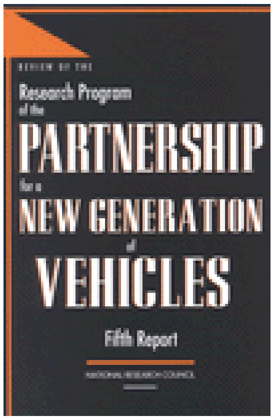

Review of the Research Program of the Partnership for a New Generation of Vehicles: Fifth Report

Standing Committee to Review the Research Program of the Partnership for a New Generation of Vehicles, National Research Council

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REVIEW OF THE RESEARCH PROGRAM OF THE PARTNERSHIP FOR A NEW GENERATION OF VEHICLES

FIFTH REPORT

Standing Committee to Review the Research Program of the Partnership for a New Generation of Vehicles

Board on Energy and Environmental Systems
Commission on Engineering and Technical Systems
Transportation Research Board
National Research Council

Washington, D.C. 1999

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the 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 content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the follow individuals for their participation in the review of this report: Gary Borman, University of Wisconsin; L. Gary Byrd, Consulting Engineer; Dale Compton, Purdue University; Robert Frosch, Harvard University; Theodore Geballe, Stanford University; Phillip Myers, University of Wisconsin; F. Stan Settles, University of Southern California; Karl J.

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While the individuals listed above have provided constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring committee and the NRC.

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Executive Summary

This is the fifth report by the National Research Council Standing Committee to Review the Research Program of the Partnership for a New Generation of Vehicles (PNGV). The PNGV program is a cooperative research and development (R&D) program between the federal government and the United States Council for Automotive Research (USCAR), whose members are DaimlerChrysler Corporation, Ford Motor Company, and General Motors Corporation. One of the aims of the program, referred to as the Goal 3 objective, is to develop technologies for a new generation of vehicles that could achieve fuel economies up to three times (80 mpg) those of comparable 1994 family sedans. At the same time, these vehicles must be comparable in terms of performance, size, utility, and cost of ownership and operation and meet or exceed federal safety and emissions requirements. The intent of the PNGV program is to develop concept vehicles by 2000 and production prototype vehicles by 2004.[1]

In this report, the committee again examines the overall adequacy and balance of the PNGV research program to meet the program goals and requirements (i.e., technical objectives, schedules, and rate of progress), as well as the use of ongoing systems analysis to guide R&D, progress towards meeting long-range component and system-level cost and performance goals, progress in research on

[1]Goal 1 is to improve national competitiveness in manufacturing significantly. Goal 2 is to implement commercially viable innovations from ongoing research on conventional vehicles. Because the Goal 3 concept vehicle demonstrations are focusing on relatively near-term technologies, the distinctions between goals 1, 2, and 3 are becoming blurred. For the most part, the committee has focused on efforts to meeting Goal 3.

vehicle emissions and advanced materials, and efforts to provide interfaces among government R&D projects in support of the PNGV. This Executive Summary highlights the committee's principal findings and recommendations; detailed recommendations can be found in the body of the report.

PROGRESS AND MAJOR ACHIEVEMENTS

The updated PNGV Technical Road Map, which details performance objectives and lays out milestones and schedules in each major technology area, provides a good summary of program goals. Since the PNGV technology selection process was completed at the end of 1997 (reviewed in the fourth report), technical developments have been focused on the following technology areas: (1) four-stroke direct-injection (4SDI) engines, including compression-ignition direct-injection (CIDI) engines and spark-ignition direct-injection engines; (2) fuel cells; (3) batteries for energy storage; (4) power electronics and electrical systems; (5) structural materials; and (6) manufacturing processes. Efforts are also under way to reduce energy losses by improving vehicle aerodynamics, reducing rolling resistance, improving the efficiency of vehicle accessories, and recovering energy and storing it in the batteries during vehicle braking.

In the past year, more progress was made towards meeting PNGV goals than in previous years of the program. In the view of the committee, much of this progress can be attributed to the attitude and efforts of the PNGV technical teams, which appear to be working more cooperatively towards meeting common goals than in past years. The committee considers this to be a very positive change that has provided a needed boost to continuing technical productivity. The PNGV also responded positively to most of the committee's recommendations in the fourth report.

Four-Stroke Direct-Injection Engines

The USCAR partners are making good progress toward meeting their targets, with the exception of emissions and cost targets, which still present significant challenges. Because the engine systems are still under development, emissions controls and costs are either unknown or at a very early stage of optimization. A number of notable accomplishments have been made for CIDI engines, including the development of a prototype fuel-injection system with desirable operating characteristics, especially in terms of controlling for specific power and noise; regulating vibration and harshness; improving the understanding of fundamental, in-cylinder combustion processes; reducing particulate emissions through fuel modifications; developing a fueling system for dimethyl ether (a possible alternative fuel); and developing lean-NO_x catalyst systems that have demonstrated promising removal rates.

Fuel Cells

Although major obstacles must still be overcome to meet the targets for realizing a practical, automotive fuel-cell system, impressive progress has been made in the past year. For example, in the area of fuel processors (converting gasoline to hydrogen for use by the fuel cell), a steady-state partial-oxidation gasoline reformer and carbon monoxide cleanup system has exhibited good results, and the development of a 50-kW preferential oxidation system has allowed the first meaningful transient measurements. In the area of fuel-cell stacks, important cost reductions have been identified with composite bipolar plates and continuous manufacturing processes, and the tolerance to carbon monoxide was increased to 100 ppm. In the area of systems integration, a significantly improved systems analysis model has been developed and transferred to the fuel-cell developers.

Batteries

The electrochemical battery is still the most promising technology for energy storage in hybrid electric vehicles (HEVs). The development of cells and modules continues apace, as does abuse and safety testing. Programs have been initiated for 50-V modules. For lithium-ion batteries, energy and power goals appear to be attainable, but meeting cycle-life and calendar-life targets is questionable. The lithium-ion technology uses organic materials that can burn, and disquieting fire and smoke have been observed in some tests. The nickel metal hydride system uses an aqueous electrolyte, which eliminates many of these problems. The PNGV now recognizes that innovations will be required, perhaps even innovations in cell chemistry, to meet its targets.

Power Electronics and Electrical Systems

The electrical and electronic systems technical team has made excellent progress in the last year. The team's program is now well structured, well organized, and well managed. Projects by the national laboratories and Cooperative Automotive Research for Advanced Technologies, as well as projects by the Small Business Innovative Research program, are part of a coordinated program to address technical objectives. Now that an automotive integrated power module has been specified, the results of the Navy's power electronic building block program can be modified to meet the unique requirements of PNGV, as the committee recommended in its fourth report. The committee's concerns that the present cost targets for power electronics and motors may be unrealistic with known and projected technology have yet to be addressed.

Structural Materials

Aluminum continues to be the leading candidate material for the Goal 3 vehicles. Efforts are under way to reduce the cost of aluminum sheet through the development of a thin-slab continuous-casting process; during the past year, aluminum sheet produced from direct-cast thin slabs has demonstrated excellent formability characteristics. A program to develop low-cost alloys that do not require heat treatment is also under way. Another accomplishment was the construction of a body-in-white using a combination of carbon fiber-reinforced plastic (CFRP) and aluminum materials, which demonstrated an impressive 68.5 percent weight savings over a baseline steel structure. Although CFRP has impressive possibilities, because of its high cost and long production cycle time, it is still a long-term alternative to aluminum.

Manufacturing Processes

Significant progress was made in the manufacturing processes for vehicles and specific components, including the optimization of methods for light metal castings; the demonstration of a high-volume programmed powder preform process for producing structural composites; modifications of coatings and designs to improve high-speed drilling processes; the demonstration of compression-molded composite bipolar plates for fuel cells to replace machined graphite plates; and the demonstration of a continuous process for manufacturing fuel-cell membrane-electrode assemblies to replace individual layups.

MAJOR TECHNICAL AND COST BARRIERS

For the most part, the PNGV's efforts during the past year towards meeting its long-term and short-term objectives have been appropriate and have resulted in very significant achievements. A number of extremely difficult challenges remain, however, which is to be expected with a large, complex development program like the PNGV. These major challenges, which are still significant barriers to the achievement of PNGV's objectives, are discussed below.

Emissions Issues and Trade-offs

As the committee noted in the third and fourth reports, the most difficult technical challenge facing the CIDI engine program will be meeting the standards for NO_x and particulate emissions. (The 4SDI engine team is well aware of this challenge.) In addition, meeting an even more stringent research objective (0.01 g/mile) for particulate matter instead of the 0.04 g/mile PNGV target would require additional technological breakthroughs. Events outside the PNGV, especially the California low-emission vehicle (LEV-2) standards and the

Environmental Protection Agency's (EPA's) anticipated new Tier II proposals, may also affect the commercial viability of advanced vehicles. The committee is concerned that continual changes in standards have placed immense burdens on PNGV's technical development process and its ability to stabilize productive research directions.

The capability of the CIDI engine to meet future emissions requirements is uncertain and will undoubtedly require important developments in NO_x catalyst technology, particulate trap technology, and power-train sensor and control technology. Fuel composition will also be an important consideration. For example, low-sulfur fuel will improve catalyst efficiency and durability and reduce the amount of particulate mass emitted. Other fuel changes (substantially reduced aromatic content, use of oxygenated organic compounds) may be necessary. The design trade-offs among engine control, the exhaust-gas treatment technology, and fuel will have important implications for cost, fuel economy, and emissions.

The gasoline spark-ignited direct-injection (GDI) engine, considered the best short-term backup technology to the CIDI engine, has its own problems with the engine and exhaust-gas treatment emissions technologies, such as trade-offs between fuel economy and the engine design, the cost and effectiveness of the exhaust catalyst system, unresolved questions about particulate emissions, and fuel composition requirements (especially fuel sulfur levels). However, the GDI's potential for achieving the California LEV-2 and EPA Tier II requirements is significantly better than that of the CIDI engine.

Unresolved emissions-control issues also relate to fuel-cell technology. When a fuel cell is used with a gasoline or methanol reformer onboard the vehicle, there could be emissions from the reformer, especially during transient operation. The limited data available to date indicate that emissions during steady-state operations can be kept extremely low, but no data exist for transient operating conditions. Fuel sulfur levels must also be kept very low.

According to presentations by the PNGV (by government and industry representatives) to the committee, the interdependence of power trains (4SDI engine or fuel cell), fuel economy, and emissions has not being adequately addressed. The current California regulatory proposals on NO_x and particulate emissions are likely to preclude the use of the very efficient CIDI engine in the United States unless effective exhaust-gas after-treatment technology can be developed or the emission standards are revised. The successful development of exhaust-gas after-treatment technologies will depend on the extent and rate of implementation of improvements in diesel fuel. To date, the responsible government agencies participating in the PNGV have pursued their specific agency objectives without taking into account the interdependency of these issues. The committee believes the PNGV program represents an opportunity to examine these critical interdependencies and recommends that the PNGV leadership develop appropriate coordinating policies. The technological choices for meeting the PNGV goals and time frames are limited, and a clear policy on fuel standards, emission regulations, fuel economy, and cost expectations will be essential for meeting them.

Cost of Four-Stroke Direct-Injection Hybrid Electric Vehicles

With the advanced technologies under development by the PNGV, even if performance targets are eventually met, the costs of vehicles are projected to be much higher than for conventional vehicles. This cost penalty will be exacerbated with an HEV, which is more complex than a nonhybrid vehicle. Thus, the cost reduction involving design, vehicle trade-offs, and manufacturing also remains a significant barrier to the realization of an affordable Goal 3 vehicle.

A number of issues have cost implications for a near-term 4SDI-powered vehicle including: emission reductions; a less expensive supply of base materials for the manufacture of reduced-mass body/chassis assemblies, as well as new mass-manufacturing processes; mass reductions in the engine/drivetrain and other components; and improvements in air conditioning, power steering, and other accessories to reduce vehicle mass and meet manufacturability requirements. A successful HEV configuration for the 4SDI engine (or for a fuel-cell vehicle) will also depend on motor and power electronic technologies being reasonably well defined and will require mass manufacturing. The HEV system will also depend heavily on a robust, lightweight, low-cost battery, but battery technologies face significant barriers to meeting cost and performance targets. The lithium-ion system, which appears to be the most promising candidate, will still require the development of mass manufacturing capabilities.

Fuel-Cell Cost and Performance

Although impressive progress has been made in critical areas, a long list of challenges (and some, undoubtedly, not yet identified) remain to be resolved. The successful demonstration of composite bipolar plates and continuous-process membrane-electrode assemblies will go a long way towards achieving cost goals for fuel-cell stacks. However, the "multifuel" fuel processor and carbon monoxide cleanup systems are still in the early stages of laboratory development, and potential manufacturing and materials problems have only begun to be identified. The compressor/expander systems are at an intermediate stage of development, but a final product has not been identified, and manufacturing approaches have yet to be defined. The tolerance of the fuel-cell stacks to carbon monoxide and other impurities is still uncertain. The performance of the system of fuel processor, cleanup system, and fuel-cell stack is also uncertain because no working gasoline-fueled systems have been developed, and the systems model is still unverified. Furthermore, no long-term durability tests for major components have been conducted, and only a few high-volume manufacturing processes have been identified. Consequently, meeting the PNGV targets for fuel-cell cost and performance still presents significant challenges.

Fuels Strategy

As the committee noted in its fourth report, significant changes in automobile power plants would have wide-ranging effects on the fuels industry. Even if the PNGV program can meet its Goal 3 target with power plants such as the CIDI engine or a fuel cell, marketing the vehicles powered by them may be limited, or even prohibited, by the unavailability of suitable fuels. Therefore, it is vitally important that the PNGV pursue the development of appropriate fuels concurrently.

The PNGV recognizes the importance of modified fuel in achieving emission targets for CIDI engines and is testing various fuels. Ad hoc pairings of fuel companies and auto manufacturers have developed test programs to evaluate the effects of various fuels on emissions, as well as on after-treatment catalysts.

The U.S. Department of Energy (DOE) has taken the lead in addressing the fuels infrastructure issues, with analyses of the effects of potential changes in fuels and power plants on the infrastructure, cost, energy, and environment. These projections would be more credible if DOE had critical input from the major petroleum companies that would be involved in implementing the changes and could validate the assumptions underlying DOE's projections in practical business terms. EPA should continue to be involved in planning and be made fully aware that if exhaust emission standards are too stringent they could either preclude the use of the most fuel-efficient power plants or require the distribution of a fuel that could not be made available economically or in time to meet PNGV goals. Regular interactions between DOE and EPA might help to elucidate and resolve the necessary trade-offs.

Overall, the attention to the fuels issues associated with the PNGV program has increased, but no mechanism has been established to address the fundamental trade-offs between vehicle exhaust emissions and energy efficiency at the government-agency policy level, and long-range strategic issues are not being addressed effectively by the fuels industry or the automobile manufacturers.

Cost and Performance of Electrochemical Batteries

Meeting the PNGV targets for calendar life and cycle life, but also for specific energy and cost, is in serious jeopardy for both electrochemical battery systems (lithium-ion and nickel metal hydride). Consequently, some national laboratories are being enlisted in a new effort to define generic (nonproprietary) baseline electrochemistry and to show, by example, how to elucidate the failure mechanisms of a system. The development of new electrochemistry is equivalent to starting over. Even though lithium-ion batteries may be preferable in the long term (year 2004) because of their high efficiency and high specific energy, ongoing problems have revealed that nickel metal hydride batteries should also be made available (and perhaps even advanced lead-acid, nickel-cadmium, or nickel-zinc batteries) for the year 2000 concept vehicles,

Achieving adequate calendar life and cycle life, as well as safe abuse tolerance under representative operating conditions and low cost, remain major challenges for PNGV's battery program. The PNGV must put these issues in perspective by (1) developing a better understanding of the factors that control calendar and cycle life, (2) conducting more realistic simulations of likely abuse conditions and their effects, and (3) developing a better understanding of the factors that affect mass-manufacturing costs.

VEHICLE SYSTEMS ANALYSIS

The timely application of vehicle systems analysis by the PNGV is critical for making engineering trade-offs and setting the performance and cost priorities for subsystem technologies. The systems analysis team is now qualified to provide analysis and modeling support to all of the technical teams. At this phase of vehicle development, all of the technical teams should be closely aligned with the systems analysis group and using the systems model and associated analytical support services in making their decisions. The committee concluded, however, that this is not the case.

Although the second-generation vehicle model has been created, essential validation of PNGV models still remains to be done. The designs of individual concept vehicles by the USCAR partners are proceeding, based on proprietary sophisticated vehicle, subsystem, and component models. Considerable work is being done by government laboratories, suppliers, and academic institutions but is not being guided by validated models. The USCAR partners should find a means of supporting the validation of the PNGV models.

The lack of adequate cost models is still a major concern given the magnitude of the projected cost reductions for PNGV vehicles in keeping with the Goal 3 objectives. Without compromising proprietary considerations, cost models should be developed for use by all of the component and subsystem teams. Design decisions by all of the technical teams should be based on these models.

ADEQUACY AND BALANCE OF THE PNGV PROGRAM

Once again, the committee finds it difficult to assess the efforts and resources applied to the PNGV program because no funding plan was made available. In several previous reports, the committee concluded that the resources allocated to PNGV activities were incommensurate with the magnitude of the challenges to meet the Goal 3 objectives. The committee is encouraged this time, however, by several trends. First, the number of technologies was winnowed down during the technology selection process at the end of 1997, allowing PNGV to better focus available resources. Second, the fiscal year 1999 budget for DOE's Office of Advanced Automotive Technologies provided moderate increases for the development of some long-range technologies, like fuel cells. However, these amounts are still far below the level needed to meet the challenges on a timely basis. Third, the three USCAR partners have substantially increased their proprietary efforts towards the development of concept vehicles, and impressive vehicle-development teams have been formed by each car company. Finally, the PNGV technical teams appear to be working well together. Despite these positive developments, the committee believes the PNGV program will need additional resources. Furthermore, it is essential that other government agencies (e.g., EPA) and other industries (e.g., petroleum refiners and automotive component manufacturers) be brought more fully into the PNGV program.

The committee believes the near-term and long-term technologies the PNGV has focused on have the potential to meet the program's objectives. Some critics of the program have suggested that the CIDI engine should not be pursued for the U.S. market because of its particulate and nitrogen oxides emissions. However, the committee believes that potential fuel economy and the high degree of technical maturity of the CIDI engine warrant continued development, especially in light of the uncertainties facing fuel-cell technologies. In addition, extensive markets in Europe and Asia for high fuel-economy vehicles offer an opportunity to improve the fuel economy and reduce emissions worldwide.

GOVERNMENT INTERFACES

Seven government agencies are involved in the PNGV program, with the U.S. Department of Commerce playing a lead role. Not all R&D by these agencies is directly relevant to the goals of the PNGV. Some R&D (e.g., R&D in DOE's Office of Advanced Automotive Technologies) is directly relevant to the PNGV and is coordinated with the PNGV technical teams; some is directly relevant but is not coordinated with the PNGV technical teams; and some is only indirectly related to PNGV or supporting long-term research. The seven government agencies also have different missions, and government R&D (either directly or indirectly related to PNGV) takes place in many departments and laboratories. The program office of the U.S. Department of Commerce is doing a commendable job of promoting the interests of PNGV among government organizations and providing workable interfaces in its proactive support of the program.

