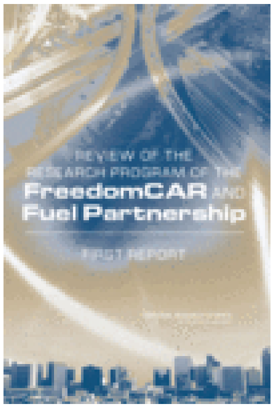

Review of the Research Program of the FreedomCAR and Fuel Partnership: First Report

Committee on Review of the FreedomCAR and Fuel Research Program, National Research Council

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REVIEW OF THE RESEARCH PROGRAM OF THE **FreedomCAR** AND **Fuel Partnership**

FIRST REPORT

Committee on Review of the FreedomCAR and
Fuel Research Program, Phase 1

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

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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:

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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 William H. Press (NAS) and Maxine L. Savitz (NAE). Appointed by the National Research Council, they were responsible for making certain 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.

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Executive Summary

THE FREEDOMCAR AND FUEL PARTNERSHIP

This is the first report of the Committee on Review of the FreedomCAR and Fuel Research Program, Phase I, formed in the fall of 2004 by the National Research Council (NRC). This FreedomCAR and Fuel Partnership is a collaboration among the U.S. government—in particular, the U.S. Department of Energy (DOE)—the U.S. Council for Automotive Research (USCAR), whose members are DaimlerChrysler Corporation, Ford Motor Company, and General Motors Corporation), and five major energy companies: BP America, Chevron Corporation, ConocoPhillips, ExxonMobil Corporation, and Shell Hydrogen (U.S.). At DOE, the program is managed through the Office of Energy Efficiency and Renewable Energy (EERE). This is a broad, very challenging research effort to assist in the development of high-risk technologies that will enable the vision of "a clean and sustainable transportation energy future" (DOE, 2004). To achieve that future, the program envisions a transition pathway involving more efficient internal combustion engines (ICEs), followed by increasing use of advanced ICE hybrid electric vehicles and then, by 2015, enablement of the private sector to make a decision about the commercialization of fuel-cell-powered personal transportation vehicles that run on economically competitive hydrogen produced from a variety of energy sources. Research goals have been established for 2010 and 2015 that, if attained, promise to overcome the multiple high-risk barriers to achieving that vision.

A major strength of the FreedomCAR and Fuel Partnership is that, like its predecessor, the Partnership for a New Generation of Vehicles (PNGV) program, it is organized around joint industry/government research teams. This structure brings the capabilities of the nation's federal laboratories and other research institutions to bear on overcoming the problems, identified by industry, that are critical to achieving the program vision. This kind of cooperation is a very effective way to develop technologies that will satisfy all of the requirements for the deployment of radically new systems in the marketplace on a large scale. However, unlike the PNGV program, which aimed at the development of concept and preproduction prototype automobiles, the FreedomCAR and Fuel Partnership addresses the development of advanced technologies for all light-duty passenger vehicles—for example, cars, sport utility vehicles, pickups, and minivans. Another strength of the new partnership is that it includes fuel production and infrastructure technologies and that it includes five energy companies, adding essential knowledge about fuels to the program.

The funding in FY05 for DOE programs falling under the purview of the FreedomCAR and Fuel Partnership is about $310 million and covers basic research, applied research, development, learning demonstrations, and deployment (including education that supports technology transfer and adoption). The complexity of the FreedomCAR and Fuel Partnership is evident from the broad scope of the technical areas addressed:

- Internal combustion engines (both petroleum- and hydrogen-fueled),
- Fuel cell power systems,
- Fuel cells,
- Hydrogen storage systems,
- Energy storage systems for hybrid vehicles,
- Electric propulsion systems,
- Hydrogen production and delivery systems, and
- Materials for lightweight vehicles.

There are 11 technical teams consisting of individuals from the national laboratories, the private sector, and the federal government:

- Advanced combustion and emissions control,
- Fuel cell systems,
- Onboard hydrogen storage,
- Electrochemical storage,
- Electrical and electronics,
- Materials,
- Hydrogen production,
- Hydrogen delivery,
- Fuel/vehicle pathway integration,
- Codes and standards, and
- Systems engineering and analysis.

DOE is the lead government agency in the Partnership, and a number of its offices are involved. EERE has primary responsibility for the program through its

FreedomCAR and Vehicle Technologies (FCVT) program and its Hydrogen, Fuel Cells, and Infrastructure Technologies (HFCIT) program. In addition, research and development (R&D) on hydrogen production from coal and nuclear energy is carried out in DOE's Office of Fossil Energy (FE) and its Office of Nuclear Energy, Science and Technology (NE). The Office of Science's Basic Energy Sciences (BES) program is focused on fundamental work in such areas as hydrogen production, hydrogen storage, and catalysts. The U.S. Department of Transportation also participates in safety-related work.

FOCUS OF THE COMMITTEE'S REPORT

An earlier NRC report, *The Hydrogen Economy*: *Opportunities, Costs, Barriers and R&D Need*s (NRC/NAE, 2004), addressed many of the R&D activities associated with the hydrogen parts of the program, such as hydrogen production, distribution, dispensing, and storage, as well as a transition strategy for making hydrogen more widely available. That report provides an excellent review of the challenges and potential benefits of using hydrogen as a transportation fuel and offers recommendations for the DOE R&D program. The current committee used the results of *The Hydrogen Economy* report and referred to its recommendations. The current report presents the committee's evaluation of DOE-sponsored research efforts directed at the goal of a hydrogen economy under the FreedomCAR and Fuel Partnership and offers comments and suggestions on the technical directions, strategies, funding, and management of the Partnership. Because *The Hydrogen Economy* report had just been published as the current committee was being constituted, with regard to the hydrogen technology parts of the Partnership, the committee reviewed just the plans of the three new hydrogen-fuel-related technical teams (hydrogen production; hydrogen delivery; fuel/vehicle pathway integration).

The primary charge to the committee was as follows:

- Review the challenging high-level technical goals and timetables for government and industry R&D efforts in the various technical areas being addressed by the Partnership.
- Review and evaluate progress and program directions since the inception of the Partnership towards meeting the Partnership's 2010 technical goals, and examine ongoing research activities and their relevance to meeting the goals of the Partnership.
- Examine and comment on the overall balance and adequacy of the FreedomCAR and Fuel research effort, and the rate of progress, in light of the technical objectives and schedules for each of the major technology areas.
- Examine and comment, as necessary, on the appropriate role for federal involvement in the various technical areas under development.

- Examine and comment on the Partnership's strategy for accomplishing its goals.

This Executive Summary presents only the main conclusions and recommendations of the committee's report. The body of the report contains additional observations, findings, and recommendations on specific aspects of the program. The rest of the Executive Summary presents the technical areas discussed in Chapters 3 and 4 and briefly addresses crosscutting issues.

AN EXTREMELY CHALLENGING PROGRAM

The FreedomCAR and Fuel Partnership is an extremely challenging program, whose ultimate vision involves a fundamental transformation of automotive technologies and the supporting fuel infrastructure. Many technical barriers exist and need to be overcome to achieve this vision, and fundamental invention is probably needed to meet the program's technical performance and cost targets. Even if the technical targets are met, transitioning from the current fuel infrastructure based on gasoline and diesel fuel to one based on hydrogen derived from a variety of sources will be a formidable social and economic challenge.

The committee believes that research in support of this vision is justified by the potentially enormous beneficial impact for the nation. At this early stage, no insurmountable barriers to achievement of this vision have been identified but several critical components of the program have been noted. Specific, quantitative 2010 and 2015 technology and cost goals have been established by the technical teams. These goals bear on each important element of the program, and the current status of the program relative to these goals is discussed in the body of this report. In view of the large number of unknowns and the need for breakthroughs, the committee does not feel that it is appropriate or useful at this time to speculate on the probability of this program achieving its long-term vision according to its current plan. Funding levels and the consequent research results during the next few years should allow future reviews to make a more firmly based assessment.

TECHNICAL AREAS

Advanced Combustion Engines and Emission Controls

Conclusion. The various types of ICEs will play a critical transitional role in achieving the FreedomCAR and Fuel Partnership's long-term goal. Even assuming the successful eventual transition to hydrogen as a primary transportation fuel, the ICE will be the automotive power plant that consumes most of the fuel in the fleet for several decades during the transition. Reducing the fuel consumption and emissions of ICEs is, therefore, critically important. Novel emission reduction and control technologies are needed, and the cooperation of energy companies in research programs aimed at these technologies will increase the likelihood of finding solutions using hydrocarbon-based or alternative liquid fuels. Hydrogen might also become a fuel for the ICE if a viable system for its production, distribution, and storage for transportation vehicles is developed and implemented.

Fuel Cells and Hydrogen Storage

Conclusion. The Partnership has an extremely ambitious goal: to develop both vehicle and infrastructure technology that would make it possible for automotive companies to decide in 2015 whether or not to build commercially viable fuel-cell-powered vehicles. The development of commercially viable fuel cells and onboard hydrogen storage is, without question, the most difficult vehicular aspect of this program. Multiple challenges are being addressed: performance, durability, efficiency, and cost, and they are being worked on at all levels: basic technology, the individual components, stacks, and systems. For fuel cells, durability and cost are the most difficult goals, and for hydrogen storage, the most difficult are size, weight, and cost. In most instances, solutions depend on yet-to-be-conceived or -proven component and manufacturing technology rather than incremental improvement. While this makes outcomes difficult to predict, the committee agrees with the strategy and research directions that DOE is taking to address both the fuel cell and hydrogen storage areas; however, some areas need greater effort.

Recommendation. DOE should expand activity and raise priorities on membrane R&D, new catalyst systems, and electrode design (with the BES program). In particular, the Partnership should focus the national laboratories and other appropriate scientific centers on fundamental failure mechanisms, including a better understanding of the chemistry, physics, and materials involved.

Recommendation. In view of the risk posed to the entire hydrogen program by the currently unmet need for a viable hydrogen storage system, the hydrogen storage technical team and the FreedomCAR and Fuel Partnership leadership team should report annually to all program participants, DOE, and Congress on the state of hydrogen storage technology worldwide relative to the goals and targets of the program.

Electrochemical Energy Storage for Electric Vehicles

Conclusion. Since using hydrogen as a transportation fuel would necessitate several significant breakthroughs, other alternatives to achieve the program goals should be explored and additional research supported if such alternatives show comparable prospects for success. The committee suggests that high-energy batteries for pure battery electric vehicles might be such an alternative. The development of high-energy batteries would also increase the efficiency of advanced hybrid electric vehicles and fuel cell vehicles and accelerate the deployment of plug-in hybrid vehicles.

Recommendation. Searching for breakthrough technology in the area of high-energy batteries for electric vehicles should be a high priority of the program.

Electrical Systems and Electronics

Conclusion. The multiple systems in a fuel cell hybrid electric vehicle require both control and coordination. These functions will be provided by electronics, both for power and signal needs. The integrating role of a vehicle's electrical system makes it a critical-path technology, both functionally and economically. Thermal performance and cost are major challenges for both the propulsion and power electronics systems. Closer coordination of activities in this area is essential to meet the milestones of the program.

Recommendation. The electrical and electronics technical team should develop a process for coordinating the diverse activities it is overseeing. Integrating the electronics with the motor may well provide significant cost advantages. The team should consider such potential benefits and develop aggressive targets for an integrated system by 2010 and 2015. In addition, it should become aware of and leverage the high-temperature semiconductor, packaging, and thermal management work being funded by government agencies at universities, commercial organizations, and the national laboratories.

Hydrogen Fuel Production and Distribution

Conclusion. The committee compliments DOE on rapidly implementing most of the recommendations from *The Hydrogen Economy* and encourages program managers to ensure that sufficient efforts go into developing technologies and resolving issues for the transition period. Since the ultimate goal of a widespread hydrogen-fueled transportation system requires a massive infrastructure change, attention to the transition period and to how such change might be systematically achieved is critical. Systems analysis is an important tool for helping to understand and accelerate this transition.

Recommendation. DOE should pay special attention to the transition from the current ICE fuels infrastructure to a nascent hydrogen economy. As part of this attention, DOE should further focus the achievements of the fuel/vehicle pathway integration technical team by placing greater emphasis on the transition to hydrogen in its systems analysis work and should apply its systems capabilities to analyzing whether the cost goals for hydrogen production, established for a mature hydrogen economy, are appropriate for the transition. Specifically, this analysis should examine whether setting a hydrogen cost goal during the transition that is higher than the cost goal for a mature hydrogen economy would speed or impede the introduction of fuel-cell-powered vehicles.

Conclusion. Providing hydrogen for fuel-cell-powered vehicles during the transition period will initially require many refueling locations for a relatively small number of vehicles. This would probably be best accomplished by generating hydrogen at or near these locations rather than at large central hydrogen production facilities.

Recommendation. The committee believes that significant development efforts should be directed to distributed hydrogen production, including natural gas reforming and electrolysis as well as exploratory work on other distributed generation options.

Conclusion. Successfully dealing with the need for carbon sequestration is critically important to making coal and natural gas acceptable energy sources in a carbon-constrained world. Research in this area should be an integral part of the program.

Recommendation. DOE should create a carbon capture and storage (CCS) system subteam (under the hydrogen production team) in the FreedomCAR and Fuel Partnership and make it part of the overall Hydrogen Fuel Initiative.

Materials

Conclusion. Vehicle programs designed to achieve major fuel economy improvements must incorporate significant weight savings. The widespread application of lightweight materials and innovative manufacturing processes is necessary to attain this goal. FreedomCAR has set a vehicle weight reduction target of 50 percent, with the additional criterion "affordable cost." Affordability is the main barrier to meeting the 50 percent goal, and it is unlikely to be achieved within the time frame of this program. The alternative is to relax the weight reduction goal or allow a cost penalty or some combination of the two. The fundamental issue with carbon-fiber-reinforced polymers is the development of low-cost carbon fibers.

Recommendation. More extensive research on carbon-fiber-reinforced polymers and direct cooperation with the major fiber manufacturers appear necessary for any hope of success within the program time frame. Meanwhile, R&D on manufacturing of vehicle structures should continue.

Conclusion. Overall, although cost reduction is the most important need in many structural materials programs, the committee believes that research activities, with a few exceptions, will do little to achieve this goal.

Recommendation. DOE should review its expenditures on materials research to see if some of them should be applied instead to potentially more fruitful areas of research, such as hydrogen storage materials, batteries, fuel cells, and infrastructure.

CROSSCUTTING ISSUES

Safety

Conclusion. The transition to using hydrogen as a primary transportation fuel raises a multitude of safety questions that must be dealt with by many participants during each phase of the program. The committee believes that this is an extremely important subject that deserves continuing high-level attention and additional funding. Both real and perceived safety concerns exist, and all of them must be proactively and effectively dealt with to ensure the success of the program. The critical need to develop safety-related technology, codes, and standards (including vehicle standards) and inculcate widespread safety awareness before hydrogen vehicles can be widely introduced justifies a focused effort in this area. This effort should include the wide dissemination of DOE, National Highway Traffic Safety Administration (NHTSA) and USCAR reports and peer-reviewed papers on hydrogen safety issues.

Recommendation. DOE should form a new, crosscutting safety technical team with a mission that includes broad hydrogen-related safety issues, not only for the Office of Hydrogen, Fuel Cells and Infrastructure Technology (HFCIT), but for the other DOE offices as well. This new team should incorporate the existing codes and standards technical team as a subteam. Both DOE and NHTSA need enough resources to carry out their assigned safety roles.

Public Concerns

Conclusion. In addition to the very demanding technical challenges, some issues surrounding societal acceptance may be pivotal and ultimately determine the feasibility of creating a fleet of hydrogen-fueled vehicles and a supporting infrastructure. The present review of the FreedomCAR and Fuel Partnership focuses on the technical challenges. However, the committee considers it important to recognize that implementing the current program vision will require not only substantial technical breakthroughs but also successful efforts to address public concerns about the widespread use of hydrogen as a transportation fuel. The learning demonstrations program, just getting under way, should be a big step in this direction. The committee also notes that there is a need to understand the potential long-term ecological and environmental effects of the change to a hydrogen-fueled economy.

Recommendation. DOE, in collaboration with the Environmental Protection Agency, should systematically identify and examine possible long-term ecological and environmental effects of large-scale hydrogen use and production from various energy sources.

Importance of Systems Analysis

Conclusion. The FreedomCAR and Fuel Partnership has made an excellent start on developing significant systems analysis capability and has been particularly responsive to the relevant recommendations of the report *The Hydrogen Economy*.

Recommendation. The FreedomCAR and Fuel Partnership should use its systems analysis capability routinely in the program management process, establishing goals, evaluating trade-offs, setting priorities, and making go/no-go decisions.

Conclusion. To date the systems analysis technical team has focused on the development and refinement of systems analysis tools to predict vehicle and component characteristics. The committee believes that there is need for more than this. The complex nature of the program makes it critical to develop and use a robust, overall well-to-wheels systems analysis that will enable informed trade-off decisions throughout the program.

Recommendation. An ongoing, integrated well-to-wheels assessment should be made of the Partnership's progress toward its overall objectives of reducing the nation's oil dependence and introducing hydrogen as a transportation fuel, if appropriate. This assessment should examine possible trade-offs between the individual goals of the fuel program and the vehicle program, as well as between short-term goals and long-term goals, and between energy sources, to guide future research priorities and, ultimately, national transportation energy policy.

Program Balance and Funding

Short- and Longer-Term Goals

Conclusion. The Partnership involves both short-term goals related to hydrocarbon-fueled vehicles used during a transition period and much longer-term goals aimed at enabling "a clean and sustainable transportation energy future." The committee considers the current split of funding between the long-term and shorter-term goals to be appropriate. Hydrogen-related activities—for example, fuel cells, hydrogen production, distribution, and safety—absorb approximately 70 percent of the funds. The remaining funds support the development of transition technologies, where cost is often the most significant barrier.

Congressionally Directed Funding

Conclusion. During the last 2 years, congressionally directed funding to specific recipients and activities has diverted resources from efforts focused on critical program goals, particularly in the hydrogen portion of the program. The committee believes this earmarking increases the risk of missing critical program milestones and targets, places high demands on DOE management time, and signals to the industry partners somewhat less than full government support for the program goals. If this practice continues and appropriations are not increased to compensate for it, milestones for the program will most certainly have to slip. Congressional and administration leaders should be made aware of how congressionally directed funding affects program timing and leads to shortfalls in meeting its goals. In addition, DOE should ensure that these leaders understand the critical importance of the key parts of the FreedomCAR and Fuel Partnership to achieving its long-term, high-level goals.

Strategy for Accomplishing Goals

Program Management and Communications

Conclusion. Overall the committee is encouraged by the progress the FreedomCAR and Fuel Partnership has made in program management and communications across the many activities and interfaces of the DOE offices and contractors, USCAR, and the energy companies.

Setting Priorities

Conclusion. The committee believes that the setting of priorities needs more emphasis. It appears to the committee that several technical programs may not be contributing solutions to the most critical and important issues. There have not been any integrated assessments of overall progress toward the broad objectives of reducing petroleum demand and introducing hydrogen. Such assessments would be valuable in informing the Partnership's high-level program decision making.

Recommendation. The FreedomCAR and Fuel Partnership should perform an overall program evaluation, using go/no-go decisions and setting priorities that focus resources on programs that will contribute most to solving the problems critical to the success of the long-term program goals.

Value of Learning Demonstrations

Conclusion. The learning demonstrations program is very important to validate current component and systems concepts and to uncover previously unknown issues. Such demonstrations will establish many system and engineering parameters for a complete operating hydrogen supply and a fuel cell transportation system. These cooperative programs are well designed. Information will be collected from both vehicle and infrastructure components, pooled, and shared. It will guide the technical teams as well as the systems and modeling efforts and help to establish appropriate program priorities.

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1

Introduction

BACKGROUND

The U.S. Department of Energy (DOE) has been involved for almost 30 years in research and development (R&D) programs related to advanced vehicular technologies and alternative transportation fuels. In particular, in 1993, during the Clinton administration, the Partnership for a New Generation of Vehicles (PNGV) was formed between the federal government and the auto industry's U.S. Council for Automotive Research (USCAR).[1] The PNGV sought to significantly improve the nation's competitiveness in the manufacture of future generations of vehicles, to implement commercially viable innovations emanating from ongoing research on conventional vehicles, and to develop vehicles that achieve up to three times the fuel efficiency of comparable 1994 family sedans (NRC, 2001; PNGV, 1995; The White House, 1993).[2]

The election of President Bush in 2000 resulted in changes in direction and organization of a number of DOE R&D programs and the creation of new, multiyear program plans for vehicle and fuel R&D efforts (DOE, 2004a,b). In January 2002, the Secretary of Energy and executives of DaimlerChrysler, Ford,

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[1] USCAR, which predated the formation of PNGV, was established by Chrysler Corporation, Ford Motor Company, and General Motors Corporation. Its purpose was to support intercompany, precompetitive cooperation that would reduce the cost of redundant R&D in the face of international competition. Chrysler Corporation merged with Daimler Benz in 1998 to form DaimlerChrysler. USCAR currently supports a number of consortia (Appendix A).

[2] The goal of PNGV that attracted the most attention from the news media was the development of a family sedan that would achieve a fuel economy of 80 miles per gallon (mpg) and cost the same as a comparable 1993 sedan. The media usually ignored the fact that the goal had been set as "up to 80 mpg," not "80 mpg."

and General Motors announced a new government-industry partnership between DOE and USCAR called FreedomCAR, with CAR standing for Cooperative Automotive Research. The new partnership supersedes and builds upon the PNGV program. In September 2003, FreedomCAR was expanded to include five large energy companies—BP America, Chevron Corporation, ConocoPhillips, ExxonMobil Corporation, and Shell Hydrogen (U.S.)—to address issues related to the supporting fuel infrastructure. The expanded scope of the partnership was acknowledged by changing the name to FreedomCAR and Fuel Partnership.[3] The long-term goal of the program is to "enable the full spectrum of light-duty passenger vehicle classes to operate completely free of petroleum and free of harmful emissions while sustaining the driving public's freedom of mobility and freedom of vehicle choice" (DOE, 2004a).

The FreedomCAR and Fuel Partnership differs in several ways from PNGV. PNGV focused on replacing the family sedan (that is, a midsize automobile such as the Concorde, Lumina, or Taurus) with a marketable, more fuel-efficient design. It included specific vehicle milestones—namely, a concept vehicle by 2000 and a preproduction prototype by 2004. The FreedomCAR and Fuel Partnership addresses the development of advanced technologies for all light-duty passenger vehicles: cars, sport utility vehicles (SUVs), pickups, and minivans. It also addresses technologies for hydrogen production, distribution, dispensing, and storage, which were not a part of the PNGV program. It is a partnership between USCAR and one government agency, DOE, which collaborates with other agencies as needed. In PNGV, many agencies were involved and the lead agency was the Department of Commerce.[4] No new government money was appropriated for PNGV. Each participating agency was expected to reprogram existing R&D funds to support PNGV goals. The FreedomCAR and Fuel Partnership started with a presidential commitment to request $1.7 billion over 5 years (FY04 to FY08), with FY05 appropriations of about $310 million and an FY06 presidential budget request of about $360 million (Garman, 2005).[5] Funding for research, development, and demonstration activities goes to universities, the national labo-

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[3] In February 2003, before the announcement of the FreedomCAR and Fuel Partnership, the President announced the FreedomCAR and Hydrogen Fuel Initiative to develop technologies for (1) fuel-efficient motor vehicles and light trucks, (2) cleaner fuels, (3) improved energy efficiency, and (4) hydrogen production and nationwide distribution infrastructure needed for vehicle and stationary power plants, to fuel both hydrogen internal combustion engines (ICEs) and fuel cells (DOE, 2004a). The expansion of the FreedomCAR and Fuel Partnership to include the energy sector after the announcement of the initiative also supports the goal of the Hydrogen Fuel Initiative.

[4] The federal agencies involved in PNGV included the Department of Commerce, DOE, the Environmental Protection Agency (EPA), the Department of Defense (DOD), the National Science Foundation (NSF), the Department of Transportation (DOT), and the National Aeronautics and Space Administration (NASA).

[5] The FY05 appropriation breaks down as follows: hydrogen technology, $120 million; fuel cells, $75 million; vehicle technologies, $85 million; Office of Science, $29 million; DOT, $0.55 million (Chapter 5, Tables 5-1 and 5-2).

ratories, and private companies. Especially in the case of development activities, projects are often cost shared between the private sector and the federal government (see Chapter 5 for further discussion).

The Partnership plays an important role in the planning, pursuit, and assessment of high-risk R&D for many of the needed vehicle and fuel technologies. Federal funds enable much of this work to move forward. The Partnership also serves as a communication mechanism for the interested players, including government, the private sector, the national laboratories, universities, the public, and others.

GOALS AND TARGETS

The long-term goal of the FreedomCar and Fuel Partnership is to enable the transition to a transportation system "that uses sustainable energy resources and produces minimal criteria or net carbon emissions on a life cycle or well-to-wheel basis" (DOE, 2004b). Starting to reduce the nation's dependence on imported petroleum is central to this goal. The current plan envisions a pathway initially involving more fuel-efficient internal combustion engines, followed by increasing use of hybrid electric vehicles and, ultimately, transition to an infrastructure for supplying hydrogen fuel to fuel-cell-powered vehicles (DOE, 2004b).

To address the technical challenges associated with this envisioned pathway, the FreedomCar and Fuel Partnership has established specific, quantitative 2010 and 2015 technology and cost goals in eight areas:

- ICEs (both petroleum- and hydrogen-fueled),
- Fuel cell power systems,
- Fuel cells,
- Hydrogen storage systems,
- Energy storage systems for hybrid vehicles,
- Electric propulsion systems,
- Materials for lightweight vehicles, and
- Hydrogen production and delivery systems.

These goals and the research related to their attainment will be discussed later in this report. Technical teams, as noted in the next section, "Organization of the Partnership," have also been formed to deal with specific technical areas and other crosscutting needs in the program.

ORGANIZATION OF THE PARTNERSHIP

The FreedomCAR and Fuel Partnership consists of a number of oversight groups and technical teams that have participants from government and industry (see Figure 1-1). The Executive Steering Group, which is responsible for the governance of the Partnership, comprises the DOE assistant secretary for energy

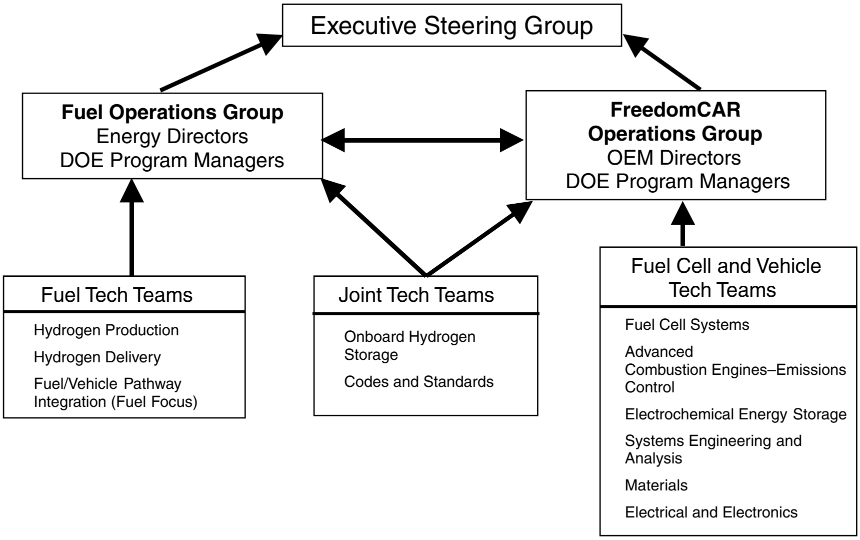

FIGURE 1-1 FreedomCAR and Fuel Partnership organizational structure. SOURCE: R.F. Moorer, "FreedomCAR and Fuel Partnership peer review," Presentation to the committee on November 17, 2004.

efficiency and renewable energy (EERE) and a vice-presidential- or presidential-level executive from each of the Partnership companies. It meets as needed. The FreedomCAR Operations Group, made up of DOE program managers and USCAR member company directors, is responsible for direction of the technical teams and prioritization of research issues. The Fuel Operations Group, made up of DOE program managers and energy company directors, is responsible for the direction of the fuel technical teams. Periodically, the FreedomCAR Operations Group and the Fuel Operations Group hold joint meetings to coordinate fuel and power-plant issues and identify strategic or policy issues that warrant attention by the Executive Steering Group (DOE, 2004c).

The Partnership has formed 11 industry-government technical teams responsible for R&D on the candidate subsystems (see Figure 1-1). Most of these technical teams focus on specific technical areas, but some, such as codes and standards and systems engineering and analysis, focus on crosscutting issues. A technical team consists of scientists and engineers with technology-specific expertise from the USCAR member companies, energy partner companies, and national laboratories, as well as DOE technology development managers. They may come from other federal agencies if approved by the appropriate operation group(s). A technical team is responsible for developing R&D plans and roadmaps, reviewing research results, and evaluating technical progress toward meeting established research goals (DOE, 2004c). Its discussions are restricted to nonproprietary topics. Fuel cell and vehicle technical team members come from the USCAR partners and DOE. They address the same topics as they did under the PNGV—namely, fuel cells, advanced combustion and emissions control, systems engineering and analysis, electrochemical energy storage, materials, and electrical systems and power electronics.

The three teams in the hydrogen fuel technical teams and the codes and standards technical team are new. In May 2003, the USCAR partners and DOE invited five energy companies to join the Partnership. In September 2003, the energy companies attended the joint meeting of the two operations groups and the meeting of the Executive Steering Group. Two Fuel Operations Group technical team reviews took place in 2004. Three teams—hydrogen production, hydrogen delivery, and fuel/vehicle pathway integration—each have members from the energy companies and DOE, and there are two joint technical teams connecting the fuel teams and the vehicle teams: an onboard hydrogen storage team and a codes and standards team.

At DOE, primary responsibility for the FreedomCAR and Fuel Partnership rests with EERE.[6] The two main program offices within EERE that are involved in the activities of the Partnership are the FreedomCAR and Vehicle Technologies (FCVT) program and the Hydrogen, Fuel Cells, and Infrastructure Technologies (HFCIT) program.

The FCVT program has the following specific goal: to support "R&D that will lead to new technologies that reduce our nation's dependence on imported oil, further decrease vehicle emissions, and serve as a bridge from today's conventional power trains and fuels to tomorrow's hydrogen-powered hybrid fuel cell vehicles" (DOE, 2004b). The FreedomCAR and Fuel Partnership, the focus of this report, and the 21st Century Truck Partnership are both within FCVT.[7]

The FreedomCAR and Fuel Partnership activities in the FCVT program are organized into a number of areas:

- Vehicle systems analysis and testing to provide an overarching vehicle systems perspective to the technology R&D subprograms and activities in the FCVT and HFCIT programs;
- Hybrid propulsion systems for light-duty vehicles, which includes activities on advanced internal combustion engine (ICE) power trains and hydrogen ICE power trains as well as testing on various fuel and propulsion system combinations;
- Energy storage technologies (batteries and ultracapacitors);
- Advanced power electronics and electric machines;

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[6] EERE has a wide variety of technology R&D programs and activities related to renewable energy technologies, such as the production of electricity from solar energy or wind or the production of fuels from biomass, to the development of technology to enhance energy efficiency, whether for vehicles, appliances, buildings, or industrial processes. It also has programs on distributed energy systems (see Appendix B for an EERE organization chart).

[7] DOE supports several other programs related to the goal of reducing dependence on imported oil. The 21st Century Truck Program supports R&D on more efficient and lower emission commercial road vehicles.

- Advanced combustion engine R&D, which in concert with the work on light-duty hybrid propulsion systems focuses on enabling technologies for energy-efficient, clean vehicles powered by advanced ICEs using clean hydrocarbon-based and non-petroleum-based fuels and hydrogen;
- Materials technology for lightweight vehicle structures and for propulsion system materials, including power electronics and combustion engines; and
- Fuels technologies to allow current and emerging advanced ICEs and emission control systems to be as efficient as possible while meeting future emission standards and to reduce reliance on petroleum-based fuels.

