities and government labs.

The Multiphase Flow with Interphase Exchange (MFIX) computational fluid dynamics (CFD) code has been improved and established as an open source code for the research community.

Response to Recommendations from the Committee's 2000 Report

The committee had a number of recommendations in its 2000 report (NRC, 2000). They are recounted below, along with DOE's response.

> **Recommendation.** The Vision 21 Program Plan should be modified to address the need for a hierarchy of models suitable for preliminary design and scoping studies, as well as for detailed final designs. This hierarchy should range from simple, transparent models showing basic mass and energy balances, costs for process units, and integrated systems to more complex and detailed models of components and systems. The hierarchy should also reflect the differing needs for dynamic simulations and steady-state models of components and systems. It should also include the capability of coupling performance models and cost models, as well as analyzing the effects of uncertainty.

In response to this recommendation, DOE has awarded several modeling contracts under the Vision 21 Program solicitation and related programs. One project at the NFCRC is analyzing designs for Vision 21 reference plants. A basic description of five possible plant configurations should be completed by the end of 2002. Other projects are developing software capabilities to analyze Vision 21 plants at various levels of detail. However, there appears to be no formal coordination among these projects, nor is it clear whether, or to what extent, DOE and others will have access to these modeling capabilities in all cases.

> **Recommendation.** The U.S. DOE should work closely with potential model users and model developers in industry, academia, government, and nongovernmental organizations (NGOs) to define the specific goals, objectives, and priorities of the component modeling and systems modeling for Vision 21. The goals, objectives, and priorities should reflect the integration of, and need for, experimental or field data to support computer models.

Vision 21 workshops have been held to increase outreach to potential model developers. These have mainly concentrated on detailed modeling of components and on advanced computing frameworks for creating new methods of modeling systems. Almost all of the projects are with academia and government laboratories. Interface with industry and evaluation of the use of engineering models for design, cost, and performance still seems to be a weak point of the modeling effort. It is not clear to what extent these activities have been used to set priorities in modeling across the Vision 21 Program.

> **Recommendation.** The U.S. DOE should review the current state of the art of science-based modeling capabilities at both the component and systems levels and use this review as a basis for refining its expectations for Vision 21 models. This assessment should clearly identify and distinguish among modeling capabilities at different levels of detail (e.g., mechanistic (molecular or microscale) modeling vs. more empirically based engineering models).

It appears to the committee that there is still a strong emphasis in the Vision 21 Program on developing very detailed (e.g., CFD-based) models of process components, with less attention to engineering models better suited to research guidance.

> **Recommendation.** The U.S. DOE should develop a management plan and an institutional capability to carry out computer-based modeling, systems analysis, and systems integration activities. The management plan should include mechanisms for verifying or qualifying the performance of models; assessing and characterizing their reliability; maintaining and updating all Vision 21 models and modeling capabilities: and ensuring that models and modeling capabilities are openly developed, validated, and made available to interested parties.

The outsourced projects funded under recent Vision 21 solicitations are not responsive to this recommendation. Creation of an institutional capability to develop, validate, and maintain a set of models appropriate for Vision 21 will require a much higher level of resources and management attention.

Issues of Concern

The current project in Vision 21—to develop a framework for very detailed (e.g., CFD) models coupled with dynamic systems simulation—is a noble goal. It should be pursued insofar as these capabilities may eventually be very useful. However, the approach is very complex, and it is far too early in its development to provide the research guidance needed right now for system design, selection of the technology components critical for success, and ongoing economic evaluation of overall systems concepts integrated directly into the program.

The engineers and project developers of the stakeholder company that will have to invest in the new technologies that go into a Vision 21 plant (as well as the management, which must commit funds) will need to understand the implications and advantages of the system in the terms (such as engineering model language) with which they are familiar. For any company evaluating the commercial use of a specific externally developed technology, there is always a tortuous exercise of incorporating the vision and the cost assumptions into the local systems and models used by the company to determine its own view of the viability and attractiveness of the proposition. This is true even if the purveyor of the technology develops and uses models that have been validated and accepted in the industry over many years of practice.