SELECTED RECOMMENDATIONS

The committee has picked a limited number of recommendations to highlight in the Executive Summary. Most of the specific technical recommendations for each subsystem appear in the main body of the report.

Recommendation. The PNGV four-stroke direct-injection technical team should develop projections of the performance of compression-ignition direct injection and gasoline direct-injection power-train systems, especially comparisons of the estimated emissions and fuel economy for each system. These projections would be a first step toward the quantification of trade-offs between emissions and fuel economy based on current and emerging state-of-the-art technologies.

Recommendation. The federal government agencies involved in the PNGV program should review how future emissions requirements (especially NO_x and particulates), fuel economy, and carbon dioxide emissions, as well as fuel quality, will affect the choice of the compression-ignition direct-injection engine as the most promising short-term combustion engine technology; a program plan that responds to that assessment should be developed. The PNGV, especially the U.S. Department of Energy and the Environmental Protection Agency, should work closely with the California Air Resources Board on these issues.

Recommendation. A comprehensive mechanism should be established to help define feasible, timely, and compatible fuel and power-plant modifications to meet the PNGV goals. This mechanism will require extensive cooperation among not only automotive and fuels industry participants at all levels of responsibility, but also among technical and policy experts of the relevant government organizations.

Recommendation. The PNGV should conduct life-cost and performance-cost trade-off studies, as well as materials and manufacturing cost analyses, to determine which battery technology offers the best prospects and most attractive compromises for meeting capital and life-cycle cost targets.

Recommendation. Without compromising proprietary information of the USCAR partners, the PNGV should conduct in-depth cost analyses and use the results to guide subsystem and vehicle affordability studies.

1

Introduction

On September 29, 1993, President Clinton initiated the Partnership for a New Generation of Vehicles (PNGV) program, which is a cooperative research and development (R&D) program between the federal government and the United States Council for Automotive Research (USCAR), whose members are DaimlerChrysler Corporation, Ford Motor Company, and General Motors Corporation (GM).[1] The purpose of the PNGV program is to improve substantially the fuel efficiency of today's automobiles and enhance the U.S. domestic automobile industry's productivity and competitiveness. The objective of the PNGV program over the next decade is to develop technologies for a new generation of vehicles that can achieve fuel economies up to three times (80 miles per equivalent gallon of gasoline) those of today's comparable midsize sedans, with comparable performance, size, utility, and cost of ownership and operation, and meeting or exceeding federal safety and emissions requirements (The White House, 1993).

The PNGV declaration of intent includes a requirement for an independent peer review "to comment on the technologies selected for research and progress made." In response to a written request by the undersecretary for technology administration, U.S. Department of Commerce on behalf of the PNGV, the National Research Council in July 1994 established the Standing Committee to Review the Research Program of the Partnership for a New Generation of

[1]USCAR, which predated the formation of PNGV, was established to support intercompany, precompetitive cooperation to 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 is currently comprised of a number of consortia as shown in Appendix F.

Vehicles. The committee conducts annual independent reviews of the PNGV's research program, advises government and industry participants on the program's progress, and identifies significant barriers to success. This is the fifth review by the committee; the previous studies are documented in four National Research Council reports, which provide further background on the PNGV program and the committee's activities (NRC, 1994, 1996, 1997, 1998a).

The PNGV goals and the considerations underlying all of the National Research Council reviews articulated in the partnership's program plan are (PNGV, 1995):

> **Goal 1. Significantly improve national competitiveness in manufacturing for future generations of vehicles.** Improve the productivity of the U.S. manufacturing base by significantly upgrading U.S. manufacturing technology, including the adoption of agile and flexible manufacturing and reduction of costs and lead times, while reducing the environmental impact and improving quality.

> **Goal 2. Implement commercially viable innovations from ongoing research on conventional vehicles.** Pursue technology advances that can lead to improvements in fuel efficiency and reductions in the emissions of standard vehicle designs, while pursuing advances to maintain safety performance. Research will focus on technologies that reduce the demand for energy from the engine and drivetrain. Throughout the research program, the industry has pledged to apply those commercially viable technologies resulting from this research that would be expected to increase significantly vehicle fuel efficiency and improve emissions.

> **Goal 3. Develop vehicles to achieve up to three times the fuel efficiency of comparable 1994 family sedans.** Increase vehicle fuel efficiency to up to three times that of the average 1994 Concorde/Taurus/Lumina automobiles with equivalent cost of ownership adjusted for economics.

As the committee noted in its third and fourth reports, and as has been noted in a number of other studies, achieving significant improvements in automotive fuel economy and developing competitive advanced automotive technologies and vehicles can provide important economic benefits to the nation, improve air quality, improve the nation's balance of payments, and reduce emissions of greenhouse gases to the atmosphere (DOE, 1997; NRC, 1992, 1997, 1998a, 1998b; OTA, 1995; PCAST, 1997; Sissine, 1996). However, crude oil prices have fallen precipitously recently, and U.S. gasoline prices are relatively low, giving automobile purchasers little incentive to consider fuel economy as a major factor in their purchase decisions. In addition, the U.S. automotive market continues to experience a substantial increase in the sales of light trucks, especially sport utility vehicles, which have lower legislated fuel economy requirements than automobiles. The lack of market incentives in the United States for car buyers to purchase vehicles with high fuel economy has made it difficult to realize the public benefits from improvements in fuel economy.

The PNGV strategy of developing an automobile with a fuel economy of up to 80 mpg that maintains current performance, size, utility, and cost levels and meets safety and emissions standards, would circumvent the lack of economic incentives for buying automobiles with high fuel economy. If the PNGV strategy is successful, buyers will purchase vehicles with all of the desirable consumer attributes, as well as greatly enhanced fuel economy. The development of this vehicle, as the committee noted in its previous reports, is extremely challenging. But this ambitious goal and the PNGV program have helped stimulate the rapid development worldwide of the required technologies, which highlights the potential strategic value of programs like the PNGV and the importance of staying abreast of developments in foreign technology. Even if the Goal 3 vehicle does not achieve the triple-level fuel economy but approaches the cost and performance objectives, it may still be far more fuel-efficient than current vehicles, which would be an outstanding achievement.

The PNGV's objective is to bring together the extensive R&D resources of the federal establishment, including the national laboratories and university-based research institutions, and the vehicle design, manufacturing, and marketing capabilities of both the USCAR partners and suppliers to the automotive industry. In general, government funding for the PNGV is primarily used for the development of long-term, high-risk technologies. Funding by USCAR and industry is generally used to develop technologies with near-term commercial potential, to implement government technology developments into automotive applications, and to produce concept vehicles. Substantial in-house proprietary R&D programs are also under way at USCAR partners' facilities.

Technical teams responsible for R&D on the candidate subsystems, such as fuel cells, four-stroke direct-injection (4SDI) engines, and others, are central to the PNGV. A manufacturing team, an electrical and electronics power-conversion devices team, a materials and structures team, and a systems-analysis team are also part of the PNGV organization (NRC, 1996, 1997, 1998a). Technical oversight and coordination are provided by the vehicle-engineering team, which provides the technical teams with vehicle-system requirements, which are supported by the systems-analysis team.

At the end of 1997, the PNGV reached a critical milestone of technology selection (often referred to as the technology "downselect" process) based on assessments of system configurations for alternative vehicles. In this process, several technology options were eliminated as leading candidates, such as gas turbines, Stirling engines, ultracapacitors for energy storage, and flywheels for energy storage. After reviewing this process during its fourth review, the committee endorsed the technology selections (e.g., four-stroke, internal-combustion engines, fuel cells, batteries, power electronics, and structural materials). Since then, the PNGV has focused available resources on fewer technologies with the intent of defining, developing, and constructing concept vehicles by 2000 and production prototypes by 2004 (PNGV, 1995). The USCAR partners are developing separate concept vehicles, drawing on the spectrum of technologies developed under the PNGV and in-house proprietary technology, but neither the PNGV nor USCAR will design or build a concept car, a decision that the committee supports.

Although the technologies most likely to result in concept and production prototype vehicles that could meet the Goal 3 requirements were selected during the downselect process, as other longer-range technologies continue to evolve, they may be incorporated into subsequent concept vehicles, as appropriate, and a series of concept vehicles will probably be developed after 2000. Since the beginning of the program, the PNGV has addressed many technology areas, including advanced lightweight materials and structures; efficient energy-conversion systems (including advanced internal combustion engines, gas turbines, Stirling engines, and fuel cells); hybrid electric propulsion systems; energy-storage devices (including high-power batteries, flywheels, and ultracapacitors); efficient electrical and electronic systems; and systems to recover and utilize exhaust energy and braking energy.

This fifth PNGV review was conducted by a 14-member committee with a wide variety of expertise (see Appendix A for biographical information). The committee was asked to address the following tasks in this review (see Appendix C for the complete Statement of Task):

> (1) In light of recommendations from the fourth review, for each of the major technology selection focus areas (i.e., four-stroke direct injection engines, fuel cells, energy storage, electronic and electrical systems, and materials), examine the overall adequacy and balance of the PNGV research and development efforts to meet the program goals and requirements (i.e., technical objectives, schedules, and rate of progress necessary to meet the requirements).
>
> (2) Examine the ongoing systems analysis effort and the process by which it is guiding the PNGV to make decisions on R&D directions.
>
> (3) Examine the efforts and progress towards PNGV's long-range component and system-level cost and performance goals.
>
> (4) Examine ongoing PNGV-related efforts in the areas of vehicle emissions research and advanced materials research, and the process by which results are targeting both long-range and shorter-range PNGV goals.

(5) Review the government efforts to provide interfaces among different government agency R&D activities in support of PNGV.

The conclusions and recommendations in this fifth report are based on the committee's meetings, presentations, and other data-gathering activities (see Appendix D).[2] Some of the material reviewed by the committee was presented by USCAR as proprietary information under an agreement signed by the National Academy of Sciences, USCAR, and the U.S. Department of Commerce (on behalf of the federal government). Appendix E lists all of the recommendations contained in this report.

As with any program, opinions of the goals often differ. Some think the time frame should be longer to allow for the maturation of some of the longer-range technologies; some think that, rather than a fuel economy target, the goals should be to reduce the combined emissions of greenhouse gases. As the committee noted in previous reports (NRC, 1996, 1997, 1998a), all of these reviews were undertaken with the understanding that the vision, goals, and target dates for the PNGV were articulated by the president and that the appropriate R&D programs had been launched. Assuming that the PNGV partners will seriously pursue the objectives of the program, the committee understands its role as providing independent advice to help the PNGV achieve its goals. Therefore, the committee has tried to identify actions that could enhance the program's chances for success and refrained from making judgments on the value of the program to the nation. The goals were accepted as given, including goals 1 and 2, which, unlike Goal 3, are open-ended and do not have quantitative targets and milestones. The objectives of goals 1 and 2, in many instances, support progress toward Goal 3, especially in support of the development of manufacturing capabilities for the advanced automotive technologies being considered for the Goal 3 vehicle. The committee's objective continues to be to review the R&D program as presently configured and to assess the PNGV's progress toward, and potential for, achieving its goals. However, because regulatory and market changes continue to occur, the PNGV should reassess its objectives, as necessary.

[2]The committee formed the following subgroups: Systems Analysis and Electrical and Electronic Systems; Batteries; Fuels; Fuel Cells; Internal-Combustion Engines and Emissions Control; Materials; and Cost Analysis. For a list of members of the subgroups see pages iii and iv.

2

Development of Vehicle Subsystems

CANDIDATE SYSTEMS

The ultimate success of the PNGV program will depend on integrating R&D programs that can collectively improve the fuel efficiency of automobiles within the very stringent boundary conditions of size, reliability, durability, safety, and affordability of today's vehicles. At the same time, the vehicles must meet even more stringent emission and recycling levels and must use components that can be mass produced and maintained in a manner similar to current automotive products.

In order to achieve the Goal 3 fuel economy upper limit of 80 mpg, the energy conversion efficiency of the chemical conversion system (e.g., a power plant, such as a compression-ignition direct-injection [CIDI] engine or a fuel cell) averaged over a driving cycle will have to be at least 40 percent, approximately double today's efficiency. This extremely challenging goal will require assessing many concepts. For example, the primary power plant will have to be integrated with energy-storage devices, and the vehicle structure will have to be built of lightweight materials to reduce vehicle weight.

The hybrid electric vehicle (HEV), which is the PNGV power train of choice, uses an energy-storage device to reduce the fluctuations in demand on the primary power plant, thereby permitting a smaller power plant that operates at optimum conditions for increased energy-conversion efficiency and reduced emissions, as well as recovery of a significant fraction of the vehicle's kinetic energy during braking operations. The PNGV is currently sponsoring research on batteries as energy-storage devices.

Achieving the high fuel economy objective for the Goal 3 vehicle will require more than improving the energy-conversion efficiency of the power train (including energy converters and transmissions) and reducing other energy losses in the vehicle. Vehicle weight reduction through new vehicle designs and lightweight materials will be extremely important for achieving the very ambitious fuel-economy objectives.

The committee re-evaluated the candidate energy-conversion and energy-storage technologies that survived the 1997 technology selection process, as well as candidate electrical and electronic systems and advanced structural materials for the vehicle body. The technologies evaluated in this chapter are listed below:

- four-stroke internal-combustion reciprocating engines
- fuel cells
- electrochemical storage systems (rechargeable batteries)
- electrical and electronic power-conversion devices
- structural materials

The committee reviewed R&D programs for each of these technologies to assess progress so far and the developments required for the future. The updated PNGV Technical Roadmap provides a good summary of the program goals (PNGV, 1998). In the committee's opinion, the PNGV has made substantial progress in assessing the potential of most candidate systems and identifying critical technologies that must be addressed to make each system viable. As discussed further in the remainder of the report, significant progress has been made toward meeting the program's goals. A few exceptions are noted in the sections describing specific technologies.

Because the global competitiveness of the U.S. automotive industry is a key consideration in the development of advanced automotive technologies, the committee also describes some international developments in the technology areas, based both on its own knowledge and experience and on selected information-gathering activities. An extensive review of worldwide developments, however, was not part of the committee's task. Additional information can be found in the fourth report (NRC, 1998a).

INTERNAL-COMBUSTION RECIPROCATING ENGINES

To meet the Goal 3 fuel economy target, an engine will have to be integrated into an HEV configuration. The 4SDI (four-stroke direct-injection) technical team continues to research four potential engine configurations as power plants for the HEV (see Figure 2-1). The CIDI engine, the homogeneous-charge compression-ignition engine, the gasoline direct-injection (GDI) engine, and the homogeneous-charge spark-ignition engine are all being evaluated as candidate power plants.

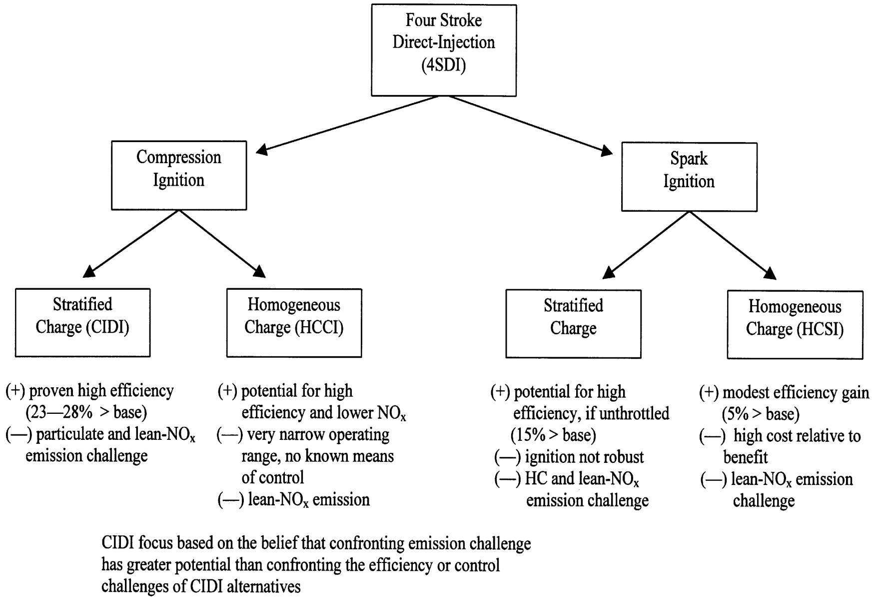

FIGURE 2-1 Alternatives for energy conversion. The baseline engine is the port fuel injection homogeneous charge spark injection for model year 1993.
SOURCE: Belaire et al. (1998).

The 4SDI technical team continues to believe that the CIDI engine has the potential for the highest fuel-conversion efficiency. In addition to better fuel economy, the performance of the CIDI engine is superior to other engine types in terms of evaporative, cold-start, hydrocarbon, and carbon monoxide (CO) emissions. However, there are still significant challenges to be overcome in the development of CIDI HEV systems that meet all of the PNGV targets. These challenges include reducing the emissions of nitrogen oxides (NO_x) and particulates, reducing the weight of the power plant, and reducing costs.

For other candidate power plants, such as the GDI engine, reducing emissions may represent less of a challenge than increasing the fuel economy. The exhaust-gas after-treatment systems for gasoline engines are technically more mature than those for CIDI engines, and there are reasons to believe that the PNGV emission targets, and perhaps even the more stringent research targets, could be met with GDI engines.[1] However, it is not likely that the Goal 3

[1]Meeting the particulate research objective will be a challenge for both the CIDI engine and the GDI engine. Recent data on number of particulates emitted from the GDI engine indicate levels one to three orders of magnitude higher than the modern port-fuel-injected, spark-ignition engine (Graskow et al., 1999).

fuel-economy target (triple the fuel economy of current vehicles) could be achieved with GDI engines. Overall system cost remains a considerable challenge for all engines.

In the past year, the necessity of taking an integrated approach to the power train has become apparent. That is, the development should involve the entire power train system, which includes the engine, drivetrain, fuel, exhaust-gas after-treatment, and sensors and controls, to take into account the synergistic or antagonistic effects of individual components of the system. According to the 4SDI technical team, the emission targets cannot be met with a reciprocating piston, combustion power plant through combustion control alone, regardless of the power plant under investigation. Meeting the proposed targets will require both fuel modifications and extensive exhaust-gas after-treatment. Therefore, in addition to ongoing work on combustion control, research in these two areas has increased markedly during the past year.

Technical Targets

All of the USCAR manufacturers are developing in-house concept vehicles, and all are developing a CIDI hybrid system as one of the leading candidate power trains. The technical targets for the CIDI engine for the years 1998 and 2004 are listed in Table 2-1, but because the manufacturers are currently involved in proprietary vehicle development, it is not possible to list the current performance numbers for the CIDI engine systems.