The HFCIT program directs activities in hydrogen production, storage, and delivery and integrates them with transportation and fuel cell development activities. The proton exchange membrane (PEM) fuel cell R&D is undertaken in the HFCIT program. The program is focused on

- Overcoming technical barriers through R&D on hydrogen production, delivery, and storage technologies, as well as fuel cell technologies for transportation, distributed stationary power, and portable power applications;
- Addressing safety concerns and developing model codes and standards;
- Validating and demonstrating hydrogen fuel cells in real-world conditions; and
- Educating key stakeholders whose acceptance of these technologies is critical to their success in the marketplace (DOE, 2004a,b).

The manager of HFCIT is the overall DOE hydrogen technology program manager.

Some activities related to the HFCIT program focus are not within EERE. The Office of Fossil Energy (FE) supports the development of technologies to produce hydrogen from coal, as well as carbon capture and sequestration programs. The Office of Nuclear Energy, Science and Technology (NE) supports research into the potential use of high-temperature nuclear reactors to produce hydrogen, while the Office of Science (SC) supports fundamental work on new materials to store hydrogen; catalysts; fundamental biological or molecular processes for hydrogen production; fuel cell membranes; and other basic science areas (DOE, 2004d,e). An overall evaluation and strategic review of these hydrogen technology R&D activities was undertaken by the NRC's Committee on Alternatives and Strategies for Future Hydrogen Production and Use, and the current study references the results of that study and its recommendations, which are contained in the report *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs* (NRC/NAE, 2004), referred to as *The Hydrogen Economy* in the remainder of the present report.

INTERRELATIONSHIP OF VEHICLE AND FUEL TECHNOLOGIES

Historical examples illustrate the importance of linking vehicles and fuels, not only for setting technical targets but also for addressing infrastructure barriers to widespread use. As noted in the preceding sections, the FreedomCAR and Fuel Partnership addresses R&D for both vehicles and fuels. The critical interrelationship between vehicles and fuels has been recognized for many years. This recognition led, for example, to the formation of the Coordinating Research Council (CRC) by the automobile companies and the major oil companies in 1942. CRC worked on technical issues at the vehicle/fuel interface and, during the two decades that followed, enabled the introduction of high-octane gasoline and higher compression engines with increased specific power and efficiency. NRC reviews of the PNGV program during the 1990s also called for cooperation between the PNGV program and the fuel industry.

Examples of important advances brought about by technological change at this vehicle/fuel interface include the introduction of unleaded gasoline in 1971 and reformulated gasoline (RFG) in the early 1990s. Unleaded gasoline provided an immediate reduction in vehicle exhaust emissions and, more important, enabled the introduction of first-generation catalytic converters. Since these were essential to comply with the 1970 Clean Air Act, the phase-in of unleaded fuel was mandated by EPA.

The Auto-Oil program, launched as a collaborative effort between the automotive and oil industries in the mid-1980s, led to RFG, adopted by EPA and mandated in the 1990s. Similarly, reduced sulfur in diesel fuel has been shown to reduce exhaust emissions significantly and also is essential for facilitating the introduction of advanced exhaust aftertreatment devices. Consequently, EPA has mandated the phase-in of low-sulfur diesel fuel commencing in 2006.

Because infrastructure and availability are just as important as the technical specifications of the fuel and its compatibility with the power plant, EPA mandates the availability of unleaded gasoline and low-sulfur diesel fuel. Efforts to introduce on a wide scale alternative fuels such as methanol, ethanol, and compressed natural gas have all foundered, in part owing to unavailability. Apart from the incentive created by the Energy Policy Act of 1992 for fleets to use alternative fuels, there is no compelling reason for consumers to demand them. Indeed, there are disincentives, such as economics and/or inconvenience, that discourage their use. It has been repeatedly demonstrated that unless a fuel is widely available, easy to refuel, and competitively priced it will not enjoy widespread use as a replacement for gasoline.

Fuels composed mainly of alcohol, such as 85 percent methanol (M85) and 85 percent ethanol (E85), work well in vehicles designed to accept them, and there are now well over 4 million vehicles in the United States equipped to operate on M85 or E85. However, despite their ease of use, there are fewer than 200 predominately alcohol filling stations nationwide, compared with about 168,000 retail gasoline stations (National Petroleum News, 2004). Since alcohol fuels cost more than gasoline (on an equivalent-energy basis) and limit vehicle range, there is no incentive for customers to use them and hence no business case for producing the fuel or building refueling stations.

Compressed natural gas (CNG) also performs well in CNG-compatible vehicles, especially dedicated CNG vehicles (more so than dual-fuel vehicles), but it also has enjoyed only limited success. CNG is mainly used in niche markets such as city buses, airport vans, some taxis, and other fleets. Again, limited availability and reduced vehicle range, combined with inconvenient refueling and lack of a secondary vehicle market, resulted in the absence of a positive business case for operators or energy producers.

To overcome the challenges, whether they be technical, economic, or public policy, of vehicle/fuel compatibility and fuel availability, any attempt to introduce a radically different vehicle fuel, such as hydrogen in any form, must involve a dedicated effort by all interested parties, including vehicle manufacturers, the energy industry, and the government. While there is no guarantee that such collaboration will ultimately be successful, its absence will guarantee failure. One of the major strengths of the FreedomCAR and Fuel Partnership is that its membership includes three of the essential stakeholders to identify, define, and oversee the needed research, as described in the previous sections in this chapter.

ADVANCED INTERNAL COMBUSTION ENGINES AND FUELS

Even in the most optimistic scenario postulated in the National Academies report *The Hydrogen Economy*, only 10 percent of new vehicles and 6 percent of the total miles traveled in 2024 are projected to be hydrogen-fueled fuel cell vehicles (NRC/NAE, 2004). The remaining 90 percent of new vehicles are projected to be conventionally powered vehicles, either hybrid or nonhybrid. Consequently, by far the greatest contribution to reduced energy use and emissions by and from the U.S. vehicle fleet over the next 20 years and beyond will come from continued improvement in ICEs, hybrid electric vehicles, and their fuels.

Despite increasingly stringent emissions requirements and the seemingly insatiable demand by vehicle customers for increased performance, the fuel efficiency of domestic cars and light trucks (pickups, SUVs, vans) has been increasing steadily at 1.5 percent per year for at least 20 years. Figure 1-2 shows fuel efficiency as ton-miles per gallon (mpg) for cars and trucks, respectively.

This steady increase in fuel efficiency has been masked by increasing vehicle content, hence weight, acceleration performance, and a shift in the fleet mix from cars to light trucks. Consequently, overall U.S. fleet fuel economy (as indicated by the Corporate Average Fuel Economy [CAFE] measure) has remained relatively stable, or even declined, in recent years (Figure 1-3).

To reduce transportation fuel use, current industry-wide efforts to improve ICE efficiency and further develop relevant fuels must continue or accelerate. This is true regardless of the degree to which hybrid electric vehicle power trains

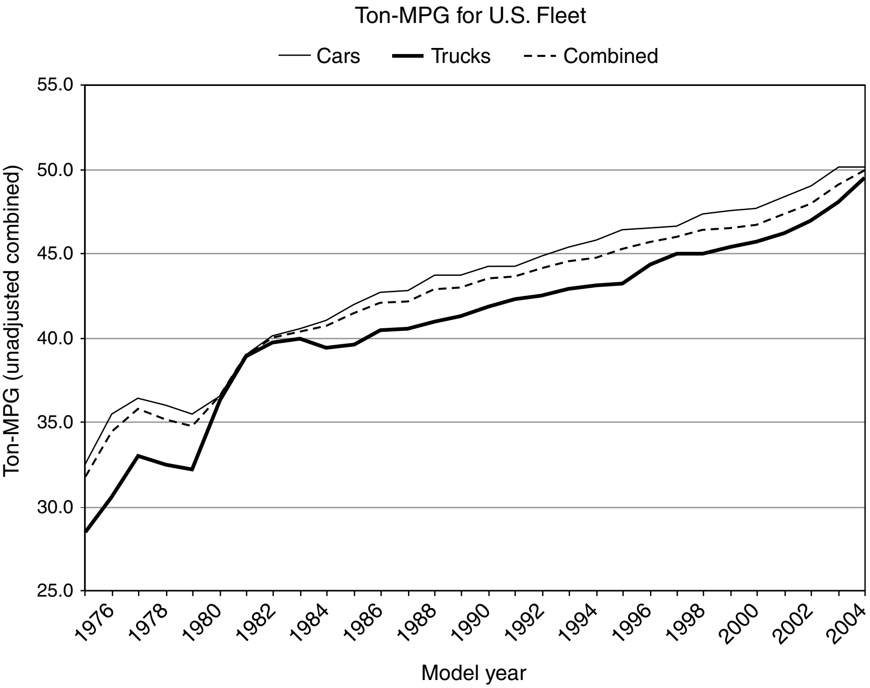

FIGURE 1-2 Fuel efficiency for U.S. fleet by model year for cars and trucks, expressed as ton-mpg. The metric ton-mpg provides an indication of a vehicle's ability to move weight. It is a measure of power train/driveline efficiency. SOURCE: EPA, 2004.

proliferate or regardless of whether advanced diesel engines achieve customer acceptance and meet emission standards. The urgency of this task is amplified by the reality that with approximately 16 million new vehicles sold in the United States every year, it takes almost 15 years to turn over the national fleet of roughly 225 million vehicles.

While much of the FreedomCAR and Fuel Partnership activity is devoted to fuel cell vehicles and hydrogen fuel, further improvement in conventional ICEs and hybrid electric vehicles can contribute significantly to the goals of energy independence and reduced carbon emissions and should benefit from continued collaboration between industry engineers and the national laboratories in this area.

The four-stroke, direct-injection engine technical team accomplished a great deal in the PNGV program, especially in the diesel (compression ignition direct injection [CIDI] engines) and four-stroke gasoline direct injection (4SDI) areas, and it has continued many of the most promising concepts under the FreedomCAR and Fuel Partnership umbrella. In particular, nitrogen oxides (NO_x) and particulate emissions objectives in PNGV were far more stringent than those anywhere

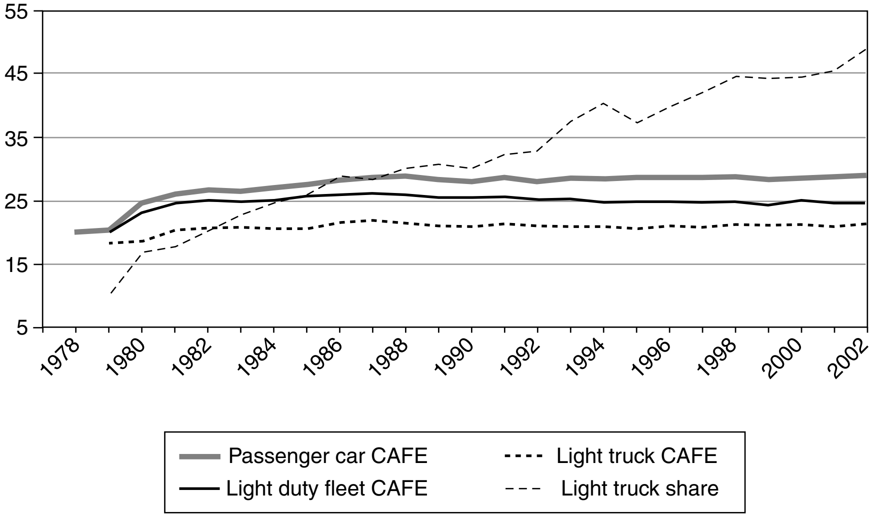

FIGURE 1-3 Fuel economy of the U.S. automotive and light truck fleet for model years 1978 to 2002. The fuel economy curves are in miles per gallon (mpg) and the light truck share is in percent. SOURCE: NHTSA, 2003.

else in the world, in anticipation of the upcoming EPA Tier 2 requirements. The PNGV partners drew on all of their global resources to develop candidate exhaust aftertreatment systems to address these goals, and the results of this development, which were shared with the entire OEM and supplier industry, are beginning to appear on production vehicles in Europe, Japan, and the United States, as increasingly stringent regulations require, and improved, low-sulfur fuels permit.

Given the limits of aftertreatment, renewed emphasis is also being applied to reducing engine-out emissions, again building on work commenced within PNGV; in particular, the so-called homogeneous charge compression ignition (HCCI) and low-temperature combustion (LTC) concepts are of great interest. The status of FreedomCAR and Fuel Partnership efforts on ICE and emissions control development is discussed further in Chapter 3.

ADVANCED FUEL CELL VEHICLES AND FUELS

The basic concept of the fuel cell was invented in 1839, and attempts to apply it as a vehicle prime mover date back to the 1960s. However, serious development of the PEM fuel cell began worldwide only in the 1990s, with the growing awareness that a hydrogen-fueled fuel cell is one of the very few candidates capable of achieving the holy grail of zero vehicle emissions, high efficiency, reduced dependence on petroleum, and—potentially—zero (systemwide) carbon dioxide (CO_2) emissions.

Successive generations of fuel cell vehicles have demonstrated increasingly compact systems and improved functionality. Various methods of providing on-board hydrogen, from the on-board reformation of hydrocarbon fuels (e.g., gasoline or methanol) to the storage of compressed or liquefied hydrogen gas, have been demonstrated, with most current demonstrations using compressed storage. The remaining vehicle issues are primarily on-board storage of sufficient hydrogen, system functionality, durability and reliability, and total system cost. Technical team activity in these areas is covered in detail in Chapter 3.

While a major obstacle to the deployment of fuel cell vehicles is clearly the absence of a hydrogen fuel production and distribution infrastructure, work to address this has only recently begun. The primary issues here are how to produce hydrogen economically without exacerbating carbon dioxide emissions and how to deliver it safely and cost-effectively to the point of vehicle refueling. The enablers of hydrogen production and distribution were fully enunciated in *The Hydrogen Economy* (NRC/NAE, 2004). Chapter 4 describes progress in this area.

The issue of safety pervades virtually every aspect of the pursuit of a hydrogen economy. The propensity of hydrogen to find even the most infinitesimal leak path, its low ignition energy, its flammability over a very wide range of concentrations, and the invisibility of its flame are well known. Less well understood are its behavior in the event of vehicle impact and the adequacy of emerging codes and standards. This important subject is discussed in Chapter 2.

COMMITTEE APPROACH AND ORGANIZATION OF THIS REPORT

The Hydrogen Economy discusses many of the R&D activities associated with the hydrogen technology parts of the FreedomCAR and Fuel Partnership, such as hydrogen production, distribution, dispensing, and storage, as well as the transition strategy for making hydrogen more widely available (NRC/NAE, 2004). It provides an excellent review of the challenges and potential benefits of using hydrogen as a transportation fuel and offers recommendations for the DOE R&D program, and the current committee has used its results and referred to its recommendations. The current report presents the committee's evaluation of the DOE-sponsored research efforts to achieve the hydrogen economy through the FreedomCAR and Fuel Partnership and offers comments and suggestions on the technical directions, strategies, and funding and management of this very important program. Because *The Hydrogen Economy* had just been published as the current committee was being constituted, with regard to the hydrogen technology parts of the Partnership, the committee reviewed just the plans of the three new fuel-related technical teams.

The statement of task for this committee is as follows:

> The National Academies' National Research Council (NRC), through its Board on Energy & Environmental Systems and Transportation Research Board (TRB) established a committee to conduct an independent, credible and unbiased review of the research pro-

> gram of the FreedomCAR (Cooperative Automotive Research) & Fuel Partnership, a program undertaken by the U.S. government in collaboration with the U.S. Council for Automotive Research (USCAR) and five major energy companies. (See Appendix C for biographical information about the committee members.) The primary tasks of the committee were as follows, and are addressed in the committee's report:
>
> (1) Review the challenging high-level technical goals and timetables for government and industry R&D efforts, which address such areas as electric propulsion systems, internal combustion engine (ICE) powertrain systems, electric drivetrain energy storage, material and manufacturing technologies, ICE powertrain systems operating on hydrogen (H), fuel cell power systems, fuel cell systems (with fuel reformer), H refueling systems, and H storage systems, as well as any safety issues that may arise from the use of new technologies.
>
> (2) Review and evaluate progress and program directions since the inception of the Partnership towards meeting the Partnership's 2010 technical goals, and examine on-going research activities and their relevance to meeting the goals of the Partnership.
>
> (3) Examine and comment on the overall balance and adequacy of the FreedomCAR & Fuel research effort, and the rate of progress, in light of the technical objectives and schedules for each of the major technology areas.
>
> (4) Examine and comment, as necessary, on the appropriate role for federal involvement in the various technical areas under development.
>
> (5) Examine and comment on the Partnership's strategy for accomplishing its goals, which might include such issues as (a) program management and organization; (b) the process for setting milestones, research directions, and making Go/No Go decisions; (c) collaborative activities needed to meet the FreedomCAR & Fuel's goals (e.g., among the Office of FreedomCAR and Vehicle Technologies, the Office of Hydrogen, Fuel Cells, and Infrastructure Technologies, the U.S. Department of Transportation, USCAR, universities, the private sector, and others); and (d) other topics that the committee finds important to comment on related to the success of the program to meet its technical goals.
>
> (6) Write a report documenting its conclusions and recommendations.

The committee met three times to hear presentations from DOE and industry people involved in the management of the program and to discuss insights gained from both the presentations and written material gathered by the committee (see Appendix D for a list of committee meetings). The committee established subgroups to investigate specific technical areas and formulate questions for the program leaders to answer. The subgroups also held discussion sessions with the FreedomCAR and Fuel Partnership technical team leaders to clarify answers to questions and understand the team dynamics.

The Executive Summary presents the committee's main conclusions and recommendations. This chapter (Chapter 1) provides background on the FreedomCAR and Fuel Partnership, its organization, and the dual nature—vehicle development and fuel development—of the program. Chapter 2 examines the important crosscutting issues that the program is facing. Chapter 3 looks more closely at R&D for vehicle technology, and Chapter 4 examines R&D for hydrogen production, distribution, and dispensing. Finally, Chapter 5 presents an overall assessment.

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2

Major Crosscutting Issues

This chapter addresses the main crosscutting issues that the committee identified in its review of the FreedomCAR and Fuel Partnership. Given that much of the Partnership is relatively recent, the committee deems it important to address some issues early: program decision making, safety, learning demonstrations, and program structure. Some of these issues touch on the broader context on which the successful adoption into the marketplace of the technologies under development depends. The committee believes that proper attention to its recommendations will help move the program's progress and increase its chances of success. It focuses on specific technical areas in Chapters 3 and 4.

PROGRAM DECISION MAKING

Program Management and Organization

As described in Chapter 1, most of the government programs on more efficient vehicle and engine technology, fuel cells, and hydrogen are in DOE, but some programs are in other agencies, such as the Department of Defense (DOD), the Department of Transportation (DOT), and the Environmental Protection Agency (EPA). The FreedomCAR and Fuel Partnership under review by the committee is a substantial piece of the larger whole. Coordination of all advanced vehicle and hydrogen programs is essential if they are to have an optimal impact. The vehicle systems programs form a fairly coherent whole, while the hydrogen production delivery and storage programs are diverse and explore many different pathways to the use of hydrogen as a transportation fuel.

To integrate the planning, budgeting, and management of the many DOE programs constituting the FreedomCAR and Fuel Partnership, DOE's Office of Energy Efficiency and Renewable Energy (EERE) issued the Hydrogen Posture Plan in February 2004 (DOE, 2004a). The plan describes DOE's intended role in hydrogen energy R&D and its pursuit of an accelerated path to the deployment of hydrogen fuel cells, and the associated infrastructure. Within DOE, a working group was established with representatives from the Offices of Energy Efficiency and Renewable Energy; Fossil Energy; Nuclear Energy, Science, and Technology; Science; Management, Budget, and Evaluation/chief financial officer; and Policy and International Affairs (in an oversight capacity). While the broader management of many of these DOE program activities lies beyond the statement of task for the committee, it is important to note that the planning, budgeting, execution, evaluation, and reporting of the government's hydrogen-related programs be well coordinated and integrated.

The committee finds that, while there has been commendable progress in managing the various transportation-related hydrogen activities across DOE, further improvements are needed. The committee identified two areas that need special attention: (1) carbon capture and sequestration and (2) basic energy research. The cost-effective, large-scale production of hydrogen may require that coal be the primary energy source. Carbon capture and sequestration would then be essential to reduce the emission of greenhouse gases. The potential of carbon sequestration to enable hydrogen production appears to play only a minor role in the current work on capture and sequestration (see Chapter 4).

DOE's various presentations to the committee indicated a strong focus on technology development and technology demonstration. It was also apparent that new technologies are likely to be required in hydrogen storage, fuel cell membranes, and electrodes. The committee encourages DOE to ensure that its Basic Energy Sciences Division in the Office of Science is appropriately involved in fundamental research critical to the FreedomCAR and Fuel Partnership.

Congressionally Directed Funding

The committee's review of the FreedomCAR and Fuel Partnership found that in certain program areas, congressionally directed activities (earmarking) of funds had a serious negative impact on the program. Of concern to the committee is the allocation by Congress of significant funds to specific organizations for activities that will contribute little to achieving the Partnership's objectives. Although DOE has some discretion over the allocation of funds not earmarked, over the past 2 years, earmarking has effectively removed about $80 million from the funding for planned programs. This has negatively impacted projects in safety, the production of hydrogen from fossil fuel and renewable energy sources, and hydrogen storage. One possible result is that not enough knowledge and technology will be available by 2015, when commercial feasibility will be assessed, making a positive assessment less likely. In addition to increasing the chances that critical program milestones will be missed, earmarking has forced DOE managers to spend a lot of time trying to adapt programs so they contribute as much as possible to priority goals. It also signals to industry partners somewhat less than full government support for the program goals. This committee feels strongly that all of the funds appropriated for this FreedomCAR and Fuel Partnership should contribute directly to achieving the Partnership's objectives.

Congressional and administration leaders should be made aware that congressionally directed funding affects program timing and leads to shortfalls in meeting goals. DOE should ensure that these leaders understand how critical key parts of the FreedomCAR and Fuel Partnership are to achieving the program's long-term, high-level goals.

Determining Priorities, Milestones, and Go/No-Go Decisions

Priorities, key milestones, and critical decisions within the FreedomCAR and Fuel Partnership must be determined in the appropriate systems context. For example, engine improvements must be evaluated in the context of the vehicle. It is the impact of vehicle improvements in context of the total vehicle fleet that really matters, and this impact depends on production volumes and the fraction of total fleet mileage accounted for by these improved vehicles. Several questions are raised by the need for a technology-development program focused on component technologies to conduct integrated evaluations in the appropriate system context.

For example, each technical team has a detailed set of milestones and decision-making points in its strategic plan. These milestones allow assessing the progress of individual technology development projects, but it is not clear how individual team plans can be integrated into a broader assessment of progress and consequent decision making. Ultimately, the Partnership succeeds when car companies incorporate these new technologies into specific vehicle designs that are attractive to the public and subsequently become part of the vehicle fleet.

The FreedomCAR and Fuel Partnership needs to identify and define appropriate priorities, milestones, and decision criteria in a context that goes beyond the individual technology areas. For example, if substantial demand for electricity for hydrogen generation is anticipated, multisector energy perspectives and inputs will be necessary to assess the prospects for carbon capture and sequestration as well as the electricity generating requirements and the impact of hydrogen generation on natural gas demand.

The committee feels that the FreedomCAR and Fuel Partnership management teams have not yet resolved how best to address these broader program assessment issues. Nor do they appear to have developed plans to carry out analysis of these issues that would support the decision-making process. The management structure outlined in Chapter 1 appears to the committee to be appropriate for the management tasks, but it is not clear how the structure allows for decisions about the Partnership's progress toward commercialization of fuel cell, hydrogen infrastructure, and transition propulsion systems and vehicle technologies. DOE should consider identifying a working group to support overall program management. The working group should perform technology assessments in an appropriate systems framework; check targets and revise them if necessary; evaluate the broader impacts of the technologies being developed in the program on major problems such as overall fleet petroleum consumption and greenhouse gas emissions; and assess progress towards commercialization. While DOE has established a systems analysis capability to do much of this analysis, it is not clear whether or how it is planning to do so, nor does it appear to be adequately staffed to do so. As noted in the next section, "Systems Analysis and Simulation," the systems analysis focus appears to be on developing the systems analysis tools rather than using them for more broadly based and integrated assessments.

An important aspect of the Partnership's decision making is that because the context for an assessment changes with time, so do the targets set for each component technology. One example of this is that the cost targets depend on the price of crude oil and natural gas. Also, because it is the total integrated cost of all the components that is critical to marketability, program management must have processes for reevaluating technology and cost targets as the program progresses.

Because of the importance and challenge of making Partnership decisions in these broader contexts, the committee makes the following recommendation:

Recommendation. An ongoing, integrated, well-to-wheels assessment should be made of the Partnership's progress toward its overall objectives of reducing the nation's dependence on oil and introducing hydrogen as a transportation fuel, if appropriate. This assessment should examine possible trade-offs between individual goals of the fuel program and the vehicle program, between short-term and long-term goals, and between energy sources, to guide future research priorities and, ultimately, national transportation energy policy.

Systems Analysis and Simulation

The previous discussion makes it evident that extensive systems analyses and simulation models are required to make informed decisions and manage the FreedomCAR and Fuel Partnership intelligently. Over the past several years, DOE has successfully developed many models to predict vehicle and component characteristics. Similarly, the production and distribution of fuels can be modeled to permit the comparison of production methods and of candidate fuels.

One important model, the so-called "well-to-wheels" analysis, enables comparisons of alternative fuels and vehicle system architectures by predicting overall energy efficiency and emissions performance of the entire system, taking into account the widely varying energy efficiency of alternative fuel production processes and the behavior of corresponding vehicle systems.

The critical importance of developing systems analysis and simulation was a recurring theme throughout the Partnership for a New Generation of Vehicles (PNGV) program. The seventh and final report on the PNGV program (NRC, 2001) recognized considerable progress in this area, but it encouraged increased effort in system modeling. The report also criticized the lack of progress in cost modeling.

The Hydrogen Economy (NRC/NAE, 2004) devoted one of its main recommendations to the urgent need for systems analysis, offering guidance in 10 areas. In response to these recommendations, DOE has been developing a systems analysis plan, a preliminary draft of which was presented to the committee. The key resources are in place, and individuals have been identified to take the lead on key analysis elements. Figure 2-1 depicts the main analysis domains—technical, cost, and market/benefits—and gives examples of applicable models.

The overall organization structure, as discussed in Chapter 1, is depicted in Figure 2-2, with the systems analysis functions added. The overall systems analysis budget for FY05 is $17.592 million, over half of which is devoted to Vehicle Systems Analysis and Hydrogen Infrastructure Analysis, with the remaining budget devoted to analysis of individual technologies.[1]

Progress to date is shown in Table 2-1. Six areas register significant progress, and two register partial progress; plans are in place for the remaining two.

In summary, the committee commends DOE on progress to date in addressing the systems analysis issue and especially on its response to the recommendations in *The Hydrogen Economy*. The plans and the personnel in place appear sound, and the overall approach is robust. If there are weaknesses, they probably lie in modeling (1) cost to the consumer and (2) consumer behavior in the face of a market transition to a radically different vehicle. Modeling cost is particularly difficult since it must rely on assumptions about future processes and products, and the necessary input data are highly proprietary.

Recommendation. The FreedomCAR and Fuel Partnership should develop and refine its models for consumer behavior during a market transition to radically different vehicles and should also explore ways to enhance the effectiveness of its cost models.

Finally, it appears that the systems analysis efforts are focused on developing and refining the systems analysis tools. While important, there is an additional responsibility to use the tools that are developed to provide overall program management or at least to perform technology assessments, goal checking, evalu-

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[1] S. Chalk, "Systems Analysis Introduction," Presentation to the committee on January 24, 2005.

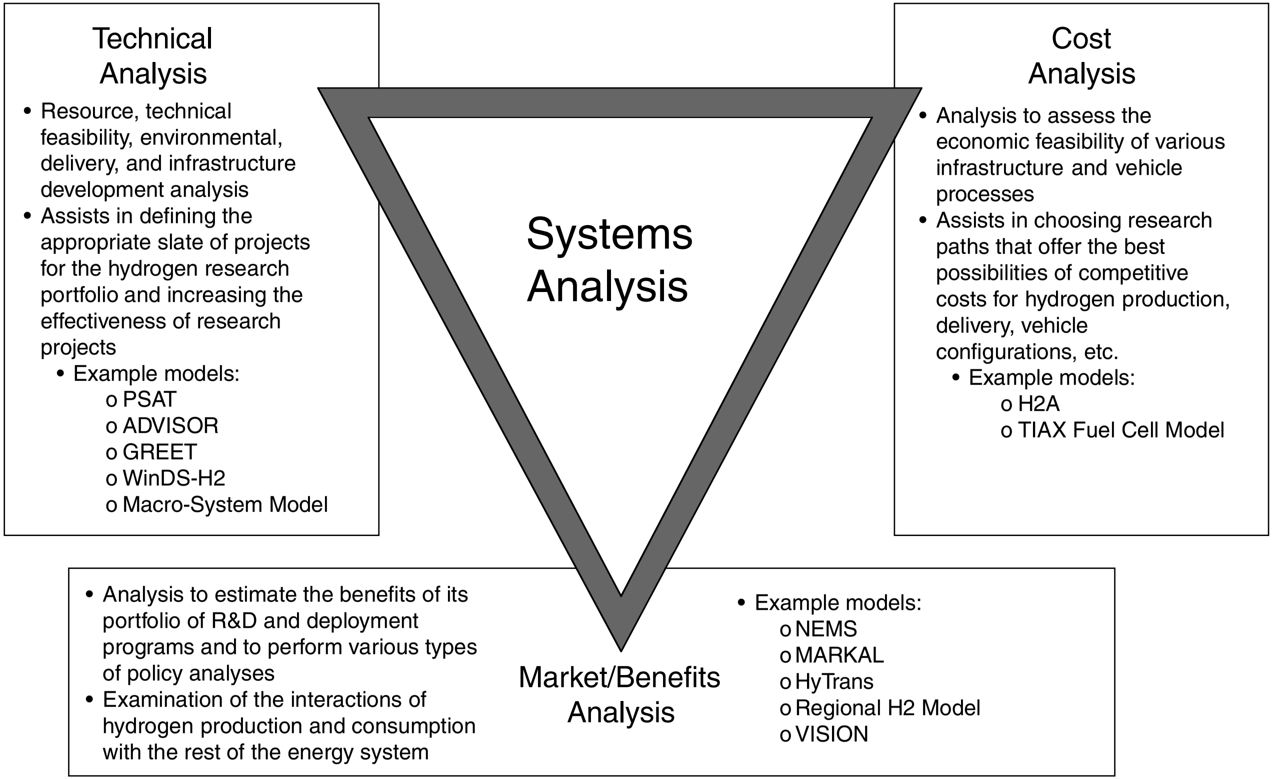

FIGURE 2-1 Analysis domains for systems analysis efforts by the FreedomCAR and Fuel Partnership. SOURCE: S. Chalk, “Systems analysis introduction,” Presentation to the committee on January 24, 2005.