In the case of Vision 21, the problem is compounded by the fact that the plants will be complex systems that include many new technologies developed and implemented by different industries (e.g., power production, chemical production, fuel cells, carbon sequestration). Each company considering participation in this endeavor will have to assess not only the attractiveness and risk of its own part of the system, but also the risk of nonperformance of the other parts of the system. For this, they are likely to look to companies in other industries that are their potential partners for assurance (or possibly even guarantees) that their technology will function properly. This process of separate internal modeling, cross validation, and risk minimization is likely to be very slow and hampered by miscommunication. It will also probably result in suboptimal plant designs because each participating partner will optimize its own part separately.

If the Vision 21 Program is to be successful in defining technologies and systems that will be commercially viable and implementable within the time frame of 15 years, it is essential for DOE to develop robust, credible capabilities to model Vision 21 systems using widely available engineering modeling tools. This capability should be developed in partnership with industry, academia, professional associations, and other stakeholders, but DOE should be the central point at which this capability resides.

It is a concern of the committee that the priorities for the modeling efforts in the Vision 21 Program are biased too far toward the development of advanced modeling tools as opposed to engineering performance and cost models for Vision 21 plants and components that can be used internally for program planning and assessment.

One of the critical activities that clearly needs more attention is providing research guidance for the Vision 21 projects. Research guidance studies aim to identify the critical technical issues that need to be addressed by the project team. These critical issues can include both cost and operability considerations. The starting point for a research guidance study is an analysis of the chemistry, physics, and engineering of the process under review with particular attention to fundamental limitations arising from thermodynamic considerations. The next step is identifying the process steps likely to have a major impact on the cost and operability of the process. For each step the team can identify the performance target that needs to be demonstrated if the process is to be economical. For example, in most membrane processes the mass flux through the membrane and the installed cost of the membrane are critical issues to be addressed early in the R&D plan. In fuel cells, scale-up and membrane assembly cost are critical; in separations, mass flux per unit cross-sectional area; in reactors, catalyst productivity and also mass flux per area; and so forth. Once integrated plant designs have been identified, the reliability, availability, and maintainability (RAM) of the overall facility must be analyzed. Here the focus is on interactions among the various components of a complex plant.

One of the most effective ways to address these problems is for the Vision 21 Program to provide models and cost analyses of Vision 21 plants using widely available modeling tools. These models would be developed and backed up by a team of experienced design engineers who are integrated with the project and colocated with Vision 21 program management. If these models are not developed by the Vision 21 Program and validated through several years of interaction with the project teams and the relevant target industries, then the overall engineering systems model will have to be developed after the fact by a consortium of interested companies. It may be difficult to “recruit” companies willing to commit their own resources to this multicompany process. This glitch could easily delay implementation of Vision 21 projects by many years.

Finding and Recommendations

Finding. As it is being implemented, the Vision 21 Program Plan will not create adequate capability to build credible and useful engineering and cost models of Vision 21 plants. The program still lacks a clear plan for managing the development of computer-based modeling capabilities necessary for overall success of the program.

There still appears to be inordinate confidence in the ability to develop advanced computing capabilities to create "frameworks" for very detailed mechanistic models to be tied together into systems models that can be used for engineering evaluations and dynamic simulations. While this may well be a laudable long-term goal, this particular set of projects cannot be counted on to provide credible systems performance modeling or useful guidance for system selection and research guidance within the time frame of Vision 21. That is still an unrealistic expectation within the program and may be leading to a misallocation of resources in the modeling component of the Vision 21 Program.

Based on this finding, the committee believes the focus should be on developing an engineering modeling team that is integrated directly with the Vision 21 management to provide engineering analysis and research guidance. This team can provide an independent perspective within the project on the value of various technologies in the context of Vision 21 schemes as well as on the probability of successful development. In the process of developing Vision 21 flowsheets, they can identify the technology bottlenecks—that is, in the most promising schemes, What are the most critical technologies yet to be developed? and What is the risk-weighted value of developing those technologies? The continued refinement of the process schemes and iteration with the project teams can be used in this way to manage the portfolio of specific technology development projects according to their value and probability of success.