The USCAR partners are making good progress toward meeting the targets for thermal efficiency, specific power, package volume, noise, and vibration. The emissions, exhaust-gas after-treatment performance, and cost targets represent significant challenges. Because the engine systems are still under development, the emissions performance and costs are either unknown or at a very early stage of optimization.

Program Status, Progress, and Highlights

The 4SDI technical team continues to interact extensively with other working groups both within and outside PNGV to maximize its coverage. The team has established cooperative relationships with energy companies to obtain special fuels for testing and has been working with the USCAR Low Emission Program to improve port-fuel-injected (PFI) spark-ignition (SI) engines and spark-ignition direct-injection (SIDI) engines. The 4SDI technical team is also involved in cooperative R&D agreements (CRADAs) between the national laboratories of the U.S. Department of Energy (DOE), industries, and universities to study the fundamentals of combustion and the development and performance of exhaust-gas after-treatment systems.

TABLE 2-1 Current Performance Characteristics and Targets of CIDI Engine Systems

Characteristic	1998 Target	2004 Target
Best BTE	43%	45%
BTE @ 2,000 rpm, 2 bar BMEP	27%	30%
Displacement specific power	40kW/liter	45kW/liter
Weight specific power	0.53kW/kg	0.63kW/kg
Package volume	0.13 m^3	0.09m^3
Mount vibration maximum @ firing order	47N	40N
One-meter noise maximum	97dBA	90dBA
Engine-out NO_x emissions	2.7g/kWh	1.5g/kWh
Engine-out PM emissions	0.26g/kWh	0.16g/kWh
NO_x after-treatment efficiency	25%	40%
PM after-treatment efficiency	0%	75%
FTP 75 NO_x emissions	0.4g/mile	0.2g/mile
FTP 75 PM emissions	0.06g/mile	0.04g/mile[a]

[a]The PNGV target is 0.04 g/mile, whereas the research target, sometimes referred to as the "stretch research objective," was set in 1997 at 0.01 g/mile (NRC, 1998a). Measuring levels of particulates at 0.01 g/miles is a challenge to current measurement techniques whose variability is as high as the research objective.

Source: Based on Table III-F in the Technical Roadmap (PNGV, 1998).

Acronyms: FTP = federal test procedure; BTE = brake thermal efficiency; BMEP = brake mean effective pressure; PM = particulate matter; N = newtons; dBA = decibels absolute.

Engines

Even though the CIDI engine in an HEV configuration is considered the most likely power plant system for meeting the Goal 3 fuel economy target, other configurations of the reciprocating piston engine, including further development of SIDI gasoline engines and PFI SI engines, are being investigated in parallel programs. In addition, research on homogeneous-charge compression-ignition engines has been initiated at the Combustion Research Facility at Sandia National Laboratories (SNL) in Livermore, California. Although developments during the past year did not change the relative rankings of the engine types in terms of their potential fuel economy, the challenge of meeting the projected exhaust emission target (NO_x level of 0.2 g/mile, and a research target for particulate matter of 0.01 g/mile) represents a considerable stretch at this time, especially for the CIDI engine.

A number of notable accomplishments in the 4SDI area achieved during the last year are listed below:

- Desirable characteristics of a fuel-injection system have been identified, and a prototype injection system has been fabricated. The injection system is a piezoelectric system with variable rate shape and controlled opening and closing nozzle capabilities. Tests using this injection system will be conducted at FEV.

- The Ford direct-injection, aluminum-block, through-bolt assembly (DIATA) engine was demonstrated to have specific power output levels comparable with state-of-the-art diesel engines and noise, vibration, and harshness levels comparable to state-of-the-art SI engines. Also a dimethyl ether fueling system has been developed for the DIATA engine to test this alternate fuel.
- Initial results of the fundamental combustion studies at SNL, Wayne State University, and the University of Wisconsin were reported. In-cylinder combustion visualization experiments are under way at SNL; additional engine tests are being run at Wayne State University; and three-dimensional simulations are being performed at the University of Wisconsin. In addition, an homogeneous-charge compression-ignition program has been initiated at SNL.
- Preliminary assessments of the incremental cost, including emissions controls, associated with replacing the current SI engine with an advanced CIDI engine have been made. A breakdown of the costs shows an increase of approximately $900 compared to the target cost.

Fuel Formulation

The PNGV emission targets represent a technological stretch, particularly for the CIDI engine. Discussions are under way among regulatory bodies and various environmental groups (Environmental Protection Agency [EPA], the California Air Resources Board [CARB], and the South Coast Air Quality Management District [SCAQMD], among others) about reducing the regulated levels of emissions.[2] In response, PNGV is investigating the requirements of reformulated or different fuels for CIDI engines:

- DOE, which has taken the lead in involving the USCAR partners and energy companies, has been organizing meetings and technical interchanges.

[2]For example, the CARB LEV (low-emission vehicle) II standards are: LEV emissions of 0.05 g/mile NO_x, 0.01 g/mile particulate matter, 0.075 g/mile NMOG (nonmethane organic gases); ULEV (ultra-low emission vehicle) emissions of 0.05 g/mile NO_x, 0.01 g/mile particulate matter, and 0.04 g/mile NMOG; and SULEV (super ultra LEV) emissions of 0.02 g/mile NO_x, 0.01 g/mile particulate matter, and 0.01 g/mile NMOG. EPA default Tier 2 standards are: 0.2 g/mile for NO_x and 0.125 g/mile for hydrocarbons. The committee understands that EPA will propose new Tier 2 standards in 1999.

- The reduction of particulate matter was demonstrated for three diesel fuels: a very low-sulfur fuel, a Fischer-Tropsch fuel, and DMM15 (a blend of low-sulfur diesel fuel and 15 percent dimethoxymethane, which reduced particulate matter emissions by 60 percent). These results demonstrated that emissions can indeed be reduced through fuel modifications.
- Test fuels were delivered to each of the three USCAR partners to be incorporated into their engine development programs.
- The EPA completed comparisons of emissions from a premier diesel-based fuel with Swedish City Diesel fuel (a very low-sulfur, low-aromatic, high-cetane fuel), which demonstrated a particulate matter reduction and a nominal NO_x reduction. Tests were conducted in engines of larger size than would be used in the vehicles under development in the PNGV program.
- The DOE initiated a program to promote collaboration with energy companies in the development of fuels capable of achieving the new research target in CIDI engines.
- New programs for testing alternative fuels for CIDI engines were started by the USCAR partners.
- A fueling system for dimethyl ether, a possible alternative fuel, was developed by AVL List GmbH.
- U.S. automobile manufacturers suggested a 30 ppm sulfur standard to the fuels industry.

The 4SDI technical team projects that the CIDI HEV performance could meet the triple fuel economy targets (Goal 3) at Tier 2 levels with a reformulated diesel fuel with a very high cetane number, very low aromatics, and no sulfur. They also predict that meeting the emission targets will not be possible without a reformulated fuel.

Exhaust-Gas After-treatment

Although reformulated fuels can significantly lower the emission of particulate matter (e.g., a low sulfur, DMM15 fuel) relative to a premier diesel fuel, their effect on NO_x emissions is small (<10 percent). Therefore, an after-treatment system that meets the cost and performance target remains a critical challenge.

Two lean-NO_x catalyst technologies are under active development for the CIDI engine by the PNGV program and elsewhere. The first, catalyst materials supported on a ceramic monolith structure, can reduce NO_x to nitrogen by reaction with hydrocarbons under lean (low fuel-air ratio) engine operating conditions. Because the hydrocarbon levels in CIDI engine exhaust are low, additional hydrocarbons must be added upstream of the catalyst to achieve this reduction, which lowers fuel economy by a few percent. The national laboratories are actively engaged in developing promising catalytic materials as part of the PNGV program, and technology transfer to the major catalyst manufacturers has been initiated. In October 1998, DOE's Office of Advanced Automotive Technologies released a solicitation for proposals for much larger, more focused two to three year engineering-development projects. The solicitation is intended to involve the automotive manufacturers, component suppliers, and catalyst suppliers. Awards have been announced and include catalyst suppliers as subcontractors.

In the past year, under the terms of a CRADA, catalyst suppliers have prepared a full-brick, monolithic device for testing using catalyst formulations developed by the national laboratories. NO_x removal using the full-brick device is comparable to the removal in laboratory tests using powder catalysts. With the injection of diesel fuel into the exhaust gas, 30 to 35 percent of NO_x was removed in a dynamometer test following the federal test procedure (FTP) cycle. Long-term stability tests will be performed with assistance from catalyst manufacturers. The committee is encouraged by the PNGV's increasing emphasis on the development of practical lean-NO_x catalyst systems for the CIDI engine and urges PNGV management to pursue these R&D initiatives aggressively.

The second lean-NO_x exhaust-treatment technology is plasma-assisted catalysis, where the exhaust flows through a nonthermal (low-temperature) plasma discharge and over a catalytic surface. This technology is at an earlier stage of development than the lean-NO_x (selective-reduction) catalyst approach summarized above, and its potential is less clear. The plasma-discharge power requirements would increase vehicle fuel consumption by a few percent. Several national laboratories are actively involved in research on this technology as part of the PNGV program, and results to date are promising. The underlying science is not fully understood, however, and very little engine testing of this technology has been attempted.

The PNGV stated goal for plasma reduction of NO_x is a 50 percent reduction in NO_x with less than a 5 percent fuel economy penalty. To date, only bench-scale tests of plasma technology have been done at a space velocity[3] of one-half the value expected for CIDI engines based on typical engine configurations. N_2 production was detected, but no N_2O, HNO_3, or HONO by-product species. At these low space velocities, using a two-stage packed-bed reactor, NO_x reduction was 65 to 70 percent, with a fuel consumption equivalent of 0.5 to 1 percent. These results were obtained with simulated diesel exhaust. Strong temperature dependence of the NO_x reduction efficiency was also observed. The committee feels that PNGV should increase its efforts toward understanding, evaluating, and developing nonthermal plasma-catalysis technology, which may prove to be more effective than selective lean-NO_x catalytic reduction.

[3]The space velocity (the volumetric flow rate of gas divided by the volume of the reactor) is a critical parameter to model in laboratory tests. The conditions for the tests do not duplicate the conditions required in an engine.

The technical team is encouraging more interactions between researchers on light-duty CIDI engines and the developers of heavy-duty engines. The focus of these interactions is on fuels and after-treatment, including research on lean-NO_x catalysis and nonthermal plasma-assisted catalyst systems of exhaust-gas after-treatment. Prototype hydrous metal oxide-supported bulk powder catalysts have shown up to 70 percent NO_x conversion efficiency in laboratory experiments at temperatures as low as 170°C. Hydrous metal oxide-supported catalyst on alumina-cordierite monolith cores have shown reduction efficiencies of up to 60 percent at temperatures of approximately 200°C.

Sensors and Controls

To meet the PNGV performance and emission targets, precise control must be maintained over the entire power-train system, ranging from in-cylinder combustion processes to the flow rate of reductant into exhaust-gas after-treatment systems. This can be accomplished only if the requisite sensors and control algorithms are also developed. The development of the sensors (e.g., for combustion, temperature, pressure, emissions, and other parameters) and control technologies is being pursued through the USCAR Low Emission Program. Eight technical approaches to sensors were being investigated: electrochemical, thickness shear-mode quartz resonator (TSM), ion mobility, microwave, surface acoustic wave (SAW), infrared, mass spectrometry, and millimeter wave. Of these technologies, it has been determined that only four are viable: electrochemical, TSM, ion mobility, and microwave. Laboratory testing of prototypes (e.g., NO_x sensors) is under way, and the Low Emission Program is performing dynamometer-screening tests of two devices.

Current Program Elements

The key performance challenges for achieving the PNGV targets have been identified in the context of 4SDI engines as achieving the very low required levels of NO_x and particulate matter emissions while maintaining performance. The goals of the technical program are to develop enabling technologies in the areas of fuels, combustion systems, after-treatment, and controls and sensors.

An important aspect of the program for the next year is to begin testing integrated systems, i.e., to initiate fuel system, combustion control, and after-treatment programs with suppliers. This will be done through DOE solicitations for both CIDI and SIDI engines. Test programs will be run at the USCAR partners' facilities in conjunction with tests at FEV and AVL List GmbH. Each program will have a slightly different focus. The programs at GM, Ford, and DaimlerChrysler will include special fuel blends in the test matrix, and tentative plans have been made to include after-treatment devices. Passive and active lean-NO_x systems, plasma-catalyst systems, particulate and NO_x traps, and storage catalysts are being considered.

Engines

In addition to tests on integrated systems, investigations of advanced single-cylinder engines are planned to determine the potential for combustion control via an advanced fuel-injection control. Also, a substantial increase in the homogeneous-charge compression-ignition program at SNL is planned. The objective of these programs is to further a fundamental understanding of combustion regimes and control approaches.

Fuel Formulation

The incorporation of fuel specifications and the effects of various fuels on engine performance and emission systems will continue to be a major focus of the 4SDI technical program. The 4SDI team plans to continue testing fuels at Southwest Research Institute (SWRI) with the objective of optimizing the combustion parameters for a given fuel. DOE and the Engine Manufacturers Association (EMA) are planning a fuels/after-treatment test program, which should be coordinated with the test programs of the USCAR partners. In addition, the teams plan to initiate an investigation of the toxicity and lubricity of reformulated fuels.

Exhaust-Gas After-treatment

The primary objectives of research on the lean-NO_x catalytic systems are to enlarge the temperature window of effective catalyst activity and to involve catalyst suppliers in the program. Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), Oak Ridge National Laboratory (ORNL), Pacific Northwest National Laboratory (PNNL), and SNL are participating. The project plan is to demonstrate the catalyst performance first using bulk powder, then incorporated into a monolith core, and finally using a full-size brick. In fact, two patents for hydrous metal oxide-supported materials were issued in 1998. Tests on dynamometers of several vendor-supplied bricks are ongoing at ORNL. In 1999, testing will be done with a smaller CIDI engine that is more representative of the power plant for the PNGV concept vehicles.

Engine testing of the plasma-assisted catalyst is scheduled to begin in 1999, which would enable the technical team to evaluate the effect of the plasma on the particulates in the exhaust. In addition to engine testing, work will continue on the development of enhanced catalyst materials and models to characterize the chemistry during plasma discharge.

Sensors and Controls

The development of sensors to provide data to control systems continues to be a critical aspect of the fuel, combustion, and exhaust-gas after-treatment system. Major breakthroughs are still needed in all four sensor technologies under development: electrochemical, TSM, ion mobility, and microwave. In the coming year, basic research will continue in these areas, as well as testing of prototype sensors on dynamometers and vehicles. NO_x sensor development is also planned.

International Developments

All industrial members of the 4SDI technical team are intimately involved with, and aware of, through their respective companies, the development of CIDI engines in Europe. These companies are competing internationally and participating in the development and marketing of CIDI engines for the European market. According to the 4SDI technical team, Europe and Japan have devoted far more resources to research on CIDI engines than the United States. The committee was not informed of the status of engine development and technical directions in Asia.

Assessment of the Program

The committee believes the 4SDI technical team has correctly identified the major technical challenges facing 4SDI engines for use in HEVs. The CIDI engine has the highest potential for near-term low fuel consumption in a PNGV vehicle. However, the interdependence of often conflicting trade-offs between emissions, fuel economy, and fuel type are major concerns. As regulatory requirements for emissions (NO_x and particulate matter) become tighter, unless the fuel is reformulated, it is not likely that the CIDI engine, or any other 4SDI power plant, will be able to meet the PNGV targets for fuel economy and emissions. If the PNGV program waits for alternate technologies to mature sufficiently to meet the PNGV goals, significant midterm gains in fuel economy may not be realized.

Fuel economy should be considered a systems problem. In other words, the engine, fuel formulation, exhaust-gas after-treatment, and controls and sensors must be considered as interdependent system components. A systems approach will require a cooperative effort between the automobile and fuel industries to create a balanced program. Neither industry is likely to invest in a balanced program until a cooperative interchange has been established.

Engines

Continued fundamental investigations of engine combustion will be required to exploit and expand advantageous operating regimes of the combustion engine. Certain operating regimes, for example homogeneous-charge compression-ignition, are known to have good fuel-conversion efficiency and low emissions. However, the range of engine operating conditions in which this mode of combustion can be successfully maintained is limited. A detailed understanding of the fundamental processes governing this type of combustion may lead to a wider operating range. Similarly, the extent to which the combustion process can be controlled via an advanced, highly controllable fuel-injection system, and resultant emissions, are not well understood. This is an area that could yield large short-term benefits. Finally, with a more complete understanding of the fundamentals, the phenomena that can be measured with sensors could be determined, as well as methods of processing the readings of those sensors into control strategies.

If the PNGV determines that any of the 4SDI engines will not be able to meet the emission targets, new priorities will have to be set. It seems unlikely that alternative power plants, such as fuel cells, will be sufficiently developed in time to meet the PNGV time frame. Therefore, some version of a combustion engine will probably have to be used. If so, the PNGV may have to prioritize the performance and criteria pollutant emission goals. For example, if emission standards are considered non-negotiable, reduced fuel economy would have to be accepted. In that case, the CIDI engine might no longer be considered the most promising power plant for the concept car. At this time, the 4SDI technical team is attempting to identify critical challenges and has not addressed this issue. If this situation does arise, all of the PNGV partners should be actively involved in the prioritization, which will affect the power plant for the concept vehicle and the direction of future research.

Fuel Formulation

The time required to determine new fuel formulations and to change established refining and distribution systems are issues that need to be examined carefully. It is unlikely that a reformulated fuel that requires major infrastructure changes could be implemented in time for the PNGV concept vehicles. Furthermore, the exact composition of an ideal new fuel has not been determined.

To date, experimental investigations of fuel formulations and interactions between the chemical composition of the fuel and CIDI engine combustion and emission characteristics have been very limited. Because of the adverse effect of sulfur on emissions, reducing the sulfur content of fuel to very low levels will be necessary (Tanaka and Takizawa, 1998; Wall and Hoekman, 1984). Cetane number, density, and aromatic content have often been cited as fuel properties that greatly influence exhaust emissions. It is difficult to assess the effects of different fuel properties since they are correlated with one another. However, recent data from a carefully controlled experiment indicated no apparent relationship between exhaust emissions and these fuel properties (Ryan et al., 1998). In another fuel characteristics study, Takatori et al. (1998) observed that a test fuel produced more particulate matter precursors than a base diesel fuel, even though the tested fuel had a lower distillation temperature, fewer aromatics, and lower sulfur content. The test data also suggested that branched and ring structures in the saturatedhydrocarbons portion of real diesel fuels could produce more particulate emissions than linear alkanes. As these studies show, the optimum characteristics of a new fuel have not been determined. More research will be necessary to resolve these issues for the development of a 4SDI engine system that meets PNGV Goal 3 targets.

Exhaust-Gas After-treatment

A critical component of the fuel-engine-exhaust emission system is the catalytic treatment of the exhaust. The lifetime conversion efficiency of these systems is still not known. Although substantial progress has been made, the PNGV must maintain its efforts if there is to be any possibility of meeting the emissions goals. The exhaust-gas after-treatment systems will also place requirements on the fuel composition, and technical teams working in this area should coordinate their work with work on fuel formulation.