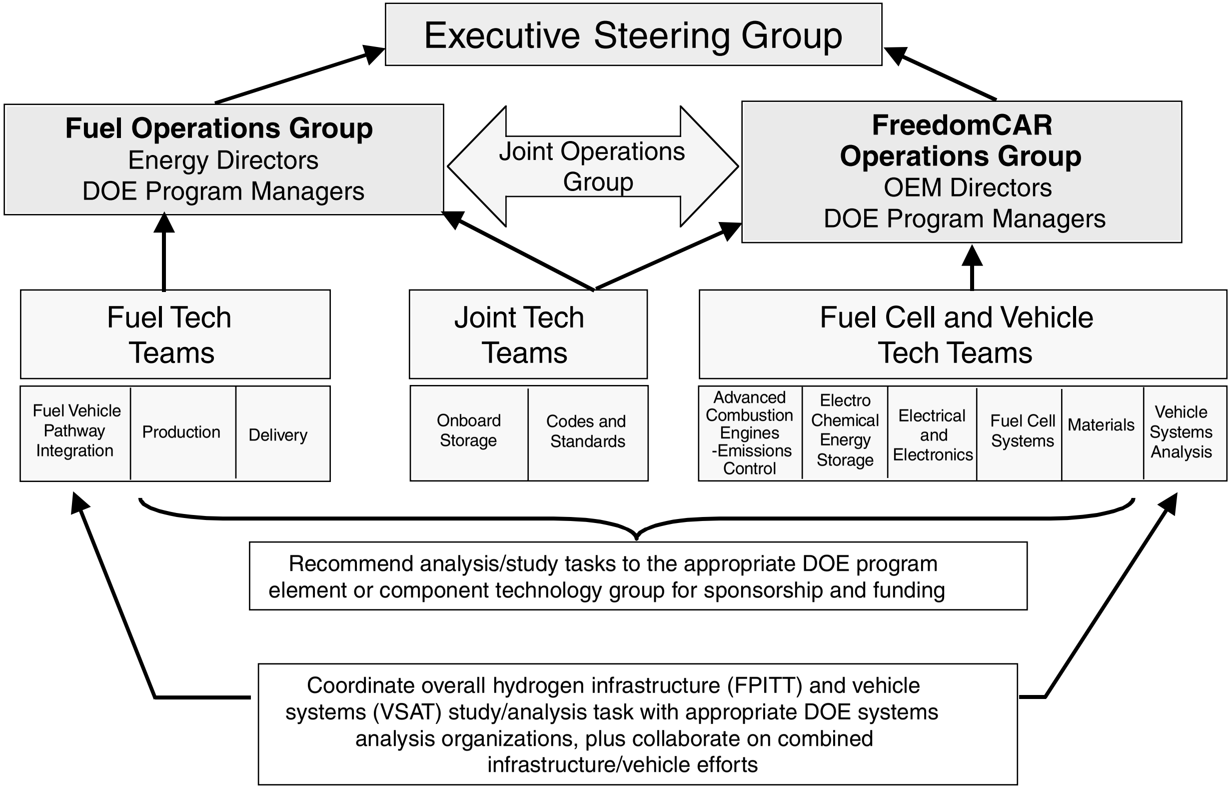

FIGURE 2-2 Overview of the systems analysis activity. SOURCE: S. Chalk, “Systems analysis introduction,” Presentation to the committee on January 24, 2005.

TABLE 2-1 Progress on Systems Analysis Activities

Area	Recommendation	Status	Comments
Concept	• An independent, well-funded, professionally staffed and managed Systems Analysis function, separated by a firewall from technology development functions, is essential to success of the Program. It must be managed independently of the various DOE line R&D programs in order to minimize both the existence and the appearance of technology bias.	✔	
Funding	• Should be on the order of $10M per year—without such a level, research priorities and results will be less understood.	✔	Approximately $12.0M for FY05
People	• Most important ingredient is the people who do the work. There are relatively few with the training, talent, and background to be able to properly identify, evaluate, trade off, and deal with the myriad of technical and economic parameters characteristic of complex energy technologies. A core of specially selected people is essential.	✓	Key personnel in place; additional analysts and modelers need to be identified
Modeling	• Systems modeling for the hydrogen supply evolution should be started immediately, with the objective of helping guide research investments and priorities for the transportation, distribution, and storage of hydrogen.	✔	Many component, element, and transition models
Approach	• Develop/employ a Systems Analysis approach to ○ understanding full costs, ○ defining options, ○ evaluating research results and ○ helping balance the program for short, medium, and long term.	✔	
Coordination	• Systems Analysis is needed to coordinate the multiple parallel efforts within the program.	✔	
Integration	• The program needs to be implemented within a balanced, overall DOE national energy R&D effort	✔	
Transition	• The complex evolution of the transportation and delivery and storage systems would benefit from Systems Analysis to help guide the optimum research and technology investment strategies for any given stage of the evolution.	✓	
Envelopes	• Detailed analysis within envelopes (from unit operations to a fully integrated system) and across the national energy system must be part of the function.	🗸	
Scope	• Implement the function for all U.S. energy options, not just hydrogen.	🗸	PBA plans to put H_2 module in NEMS

✔ **= substantial progress** ✓ **= partial progress** 🗸 **= plans in place**

NOTE: PBA, Office of Planning, Budget and Analysis; NEMS, National Energy Modeling System.
SOURCE: S. Chalk, "Systems analysis introduction," Presentation to the committee on January 24, 2005.

ation of the broader impacts of competing technologies, and commercialization assessment. Responsibility for performing these tasks needs to be assigned and a work plan drawn up to address this expectation. Additional resources may well be required. It is in these areas that the committee recommends emphasis as the plan for systems analysis is solidified.

Recommendation. The FreedomCAR and Fuel Partnership should assign responsibility for overall program management and for the complex analyses to support program management, such as technology assessments, goal checking, evaluating the broader impacts of the technologies on the major problems, commercialization assessment, and decision making, among others.

SAFETY

Safety is a topic that pervades virtually every aspect of the pursuit of a hydrogen economy, and it is one of the major hurdles to the use of hydrogen as a transportation fuel. Large quantities of hydrogen are manufactured and used today throughout the world without undue safety hazards. Safety becomes an issue, however, when it is in consumer hands and on board a vehicle. *The Hydrogen Economy* (NRC/NAE, 2004) emphasized safety from both technical and societal perspectives. Some of the issues are well known—for example, hydrogen's propensity to find even the most infinitesimal leak path, its low ignition energy, its flammability over a wide range of concentrations, and its lack of a visible flame. Other issues, such as the potential consequences when a hydrogen powered vehicle crashes, and the adequacy of emerging codes and standards, are less well understood. In addition, an excellent safety record is essential to the public acceptance of hydrogen vehicles. Addressing public concerns about the widespread use of hydrogen as a transportation fuel could be critical in determining the feasibility of creating a fleet of hydrogen-fueled vehicles and their supporting infrastructure.

Hydrogen Safety Program

The purpose of the DOE Safety, Codes, and Standards program is to ensure that DOE's R&D is conducted in a safe, exemplary manner and that deployed elements of the hydrogen-fueled transportation system have an acceptable level of risk. The elements of the program include producing and maintaining a DOE Safety Plan, a best engineering practices document for hydrogen systems, and extensive support for the development of national and international codes and standards that will allow the deployment of the hydrogen infrastructure and hydrogen-fueled vehicles.

The Hydrogen Safety Review Panel (HSRP) is an important part of DOE plans to ensure that its hydrogen research is conducted in a safe manner. The panel has updated a safety guidance document specifying requirements for DOE contractors (DOE, 2004b). It has made safety site visits to approximately 10 contractors. It is also involved with the review of safety plans that have recently been required on new DOE procurements. The panel reports to the manager of the Office of Hydrogen, Fuel Cells, and Infrastructure Technology (HFCIT). The manager of HFCIT also has overall DOE responsibility for the hydrogen technology program, which, as noted in Chapter 1, encompasses activities in other offices within DOE, including the FreedomCAR and Vehicle Technologies Office (FCVT); the Office of Fossil Energy (FE); the Office of Nuclear Energy, Science and Technology (NE); and the Office of Science (SC). These other offices do not have hydrogen safety offices and intend to rely on HFCIT for their safety support.

The budget of the Safety, Codes, and Standards program was about $6 million in FY04 and FY05. It was appropriated $16 million in FY05, but this money had to be reallocated to balance other parts of the program that were severely impacted by congressionally directed activities (earmarks). The Safety, Codes, and Standards program was the most severely impacted by congressional earmarks, making it, in effect, level-funded in FY05. The President's FY06 budget request recommends $13.1 million for this program.

The top-level allocation of FY05 funds is shown in Table 2-2. Four national laboratories (Sandia National Laboratories at Livermore, California, Pacific Northwest National Laboratory, Los Alamos National Laboratory, and the National Renewable Energy Laboratory) will perform the major portions of the work. There are just two federal employees working in the DOE headquarters Safety, Codes and Standards program.

DOE and USCAR set up a codes and standards technical team about a year ago. The team has representatives from the automotive and energy companies, DOE, and National Highway Traffic Safety Administration (NHTSA). It has spent the first year preparing a roadmap, which is now in first draft form. Detailed descriptions of deliverables for the team do not exist yet. The near-term need is for interim codes and standards for the transition period.

Priority

The transition to hydrogen as a primary transportation fuel raises a multitude of safety questions that must be dealt with by many participants during each phase of the program. It will require a set of codes and standards, including those for on-site hydrogen production and dispensing at fueling stations. The committee observed that the DOE Safety, Codes, and Standards program addresses one of the highest priority areas of the entire FreedomCAR and Fuel Partnership but is also one of the least mature efforts at this early stage. The following discussion and recommendations elaborate on the importance of the Safety, Codes and Standards program.

TABLE 2-2 FY05 Budget for Hydrogen-Related Safety Codes and Standards Activities

Project	FY05 Funding ($)
Hydrogen release R&D	500,000
Materials R&D and handbook	412,000
Risk assessment and analysis	450,000
Hydrogen R&D subcontract support (modeling, SRI facilities, and International Energy Agency Safety Annex)	360,000
Safety Panel	350,000
Codes and Standards National Template (National Renewable Energy Laboratory execution of National Codes and Standards Template)	850,000
National template for contracts and subcontracts (support of codes and standards organization activities, i.e., NFPA, ICC, ASME, SAE, ANSI, CSA-America, NHA)	975,000
International codes and standards development	400,000
Office safety plan, lessons learned, best practices	329,400
Funding of DOT activities (NHTSA, RSPA)	790,000
HAMMER—safety training of officials and first responders	300,000
Taxes (7.8%) (SBIR, overarching analysis, international activities)	483,600
Total	6,200,000

NOTE: ANSI, American National Standards Institute; ASME, American Society of Mechanical Engineers; HAMMER, Hazardous Materials Management and Emergency Response facility at Pacific Northwest National Laboratory, Richland, Washington; ICC, International Codes Council; NFPA, National Fire Protection Association; NHA, National Hydrogen Association; NHTSA, National Highway Traffic Safety Administration; RSPA, Research and Special Projects Administration; SAE, Society of Automotive Engineers; SRI, Stanford Research Institute; SBIR, Small Business Innovation Research program.

SOURCE: Information supplied by DOE in response to questions from the committee.

Technical Teams

The current technical team is focused just on codes and standards, not on overall safety issues. Codes and standards are necessary to allow the deployment of the hydrogen infrastructure, vehicles, and other equipment into the public domain. They are necessary but are not by themselves sufficient to ensure the safety of the overall activity. There does not appear to be any top-down process in place to allocate risk to the various parts of the end-to-end system. Safety is inherently a systems issue. To enhance the safety mission, the current codes and standards technical team should be made part of a safety team with a broader mission that would interact closely with the other technical teams involved in hydrogen use learning demonstrations (these will involve the public; see section "Learning Demonstrations"). This new safety technical team should identify needed information related to safety issues at different levels, perform system-based safety analysis and definitions, develop draft codes and standards, set up a timetable and milestones to examine available models to predict safety, collect and generate information related to safety when lacking, and coordinate with other technical teams to set priorities and provide timely guidelines for setting safety performance targets.

The responsibility of a safety technical team should start where the hydrogen is produced and end where it is consumed ("follow the hydrogen"). It should cover all of the equipment in the entire system and each component from its manufacture to its ultimate recycling and disposal. Special emphasis should be given to the interface between the consumer and the hydrogen supply system at the filling station.

Safety should not be limited to just hydrogen hazards—it should also include crashworthiness, high-pressure and -temperature gas, toxicity, asphyxiation, high voltage, energy storage in batteries, and other potential hazards.

A safety technical team should also address the presence of hydrogen-fueled vehicles in buildings, tunnels, and other confined spaces. A recent study by Parsons-Brinkerhoff (2004) sponsored by the California Fuel Cell Partnership studied hydrogen cars in four types of parking structures. For the assumptions made, it was concluded that no modifications were necessary to the buildings. This result needs to be independently validated and a wider range of hydrogen release scenarios considered. Clearly, if *any* modifications to existing buildings are required (such as hydrogen sensors and/or increased ventilation), this will constitute another major infrastructural barrier to the widespread deployment of hydrogen cars.

It would be desirable for all the other technical teams involved with hydrogen to designate a safety person as a liaison to the safety technical team, which should provide safety guidance to the other technical teams. It would also be appropriate for the non-HFCIT DOE offices to have representatives on the safety technical team. Currently, the HFCIT Safety, Codes, and Standards program element is the focal point for safety for the other parts of DOE that are engaged in hydrogen-related work. However, there is little evidence that those offices are actively making use of the program.

The safety technical team, DOE, NHTSA, and the various codes and standards organizations should attempt to have draft codes and standards published as soon as possible. Some currently exist, and some may be issued soon enough to affect the learning demonstrations that are under way. Those released later will help with the transition from 2009 to 2015 and beyond.

Recommendation. DOE should form a new crosscutting safety technical team with a mission that includes broad hydrogen-related safety issues not only for HFCIT but for the other DOE offices as well. The new team should incorporate the existing codes and standards technical team as a subteam. The other offices should assign a person to be responsible for safety and to interface with the safety technical team. The safety, codes and standards effort needs adequate resources so that it can accomplish the goals identified in its roadmap.

Vehicle Standards and NHTSA

NHTSA is responsible for vehicle safety standards. It recently published a 4-year R&D plan for hydrogen-fueled vehicles (NHTSA, 2004). A NHTSA representative is appropriately included on the codes and standards technical team, and the codes and standards roadmap includes a number of vehicle safety deliverables; it does not, however, include all the important milestones from the NHTSA R&D plan. The codes and standards team should examine the NHTSA plans and integrate into its roadmap any milestones that are appropriate. Also, NHTSA can benefit from the various hydrogen release experiments being conducted by Sandia National Laboratories at Livermore.

NHTSA has been asked by the automotive industry and by DOE to have draft standards for hydrogen-fueled vehicles by 2010. It would be desirable to have interim standards in place for the learning demonstrations that began recently. Unfortunately, however, it will most likely take several years to develop such standards, which should be performance-based and not prematurely lock in any particular technology.

Although NHTSA has been planning hydrogen R&D activities for several years, a lack of funding has kept it from pursuing them. NHTSA estimates that it will need about $4 million to $5 million per year to develop these standards (a total of about $20 million). It is important that when such standards are developed they be harmonized internationally.

DOE is planning to transfer a small amount of money in FY05 to NHTSA to get its program started. The President's proposed budget for FY06 includes $2.3 million for DOT for its hydrogen activities. A portion of that funding will go to NHTSA.

The existing NHTSA plan relies heavily on crash testing prototype hydrogen vehicles. The committee thinks this activity is premature because the technology of the hydrogen vehicles will change dramatically over the next 5 to 10 years. The committee believes that NHTSA should instead focus more on analysis and research to establish the technical basis for its standards. Using finite element models to investigate crashworthiness issues and computational fluid dynamics models to examine fire risks from and to the hydrogen-containing components of a vehicle are examples of appropriate near-term activities. NHTSA should delay its crash testing of prototype vehicles until an appropriate generation of vehicles is available.

A separate but related DOT issue is pipelines. DOT's Pipeline and Hazardous Materials Safety Administration (PHMSA)[2] is responsible for pipeline safety.

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[2] Prior to the creation of PHMSA in February 2005, pipeline safety was the responsibility of the Research and Special Projects Administration (RSPA).

As the FreedomCAR and Fuel Partnership develops a clearer view of the likely form and timing of a hydrogen delivery system, DOT may need to develop codes and standards for carbon dioxide (CO_2) pipelines as well, which may be needed for CO_2 delivery to carbon sequestration sites.

Recommendation. NHTSA should begin its hydrogen R&D program in FY05 by focusing on the effects of hydrogen releases and other potential hazards with hydrogen-fueled vehicles, as well as analyses and research to determine the right mix of system-level and component-level standards. NHTSA should also work with other U.S. and international safety groups to establish global standards for hydrogen-fueled vehicles.

Publication, Openness, and Safety Documents

Safety is an overriding consideration for the successful transition to a hydrogen economy based on hydrogen-fueled vehicles. An excellent safety record is essential for public acceptance of hydrogen vehicles. For this reason, everyone in the field should openly share information related to safety. In the NHTSA Docket (NHTSA, 2004, Document 19), the auto company Bayrische Motor-Werken" (BMW) states as follows: "The issue of safety in the use of hydrogen should always be treated in the same way along commonly agreed lines, not as a competitive feature distinguishing one company from another."

Accordingly, safety research results should be presented at professional societies and in peer-reviewed journals. DOE and others have been working on hydrogen fuel cells, tanks, and other components for many years. This work goes at least as far back as the Spark M. Matsunaga Hydrogen Research, Development and Demonstration Act of 1990 and was also part of the PNGV program, yet very little research related to safety has been published.

As the amount of hydrogen research increases and the number of hydrogen-fueled vehicles increases, incidents will occur in which hydrogen is unintentionally released, sometimes causing fire and/or explosion. It is important that accidents of this type be investigated and that the lessons learned be made available to the public. Any attempts to cover up such incidents will backfire and cause public skepticism. Transparency is the best long-term policy.

The National Transportation Safety Board's (NTSB's) methods for transportation accident investigation may be a useful model. In the early days NHTSA may also want to investigate high-delta-V (large changes in velocity) crashes of hydrogen vehicles that do not result in a hydrogen release. While there are significant differences between hydrogen-fueled and natural-gas-fueled vehicles, there are also some similarities, especially for vehicles that store their fuel as high-pressure gas. Since there are over 100,000 compressed natural gas vehicles on the road, there is a much larger accident pool to investigate.

Incidents should be written up and made available to the public and to others in the field. Learning from past mistakes will take place, and the engineering and the codes and standards will gradually improve. For example, a recent hydrogen leak during fueling at Ballard Systems in Canada was written up in a noncontroversial way and published in the newsletter of a fuel cell conference (Kinzey, 2004). This is a positive example of how an incident should be reported.

It is important to have factual information, scientific and engineering data, and lessons learned readily available. The Web sites of DOE, NHTSA, and USCAR could be improved (and interlinked) to make it easier to find hydrogen safety information.

The Safety, Codes, and Standards plan identifies two safety documents—a safety plan and a best engineering practices document. The former is due this year and the latter in 2007. Both are important, and the latter should be expedited if possible. HSRP membership, meeting minutes, site visit reports, and other products should be made available on the DOE Web site.

Recommendation. DOE, USCAR, and NHTSA should prepare and maintain a bibliography of hydrogen-safety-related reports and papers and make that information available on their Web sites in a user-friendly manner. NHTSA and DOE should develop investigation protocols and have investigation teams ready to visit serious incidents anywhere.

Budget and Schedule

The amount appropriated for the Safety, Codes and Standards program is much less than was requested. There are many milestones on the Codes and Standards Roadmap coming up in the next 2 to 3 years. The committee is concerned that many milesones will slip as a result of the severe cuts in this budget in FY05, jeopardizing the goal of having all of the codes and standards in place by 2010.

Recommendation. DOE should examine the budget and schedule estimates for each of the codes and standards deliverables and also for the other safety activities of the Safety, Codes and Standards program. To the extent that the budget and schedule are incompatible, changes should be reflected in the next update of the roadmap.

LEARNING DEMONSTRATION: NATIONAL HYDROGEN VEHICLE/INFRASTRUCTURE PROGRAM

The FreedomCAR and Fuel Partnership includes a variety of R&D and demonstration activities for fuel cell vehicles and hydrogen fuel systems. Approximately 13 percent of the FY05 budget for the program was focused on demonstration activities, and what DOE calls learning demonstrations that will operate during the next few years were announced. Any advanced technology, no matter how well tested by its developers, will show unanticipated characteristics when placed in the hands of the users. Some technologies—software, for example—require alpha and beta versions before a truly commercial product can be claimed. This kind of feedback will be especially important for the FreedomCAR and Fuel Partnership because of the long-term, high-risk research agenda and because public safety must be ensured in the face of highly energetic materials—for example, hydrogen and high-voltage batteries. To be sure, the private participants (e.g., the automotive and fuel companies) provide some feedback to DOE, but this would remain incomplete without feedback from the actual users.

Thus the learning demonstration program should be considered an essential component of the FreedomCAR and Fuel Partnership. Rather than attempting to demonstrate that these technologies are commercially ready, the program will collect and analyze the experience of the early adopters of hydrogen vehicles and fuels infrastructure technologies in order to inform the research programs. Further, the use of private companies as partners will help disseminate the learning beyond DOE. Recognizing that the learning demonstration program is in its early stages, the committee recommends several points for DOE to consider as this program unfolds.

Recommendation. The FreedomCAR and Fuel Partnership should continue to develop prompt and effective channels of communication among its members to disseminate the learning from the demonstrations. The results should also be disseminated to supporting organizations outside the Partnership in order to promote widespread innovation and competition. But once the learning demonstration for a project has been carried out, the project should be reassessed to see whether further operation is warranted.

Recommendation. DOE management should keep the demonstration projects focused on their primary purpose—the accumulation, analysis, and dissemination of experience from the field.

Safety should be stressed throughout the learning demonstration program, because an accident early on could attract publicity out of proportion to its true consequences.

Recommendation. Among the high priorities for feedback, DOE should identify precursor incidents that point to incipient safety problems and should develop appropriate methods for training first responders to deal with hydrogen-related emergencies.

Recommendation. The FreedomCAR and Fuel Partnership should develop effective channels of communication among its members to disseminate lessons learned and communicate to appropriate organizations outside the Partnership to promote in them a culture of innovation and competition within the developing support structure.

PROGRAM STRUCTURE

Goals and Targets

The partners of the FreedomCAR and Fuel Partnership have done a commendable job of establishing explicit goals for a wide variety of technologies for achieving "a clean and sustainable transportation energy future" (DOE, 2004c). The long-term future envisioned in the program is one of fuel-cell-powered vehicles that run on hydrogen produced from a variety of energy sources. The target year is 2015 for achieving a host of technology and cost goals that might enable private companies to make a decision about the commercialization of such vehicles. This is an ambitious target for reasons that were noted in *The Hydrogen Economy* (NRC/NAE, 2004) and that are detailed in the technology assessment portions of this report.

The committee concurs with the observation on p. 116 of *The Hydrogen Economy* that "DOE should keep a balanced portfolio of R&D efforts and continue to explore supply-and-demand alternatives that do not depend on hydrogen." The FreedomCAR and Fuel Partnership plan does not discuss any of these alternatives—for example, battery-electric vehicles or synthetic fuels made from fossil fuels or biomass—although DOE does support research in some of them (DOE, 2004c). The committee observes that with research breakthroughs in these alternative areas comparable to the breakthroughs required for the program as it is currently defined, the FreedomCAR vision still might be achieved without facing some of the infrastructure problems created by a shift to hydrogen. (See Chapter 3 for further discussion of electric vehicle battery technology.)

Recommendation. The program should perform high-level systems analyses that identify the potential, the challenges, and the specific research breakthroughs for alternatives that could achieve the program vision without requiring a hydrogen infrastructure, and it should use these results to help define R&D efforts and allocate funds within DOE.

Strategic Planning for the Partnership

As noted in Chapter 1, five energy companies joined the program in September 2003, more than $1^1/_2$ years after its inception. This was an important step that enabled the program to tap the expertise and judgment of people in the energy field. The committee commends the energy companies for the progress that they have made in establishing technical teams and engaging the important fuel-related issues.

The Executive Steering Group (see Figure 2-2), with high-level representation from the three automotive companies, the energy companies, and the government, is responsible for the overall direction of the program. One of its most important responsibilities is to ensure that the strategic direction of the program adjusts as technology advances, the marketplace changes, and new information becomes available. Developing an entirely new, radically different transportation system that meets the goals of this program and our nation is a formidable task. Finding the best way forward demands the best thinking and close cooperation of people with backgrounds and knowledge in many areas. The Executive Steering Group may want to consider chartering an ongoing strategic planning activity to carry out this important task.

The committee has observed that there are many pathways by which to achieve the ultimate goals of this program. Some could involve energy sources other than petroleum or natural gas—perhaps coal or nuclear power. A comprehensive strategic plan should certainly consider all of these options and suggest research in those areas that might contribute to achieving the goals of the program.

Roles of the Federal Government and Industry

The FreedomCAR and Fuel Partnership, like its predecessor, the PNGV program, is based on the sponsorship of research projects which, if successful, will enable the production of new vehicles that enjoy widespread customer acceptance and help to achieve some important societal goals. The research projects are chosen jointly by representatives of government and industry with the intent of developing technologies able to achieve the desired results and capable of being widely deployed in mass-produced vehicles. This is the essence of the Partnership. The government establishes the societal goals to be addressed and funds and manages the program. Industry identifies the technologies needed, sets critical performance and cost parameters, and, in some instances, participates in the research.

Figure 2-3 illustrates this relationship. It shows the FreedomCAR and Fuel Partnership as a framework for directed, focused communication of marketplace performance requirements, public sector needs, and research results. The framework embodies three premises:

- That high-risk, precompetitive research can expand the technical options available to the participating automotive and energy companies;
- That the effectiveness of this precompetitive research will be increased by a more thorough understanding of the realities of the marketplace; and
- That focused channels of communication among these companies as well as between them and the DOE research programs can accelerate the application of this new technology to meet public goals in a competitive marketplace.

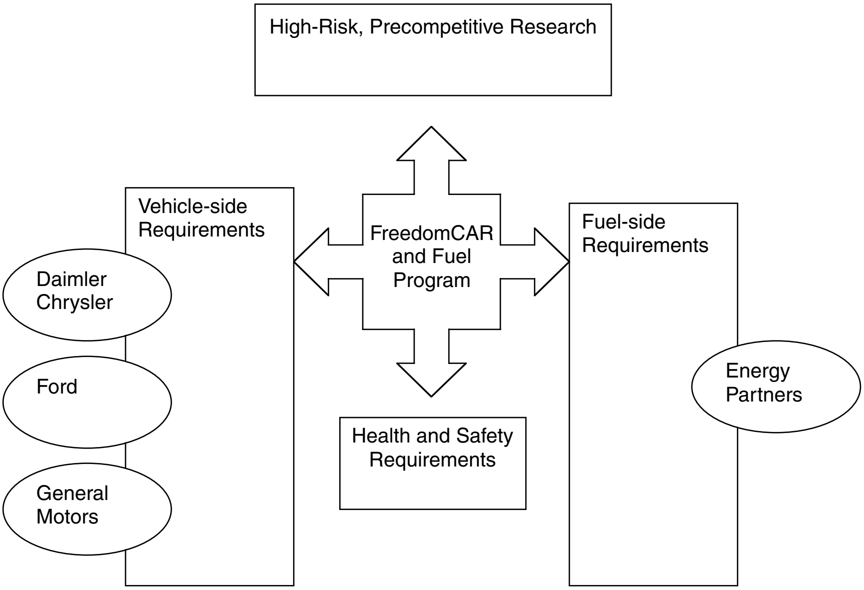

FIGURE 2-3 FreedomCAR and Fuel Partnership as a framework for communication.

For this relationship to work, the program's precompetitive research must be adopted by the industrial partners, developed and made a part of their product and process development programs and, ultimately, successfully introduced in commercially acceptable products. Achieving this result can be a major challenge. Many large companies have experienced difficulty in transitioning even their internal research results to commercial products. It is too early in the FreedomCAR and Fuel Partnership to expect to find significant examples of this part of the process, and the process itself is not clearly defined. But it is not too early for the partners to examine the organizational and other barriers to successful commercialization and find ways to overcome them. This should become an ongoing, shared activity as the partnership matures.

Government and industry leaders in the Partnership appear to recognize that it is a high-priority management task to develop better ways to ensure that this transition of research results to commercial products occurs smoothly. While the target date for deciding on commercialization of a hydrogen-fueled transportation system is 2015, 10 years away, the commercial potential of each technology must be assessed on an ongoing basis. To stress the importance of this step, the committee makes the following recommendation:

Recommendation. The FreedomCAR and Fuel Partnership and USCAR leadership should examine the effectiveness of the current process for transferring technology from DOE projects to within-the-industry activities and develop and implement procedures that will make such transfer as effective as possible.

FreedomCAR in the Policy Context

Two broad public objectives drive federal support for the FreedomCAR and Fuel Partnership:

- To enhance the nation's energy security by reducing and eventually eliminating the use of petroleum in light-duty vehicles.
- To improve the global environment by reducing and eventually eliminating greenhouse gas emissions and criteria pollutants from light-duty vehicles.

If these public objectives are to be achieved in a society that allocates resources chiefly through the marketplace, then consumers must find the new generation of vehicles more attractive than current vehicles. Vehicles with advanced petroleum-saving technologies—improved internal combustion engine (ICE) vehicles, hybrid electric vehicles (HEVs), and hydrogen fuel cell vehicles (HFCVs)—must compete successfully with the market incumbent, the conventional ICE vehicle with a mechanical drive train.

The FreedomCAR and Fuel Partnership has interpreted this competition strictly as a technological challenge on the supply side of the market—vehicles and fuels. Thus the program goals require the new technologies to achieve the road performance, carrying capacity, variety, cost, and safety of the conventional vehicle fleet. The HFCVs face an additional challenge—fueling stations must be everywhere when new HFCVs are introduced on a broad scale.

This section contains some committee observations regarding two policy issues that could influence the pace and ultimate success of the FreedomCAR and Fuel Partnership:

- Demand-side policies that could add market pull to advance the fuel-efficient technologies offered by the program and
- The societal implications of alternative pathways to a hydrogen economy.

Beyond Technology: Policies for Greater Demand Pull

To understand how policies can influence the demand side of the market, consider the basic economics of the consumer purchase decision. As long as fuel remains readily available for about $2.00 per gallon, new car buyers have reason to be ambivalent about paying more for a vehicle with improved fuel economy.[3]

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[3] D.L. Greene, "Improving the nation's energy security: Can cars and trucks be made more fuel efficient?," Testimony to the U.S. House of Representatives' Science Committee on February 9, 2005.

This implies that some policy intervention beyond the availability of new technology might accelerate a transition to HEVs and, ultimately, fuel cell vehicles.

The FreedomCAR and Fuel Partnership is currently configured to enhance the capacity of automakers to offer fuel efficiency improvements and other desirable attributes at a cost that attracts buyers, even at current fuel prices. However, these technical programs operate only on the supply side of the market. If the hydrogen economy is to emerge as a reality in the 2015-2020 time period envisioned by Presidential policy statements, then it would be appropriate to consider policies that could stimulate the demand for vehicles offering greater fuel economy and thereby reduce the risk of delaying the hydrogen economy.

The technology goals for the FreedomCAR and Fuel Partnership assume that federal policy will not intervene decisively in the marketplace to tip the competitive balance in favor of fuel cell or hybrid vehicles. Thus, the technology goals are set to match the vehicle performance that U.S. consumers have become accustomed to, and the cost goals are meant to achieve vehicle cost parity. If, especially during the transition period, fuel cell vehicles cost more than vehicles using the competing technologies, policy interventions might be used to facilitate the transition, moderating its targets and speeding the introduction of the new technologies into the marketplace.

Four broad classes of market intervention promise to complement the technology development of the FreedomCAR and Fuel Partnership. The first two, cap-and-trade programs and motor fuel taxes, influence the demand side of the market—that is, they motivate customers to prefer more fuel-efficient vehicles—by raising the price of transportation fuel. The third, Corporate Average Fuel Economy (CAFE) standards, operates chiefly on the supply side by requiring auto and light truck manufacturers to increase vehicle efficiencies or modify the composition of their fleets. And the fourth class, subsidies, can operate on either the supply side or the demand side of the market. To the extent that these or similar policies are implemented, the market penetration of improved ICE drive trains, HEVs, and HFCVs would accelerate. Each will be discussed in turn.

Cap-and-Trade Programs Trading programs have long been used by the federal government to achieve environmental goals—reducing sulfur dioxide emissions from stationary plants and reducing the use of ozone-depleting chemicals, for example. As envisioned in recent literature, the government would set a cap on carbon emissions from all sources, including the production of motor fuels, and issue allowances to burn, produce, and import only the amounts of fuel that correspond to that cap (Pizer and Kopp, 2003). After the initial allocation, firms would be allowed to trade allowances, thus creating a market value for them. The net effect would be an increase in the cost of conventional motor fuels and a greater incentive for customers to prefer HEVs or HFCVs. (The incentive for vehicle owners to modify their driving behavior with the current fleet would provide an ancillary benefit.)