Recommendation. Sufficient resources should be redeployed to create an engineering modeling team that will be colocated with the program leadership. The objectives of this team will be to develop the capability to create credible engineering and cost models for Vision 21 plants (including major components of plants), provide research guidance to program leadership and to project teams for evaluation and selection of critical technologies in the context of Vision 21, and to validate the engineering modeling capabilities and results with relevant industry partners.

Recommendation. One of the first assignments of the engineering modeling team should be a quick benchmarking study on the modeling, optimization, and management of large, complex systems as practiced by established industries in similar situations. Large refineries are one good example of well-developed systems that manufacture many products: in producing and exporting power, they optimize around downtime or changing performance characteristics of key components or changing feedstock specifications.

Recommendation. Systems modeling capability should be an integral aspect of the Vision 21 Program. It is important for the Vision 21 project management as well as the entire project team to interact regularly with the modeling team. A process should be created in the Vision 21 Program for regular interaction of all of technology development teams and project management with the engineering modeling team to review and understand the overall system models and the cost implications of specific technology issues. This process should be utilized to create new process and technology concepts.

CONVERSION OF SYNTHESIS GAS TO FUELS AND CHEMICALS

Introduction

Commercial production of liquid fuels from coal-derived synthesis gas (syngas) was started in the mid-1950s in South Africa. The basis for this industrial complex was the pioneering work done by Franz Fischer, H. Tropsch, and others in Europe in the earlier part of the 20th century. The economic driver for this technology commercialization was the desire to make fuels from the abundant coal resources in the country. The need for this technology was reinforced later on by the embargo on trade with South Africa by most other nations. Pilot-scale demonstrations of coal-based Fischer-Tropsch (F-T) fuels have also taken place in the United States, Japan, and Russia. Moreover, before and during World War II, significant quantities of F-T fuels were made in Germany from coal.

The catalyst of choice for coal-derived syngas conversion to F-T fuels is iron, with promoters added for reduced attrition of catalysts, sintering, and increased reactivity. Reactor technology has evolved from early fixed-bed reactors to the preferred option today, three-phase (gas, liquid, and solid catalyst) liquid fluidized reactors. Coal-based syngas is also used to make other important industrial products, including methanol and hydrogen. The technology has improved along the same time line. The catalyst of choice for methanol is copper, and for hydrogen production, nickel. The preferred reactors are fixed-bed or tubular reactors.

While the technology for making fuels and chemicals is widely available and has been commercially demonstrated, only a small fraction of overall production is from coal-derived syngas. The main reasons are the higher cost of making syngas from coal than from natural gas and the lower molar ratio (<1.0) of hydrogen to carbon monoxide produced in coal gasifiers. Production of syngas from methane gasifiers or steam reformers is significantly cheaper, and the molar ratio is closer to the desired ratio (>2.0) for making methanol and fuels. When syngas from a coal gasifier is used to make these products, about half of the carbon monoxide has to be reacted with steam to produce carbon dioxide and hydrogen (water gas shift reaction). The key reason why iron is the preferred catalyst when making fuels from coal-derived syngas is that iron catalyzes both the water gas shift and the F-T fuels reactions.

In the last two decades a major effort has been under way to produce fuels from methane-derived syngas. These efforts, which are international in scope, are based on sophisticated scientific and engineering concepts and enjoy strong participation by the energy and chemical industry. The Proceedings of the Sixth Natural Gas Conversion Symposium, published by Elsevier, capture the breath and depth of the effort under way (Elsevier, 2001). Previous symposia whose proceedings were also published by Elsevier, give an excellent retrospective on the evolution of this technology (Elsevier, 1997, 1998).