Even with the best catalysts developed by the national laboratories, the NO_x-treatment device would still be quite complicated, involving the use of multiple catalysts for operation over a wide temperature window, as well as sensors and control systems for fuel injection into the exhaust gas. These catalysts also produce a substantial amount of nitrous oxide (N_2O) as a product (Acke et al., 1998; Lee and Kung, 1998). Further catalyst development is needed to lower the nitrous oxide production because of its high global-warming potential.[4]

Particulate matter emissions can be reduced with exhaust-treatment technology through a combination of an oxidation catalyst and particulate trap. This approach has received less attention recently because engine controls plus an oxidation catalyst and some sulfur reduction in diesel fuel have been highly effective in reducing the particulate emissions of CIDI engines, and additional improvements are possible. However, the proposed particulate standards could not be met with engine controls and short-term fuels improvements, so particulate-trap technology should be reexamined.

The committee urges PNGV management to determine whether sufficient effort is going into the development of control technologies for particulate emissions from CIDI engines. If not, the program plan should be modified accordingly. The interactions and trade-offs among particulate-control technology, NO_x-control technology, fuel requirements, fuel economy, and cost must be continued.

[4]On a 100-year horizon, the global warming potential of nitrous oxide is 320, compared with unity for carbon dioxide (UN, 1995). Global warming potential takes into account how different molecules absorb infrared radiation emitted by the earth and the expected residence time in the atmosphere of a molecule. The PNGV is analyzing a number of economic and environmental impacts of different vehicle/fuel combinations, including the emissions of greenhouse gases from the entire fuel cycle (Wang et al., 1998).

Recommendations

Recommendation. The 4SDI team should continue its program plan but should provide a more quantitative means of assessing progress and technical status relative to targets. In particular, the program should focus on exhaust-gas after-treatment and the development of performance or fuel specifications for a clean diesel fuel.

Recommendation. The 4SDI technical team should develop projections of the performance of compression-ignition direct-injection and gasoline direct-injection power-train systems, especially comparisons of the estimated emissions and fuel economy for each system. These projections would be a first step toward the quantification of trade-offs between emissions and fuel economy based on current and emerging state-of-the-art technologies.

Recommendation. Because one of the objectives of the PNGV program is to develop a vehicle that will be competitive in a global market and because fuel economy is a stronger market force in Europe and Asia than in the United States, the PNGV should continue development of the compression-ignition direct-injection engine.

FUEL CELLS

Fuel cells are considered the probable long-term replacement for internal-combustion engines in automobiles and other transportation systems. Indeed, this perception is growing as more people and organizations learn of the potential for massive reductions in emissions and, depending on fueling system implementation, significant increases in thermal efficiencies compared to internal-combustion engines. Undoubtedly, the PNGV's activities have contributed to this perception and have stimulated many fuel-cell programs both nationally and internationally.

All of the evidence available to the committee continues to indicate that fuel cells have the potential for emission and efficiency gains. However, many important technical issues must still be resolved, including bringing down the high cost. Most of the unresolved technical issues are related to the use of liquid hydrocarbon fuel on board the vehicle, especially problems associated with gasoline as the onboard fuel.

The use of a liquid fuel entails a fuel processor.[5] A fuel processor is not an "instant-on" device but requires time to reach the internal temperatures necessary to reform liquid fuel into a hydrogen-rich gas. Reaching the reformation temperatures requires considerable heat, which is provided by burning some of the fuel,

[5]A direct methanol system is in the early development stage but is likely to be on a much longer time scale than reformer systems.

either in an external burner (e.g., steam reformer) or an internal burner (e.g., partial-oxidation [POX] or autothermal reformer). In either case, unburned hydrocarbons and CO are produced, which could be released to the atmosphere. The start-up delay caused by the fuel processor warm-up time is a major reason for considering a hybrid vehicle with a reserve of stored energy (e.g., a battery) and enough available power to drive the vehicle until fuel-cell power is available. Other reasons for a hybrid vehicle are for fast power response (also related to transient response of the fuel processor) and to provide a reservoir for recovering part of the braking energy through regeneration (which is not related to the characteristics of a fuel processor).

In terms of fast start-up, fast response time, essentially zero emissions, high system efficiency, and the least complex energy converter, the preferred fuel is gaseous hydrogen. However, because of its very low density, it is very difficult to store enough hydrogen gas onboard the vehicle to travel more than about 100 miles. Other problems include the lack of infrastructure for widespread distribution, high cost (two to three times the cost of gasoline on an energy basis), and problems with refueling and indoor storage.

The most likely candidates of the liquid-hydrocarbon fuels are methanol and gasoline. Methanol can be reformed at a much lower temperature than gasoline (about 400°C vs about 700°C for gasoline) and has a hydrogen/carbon ratio about double that of gasoline. But, like hydrogen, methanol fuel has virtually no infrastructure for distribution. Thus, gasoline (probably reformulated to lower vapor pressure and with some sulfur removed) is the PNGV's fuel of choice, at least in the near term. The methanol industry, however, appears to be highly motivated to develop both production and infrastructure capabilities. Potential environmental and health impacts of methanol are well known and are being addressed by potential methanol suppliers and relevant government agencies.

Gasoline is a rational choice at this time because no vehicle could be attractive to the general public without the widespread availability of fuel at a competitive price. Even so, the choice of gasoline aggravates the technical (and cost) problems of the development of an acceptable fuel-cell power train for the PNGV program. In fact, most of the PNGV's funding and efforts in the past year have been focused on the development of fuel processors. This situation is not expected to change in 1999. The PNGV's efforts have been aimed primarily at making the processor smaller, lighter, cheaper, faster responding, more efficient, and capable of producing lower concentrations of CO (which dramatically reduces fuel-cell stack performance). At the same time, parallel efforts are under way to make fuel-cell stacks more tolerant to the CO being produced by the POX gasoline reformers. The hope is that these simultaneous efforts to reduce the production of CO by the fuel processor/cleanup system and to increase the tolerance of the fuel-cell stack to CO will converge on workable system components. In view of the difficulties associated with the development of a gasoline system, the PNGV should rethink its overall rationale for fuel selection.

As design and analysis continue, it has become evident that there is a big difference between fuel-cell *components* that perform satisfactorily and a fuel-cell *system* that performs satisfactorily. Obviously, most of the PNGV's efforts to date have focused on components and subsystems. However, the committee believes that system integration and control problems will also present formidable challenges. Until very recently, however, systems issues have received little attention. This was partly a reflection of the emphasis on the development of components, but partly also a result of the delayed development of (still unverified) system simulation tools. A fuel-cell system model has reportedly now been developed and transferred to the systems analysis team and developers, and validation of the model with data from a 10-kW integrated fuel-cell system is planned.

Besides the lack of system simulations, there is still a need for experimental data for a gasoline fuel-cell *system*. A breadboard gasoline reformer was tested, as well as cleanup components for the reformate gas produced by the reformer that then enters the proton-exchange-membrane (PEM) fuel-cell stack. However, these components did not create a complete system, and only minimal operational capability was demonstrated for the processor and stack. Even though impressive accomplishments have been made, the committee concluded that additional progress will be necessary, even essential, for the development of a successful gasoline fuel-cell energy converter.

Program Status and Progress

Milestone Schedule

Based on a presentation to the committee in October 1998, the fuel-cell concept vehicle is expected to be several years behind the original PNGV schedule. A fuel-flexible[6] concept car could possibly be ready by about 2003 or 2004 (Milliken, 1998). However, comments to the press by automotive company executives have suggested that fuel cells will be available for production at an earlier date. Several completed and planned events are directed at achieving a fuel-cell system for a concept vehicle. The following activities have been completed:

- In 1997, AD Little (ADL) demonstrated a 1-kW gasoline fuel processor with a PEM stack.
- In 1997, Ford/International Fuel Cells (IFC) demonstrated a 50-kW PEM stack with hydrogen.
- In 1998, GM demonstrated a brass-board methanol 30-kW fuel processor with PEM stack and system.

[6] Fuel-flexible or multifuel might be misleading terms. For near-optimum performance, the fuel processor would have to be tailored for a specific fuel.

Activities in progress or about to be started include the following:

- PlugPower will demonstrate integration of a 10-kW fuel-flexible fuel processor with a PEM stack.
- PlugPower will demonstrate a 30-kW hydrogen-fueled PEM stack.
- In 1999, IFC and PlugPower plan to demonstrate a 50-kW fuel-flexible fuel processor with a PEM stack.

The completed activities have already led to the demonstration of a methanol "mobile platform," and a hydrogen "mobile platform" will be announced soon. These are expected to lead to a "fuel-flexible mobile platform" by about 2002. The subsequent development of a 50-kW fuel-flexible fuel processor integrated with a PEM fuel-cell system by about 2003 could lead to a fuel-flexible concept car by about 2004. The milestone schedule projected by PNGV seems ambitious but possible. Significant progress was made in 1998 in virtually all areas, including stacks, components, fuel processing, system modeling, and overall system integration (for a methanol system).

Stacks and Other Components

A compression-molded carbon-composite bipolar separator plate, which is an important component for fuel-cell stacks, was demonstrated in 1998 by the Institute for Gas Technology (IGT). This plate had a materials cost of only $4/kW, which, combined with a conceptual design for mass production, is expected to meet the cost goal of $10/kW. The performance of the plate met or exceeded the performance of machined graphite plates.

In the past year, impressive improvements were made in anode tolerance to CO. Tests were conducted at LANL with up to 100 ppm of CO in reformate with no apparent performance penalty compared to reformate with no CO. However, an anode-platinum loading of 0.6 mg/cm^2 and 4 percent air injection were required, and durability has not been tested. This concept is expected to be incorporated into PlugPower stacks for testing in 1999.

The 3M Company tested prototypes of high-volume, potentially lower-cost membrane-electrode assemblies (MEAs), which could dramatically reduce costs. Although excellent performance was demonstrated with low platinum loadings (0.1 mg/cm^2), the data were only for hydrogen/oxygen. The performance for reformate/air has not been determined.

Fuel Processors

A catalyzed POX reformer was designed and tested at ANL. The tests were performed with standard gasoline and produced a start-up time (based on 30 percent H_2 concentration compared to a theoretical maximum of 40 percent) of less than four minutes. Although this time is still longer than the 30-second start-up target, it is much shorter than the tens of minutes that had been required.

LANL has designed and tested a 50-kW modular preferential-oxidation (PrOx) fuel processor that, through three stages, reduced CO from 8,000 ppm to 30 ppm. However, the cleanup target was 10 ppm, and approximately 4 percent of the hydrogen was also consumed in the oxidation process.

PNNL continues to work on microchannel heat exchangers with the development of a 50-kW gasoline vaporizer. The vaporizer volume is only about 300 cm^3, which is about 10 percent the size of a conventional vaporizer of the same capacity. Preliminary tests show a low pressure drop (about 3.5 psi at rated flow) and no noticeable performance degradation due to "fouling." This technology could be extremely important for reducing the size and weight (and even the cost) of components of heat exchangers.

Systems

GM has built and operated a 30-kW methanol brass-board system using a GM methanol steam reformer and a Ballard PEM stack. The system includes sensors and controls that allow automatic operation and generally available automotive components. Steady-state emissions were essentially undetectable, although start-up and transient emissions were not measured. The peak system efficiency was considerably lower than predicted (30 percent compared to 38 percent), and peak power was 25 kW, as compared to the expected 30 kW. The performance loss was attributed to the CO cleanup system.

ANL has completed the development of a computer model of a fuel-cell system, which has been transferred to systems-analysis teams and fuel-cell developers. The model has not yet been verified with experimental system results.

Clearly, impressive technical progress has been made in the past year. However, the results also show that much more remains to be done. For example, in the systems area, a steam-reformed methanol brass-board system should be considerably less difficult to integrate and control than a gasoline system utilizing POX and subsequent "cleanup." Even so, the methanol systems did not meet performance goals, and no start-up or transient data are available. Parallel efforts to increase CO tolerance of the stack and decrease the CO output from the fuel-processor/cleanup system have been successful but at a high cost in terms of other important parameters, such as size, catalyst loading, and fuel consumption.

Attempts so far to develop turbomachinery to provide the PEM pressurization with acceptable size, cost, and performance have been partially successful, but none of the designs comes close to meeting all of the goals. However, efforts are continuing to improve nonpressurized systems. At this point, it is not clear if a pressurized system would have advantages in terms of overall system cost and performance over a nonpressurized system.

Costs

Significant cost reductions seem to be within reach in several areas, such as MEAs and molded separator plates. In areas such as the air pressurization system and fuel processing, however, costs are still very high. The most recent study by Ford/Directed Technologies, Inc. (DTI), projected costs based on "known but not implemented" processes at $77/kW. This projection is very encouraging compared to the $500/kW estimated by the PNGV during the committee's fourth review and compared to the target of $50/kW for a 2004 concept vehicle (NRC, 1998a). The methods and assumptions used by Ford/DTI were not disclosed but were reported to be "rigorous" and "detailed."

International Developments

Both Europe and Japan are continuing to make substantial efforts to develop fuel-cell technology and fuel-cell-powered vehicles. Ballard Power Systems, Inc., of Canada and their activities with joint venture partners, DaimlerChrysler and Ford, still represent the most visible efforts to commercialize stacks, fuel-cell energy converters, and electric drive components for vehicles. The companies have indicated production volumes of fuel-cell systems of thousands by 2002, 40,000 by 2004, and 100,000 by 2006. Ballard has also entered into a joint venture with GEC Alsthom to supply fuel cells for stationary applications in Europe and Canada. Ballard continues to supply stacks for the majority of both U.S. and foreign fuel-cell vehicle programs. The company has also supplied three hydrogen-fueled buses to Chicago and several to Vancouver, as well as one methanol-fueled 40-ft bus to Georgetown University (in Washington, D.C.).

In August 1998, United Technologies Corporation (UTC) formed a limited liability company, IFC, LLC, to expand its fuel-cell business in the transportation market. Toshiba Corporation and UTC are equity investors in IFC, LLC.

DaimlerChrysler is continuing to develop the A-car class methanol-fueled NECAR IV and is apparently developing a hydrogen-fueled version of this vehicle for demonstration and testing. Toyota now has a new methanol-fueled vehicle in addition to its earlier hydrogen-fueled vehicle.

Progress and Status

Clearly, major obstacles must still be overcome before the PNGV can reach essential targets to realize a practical automotive fuel-cell system. However, in the committee's opinion two very positive developments have taken place in the past year. Impressive progress has been made, and PNGV seems to have been very responsive to the committee's recommendations in its fourth report (NRC, 1998a).

In the critical area of fuel-processor development, a steady-state POX gasoline reformer/CO cleanup system (at ANL) has shown good results with low CO and more than 35 percent hydrogen yield. With the development of a 50-kW PrOx (at LANL), the first meaningful transient measurements have been made. Plans presented to the committee for 1999 include the integration of a 50-kW (by Epyx) POX reformer with a two-minute start-up time with IFC and PlugPower components and the demonstration of a bench-scale microchannel steam reformer for iso-octane by PNNL. Other significant activities are planned in design, scale-up, and expanded tests by ANL, LANL, Hydrogen Burner Technology (HBT), and others.

In stack development, important cost reductions have been identified with the composite bipolar plates (by IGT) and continuous manufacturing of MEAs (by 3M). The tolerance to CO was increased to 100 ppm (by LANL), although at a significant cost in catalyst loading and hydrogen consumption. Notable events planned for 1999 include the development and testing of four reformate-capable stacks (by IFC, PlugPower, Energy Partners, and AlliedSignal) and the continuation of the stack development programs mentioned above.

In the systems integration area, a baseline design has been completed for a gasoline system (by IFC, PlugPower, and Epyx), and the committee was told that a significantly improved systems-analysis model has been developed (by ANL) and transferred to users. The testing of the "integrated" 10-kW fuel processor and stack (by PlugPower and Epyx) was done in 1998 and subsequent tests are planned for 1999. Other plans for 1999 include the integration of the fuel-flexible processor and 50-kW stack (by IFC, PlugPower, and Epyx) and continued development of the system model (by ANL).

Major problems and uncertainties remain in the areas: (1) the air compressor/turbine still must overcome challenges with regard to performance, size, and cost; (2) the fuel processor/CO cleanup development is still in the laboratory/brassboard stage; (3) stack tolerance to CO and other impurities is still an issue; and (4) system integration remains a challenge because there is no working gasoline system, and the systems model is as yet unverified and limited. Furthermore, almost no long-term durability tests for major components have been performed or planned, and only a few high-volume manufacturing processes have been identified.

In summary, the committee commends the PNGV for making impressive progress in critical areas, as well as for responding positively to the committee's recommendations. Nevertheless, a long list of identified deficiencies (and many not yet identified) remain to be resolved. The potential benefits of automotive fuel-cell systems, however, are sufficiently high to justify the PNGV's continued efforts in this area.

Recommendations

Recommendation. PNGV should re-examine its fuels selection for fuel cells, taking into account the anticipated technical difficulties and cost implications of using gasoline as the onboard fuel.

Recommendation. PNGV should focus on improving stack performance without the use of a multi-atmosphere pressurization system.

Recommendation. PNGV should evaluate and compare reasonably optimized fuel-processor systems for different fuels to determine if the fuel-flexible or multifuel processing systems would be cost effective and would provide acceptable performance compared to systems optimized for a single fuel.

ELECTROCHEMICAL ENERGY STORAGE

Introduction

To reach the fuel-efficiency goals of up to three times the value prevailing for midsized passenger vehicles in 1993, an energy-storage subsystem will be necessary to provide load leveling for the primary power plant and to store energy recovered through regenerative braking. Load leveling in an internal-combustion engine can reduce the size and mass of the engine, improve the average thermal-energy efficiency, and permit better emissions control. It can also improve fuel economy by recovering some braking energy. Energy-storage technology can provide similar advantages of size reduction, thermal-energy efficiency, and regenerative braking if applied to vehicles using fuel cells and reformers, which have cold-start and transient-response limitations. With sufficient energy storage, an HEV can operate at a meaningful range on battery power alone, with zero emissions emitted directly by the vehicle.

PNGV is no longer focusing on ultracapacitors and pseudocapacitors, which are better suited for applications with discharge times substantially shorter than 18 s. They are also costly and have low specific energy. The PNGV has currently discontinued development of flywheels for energy storage on the vehicle, largely because of safety concerns. As a consequence, batteries designed for high specific power are now the most likely means of energy storage. Of these, lithium-ion batteries, which have high efficiency and high specific energy, have become the preferred technology in the long term but may not be available by 2000. The nickel metal hydride battery, which presents less of a challenge for control and safety, could be available by 2000.

Table 2-2 shows the targets for energy storage, as well as the status of lithium-ion and nickel metal hydride battery systems with respect to some targets. Results are generally for cells rather than for complete battery subsystems. The power-assist HEV configuration provides partial load leveling and recovery of braking energy for a fast-response engine like a CIDI in a parallel-hybrid configuration. The dual-mode HEV configuration involves more extensive load leveling, such as a fuel cell in a series configuration.