Motor Fuel Taxes In addition to the federal government, states and localities tax motor fuels. These taxes averaged $0.41 per gallon of gasoline in 2002 according to the Congressional Budget Office (CBO). Such taxes directly create an incentive to purchase more fuel-efficient vehicles and influence driving patterns for all vehicles. However, recent analyses suggest that the per-gallon tax would have to be very substantial to make consumers willing to pay a premium for a more efficient vehicle. For example, the CBO estimates that an additional $0.46 per gallon fuel tax would cause a reduction of only 10 percent in gasoline consumption over a 14-year period (CBO, 2004). In addition, the strength of the incentive depends on a consumer perception that the tax-induced increase in the price of gasoline is permanent and structural, not to be offset later by declining fuel costs.

CAFE Standards Currently, each automaker's annual production is divided into three "fleets": imported passenger cars, domestically produced passenger cars, and light trucks (pickups, minivans, and SUVs). If the average fuel economy of each fleet does not meet or exceed the standard set for it, the automaker must pay a penalty. The current standards are set at 27.5 miles per gallon (mpg) for domestic and imported cars, and, until recently, 20.7 mpg for light trucks. In 2003 NHTSA issued a new rule for light trucks that increased the standard to 21.0 mpg for model year (MY) 2005, 21.6 mpg for MY 2006, and 22.2 mpg for MY 2007. Vehicles weighing over 8,500 pounds are exempt. However, fuel economy standards offer no incentive for further innovation once the standards have been achieved. And because they operate only on the supply side of the market, they have no influence on driver behavior, miles traveled, or other important aspects of fuel consumption (NRC, 2002).

If new CAFE standards were proposed, the policy might consider the economic efficiency improvements that could come from a trading approach suggested by the NRC committee that wrote the aforementioned report. Under this approach, automakers facing high costs of improving the fuel economy of their fleets would be allowed to purchase fuel economy credits from automakers able to exceed the standards. This would reduce the disruptive effects of the regulation and improve its economic efficiency (NRC, 2002).

Subsidies A simple buy-down of the costs of the transition could also tip purchase decisions toward a vehicle with improved fuel economy. Though direct payments might be possible, so might be tax incentives. Typically these take the form of tax credits for the purchase of specified vehicle types, such as the credit currently offered for purchase of an HEV. However, the effectiveness of a tax credit incentive varies with the tax status of the individual.

An alternative incentive scheme at time of vehicle purchase is "feebates." Purchasers of low fuel economy vehicles pay an additional fee; those who buy a fuel-efficient vehicle receive a rebate. This fee and rebate system can be revenue neutral. Feebate policies typically charge maximum fees of about $1,500 per vehicle and give maximum rebates of about $500. Such a scheme could provide market incentives that support future CAFE requirements.

The challenges posed by a transition to a hydrogen economy within the time implied by the President's 2003 State of the Union address are substantial, and the likelihood of meeting them might be increased by market intervention. Such intervention would provide a demand-pull to complement the technology-push during the early phases of the transition. Such interventions, of course, lie beyond the scope of the FreedomCAR and Fuel Partnership. Nevertheless, because they could certainly influence the success of the Partnership, they should be included in general discussions of energy policy.[4]

Recommendation. DOE should analyze the implications of alternative market interventions for the technical goals of the FreedomCAR and Fuel Partnership. These implications then could be included in DOE's policy deliberations.

ENVIRONMENTAL IMPACTS OF ALTERNATIVE PATHWAYS

In the long-range portion of the FreedomCAR and Fuel Partnership, DOE has focused on the production of hydrogen and fuel cells to achieve a variety of national goals. In this connection, some observations relating to the environment are appropriate. It is clear that the hydrogen needed to power the vehicles must be based on fossil-free feedstocks, or, if it is based on coal, oil, or methane (natural gas), a huge carbon sequestration program will be required. It is also clear that the one incentive to use hydrogen to carry energy to vehicles is the elimination of their carbon dioxide emissions. Liquid hydrocarbon fuels can be made readily from natural gas or coal and would avoid the difficult production, distribution, and storage problems of hydrogen.

Using hydrogen to reduce greenhouse gases while shifting to a greater use of domestic sources of energy significantly constrains the energy sources that can be used. Specifically, the energy must come from wind machines, photovoltaic cells (PVs), fossil fuels (with sequestration), sustainably grown biomass, nuclear power plants, or hydroelectric dams.[5]

Although hydrogen itself poses little environmental threat when it is oxidized to water in a fuel cell, the same cannot be said for most of the primary energy sources that would be used in its production. A few impacts include the setting aside of large amounts of land to make electric power for electrolysis using PVs, wind turbines, and biomass; the disturbance of wildlife and birds of prey by the large-scale deployment of PV and wind machines; the creation of

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[4] For a recent discussion of energy policy, see the report by the National Commission on Energy Policy (NCEP, 2004).

[5] Biomass can also serve as a limited gasification feedstock for hydrogen production.

large amounts of low- and high-level radioactive wastes from nuclear power plants; the sequestration of large amounts of CO_2 from fossil sources of hydrogen; and the consumption of large amounts of fresh water if electrolysis is employed to make the hydrogen.

In June 2003, a paper appearing in *Science* reviewed the “expected” impacts on the stratosphere of the hydrogen gas emissions produced for a hydrogen economy (Tromp et al., 2003; Ananthaswamy, 2003). These impacts include a cooling of the stratosphere and a loss of some of the ozone that protects humans and other components of the biosphere from ultraviolet radiation.

Hydrogen has also been associated with increased global warming through atmospheric reactions of trace amounts of hydrogen with ozone and methane, both themselves greenhouse gases (Derwent, 2003, 2004). This effect may require setting a cap on the overall well-to-wheels leakage into the atmosphere.

Although the production of enough hydrogen to meet the entire transportation needs of the country could have significant deleterious environmental impacts, there appears to be no systematic DOE program to identify, study, and model them. The impacts need to be carefully evaluated to ensure that long-term national energy planning succeeds. Such a study would allow comparing potential hydrogen sources, making trade-offs among them, and developing mitigation measures.

Recommendation. DOE, in collaboration with the Environmental Protection Agency, should systematically identify and examine possible long-term ecological and environmental effects of the large-scale use and production of hydrogen from various energy sources.

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Vehicle Subsystems

INTRODUCTION

The long-range goals of the FreedomCAR and Fuel Partnership—to transition to a transportation system "that uses sustainable energy resources and produces minimal criteria or net carbon emissions on a life cycle or well-to-wheels basis"—are extremely ambitious (DOE, 2004a). The difficulties are compounded when the additional constraints associated with the FreedomCAR and Fuel Partnership are imposed: energy freedom, environmental freedom, and vehicle freedom. These goals and associated constraints effectively eliminate the continued evolution of the gasoline-fueled internal combustion engine (ICE) vehicle as a possible answer. "Sustainable energy resources" and "energy freedom" both suggest non-petroleum-based alternative fuels. The emphasis on "net carbon emissions" and "environmental freedom" suggests that CO_2 and other emissions from the production and consumption of alternative fuels should be reduced, through highly efficient processes, to minimize adverse environmental effects. Finally, "vehicle freedom" implies that the fuel and onboard energy conversion systems should not limit the options and choice that buyers expect to have available in their personal vehicles. These goals, if attained, are likely to mean new transportation fuel(s) utilized in more efficient power plants in lighter vehicles having reduced power requirements while maintaining equivalent utility and safety.

DOE envisions that the path to achieving the long-term goals of the FreedomCAR and Fuel Partnership involves a transition from improved gasoline- and diesel-fueled ICE vehicles, to a greater utilization of gasoline- and diesel-fueled hybrid electric vehicles (HEVs), to hydrogen-fueled ICEs and HEVs, and ultimately to hydrogen-fueled fuel cell vehicles (DOE, 2004a). For this transition to take place, the industry will require enhanced understanding in many areas so that it can develop new vehicle subsystems and vastly improved vehicles. The DOE-sponsored activities described in this section are intended to provide such understanding.

Near-term reductions in fuel consumption and emissions can be accomplished by improving ICEs. Specifically, better understanding of the combustion process and how emissions are produced could both increase efficiency and decrease engine-out emissions. Higher thermal efficiency means reduced fuel consumption and lower engine-out emissions means less extensive, and probably less expensive, exhaust aftertreatment systems. Improved ICEs, which could come in the near term, would benefit both conventional vehicles and HEVs.

The fuel cell subsystem is an energy converter that has the potential to be more efficient than an ICE. However, fuel cell systems of the type deemed appropriate for transportation systems use only hydrogen as fuel. The hydrogen can be stored onboard the vehicle in pure form or it can be extracted from hydrogen-bearing hydrocarbon fuels and water using onboard fuel processors. However, DOE effectively eliminated the latter alternative from its R&D portfolio after years of R&D offered little prospect of meeting essential cost and performance targets within the program time frames. Without this option, sufficient pure hydrogen must be carried onboard the vehicle to meet range requirements. Further, since it is extremely difficult with typical light-duty vehicles to carry hydrogen quantities with an energy content equivalent to that of a typical fuel tank filled with gasoline, it is imperative to minimize fuel consumption. This implies reducing the mass of the vehicle and maximizing the efficiency of the energy converter.

Current experimental hydrogen-fueled fuel cell systems demonstrate efficiencies approaching 50 percent over a fairly wide range of operation. Further, such systems produce zero criteria emissions (occasional discharges of small quantities of hydrogen may occur). However, there are performance, durability, and cost issues to be resolved if fuel cells are to become viable options for personal transportation vehicles.

Hybrid electric vehicles require compact, efficient, and low-cost power electronics and energy storage systems as well as other advanced electrical components to make vehicle costs and weights competitive with conventional vehicles. Many of the same technologies also are applicable to fuel cell vehicles since fuel cell vehicles will be basically electric vehicles with various degrees of hybridization. Consequently, advances in the power electronics and electrical subsystems are critical for improved viability of both mid-term HEVs as well as longer-term fuel cell vehicles.

One important means of minimizing fuel consumption for mid-term HEVs and longer-range fuel cell vehicles is the partial recovery of vehicle kinetic energy during deceleration and stopping. Thus, these vehicles will need some form of energy storage capable of accepting some of this energy (regenerative braking) and providing it back to the drive train for propulsive power. The mostly likely form of such energy storage is electrochemical (batteries), but ultracapacitors are also being investigated. For such relatively small-scale energy storage, the most important parameters are cost per kilowatt, specific power (kW/kg), and cycle and calendar life.

Even though hybrid electric vehicles are currently on the market, the projected cost savings due to higher fuel mileage will probably not offset the higher initial cost of the vehicle at foreseeable fuel prices. This implies that further cost reductions may be necessary for the hybrid vehicles to gain widespread acceptance and have a significant impact on fleet fuel mileage. Such cost reductions require additional understanding in the areas discussed.

Beyond the need for small-scale energy storage required to handle energy from regenerative braking is the need for sufficient on-board energy storage to propel the vehicle for a reasonable range without use of the power plant (e.g., fuel cell or engine). Moving in this direction could add design flexibility to HEVs and reduce some of the performance requirements for the fuel cells (e.g., start-up time and power ramp-up rate) in a fuel cell vehicle. Further increases in on-board energy storage capacity could enable plug-in hybrid vehicles (a vehicle whose battery could be recharged by plugging into a source of electricity while it is parked) or even all-electric vehicles. Both plug-in hybrids and all-electric vehicles could provide the immediate benefit of shifting some transportation energy demand from onboard petroleum-based fuels to the electric grid, which is mostly non-petroleum-based but, of course, not emission-free. The most important parameters for these energy storage systems will be cost per kilowatt-hour, specific energy (kWh/kg), cycle life, and calendar life. These storage systems would also have to maintain adequate specific power (kW/kg), even at low states of charge and low ambient temperatures.

Irrespective of the propulsion technology, reducing the mass of a vehicle for a given mission will have the effect of reducing fuel consumption. However, to conform to FreedomCAR goals, any such mass reduction would have to be accomplished without compromising safety or overall vehicle utility. To accomplish significant weight reductions, several materials, including aluminum, high-strength steel (HSS), and carbon-fiber-reinforced polymer composites could replace a large part of the (mostly) mild steel currently used. Other material substitutions, such as cast magnesium, in other vehicle components could further decrease vehicle weight. Unfortunately, thus far all of these potential material substitutions would result in large cost penalties. Therefore, research in materials production and manufacturing techniques is essential if the mass-reduction benefits of these materials are to be realized.

The following sections discuss in more detail the issues associated with the alternative technologies for vehicle components.

ADVANCED COMBUSTION ENGINES, EMISSION CONTROLS, AND HYDROCARBON FUELS

Introduction

The ICE plays a critical transitional role in achieving the FreedomCAR and Fuel Partnership's long-term goal. If the Partnership meets its objective—namely, of enabling the private sector to make a commercialization decision on fuel cell vehicles by 2015—it would still be decades after that before these vehicles penetrate the market sufficiently to have a measurable impact on total fleet fuel consumption. If commercialization is delayed beyond 2015, the impact will be pushed even further into the future. In contrast, improvements in engine and aftertreatment technologies could be incorporated into a large spectrum of new vehicles quite rapidly. With approximately 16 million new vehicles sold in the United States every year, improving the energy efficiency of vehicles sold now will have near-term and growing impact on the petroleum consumption of the entire vehicle fleet.

FreedomCAR's transition strategy to hydrogen-fueled vehicles envisions a sequence of improved ICEs, increasing use of advanced ICE hybrid vehicles and hydrogen-fueled ICE hybrid vehicles, and—ultimately—a transition to hydrogen-fueled fuel cell vehicles (DOE, 2004a). The focus of the advanced combustion engines and emission controls (ACEC) activity of the FreedomCAR and Fuel Partnership is to improve the efficiency of the engines of these transitional vehicles and reduce their emissions.

To this end ACEC has established a sequence of technical targets during the transition (Table 3-1). The benefits of improved ICEs could begin in the very near term. However, the total impact would be limited by the slow rate of market penetration and the large number—roughly 225 million—of light-duty vehicles in the current fleet. As part of the Government Performance and Results Act, EERE estimated the potential fleet fuel savings from introducing these new technologies to the market. In performing this analysis, it was assumed that the technical targets of Table 3-1 were met, and because these new technologies would add to the cost of the vehicle, the analysis was performed on a cost-competitive basis, assuming that the incremental cost of the technology is paid back by fuel savings in 3 years. Vehicle price and fuel economy were the two most important attributes characterized (DOE, 2004b). The results of the analysis indicated that for light-duty vehicles, oil savings, in millions of barrels per day (mbpd), from diesels and diesel hybrid vehicles would be approximately 0.05 mbpd in 2015, 0.22 mbpd in 2020, and 0.57 mbpd in 2025. These are small reductions considering the light-duty vehicle petroleum consumption in 2004 was approximately 8 mbpd. However, a different rate of market penetration would change these projections. These new technologies would be incorporated into the market more quickly, as enabling technologies, if the market drivers were

TABLE 3-1 Goals and Status of the Advanced Combustion Engines and Emission Controls Activity

		2004 Status		Goals by Fiscal Year			
Goals	Unit	PFI	DI	FY07	FY10	FY13	FY15
For hydrocarbon fuel							
ICE peak brake thermal efficiency	%	30	41	43	45	46	
ICE powertrain cost[a]	$/kW	20	30	35	30	30	
Projected vehicle emissions	Tier 2	<Bin 10	Bin 10	Bin 5	Bin 5	Bin 5	
Emission control fuel economy penalty[b]	%			<5	<4	<3	
Emissions durability	1,000 miles	120	120	120	120	120	120
For hydrogen fuel							
H_2 ICE peak brake thermal efficiency	%	38			45		45
H_2 ICE powertrain cost[a]	$/kW				45		30
Projected vehicle emissions	Tier 2	<Bin 5			Bin 5		Bin 5

NOTE: PFI, port fuel injection; DI, direct injection. The emission standards are based on EPA Tier 2 emission regulations. The description of the test procedures and the regulated levels for each Bin may be found at <http://www.dieselnet.com/standards/us/light.html>.

[a] High-volume production of 500,000 per year.

[b] Fuel economy penalty over combined federal test procedures due to emission control relative to diesel vehicle with 2003 emissions.

SOURCE: K. Howden and R. Peterson, “Advanced combustion and emission controls (ACEC) activities,” Presentation to the committee on November 17, 2004.

to change—for example, if the price of fuel were to increase or by any of the policy alternatives discussed in Chapter 2.

Program Technologies

Because a primary goal of the program is to reduce fuel consumption, the most fuel-efficient power plant available is being considered as the basis for the research effort. For light-duty vehicle applications, the compression ignition direct injection (CIDI, diesel) engine is the most fuel-efficient engine currently in production. It is well known, however, that current diesel engines will not meet future emission standards. Therefore, to reduce fuel consumption through the more widespread introduction of diesel engines into the market, advances must be made in emission reduction technologies. Here, the most significant barriers are cost and insufficient fundamental understanding of engine combustion phe-

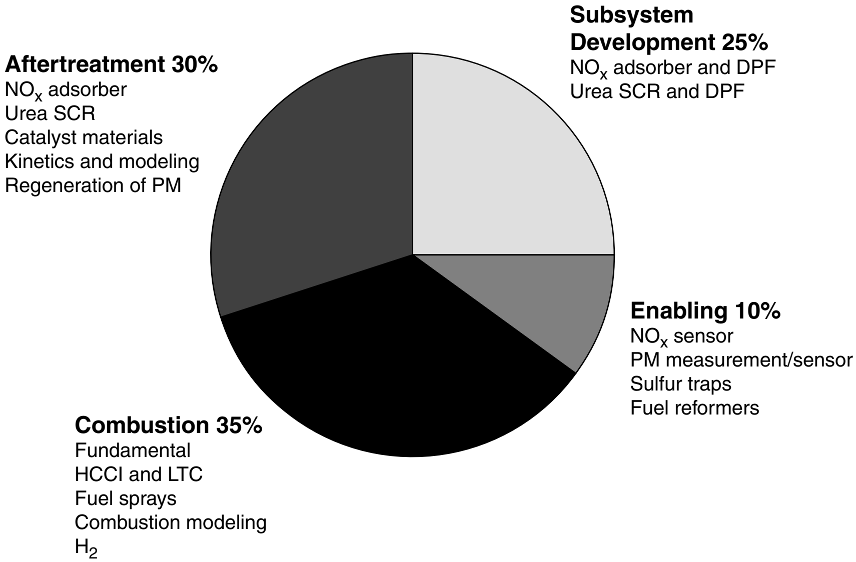

FIGURE 3-1 Technical areas and relative funding for the ACEC activity, FY04. DPF, diesel particulate filter; HCCI, homogeneous charge compression ignition; LTC, low-temperature combustion; PM, particulate matter; SCR, selective catalytic reduction. SOURCE: Response to questions from the committee to DOE, received January 19, 2005.

nomena, exhaust emission control technologies, and engine controls. It is important to realize that the phenomenon of diesel combustion and its emission reduction is fundamentally different from that of the conventional spark ignition engine. The technologies are not transferable. New technologies are required. The research directly addresses all of the barriers except cost. The operating paradigm of the program is to expand the fundamental understanding of combustion, aftertreatment, and controls phenomena in a precompetitive research environment and then let industry address cost as it works to incorporate the new technologies into vehicle power plants.

The individual project topic areas within each research focus are shown in Figure 3-1. Details on the specific research projects within those topics are available in the DOE annual report (DOE, 2003). The vehicle manufacturers all have in-house programs that could be grouped under the topic headings given in Figure 3-1. Government-supported research efforts in these areas differ from industry efforts in the nature of the understanding being sought. Industry is focused on trying to find workable engineering embodiments of the various technologies—for example, establishing the operating parameters of an engine that facilitate low-temperature combustion (LTC); a classification of combustion processes that includes homogeneous charge compression ignition (HCCI) combustion;

and devising strategies to switch from low-temperature combustion to conventional diesel combustion when loads outside the LTC regime are required. The activities supported by federal money at the national laboratories and universities are pursuing a fundamental understanding of the processes that will enable LTC technology to be extended or optimized. For example, federal programs are working to understand the thermochemical interactions that constrain LTC to its current regime. If these are better understood, a wider range of LTC will be possible, with a corresponding improvement in efficiency and reduction in emissions.

As seen from the budget distribution (Figure 3-1), the research effort tilts strongly toward the fundamentals of combustion and aftertreatment, with smaller efforts addressing component subsystems and sensors. The subsystem and sensor research programs are aimed at the question of controls. Control algorithms for the power train system will need inputs from sensors that are monitoring component performance; commands would then be issued, adjusting the engine and aftertreatment system operation.

During this last year the ACEC technical team has shifted the emphasis of its research programs. If the current diesel engine combustion process were left unaltered, the conversion efficiency for the nitrogen oxides (NO_x) and particulate matter (PM) aftertreatment systems would need to be maintained at levels in excess of 90 percent for the lifetime of the vehicle—a huge challenge. The emphasis has therefore shifted from controlling emissions with aftertreatment technologies to reducing the in-cylinder formation of emissions, thereby reducing the burden on exhaust gas aftertreatment. Research has demonstrated that LTC, of which HCCI combustion can be viewed as a subset, has the potential to generate very low levels of NO_x and PM (Akihama et al., 2001; Siebers and Pickett, 2004). The challenge is that to date, LTC has been limited to low-load operation, and the parameter space for controlling it is not well understood.

The research effort on NO_x and particulate matter aftertreatment is very closely aligned with the effort of industrial partners. The formulation and development of new or improved catalysts is conducted primarily in industry, where catalyst suppliers team with vehicle or engine manufacturers. Catalyst mechanisms such as sulfur poisoning, desulfation of lean NO_x traps, thermal aging, and soot filter regeneration are being investigated at the national laboratories using diagnostic microscopy and spectroscopy techniques not readily found in industry. These investigations use both model catalysts and real formulations. The data are being made available for the development of computer simulations of emission control devices, being done at the national laboratories and universities involved in the Crosscut Lean Exhaust Emission Reduction Simulation (CLEERS) activity.

The direct fueling of ICEs with hydrogen is also under investigation. This is an area where partner companies have in-house programs, so the DOE-supported effort is minimal. Using hydrogen in an ICE would of course provide some of the emission benefits at much lower capital cost than changing to fuel cells and electric propulsion. The focus of DOE-funded research in this area is direct injection (DI) hydrogen engines. DI hydrogen engines offer higher power density than engines in which the hydrogen is introduced in the intake manifold.

Fueling of ICEs with hydrogen through an intake manifold is also under investigation. Using hydrogen as an ICE fuel is not new. Because hydrogen has such wide flammability limits and high flame speeds, it may be possible to extend the lean operating limits of the engine, which would reduce fuel consumption and emissions. The issues associated with implementing this are pragmatic and not fundamental. Consequently much of the research on direct fueling on ICEs with hydrogen is being done by industry, with little or no DOE involvement.

One challenge with direct fueling an engine with hydrogen is the loss of volumetric efficiency because the fuel is gaseous. In addition, lean burn mixtures—combined with loss of volumetric efficiency—causes a large power reduction (for the same displacement engine), necessitating a supercharger or turbocharger to bring power levels back up. If a stoichiometric mixture of hydrogen and air is introduced into the engine in the intake manifold, hydrogen will comprise approximately 30 percent of the mixture by volume. This disadvantage can be overcome if hydrogen is directly injected into the cylinder. In this connection some fundamental issues need investigation. The penetration and mixing phenomenon surrounding low-density, high-velocity gas inside a cylinder during direct injection is the subject of DOE-supported investigations at the Sandia Combustion Research Facility. These activities are aimed at increasing the power density of a hydrogen-fueled engine.

Budget and Organization

The FreedomCAR and Fuel Partnership is focused on light-duty passenger vehicles. However, the fundamental knowledge being pursued to enable fuel-efficient technologies is not exclusive to light-duty passenger vehicles. It also applies to engines used in the commercial sector—for example, heavy-duty trucks. To capitalize on these synergies in the combustion engines and emissions technical area, the FreedomCAR and Fuel Partnership is collaborating with the 21st Century Truck Partnership, a partnership of DOE, DOD, EPA, and DOT and 15 industrial partners. The combined budget for advanced combustion for both the FreedomCAR and Fuel Partnership and the 21st Century Truck Partnership for FY04 was $54.4 million. Of this total, $19.5 million was under the direct control of the FreedomCAR and Fuel Partnership. The distribution of these directly controlled funds to the research topics is shown in Figure 3-1.

The vision of the Partnership is that hybrid vehicles will be an important part of the transition. However, because hybrid vehicles are already on the market and are being further developed by the individual automotive companies that are part of the partnership, government-funded efforts for the ACEC activity aim to get a better fundamental understanding of ICEs and aftertreatment systems. This should lead to better engines, which would become part of better hybrid power trains. The technical goals in Table 3-1 are related to engine and aftertreatment performance; hybrid vehicles as such do not appear.

The technical teams, made up of researchers at government laboratories, including the DOE national laboratories, and industry and university laboratories, have established a good process for interaction, feedback, and review. There is interaction between the technical teams of FreedomCAR and 21st Century Truck in the form of crosscut teams, workshops, biannual program reviews, and discussions facilitated by memoranda of understanding. The industrial partners provide input for the setting of research priorities through the workshops and technical reviews, whose outcomes are reflected in DOE solicitations for proposals. As technologies are considered for commercialization the developmental research is performed by vertically integrated teams of industry partners.

Achievements

Quantifying the achievements of the ACEC activity is challenging in that the primary outcome of the government-supported research is new knowledge. In this sense, progress is good. The advanced combustion and emissions control technical team has demonstrated new understanding of the LTC process, including HCCI, and has achieved low-temperature operation in running engines. New understanding of phenomena occurring at the spray nozzle tip, where fuel atomization and air entrainment begin, has been obtained through x-ray imaging, and the boundaries of clean, injection-driven combustion are being expanded. Operational windows of lean catalyst and mechanisms of catalyst poisoning are being studied, and a real-time exhaust stream particulate sensor is being tested. These are important accomplishments; however, it is not known at this time to what extent these advancements in knowledge will be integrated into light-duty vehicle power plants in the near term.

Comments and Recommendations

The various types of ICEs will play a critical transitional role in achieving the FreedomCAR and Fuel Partnership's long-term goal. Even assuming the eventual success of hydrogen as a primary transportation fuel, for several decades ICE will be the automotive power plant that consumes most of the fuel in the fleet. Reducing its fuel consumption and emissions is therefore critically important. Novel emission technologies are needed, and the cooperation of energy companies in such research will increase the likelihood of finding solutions.

The energy companies joined the Partnership in September 2003, adding a new dimension to the program: Now, the impact of fuel modification or substitution on the combustion, emission, and aftertreatment performance can be examined. The variety of fuels that could be investigated is huge, as is the number of pragmatic constraints relative to refining and distribution that need to be considered. The role of fuel characteristics in ongoing research and how best they should be integrated into the program is not well known at this time. Many of the research activities within the ACEC use pure fuels or controlled mixtures. Fuel composition could be systematically varied to enhance our understanding of different chemical processes during combustion and the reduction of emissions by catalyts or to evaluate the impact of fuel composition on the fundamental processes being studied. The issue of real-world fuels found in the marketplace and whether their properties can be used as enablers to achieve desirable results is not part of the program at this time. It is difficult to know whether this will be a fruitful area of research, but it should be considered. It seems that the energy company partners are still not completely integrated into this research program.

Much of the fundamental work is being done with pure fuels or simple blends. Knowing the extent to which these pure fuels or simple blends will be representative of real-world fuels expected to be available in the marketplace (for example, low-sulfur fuels or reformulated gasoline contain small amounts of sulfur or oxygenates) or knowing their deficiencies relative to real-world fuels will be important in interpreting the fundamental results achieved in the laboratory for expected behavior in real-world application.

Recommendation. DOE should encourage the energy industry to become involved in establishing research parameters for the work on pure fuels that will be most relevant to real-world fuels expected in the marketplace.

If specific fuel blends are identified as having a positive impact on meeting the technical targets for an advanced ICE, it will be important to understand the ability of the energy companies to make those blends and what the costs and capital requirements would be.

Recommendation. DOE and the energy industry should develop refinery models for making tailored fuel blends.

At present, there is still no commercially attractive aftertreatment system for CIDI engines that meets the EPA Tier 2, Bin 5, emission standard. Industry is intensely pursuing the development of various technologies for PM and NO_x removal. In general, aftertreatment systems are unsatisfactory in terms of their cost, fuel penalty, durability, or effect on engine performance. This is particularly so for NO_x removal devices. Engine manufacturers and catalyst companies devote significant in-house effort to satisfying the Tier 2 standard. In accordance with the mission of the FreedomCar and Fuel Partnership to "examine precompetitive, high-risk research," the ACEC technical team is encouraged to identify breakthrough and innovative technologies that could provide long-term solutions to the CIDI emissions problems and to begin to anticipate, analyze, and look for solutions to potential emissions problems and solutions for emerging fuels, the fuel infrastructure, and propulsion systems. For example, the emissions problem associated with a distributed hydrogen production system could be quite different and costly, and treatment of emissions from low-temperature combustion could pose new challenges.

Recommendation. Increased emphasis should be placed on novel emission control technologies, and the advanced combustion and emission controls technical team should plan for, analyze, and seek solutions for emission problems associated with emerging fuels, fuel infrastructure, and propulsion systems.

FUEL CELLS

If hydrogen is to account for a significant share of the fuels used for transportation, the transition will be greatly facilitated by fuel cell power systems whose performance and cost are compatible with automotive requirements. This is especially true if costs and onboard storage continue to be problem areas for hydrogen. Fuel cells promise higher conversion efficiencies for hydrogen than ICEs, thus reducing fuel consumption and onboard storage requirements by increasing equivalent fuel economy.

Fuel cell systems are operating successfully on hydrogen in dozens of experimental vehicles in the United States and several other countries. These systems are not compatible, however, with the requirements for mass-manufactured automobiles. They are too expensive, too large, and too heavy, and they have performance problems such as slow start-up and slow power transients, and poor durability, such as degraded performance and limited component life. The status in 2004 of these and other characteristics as well as the targets for 2005 and 2015 are shown in Table 3-2. As can be noted, the 2005 targets (established in 2003) were essentially being met in 2004 in some areas but still had a long way to go in others, such as durability, survivability, and start-up time. Indeed, a review of these parameters not only through the early stages of the FreedomCAR program but also through the entire PNGV program preceding FreedomCAR would show impressive and continuing progress in every area. However, comparing the 2005 targets with the 2015 targets shows clearly that much additional progress is needed.

As delineated in Table 3-3, the fuel cell program is focused on R&D to improve fuel cell technologies for both transportation and stationary applications. The fuel cell program is being implemented by DOE's Office of Hydrogen, Fuel Cells, and Infrastructure Technology Program (HFCIT), which is identifying and developing the critical technology and knowledge needed. The fuel cell part of the FreedomCAR and Fuel Partnership is organized to facilitate the engagement of automobile developers, component suppliers, and related participants so as to meet the 2015 objectives. It is a multidimensional, complex effort spanning many

TABLE 3-2 Technical Targets for an 80-kWe (net) Integrated Transportation Fuel Cell Power System Operating on Direct Hydrogen[a]

			Goals		
Characteristic	Unit	2004 Status	2005	2010	2015
Energy efficiency[b] at 25% rated power	%	59	60	60	60
Energy efficiency at rated power	%	50	50	50	50
Power density	W/L	450	500	650	650
Specific power	W/kg	420	500	650	650
Cost[c]	$/kWe	125	125	45	30
Transient response time	s	<3	2	1	1
Cold start-up time to max power					
at –20°C ambient	s	120	60	30	30
at +20°C ambient	s	60	30	15	15
Emissions		zero	zero	zero	zero
Durability[d]	hr	1,000	2,000[e]	5,000[f]	5,000
Survivability[g]	°C	–20	–30	–40	–40

[a] Targets exclude hydrogen storage and are based on an aerodynamic 2500-lb vehicle.

[b] Ratio of DC output energy to the lower heating value of the input fuel (hydrogen). Peak efficiency occurs at about 25% rated power.

[c] Includes projected cost advantage of high-volume production (500,000 units per year).

[d] Performance targets must be achieved at the end of the durability time period.

[e] Includes thermal cycling.

[f] Includes thermal cycling and realistic drive cycles.

[g] Achieves performance targets after 8-hour cold-soak at temperature.

SOURCE: DOE, 2005.