In the Vision 21 Program, one option considered is the conversion of a portion of the syngas from coal gasifiers to fuels and chemicals. The committee does not dispute the technical feasibility of the scheme. Rather, its assessment is based on seeking the best allocation of the resources available to advance Vision 21 technologies to commercial readiness by 2015. If for either strategic reasons (the need to increase domestic production of fuels and chemicals) or economic reasons (price of crude oil well above $30/barrel) large-scale production facilities were needed in the United States or other parts of the world, such as China, the technology is available from industry. A second factor also leads the committee to question the proposed development and demonstration program—namely, the high level of research, development, and commercialization activity currently being pursued by private industry (estimated at close to $100 million per year) in the United States and other countries (McWilliams, 1997).

Milestones and Goals

The goal of the clean fuels effort by the Office of Fossil Energy is to promote the development and deployment of affordable technologies that produce clean, high-performance liquid and gaseous fuels from a variety of secure energy resources. The objective of the Vision 21 Program is to develop technologies that integrate well with Vision 21 plants and that can narrow the cost difference between coal and petroleum-based fuels.

The specific milestones identified for the syngas to fuels/chemicals activity are as follows:

- Start-up prototype plants coproducing power and fuels/chemicals (2010);
- Complete Vision 21 advanced coproduction plant designs (2010); and

- Start-up of commercial coproduction plants using advanced Vision 21 technologies (2015).

Current Status and Significant Accomplishments

The Vision 21 team highlighted the following accomplishments specific to syngas to fuels/chemicals activities:

- Texaco and Waste Management and Processors of Gilberton, Pennsylvania, are on schedule to complete engineering design of coproduction complexes by early 2004.
- The University of Kentucky's Center for Applied Energy Research is working on iron catalyst technology and has developed new catalysts, tested catalysts for industry, and trained personnel to be employed by industry.
- At the LaPorte, Texas, facility operated by Air Products, Texaco tested the Rentech F-T technology and Air Products completed tests to make dimethyl ether (DME) and methanol. New catalyst formulations were identified, and their reaction mechanism was validated.
- A Consortium of Fossil Fuel Science was established with the objective of reducing the cost of synthesis gas conversion to products. Research is under way on supercritical F-T synthesis, new catalysts for the conversion of methanol to ethylene and propylene, and nanoscale iron catalysts for the conversion of methane to hydrogen, and carbon nanotubes.
- Research on modeling slurry reactors and on computational chemistry for iron catalysts has been funded.

Response to the Recommendations from the Committee's 2000 Report

The Vision 21 team seems to have responded positively to the recommendation to place greater emphasis on chemistries, catalysts, and reactor schemes other than iron-based F-T synthesis catalysts and slurry reactors (NRC, 2000). However, work continues on detailed engineering design/economic feasibility studies of coproduction complexes and on pilot-plant demonstration runs, all aimed at making F-T fuels and methanol/DME. These activities parallel activities by industry and should not be part of the program.

Issues of Concern and Barriers Remaining

The committee is concerned about the focus and level of effort in this area. As mentioned before, the conversion of syngas to fuels and chemicals is being pursued very intensely by industry, and the efforts range from research to commercialization. While the preferred source of syngas is "remote" (and thus inexpensive) natural gas, the desired composition of the feed used in the syngas conversion reactors is determined by the desired product (fuel or chemical), not by the source of the syngas (coal, methane). It is important to note that even with inexpensive natural gas as the feed, syngas conversion plants are at best marginally competitive with fuels from crude oil. Moreover, every credible economic analysis of coal to fuels vs. electric power complexes has shown fuels to be even less attractive (Gray and Tomlinson, 1997). The key to improving the economics is finding a much cheaper way to make syngas in coal gasifiers.