"Available energy" is defined as energy that can be delivered within the state-of-charge (SOC) range where discharge and regenerative pulse-power

TABLE 2-2 Design Targets and Present Performance for Short-Term Energy Storage

	PNGV Targets		1998 Performance	
	Power Assist	Dual Mode	Li-ion	NiMH
Pulse discharge (constant for 18 s)	25kW	65kW		
Maximum regenerative pulse power (at start of a 10 s trapezoidal pulse)	30kW	40kW[a]		
Available energy	0.3kWh	3kWh		
Energy efficiency[b]	(90%	(95%	93%	77%
Cycle life at ΔSOC = 1.5%	200k cycles	200k cycles		
at ΔSOC = 3%	120k cycles	120k cycles		
Calendar life	10yrs	10yrs	2.5yrs[c]	5yrs
Maximum mass	40kg	65kg		
Maximum volume	32L	40L		
Production costs @ 100k/yr	$300	$500		
Operating temperature range	–40° to 52°C	–40° to 52°C		
Available specific energy	12Wh/kg	83Wh/kg	38Wh/kg	12Wh/kg
Available energy density	24Wh/L	188Wh/L	82Wh/L	36Wh/L
Specific power (18 s discharge)	960W/kg	1,800W/kg	960W/kg	290W/kg
Cost per rated energy	$833/kWh	$134/kWh	$450/kWh	$1400/kWh

[a]Revised downward from 70 kW.
[b]The corresponding electric vehicle target is 75%.
[c]Based on higher temperature accelerated testing.

Acronyms: kWh = kilowatt hour; Wh = watt hour; SOC = state of charge.

Source: Haskins (1998).

targets can both be met. The available energy is always less than the "rated energy," which is defined here as the energy delivered at the one-hour discharge rate. These are both larger than the discharge energy delivered in a specified one-minute cycle designed to approximate urban driving conditions. (For example, acceleration of a 1,000-kg vehicle to 100 km/h requires 0.1 kWh for kinetic energy alone.)

The performance and cost targets for the battery are substantially more difficult for the dual-mode HEV configuration and they may preclude any series hybrid vehicle (as for a fuel cell) if there is strict adherence to the stated targets. Full hybridization, which has system limits on mass, volume, and cost, would create severe, perhaps impossible, requirements for the dual-mode hybrid, thereby eliminating an important option for trade-offs of performance, emissions, and cost from the PNGV's strategy.

The performance results shown in Table 2-2 correspond to batteries of a particular design, usually associated with the power assist. Better results, including lower cost per rated energy and higher rated specific energy, can be expected from a battery developed explicitly for applications with the same 18 s power pulse as the battery for power assist and larger capacity. The performance results presented to the committee show that results vary substantially among battery developers.

Status and Progress

Accomplishments

Cell and module development have continued apace. The vast majority of resources is devoted to battery development, fabrication, and testing. At present, three developers are working on lithium-ion batteries. SAFT has built and tested 13-Ah cells and has developed a 50-V module. PolyStor has achieved 1,920 W/kg and 100 Wh (rated)/kg in cells of about 1 Ah and 800 W/kg and 100 Wh(rated)/kg in 10-Ah cells. VARTA has achieved 1,500 W/kg and 99 Wh/kg in very small cells and is working on 6-Ah cells. Energy and power goals thus appear to be attainable, but in all cases achievement of the goals for cycle life and calendar life is questionable for lithium-ion technology. VARTA, the sole developer for nickel metal hydride batteries, has achieved 400 W/kg and 30 Wh/kg in 10-Ah cells. VARTA has also delivered a 40-cell nickel metal hydride module for testing.

Programs for 50-V module demonstrations have been initiated at PolyStor ($9.5 million for 21 months beginning March 1998) and VARTA ($8.3 million for 24 months beginning March 1998). These studies are being funded in the usual way with PNGV and the developer sharing costs.

Abuse and safety testing of advanced batteries also continues. The lithium-ion technology uses organic materials that can burn, and fire and smoke have been observed in some abuse tests. The nickel metal hydride system, which uses an aqueous electrolyte, avoids many of these problems.

Mass, volume, and cost goals from the battery subsystem have been allocated to the cell and module levels during the design and development of these components. Such allocations could be made for the power-assist mode but not for the dual mode. Furthermore, the cycle-life targets for cells and modules have not been specified.

During the past year, the PNGV identified a mismatch between the goals for power assist and the dual-mode hybrid-vehicle configuration (see Table 2-2). A battery technology that just meets the power-assist targets will be too high by factors of 5.7, 5.3, and 8 on the dual-mode cost, weight, and volume targets, respectively. For example, the power-assist mode allows 32/0.3 = 107 L/kWh, whereas the dual model permits only 40/3 = 13.3 L/kWh. This means that a battery system that just meets the former target would miss the latter by a factor of 8. The other ratios are more complicated by considerations of breakdown to module and cell levels but are similar in concept. Put another way, much higher values of specific available energy and specific rated energy would be required, values that are unlikely to be met by the candidate technologies. The PNGV has not revised the targets to resolve this discrepancy.

The PNGV now recognizes that innovations, perhaps even innovations in cell chemistry, will be necessary to achieve abuse tolerance, calendar or cycle life, and cost targets. For example, meeting the calendar-life target will require innovations in the basic lithium-ion electrochemistry. PNGV plans to mobilize the national laboratories in a new way to address these problems, avoiding proprietary issues by having them explore and refine a generic baseline chemistry, including improvements in intrinsic chemical stability.

High-power batteries require thinner electrodes than the lower power batteries used for electric vehicles. Therefore, manufacturing techniques will have to be improved. Unresolved issues for both hybrid and electric vehicle batteries include control, thermal stability, and cell stress levels in series strings of cells.

Assessment of the Battery Program

Meeting the PNGV targets, especially for calendar life and cycle life, but also for specific energy and cost, is in serious jeopardy. Consequently, PNGV is enlisting the help of national laboratories to define a generic (nonproprietary) baseline chemistry and to show, by example, how to elucidate the failure mechanisms of a system. Developing new electrochemistry is equivalent to starting over in this area.

Even though lithium-ion batteries may be preferred for the long term (2004) because of their higher efficiency and specific energy, nickel metal hydride batteries should be made available (and perhaps even advanced lead-acid, nickel-cadmium, or nickel-zinc batteries) for year-2000 vehicles.

The PNGV should seriously consider the consequences for vehicle goals if the battery targets cannot be met. A suitable model of the unit cell would permit trade-offs of battery size, performance, and cost against vehicle characteristics. For a specified battery type, say lithium-ion or nickel metal hydride, the battery could be sized to provide the required power and energy over a specified time profile, with iteration between the battery model and the vehicle model. Without these trade-offs, a fuel-cell powered, series hybrid vehicle may have to be precluded. If the interactions among partial hybridization and the size, fuel efficiency, transient response, and emissions of the primary power plant are well understood, the disparity between targets for power-assist and dual-mode hybrid vehicles could be eliminated.

Despite these problems, a battery remains the most promising technology for energy storage in hybrid vehicles. Hybrids are being developed, and have been demonstrated, outside the program with batteries that fall far short of the very aggressive PNGV performance and cost targets. At 0.3, or even at 3 kWh, energy storage is not a dominant subsystem with respect to weight, volume, or cost, and some relaxation of the targets should be possible.

Major challenges of PNGV's battery program are still calendar-life and cycle-life targets and safe abuse tolerance under representative operating conditions, as well as low cost. The PNGV needs to put these issues into perspective by (1) developing a better understanding of the factors that control calendar life and cycle life, (2) conducting more realistic simulations of abuse conditions and their effects, and (3) developing a better understanding of the factors that control battery costs in mass manufacturing. Combined with a more transparent relationship between hybrid-power-train performance and battery-performance targets, PNGV could then determine if the emerging battery technologies could meet redefined targets and goals. PNGV should make this determination before making decisions that will have major consequences for the program's schedule and prospects of success (e.g., the development of alternative battery electrochemistries).

In summary, if energy-storage performance goals are relaxed and redefined, the hybrid concept could be implemented and tested even though the batteries currently under development are unlikely to meet the present targets. The program is and will remain dominated by battery development and testing, but the performance goals and cost estimates could use some reevaluation. The PNGV is well aware of the problems related to cycle and calendar life and safety, and the committee does not feel compelled to make recommendations to address these issues. The committee is not calling for a drastic reorientation of the program because the development of high-risk systems, like lithium-ion and nickel metal hydride batteries, is appropriate for the PNGV, and more conventional batteries provide suitable fallback positions. Failure to meet goals may reflect the inappropriateness of the goals rather than the impending failure of the entire project.

International Developments

The development of high-power batteries for the PNGV program is based on the work of European developers (e.g., SAFT and VARTA). The PNGV reported little to the committee on developments in Japan, where lithium-ion technology is more advanced and is already being used in HEVs.

Recommendations

Recommendation. The PNGV should update its energy-storage requirements and goals by means of subsystem models integrated with overall system analysis. In addition to specific energy, test results should be reported for energy efficiency and specific power over well defined test protocols and compared to the refined performance goals.

Recommendation. The PNGV should decide whether safety issues with lithium-ion batteries will preclude their introduction for energy storage in hybrid electric vehicles.

Recommendation. The PNGV should conduct life-cost and performance-cost trade-off studies, as well as materials and manufacturing cost analyses, to determine which battery technology has the best prospects and most attractive compromises for meeting capital and life-cycle cost targets.

FLYWHEELS

A flywheel energy-storage subsystem on board an automobile has been defined as a relatively low-energy device (i.e., with 30 kW of power and 300 Wh of energy storage) suitable for application to fast-response power plants. A fast-response power plant, which has a similar response time to a conventional automotive engine, places a much lower requirement on power output of the flywheel than a slow-response power plant. The higher energy demands of slow-response power plants would require a large, more costly subsystem, and the flywheel has, therefore, been judged to have possible application to the less demanding power-assist HEV mode. Because of the issues of cost and weight, as well as testing to demonstrate a safety design that would contain the flywheel in case of failure, the PNGV does not consider this technology to be available for the 2000 concept vehicles, although it may still be useful for post-2000 concept-vehicle systems. Currently, the PNGV has discontinued the development of flywheels. Realizing applications of flywheel subsystems would depend on whether the vehicle system modeling indicated that cost and performance would be acceptable.

Status

In the past year, only limited systems-analysis modeling has been conducted. Design approaches for flywheel safety and failure containment have been proposed, but very limited validation testing has been done. Until test results are available and the cost of associated electronics is understood better, the PNGV does not plan to develop further systems modeling. DOE is maintaining contact with, and monitoring activities within, the flywheel technical community although no funds have been allocated for fiscal year 1999 for flywheel development. The PNGV is monitoring the progress of two flywheel programs, the joint Aerospace Flywheel Program (a cooperative project of the Air Force and the Defense Advanced Research Projects Agency, and the National Aeronautics and Space Administration) and the Defense Advanced Research Projects Agency Flywheel Safety and Containment Program.

Plans

In anticipation of future systems modeling, LLNL is developing a second-generation flywheel model to be included in the PNGV vehicle-systems model. LLNL is procuring a flywheel from the Trinity Battery Company and has an agreement with the University of California, Davis, for installation and testing on an HEV; the university is seeking financial support from the California Energy Commission.

Recommendation

Recommendation. Because limited progress is expected on the flywheel device, the PNGV considers it a post-2000 technology. Given that no money has been allocated for flywheel development in PNGV's fiscal year 1999 budget, the PNGV should follow through on monitoring developments in other flywheel programs.

POWER ELECTRONICS AND ELECTRICAL SYSTEMS

The three USCAR partners are pursuing two design philosophies for the HEV. One is the dual-mode hybrid, in which primary propulsion can be provided by either the electrical or internal-combustion engine drive system; the other is the power-assist HEV (sometimes referred to as the "lite" hybrid), in which an electrical drive augments primary internal-combustion engine propulsion power during acceleration and provides the vehicle with electric power for moving from standstill. In either case, success depends on the development of efficient, economic actuators, motors, and power electronic converters.

Status and Progress

The electrical and electronic systems technical team (EE technical team) has made impressive progress over the last year. The team's program is now well organized and managed. Projects at the national laboratories by DOE's Cooperative Automotive Research for Advanced Technologies (CARAT) program and by the Small Business Innovative Research (SBIR) program have been integrated into a coordinated program to address technical objectives. Now that the automotive integrated power module (AIPM) has been specified, results of the Navy's power electronic building block program can be directed toward meeting the unique requirements of the PNGV, a concern raised in the committee's fourth report (NRC, 1998a). PNGV noted that: "The AIPM is intended to be flexible and scalable to meet a large number of applications in advanced vehicles. System integration issues include delivery of complete scale modules incorporating the principles of design for manufacturability and means to update DOE existing cost analyses" (Malcolm, 1998).

An electric motor/gearbox specification has been drafted in collaboration with the systems-analysis team, and it was reported to the committee that a request for proposals (RFP) for its design and construction was planned for early 1999. The committee is pleased to see that the EE technical team has been collaborating with the systems-analysis team, as recommended in the committee's fourth report.

During the last year, the EE technical team has either initiated or redirected a large number of industrial and national laboratory activities to address the important issues of high-performance/low-cost materials, new manufacturing technologies, system integration, and standardization. These efforts can be broadly categorized as AIPM development, electric-motor development, and the integration of the AIPM with the motor. A number of national laboratory projects are directed at developing new dielectric materials and dielectric-deposition processes for the manufacture of capacitors, which are expensive and environmentally sensitive components in power-electronic systems. New thermal-management materials, such as carbon foam, are also being investigated for possible application in power-electronic systems.

Assessment of the Program

In its fourth report, the committee expressed concern about the PNGV's prospects for meeting its cost targets for power electronics and motors. The EE technical team has verified the presently achievable cost of $15/kW (peak) for power electronics through modeling done separately by each USCAR partner. The 2004 target of $7/kW (peak), a reduction of more than 50 percent from today's calculated but unvalidated cost, will require substantial innovations in component and manufacturing technologies. Although some of the technology development programs in the national laboratories (e.g., nanostructure multilayer capacitors) look promising, their projected costs are still uncertain.

Based on an analysis using DOE's cost models, the EE technical team believes the 2004 target to be realistic. The analysis necessarily relies on the assumption of innovative developments in component and manufacturing technologies, although these have not been identified. The DOE cost model does an excellent job of analyzing historical cost data for power-electronic converters in different power categories and breaking the cost down by component and process. However, although the EE technical team has done an excellent job of identifying cost obstacles and initiating or redirecting development programs to overcome them, the cost projections to the year 2004 seem to be simple extrapolations. This issue is critical because it affects the economics of other vehicle systems that rely on power electronics (e.g., fuel cells and accessory drives).

The committee is concerned about the limited response to the RFP for development of the AIPM, which may reflect an industry opinion that achieving the AIPM specifications is not feasible. However, the small response may also reflect a concern that there is no near-term market at present for the AIPM or that potential respondents are already working with an automotive manufacturer on proprietary power-electronic developments.

Because the RFP for the motor/gearbox was just issued, industry's response is not yet known. However, the committee expressed its concern last year that the target motor cost of $4/kW might be unrealistic in light of the fact that today's cost of $10/kW is essentially the cost of materials. The projected increase in power density, from 4 kW/l to 5 kW/l, does not represent a sufficient reduction in materials to account for the desired decrease in cost.

Three small subgroups of the committee visited the three USCAR partners and were provided with proprietary presentations of prototype vehicles. In two of the three vehicles, the electrical system and drive designs were elegant and well conceived, which was reflected in vehicle performance. Functionality of the power electronics and electrical system is not an issue in these vehicles.

Although the development of electrical accessories was not explicitly addressed during this review, the committee notes that several of the development programs under the EE technical team's umbrella are focused on accessories. The compressor motor for the air conditioner and an electrical turbocharger assist are two examples.

Recommendations

Recommendation. The PNGV should review its power-electronics and motor cost targets for 2004 to determine if they are realistic based on known and projected technology. Because of the reliance of other vehicle systems on power electronics, the PNGV must have a high level of confidence that its cost projections can be met.

Recommendation. The PNGV should conduct a thorough analysis of the electrical-accessory loads to ensure that targets for supplies of electrical energy are consistent with system needs.

STRUCTURAL MATERIALS

The reduction of vehicle mass through improved design, lightweight materials, and new manufacturing techniques is one of the key strategic approaches toward meeting the PNGV Goal 3 fuel economy target.[7] Figure 2-2 shows the design space for trade-offs between power-train efficiency and vehicle-mass reduction. To achieve the 80 mpg target of Goal 3, however, additional measures,

[7]This section focuses on PNGV progress on structural materials. The issue of vehicle crashworthiness is addressed in Chapter 4.

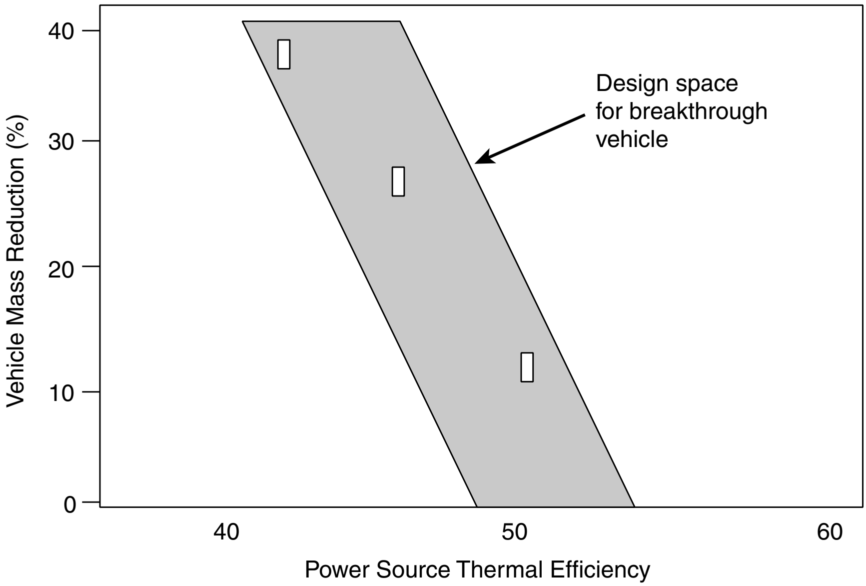

FIGURE 2-2 PNGV design space.
SOURCE: PNGV (1998).

such as regenerative braking with 70 percent efficiency, improved driveline efficiency, and reduced aerodynamic drag, will be necessary. According to the systems analyses on which the results in Figure 2-2 are based, a 50 percent reduction in the weight of the baseline vehicle is equivalent to improving the power-train thermal efficiency by about 9.4 percent above the baseline value (about 18.2 percent for the urban-highway cycle). After considering the options, the PNGV decided to adopt the following targets: 40 percent mass reduction, 40 percent power-train thermal efficiency, and a regenerative braking system with 70 percent efficiency. These must be achieved while the baseline vehicle performance, size, utility, and cost of ownership are maintained.