TABLE 3-3 Funding for Fuel Cell Technology Programs (thousands of dollars)

Technology Component (Interior Appropriations)	FY04	FY05	FY06 Request
Transportation systems	7,317	7,495	7,600
Distributed energy systems	7,249	6,902	7,500
Fuel processor R&D	14,442	9,721	9,900
Stack component R&D	24,551	32,541	34,000
Technology validation	9,828	17,750	24,000
Technical program mgmt support	395	535	600
Total	63,782	74,944	83,600

SOURCE: Provided by DOE in response to a request by the committee. Interior Appropriations refer to the Congressional Subcommittee on the Interior and Related Agencies, which funded these activities.

technologies across a number of organizations, including government agencies, national laboratories, automotive fuel cell developers, original equipment manufacturers (OEMs), and potential suppliers. Owing to the interdependency of the fuel cell and hydrogen, there is also a growing and evolving relationship with the fuel component of the Partnership. To maximize the chances for a successful outcome, plans and schedules must be adhered to, yet the fuel cell program must be flexible enough to allow evolutionary changes to it.

A successful fuel cell development effort will, by itself, not guarantee that the key objectives of the FreedomCAR and Fuel Partnership are met. Success also depends on achieving on-board hydrogen storage, related systems integration, and the broader requirement of a hydrogen fueling infrastructure. The efforts must be fully interactive. For example, fuel quality standards are partly driven by fuel cell developers.

The fuel cell program is focused on the high-risk, precompetitive, industry-wide issues that are hindering the technological and commercial success of the power generation module (stack) and related ancillary processes. The program is broken down into critical and enabling components, with the funding allocated to diverse teams in industry and academia. Selection of the critical components was based on the outcome of workshops organized and facilitated by DOE. Specific technology and cost targets were set by the industry participants and then formulated into a technology milestone plan (DOE, 2005). The primary themes are stack subcomponent (e.g., catalyst, plate hardware, membranes) development, operation, durability, efficiency, and cost; hydrogen fuel as it relates to stack performance; and transportation power systems (cost and performance analyses). The funding for each technology component is presented in Table 3-3. The results of the development efforts are communicated among the technical teams and may ultimately be integrated into the program of an individual developer of automotive fuel cells.

Technology Issues

The PEM fuel cell is based on compartmentalized hardware (cells), in which the reactant gases (H_2 and air) are separated by a membrane. The catalyst, which is in intimate contact with the membrane, initiates the chemical reactions that generate power. Coolants, cell separators, and sensors are other parts of the package. The properties of the membrane and catalyst layers, which impact performance and reliability, are highly dependent on water content. If water is not properly managed in the cell, failure modes are enabled, reducing lifetime, reliability, and durability (the focus of many FreedomCAR projects). The key goals are for a fuel cell vehicle to achieve characteristics, including power and drivability, manufacturability, and cost, that do not compromise consumer expectations. The technical targets necessary to meet these key goals (see Table 3-2) do not take into account the benefits of overall fuel efficiency and protection of the environment. Some of the more important 2015 technical targets are these: 60 percent peak efficiency; 300-mile driving range (vehicle target); 5,000-hr lifetime; \$30/kW cost for the fuel cell system; low Pt catalyst loading (<0.2 g/kW); and 30 s at 20°C cold start-up capability.

Although the near-term FreedomCAR objectives for the development and eventual commercialization of membrane fuel cell technology are currently on target, deployment in the automotive sector in the long term is still at considerable risk. Performance, reliability, durability (current stack lifetimes of 1,000 hr vs. the project goal of 5,000 hr), and cost (estimated at ~\$125/kW in 2004 vs. the goal of \$30/kW, not including the hydrogen storage system) remain major obstacles (DOE, 2005). (The estimated cost of a fuel cell with a hydrogen storage system is about \$175/kW [TIAX, 2004]. However, the validity of these cost estimates is questionable and is discussed further in the section "Cost Issues.")

Some of the critical technical barriers will need breakthrough invention, not just incremental improvements to existing technology. For example, to meet the 2015 targets, it is expected that new materials for membranes, catalysts, catalyst supports, and plate compositions will have to emerge. This adds a high degree of risk to the overall development effort, and the large improvements that are needed make it likely that additional unforeseen roadblocks will arise as the program proceeds.

Because many elements of the program are carryovers from earlier DOE-funded initiatives—for example, the PNGV program (NRC, 2001)—selected activities and development plans are already in place to address the known critical issues. For example, the technical roadmap (DOE, 2005) contains detailed plans and schedules for new membrane development, lower catalyst loadings and increased electrode durability. However, in order to meet the overall targets for fuel cells, it is likely that the various technical scenarios will probably have to be revised as new technologies and issues emerge. The roadmap calls for several specific development activities to take place in parallel. However, the most critical issues may have to be resolved before secondary, less important issues can be addressed. DOE leadership, along with the technical teams, must be alert and make needed changes to the roadmap as they are required.

A number of critical technical issues that are shared by the entire fuel cell industry must eventually be resolved if the overall program goals are to be achieved. Because many of these issues relate to the subcomponents of the fuel cell stack, they involve vendors, suppliers, and OEMs. DOE understands such issues and dynamics and has provided substantial project funding for these areas. The primary technical issues that are being addressed are short-lived membranes, degraded catalysts, suboptimal stack design, and complicated operating strategies. In addition, the high costs of the membrane materials (>\$200/m^2 vs. the target of \$50/m^2 at volume) are problematic. Since most membrane properties are affected by the water concentration, new materials with a lower hydration dependency are required. Current and planned efforts focus on these challenges.

The quantities of platinum catalyst required to meet performance and reliability targets are currently excessive (~1 mg/cm^2 vs. a target of 0.2 mg/cm^2) yet, even with this high loading, cells still exhibit gradual degradation in performance. Existing and new projects will have to come up with novel advances in both catalysts and catalyst layer architecture to resolve this problem. Since catalyst performance is related to operating conditions, gas distribution, and membrane interactions, the technical teams must continue to coordinate and enhance their activities. The 2004 Annual DOE Merit Review, held in Philadelphia in May 2004, reports initial progress in these key areas of more durable membranes and lower catalyst loadings.[1]

The inadequate lifetime and performance characteristics of today's vehicular fuel cell systems can be contrasted with those of stationary applications that use nearly the same technology. Stationary fuel cell systems have demonstrated lifetimes of 8,000 hr compared to the FreedomCAR goal of 5,000 hr (DOD, 2003).[2] DOE is taking a proactive role in learning the causes of such differences by funding selected stationary projects to obtain additional understanding. These projects could be extremely valuable to the project teams by providing an understanding of the importance of differences in operating modes, water management, and impact of environmental conditions. It is difficult to assess the results of such programs at this time but it is expected that recent and future workshops facilitating direct interactions between vehicle and stationary developers will accelerate successful solutions.

There are significant schedule risks attached to current development efforts since there is no clear path to achieving acceptable reliability, performance, and cost solutions. Therefore, the fuel cell program should be carefully monitored and frequently assessed. The present limitations of membranes and electrodes and the status of related stack development should be given the highest priority within HFCIT and in efforts funded in other DOE programs (such as Basic Energy Sciences [BES], in the Office of Science). Longer term, next-generation, outside-the-box concepts of the kind that are typically funded by BES are highly encouraged by the committee. It is not apparent that there are any significant *radical* technical R&D initiatives in the current fuel cell program, and even if a decision to commercialize membranes and electrodes can be made in 2015, DOE should continue to support the development of next-generation materials.

While it is possible that viable solutions may emerge during the remaining decade, there is no guarantee that any of the solutions will meet the stringent requirements of the fuel cell program. Understanding the failure mechanisms of current materials is often the way to develop new concepts and solutions. Such

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[1] Annual DOE Program Review Proceedings available on the Web at <http://www.eere.energy.gov/hydrogenandfuelcells/2004_annual_review.html>.

[2] Personal communication between committee member Glenn Eisman and Alan Feitelberg, Plug Power. Also see Roger Saillant, "Stationary fuel cells," Plenary address at the 2004 Fuel Cell Seminar, San Antonio, Texas.

mechanisms must be painstakingly studied and delineated and, therefore, it is important that some of our strongest and most talented scientists and engineers, particularly at the national laboratories, focus on them in a precompetitive, open environment.

There are also significant government activities outside the Department of Energy—for example, in the Defense Advanced Research Projects Agency (DARPA), DOD, the Department of Commerce's National Institute of Science and Technology (NIST), and the National Science Foundation—that are contributing to related fuel cell technical issues. FreedomCAR can learn from the knowledge and technical direction of such activities and incorporate them into its own effort. In some cases DOE is already funding such activities. A case in point is the development of a new process to assist in the understanding of fuel cell performance related to water dynamics. The technique, based on the imaging of fuel cells, is under development at the Neutron Research Center at NIST. The NIST effort is important in that it has been able to develop a CAT-scan-like technique to "see" the water within a working cell, enabling the development of concepts that might improve performance. This is a considerable achievement and one of the most significant analytical advances in the membrane fuel cell realm in decades. The NIST facility offers the entire fuel cell community unique research opportunities that previously eluded them.

Cost Issues

The program is in the process of developing a comprehensive cost model for fuel cell systems (TIAX, 2004). Because the program is so complex, the model is a work in progress, and the technology is evolving, it is too early for the committee to assess the viability and accuracy of specific findings at this time. In its present form, the model should be useful for tracking cost changes with design modifications, for establishing goals for component cost, and for prioritizing cost reduction targets. However, the committee found that TIAX predictions had not yet been validated against the cost of existing entire fuel cell systems, making such predictions speculative. Furthermore, details of the economies expected with manufacturing improvements and the large-volume production of components must be carefully documented and validated for reasonableness before a realistic systems cost estimate can be established. The program is currently reporting a large-volume cost for the fuel cell system of $125/kW and $175/kW with hydrogen storage (TIAX, 2004). These estimates are well below the published costs for many experimental systems (as they should be), but it was not possible for the committee to verify their validity.

For viable fuel cell systems costs to reach the FreedomCAR goal of ~$30/kW, low-cost materials, new, high-volume manufacturing technologies, and better performance and reliability must converge. Currently, membranes and catalysts are both costly. Volume manufacturing may alleviate some of the cost burden, but the catalyst pricing is dictated by market dynamics (the price of platinum in 2004 was $900 per ounce, nearly twice the average price during the 1990s). The unpredictable cost of platinum provides further incentive to reduce catalyst loadings and/or develop a nonprecious metal system. While the balance-of-plant costs are not insignificant, they are based on more conventional engineering processes.

The analysis of costs associated with the fuel cell (TIAX, 2004) points to and supports the conclusion that significant advancements must be made in order for the FreedomCAR cost targets to be met. Such analyses are extremely valuable, but because they are based on numerous assumptions, it is too early to attach any great significance to them. This is especially true for elements related to the power generation module, because such technology is still evolving.

Findings and Recommendations

Overall, the committee finds that the DOE fuel cell program is well organized, has a well developed and comprehensive technology roadmap, has focused on the appropriate priorities and initiatives, and has effectively budgeted and applied program and project management processes. The facilitation of the relationships between the various groups and the ability to set targets that are appropriate yet not without risk are examples of successful program implementation by EERE, with execution by the supporting teams.

The results of this review are indicative of a program that is in its early stages. The review finds that a foundation has been laid that will address the critical issues. The reallocation of project funds to more basic and applied research addressing more fundamental issues is an example of recent proactive changes in the program. It should be pointed out that although the program is sound on numerous fronts, its success is highly dependent on communication and cooperation among the members of the fuel cell technical teams. Fortunately, communication between different parts of EERE, as well as among EERE managers at the various technical teams, is well established, though in some cases not formalized.

Procedures are in place for effective communication and project coordination, leading to the aforementioned conclusion that the fuel cell program is being efficiently managed. The annual merit program review is one such procedure. Because the program is so complex and the detailed objectives are spread over so many technical teams and academic and industrial projects, an additional level of scrutiny for specific efforts would be beneficial. It is also expected that the go/no-go decision making process will continue and that additional evaluation mechanisms will be incorporated into the effort.

Recommendation. DOE should broaden its collaboration with industry, academia, and other government agencies on precompetitive, industry-wide technical issues and solutions. Stationary fuel cell developers should be included as well. For example, DOE could sponsor one or more conferences, workshops, debates, or forums to facilitate in-depth interactions or it could set aside some discretionary funds that would allow program managers to accelerate progress on promising new ideas.

Recommendation. To promote new fuel cell water and hardware imaging techniques that could address technical barriers, DOE should enhance its existing collaboration with the NIST Neutron Research Center. DOE should also determine whether similar capabilities exist at the national laboratories and related academic centers so it could capitalize on this significant analytical advancement.

Recommendation. DOE should expand activity and place a higher priority on membrane R&D, new catalyst systems, and electrode design (with the BES program). In particular, the national laboratories and other appropriate scientific centers should be focused on the fundamental failure mechanisms, including a better understanding of the chemistry, physics, and materials involved.

HYDROGEN STORAGE

Hydrogen storage activities are organized within the DOE Hydrogen Fuel Initiative (HFI), with oversight by the hydrogen storage technical team of the FreedomCAR and Fuel Partnership. As the technical team noted in its presentation to the committee's November 2004 meeting, "Hydrogen storage is critical to the success of the hydrogen economy! No current technology meets the needs for hydrogen storage." The goal of the hydrogen storage technical team is to drive the development and demonstration of commercially viable hydrogen storage that meets FreedomCAR goals.

Hydrogen storage is a key enabling technology for the advancement of fuel-cell-powered technologies for all applications—transportation, stationary, and portable. The goals for hydrogen storage on board the vehicle are shown in Table 3-4. These goals are chosen to drive the development of technologies that will compete with current vehicles in terms of cost, performance, and durability. The mass goal is based on providing a vehicle with a driving range of more than 300 miles. The volume required must leave enough space to satisfy other functional needs. Gravimetric, volumetric, and cost targets have been developed for 2010 and 2015. These goals represent a consensus within the DOE hydrogen technology program. They are used by the technical teams to select and evaluate prospective hydrogen storage materials and related technologies. The 2015 energy density goal of 2.7 kWh/L and specific energy goal of 3.0 kWh/kg are half of what is provided by gasoline (6 kWh/L). A bulky hydrogen storage technology that does not meet these goals would increase fuel consumption and decrease the useable space available on-board the vehicle. Other targets include system fill time, temperature, pressure, flow rates, cycle life, and transient response time.

No current hydrogen storage technology meets the 2015 target. Figure 3-2 shows estimates provided by DOE to the committee for current storage technolo-

TABLE 3-4 Hydrogen Storage Goals

Parameter	2010	2015
Specific energy (net), kWh/kg	2.0 (7.2 MJ/kg) (6% by weight)	3.0 (10.8 MJ/kg) (9% by weight)
Energy density (net), kWh/L	1.5 (5.4 MJ/L) (0.045 kg/L)	2.7 (9.7 MJ/L) (0.081 kg/L)
Storage system cost, $/kWh	4	2

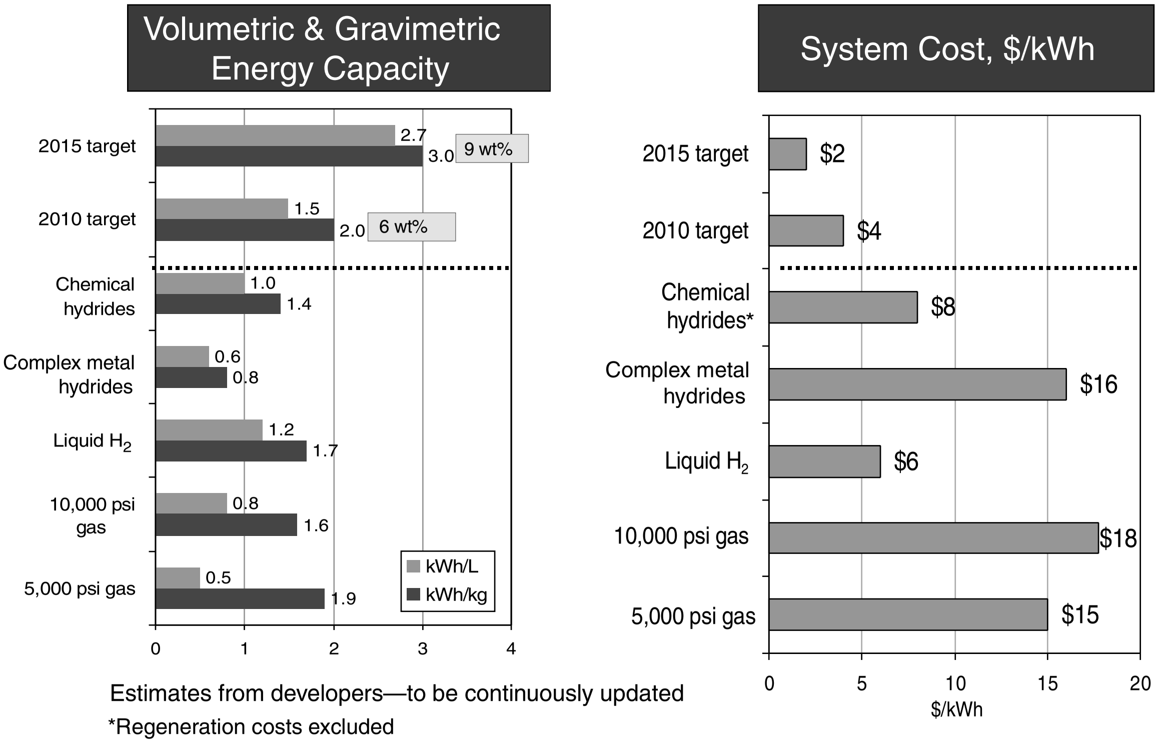
SOURCE: S. Satyapal, S. Jorgensen, and F. Bavarian, "Hydrogen storage joint technical team," Presentation to the committee on November 18, 2004.

gies. Compressed hydrogen and liquid hydrogen, followed by chemical hydrides, come closer to meeting the goal than do the complex metal hydrides or carbon. The hydrogen storage technical team has developed a roadmap of tasks, milestones, and go/no-go decision points to guide the R&D and evaluation of these alternatives.

The committee believes that hydrogen storage technology is one of the greater risks for reaching the program goals in 2015. Hydrogen storage needs a breakthough discovery as the forerunner of development and innovation. Some vehicle manufacturers have in-house programs for hydrogen storage, but they are not able to pursue all of the options. They tend to focus more on the implementation challenges than on broad-based, high-risk exploratory research.

It is too early for the committee to assess technical progress, because the hydrogen storage projects were funded for the most part starting in FY05. The program technical goals are judged by the committee to be appropriate for a commercially viable vehicle, but target dates cannot be set with any certainty. Discovery is needed and cannot be scheduled.

While on-board hydrogen storage is a critical issue for vehicle use, it is also very important for the development of infrastructure (see Chapter 4). Hydrogen will also have to be stored at the dispensing site and at intermediate points in the transport network. Both the infrastructure and on-board storage needs would benefit from a research breakthrough that would significantly increase energy density and reduce the cost of the storage system. One possibility is an integrated solution to the dual difficulties of infrastructure/on-board storage—for example, chemical hydrides, which might be transferred (in cartridge form) to the vehicle. However, recharging a vehicle storage system with gaseous hydrogen appears to be preferable from the standpoints of speed and simplicity.



Estimates from developers—to be continuously updated

*Regeneration costs excluded

FIGURE 3-2 Status of hydrogen storage technologies relative to targets. No current technology meets these targets. SOURCE: S. Satyapal, S. Jorgensen, and F. Bavarian, "Hydrogen storage joint technical team," Presentation to the committee on November 18, 2004.

In all, 71 hydrogen storage projects were funded in FY05, for a total of $23,654,000. Three centers of excellence were established under the leadership of the national laboratories. Other areas receiving funding are the new, independent, so-called Grand Challenge projects being carried out at universities, industry, and national laboratories. New materials and concepts, physical storage off-board, and analysis are also being studied. Physical storage off-board is important because off-board storage will be required at all hydrogen fueling stations.

Tanks for the on-board storage of compressed and liquid hydrogen are being developed by the private sector and are now only a small effort within the program. The focus of the work on tanks within the program is on cost reduction and advanced concepts such as cryocompressed hydrogen and conformable tanks in various shapes. The primary cost driver is tank materials, with carbon fiber representing 40-80 percent of the material cost. Future efforts in compressed and liquid hydrogen storage tanks will involve off-board storage. Metal hydride hydrogen storage materials are not expected to meet the targets, but work in this area is providing an understanding of storage capacity and reversibility. Carbon-based materials for hydrogen storage will focus on reproducibility of results, on-site peer review of projects, and verification of results using standard materials. A go/no-go decision point on carbon nanotubes is scheduled for the fourth quarter of FY06. In chemical hydrogen storage, the storage material is recharged with hydrogen off-board the vehicle and, following use, is recovered and recycled. A chemical composition with a hydrogen capacity of 5.5 percent by weight has been demonstrated. The main technical issue that needs to be addressed for this approach to be viable is off-board regeneration efficiency. Reversible chemical hydrogen is the focus of many exploratory projects. Reversible storage would permit charging the system with hydrogen on-board the vehicle and eliminate recovery and reprocessing of the spent fuel material.

Findings and Recommendations

The hydrogen storage technical team is newly formed and received significant funding only in FY05. Further, DOE's Office of Science basic research on hydrogen storage was first funded in FY05 as well. Although many approaches are worthy of consideration, most will not be able to demonstrate adequate capacity and/or suitable storage release characteristics.

Recommendation. In view of the exploratory nature of the work and the need to take technical risk and thereby foster discovery, DOE should check progress at appropriate times with go/no-go decisions. In this way, new ideas are able to emerge and the most promising approaches are adequately supported.

A center-of-excellence approach involving collaboration among the national laboratories, universities, and industry is being taken by the hydrogen storage program. Three centers of excellence have been selected based on a program solicitation: one on metal hydrides, one on chemical hydrides, and one on solid state, carbon-based materials. The center of excellence approach should enable focused interdisciplinary research by teams of researchers that provide for sharing of facilities and rapid dissemination of findings. The FY04 and FY05 hydrogen storage project participants at the time of the committee review are shown in Appendix E.

Recommendation. The center-of-excellence research model should be carefully evaluated in parallel with peer review of the research. The committee believes centers of excellence are a good concept, but DOE should wait for an evaluation of the three centers' performance before expanding the concept to other areas of research.

Recommendation. In view of the risk posed to the entire hydrogen program by the need for a viable hydrogen storage system, the hydrogen storage technical team and the FreedomCAR and Fuel Partnership leadership team should report annually to all program participants, DOE, and Congress on the state of hydrogen storage technology worldwide relative to the goals and targets of the program.

ELECTRICAL ENERGY STORAGE

The FreedomCAR and Vehicle Technologies (FCVT) program is responsible for advancing the development of energy storage systems. The primary focus of the effort is the development of advanced batteries and includes work on ultracapacitors. Advanced battery work in support of all light- and heavy-duty vehicles is conducted through this program. Energy storage technologies are critical enablers for the development of fuel-efficient ICE hybrid electric vehicles (HEVs) as well as fuel cell hybrid electric vehicles (FCHEVs). Advanced batteries can also be the primary source of power for plug-in hybrids and electric vehicles that provide alternatives to reduced petroleum consumption.

DOE has supported battery research for a long time. With the formation of the United States Advanced Battery Consortium (USABC) in 1991, followed by the establishment of the PNGV program in 1993, the battery effort was directed more toward large battery modules. The PNGV program advanced technologies for nickel metal hydride (NiMH), lithium ion (Li-ion), and other rechargeable batteries for hybrid automotive applications. At that time it was realized that most battery systems under consideration had one or more problems—such as abuse tolerance, cost, and calendar life—limiting their potential use. Thus in 1997 the DOE initiated applied battery research, mainly based at five DOE national laboratories. In 2000, a long-term exploratory research activity program was organized to understand fundamental impediments to the development of advanced batteries.

Today the technology effort for storing electrical energy is organized into three subactivities:

- Battery development, the primary activity, consists of full battery system module development, technology assessment, and benchmark testing.
- Applied battery research focuses primarily on gaining an understanding of failure modes and limiting parameters of the Li-ion system that currently is closest to meeting the technical goals of HEVs.
- Long-term exploratory research focuses on specific electrochemical systems to solve fundamental problems limiting the performance of advanced battery systems.

DOE undertakes these efforts in collaboration with USABC, and the work is conducted at battery developers, DOE national laboratories, and universities and through Small Business Innovation Research (SBIR) grants. The total budget for all energy storage technologies in FY04 and FY05 was \$22.3 and \$23 million, respectively. Of this total, most of the funds, over 75 percent, are used to fund the battery development effort. In FY05, \$17.4 million is allocated to battery development, \$1.4 million to applied battery research, and \$4.2 million to long-term exploratory research.

The plan of FCVT is to develop affordable advanced batteries covering the full range of applications, including start/stop 42-V systems, power assist for HEVs, FCHEVs, and battery electric vehicles (EVs). The technical targets for the various applications are listed in Table 3-5. As noted in FCVT's multiyear plan, a primary goal of the energy storage program is to develop by 2010 an electric drive train that includes a battery with a 15-year life at 300 Wh of available energy, discharge power of 25 kW for 18 s, and a \$20/kW cost (DOE, 2004a).

Program Status and Assessment

The main achievement of the battery effort is the demonstration of high-power Li-ion batteries that will be able to meet or exceed most of the performance targets for an HEV, including specific power, power density, specific energy density, and cycle life. Battery calendar life is now estimated to be greater than 10 years vs. the target of 15 years. These batteries have two major deficiencies: abuse tolerance and cost. Li-ion high-power batteries are not intrinsically tolerant of abuse such as short circuits, overcharge or overdischarge, vibration, and fire. Some of these issues can be addressed by external electronic control; however, it is imperative to continue to look for battery chemistries that are resistant to voltage or thermal abuse.

Partly to address abuse tolerance, the battery effort has programs to develop Li-ion/gel polymer and lithium sulfur (Li/S) batteries. The gel electrolyte in a Li-ion battery is expected on the one hand to reduce the rate at which the electrolyte reacts with the electrodes during abuse conditions. On the other hand, it may reduce the power capability of the battery, particularly at low temperatures. The Li/S battery is expected to be more abuse tolerant due to a sulfur shuttle reaction. In addition, it has the theoretical potential to meet all the EV performance targets.

However, several technical barriers have to be overcome to make the Li/S chemistry work efficiently, particularly dendritic growth of metallic lithium during cycling. The Li-ion/gel polymer battery and the Li/S battery are being tested to determine how they will meet the various performance targets in Table 3-5. A go/no-go decision based on the performance data will be made in FY06.

Further understanding and control of thermal abuse is being done through battery thermal management studies at the National Renewable Energy Laboratory (NREL) using thermal modeling, characterization, and control. This work is critical, not only for managing thermal abuse conditions but also for achieving more uniform temperature control over the battery module, which should increase battery life.

Battery development teams are working on several fronts to reduce the cost of the Li-ion battery. They are assessing new cathode materials, such as a spinel-based lithium manganese oxide and lithium iron phosphate as an alternative cathode material for Li-ion batteries. These materials are a lower cost alternative to the lithium cobalt oxides used today and may have greater stability under abuse conditions. Other cost reduction efforts are based on earlier studies showing that the cost of nonactive material in a high-power battery, particularly the separator material, can exceed the cost of the active material. Thus, support is being provided to develop low-cost polypropylene-based materials with a cost goal for the separator of $\$1/m^2$. The goal is to have a direct replacement for the current separator material that is cheaper and more stable at high temperature.

The main barriers for high-power batteries—abuse tolerance, cost, and calendar life—are also being pursued by the applied battery research and the long-term exploratory research groups. Both groups are looking at newer materials and electrochemical couples to obtain a basic understanding of the failure mechanisms and factors that limit performance of the systems. The applied battery research activity is conducted primarily at five national laboratories—Argonne National Laboratory, Brookhaven National Laboratory, Idaho National Engineering and Environmental Laboratory (INEEL), Lawrence Berkeley National Laboratory (LBNL), and Sandia National Laboratories (SNL). The focus here is to work on a second-generation Li-ion system, determine performance and failure mechanisms, and relate them to the individual components of the system. The long-term battery research is carried out primarily at LBNL and looks at the performance of a large number of promising electrode materials and electrolytes and determines their limitations by advanced material diagnostics and sophisticated modeling studies.

The committee commends the FCVT program for expanding its primary focus on battery development to include both the basic and applied research necessary to enhance the performance of the battery. The committee believes strongly that this expanded process should continue and that funding and effort on long-term exploratory research and applied battery research should be accelerated. It is clear that solutions to the main barriers of abuse tolerance, cost, and calendar life for high-power batteries will come only with the introduction of new materials and electrochemical couples and from a better understanding of the factors that limit battery performance. Thus the efforts being conducted in the

TABLE 3-5 Technical Targets for Electrochemical Storage

		42-volt			HEV (Power-Assist)		Fuel Cell Vehicle	Battery EV	
Target	Unit	Stop Start	M-HEV	P-HEV	Low Power	High Power	Low Power	Commercial-ization	Long Term
Discharge power	kW	6 for 2 s	13 for 2 s	18 for 10 s	25 for 10 s	40 for 10 s	25 for 18 s		
Specific power-discharge, 80% DOD/30 s	W/kg							300	400
Regenerative pulse	kW	N/A	8 for 2 s	18 for 2 s	20 for 10 s	35 for 10 s	25 for 5 s		
Specific power-regeneration, 20% DOD/10 s	W/kg							150	200
Engine-off accessory load	kW	←	3 for 5 min	→					
Recharge rate	kW	2.4	2.6	4.5					
Power density	W/L							460	600
Available energy at 3 kW	Wh	250	300	700	300	500	250		
Specific energy—C/3 discharge rate	Wh/kg							150	200
Energy density—C/3 discharge rate	Wh/L							230	300
Specific power/specific energy ratio	h^{-1}							2:1	2:1
Total energy	kWh							40	40

Energy efficiency on load profile	%	90	90	90	90	90	90		
Cycle life profiles (engine starts)	cycle	← 450,000 →			300,000	300,000	TBD	1,000 at 80% DOD	
Calendar life	year	15	15	15	15	15	15	10	10
Cold cranking power at –30°C	kW	← 8 at 21V minimum for 2 s →			5 for 2 s	7 for 2 s	5 for TBD min		
Maximum system weight	kg	10	25	35	40	60	32		
Maximum system volume	liter	9	20	28	32	45	26		
Price at 100,000 units/year	$	150	260	360	500	800	400		
Price for 25,000 units (40 kWh)	$/kWh							<150	100
Maximum operating voltage	Vdc	48	48	48	400	400	440		
Minimum operating voltage	Vdc	27	27	27	← >0.55 x V_{max} →				
Maximum self-discharge	Wh/d	<20	<20	<20	50	50	50		
Operating temperature range	°C	← –30 to +52 →			← –30 to +52 →			–40 to +50	–40 to +85
Survival temperature range	°C	← –46 to +66 →			← –46 to +66 →				

NOTE: M-HEV, mild hybrid electric vehicle; P-HEV, power assist hybrid electric vehicle; DOD, depth of discharge.
SOURCE: T. Duong and A. Habb, “Electrochemical energy storage,” Presentation to the committee on November 17, 2004.

applied and long-term research groups are crucial to meeting all the target goals of a high-power battery. At present less than 25 percent of the total energy storage budget is allocated to the applied and long-term research. This share should be increased significantly.

Most of the work sponsored by the energy storage technology team is directed to the development of high-power batteries. Specifically, in FY04, 80 percent of the funds were spent on high-power batteries for HEVs. Some funds were used to develop high-energy batteries to meet the target for an EV. The applied and long-term exploratory research on new materials and electrochemical couples is also primarily for high-energy batteries. The committee recognizes that the distinction between a high-power and high-energy battery is somewhat arbitrary, particularly when attempting to gain a basic understanding of the factors limiting the performance of the battery. The fundamental property of a battery is its specific energy, and generally the specific power is determined by design optimization for a given application. Thus, the Li-ion battery is a high-energy battery that has been optimized to meet the power and cycle life requirements of a high-power battery for HEV applications, and increased effort on high-energy batteries will increase the likelihood of meeting the high-power battery goals for hybrid application.