A fundamental limitation in the conversion of coal to fuels (including hydrogen) is the thermal and carbon efficiency of the process. The Vision 21 Program objectives include a 75 percent efficiency objective for fuels-only plants. This target efficiency is based on an analogy to the efficiency of processes such as petroleum refining and other syngas routes to fuels. This analogy is incorrect. Indeed, it is possible to calculate the maximum theoretical efficiency from fundamental principles of thermodynamics. The chemical equations that define this analysis are these:

$$2.25\ CH_{0.8} + 1.25\ O_2 \rightarrow CH_2 + 1.25\ CO_2$$
$$2.25\ CH_{0.8} + 2.25\ O_2 \rightarrow H_2 + 2.25\ CO_2$$

The maximum theoretical carbon efficiency when making hydrocarbon fuels is less than 50 percent, and more carbon is produced as CO_2 than is retained in the fuel. In the case of hydrogen the thermal efficiency of the process is only 30 percent. These theoretical maximum efficiencies can be compared with the results of engineering analyses of coal-to-fuels complexes (Gray and Tomlinson, 1997). That study, conducted for the DOE, estimated the carbon efficiency of the fuels-only plant at 42 percent. The efficiencies should also be compared with the efficiency of a natural gas-to-fuels process, where the theoretical efficiency is 75 percent and actual plant experience shows efficiencies of 60-63 percent.

Findings and Recommendations

Finding. The program plan in Vision 21 for syngas to fuels/chemicals is heavily focused on activities that parallel R&D and commercialization activities by private industry throughout the world. This particularly applies to pilot-plant demonstrations, engineering design/feasibility studies, and testing of commercial catalysts and reactors.

Finding. A positive trend in the syngas to fuels/chemicals program is the initiation of some exploratory research on catalysts aimed at making higher-value fuels and chemicals from coal-derived syngas. Since this is an area of research that has already been thoroughly investigated, the specific research directions and the rate of progress should be carefully monitored by DOE/NETL.

Recommendation. The committee recommends a modest effort in exploratory catalysis research aimed at the selective conversion of syngas to high-value fuels and chemicals.

Recommendation. Detailed engineering design/economic feasibility studies of coal coproduction complexes and large-scale, pilot-plant demonstration runs of conventional processes to make low-value fuels such as diesel, methanol, and DME should not be funded by the Vision 21 Program.

ADVANCED COAL COMBUSTION

Introduction

The Advanced Combustion Technologies Program is a very important component of the Office of Fossil Energy R&D program. It offers a near-term technological solution to improving efficiency and environmental performance in existing fossil-fuel power plant units, especially coal-fired power plants, and new units that may need to be constructed before Vision 21 systems are available or if Vision 21 systems prove unable to achieve the desired levels of performance and costs. The advanced combustion program encompasses the development of high-performance combustion systems, both suspension fired and fluidized bed, including ultra-low-NO_x combustion and combustion systems that burn fuels in O_2/CO_2 mixtures and produce exhaust streams containing only CO_2 and water. These advanced combustion systems, except perhaps the O_2-based combustion, will not achieve the goals of a Vision 21 system; rather, they are a technology bridge between today's combustion systems and the point in time when Vision 21 systems are commercially ready.[18] The Advanced Combustion Technologies Program will offer the opportunity to repower, modernize, and upgrade existing electric generating units or to install new units to replace the existing fleet before Vision 21 plants are commercially available. These early commercial applications of advanced combustion systems can serve as a platform on which Vision 21 equipment will gain operating experience and construction know-how, while increasing reliability and decreasing costs. Opportunities for proving Vision 21 components will allow achieving the overall goal—commercial designs by 2015—because the marketplace will be able to rely on the experience gained during these advanced combustion system applications. The Advanced Combustion Technologies Program provides an enabling opportunity as well as a fallback position for Vision 21 technologies and the nation's electric generating technology.

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[18]J. Marion, ALSTOM Power Inc., "The Evolution of Coal Combustion Technology for Electric Power," Presentation to the committee on May 21, 2002.

Milestones and Goals

The Advanced Combustion Technologies Program objective is the development, demonstration, and commercial deployment of advanced coal-fired combustion systems in the United States and abroad. These power plants will offer significant improvements in performance and cost.

Key goals[19] include:

- By 2005, develop a 42 percent (HHV) efficient low emission boiler system (LEBS) with lower emissions and cost than existing pulverized coal (PC) technology, for repowering or retrofitting existing plants.
- By 2010, develop a 47 percent (HHV) efficient indirectly fired power system (IFPS)—gas turbine combined cycle and advanced PC boiler—with lower emissions and costs than existing PC plants.
- By 2010, demonstrate pressurized, fluidized-bed combustion (PFBC) with over 50 percent (HHV) efficiency and better environmental performance and lower cost than other combustion systems.