The PNGV has set substantial vehicle weight-reduction targets for various subsystems (Table 2-3). These targets will result in an overall reduction in curb weight of 1,200 lbs (40 percent), leading to a 2,000-lb vehicle.

Materials Road Map

The PNGV materials team has developed a road map that identifies lightweight material alternatives for the major subsystems of the vehicle. Alternative materials are prioritized based on their weight-saving potential and feasibility to meet the PNGV time requirements. Technical challenges are also identified and

TABLE 2-3 Weight-Reduction Targets for the Goal 3 Vehicle

Subsystem	Current Vehicle (lbs)	PNGV Vehicle Target (lbs)	Mass Reduction (%)
Body	1,134	566	50
Chassis	1,101	550	50
Power train	868	781	10
Fuel/other	137	63	55
Curb weight	3,240	1,960	40

Source: Stuef (1997).

prioritized by the likelihood that solutions can be found to overcome the challenges. The road map is summarized in Table 2-4. The absolute magnitude of the weight-saving potential depends not only on the density and structural properties but also on where the use of these materials is suitable.

The committee was pleased to see that 38 projects have been established to address the technical challenges identified in the materials road map. In addition, the R&D portfolio is supported by 13 manufacturing technical-team projects and five supplier projects. The committee believes that these projects have the potential to overcome the barriers that have made it difficult to use alternate materials in today's vehicles. The committee recognizes that many of these programs have just been initiated and that, therefore, there is little progress to report at this time. The committee has suggested that the materials technical team use the U.S. Automotive Materials Partnership (USAMP) project tracking system as a means of reporting progress to the committee on an annual basis.

The requirement that there be no increase in the overall cost of vehicle ownership presents an obvious hurdle to meeting the PNGV's fuel economy goal. This is shown clearly in Table 2-4, where the reduction in the cost of feedstock is a common challenge for all alternate materials. The committee is pleased to note that PNGV personnel are working closely with materials suppliers to develop less costly manufacturing processes and new design practices that utilize materials more efficiently.

Status and Progress

The major material alternatives under consideration in 1998 for reducing vehicle weight are discussed below in terms of the primary vehicle subsystems: body, chassis, and power train. These subsystems account for 96 percent of the weight of the Goal 3 baseline vehicle (Table 2-3). For each subsystem, there are several competing alternative materials. The weight savings quoted for various

TABLE 2-4 Materials Road Map: Weight-Savings Potential and Technical Challenges

Materials[a]	Weight-Savings Potential (lbs)	Primary Subsystem	Primary Challenge
Aluminum	600	body	feedstock cost
Magnesium	150	chassis/body power train	feedstock cost
Polymer composite (GFRP) components	150	body	high-volume manufacturing
Polymer composite BIW (CFRP)	500	body	low-cost carbon fiber
Steel	>120	body	design manufacturing concepts
Metal matrix composites	30–50	chassis and power train	feedstock cost
Titanium	50	chassis and power train	feedstock cost
Glazing materials	50	body	safety regulations and cost

[a]Materials are listed in decreasing priority.

Acronyms: GFRP = glass fiber-reinforced polymer; CFRP = carbon fiber-reinforced polymer; BIW = body-in-white.

Source: PNGV (1998).

subsystems and components do not take into account secondary weight savings that derive from the fact that certain components may be downsized in keeping with the total weight of the vehicle. Examples of candidate subsystems are: wheels, brakes, suspension components, and power trains. If a vehicle is designed from the ground up, secondary weight reductions can be as much as 0.5 lbs for every 1.0 lb of primary weight reduction.

Body System

The baseline vehicle body system weighs approximately 1,100 lbs and is targeted for 50 percent weight reduction. Because the body-in-white (BIW)

(590 lbs) and the closure panels (220 lbs) account for a large fraction of the weight, the PNGV team is concentrating on reducing the weight of these components and has identified weight-saving opportunities of aluminum sheet to be in the range of 50 to 55 percent, or 400 to 450 lb. Competing with aluminum sheet are glass fiber-reinforced polymer composites (GFRP) and carbon fiber-reinforced polymer composites (CFRP). GFRP materials, which may be considered for closure panels, offer only a 25 to 35 percent weight savings. The PNGV materials team has fabricated a BIW from CFRP sheet and sandwich materials that achieves a 68.5 percent weight reduction over the Multimatics baseline vehicle (Multimatics is a Canadian manufacturer of automotive parts). Another alternative is a more efficiently designed steel BIW, which has been demonstrated by the American Iron and Steel Institute ultralight steel auto body project. This approach has the potential of a 20 percent (120 lbs) weight reduction in the BIW structure and a cost reduction of $154. If more efficient design techniques are applied to all alternative-material BIW concepts, the 50 to 55 percent weight savings of aluminum over steel should remain intact.

The U.S. automotive industry has considerable production experience in stamping aluminum closure panels, usually deck lids or hoods, and in many cases aluminum panels have been put into high-volume production, in spite of a sizable cost penalty. In this situation, a 40 to 50 lb weight reduction is considered worthwhile because it keeps an "overweight" vehicle from being classified in a higher weight class, where it is more difficult for the vehicle to meet the tailpipe emission standards and corporate average fuel economy (CAFE) standards.

As a matter of public record, several aluminum-intensive prototype vehicles have been built outside the PNGV program by the USCAR partners and evaluated for ride, handling, noise, vibration, and harshness, crashworthiness, and production processes, such as stamping, extruding, joining, and painting (Jewett, 1997). Thus, the change to an aluminum-intensive vehicle would not be a major technological challenge because the USCAR partners already have extensive design and manufacturing expertise with this material. The challenge is to develop new processing methods, especially for feedstock materials, so that an aluminum-intensive vehicle can be manufactured as inexpensively as a steel vehicle. Based on a price for aluminum of $1.60/lb (Table 2-5) and average weight savings of 47 percent, the cost penalty of an aluminum BIW is estimated at $400, including incremental manufacturing costs. Current PNGV programs involving direct casting of thin aluminum sheet, which avoids expensive hot-rolling processes, have the potential to reduce the cost of aluminum sheet to $1.00/lb (Table 2-5), which would reduce the BIW cost penalty to $200. With a more efficient design, a 55 percent weight savings may be possible, which would reduce the cost penalty even further.

Recyclability of the major materials of the vehicle is an important requirement. Today 75 percent of the materials of an average vehicle is recycled; PNGV has set a target of 80 percent. The procedures and processes for recycling

TABLE 2-5 Material Cost Targets

Material	Current Cost ($/lb)	Target Cost ($/lb)	Product Form
Aluminum	1.40 to 1.60	1.00	sheet
Magnesium	1.65	1.20	ingot
Carbon fiber	> 8.00	3.00	fiber
Aluminum metal-matrix composites	2.00	1.40	ingot
Titanium	8.00	2.00	bar, sheet

Source: Sherman (1998).

aluminum are already in place, and much of the material is returned to high-value applications.

The cost estimates given above include an allowance of $0.50/lb for the scrap value of aluminum. Given the current process for shredding vehicles and recovering their metal content, techniques will be necessary for separating higher value aluminum sheet from aluminum castings. Programs that could accomplish this are included in the PNGV Materials Roadmap.

In the committee's fourth report, a number of serious obstacles were discussed that would have limited the use of CFRP composite materials in meeting Goal 3 (NRC, 1998a). During the past year, however, some exciting progress has been made in the development of thin (1.0 mm) CFRP sheet and aluminum honeycomb lamellae sandwiched between CFRP layers.

A hybrid material BIW was fabricated from a variety of multilaminate materials, as shown in Figure 2-3. The PNGV BIW weighed 90 kg on a baseline BIW that weighed 285 kg in steel, or a 68.5 percent weight savings. This is significantly better than the 59 percent forecast by the PNGV materials team last year and close to what might be expected from a structural analysis assuming adequate material properties. The reduction was achieved in part by very stiff CFRP lamellae (1.0 mm), which can be formed much like steel into box beams and other more complicated shapes.

In the past, work by the USCAR Automotive Composites Consortium showed that it was difficult to achieve good frontal crash response from polymer-composite front-end structures. Some of these early problems have been overcome. In the PNGV hybrid material BIW (including CFRP thin sheet, sandwich panels, and aluminum front ends), lower cost, extruded or hydro-formed aluminum beams were used in the front-end structure to ensure adequate crash response, which was verified by 30 mph frontal-crash simulations. Finite element analyses showed that static bending and torsional stiffnesses were significantly better than for the baseline steel vehicle and that frequencies of the first bending and torsional modes were shifted to higher values.

The committee considers these results very encouraging, even though there is still much to be learned about (1) composite design techniques, (2) the consistency

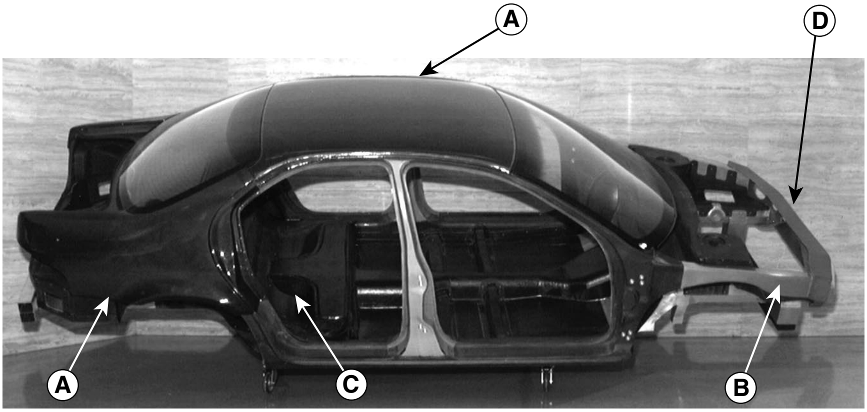

FIGURE 2-3 Multimatics PNGV hybrid-material body structure. Some selected materials used are as follows: (A): sandwich panel (aramid fiber-reinforced core with carbon/epoxy skins); (B) aluminum sheet metal; (C) sandwich panel (aluminum honeycomb core with carbon/epoxy skins); (D) sandwich panel (aluminum honeycomb core with hybrid carbon/aramid/epoxy skins).

SOURCE: Adapted from Todd (1998) and a photograph given to the committee by USCAR.

of mechanical properties in high production volumes, and (3) the reduction of manufacturing-cycle times. Finally, methods for recycling materials into high-value applications to take advantage of their intrinsic properties, as opposed to using them only as filler, must still be developed.

The major barrier to the intensive use of CFRPs for a Goal 3 vehicle is the high cost of the carbon fibers. As shown in Table 2-5, the cost of carbon fiber must be reduced from $8.00/lb to $3.00/lb. Currently, the cost of a CFRP BIW is much higher than for a steel or aluminum BIW. The committee was pleased to note that an ORNL project has demonstrated the production of carbon fibers by microwave heating, which may have the potential to reduce processing costs by 50 percent or more. Other concepts are being pursued to reduce the cost of precursor materials.

In another project, a lightweight interior has been developed, including lightweight seats, and magnesium frames, door-trim panels, and overhead system, all of which allows a 40 percent mass savings in the interior with a minimal cost penalty.

Also, work continues on lightweight glazing materials (e.g., thin glass and polymers), which offer a potential weight savings of 50 lbs. The major concerns about polymers are abrasion/scratch resistance and cost.

Power Train and Chassis System

The total weight in the power train and chassis subsystems for the baseline vehicle is 1,101 lb and 868 lb, respectively, and the targeted weight savings are 561 lb (50 percent) and 87 lb (10 percent), respectively. Thus, the total targeted weight savings for the two subsystems is 648 lb, whereas the total identified weight savings, based on the PNGV Materials Roadmap (Table 2-4), is 325 lb, a shortfall of 323 lb. Thirteen of the 38 projects in the materials road map (Table 2-4) are directed toward reducing the weight of the power train and chassis, but the committee was apprised that progress has been made in only a few projects, primarily because many of the projects in this category are new. The materials technical team has identified a process for tracking progress in all road-map projects.

Cast aluminum has been used extensively in the power-train subsystem, replacing cast iron over the past two decades in most cylinder heads and intake manifolds and increasingly replacing cast iron in cylinder blocks. This trend is expected to continue. Moreover, magnesium will be used increasingly in the power train, chassis, and body subsystems. The PNGV materials road map includes major initiatives to reduce the costs of feedstock and improve the casting processes for both materials. Progress in the cast light-metals programs includes the creation of a cast light-metal material-property database (CD-ROM) that correlates with cast microstructures, the development of a fiber-optic infrared temperature sensor for on-line process control, and the development and validation of a simulation model to predict the monotonic tensile properties of cast metals.

Studies to improve the machinability of magnesium castings and to develop a low-cost, high-temperature alloy are also under way. Improved processes for recycling magnesium will have to be developed.

Aluminum metal-matrix composite applications in chassis and power-train subsystems account for only 30 to 50 lb. The major hurdles to developing applications of this material are feedstock costs (Table 2-5) and the development of a reliable process for fabricating the composites. A low-cost powder-metal process is under development, but no progress was reported for this period.

The applications for titanium are in the chassis (40 lb potential savings) and power-train (10 lb potential savings) subsystems. The components of interest are springs, piston pins, connecting rods, and engine valves. A program designed to lower the cost of titanium feedstock has been initiated during the past year.

Program Assessment and Plans

Body System

In the past year, aluminum sheet has been the leading structural-material candidate for the Goal 3-vehicle technology-selection process because (1) the demonstrated weight savings (50 percent) meets, and might exceed, the Goal 3 target, (2) it has the best chance of meeting the affordable cost target, (3) the USCAR partners have an extensive knowledge base for the design and fabrication of components from aluminum sheet, (4) a supplier infrastructure for ore, feedstock, and semifinished materials already exists, (5) existing stamping facilities for steel can be used for aluminum without major modifications, and (6) considering all of the alternate materials, aluminum is the most recyclable alternative and would cause the fewest disruptions in the existing recycling industry for steel-bodied automobiles.

A major CRADA has been initiated between Reynolds Metals, LANL, and the USAMP to reduce the cost of aluminum sheet through the development of a thin-slab (less than 1 in thick) continuous-casting process to replace the more costly ingot-based process used today. During the past year, automotive sheet was produced from direct-cast thin slabs that demonstrated excellent formability. Another program to develop low-cost, non-heat-treatable alloys competitive with the 6000 series aluminum alloys is also under way and is about to initiate stamping trials. However, additional developments beyond continuous casting of sheet will be necessary to reduce the current manufacturing and assembly cost penalty of parts fabricated from aluminum sheet. The added costs are associated with differences in spring-back characteristics, die maintenance, joining technologies, and recycling costs.

During the past year, the fabrication of a hybrid material, CFRP BIW, from thin sheet and sandwich materials, as well as some aluminum extrusions, demonstrated an impressive 68.5 percent weight savings over a steel baseline vehicle. Even though this weight savings is impressive, CFRP technology must be viewed as a long-term alternative to aluminum. The cost of carbon fiber and a short cycle-time fabrication process are major issues that probably cannot be resolved in time to support Goal 3, year-2000 concept vehicles. Nevertheless, the promising development of CFRPs should be continued with applications targeted beyond Goal 3. An R&D program is in place at ONRL to produce low-cost carbon fiber by microwave processing. Future programs should concentrate on reducing the cost to $3/lb, developing a process for mass producing components in thin sections, acquiring a deeper understanding of reliable design for complex loading conditions, and developing high-value applications for the recycled material.

The injection molding of GFRPs being investigated by DaimlerChrysler and the Automotive Composites Consortium (thermoset resins) offers potential weight savings of 25 to 35 percent, which is considerably less than aluminum or CFRP. With this technology, the Goal 3 target would be missed by a sizeable margin. However, for Goal 1 and Goal 2 applications, GFRP may compete effectively on a cost basis with aluminum for body panels and certain structural applications because large integrated parts can be made and lower cost dies can be used, thus reducing assembly and manufacturing costs. Nevertheless, the extensive design and production experience with aluminum for body panels and structural applications, as well as the available supplier infrastructure, gives aluminum an edge in the near term.

Power Train and Chassis System

Several important R&D studies are in place to reduce the costs and improve the properties of aluminum and magnesium castings, including sand casting, semipermanent mold casting, squeeze casting, and high-pressure die casting. Progress in this area was discussed in the preceding section.

Also, the committee was pleased to see that programs have been initiated with titanium and aluminum metal-matrix composites that will help to reduce feedstock and processing costs. In the coming year, gerotors (rotating part in an air-conditioning compressor) and timing sprockets are expected to be fabricated by the low-cost powder-metal process technology for metal-matrix composites. Other new projects that will be initiated include low-cost magnesium, high-temperature magnesium, and low-cost cast metal-matrix composites.

The committee noted that there was minimal discussion of progress in this area, probably because many of the programs are in the early stages of development.

Recommendations

Recommendation. The committee continues to believe that fabricated aluminum sheet should be the primary candidate for the body-in-white and closure panels for the year-2000 concept vehicles. The development of the low-cost continuous-casting process of aluminum sheet should be given a high priority in terms of resources and technical support. In addition, low-cost processes to overcome the cost penalty associated with the manufacturing and assembly of parts from aluminum sheet should be pursued.

Recommendation. The best long-term candidate—beyond year 2000—is the hybrid-material body-in-white, featuring thin carbon fiber-reinforced polymer sheet, sandwich panels, and aluminum front ends. The development program for low-cost carbon fiber should be continued for longer term applications beyond Goal 3. A low-cycle-time process and better recycling methods should also be pursued.

Recommendation. The PNGV materials technical team should endeavor to decrease the gap between the PNGV targets for weight savings and the actual identified weight savings for the power-train and chassis subsystems.

3

Systems Analysis

Systems analysis based on effective computer modeling tools is the most effective and efficient way to ensure the optimization of vehicle performance for selected vehicle configurations, as well as for studying trade-offs between candidate subsystems during the technology-selection process. Models facilitate the preparation of specifications for each candidate subsystem and support the establishment of engineering targets. The ongoing, timely verification of selected technologies and the trade-off process for defining demonstration vehicles will depend heavily on the results of systems analyses. Achieving the Goal 3 fuel-economy level of three times the current level and other critical attributes, like emissions and the cost of ownership, will require effective modeling. (See previous committee reports for further discussions of modeling vehicle systems [NRC, 1996, 1997, 1998a]).

The systems-analysis team is responsible for developing computer models of components, subsystems, and the integrated vehicle, including the environment and driver. Working with the other PNGV technical teams, the systems-analysis team's objective is to provide analytical support for defining requirements. Analytical support facilitates the evaluation of competing technologies and vehicle concepts, as well as the timely selection of overall vehicle concepts for meeting the Goal 3 objectives.

The technology-selection (the "downselect") process was completed in 1997 during the committee's fourth review. The systems-analysis team must now support the technical teams with models and analyses to ensure that performance is optimized to meet vehicle requirements. In the fourth report, the committee recommended that more rigorous cost and design-reliability models be created as soon as possible to ensure that the concept vehicle is designed with these parameters in mind. Because vehicle cost is a major issue for the PNGV, early attention to this requirement will be critical.