The target requirements for the HEV listed in Table 3-5 show that as one moves from a 42-V application to a more demanding power-assist HEV and then to a FCHEV, the power requirement increases from 13 kW to 25 kW. Not only is the power increased for the more demanding hybrid applications, but it is also required for a longer time, increasing from 2 s in the 42-V application to 18 s for a FCHEV (DOE, 2004a). Thus one would require a battery with not only a higher power rating but also significantly higher specific energy. It is clear that various hybrid designs will have different power requirements and there is continuum of energy requirements. Higher energy can be utilized to gain a better mix of power and energy density in battery design for a given application or it can also be used to optimize the size of the ICE engine.

The target requirements for an EV are listed in Table 3-5. The main requirement is a high-energy battery with specific energy of 200 Wh/kg and 2:1 power to energy ratio. An EV represents an alternative route to achieving the primary goal of the FreedomCar and Fuel Partnership: energy independence and an environmentally friendly transportation system. The development of high-energy batteries is consistent with DOE's goal of investing in high-risk technologies. The challenge of such an effort is probably no greater than the challenges of hydrogen storage and the hydrogen infrastructure requirements for a hydrogen fuel cell vehicle. The committee feels that the effort for high-energy batteries should be significantly increased.

Ultracapacitors

The double-layer capacitor (DLC), commonly referred to as an ultracapacitor, is an energy storage device having a state-of-the-art energy density about 1/10 that of a Li-ion battery but a power density about 10 times that of a Li-ion battery. DLCs in large sizes (>5,000 farads) are receiving considerable international research attention and could prove to be an important element in a FCHEV. Current research is focused on innovative electrode structures and new electrolytes, the goal being to achieve both a higher cell voltage and a larger specific capacitance. The DLC has no mass transport and compared with a battery, has a considerably longer cycle life and better tolerance of temperature extremes. As noted in the section "Electric Propulsion, Electrical Systems, and Power Electronics," the FreedomCAR program has benchmarked commercially available DLCs. In view of the potential benefits of a high-energy-density DLC, the funding of research in advanced DLC technologies may be warranted.

Comments and Recommendations

Efforts directed toward the development of new materials and electrochemical couples in these programs present the best chance to remove the major barriers of abuse tolerance, cost, and calendar life for high-power batteries.

Recommendation. DOE should direct more of its effort and funding for high-power batteries for HEVs to applied and long-term exploratory research rather than battery development.

High-energy batteries for electric vehicles and plug-in hybrid applications would also serve to meet the FreedomCar and Fuel Partnership goals. Further, more support for high-energy battery research would increase the likelihood of meeting the requirements of various HEVs for high-power batteries.

Recommendation. A significantly larger effort and higher priority should be placed on searching for breakthrough technology in the area of high-energy batteries for electric vehicles.

Recommendation. In view of the potential benefits of a high-energy-density DLC in hybrid vehicles, the energy storage technical team, in conjunction with the electrical and electronics system technical team, should maintain an activity that explicitly monitors progress of international DLC research programs and should consider funding research in advanced DLC technologies.

ELECTRIC PROPULSION, ELECTRICAL SYSTEMS, AND POWER ELECTRONICS

The multiple systems in both hybrid electric vehicles (HEVs) and fuel cell hybrid electric vehicles (FCHEVs) require both control and coordination. These functions will be provided by electronics, both power- and signal-level. Although a fuel cell (FC) alone may be compatible with the dynamic requirements of electrical traction, regenerative braking requires that the FC be augmented by an energy storage device—e.g., a battery or an ultracapacitor. This electrical energy storage may also be used to enhance the dynamic performance of the propulsion system by, for instance, providing fast transient power for acceleration. The battery may also be used for drive-away when fuel cell start-up time is excessive. The charge/discharge cycles of this device will require power electronics. Control of the FC itself will also require electrical system controls. The integrating role of the vehicle electrical system makes it an important technology, both functionally and economically. However, the FreedomCAR goal for the electrical and electronics (EE) technical team, as stated, is limited to the propulsion system—that is, the electric machine and the power electronics to drive it.[3] Although the multiyear plan of the FCVT program also states this goal, the surrounding discussion does refer to many of the other EE functions necessary for the complete system (DOE, 2004a; FCVT, 2004).

Program Status and Progress

Within the restricted goals established for the EE systems, the EE technical team has built on the results of the motor and electronics development in the PNGV program. The power electronics technology for FreedomCAR is evolving from the PNGV-funded automotive integrated power module (AIPM) developments. While several companies (one is Rockwell Automation) continue to develop AIPMs that may be applicable to FreedomCAR, the FCVT program is currently funding work at Semikron.

Table 3-6 shows the power electronics and traction motor status in 2003, the 2010 targets, and the gap between status and target. The reported status of the power electronics in November 2004 had not changed from that in 2003. The principal challenges are thermal performance, lifetime, and cost. Although the 2003 status for power electronics shows a lifetime of 15 years, this is with a coolant temperature of 70°C. The lifetime would be considerably less at the 2010 target temperature of 105°C. Although the specific power and volumetric power density of the motor are still shy of their 2010 targets, it is the motor cost and thermal performance that remain the most significant challenges. The committee is not convinced that the motor cost goal of $7/kW is achievable, since the cost is principally a matter of commodity prices (e.g., copper and iron prices), and it seems unlikely that cost can be reduced much through research.

Thermal performance of the power electronics has been a challenge using conventional component technology, and the EE technical team is exploring

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[3] S. Rogers and V. Garg, “Electrical and electronic tech team—NAS review,” Presentation to the committee on November 18, 2004.

TABLE 3-6 Technical Targets for Power Electronics and Electric Motors

	2003 Status	2010	Gap
Power electronics (inverter/controller)[a]			
Specific power at peak load (kW/kg)	11	>12	1
Volumetric power density (kW/L)	11.5	>12	0.5
Cost[a] ($/kW peak)	6	<5	1
Efficiency (%)	97	97	0
Coolant inlet temperature (°C)	70	105	35
Lifetime (yr)	15	15	0
Electric motors (traction)[a, b]			
Specific power at peak load (kW/kg)	1.0	>1.3	0.3
Volumetric power density (kW/L)	3.5	>5	1.5
Cost ($/kW peak)	15	<7	8
Efficiency (%)	>90 at 35% to 100% maximum speed	>93 at 10% to 100% maximum speed	

[a] The targets are based on a series power train with 30-kW continuous power and 55-kW peak power. Entries for 2003 are taken from AIPM and automotive electric motor drive (AEMD) specifications.
[b] Technical targets include the gearbox and connectors.
SOURCE: FCVT, 2004.

alternatives through an advanced R&D program whose salient elements are the development of silicon carbide (SiC)-based converters and high-temperature capacitors. The Semikron inverter is being retrofitted with SiC diodes, and a number of research programs at different organizations are directed toward higher temperature capacitors. New thermal management techniques applicable to both the electronics and the motor are being explored.

The EE technical team is pursuing the development of an integrated motor controller chip. The preliminary design was completed in October 2004 and testing was to have occurred in December 2004. The vision is that such integration will reduce system costs.

The FreedomCAR and Fuel Partnership and INEEL have benchmarked the commercially available DLCs and identified their potential for HEVs (see discussion of DLCs in the section on electrical energy storage). Oak Ridge National Laboratory (ORNL) has done a detailed analysis of the Toyota Prius second-generation hybrid motor to evaluate its design and performance and the processes used in its manufacture. A very preliminary analysis of the Prius drive electronics has also been performed, with a more detailed analysis of performance and construction planned for the near future. To the committee's knowledge, the results of these analyses have not yet been used for guidance in the specification or design of the FreedomCAR vehicle EE components.

Assessment of the Program

The EE component of the FreedomCAR program is addressing a diversity of challenges. Development programs are spread among national laboratories, universities, commercial contractors, and the three automotive companies (OEMs). The particular problems being addressed by these organizations appear to be well defined and relevant to the FreedomCAR and Fuel Partnership goals. The quality of these activities and their results to date are also good, though several of them are in the early stages.

While all these activities are addressing important EE issues, a process for coordinating their output to address systemic Partnership goals was not apparent in either the presentations or written material provided to the committee. This will be no small task given the diversity and large number of activities.

Of particular interest will be the benchmarking of FreedomCAR EE developments against both the components and the integrated systems of the Toyota Prius. For example, since the Prius's physical and performance characteristics are similar to those of the FCHEV, many of the metrics for the latter should be similar to those for the Prius—for example, thermal performance, cost, efficiency, and energy/power densities. Toyota has invested considerable resources in the continuing redesign of the Prius motors and power electronics, and the FreedomCAR program should exploit this investment to its advantage. The results of the ORNL benchmarking exercise should be used to help establish the starting point for the EE technical team's more aggressive research agenda and goals.

Since electronic controls serve as the interface for all the subsystems in the FCHEV, coordination among the technical teams to assure that the interfaces are correctly defined is crucial for system integration. To date the interaction among the technical teams has been informal and infrequent. The quarterly meetings among technical team chairs and the USCAR FreedomCAR directors address operational issues, not the tactical issues necessary for specifying interface tasks. There is an all-technical-team meeting every other year, but this relaxed schedule cannot achieve the coordination needed. Given its central role at the interfaces, the EE technical team should probably serve as the catalyst for the coordination process. Furthermore, it is not clear to the committee that progress in one area that has implications for the specifications or parameters in other areas is communicated to or recognized by those other areas.

Recommendations

The interfaces among the many subsystems in the FCHEV are not only critical to safe and proper vehicle operation but also may contribute significantly to vehicle cost, and the committee is concerned that this issue is not receiving adequate attention.

Recommendation. The EE technical team should play a leading role in coordinating the specifications for the interfaces among the many vehicle subsystems, using established standards where they exist and accelerating the development of new ones where they are needed.

Recommendation. The EE technical team should identify the R&D path leading to the motor cost goal, or it should reassess that goal.

Recommendation. The EE technical team should use its evaluation of the state of the art of HEV technology to update and establish the team's future research agenda and goals.

Recommendation. The EE technical team should develop a process for coordinating the diverse activities it is overseeing.

Recommendation. Integrating the electronics with the motor may well provide significant cost advantages. The EE technical team should consider these potential advantages and extend Table 3-6 to include aggressive targets for an integrated system in 2010 and 2015.

Recommendation. High-temperature power electronics and advanced thermal management systems will significantly impact the size, weight, cost, and reliability of the EE subsystems. FreedomCAR work in this area appears to be limited to the application of SiC devices to the Semikron inverter. The EE technical team should be aware of and leverage the work on high-temperature semiconductors, packaging, and thermal management being funded by government agencies at universities, commercial organizations, and the national laboratories.

STRUCTURAL MATERIALS

Vehicle programs designed to achieve major fuel economy improvements must incorporate significant weight savings. The widespread application of lightweight materials and innovative manufacturing processes are necessary to attain this goal. The FreedomCAR and Fuel Partnership has set a vehicle weight reduction target of 50 percent, adding the criterion "affordable cost." These objectives in weight and cost are not dissimilar to those in the predecessor PNGV program and thus allow continuation of the materials programs already in place. Perhaps more important, the same materials technical team is in place to continue these efforts, which have been under way for a number of years, without major perturbations in objectives or content. These programs were reviewed extensively by the NRC Standing Committee to Review the Research Program of the PNGV Program in its seventh report (NRC, 2001). The current review of the FreedomCAR and Fuel Partnership will concentrate on the relevance and adequacy of the overall materials programs rather than the specific details of individual programs, which were covered in the previous PNGV report.

Material Thrusts

Virtually all of the important materials programs in place when the FreedomCAR program was initiated have been continued. In summary, the programs consist of R&D on materials known to be capable of producing very significant weight savings when applied extensively throughout the vehicle structure—namely, high-strength steels, aluminum alloys, and carbon-fiber-reinforced polymer (CFRP) composites. In addition, work on the selective application of cast aluminum alloys, cast magnesium alloys, aluminum metal matrix composites, and titanium alloys is under way. Owing to the lower densities (except HSS), all these materials achieve the weight savings, but usually at a very significant cost penalty compared with current materials. Thus, while there are some major technical obstacles to the extensive application of these lightweight materials, the paramount challenge to the program is achieving cost parity, or "affordability." The difficulty of achieving affordability cannot be overemphasized, and all the large research programs should include a roadmap showing how to reach the cost target.

HSS structures are probably the closest to approaching affordability but are only likely to achieve about half of the targeted weight reduction. As documented in the last NRC review of the PNGV program, there is an extensive program under way in the steel industry to maximize weight savings in body structures through optimal use of HSS and innovative manufacturing practices (NRC, 2001). This program, known as the Ultralight Steel Auto Body-Advanced Vehicle Concept (ULSAB-AVC), adequately covers HSS development and capability. Additional research on HSS within the FreedomCAR and Fuel Partnership does not appear to the committee to be necessary. The NRC report recommended that the materials technical team closely monitor the ULSAB-AVC program, not only for the potential use of HSS but for the possible transfer of innovative (weight-saving) manufacturing processes to other low-density materials, in particular aluminum alloys (NRC, 2001). The current committee enthusiastically endorses this recommendation.

The only current competitors to HSS for extensive vehicle applications are aluminum alloys and CFRP composites. These material families are capable of meeting the overall weight-saving target, but their cost penalty is large. While not minimizing the manufacturing difficulties associated with both classes of materials, it is the cost of the feedstock material that will most seriously prevent widespread application. In the case of aluminum alloys, previous projects for demonstrating lower cost feedstock—for example, continuous cast sheet for body structures—have not resulted in the commercial development of any such material. Similarly, CFRP composites await the arrival of low-cost carbon fibers, a holy grail that has eluded the fiber industry for decades and is unlikely to be achieved without the enthusiastic participation of large carbon fiber producers. While the current committee supports some research activities in both aluminum alloys and CFRP, greater

TABLE 3-7 Weight Savings for Lightweight Materials

Lightweight Material	Material Replaced	Mass Reduction (%)	Relative Cost (per part)[a]
HSS	Mild steel	10-24[b]	1
Aluminum	Steel, cast iron	40-60	1.3-2
Magnesium	Steel or cast iron	60-75	1.5-2.5
Magnesium	Aluminum	25-35	1-1.5
Glass FRP[c]	Mild steel	25-35	1-1.5
Carbon FRP[c]	Mild steel	50-65	2-10+
Aluminum MMC[d]	Steel or cast iron	50-65	1.5-3
Titanium	Alloy steel	40-55	1.5-10+
Stainless steel	Mild steel	25-40	1.2-1.7

[a] Includes both materials and manufacturing costs; the lower bound of unity is a future projection.
[b] The lower bound is taken from Powers (2000) and the upper bound from NRC (2000).
[c] FRP, fiber-reinforced polymer.
[d] MMC, metal matrix composite.
SOURCE: Powers, 2000.

efforts to gain the cooperation of the major material manufacturers would clearly be critical to any future long-term use of these materials.

In the R&D areas for more selective applications, the materials technical team reported an increasing interest in magnesium alloys based on their potential to offer major weight savings in cast applications. Programs in this arena seem very appropriate because of the low density of the materials and the significant opportunities in materials development that are necessary for successful applications. It is likely that magnesium materials will be useful only in cast applications, and these should be the focus of the FreedomCAR programs, including significant basic materials research. While the technical team expressed guarded optimism that magnesium sheet structures might have some potential, this topic would not appear to be fruitful without some major substantial participation from the raw materials industry.

For reference purposes, Table 3-7, adapted from the PNGV report (NRC, 2001; Powers, 2000), illustrates the relative costs of low-density materials and associated manufacturing costs. The relative cost column indicates the potential cost penalties resulting from application of the various material technologies under consideration.

Recommendations

The materials technical team has the benefit of several years' experience and obviously operates very cooperatively. It has clearly benefited from the earlier NRC reviews of the PNGV program and encompasses in its R&D portfolio all the opportunities for weight reduction afforded by current and future materials.

Recommendation. The only FreedomCAR effort on HSS should be careful monitoring of outside programs with the objective of adopting novel manufacturing and assembly methods to aluminum structures. This recommendation mirrors the previous NRC recommendation on the PNGV program.

The cost of a high-volume material such as aluminum is not likely to be reduced by federally sponsored research. Such cost reduction will be achieved only with increased application and production.

Recommendation. The most important aspect of the stamped aluminum program is cost reduction, particularly for the feedstock material. Efforts in manufacturing should be limited until progress in the cost area has been achieved.

The fundamental issue with CFRP composites is the development of low-cost carbon fibers. The award of a single research grant to a national laboratory does not reflect the importance of this problem. Low-cost carbon fibers would also reduce the costs of several of the hydrogen storage options.

Recommendation. More extensive research programs on CFRPs, combined with the direct cooperation of the large fiber manufacturers, appear mandatory for any hope of success within the program time frame. Meanwhile, R&D for manufacturing of structures should continue.

Recommendation. Longer-term research programs in magnesium alloys should be funded because of the weight savings these materials could offer. Cast materials should be the primary emphasis, with limited exploratory work on wrought materials. Increased activity in this area is highly recommended.

Recommendation. The materials technical team should provide technical materials input to other technical teams—for example, electronics, the hydrogen onboard supply system, magnets, motors, fuel cell structural issues—where such input would be useful. The team has never been asked to do this, but it could be extremely useful to the overall program.

Recommendation. The materials technical team should provide models of weight reduction/cost trade-offs to the systems analysis and engineering team. This would help define the singular objectives for individual systems and allow some flexibility in the focus of cost reduction efforts.

Recommendation. Overall, since cost reduction is the main need in many of the materials programs, the committee suspects that research activities are of somewhat limited benefit. Thus, much of this research funding might better be expended on other more challenging research areas, such as hydrogen storage materials, batteries, fuel cells, and the infrastructure.

Comment on Vehicle Weight Reduction Target

In the opinion of this review committee, it is extremely unlikely that a 50 percent reduction in vehicle weight (at anywhere close to cost parity) can be achieved in the 2010 to 2012 time frame without increasing vehicle costs substantially. It might be prudent for FreedomCAR to reconsider this probably unattainable target and adopt a more realistic goal–for example, a 30 percent overall weight reduction with minimal (say, <5 percent) cost penalty. The overall system objectives could either directly reflect this change, or targets in other systems areas might be adjusted in compensation. The only other alternative is to maintain the current 50 percent weight saving goal but allow for a significant cost penalty—probably unacceptable to both the automotive industry and the automotive consumer.

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4

Hydrogen Production, Delivery, and Dispensing

PROGRAM OVERVIEW

Prior to the announcement of the FreedomCAR and Fuel Partnership, President Bush announced in February 2003 the FreedomCAR and Hydrogen Fuel Initiative (HFI) to develop technologies for (1) fuel-efficient motor vehicles and light trucks, (2) cleaner fuels, (3) improved energy efficiency, and (4) a hydrogen production and nationwide distribution infrastructure for vehicle and stationary power plants, to fuel both hydrogen internal combustion engines (ICEs) and fuel cells (DOE, 2004). The expansion of the FreedomCAR and Fuel Partnership to include the energy sector that occurred after the announcement of HFI now includes the HFI, whose focus is on hydrogen technology as described in the following sections.

The objective of DOE's HFI is to bring cost-competitive hydrogen fuel technology and infrastructure to the market in order to significantly reduce the following:

- Oil imports in order to increase national energy security;
- Carbon dioxide (CO_2) emissions, to head off potential climate change impacts; and
- Criteria emissions, to improve health and environmental quality.

As discussed in Chapter 1 and as indicated in Chapter 5, Table 5-1, HFI's hydrogen technology R&D incorporates the activities of the Hydrogen, Fuel Cells and Infrastructure Technology (HFCIT) program except those focused on proton exchange membrane (PEM) fuel cell development. The initiative cuts across four DOE offices—the Office of Energy Efficiency and Renewable Energy (EERE); the

Office of Fossil Energy (FE); the Office of Nuclear Energy, Science and Technology (NE); and the Office of Science's Basic Energy Sciences (BES) Program. Overall responsibility for HFI rests with the Hydrogen, Fuel Cells, and Infrastructure Program Manager in EERE. Important elements of the program are hydrogen production, hydrogen delivery and dispensing, hydrogen storage, safety codes and standards, infrastructure validation, and education. For FY05, funding is $169 million for the entire HFCIT program, which includes about $75 million for fuel cells and $38 million for projects in hydrogen production, delivery, and storage (see Chapter 5, Table 5-1). For FY05, $37 million of the HFI program funds are congressionally directed (earmarked). (See Chapter 3, "Vehicle Technologies," for discussion of onboard hydrogen storage for the vehicle and Chapter 2, "Major Crosscutting Issues," for discussion of safety, codes, and standards.)

NRC Report *The Hydrogen Economy*

The NRC/NAE report *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs* (NRC/NAE, 2004) noted the central importance of the HFCIT program to improving U.S. energy security and environmental protection. It presented recommendations on program plans and operations. In particular, the report emphasized the development of technologies both to facilitate the early transition to the hydrogen economy and to ensure its long-term viability. That report also recommended that the program shift its emphasis in several key areas. The program's management has responded rapidly to these recommendations, most of which have been incorporated into the program during the past several months.

The principal recommendations of the 2004 report on *The Hydrogen Economy* may be summarized as follows:

- DOE should take a systems approach to understand the complex interactions across the well-to-wheels hydrogen system.
- Increased emphasis should be placed on breakthrough research in on-vehicle hydrogen storage systems, fuel cell cost and performance, and photoelectrochemical hydrogen processes. In addition, efforts on distributed—at the filling station—hydrogen generation technologies should be increased to support the early introduction of hydrogen fuel cell vehicles into the market. Further, given the potential importance that coal may play in a future hydrogen system, there should be closer coupling among DOE's hydrogen, fuel cell, and carbon capture and sequestration efforts.
- Increased emphasis should be placed on developing technologies for hydrogen generation and on developing solutions to nontechnical issues for the transition period to the fully functional hydrogen economy.

The committee compliments DOE on rapidly implementing most of the recommendations in *The Hydrogen Economy* and encourages program management to ensure that sufficient effort is devoted to developing technologies and resolving issues for the transition period.

Recommendation. Recognizing that changes in large, complex programs necessarily occur at a measured pace, the committee nevertheless recommends special attention to three areas: the transition from the current ICE/fuels infrastructure to a nascent hydrogen economy; on-vehicle hydrogen storage; and carbon capture and sequestration.

Specific recommendations on hydrogen production, delivery, and dispensing activities in the FreedomCAR and Fuel Program are offered in other sections of this chapter.

Earmarking

The interim milestones of the hydrogen production, delivery, and storage component of the program have been delayed owing to significant congressionally mandated activities (earmarking)—approximately $37 million—in both the FY04 and the FY05 hydrogen program budgets (DOE, 2005). Although DOE has some flexibility to allocate funds not earmarked, budgets for the hydrogen production, delivery, infrastructure, and safety parts of the HFI were reduced by 50 percent. DOE continued to fund 80 percent of the hydrogen storage program because of its critical importance to the success of the FreedomCAR and Fuel Partnership. In contrast, the vehicle and fuel cell efforts in the overall FreedomCAR and Fuel Partnership were not earmarked, creating a disconnect in the ability to reach milestones between the two parts of the program. In the opinion of the committee, the earmarked projects will not help the program meet its goals, and the lower funding on critical projects will reduce its chances of success. The earmarked projects upset the balance of the program because they prevent some work from being done. The earmarked projects do not benefit from technical team input and oversight and are not selected by peer review, nor were they subject to review by the committee.

Recommendation. The committee strongly recommends that the Hydrogen Technology R&D be fully funded at the $99 million level for the areas indicated in the FY06 Presidential budget request to Congress.

FreedomCAR and Fuel Partnership

Within the FreedomCAR and Fuel Partnership, part of the HFI is managed by three new technical teams: (1) fuel/vehicle pathway integration, (2) hydrogen production, and (3) hydrogen delivery. These technical teams were established in 2004, when the energy companies joined the Partnership. While HFI has been progressing for several years, the energy companies have only been part of the

FreedomCAR and Fuel Partnership for the past year. The accomplishments of the new teams so far have been primarily defining and scoping the work to be done.

The committee is impressed by the rapid start-up of the fuel technical teams and impressed by how well the members and DOE are working together. The teams have set aggressive completion targets consistent with the overall hydrogen program goals. The committee encourages the teams to keep moving forward and frequently check their progress with go/no-go decisions and adjust their efforts accordingly. This is particularly important since the Partnership is in its early stages and its direction may shift as new knowledge is acquired.

HYDROGEN FUEL PATHWAYS

The hydrogen fuel/vehicle pathway integration effort is new to the Partnership. This is a very significant addition as the team is charged with looking across the full hydrogen supply chain—well to tank. Specifically, the goal of the integration effort is to (1) analyze issues associated with complete hydrogen production, distribution, and dispensing pathways, (2) provide input to the Partnership on setting targets for individual components, (3) provide input to the Partnership on needs and gaps in the hydrogen analysis program, and (4) work toward full transparency of all analysis activities.[1]

This technical team has an important role to play in providing input and guidance to the new systems analysis efforts in DOE. It also must work with the vehicle systems and engineering analysis team to integrate the entire hydrogen program on a well-to-wheels basis. Targets and milestones for individual components can be analyzed and reset, improving program prioritization and management.

The team has made a lot of progress. It established a set of principles to shape its effort. One of the most important principles is this: “Targets for the cost of hydrogen from energy source to vehicle should be pathway independent.” In addition, the team has developed a framework to evolve the hydrogen program technical targets and addressed difficulties in using current DOE technical targets to assess complete hydrogen fuel pathways.

The committee is encouraged by the approach the team has adopted in its “Framework for Pathway Analysis,” which will encompass well-to-tank costs, energy use, and CO_2 emissions. There are some significant challenges ahead. Providing input and guidance to layered models created by others, such as the Macro Systems model, the Transition model, and the Systems Analysis Plan, poses a serious coordination challenge.

Systems analysis is an especially important tool to help understand and prepare for the transition to a hydrogen economy. Many technologies may emerge

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[1] D.J. Gardner, Jr., and D. Joseck, “Fuel pathway integration tech team-NAS review,” Presentation to the committee on November 17, 2004.

but not become widespread. During the transition, a highly dynamic and uncertain phase, divergent vehicle and dispensing designs may appear in niche markets, offered by those seeking to demonstrate the technology and purchased by the early adopters. It will be important to try to understand the conditions under which such technologies might remain in these niche applications or, perhaps, become more widespread. As an example, high-technology all-electric vehicles recently failed to gain market share in competition with the ICE for mainstream auto markets; yet, scaled-down versions of these electric vehicles compete quite well in certain personal transportation applications, such as are found in retirement or private residential communities.

Consequently, although it is not possible to predict which technologies will emerge from their niches to capture mainstream markets, it will be important to understand the technology adoption mechanisms. Therefore, the immediate contribution of these or other niche concepts are the lessons that they provide for other, possibly superior technologies that will eventually prevail in the mainstream marketplace. An appropriate set of systems analyses that model technology adoption could help in understanding and accelerating the transition. For example,

- DOE could learn from and aggregate the experience of niche demonstrations around the country to ensure that others benefit from them;
- The models could guide DOE's technology programs so that they provide the precompetitive technology base that would best support a rapid and effective transition to the mature hydrogen economy; and
- They could address whether DOE's current goals for the cost of delivered hydrogen match the needs of the transition (as opposed to the mature) marketplace.

Recommendation. The committee recommends as follows:

- That DOE further focus the achievements of the fuel/vehicle pathway integration team by placing greater emphasis on the hydrogen transition in its systems analysis work;
- That the results of this systems analysis work be used to assist in identifying needs for the development of codes and standards and for the training of local zoning officials and emergency responders; and
- That DOE apply its systems capabilities to analyze whether the cost goals for hydrogen production, established for a mature hydrogen economy, are appropriate for the transition.

HYDROGEN PRODUCTION

The hydrogen production goals assume that U.S. energy security will best be enhanced by producing hydrogen from a diverse set of feedstocks and that no single candidate feedstock will probably be capable of providing all energy needs over the long term. The mission of the hydrogen production technical team is to "drive the development of commercially viable centralized and distributed hydrogen production technologies that meet the FreedomCAR and Fuel Partnership goals."[2]

The program encompasses the following (energy) sources for the generation of hydrogen: natural gas, coal, nuclear heat, biological systems, wind, and the sun. The overarching technical challenges in all areas are cost reduction, improved energy efficiency, and technological feasibility. The program considers distributed hydrogen generation (where hydrogen is produced at the filling station) as the most viable approach for hydrogen production and hydrogen delivery for the transition period. *The Hydrogen Economy* (NRC/NAE, 2004) estimated that in the most optimistic plausible case, significant hydrogen-fueled vehicle penetration (>50 percent) would not occur before 2035). Initially, then, hydrogen will be produced locally and a hydrogen delivery infrastructure is not required. Furthermore, it is unlikely that there would be investors willing to put significant capital at risk to distribute hydrogen, given all the uncertainties. The first fueling stations will need to be in areas that serve a small local market of vehicles. The volume of hydrogen demand will not be great enough to support central production, and distributed production might not achieve the fuel savings and carbon capture of the ultimate solutions. The reason to start with distributed stations is to get the number of hydrogen-fueled fuel cell vehicles large enough to justify centralized production. In other words, it could solve the significant chicken-and-egg barrier to widespread penetration of hydrogen-fueled fuel cell vehicles into the market; indeed, it might be the only solution.

The technologies for near-term distributed generation are the reforming of natural gas and small-scale water electrolysis. For the longer term, the vision is centralized production of hydrogen that will take advantage of economies of scale and use a more diverse set of feedstocks. However, the centralized approach requires the development of a massive hydrogen distribution infrastructure for hydrogen delivery and dispensing. In addition, since coal would probably play a significant role in a hydrogen economy, carbon capture and storage (CCS)—or sequestration—technologies and systems will have to be developed (NRC/NAE, 2004). From a societal standpoint, these infrastructure issues are some of the most difficult barriers to the program's realization.

In summary, the most cost-efficient means of providing hydrogen in the long term is centralized plants and a network of distribution pipelines. However, distributed hydrogen production will be the means of hydrogen production and delivery during the transition period, which could be long, and, as stated in *The*

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[2] P. Devlin and S. Schlasner, "Hydrogen production tech team—NAS peer review," Presentation to the committee on November 17, 2004.

Hydrogen Economy, resources must be applied to distributed technologies in order to meet the need from 2010 to 2030 (NRC/NAE, 2004).

Technical targets for hydrogen production, delivery, and dispensing have been set for 2010 and 2015. The targets are R&D milestones and are different for each feedstock based on factors like the feedstock characteristics and cost, the state of development of the technology, and the expected production unit size. A total of 54 projects are being funded during 2005 in the hydrogen production and delivery area. The total funding is $14,218,000, and projects range in size from $100,000 to $800,000.

The committee considers the interrelationships among the elements of the program to be an essential feature that is being very appropriately addressed both through the working relationships of the DOE program managers and through the coordination of program goals and objectives. However, the overall program would be improved by expanding the scope and frequency of the coordination efforts.

Recommendation. Even closer coordination with other DOE programs would be beneficial, including programs in the Office of Fossil Energy (FE) and the Office of Nuclear Energy, Science and Technology (NE). Representatives from FE and NE should be added to the fuel/vehicle pathway integration and hydrogen production technical teams, and FE and NE should be linked closely with systems analysis efforts in the Hydrogen, Fuel Cells and Infrastructure Technology program.

Recommendation. The committee believes that significant development efforts should be directed to distributed hydrogen production, including natural gas reforming and electrolysis, as well as exploratory work for other distributed generation options.

Coal and Carbon Sequestration

Coal is a viable option for producing hydrogen in very large, centralized plants. The United States has enough coal to make all of the hydrogen that the economy could need for more than 200 years. U.S. estimated recoverable reserves of coal are about 270 billion short tons (EIA, 1999). In addition, new and very promising gasification technology is under development that can lead to high-efficiency hydrogen manufacture at costs comparable with those of gasoline.[3] It would require over 100 million metric tons a year of hydrogen to fuel the

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[3] The *Hydrogen Economy* estimated the current cost of coal gasification to produce hydrogen at about $2.10/kg H and the future cost at about $1.70/kg H, whereas the gasoline-efficiency-adjusted cost of gasoline for a gasoline-fueled hybrid electric vehicle was estimated to be $2.12/kg H, assuming a petroleum cost of $30/barrel (NRC/NAE, 2004).

entire U.S. light-duty vehicle fleet by 2050, assuming that hydrogen fuel cell development is successful and meets current goals.