Response to Recommendations from the Committee's 2000 Report

In 2000, the committee found that the advanced combustion technologies in the Office of Fossil Energy's core power generation program were limited by practical engineering to efficiencies of 45 to 50 percent, which are substantially below Vision 21 Program goals of 60 percent (NRC, 2000). A second finding was that the dilute CO_2 stream from combustion would be more expensive to separate than that from gasification. For these reasons the committee recommended that the advanced combustion program not be included in the Vision 21 Program unless new approaches were conceived that could achieve the 60 percent goal. Innovative configurations to achieve the Vision 21 goals using advanced combustion have been investigated by DOE, but no ready solution has emerged. However, the O_2/CO_2 combustion option appears to hold some promise for increased efficiency and carbon sequestration options.

Issues of Concern and Remaining Barriers

The issues of advanced combustion system's efficiency and the dilute CO_2 stream from combustion remain as large hurdles to advanced combustion systems achieving Vision 21 goals and remaining in the program.

[19]NETL Advanced Combustion Technologies Program Goals, available online at <http://www.fetc.doe.gov/coalpower/combustion/index.html>.

Finding and Recommendation

Finding. The Advanced Combustion Technologies Program is an important component of the Office of Fossil Energy R&D program and should be vigorously pursued, but outside the Vision 21 Program. The advanced combustion technologies have the potential to significantly improve efficiency and environmental performance over today's electric generating technologies and can enable the upgrading of the existing fleet of power plants or the construction of new plants. The advanced combustion technologies can also serve as a fallback alternative if the Vision 21 goals prove unobtainable technically or economically.

Recommendation. The Advanced Coal Combustion Technologies Program should be vigorously pursued outside the Vision 21 Program in order to meet any commercial needs for coal-fired generating capacity with much better performance and emission levels than current combustion technologies before Vision 21 technologies are commercially available.

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Appendixes

A

Biographical Sketches of Committee Members

James J. Markowsky (NAE), *chair,* is retired executive vice president of American Electric Power (AEP) Service Corporation, where he led the Power Generation Group and was responsible for fossil-fueled and hydroelectric generating facilities, affiliate coal mining, coal procurement and transportation, and environmental services. He is a member of the NRC's Board on Energy and Environmental Systems and previously served as a member of its Energy Engineering Board and as chairman of the Committee on R&D Opportunities for Advanced Fossil-Fueled Energy Complexes. He received a B.S. degree in mechanical engineering from Pratt Institute, master's degrees from Cornell University and the Massachusetts Institute of Technology, and a Ph.D. (mechanical engineering) from Cornell University.

David H. Archer (NAE) is an adjunct professor at Carnegie Mellon University. He is a consulting engineer, having retired from the Westinghouse Electric Corporation, and has extensive expertise in the design and evaluation of innovative fossil-fueled power generation systems. His work has included basic studies of flame behavior as well as applications of combustion turbines, high-temperature fuel cells, gasifiers, fluidized-bed combustion, and hot gas cleaning. He served on a number of NRC committees, including the Committee on R&D Opportunities for Advanced Fossil-Fueled Energy Complexes. He joined Westinghouse in 1960. Dr. Archer holds a B.S. in chemical engineering from Carnegie Mellon University and a Ph.D. in chemical engineering and mathematics from the University of Delaware.

Ramon L. Espino is currently research professor at the University of Virginia, Charlottesville; he has been on the faculty since 1999. Prior to joining the Department of Chemical Engineering, he was with ExxonMobil for 26 years. He held a number of research management positions in petroleum exploration and production, petroleum processes and products, alternative fuels, and petrochemicals. He has published about 20 technical articles and holds nine patents. Dr. Espino's research interests focus on fuel cell technology, specifically in the development of processors that convert clean fuels into hydrogen and of fuel cell anodes that are resistant to carbon monoxide poisoning. Another area of interest is the conversion of methane to clean liquid fuels, specifically the development of catalysts for the selective partial oxidation of methane to synthesis gas. He served on the NRC Committee on R&D Opportunities for Advanced Fossil-Fueled Energy Complexes. Dr. Espino received a B.S. degree in chemical engineering from Louisiana State University and an M.S. and a Doctor of Science in chemical engineering from the Massachusetts Institute of Technology.