PROGRAM STATUS AND PLANS

Analysis and Modeling

In the past year, considerable effort, including a good deal of debugging and training, has been spent on the development of the PNGVSAT 2.0 vehicle model. A major seminar, attended by 55 people from the technical teams and other supporting groups, was held to familiarize and train individuals in the use of the systems model. Subsystem and component analysis and modeling support are now being provided to *some* technical teams, notably, as reported in the PNGV's presentations to the committee, the vehicle-engineering, fuel-cell, and EE teams. Not all of the technical teams are making use of this support, however, even though the selection of the concept-vehicle configuration and the optimization of subsystem interfaces are vital at this phase of the program.

Subgroups of the committee met with the three USCAR partners individually to review the development of their proprietary concept vehicles. All three are using sophisticated, proprietary modeling and analysis to optimize vehicle performance. Government-supported technology development by suppliers, academic institutions, and government laboratories should also have access to validated PNGV models. Therefore, PNGV should find a means of validating its models in cooperation with the USCAR partners without compromising the proprietary considerations of the individual companies.

Although the systems-analysis team has made provisions for incorporating cost modeling and reliability analysis into its simulation, cost modeling and reliability analyses are not being used effectively by the PNGV management or technical teams. Because vehicle affordability is a major issue, an early understanding of the key issues influencing cost is vital for overcoming cost problems and selecting alternative designs. For example, the achievable cost of the power-electronics subsystem of $15/kW (peak) must be reduced by 50 percent to meet the target.

In the updated PNGV Technical Roadmap, the committee was pleased to see that Section IIIA, Vehicle Systems Overview, now includes a detailed list of vehicle requirements (PNGV, 1998). These requirements are extremely important for defining vehicle-performance targets, which should be used by all technical teams to guide their development efforts. The PNGV also provided the committee with a summary of fuel-economy projections for all candidate systems.

Significant efforts are being made to develop overall control strategies (at Oakland University) and optimization software (at the University of Michigan). Both will be vital to making informed design choices and optimizing the performance of vehicle subsystems in harmony with total vehicle-performance requirements.

The systems-analysis team is also evaluating several proposals for CRADAs that would provide support from five national laboratories in the areas of control strategy and verification, component/subsystem modeling, and specific technology requirements, such as thermal modeling.

Plans

An operating plan for fiscal year 1999 was reviewed by the committee. Key elements of the plan based on the evolution of the vehicle computer model, referred to as PNGVSAT with an associated version number (e.g., V.2.1), are summarized below:

- PNGVSAT V.2.1
  - — upgrade the software to Matlab 5[1]
  - — upgrade the graphical user interface (GUI) (Matlab GUI)
  - — implement support contracts
- PNGVSAT V.2.2
  - — develop more refined component models
  - — develop data to validate and populate models
  - — upgrade optimization and control
- PNGVSAT V.2.3
  - — develop voltage bus-based software tools (equivalent circuit models, new control algorithms)
  - — conduct voltage-level studies and optimization
- guide program decisions and technical targets

The committee believes that the systems-analysis team should concentrate on strengthening the capability of the component, subsystem, and vehicle models. Validation must be accomplished by the middle of 1999 to support the design and development of the concept vehicle. The PNGV management should encourage technical teams to make more effective use of the analysis and modeling capabilities of the system-analysis team, especially for subsystem and component development. The committee concluded that use of the systems-analysis resource varies. Some technical teams are not using it at all, while others have included specific actions in their development plans.

The committee feels strongly that not enough emphasis has been placed on creating and validating a cost model. The overall vehicle cost estimates reviewed with the committee did not show the subsystems and component costs in detail. The vehicle affordability issue must be addressed now so that changes can be made, if necessary. The committee recognizes that the availability of detailed,

[1]Matlab is a sophisticated, widely used engineering software package.

nonproprietary cost data is a problem. Each USCAR partner has developed detailed cost data, which was apparent during proprietary reviews during the committee's fourth review in 1997 and again during the current review. As much as possible, these data should be shared with the PNGV in a form that does not compromise a company's proprietary interests.

AREAS OF CONCERN

The systems-analysis team is now qualified to provide analysis and modeling support to all of the technical teams. At this phase of development, all of the technical teams should be closely aligned with the systems-analysis team and using the model and associated analytical support services. The committee concluded that this is not the case. PNGV management should review the situation and encourage the effective utilization of systems analysis by all of the technical teams. Unless this is done, confidence in the optimization will be compromised.

The second-generation vehicle model has already been created, but essential validation has not been done. The USCAR partners are progressing with the designs of their concept vehicles and are effectively using proprietary sophisticated vehicle, subsystem, and component models. The USCAR partners should find a means of supporting the validation of the PNGV models to guide government-sponsored R&D by national laboratories, suppliers, and academic institutions.

Given the magnitude of the necessary cost reductions for affordable PNGV vehicles in keeping with the Goal 3 objectives, the committee is concerned about the lack of adequate cost models. The committee believes that cost models for use by all of the component and subsystem teams could be created without compromising individual proprietary considerations. All of the technical teams should have reliable cost models available to support their design decisions.

The challenge facing the systems-analysis team is maintaining a balance between upgrading the vehicle model and providing the necessary support to the technical teams. The vehicle-engineering team and the PNGV management should review this situation regularly to ensure that a proper balance is being maintained.

In the fourth report, the committee stressed that reliability models for the vehicle system would be necessary. In the past year, very little work has been done in this area. The technical teams should review their plans to ensure that reliability models are identified as line items and that responsibility for their development is assigned.

RECOMMENDATIONS

Recommendation. PNGV management should take steps to ensure the effective use of systems analysis by all technical teams and to expedite the validation of the PNGV models. The USCAR partners, which are effectively using individual proprietary models to guide the designs of their concept vehicles, should provide validation support to the PNGV models.

Recommendation. Without compromising proprietary considerations, the PNGV should conduct in-depth cost analyses and use the results to guide subsystem and vehicle-affordability studies.

Recommendation. The allocation of total vehicle cost among the various subsystems and components should be redone in light of development experience of the last five years to ensure that the cost targets, which have remained relatively static, are realistic.

4

Major Crosscutting Issues

Several major crosscutting issues are considered in this chapter: (1) the adequacy and balance of the PNGV program as a whole; (2) major achievements and technical barriers; (3) vehicle crashworthiness; (4) fuel strategy; (5) emissions trade-offs; (6) PNGV goals 1 and 2; and (7) government involvement and interfaces.

ADEQUACY AND BALANCE OF THE PNGV PROGRAM

As in previous reviews, the committee finds it difficult to assess the allocation of resources for the PNGV program because no funding plan was made available. In several previous reports, the committee concluded that insufficient resources have been allocated to the program's activities considering the magnitude of the challenges facing the PNGV program to meet the objectives of Goal 3 (NRC, 1996, 1997, 1998a). Estimates of federal government appropriations for PNGV-related activities were about $263 million, $219 million, and $240 million for fiscal years 1997, 1998, and 1999, respectively (Patil, 1998) (see Table 4-1). These appropriations include work directly relevant to PNGV and coordinated with PNGV technical teams (Tier 1), work directly relevant to PNGV but not coordinated with PNGV technical teams (Tier 2), and work indirectly related to PNGV or supporting long-term research (Tier 3). Expenditures by industry for proprietary work are not known by the committee but are expected to be comparable (NRC, 1994). Visits by committee subgroups confirmed that substantial work on proprietary concept vehicles is under way.

TABLE 4-1 PNGV Total Government Budget Authority (in $ millions)

Agency Activity	FY 97 Appropriations	FY 98 Appropriations	FY 99 Request[a] Tier 1	FY 99 Request[a] Tier 2	FY 99 Request[a] Tier 3	FY 99 Appropriations
DOE	123.1	122.7	153.6	0.0	5.0	134.0
EPA	15.0	15.6	35.0	0.0	0.0	29.0
DOT	12.5	4.5	3.5	0.0	0.0	2.5
DOC	56.0	29.0	0.5	15.0	6.8	25.3
NSF	56.0	47.0			52.0	49.0
Total without DOD	262.6	218.8	192.6	15.0	63.8	239.8

[a]Tier 1: work is directly relevant to PNGV and is coordinated with PNGV technical teams; Tier 2: work is directly relevant to PNGV but is not coordinated with PNGV technical teams; Tier 3: work is indirectly related to PNGV or is supporting long-term research.
Acronyms: DOE = U.S. Department of Energy; DOT = U.S. Department of Transportation; DOC = U.S. Department of Commerce; NSF = National Science Foundation; DOD = U.S. Department of Defense
Source: Patil (1998).

The committee is encouraged by several trends in the past year. First, since the technology-selection process at the end of 1997 winnowed down the number of technologies, the PNGV has been able to focus available resources on the most important areas. Second, the fiscal year 1999 budget for DOE's Office of Advanced Automotive Technologies includes moderate increases for some of the long-range technologies, like fuel cells, although the increases are far below the level needed to overcome the serious challenges facing these technologies.[1] Third, the three USCAR partners have substantially increased their proprietary efforts towards the development of concept vehicles and have formed significant vehicle-development groups. Finally, the PNGV technical teams appear to be working well together. Despite these positive trends, however, the committee continues to believe that the program will require additional resources. Furthermore, other government agencies (e.g., EPA) and industries (e.g., petroleum companies and automotive component manufacturers) must be brought into the PNGV program.

The committee believes the near-term and long-term technologies the PNGV has selected have the potential to meet the program's objectives. Some critics of the program have suggested that the CIDI engine should not be pursued for the U.S. market because of its particulate and NO_x emissions. However, the

[1]Development of advanced technologies within the DOE's Office of Advanced Automotive Technologies is central to government activities in support of the PNGV program. In addition, this office has long-range activities planned that support technology development to meet goals and objectives beyond 2004.

committee believes that its potential fuel economy and high degree of technical maturity warrant its continued development, especially in light of the uncertainties facing fuel-cell technologies. Also, the PNGV should consider the CIDI engine for a nonhybrid vehicle. In the committee's fourth report, it was noted that the nonhybrid vehicle with a CIDI engine could provide a fuel economy of 65 mpg at significantly lower cost than the hybrid vehicle. The overall impact on vehicle-lifetime fuel economy over today's vehicle is very significant (NRC, 1998a). Extensive overseas markets in Europe and Asia for high fuel-economy vehicles offer an opportunity to improve fuel economy worldwide and reduce emissions. Overall, the committee concluded that, although the PNGV as a whole is substantially underfunded, the balance between short-term and long-term objectives is appropriate because measurable progress is being made in overcoming significant technical barriers.

MAJOR ACHIEVEMENTS AND TECHNICAL BARRIERS

The PNGV program is structured to provide parallel efforts to develop vehicle systems and subsystems (which are necessary to meet vehicle-performance and fuel-economy targets), as well as in materials and manufacturing methods (which are necessary to meet cost and mass-manufacturing targets). These efforts combined have yielded significant progress towards meeting goals 1, 2, and 3 of the PNGV program. Nevertheless, major technical barriers remain to be resolved, especially for meeting Goal 3 (a production-ready vehicle by the year 2004).

A fuel economy of 80 mpg (gasoline equivalent) for a family sedan, without sacrificing performance or utility, is being logically pursued through simultaneous efforts to reduce vehicle mass and increase the thermal efficiency of the drivetrain. The mass reductions are being pursued primarily through the substitution of aluminum and/or composites for much of the steel in present-generation vehicles. Increased (average) thermal efficiency is being pursued through more efficient energy converters (4SDI engines or fuel cells), probably in an HEV configuration. From the standpoint of meeting Goal 3, technical achievements, as well as maintaining or improving current performance in critical areas such as safety and emissions, are of primary importance.

No matter how impressive the mass reductions and gains in efficiency are, they will have little long-term value until materials, processes, and manufacturing techniques have been developed for mass manufacturing and costs have been reduced. Therefore, technical achievements in the manufacturing-related areas will be just as important as achievements in the more visible areas of vehicle and component technologies.

Achievements

Reductions in Vehicle Mass

Several advances in vehicle-mass reduction have been made in the past year. First, a lightweight, mostly composite and aluminum, hybrid vehicle-body structure was developed by the PNGV vehicle-engineering team and Multimatics. Computer simulations showed a structural performance that meets or exceeds the performance of a baseline steel vehicle, with a weight reduction of more than 68 percent. Major changes in the fabrication of the new structure are being addressed in an effort to reduce fabrication costs. Second, electromagnetic forming was demonstrated by the PNGV materials team, along with USAMP and Ohio State University, for forming aluminum hoods and door panels. Third, work is continuing to improve lightweight honeycomb materials while reducing costs. Fourth, studies on lightweight interior materials indicate a possible 40 percent mass reduction with little or no cost or comfort penalties. Finally, work in conjunction with suppliers continues for the elimination of a spare tire through the development of a "run flat" (low rolling resistance) tire.

4SDI Engines

As noted in Chapter 2, 4SDI engines are already capable of providing thermal efficiencies approaching 40 percent, at or near optimum speed and power-output operating conditions. With a hybrid configuration, much more of the operation would be near the optimum conditions, and a reservoir for storing recovered braking energy would be provided. However, emissions of NO_x and particulates are major obstacles to meeting existing and expected emissions regulations. For these reasons, the successful implementation of a 4SDI engine into vehicles for the PNGV program depends on a hybrid configuration and reductions in emissions. Some achievements in reducing emissions are listed below:

- A precise, repeatable "micropilot injection" fuel-injection system was developed by the PNGV 4SDI team with EPA and FEV.
- An auto-sized lean-NO_x catalyst removed more than 30 percent of the NO_x from the exhaust of a CIDI engine burning low-sulfur fuel. The PNGV 4SDI technical team, ORNL, and SNL were involved.
- A new fuel was blended and tested by the PNGV 4SDI technical team, SWRI, and DOE, which reduced particulate emissions by 50 percent as compared to standard diesel fuel.

Fuel Cells

Several important accomplishments were made in the past year. A rapid-start (two minutes) gasoline fuel processor was demonstrated by the PNGV fuel-cell technical team with GM and ANL. A brass-board automotive-scale CO cleanup system for a gasoline fuel processor was demonstrated by the PNGV fuel-cell technical team with LANL. A gasoline fuel processor, CO cleanup system, and small PEM stack were operated together by the PNGV fuel-cell technical team, ADL, and LANL. A complete 30-kW methanol-fueled fuel-cell brass-board engine was successfully operated by the PNGV fuel-cell technical team with GM.

Hybrid System Components

Various improvements in hybrid electric vehicle components were made in the last year. Traction motor specifications for both parallel and series hybrids were developed by the PNGV EE technical team. Twelve amp-hr lithium-ion battery cells were demonstrated in cycle testing and first-generation 50-V modules were constructed by the PNGV battery technical team with SAFT. A first-generation nickel metal hydride 50-V battery module is in a test program with the PNGV battery technical team and VARTA.

Systems-Analysis Tools

Although analysis tools are in a different category from the hardware discussed above, they are absolutely essential for matching components and operating strategies to maximize performance and efficiency. Several achievements in this area have been made. A computer model for fuel economy and optimizing control of hybrid systems was demonstrated by the PNGV systems-analysis team with TASC and SWRI. A fuel-cell system-simulation model was developed by ANL and the PNGV systems-analysis team and conveyed to users.

Energy Reduction for Vehicle Accessories

Heating and cooling loads have been reduced through a combination of focusing on passenger comfort, leveraging commercial technologies, improving cabin thermal integrity, reducing thermal mass, and improving recirculation systems. A number of technologies are being used to increase the energy efficiency of heating/cooling devices, including variable-speed scroll compressors, microchannel heat exchangers, energy-storage devices, heat recovery from electronic devices, and advanced control systems.

Manufacturing Processes

Achievements in this area can be divided into two categories: (1) achievements related to manufacturing vehicles and (2) achievements related to manufacturing specific components. Significant progress was made in both areas.

Methods for light-metal castings optimized by a materials database, on-line sensors, and modeling were developed by the PNGV materials technical team with USAMP, SNL, LLNL, and ORNL. A high-volume programmed powder preform process (P-4) for composites was demonstrated by the PNGV materials technical team with the USCAR Automotive Composites Consortium and Owens Corning. Coatings and design modifications to improve high-speed drilling were made by the PNGV manufacturing technical team. Compression-molded composite bipolar plates for fuel cells to replace machined graphite plates were successfully demonstrated by the PNGV fuel-cell technical team with IGT. A continuous process for manufacturing fuel-cell MEAs to replace individual lay-ups was demonstrated by the PNGV fuel-cell technical team with the 3M Company.

Summary

In the past year, more progress has been made towards meeting PNGV goals than in any previous year. Undoubtedly, this is partly because progress in R&D is cumulative. However, the committee believes that much of the progress can also be attributed to the attitude and efforts of the PNGV technical teams who are now working with more team spirit toward meeting common goals. The committee believes this is a very positive change that has provided a needed boost to continuing technical productivity.

Technical Barriers

Even though significant achievements have been made in many technical and manufacturing areas, many critical issues are still unresolved. These include issues related to the engine and vehicle, as well as manufacturing issues. The most significant issues are described below.

Engine and Vehicle

In spite of reductions of NO_x and particulates in 4SDI engines, there is still a long way to go to reach acceptable emissions levels with acceptable technologies. The "fuel-flexible" fuel processor for fuel-cell energy converters is still in the laboratory/brass-board stage, and no convincing evidence has been found that this is the best path to follow (as opposed to processors tailored for specific fuels). Currently, technical solutions must be found for the compressor/expander components, which are essential to a multi-atmosphere pressurized fuel-cell stack. Little effort has been made to identify "optimum" fuel properties for either 4SDI or fuel-cell energy converters.

Lithium-ion batteries appear to be almost essential for an acceptable hybrid system, but no solution has been found to the critical issue of thermal management; a reformulation of the basic chemistry might be necessary to meet life-cycle targets. To meet the goals for mass reduction, significant changes must be made to the 4SDI engine, chassis, power train, and virtually all of the electric-drive components. Further work will be necessary on air conditioning, power steering, and other accessories to approach the mass of a production vehicle and to meet manufacturability requirements. Overall system efficiency and optimum control strategy are primary concerns for "fuel-flexible" fuel cells. In fact, no complete system has yet been operated on gasoline.

Manufacturing Processes

A number of potential barriers have already been identified, and many more will certainly surface as the program moves closer to the production prototype phase. The barriers identified so far primarily relate to mass manufacturing at acceptable costs.

Lamination materials and processing for electric rotors and stators must be developed. Supplies of aluminum sheet, magnesium, and carbon fiber must be available at acceptable costs. Processes for manufacturing power electronics and electronic components, as well as high-pressure common-rail fuel-injection systems, will have to be developed. Fabrication processes will have to be improved for lithium-ion cells and batteries. Production processes will have to be developed or improved for virtually all major components and subsystems for fuel cells.