However, in a CO_2-constrained world, managing the increased CO_2 emissions from coal could become a significant barrier to its use. Since it is hard at the present time to imagine a long-term hydrogen economy in the United States without coal as a major hydrogen feedstock, the CO_2 issues must be overcome. This is particularly true when the volume of hydrogen required to significantly reduce oil imports and CO_2 emissions is considered.

To put the CO_2 issue into perspective, 6 gigatons (Gton)/year of CO_2 are emitted in the United States, 1.7 Gton of it from transportation. If coal is used to supply the hydrogen-fueled fuel cell vehicle fleet in 2050 (NRC/NAE, 2004), the CO_2 produced for transportation alone would be 6 Gton/year. Thus, CO_2 must be reduced or removed from coal plant emissions. This could potentially be accomplished through CCS—also called carbon sequestration—which involves separating and capturing the CO_2 at the plant, transporting the CO_2 to a disposal location, and storing it underground in depleted reservoirs, coal seams, or saline aquifers.

There are many questions to answer about CCS technology and its environmental impact before it can be concluded that CCS will be successful in managing the CO_2 produced when coal is the source of hydrogen for transportation. For example, the mass of CO_2 that would have to be transported by pipeline would be twice the mass of natural gas transported today. This presents huge infrastructure issues. Also, CO_2 transport and storage present safety issues. In 1986, an 80 million cubic foot eruption of CO_2 in Cameroon killed 1,800 people. Another issue is that there must be tremendous subsurface capacity to be able to handle the high volumes of CO_2 that will be generated over the next several millennia, and they must be able to trap the CO_2 for hundreds of years. While most oil and natural gas reservoirs probably have sufficient trapping capability, they probably have a CO_2 capacity of only a few decades to about 100 years.[4] Saline aquifers and/or deep ocean storage will most likely be required, and very little is known about their suitability. Finally, the costs associated with high-volume CCS are completely unknown. CCS therefore has many issues to resolve before it can be concluded that coal is a viable feedstock for hydrogen in a carbon-constrained world (NRC/NAE, 2004).

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[4] Estimates of oil and gas reservoir capacities vary, but some estimate a range from about 25 billion tons to 40 or 50 billion tons of carbon in the United States (Beecy et al., 2002); also, G. Hill, "CO_2 capture project: Hydrogen production with geologic sequestration," Presentation to the Committee on Strategies and Alternatives for Future Hydrogen Production and Use on April 23, 2003. Emissions from light-duty vehicles are about 400 metric tons carbon/year in 2000, projected to increase to 700 metric tons carbon by 2050 assuming conventional gasoline-fueled vehicles only (NRC/NAE, 2004). Thus, light-duty vehicle CO_2 emissions might be sequestered in U.S. oil and gas reservoirs for anywhere from a few decades to about 100 years.

The CCS program at DOE is managed by FE. It is funded at \$50 million to \$60 million per year, with more long-term funding planned but not appropriated. The program contains core R&D programs and regional partnerships with industry that include field tests, environmental impact studies, public education programs, and systems studies.[5] The core R&D program includes capture and geological, terrestrial, and ocean sequestration. In addition, the program has a number of milestones, including a significant 2012 goal of predicting CO_2 storage capacities with a precision of ±30 percent. Thus, the program is broad and long term.

The CCS program appears to the committee to encompass most if not all of the areas required to make CCS successful or at least to determine if CCS could prevent high volumes of CO_2 from being added to the atmosphere by the use of coal. However, it is difficult to identify any ties between the CCS and HFCIT programs.

It is very important that a CCS systems team develop an understanding of how the CO_2 delivery infrastructure will be developed and ultimately configured. For example, what would be the best location for a coal plant relative to the associated hydrogen filling stations, the CO_2 sequestration sites, and the coal supply? Successfully dealing with the need for carbon sequestration is critically important to making coal and natural gas acceptable energy sources in a carbon-constrained world. Research in this area should be an integral part of the program.

Recommendation. DOE should create a CCS systems subteam (under the hydrogen production team) in the FreedomCAR and Fuel Partnership and make it part of the overall HFI.

Terrestrial and ocean environments are options that may provide effective carbon storage over long time periods. The HFI will have to understand the real capacity and trapping integrity of hydrocarbon reservoirs and coal seams by 2010 to 2012 in order to determine if funding for the hydrogen from coal program should continue.

Recommendation. The goal of ±30 percent precision in estimating CO_2 capacity should be focused on geological storage.

Recommendation. DOE should strengthen the ties between managers of the CCS effort at HFCIT and managers at FE by developing a specific CCS program for hydrogen within FE. In addition, DOE should increase the shared management responsibility of the CCS program between EERE and FE.

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[5] L. Miller and S. Klara, "Carbon capture and storage," Presentation to the committee on March 21, 2005.

HYDROGEN DELIVERY AND DISPENSING

The hydrogen delivery and dispensing goals are based on the need to transport hydrogen long distances from the point of production to the point of use. The goal for hydrogen delivery and dispensing is as follows:

> Advance research aimed at developing low-cost, safe, and energy efficient hydrogen delivery systems. Catalyze the development of hydrogen delivery technologies that enable the introduction and long-term viability of hydrogen as an energy carrier for transportation and stationary power.[6]

The current delivery options are pipelines or tank trucks (carrying liquefied or compressed hydrogen), along with intermediate storage tanks and processing equipment. Three important issues surround the distribution infrastructure: large overall energy use during delivery, uniform codes and standards, and right-of-way approvals. Hydrogen delivery at the dispensing sites or filling stations is complicated particularly because this is where the consumer interface with the hydrogen takes place. The only long-term solution to the delivery problem may be to transport the hydrogen in liquid or solid form, using chemical hydrides or methanol as carriers. Alternatively, the transition technologies, such as electrolysis, might continue to be used.

The principal challenge in the HFCIT program is to develop a hydrogen appliance (a device at the filling station that would convert, say, natural gas into hydrogen and dispense it to a vehicle) with demonstrated mass producibility and capable of operation in service stations and, possibly, homes. The appliance would have to operate reliably and safely with only periodic surveillance by relatively unskilled personnel (station attendants and consumers). It would be the critical component of the integrated, standardized fueling facilities essential for a hydrogen transition.

The system weight and volume requirements for production, delivery, and dispensing of hydrogen are not as constrained as they are for onboard vehicle hydrogen storage. Storage losses, energy efficiency, and rapid dispensing are shared needs that will need focus as new hydrogen storage materials and processes emerge. Although there is greater latitude in energy and gravimetric densities for hydrogen storage in stationary applications than for onboard vehicle applications, new materials and process solutions must be developed for stationary applications. Currently, such densities are approximately 1 Wh/L and 1 Wh/kg regardless of the application (stationary or onboard). For large-scale stationary applications, new storage mechanisms and/or processes have to be developed. Such developments will impact (positively) both applications. The Grand Challenge, recently funded hydrogen storage initiatives involving industry and academia, has just begun. Consequently, it is too early to predict its outcome.

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[6] G. Parks and M. Paster, “Delivery tech team,” Presentation to the committee on November 17, 2004.

However, unique storage issues in the chain from production to tank are likely to be found, which could lead to high costs and energy losses. (See Chapter 3, section on hydrogen storage, for a discussion of onboard hydrogen storage for vehicles.)

As discussed in Chapter 2, the learning demonstration programs are very important to validate current component and systems concepts and to uncover previously unknown issues. They will establish many system and engineering parameters for a complete operating hydrogen supply and fuel cell transportation system, especially for addressing the interfaces between the vehicle and the hydrogen fueling appliance, and between the appliance and the on-site production and/or refueling system.

Recommendation. The technical teams working on hydrogen production, delivery, dispensing, and storage should identify the unique R&D needs for hydrogen storage for production, as well as for delivery and dispensing, that are not being adequately addressed by the current project portfolio.

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5

Overall Assessment

This chapter presents an overall assessment of the FreedomCAR and Fuel Partnership, summarizing not only its main achievements thus far, but also the main barriers that remain before the goals of the program can be achieved. Many of these issues are discussed in the preceding chapters. The chapter ends with the committee's observations on the adequacy, balance, and funding of the program.

The committee believes that research in support of the Partnership's vision is justified by the potentially enormous beneficial impact for the nation. At this early stage, no insurmountable barriers to achievement of this vision have been identified, but several critical components of the program have been noted. Specific, quantitative technology and cost goals for 2010 and 2015 have been established by the technical teams. These goals bear on each important element of the program, and the current status of the program relative to these goals is discussed in the body of this report. In view of the large number of unknowns and the need for breakthroughs, the committee does not feel that it is appropriate or useful at this time to speculate on the probability of this program achieving its long-term vision according to its current plan. Funding levels and the consequent research results during the next few years should allow future reviews to make a more firmly based assessment.

MAJOR ACHIEVEMENTS AND TECHNICAL BARRIERS

Major Achievements

Identifying the major achievements associated with the FreedomCAR and Fuel Partnership is challenging, primarily owing to two factors that make this program different from most other government-sponsored programs: (1) many of the technical activities are continuations of activities that began under the Partnership for a New Generation of Vehicles (PNGV) program (or, in some cases, even before the PNGV) and (2) the program is envisioned to be a multidecade program involving not only many technologies but technological challenges ranging from those that will probably be solved soon to those that may never be solved. Even so, there are many noteworthy achievements, both technical and nontechnical, that should be acknowledged.

Nontechnical Achievements

Nontechnical achievements are extremely important, because they provide the mechanisms for pursuing hopefully successful outcomes to the technical challenges. Among the more significant of the nontechnical achievements are these:

- *The overall strategy and implementation plan*. The plan is well thought out and well executed.
- *Active and continuing participation by both energy companies and automobile manufacturers*. Such participation is essential for any hope of identifying and solving the most critical problems and, ultimately, reaching the long-term goals.
- *The formation of numerous expert technical groups (technical teams*). Experts from government and industry are working together to identify the needed research and help advance specific technologies.
- *The creation of a priority activity to minimize the potential negative impact of inconsistent, or nonexistent, codes and standards*. This often-neglected activity is essential for the success of any pathway to the widespread production, transportation, storage, and utilization of hydrogen as a transportation fuel.
- *The development of a well-considered, well-organized, and comprehensive plan*. The plan includes short-term, mid-term, and long-term goals as well as roadmaps—some complete, some still in draft form—for pursuing these goals.
- *The emergence of more comprehensive cost models*. Cost is a barrier to the widespread acceptance of virtually every new technology being pursued, so realistic, viable cost models are extremely important.
- *The decision to create hydrogen storage centers of excellence that are expected to be working this year (2005).*
- *The establishment of the International Partnership for the Hydrogen Economy*. This partnership is a worldwide collaboration on hydrogen technologies involving 15 countries and the European Commission.
- *The convening of workshops to address essentially all of the more challenging technologies in the program.*

- *The establishment of an independent hydrogen storage test facility at the Southwest Research Institute.*
- *The initiation of basic research programs.* Research has started on the direct production of hydrogen from biological systems and from solar energy, and work on high-temperature nuclear heat processes for hydrogen production is being expanded.

Technical Achievements

Modest evolutionary achievements are evident in every area of technology being pursued. The technology areas include those associated with the advanced internal combustion engine (ICE), hybrid electric vehicles (HEVs), and fuel cell vehicles, all of which loosely correlate with the short-term, mid-term, and long-term goals of the program. The achievements include these:

- Gaining a better understanding of low-temperature combustion in ICEs and of the processes that produce emissions through sophisticated experimentation. This better understanding could lead to higher efficiency as well as lower NO_x and particulate production for both advanced ICE and hybrid vehicles. Early tests at 20 percent power have shown NO_x and soot reductions of 90 percent and 20 percent, respectively.
- Developing effective computer codes for vehicle systems analysis. Clearly, the ability to perform virtual evaluations and comparisons is a desirable alternative to building and testing actual hardware and systems. Continuing improvement in modeling and systems analysis will benefit every aspect of the program.
- The TIAX cost model shows the projected cost of compressed hydrogen automotive fuel cell systems (high-volume production) has been lowered from $275/kW (2002) to $175/kW (2004). Note, however, that the committee has not been able to validate these TIAX projections and that questions exist about the absolute values.
- Lowering the projected cost of baseline 25-kW lithium ion battery systems from $1,750 and $70/kW (1999) to $1,200 and $48/kW (2003).
- Advances in many of the longer-term technologies associated with fuel cell components, onboard hydrogen storage, and electrochemical energy storage. Unfortunately, none of these advances is a breakthrough, and breakthroughs are clearly needed at some point for these technologies to become viable.

Technical Barriers

Technical barriers are difficult to quantify. The program is very broad: Efforts range from hydrogen production and distribution to mass-produced, fuel-cell-powered vehicles. Further, the timescale for achieving various program goals range from relatively near term to 20 years or more into the future. The truly formidable technical barriers are those associated with two long-term goals: the extensive use of hydrogen as a transportation fuel and making fuel cells a viable option for powering transportation systems. It should be noted that the long-term goals of the FreedomCAR and Fuel Partnership are "energy freedom," "environmental freedom," and "vehicle freedom" rather than hydrogen fuel and fuel cell power systems per se, but thus far, these are the only options being pursued to achieve those goals. The technical barriers arise in almost every aspect of achieving widespread distribution of affordable hydrogen and in almost every aspect of devising fuel cell technologies for eventual commercialization. However, impressive progress has already been made in these areas, and the timescale is such that much more progress can be expected.

Technical Barriers for Nearer-Term Goals

The nearer-term technical barriers are mainly those associated with improving ICE vehicles and greater market penetration for hybrid vehicles. Among the more significant of these barriers are the following:

- *Affordable lightweight, high-strength materials.* There have been several candidates to replace steel. The continuous casting of aluminum sheet has not been commercialized, and the cost of carbon fibers for the reinforcement of composites remains unacceptably high.
- *Improvements in the thermal efficiency of ICEs, with concurrent reductions in emissions and particulates.* Current experimental efforts are expanding our understanding of the low-temperature combustion processes applicable to both spark ignition and compression ignition engines, but the ultimate goals have not been met.
- *Lower cost, more compact electrochemical energy storage.* Batteries are essential components of most hybrid vehicles and are likely to be for fuel cell vehicles as well. They add weight and increase costs relative to nonhybrid vehicles. Current efforts are directed primarily at lithium batteries, which seem to have the most promise for the needed advancements.
- *Lower cost, more compact electric drive motors and power electronics.* Advances are needed to gain wider acceptance for hybrid vehicles and to hasten the deployment of fuel cell vehicles.
- *Hydrogen production technologies and infrastructure for potential transition to a widespread system featuring hydrogen as the fuel for transportation.*

Technical Barriers for Longer-Term Goals

Although it is possible that other alternative fuels and energy conversion technologies might emerge, the present vision is to realize the widespread environment-friendly production of affordable hydrogen for vehicles powered by affordable, driver-friendly fuel cell systems. The realization of the hydrogen vision appears to be necessary but not sufficient to ensure the emergence of mass-produced fuel cell vehicles. On the other hand, the hydrogen vision could conceivably be realized even if the goal of fuel-cell-powered vehicles is not, since hydrogen can be used to produce power in combustion engines. That makes the infeasibility of widespread and affordable hydrogen a primary (but certainly not the only) barrier to the success of fuel cell vehicles.

Barriers to Fuel Cells Other barriers to the successful deployment of fuel cell systems for transportation include cost and performance. The most recent cost projection, which assumes mass manufacture, is about $125/kW ($175/kW including compressed hydrogen storage), roughly four times the cost goal of $30/kW (not including hydrogen storage) (TIAX, 2004). A number of areas are being pursued for potential cost savings, including the reduction or replacement of precious metal catalysts; less expensive, more durable membrane materials; and reductions in other material and production costs for membrane-electrode assemblies.

Performance barriers generally include factors that would result in operational behaviors inferior to competing ICE vehicles. Among these are start-up times of 1 minute instead of 30 s; possible damage when vehicles are parked at subfreezing (–40°C) temperatures; slow transition times from idle to full power; and unacceptably short expected operational life.

While overcoming the barriers associated with costs and performance is a formidable task, there is no reason to believe they cannot be overcome. Indeed, research activities are under way and progress has already been recorded in each area. Further, the program timescale is long enough that carefully considered approaches to resolving the various issues can be undertaken.

Barriers Associated with Hydrogen At this point, virtually everything associated with the production, distribution, and onboard storage of hydrogen for personal transportation use faces significant barriers. Since hydrogen does not exist naturally in significant concentrations on Earth, it must be produced by extraction from other substances containing hydrogen, such as (but not limited to) hydrocarbons (natural gas, petroleum, coal, etc.) and water. Typically, extraction ensures that the energy produced will be less than the energy value of the source material plus the energy required to produce it. Thus the cost of hydrogen at the fueling station is, and is likely to remain, a barrier. Many biological and electrochemical processes are being pursued to reduce costs, but the technologies are very immature and the probability of success is unknown. Also of great concern is the CO_2 that would be produced when using fossil fuels, especially coal, as a feedstock.

Owing to hydrogen's extremely low energy density, its distribution is difficult and expensive. In cryogenic liquid form (which requires more energy and is even more expensive to produce than compressed gas), hydrogen requires nearly four times as many tanker trucks (assuming the same volume) or pipeline capacity as gasoline to transport the same energy value. Depending on pressure, the volume of compressed hydrogen gas needing to be transported could be 10 times as large. Thus, the transportation of hydrogen adds to the cost barrier posed by its production. Efforts are under way to make localized production a viable and lower-cost alternative to centralized production and long-distance transportation.

Onboard storage of hydrogen remains a significant barrier. Compressed gas at up to 350 bar (~5,000 psi) is routinely used for demonstration vehicles. However, this either limits vehicle range or requires much larger fuel storage tanks than does gasoline to achieve equivalent range. Higher pressure tanks have been developed, up to 700 bar (10,000 psi), which increases range, but at a cost. This cost includes heavier, more costly tanks and additional energy for compressing the hydrogen. Metal hydrides, carbon materials, and other possibilities for storing and releasing higher fractions of hydrogen are being investigated and could reduce the storage barrier.

As with fuel cells, the timescale for resolving the many issues surrounding the use of hydrogen as a transportation fuel covers many years. However, the inability to resolve these issues could prove to be the most difficult barrier facing fuel cell vehicles.

ADEQUACY, BALANCE, AND FUNDING OF THE PROGRAM

DOE's total FY05 budget for hydrogen-related activities (hydrogen technology and fuel cells)—the Hydrogen Fuel Initiative—is about \$225 million, while that for vehicle technologies—the FreedomCAR Initiative—is about \$85 million. Thus, the total funding of relevance to the charter of the committee is about \$310 million. This is depicted in Figure 5-1. The detailed allocation of these funds by major element in the hydrogen program is shown in Table 5-1.

This level of expenditure is consistent with the priorities and recommendations of *The Hydrogen Economy* (NRC/NAE, 2004) and is also consistent with the President's commitment of \$1.7 billion over 5 years (FY04-FY08) in his 2003 State of the Union message. The emphasis is on R&D activities related to fuel cell materials and components, hydrogen production and delivery technologies, and hydrogen storage materials. The budget also includes \$29.2 million for basic science, which is consistent with *The Hydrogen Economy*, which recommended increased emphasis on the fundamental science related to hydrogen and fuel cell technologies. The Office of Science program just getting started was not reviewed in this study, but future reviews will assess its adequacy.

The FY05 funding for the DOE FreedomCAR and Vehicle Technologies (FCVT) program activity on related programs is \$85.3 million (Figure 5-1) and is allocated as shown in Table 5-2. Funding is highest for hybrid and electric propulsion (ca. \$40 million), reflecting their critical importance to both advanced

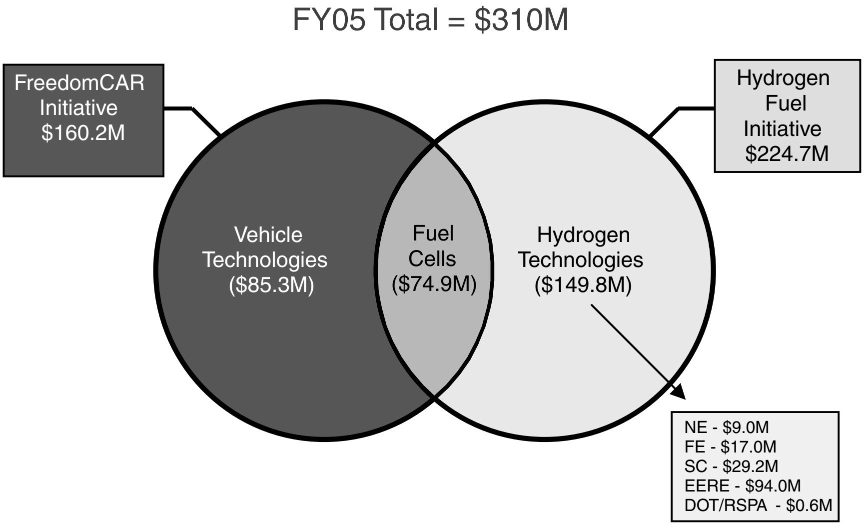

FIGURE 5-1 FreedomCAR and Fuel Partnership funding for FY05 (rounded numbers based on Tables 5-1 and 5-2). SOURCE: Adapted from DOE.

ICEs and fuel cell vehicles. The vehicle program also includes substantial funding for combustion and emissions control (ca. $19 million) and materials technologies (ca. $18.5 million). Education efforts include hydrogen education, which develops and distributes training materials to target audiences; the Graduate Automotive Technology Education (GATE) activity, creating GATE centers of excellence and multidisciplinary curricula and providing funds for research fellowships; and Challenge X, in which university teams partner with General Motors to integrate advanced vehicle technologies and appropriate fuels to minimize the use of petroleum.

The FCVT program is also responsible for the 21st Century Truck (21st CT) Partnership, a partnership similar to the FreedomCAR and Fuels Partnership but involving primarily heavy truck manufacturers. The budget for the 21st CT in FY05 is almost identical to the FCVT budget for FreedomCAR ($86 million versus $89.7 million), and the priority areas are similar, such that, overall, hybrid and electric propulsion received $45 million; advanced ICE/combustion and emissions, $54 million; and materials, $40 million.

The breakdown of the approximately $85 million for FY05 that comes from the FCVT program is national laboratories, 47 percent; industry, 40 percent; federal, 2 percent; consortia, 5 percent; universities, 4 percent; and automotive companies (OEMs), 2 percent. Funding for OEMs is exclusively for competitively selected combustion and emissions control R&D, where each OEM is part of a team that may include engineering companies, suppliers, and energy compa-

TABLE 5-1 DOE Funding for Hydrogen and Fuel Cell Technologies (thousands of dollars)

Program Area and Funding Source	FY04	FY05	FY06 Request
Fuel cell technology (Interior appropriations)			
Transportation systems	7,317	7,495	7,600
Distributed energy systems	7,249	6,902	7,500
Fuel processor R&D	14,442	9,721	9,900
Stack component R&D	24,551	32,541	34,000
Technology validation	9,828	17,750	24,000
Technical program management support	395	535	600
Subtotal fuel cell	63,782	74,944	83,600
Hydrogen technology (Energy and Water appropriations)			
Production and delivery R&D (EE)	10,083	14,218	32,173
Storage R&D (EE)	13,174	23,654	29,890
Safety, codes and standards (EE)	5,615	5,954	13,121
Infrastructure validation (EE)	5,784	9,484	14,945
Systems analysis (EE)	1,372	3,404	7,084
Education	2,417	0	1,881
Earmarks (EE)	41,967	37,292	0
Subtotal EERE hydrogen	80,412	94,006	99,094
Total EERE hydrogen and fuel cells	144,194	168,950	182,694
Nuclear energy (NE)	6,201	8,929	20,000
Fossil energy (FE)	4,879	17,085	22,000
Science (SC)	0	29,183	32,500
Total DOE hydrogen program	155,274	224,147	257,194
Total Department of Transportation	555	549	2,350
Total Hydrogen Fuel Initiative	155,829	224,696	259,554

SOURCE: Provided by DOE (on April 26, 2005) in response to a request from the committee. Note that "Interior appropriations" refers to the Congressional Subcommittee on Interior and Related Agencies. "EE" refers to the energy efficiency part of the Office of Energy Efficiency and Renewable Energy.

nies. The amount indicated for OEMs (2 percent) includes only the funding for automotive company tasks.

FY05 funding for the hydrogen program of about $225 million may be broken down as follows: national laboratories, 28 percent; industry, 32 percent; universities, 14 percent; automotive OEMs, 5 percent; energy companies, 2 percent; and congressional earmarks of 19 percent. The funding of automotive OEMs is for the vehicle learning demonstrations and includes only the demonstration associated with automotive company tasks. The learning demonstrations entail 50 percent private sector cost sharing, but the $225 million budget and the associated percentage breakdown includes only DOE funds.[1]

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[1] Information on funding breakdown supplied to the committee on January 19, 2005, in response to questions submitted by the committee to DOE.

TABLE 5-2 DOE Funding Supporting FreedomCAR and Fuel Partnership Goals in the Office of FreedomCAR and Vehicle Technologies (thousands of dollars)

Program Area Request	FY04	FY05	FY06
Vehicle systems	3,659	4,486	4,800
Ancillary systems	1,155	1,268	1,300
Simulation and validation	2,504	3,218	3,500
Innovative concepts: Graduate Automotive Technology Education (GATE)	494	493	500
Hybrid and electric propulsion	38,538	39,885	43,335
Energy storage	22,338	23,073	25,700
Advanced power electronics	13,181	13,168	13,900
Subsystem integration and development	3,019	3,644	3,735
Combustion and emissions control	18,640	18,775	20,765
Materials technologies	18,980	18,437	21,000
Propulsion materials	2,766	1,972	2,000
Lightweight materials	16,214	16,465	19,000
Fuels technologies	4,104	1,367	7,000
Advanced petroleum-based fuels	3,808	0	3,000
Non-petroleum-based fuels	296	1,367	4,000
Technology introduction	889	986	1,300
Technical/program management support	854	853	1,200
Biennial peer review of FreedomCAR	494	0	500
Total	86,652	85,282	100,400

SOURCE: Provided by DOE (on April 26, 2005) in response to a request from the committee. Note that these appropriations are through the Congressional Subcommittee on Interior and Related Agencies.

While the committee endorses the overall size and relative allocation strategy in the hydrogen program budget, there are four areas of concern. First, as discussed in Chapter 2, congressionally directed activities (earmarks) account for 40 percent of the hydrogen technology budget (about $37 million out of $94 million) in FY05 and 16 percent of the total hydrogen budget. The earmarks divert funds from required R&D areas in the program, severely restricting the ability of DOE to effectively manage the program, and have delayed several critical elements of the program, including hydrogen storage and safety.

The second area of concern is carbon sequestration. While large-scale carbon sequestration is not directly within the purview of this committee's study, its feasibility will essentially determine the likelihood of sourcing hydrogen from coal and/or natural gas in a future carbon-constrained environment and consequently affects both the economics and the viability of hydrogen as a future fuel (energy carrier). DOE needs to assess the resources being devoted to this activity in the light of its criticality to the success of the program.

The third area of concern is the balance between basic research and applied development. As illustrated in Figure 5-2, 13 percent of hydrogen program spending is on basic research, with the remaining 87 percent devoted to applied R&D and demonstrations. To some extent, the latter activity will disclose areas requiring more fundamental research and drive the research agenda and funding, but the committee cautions against overemphasis on development (which is usually best performed by the private sector) at the expense of basic research.

The fourth area of concern is the process of innovation. Historically, in fields as disparate as microelectronics and medical devices, pathbreaking commercial innovations have come from start-up companies at least as often as from the industry incumbents. The FreedomCAR and Fuel Partnership should create opportunities for start-up companies to participate in the commercialization process, either independently or in partnership with one of the member companies. This would lead to a more balanced program than one relying on industry incumbents alone.

In summary, there are four areas of concern in the hydrogen program, namely congressional earmarks, carbon sequestration, spending that may be skewed too

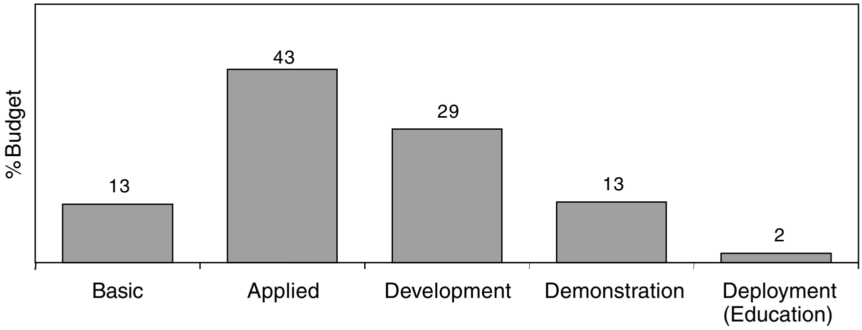

FIGURE 5-2 Distribution of funding for hydrogen technology and fuel cell activities for FY05 by RD&D category. Note that "education" supports technology transfer and adoption. SOURCE: R.F. Moorer, "FreedomCAR and Fuel Partnership peer review," Presentation to the committee on November 17, 2004.

much toward development, and the process of innovation. The committee strongly supports the HEV and advanced ICE spending but, as noted under "Structural Materials," it suggests that some of the materials spending ($19 million in FreedomCAR, $20 million in 21st CT) be reallocated to high-priority research areas.

Finally, the program involves both short-term goals that are related to hydrocarbon-fueled vehicles, used during a transition period, and much longer-term goals aimed at enabling "a clean and sustainable transportation energy future." The committee considers the current split of funding between the long-term and shorter-term goals to be appropriate. Hydrogen-related activities absorb approximately 70 percent of the funds. The remaining funds support the development of transition technologies, where in many cases cost is the most significant barrier.

REFERENCE

NRC/NAE (National Research Council/National Academy of Engineering). 2004. *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*. Washington, D.C.: The National Academies Press.

Appendixes

Appendix A

U.S. Council for Automotive Research (USCAR) Consortia

The U.S. Council for Automotive Research (USCAR) has the following consortia with the indicated missions.[1]

- Automotive Composites Consortium (ACC): To conduct joint research programs on structural polymer composites in precompetitive areas that leverage existing resources and enhance competitiveness.
- Electrical Wiring Component Applications Partnership (EWCAP): To permit and encourage cooperative research and development, which includes the joint sharing of technologies and resources to develop common electrical connection systems.
- Environmental Research Consortium (ERC): To improve understanding of the environmental impact of vehicle and manufacturing emissions.
- Low Emissions Technologies R&D Partnership (LEP): To coordinate research and development efforts on emissions control technologies through exchange of technical information and licensing of promising technical breakthroughs.
- Occupant Safety Research Partnership (OSRP): To conduct or direct precompetitive research and development on crash-test dummies and related areas such as modeling, instrumentation, data management and reduction, and subsystem safety test development.
- United States Advanced Battery Consortium (USABC): To pursue research and development of advanced energy systems capable of provid-

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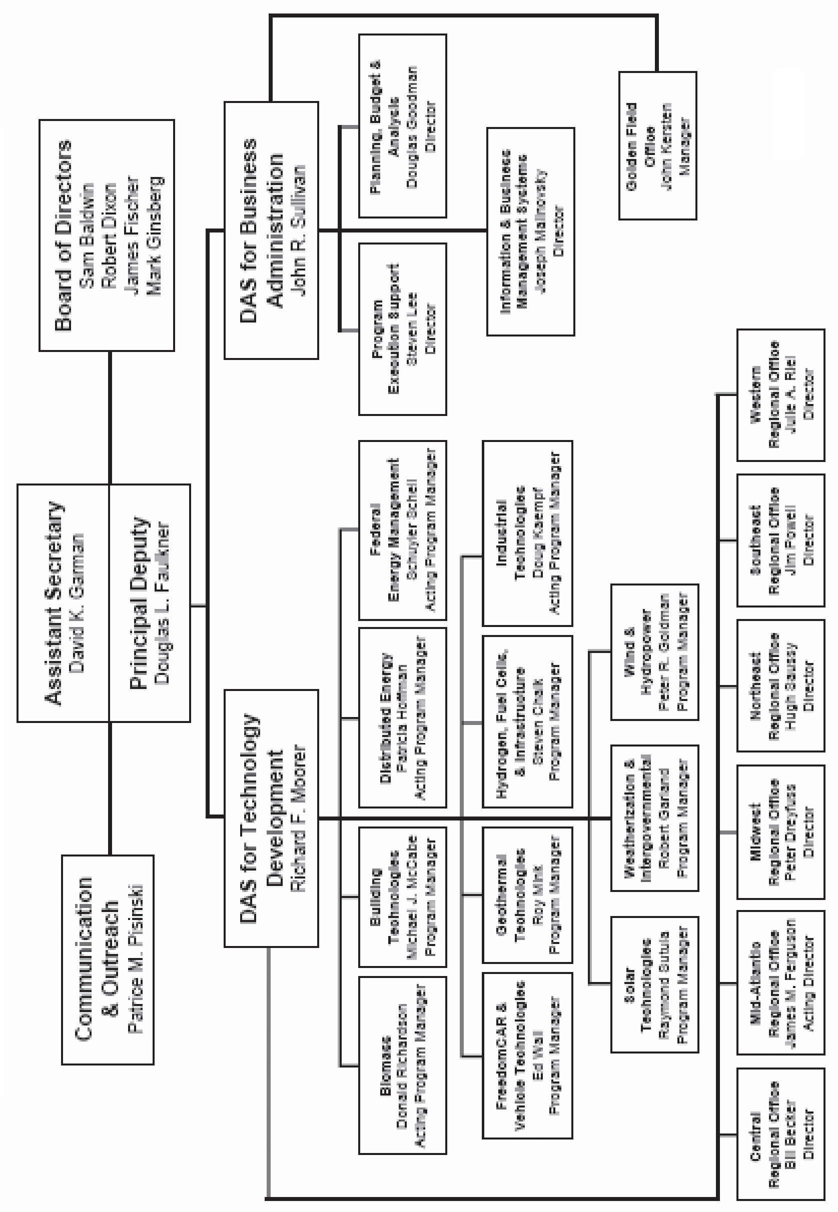
[1] Information on USCAR consortia available on the Web at <http://www.uscar.org/consortia&teams/consortiahomepages/cons&ttINDEX.htm>.

ing future generations of electric vehicles with significantly increased range and performance.