Enrique Iglesia is director, Berkeley Catalysis Center, and professor of chemical engineering at the University of California at Berkeley (and faculty scientist at Lawrence Berkeley Laboratory). He joined the University in 1993, after 11 years of industrial experience in heterogeneous catalysis and reaction engineering at Exxon Research and Engineering, which he left as head of catalysis research. He served on the NRC Committee on R&D Opportunities for Advanced Fossil-Fueled Energy Complexes. He received a B.S. (chemical engineering) from Princeton University and M.S. and Ph.D. degrees (chemical engineering) from Stanford University.

Edward S. Rubin is the Alumni Professor of Environmental Engineering and Science at Carnegie Mellon University (CMU). He holds joint appointments in the Departments of Engineering and Public Policy and Mechanical Engineering and is director of CMU's Center for Energy and Environmental Studies. His teaching and research interests at CMU are in environmental control, energy utilization, and technology-policy interactions, with a particular focus on coal-based systems. He is the author of over 200 technical papers and reports, as well as a new textbook on engineering and the environment. He has served as a member of technical and advisory committees to the U.S. Environmental Protection Agency, the U.S. Department of Energy, and the National Research Council and is a member of several technical and professional societies. He served on the NRC Committee on R&D Opportunities for Advanced Fossil-Fueled Energy Complexes and is a member of the Board on Energy and Environmental Systems. He also serves as a consultant to public and private organizations with interests in energy utilization and environmental protection. He earned a B.E.in mechanical engineering at the City College of New York and an M.S. and a Ph.D. in mechanical engineering from Stanford University.

Robert H. Socolow is a former director of the Center on Energy and Environmental Studies and is currently a professor of mechanical and aerospace engineering at Princeton University, where he has been on the faculty since 1971. He was previously a National Science Foundation fellow, and an assistant professor of physics at Yale University. Dr. Socolow is a fellow of the American Physical Society and the American Association for the Advancement of Science. His areas of research include energy utilization, the environmental effects of energy technologies, and carbon management for fossil fuels. He has served on many NRC boards and committees, including the Committee on R&D Opportunities for Advanced Fossil-Fueled Energy Complexes and the Board on Energy and Environmental Systems. He has B.A., M.A. and Ph.D. degrees in physics from Harvard University.

Samuel S. Tam is vice president of Advanced Energy Technology, Energy Delivery and Management Division, Nexant, Inc., a Bechtel affiliated company. He is responsible for project execution and business development activities in the clean fossil energy practice. Prior to joining Nexant, he was the manager for advanced petroleum and chemical technology, Bechtel Technology and Consulting, and was responsible for monitoring and developing emerging technologies in the refining and chemical industries, including conversion of natural gas to liquid transportation fuels and technologies related to greenhouse gases and global climate warming. Before joining Bechtel in 1988, Mr. Tam was a project leader at BP America, working on commercial and technology development of methanol and other alcohols as transportation fuels. He holds B.S. and M.S. degrees in chemical engineering from Ohio State University.

Stephen Wittrig is director of the Clean Energy: Facing the Future Program for BP. This is a program to invest $10 million in Chinese universities to develop and prove clean energy technologies for China and the rest of the world. Previously, he worked on the BP/Amoco merger, considering gas-to-liquids strategy and chemical technology strategy and implementation; and on special assignments for Amoco, including leading the strategy development team for gas to liquids and oxygenates. In prior assignments with Amoco, he managed the engineering and process evaluation group for new product development in chemicals; led a team developing new reactor technology for methane conversion to syngas, and worked with Amoco Oil on coal liquefaction, refinery research, and pollution control. He has a B.S. (University of Illinois, Urbana) and a Ph.D. (California Institute of Technology) in chemical engineering.