- United States Automotive Materials Partnership (USAMP): To conduct vehicle-oriented research and development in materials and materials processing to improve the competitiveness of the U.S. auto industry.
- Vehicle Recycling Partnership (VRP): To promote an integrated approach to the technical and economic feasibility of recycling for vehicles built in North America for the global marketplace.

Appendix B

Organization Chart for the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (as of August 2004)


Board of Directors
Sam Baldwin
Robert Dixon
James Fischer
Mark Ginsberg
Assistant Secretary
David K. Garman
Principal Deputy
Douglas L. Faulkner
Communication & Outreach
Patrice M. Pisinski
DAS for Business Administration
John R. Sullivan
Planning, Budget & Analysis
Douglas Goodman
Director
Program Execution Support
Steven Lee
Director
Information & Business Management Systems
Joseph Malinovsky
Director
Golden Field Office
John Kersten
Manager
DAS for Technology Development
Richard F. Moorer
Federal Energy Management
Schuyler Schell
Acting Program Manager
Distributed Energy
Patricia Hoffman
Acting Program Manager
Building Technologies
Michael J. McCabe
Program Manager
Biomass
Donald Richardson
Acting Program Manager
Industrial Technologies
Doug Kaempf
Acting Program Manager
Hydrogen, Fuel Cells, & Infrastructure
Steven Chalk
Program Manager
Geothermal Technologies
Roy Mink
Program Manager
FreedomCAR & Vehicle Technologies
Ed Wall
Program Manager
Wind & Hydropower
Peter R. Goldman
Program Manager
Weatherization & Intergovernmental
Robert Garland
Program Manager
Solar Technologies
Raymond Sutula
Program Manager
Western Regional Office
Julie A. Riel
Director
Southeast Regional Office
Jim Powell
Director
Northeast Regional Office
Hugh Saussy
Director
Midwest Regional Office
Peter Dreyfuss
Director
Mid-Atlantic Regional Office
James M. Ferguson
Acting Director
Central Regional Office
Bill Becker
Director

Appendix C

Biographical Sketches for Committee Members

Craig Marks (NAE), *chair*, is chairman of the board of trustees of Altarum, a not-for-profit scientific R&D organization engaged in the application of advanced information technology to solve national defense, health care, and environmental problems. For 27 years he worked at General Motors in engineering and management positions. He subsequently became vice president of Engineering and Technology for the TRW Automotive Sector and then vice president of Technology and Productivity for the Allied Signal Automotive Sector. In the latter position he headed an automotive research and development center and was responsible for the staff functions of manufacturing; quality, health, safety, and environment; and communications. After retiring, Dr. Marks became an adjunct professor at the University of Michigan, with a joint appointment in the College of Engineering and the School of Business Administration, where he helped found the Joel D. Tauber Manufacturing Institute. He has served on a number of NRC committees, including as chairman, Committee on Review of the Research Program of the Partnership for a New Generation of Vehicles and Committee for the Review of the Intelligent Vehicle Initiative—Phase 2. He is a member of the National Academy of Engineering and a fellow of the Society of Automotive Engineers (SAE) and the Engineering Society of Detroit. Dr. Craig holds B.S., M.S., and Ph.D. degrees in mechanical engineering from the California Institute of Technology.

Peter Beardmore (NAE) was director, Ford Research Laboratory, Ford Motor Company, prior to his retirement in August 2000. His primary research interests are in the deformation and fracture of materials, including extensive research experience in metals, polymers, and composites, and he has published over 83 technical articles. He is a recognized international authority on composite materials and on the application of new materials to automotive structures. His management responsibilities at Ford covered a wide area of research activities relative to the automotive industry, including materials, environmental chemistry, sensor technologies, automotive catalyst development, and the application of modern analytical techniques. He is a member of the American Society for Materials (ASM), The Metallurgical Society (TMS) of AIME, and the Engineering Society of Detroit (ESD). He was elected a fellow of ASM in 1989 and a fellow of ESD in 1991. In 1992, he was elected a member of the National Academy of Engineering. He holds a B.Met. in metallurgy from the University of Sheffield and a Ph.D. in metallurgy from the University of Liverpool.

David L. Bodde serves as a professor and senior fellow at Clemson University. There, he directs innovation and policy at the International Center for Automotive Research. Prior to joining Clemson University, Dr. Bodde held the Charles N. Kimball Chair in Technology and Innovation at the University of Missouri in Kansas City. Dr. Bodde serves on the board of directors of several energy and technology companies, including Great Plains Energy, the Commerce Funds, and EPRI Solutions. His executive experience includes vice president, Midwest Research Institute; assistant director of the Congressional Budget Office; and deputy assistant secretary in the U.S. Department of Energy. He is a member of the NRC's Board on Energy and Environmental Systems and recently served on the Committee on Alternatives and Strategies for Future Hydrogen Production and Use. He was once a soldier and served in the Army in Vietnam. He has a doctorate in business administration from Harvard University, M.S. degrees in nuclear engineering (1972) and management (1973), and a B.S. from the United States Military Academy.

Glenn A. Eisman is director of the Center for Fuel Cell and Hydrogen Research and professor of materials science and engineering at Rensselaer Polytechnic Institute. Dr. Eisman is also principal partner of Eisman Technology Consultants, LLC. His previous positions include chief technology officer, Plug Power, Inc.; technical leader, The Advanced Materials Program, Central Research and New Businesses, Dow Chemical Company; and project leader, discovery research R&D and inorganic chemical research, Dow Chemical Company. Dr. Eisman has extensive experience in R&D and product development for fuel cells, hydrogen technologies, electrochemical engineering, physical and inorganic solid state chemistry, and new technology commercialization and business development. He received the Inventor of the Year Award from Dow Chemical Co. (1993) and is a member of the Electrochemical Society. He received a B.S. in chemistry from Temple University and a Ph.D. in physical inorganic chemistry from Northeastern University.

David Foster is the Phil and Jean Myers Professor of Mechanical Engineering at the University of Wisconsin, where he has been a faculty member since completion of his Ph.D. He teaches and conducts research in thermodynamics, fluid mechanics, and chemical kinetics and emission formation processes in internal combustion engines. He is an active member of the Engine Research Center (ERC), of which he served as the director from 1994 through 1999. The ERC has won multiple Center-of-Excellence competitions for engine research and is world renowned for its accomplishments and its extensive facilities for research on internal combustion engines. He is now codirector of the General Motors–ERC Collaborative Research Laboratory, which was established in 2003.

Professor Foster's research activities focus on the experimental investigation of engine combustion systems and the incorporation of simplified or phenomenological models of emission formation processes into engineering simulations. Most recently he initiated work on understanding the impacts of fuels and combustion processes on the detailed characterization of diesel engine particulate matter, an important basis for understanding and mitigating the health effects of engine emissions and for developing exhaust gas aftertreatment systems.

Professor Foster is an active consultant for industries both here and abroad. He has published extensively in journals of the professional societies serving the combustion and internal engine communities. He is a recipient of the Ralph R. Teetor Award, the Forest R. McFarland Award, and the Lloyd L. Withrow Distinguished Speaker Award of the Society of Automotive Engineers. Dr. Foster is a registered professional engineer in the State of Wisconsin and has won departmental, engineering society, and university awards for his classroom teaching. He served as a member of the NRC Committee on Review of the Research Program of the Partnership for a New Generation of Vehicles for 6 years. He is a fellow of SAE. He received his B.S.M.E. and M.S.M.E. from the University of Wisconsin, Madison, and his Ph.D. in mechanical engineering from the Massachusetts Institute of Technology (MIT).

John B. Heywood (NAE) is Sun Jae Professor of Mechanical Engineering at the Massachusetts Institute of Technology (MIT) and director of the Sloan Automotive Laboratory. Dr. Heywood's research has focused on understanding and explaining the processes that govern the operation and design of internal combustion engines and their fuels requirements. Major research activities include engine combustion, pollutant formation, and operating and emissions characteristics and fuel requirements of automotive and aircraft engines. He has served on a number of NRC committees, including the Committee on Review of the Research Program of the Partnership for a New Generation of Vehicles. He has consulted for many companies in the automotive and petroleum industries and for government organizations. He has received many awards, from the American Society of Mechanical Engineers, the British Institution of Mechanical Engineers, and the Society of Automotive Engineers for his research contributions. He has a Ph.D. in mechanical engineering from MIT, an Sc.D. from Cambridge University, and honorary doctorates from Chalmers University of Technology (Sweden) and City University (U.K.).

John G. Kassakian (NAE) is a professor of electrical engineering and director of the MIT Laboratory for Electromagnetic and Electronic Systems. His expertise is in the use of electronics for the control and conversion of electrical energy, industrial and utility applications of power electronics, electronic manufacturing technologies, and automotive electrical and electronic systems. Prior to joining the MIT faculty, he served in the U.S. Navy. Dr. Kassakian is on the boards of directors of a number of companies and has held numerous positions with the Institute of Electrical and Electronics Engineers (IEEE), including founding president of the IEEE Power Electronics Society. He is a member of the NAE, a fellow of the IEEE, and a recipient of the IEEE's William E. Newell Award for Outstanding Achievements in Power Electronics (1987), the IEEE Centennial Medal (1984), and the IEEE Power Electronics Society's Distinguished Service Award (1998). He has an Sc.D. in electrical engineering from MIT.

Harold H. Kung is professor of chemical and biological engineering at Northwestern University. His areas of research include surface chemistry, catalysis, and chemical reaction engineering. His professional experience includes work as a research chemist at E.I. du Pont de Nemours & Co. He is a recipient of the P.H. Emmett Award and the Robert Burwell Lectureship Award from the North American Catalysis Society, the Herman Pines Award of the Chicago Catalysis Club, the Cross-Canada Lectureship of the Catalysis Division of the Chemical Institute of Canada, the John McClanahan Henske Distinguished Lectureship of Yale University, and the Olaf A. Hougen Professorship at the University of Wisconsin, Madison. He has a Ph.D. in chemistry from Northwestern University.

James J. MacKenzie is a senior fellow in the World Resources Institute's (WRI's) Climate, Energy, and Pollution program. Prior to joining WRI, MacKenzie was a senior staff scientist, Union of Concerned Scientists; senior staff member for energy, President's Council on Environmental Quality (CEQ); and a member of the joint scientific staff of the Massachusetts and national Audubon societies. Much of his recent research and analysis has focused on transportation technologies and the impact of the transportation system on the environment. He is coauthor (transportation chapter) of *Frontiers of Sustainability: Environmentally Sound Agriculture, Forestry, Transportation, and Power Production*; author of *Climate Protection and the National Interest*; *Oil as a Finite Resource: When is Global Production Likely to Peak?*; and *The Keys to the Car: Electric and Hydrogen Vehicles for the 21st Century*. He is also coauthor of *Car Trouble*, a book on the impacts of cars on the American scene, and of several major WRI reports, including an analysis of the subsidies to motor vehicles in the United States, the impacts of global motor vehicle use on climate change, and the effects of multiple air pollutants on U.S. forests and crops. He has also completed a policy report exploring the linkages among the problems of climate change, air pollution, and national energy security. Dr. MacKenzie received his Ph.D. in physics from the University of Minnesota and completed postgraduate work at the Los Alamos and Argonne National Laboratories and MIT before joining the Audubon Society.

Christopher L. Magee (NAE) has been with MIT since January 2002 and has a joint appointment as a professor of the practice in the Engineering Systems Division and Mechanical Engineering. He also directs a multidisciplinary research center (the Center for Innovation in Product Development). Before Dr. Magee joined MIT, he had more than 35 years of experience at Ford Motor Company, beginning in the Scientific Research Laboratory and progressing through a series of management positions to executive director of Programs and Advanced Engineering. The latter position had global responsibility for all major technically deep areas involved in Ford's Product Development Organization and consisted of about 7,000 people located in the United States, the United Kingdom, and Germany.

At the beginning of his career, Dr. Magee made major contributions to understanding the transformation, structure, and strength of ferrous materials. He was internationally recognized for this work and in his early 30's won the Howe Medal (best paper of the year in Trans-ASM/AIME) and, one year later, the Alfred Nobel Award (given by the ASCE for the single best contribution by someone under 33 from candidates from all five "founding" engineering societies (IEEE, ASME, AIME, AIChE, and ASCE). Dr. Magee then made contributions to lightweight material development, including dual-phase and other HSLA steels (including new stamping technology), and led their implementation at Ford. Simultaneously, Dr. Magee pioneered experimental work on high-rate structural collapse aimed at vehicle crashworthiness. During this latter period, Dr. Magee also led the work that initiated Ford's computer-aided engineering for structural and occupant simulation for crashworthiness. Dr. Magee has led (from 1981 on) efforts at Ford to adapt systems engineering to the modern automotive design process. In addition, he was instrumental in developing new approaches to the program creation process at Ford and from 1987 through 1999 had the technical lead for all major Ford product concept efforts.

Dr. Magee is a member of the National Academy of Engineering (since 1997), a fellow of ASM, and a participant in major NRC studies, ranging from design research to materials research. Dr. Magee received his B.S. and Ph.D. from Carnegie Mellon University and an M.B.A. from Michigan State University.

Michael P. Ramage (NAE) is retired executive vice president, ExxonMobil Research and Engineering Company. Previously he was director, executive vice president, and chief technology officer of Mobil Oil Corporation. He held a number of positions at Mobil, including general manager of exploration and producing research, development, and technical services; vice president of engineering; manager of process development; and president of Mobil Technology Company. He has broad experience in many aspects of the petroleum industry, including R&D, chemical processes, and capital project management. He is a director of the American Institute of Chemical Engineers. He served on a number of university visiting committees and is a member of a number of professional societies. He recently served as chairman of the NRC Committee on Alternatives and Strategies for Future Hydrogen Production and Use. He is a member of the National Academy of Engineering and serves on the NAE Council. He has B.S., M.S., and Ph.D. degrees in chemical engineering from Purdue University.

Vernon P. Roan is retired director of the Center for Advanced Studies in Engineering and professor of mechanical engineering at the University of Florida, where he has been a faculty member for more than 30 years. Since 1994, he has also been the director of the University of Florida Fuel Cell Research and Training Laboratory. Previously, he was a senior design engineer with Pratt & Whitney Aircraft. Dr. Roan, who has more than 25 years of R&D experience, is currently developing improved modeling and simulation systems for a fuel-cell bus program and working as a consultant to Pratt & Whitney on advanced gas-turbine propulsion systems. His research at the University of Florida has involved both spark-ignition and diesel engines operating with many alternative fuels and advanced concepts. With groups of engineering students, he designed and built a 20-passenger diesel-electric bus for the Florida Department of Transportation and a hybrid electric urban car using an internal combustion engine and lead-acid batteries. He has been a consultant to the Jet Propulsion Laboratory, monitoring its electric and hybrid vehicle programs. He organized and chaired two national meetings on advanced vehicle technologies and a national seminar on the development of fuel-cell-powered automobiles and has published numerous technical papers on innovative propulsion systems. He was one of the four members of the Fuel Cell Technical Advisory Panel of the California Air Resources Board, which issued a report in May 1998 on the status and outlook for fuel cells for transportation applications. Dr. Roan received a B.S. in aeronautical engineering and an M.S. in engineering from the University of Florida and a Ph.D. in engineering from the University of Illinois.

Bernard Robertson (NAE) is president of BIR1, LLC, an engineering consultancy specializing in transportation and energy matters that he founded in January 2004, upon his retirement from DaimlerChrysler Corporation. During the latter part of his 38-year career in the automotive industry, Mr. Robertson was elected an officer of Chrysler Corporation in February 1992. He was appointed senior vice president coincident with the merger of Chrysler Corporation and Daimler-Benz AG in November 1998 and was named senior vice president of Engineering Technologies and Regulatory Affairs in January 2001. In his last position, he led the Liberty and Technical Affairs Research group; Advanced Technology Management and

FreedomCAR activities; and hybrid electric, battery electric, fuel cell, and military vehicle development. In addition, he was responsible for regulatory analysis and compliance for safety and emissions. Mr. Robertson holds an M.B.A. from Michigan State University, a master's degree in automotive engineering from the Chrysler Institute, and a master's degree in mechanical sciences from Cambridge University, England. He is a member of the National Academy of Engineering, a fellow of the Institute of Mechanical Engineers (U.K.), a chartered engineer (U.K.), and a fellow of the Society of Automotive Engineers.

R. Rhoads Stephenson is currently a technology consultant. Previously, he held a number of positions at the Jet Propulsion Laboratory (JPL), the National Highway Traffic Safety Administration (NHTSA), and Martin Marietta Corporation. At JPL, these included deputy director and acting director, Technology and Applications Programs; manager, Electronics and Control Division; deputy manager, Control and Energy Conversion Division; and manager of the Systems Analysis Section. He also served as associate administrator for R&D at NHTSA and while at Martin Marietta worked on energy conversion devices for space power. He has been a consultant to the Motor Vehicle Fire Research Institute, has been providing peer reviews of automotive safety issues, and recently published a number of papers on crash-induced fire safety issues with motor vehicles, including hydrogen-fueled vehicles. He brings extensive expertise in vehicle safety analysis, advanced technology systems, energy conversion technologies, and energy and environmental analysis. He has B.S., M.S. and Ph.D. degrees in mechanical engineering from Carnegie Mellon University.

Kathleen C. Taylor (NAE) is retired director of the Materials and Processes Laboratory at General Motors Research and Development and Planning Center. Dr. Taylor was simultaneously chief scientist for General Motors of Canada, Ltd. Earlier, she was department head for physics and physical chemistry and department head for environmental sciences. Currently Dr. Taylor serves on the board of the North American Catalysis Society, the Advanced Photon Source scientific advisory committee at Argonne National Laboratory, the advisory board for the Nanoscale Science and Engineering Center at Columbia University, the board of directors of the National Inventors Hall of Fame, and the DOE Basic Energy Sciences Advisory Committee. Dr. Taylor was awarded the Garvan Medal from the American Chemical Society. She is a member of the National Academy of Engineering. She is a fellow of SAE International and the American Association for the Advancement of Science. She has been president of the Materials Research Society and chair of the board of directors of the Gordon Research Conferences. She has expertise in R&D management, fuel cells, batteries, catalysis, exhaust emission control, and automotive materials. She received an A.B. in chemistry from Douglass College and a Ph.D. in physical chemistry from Northwestern University.

Brijesh Vyas is currently a consultant to Bell Laboratories-Lucent Technologies. Previously, he was technical manager of the Energy Conversion Technology Group at Bell Labs-Lucent Technologies. Before that, he held positions at Brookhaven National Laboratory and the Technical University of Denmark. His primary responsibility is R&D of advanced materials and technologies for high-energy-density batteries for portable applications and forward-looking work on energy storage systems for standby applications, including batteries, flywheels, fuel cells, and photovoltaic devices. He has led the development of rechargeable lithium batteries and nickel-cadmium and nickel-hydrogen batteries. As part of the development of battery technology, he is responsible for technology transfer to manufacturing and interactions between marketing, legal, and manufacturing organizations and battery users. He served on the NRC Committee to Review the U.S. Advanced Battery Consortium's Electric Vehicle Battery R&D Project Selection Process. His expertise includes materials and electrochemistry. He received his Ph.D. in materials science from the State University of New York, Stony Brook.

Appendix D

Presentations at Committee Meetings

1. COMMITTEE MEETING, SOUTHFIELD, MICHIGAN, NOVEMBER 17-18, 2004

Program Vision: Auto Industry Perspective
William L. Peirce, General Motors

Energy Partner Perspective
Joe Kaufman, ConocoPhillips

FreedomCAR and Fuel Partnership
Steve Chalk, Richard Moorer, Ed Wall, U.S. Department of Energy

Vehicle Systems Analysis Technical Team
Lee Slezak, U.S. Department of Energy
Larry Laws, General Motors

Advanced Combustion Engines and Emission Control (ACEC) Activities
Ken Howden, U.S. Department of Energy
Richard Peterson, General Motors

Electrochemical Energy Storage
Tien Duong, U.S. Department of Energy
Ahsan Habb, General Motors

Fuel Cell Technical Team
Valri Lightner, U.S. Department of Energy
Fred Wagner, General Motors

Electrical and Electronics Technical Team
Susan Rogers, U.S. Department of Energy
Vijay Garg, Ford

Hydrogen Storage Joint Technical Team
Sunita Satyapal, U.S. Department of Energy
Scott Jorgensen, General Motors
Farshad Bavarian, ChevronTexaco

Materials Technical Team
Joe Carpenter, U.S. Department of Energy
Bob McCune, Ford

Hydrogen Production Tech Team
Peter Devlin, U.S. Department of Energy
Steve Schlasner, ConocoPhillips

Hydrogen Delivery Tech Team
George Parks, ConocoPhillips
Mark Paster, U.S. Department of Energy

Fuel/Vehicle Pathway Integration Tech Team
Fred Joseck, U.S. Department of Energy
Don Gardner, ExxonMobil

Codes and Standards Tech Team
Patrick Davis, U.S. Department of Energy
Brad Smith, Shell Hydrogen

2. COMMITTEE MEETING, THE NATIONAL ACADEMIES, WASHINGTON, D.C., JANUARY 24-26, 2005

Systems Analysis Introduction
Steve Chalk and Ed Wall, U.S. Department of Energy

Systems Analysis: Model Utilization and Integration
Fred Joseck, U.S. Department of Energy

Macro-System Model
Dale Gardner, National Renewable Energy Laboratory

Moving Toward Consistent Hydrogen Analysis: H2A
Margaret K. Mann, National Renewable Energy Laboratory

HyTrans: A Dynamic Optimization Model of Market Transitions to Hydrogen Use by Light-Duty Vehicles Integrating Fuel Supply, Vehicle Production and Consumer Demand
David L. Greene and Paul N. Leiby, Oak Ridge National Laboratory

Well-to-Wheels Analysis of Advanced Vehicle/Fuel Systems—Application of the GREET Model
Michael Wang, Argonne National Laboratory

Systems Analysis: PBA's Market Modeling and Analysis
Phil Patterson, Jeff Dowd, Randy Steer, Brian Unruh, Scott Hassell and Tien Nguyen, U.S. Department of Energy

Vehicle Systems Analysis Technical Team
Lee Slezak, U.S. Department of Energy

Systems Analysis Progress
Fred Joseck, U.S. Department of Energy

PSAT (Powertrain Systems Analysis Toolkit)
Lee Slezak, U.S. Department of Energy

Systems Integration
Dale Gardner, National Renewable Energy Laboratory

Codes and Standards Technical Team
Patrick Davis, U.S. Department of Energy
Brad Smith, Shell

Ending the Energy Stalemate: A Bipartisan Strategy to Meet America's Energy Challenges
Drew Kodjak, National Commission on Energy Policy

Hydrogen Production for a Sustainable Energy Future
C. Lowell Miller, U.S. Department of Energy

Basic Research Needs for the Hydrogen Economy: New Research Activities in DOE's Office of Basic Energy Sciences
Harriet Kung, U.S. Department of Energy

NHTSA's Hydrogen, Fuel Cell, and Alternative Fuel Vehicle Safety Research Plan
Barbara C. Hennessey, Department of Transportation

Nuclear Hydrogen Initiative: Programmatic Overview
David Henderson, U.S. Department of Energy

Hydrogen Codes and Standards: SNL Project Overview
John Keller and Chris Moen, Sandia National Laboratories

PEMFC Cost Slides for NAS Review
Eric Carlson, TIAX LLC

FreedomCAR and Fuel Partnership Peer Review: Overview Discussion
Steve Chalk and Ed Wall, U.S. Department of Energy

3. COMMITTEE MEETING, THE NATIONAL ACADEMIES, WASHINGTON, D.C., MARCH 21-23, 2005

NAS PEER Review
Ed Wall and Steve Chalk, U.S. Department of Energy

National Hydrogen Vehicle/Infrastructure "Learning Demonstration"
Steve Chalk, U.S. Department of Energy

Carbon Capture and Storage
C. Lowell Miller and Scott M. Klara, U.S. Department of Energy

Appendix E

Participants in Hydrogen Storage Projects for FY04 and FY05

INDUSTRY

Air Products
ATK/Thiokol Propulsion
Carnegie Institution of Washington
Ceralink
Gas Technology Institute
General Electric
HRL Laboratories
Intematix Corporation
Millennium Cell
Mo-Sci Corporation
NexGen Fueling
PoroGen, LLC
Research Triangle Institute
Rohm and Haas
State Scientific Research Institute
Superior Graphite Co.
TIAX LLC
TOFTEC, Inc.
US Borax

UNIVERSITIES

Alfred University
California Institute of Technology
Drexel University
Duke University
Michigan Technological University
Northern Arizona University
Northwestern University
Penn State University
Rice University
Stanford University
State University of New York
University of Alabama
University of California-Berkeley
University of California-Davis
University of California-Los Angeles
University of California-Santa Barbara
University of Connecticut
University of Florida
University of Hawaii
University of Illinois
University of Michigan
University of Missouri

University of Nevada-Reno
University of North Carolina
University of Oklahoma
University of Pennsylvania
University of Pittsburgh/Carnegie Mellon
University of Utah
University of Washington
Yale University

NATIONAL LABORATORIES

Brookhaven National Laboratory
Idaho National Engineering and Environmental Laboratory (INEEL)
Jet Propulsion Laboratory
Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
Los Alamos National Laboratory
National Institute of Standards and Technology
National Renewable Energy Laboratory
Oak Ridge National Laboratory
Pacific Northwest National Laboratory
Sandia National Laboratories
Savannah River National Laboratory

Appendix F

Acronyms and Abbreviations

21st CT	21st Century Truck
ACC	Automotive Composites Consortium
ACEC	advanced combustion engines and emission controls (technical team)
AEMD	automotive electric motor drive
AIPM	automotive integrated power module
ANL	Argonne National Laboratory
ANSI	American National Standards Institute
ASCE	American Society of Civil Engineers
ASM	American Society for Materials
ASME	American Society of Mechanical Engineers
BES	Basic Energy Sciences program (DOE)
BMW	Bayrische Motor-Werken
BNL	Brookhaven National Laboratory
CAFE	Corporate Average Fuel Economy
CAR	Cooperative Automotive Research
CBO	U.S. Congressional Budget Office
CCS	carbon capture and storage
CEQ	Council on Environmental Quality
CFRP	carbon-fiber-reinforced polymer
CIDI	compression ignition direct injection
CLEERS	crosscut lean exhaust emission reduction simulation

CNG	compressed natural gas
CO_2	carbon dioxide
CRC	Coordinating Research Council
DARPA	Defense Advanced Research Projects Agency
DLC	double layer capacitor
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
E85	85 percent ethanol
EE	electrical and electronics (technical team)
EERE	Office of Energy Efficiency and Renewable Energy (DOE)
EPA	U.S. Environmental Protection Agency
ERC	Environmental Research Consortium
ERC	Engine Research Center
ESD	Engineering Society of Detroit
EV	battery electric vehicle
EWCAP	Electrical Wiring Component Applications Partnership
FC	fuel cell
FCHEV	fuel cell hybrid electric vehicle
FCVT	FreedomCAR and Vehicle Technologies (program)
FE	Office of Fossil Energy (DOE)
FPITT	fuel pathway integration technical team
FRP	fiber-reinforced polymer
FY	fiscal year
GATE	Graduate Automotive Technology Education
GREET	Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation (model)
Gton	gigaton
H	hydrogen
HAMMER	Hazardous Materials Management and Emergency Response (facility)
HCCI	homogeneous charge compression ignition
HEV	hybrid electric vehicle
HFCIT	Hydrogen, Fuel Cells and Infrastructure Technology (program)
HFCV	hydrogen fuel cell vehicle
HFI	Hydrogen Fuel Initiative
HSRP	Hydrogen Safety Review Panel
HSS	high-strength steel

IEA	International Energy Agency
ICC	International Codes Council
ICE	internal combustion engine
IEEE	Institute of Electrical and Electronics Engineers
INEEL	Idaho National Engineering and Environmental Laboratory
JPL	Jet Propulsion Laboratory
kg	kilogram
kW	kilowatt
kWe	kilowatt-electric
kWh	kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LEP	Low Emissions Technology R&D Partnership
Li-ion	lithium ion
Li/S	lithium sulfur
LTC	low-temperature combustion
M85	85 percent methanol
mbpd	millions of barrels per day
MMC	metal matrix composite
MOU	memorandum of understanding
mpg	miles per gallon
MY	model year
NAE	National Academy of Engineering
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NCEP	National Commission on Energy Policy
NE	Office of Nuclear Energy, Science, and Technology (DOE)
NEMS	National Energy Modeling System
NFPA	National Fire Protection Association
NHA	National Hydrogen Association
NHTSA	National Highway Traffic Safety Administration
NiMH	nickel metal hydride
NIST	National Institute of Science and Technology
NO_x	nitrogen oxides
NRC	National Research Council
NREL	National Renewable Energy Laboratory
NSF	National Science Foundation
NTSB	National Transportation Safety Board

OEM	original equipment manufacturer
ORNL	Oak Ridge National Laboratory
OSRP	Occupant Safety Research Partnership
PBA	Office of Planning, Budget and Analysis
PHMSA	Pipeline and Hazardous Materials Safety Administration
PEM	proton exchange membrane
PM	particulate matter
PNGV	Partnership for a New Generation of Vehicles
PNNL	Pacific Northwest National Laboratory
PV	photovoltaic
R&D	research and development
RFG	reformulated gasoline
RSPA	Research and Special Projects Administration
SAE	Society of Automotive Engineers
SBIR	Small Business Innovation Research
SC	Office of Science (DOE)
SCR	selective catalytic reduction
SiC	silicon carbide
SNL	Sandia National Laboratories
SRI	Stanford Research Institute
SUV	sports utility vehicle
TMS	The Metallurgical Society
TRB	Transportation Research Board
ULSAB-AVC	Ultralight Steel Auto Body-Advanced Vehicle Concept
USABC	United States Advanced Battery Consortium
USAMP	United States Automotive Materials Partnership
USCAR	U.S. Council for Automotive Research
VRP	Vehicle Recycling Partnership
VSAT	vehicle systems analysis team
WRI	World Resources Institute