Ronald H. Wolk is principal, Wolk Integrated Technical Services. His previous positions include director of the Advanced Fossil Power Systems Department at EPRI and associate laboratory director at Hydrocarbon Research, Inc. He has extensive experience in assessing, developing, and commercializing advanced power generation and fuel conversion technologies, including fuel cell, gas turbine, distributed power generation, and integrated gasification combined cycle technology systems. He served on the NRC Committee on R&D Opportunities for Advanced Fossil-Fueled Energy Complexes. He has B.S. and M.S. degrees in chemical engineering from the Polytechnic Institute of Brooklyn (now Polytechnic University).

John M. Wootten is vice president, Environment and Technology, Peabody Energy. He spent most of his professional career with Peabody Holding Company, Inc., the largest producer and marketer of coal in the United States. His positions at Peabody and its subsidiaries have included that of director of environmental services, director of research and technology, vice president for engineering and operations services, and president of Coal Services Corporation (COALSERV). His areas of expertise include the environmental and combustion aspects of coal utilization, clean coal technologies, and environmental control technologies for coal combustion. He has served on a number of NRC committees, including the Committee on R&D Opportunities for Advanced Fossil-Fueled Energy Complexes. He received a B.S. (mechanical engineering) from the University of Missouri–Columbia and an M.S. (civil engineering, environmental, and sanitary engineering curriculum) from the University of Missouri–Rolla.

B

Presentations and Committee Activities

1. Committee Meeting, National Academy of Sciences, Washington, D.C., May 20-22, 2002

National Energy Policy and Coal Program
Carl O. Bauer, National Energy Technology Laboratory (NETL)

Vision 21: Overview
Lawrence A. Ruth, NETL

Vision 21 Technology Area: Gasification
Gary J. Stiegel, NETL

Vision 21 Technology Area: Gas Purification
Gary J. Stiegel, NETL

Vision 21 Technology Area: Gas Separation
Gary J. Stiegel, NETL

Combustion Technology: On the Path to Vision 21
Donald L. Bonk, NETL

High-Efficiency Engines and Turbines (HEET)
Abbie W. Layne, NETL

Innovations for Existing Plants (IEP) Program
Thomas J. Feeley, III, NETL

Coal Fuels and Chemicals: Synthesis Gas Conversion
John C. Winslow, NETL

Fuel Cells Program
Mark Williams, NETL

Advanced Research: Vision 21 Sensors and Controls Program: Vision 21 Review
Robert Romanosky, NETL

Advanced Research: Vision 21 Materials Program
Robert Romanosky, NETL

Vision 21 Simulation and Modeling
Anthony Cugini, NETL

Systems Analysis and Integration
John Ruether, NETL

Energy-Environment Policy Integration and Coordination—The E-EPIC Study
Steve Gehl, Electric Power Research Institute

Overview of Vision 21 for Coal-Based Power Generation
Randall E. Rush, Southern Company Services, Inc.

Integrated Gasification Combined Cycle
Robert S. Horton, ChevronTexaco Worldwide Power and Gasification, Inc.

The Evaluation of Coal Combustion Technology for Electric Power
John Marion, Alstom Power, Inc.

Perspective on the Vision 21 Program
Larry Grimes, National Coal Council

Development of ITM Oxygen Technology for Gasification and Power Applications
Ted Foster, Air Products and Chemicals, Inc.

2. Committee Meeting, National Academy of Sciences, Washington, D.C., July 29-31, 2002

Vision 21 Fuel Cells Program
Mark Williams, National Energy Technology Laboratory

Experience and Development Needs of Gasification Technology—the Polk Power Station Integrated Gasification Combined Cycle (IGCC) Plant
John McDaniel, Tampa Electric Company, Polk Power Station

Status and Development Needs for Fuel Cell Technology
Hossein Ghezel, FuelCell Energy

3. Committee Conference Calls, September 6, 9, and 10, 2002

Committee discussions of its draft report