Summary

For the most part, PNGV's technical efforts have been appropriately directed, and significant technical achievements have been made. However, with a few exceptions, these achievements represent progress rather than solutions. For the near-term 4SDI vehicle, additional emission reductions at affordable costs will be necessary. In addition, a lower cost supply of base materials for the manufacture of reduced-mass body/chassis assemblies must be found and mass-manufacturing processes developed. Additional mass reductions in the engine/drivetrain and other components will also be necessary.

The successful demonstration of the composite bipolar plates and a continuous process for membrane-electrode assemblies have gone a long way towards achieving the cost goals for fuel-cell stacks. However, the multifuel fuel processor and CO cleanup system are still in the early laboratory development stages, and potential manufacturing and materials problems have only begun to be identified. The compressor/expander systems are at an intermediate stage of development, but final products and manufacturing problems cannot be identified yet.

A successful HEV configuration for either the 4SDI engine or fuel cell will depend on motor and power-electronic technologies that are reasonably well defined; mass-manufacturing techniques have not been defined, however. The hybrid system will also depend heavily on a robust, lightweight, low-cost battery. The lithium-ion battery seems to be an excellent candidate but is far from a complete system with mass-manufacturing capabilities.

VEHICLE CRASHWORTHINESS

PGNV concept cars must be as safe or safer than baseline vehicles. Given that many new technologies will be introduced simultaneously, this could be a difficult task. For every new technology, new failure modes and safety concerns will have to be assessed, including crashworthiness, flammability, explosion, electrical shock, and toxicity. The committee has not reviewed safety issues in depth with the PNGV technical teams but is satisfied that they are aware of these issues and are addressing them on an ongoing basis as part of the overall program. Vehicle crashworthiness, for example, will be clarified when concept vehicles are being built. Failure modes for all promising technologies are being investigated; the safety concerns associated with handling and storing onboard hydrogen for fuel-cell powered vehicles are being examined; and computer simulations are being used to evaluate the crash performance of HEVs. Among the new technologies under consideration by the PNGV are lightweight structural materials, HEV power plants (including fuel cells), new fuels (including hydrogen), energy-storage devices (including lithium-ion batteries), and new glazing materials.

Vehicle-Fleet Issues

The PNGV concept vehicle will have to weigh about 2,000 lbs, 1,200 lbs less than the baseline vehicle. Moreover, the PNGV weight-reduction targets cannot be met by downsizing the vehicle but will require using lightweight materials and more efficient designs. The question arises as to how these lightweight vehicles, in a population of much heavier vehicles, will fare in car-to-car collisions. It has been well documented that when vehicles are downsized to reduce weight, occupant safety is reduced (DOT, 1997). If the concept vehicles developed in the PNGV program are not downsized, however, the crush space for frontal, side, and rear impacts would be comparable to that of today's vehicles, and, therefore, this may not be as big an issue as was first thought.

Crash-Energy Management

Based on a simple application of Newton's second law (force = mass × acceleration), lower mass vehicles do experience higher decelerations in barrier crashes, assuming that heavy and light vehicles have the same crush force (or resisting force). In fact, current design practices, which are based on barrier crash requirements, have used low-stiffness front ends to ensure that decelerations are in the range of 15g to 25g. It has been pointed out, however, that barrier crashes represent crashes of mirror images and do not represent car-to-car collisions (Frei et al., 1997).

If a lightweight, full-sized vehicle, such as the PNGV Goal 3 vehicle, were designed with current design practices, it would be at a disadvantage in crashes with heavier cars because the soft front end would cause most of the crash energy to be absorbed by the lighter car while significant deformation of the heavier car had barely begun. To ensure compatibility in car-to-car collisions, it has been argued that light and heavy cars should crush at the same load level, which implies that the deceleration of the lighter car would have to be larger than for the heavier car by the ratio of the mass of the heavy car to the lighter car (Frei et al., 1997). The resisting force of the lighter car structure could be designed so that the deceleration does not exceed a safe level of 40g to 50g. Another implication of this approach is that the crush distance of each vehicle would be proportional to the mass of the vehicle. The crush zone of the lighter car would have to be long enough to absorb at least its own kinetic energy. These assumptions have been confirmed in car-to-car crash tests (Frei et al., 1997; Niederer, 1993). Hence, vehicles in the PNGV program should be, and are being, designed to provide adequate crash-energy absorption and crush distance.

Crashworthiness of Alternate Materials

It is useful to compare the crash-energy absorption characteristics of the alternate materials under consideration by PNGV, particularly aluminum and CFRP. The crash-energy characteristics of an Al 6061-T6 dual-tube rail exhibits the same progressive folding behavior as steel (Haddad et al., 1989). CFRP square tubes, however, show a much finer oscillation associated with the tube failing by progressive delamination and pulverization, as well as splitting at the corners and peeling back of the sides, much like a banana skin peels. Although the crush behavior is different, an experimental comparison of the specific energy absorption of steel, aluminum, and CFRP square tubes shows that aluminum and CFRP can match the energy absorption of steel and still save weight (see Table 4-2).

Based on these test results, the committee believes that structural concepts and analytical tools are available to design lightweight PNGV concept cars that will perform safely in collisions with heavier cars because of the excellent energy absorption characteristics of the alternate materials. Nevertheless, the committee recognizes that vehicle safety research is in its infancy and believes the National Highway Traffic Safety Administration should become involved in crashworthiness studies of lightweight vehicles with designs comparable to the designs of PNGV vehicles.

TABLE 4-2 Comparisons of Square-Tube Axial Energy Absorbers[a]

Materials	Weight Savings Relative to the Baseline Material
Steel 1015	baseline material
HSLA 950	14%
Aluminum 6061-T6	52%
5052- O	43%
CFRP	91%

[a]It is assumed that the square tubes experience equal deflection in bending and equal crush load. HSLA is high-strength low-alloy steel.
Source: Magee and Thornton (1978).

Recommendation

Recommendation. The PNGV and USCAR partners should continue to make vehicle crashworthiness a high priority as they move toward realization of the concept vehicles.

FUEL STRATEGY

Importance of Fuel Considerations

The PNGV program is predicated on the assumption that the widespread deployment and use of higher fuel-economy vehicles will provide significant societal benefits. These benefits include the reduction of potentially harmful emissions to the atmosphere, reduced dependence on petroleum imports, and the consequent improvement in the U.S. balance of payments. If, in order to achieve these benefits, significant changes in fuel composition or the manner in which automotive fuel is distributed are required, then the impact of these changes should be an integral part of the program.

As the committee noted in its fourth report, significant changes in automobile power plants can have wide-ranging effects on the fuels industry (NRC, 1998a). Changed fuel characteristics may make modifications to power plants possible that would otherwise be impossible. The most promising power plants being considered by PNGV, namely, CIDI engines and fuel cells, may require extensively modified fuels. However, even if the PNGV program can achieve Goal 3 by using one of these power plants, the possibility of marketing the vehicles may be limited, or even prohibited, by the unavailability of suitable fuels. Therefore, it is vitally important that the PNGV pursue the development of appropriate fuels concurrently with the vehicle program. In addition, the PNGV must be aware of the business and economic viability of fuel changes and anticipate any environmental and energy-consumption consequences that may result from their widespread use in automobiles.

The automotive fuels industry, including both production and distribution, is a capital intensive industry that requires a long lead-time to effect major changes. Changes in fuel composition can have different impacts on different companies depending on their refining processes, sources of crude petroleum, product mix, and other factors. These factors add to the difficulty of rapid, widespread distribution of modified fuels and should be addressed explicitly by the PNGV.

Status of Fuel Considerations within the PNGV

The PNGV recognizes the importance of modified fuel in achieving emission targets for CIDI engines and is testing various fuels. Ad hoc pairings of fuel companies and auto manufacturers have developed test programs to evaluate the effects of various fuel modifications on emissions, as well as on after-treatment catalysts. Results so far have shown that lower sulfur content in petroleum fuels reduces particulate emissions and extends catalyst life. In the short term, low-sulfur fuel would enable gasoline engines to meet more stringent emission requirements; in the midterm, it would be critical to the introduction of CIDI engines; and in the long term, it would be necessary for vehicles with fuel cells using petroleum-based fuels and reformers.

The DOE has taken a leadership role on this issue. Some working groups have been formed, and ANL is assessing fuels-infrastructure issues, including capital-cost projections and assessments of the energy and environmental effects of potential fuel and power-plant changes as vehicles that meet Goal 3 are introduced (Wang et al., 1998). These projections would be greatly improved with critical input from the major petroleum companies that would be involved in implementing the changes. Input by petroleum companies would validate or reject the assumptions underlying these projections and ensure that they are based on accurate, real-world business considerations.

The EPA is also involved in decisions about fuels. EPA is aware that if exhaust emission standards are too stringent in the near term, the most fuel-efficient power plants could be precluded or could require a fuel that could not be made available economically or in time to meet PNGV goals.

Overall, the PNGV is now paying more attention to fuel issues, although no mechanism has been established at the policy level to address the fundamental trade-offs between vehicle exhaust emissions and energy efficiency. Long-range strategic issues have not been addressed effectively by the fuels industry or the automobile manufacturers.

Recommendation

Recommendation. A comprehensive mechanism should be established to help define feasible, timely, compatible fuel and power-plant modifications to meet the PNGV goals. This mechanism will require extensive cooperation among automotive and fuels industry participants at all levels of responsibility, but also among technical and policy members of relevant government organizations.

EMISSIONS TRADE-OFFS

The emissions-control potential of the power train in the context of the total vehicle is a critical performance issue. California and the EPA in their LEV-2 and Tier II standards, respectively, have extremely stringent light-duty vehicle requirements for NO_x and particulate emissions. Although the engine is the most important vehicle subsystem in terms of emissions, the power-train configuration (hybrid or direct mechanical drive), energy-storage system, total-vehicle weight, and especially fuel composition can all affect emissions control significantly. The most critical component of the total system is the exhaust-gas treatment technology (the catalyst, particulate trap, exhaust-gas sensors, and controls) used to reduce the engine-out emission levels substantially before the exhaust is released to the atmosphere.

The capability of the CIDI engine to meet future emissions requirements is uncertain. Engine-emissions controls (e.g., high-pressure fuel injection, retarded injection timing, intake air-temperature control, and exhaust-gas recirculation) are also incapable of meeting these requirements; and a fuel economy penalty of 5 to 10 percent is incurred through use of engine-emissions controls. Catalyst technology with the CIDI engine has shown promise of achieving significant reductions for NO_x but is still in the exploratory development stage. Particulate-trap technology, despite efforts over the past two decades, is at a similar stage of development. Because there are trade-offs between NO_x emissions, particulate emissions, and fuel economy when emissions control is used with the CIDI engine, effective exhaust-treatment systems for NO_x and particulates will be vitally important to achieving PNGV emissions, fuel economy, and cost targets with this engine.

The effectiveness of exhaust-treatment technology for CIDI engines is greatly affected by fuel composition. Sulfur levels in the fuel significantly influence the efficiency and durability of catalyst technologies, as well as particulate mass emissions. Other factors that influence particulate emissions are aromatic content, cetane number, volatility, and oxygenate components blended with the fuel.

The GDI engine, which is considered the best short-term backup technology to the CIDI engine, also has problems with engine and exhaust-treatment emissions technology, including trade-offs with fuel economy in the engine, the cost and effectiveness of the exhaust catalyst system, unresolved questions about particulate emissions, and fuel-composition requirements (especially sulfur levels). However, the GDI's potential for meeting California LEV-2 and EPA Tier II requirements is significantly better than that of the CIDI engine.

Like the CIDI engine, the GDI engine operates with lean fuel-air mixtures at part load to improve efficiency. The GDI, however, can also operate with stoichiometric and rich fuel-air mixtures; under these conditions, an alternative NO_x storage catalyst technology could be used that appears promising and is being developed. With this catalyst technology, NO is oxidized to NO_2 and stored on the catalyst as nitrate under lean engine operating conditions; the nitrate is decomposed and then reduced when the engine is run slightly rich for a short period (incurring a modest fuel-economy penalty). The GDI engine and this catalyst technology are currently in limited production, and extensive efforts are under way worldwide to develop them further. The committee continues to believe that the PNGV program should monitor the performance (fuel economy, emissions, cost) potential of this technology for the U.S. market and compare the operating characteristics of a GDI engine hybrid with those of the CIDI engine hybrid.

Fuel-cell technology also has unresolved emissions-control issues. When used with a gasoline or methanol reformer on board the vehicle, there is a potential for emissions from the reformer, especially during transient operation. The limited data available to date indicate that emissions during steady-state operations can be kept extremely low, but no data are available for transient operating conditions. Fuel sulfur levels must also be very low.

The PNGV systems model (see Chapter 3) is an important tool for evaluating the emissions, fuel economy, performance, and cost trade-offs for promising combinations of power-train and vehicle technologies and for optimizing the total vehicle design. The model should not only address the fuels characteristics that affect emissions, but should also assess the energy consumption and emissions from fuel production and distribution. Before the systems model can be used with confidence to assess vehicle emissions, fuel economy, and performance trade-offs, it must be validated against emissions and other performance data. Validation studies will probably identify areas where additional submodel development is required. The committee recommends that validation and improvement of the emissions components of the systems model be given a higher priority during the next year of the PNGV program.

Based on presentations made by the PNGV (government and industry members), the committee believes the interdependency of power trains (4SDI engine or fuel cells), fuel economy, and emissions is not being adequately addressed. The current California regulatory proposals on NO_x and particulate emissions are likely to preclude the use of the very efficient CIDI engine in the United States unless an effective exhaust-gas treatment technology can be developed, the prospects for which depend on the extent and rate of implementation of improvements in diesel fuel. These standards may thus inhibit increased fuel economy and reduced petroleum consumption for the nation as a whole. To date, the government agencies involved in the PNGV responsible for these issues have pursued agency objectives without taking into account the interdependency of these issues. The committee considers that the PNGV program is uniquely situated to examine these critical interdependencies and recommends that the PNGV management develop and implement coordinating policies. Given the limited choices for technologies that can meet the PNGV goals, the PNGV should establish a clear policy on fuel standards, emission regulations, and fuel economy and cost expectations.

Recommendation

Recommendation. The federal government agencies involved in the PNGV program should review how future emissions requirements (especially NO_x and particulates), fuel economy, CO_2 emissions, as well as fuel quality, will affect the choice of the CIDI engine as the most promising short-term combustion-engine technology; a program plan that responds to that assessment should be developed. The PNGV, especially the U.S. Department of Energy and the Environmental Protection Agency, should work closely with the California Air Resources Board on these issues. Once the systems model has been validated, it would be an appropriate tool to use in quantifying the necessary trade-offs.

GOALS 1 AND 2

Goal 1 is to significantly improve national competitiveness in manufacturing for future generations of vehicles through upgrades in manufacturing technology incorporating agile and flexible processes, reductions in costs and lead times, reductions in environmental impacts, and improvements in product quality. Goal 2 is to implement commercially viable innovations from ongoing research on conventional vehicles through improvements in fuel efficiency and reductions in emissions on standard vehicles, advances in safety designs, and reductions in energy demands of the engine and drivetrain. Goals 1 and 2 are open-ended and have no quantitative targets or milestones. Because the Goal 3 concept demonstration vehicles are focusing on relatively near-term technologies, the distinction between goals 1, 2, and 3 has become blurred. Some improvements in manufacturing processes related to technology development for Goal 3 are discussed in the appropriate technology sections in this report.

Goal 1

The PNGV has identified the following key challenges to the manufacturing system: (1) the development of high-volume manufacturing processes, (2) the development of cost-effective tooling and equipment, (3) ensuring ample supplies of low-cost lightweight materials, (4) reducing cycle times, and (5) providing a viable supply base for new technologies. The committee reviewed the following Goal 1 projects that were initiated previously to assess their progress (background on these projects can be found in the committee's third report [NRC, 1997]):

1. Springback predictability. Completion is expected by the end of 1999. A major remaining task is software development.
2. Intelligent resistance welding. Completion is expected by the end of 1999. A major remaining task is the development of algorithms and controls for closed-loop operation.
3. High-throughput hole making. Completion is expected by the end of 1999. An important remaining task is the testing of production prototypes.
4. Leak-test technology. Completion is expected by the end of 1999. Prototype development is a remaining task.
5. Dry-machining of aluminum. Completion is expected in early 2001. Materials development is still necessary.
6. Aluminum die casting. Initial program plans and validation of concept have been completed. Testing on full-sized development prototypes will be conducted in collaboration with suppliers.
7. Laser-welding of aluminum. The structural alloy portion has been completed.
8. Feature-based modeling. Project has been cancelled.
9. Ergonomics for hand tools. Project has been cancelled.
10. Powder paint. This is no longer a PNGV project but is now a separate industry consortium in USCAR.

New project initiatives include (1) stamping die materials and foundry practices, (2) developing reliable robust components in manufacturing, and (3) developing an integrated arc-welding cell.

Plans

The PNGV is also reviewing potential projects in (1) hydroforming development, (2) rapid prototyping, (3) nondestructive evaluation concepts, (4) magnesium processing, and (5) expansion of R&D on high-throughput hole making. The PNGV also plans to support the manufacturability assessments by the PNGV technical teams in other areas, as requested, review project portfolios of other automotive-related organizations for their relevancy to the PNGV, communicate project findings to manufacturing management of the USCAR partners, and initiate production application of projects.

Concerns

A growing number of PNGV Goal 1 projects are proprietary, especially as the technologies relate to the concept vehicle systems being developed by the USCAR partners. Consequently, it is becoming increasingly difficult for the committee to assess the PNGV's progress because target values for processes and systems are not being openly reported. However, because goals 1 and 2 are open-ended, there is no easily defined metric for measuring progress in any case.

Recommendation

Recommendation. Future committee reviews should focus on the progress of manufacturing projects toward meeting the needs of the Goal 3 technical teams in development of component and subsystem technologies.

Goal 2

The USCAR partners have been continuously adding innovative components and subsystems to conventional vehicles. For example, Ford Motor Company, in addition to numerous weight saving measures on 1997–1998 model year cars and trucks, is producing 1998 alternative and flexible-fuel vehicles to meet a variety of standards for low-emission vehicles (LEVs), super ultralow emission vehicles (SULEVs), and zero-emission vehicles (ZEVs). Ford also plans to produce light trucks with conventional gasoline engines at the LEV standard in the 1999 model year. In the past five years, GM has produced some innovative aluminum structures in Corvette vehicles. In addition, GM is incorporating lessons learned from its EV-1 electric vehicle, which has been in production for several years, into its PNGV concept-vehicle system. DaimlerChrysler has used its low-volume production Prowler and Viper vehicles to gain experience with aluminum and composite materials.

Plans

Although no specific plans have been announced, the USCAR partners are expected to continue trying out new components, subsystems, and materials on low-volume niche-market vehicles.

Concerns

The committee's assessments of progress with respect to Goal 2 will continue to be after-the-fact because the committee cannot monitor progress on a real-time basis.

Recommendation

Recommendation. Future reviews of the PNGV program should not include evaluations of progress towards Goal 2. Instead, the three USCAR partners should make nonproprietary information available to the public.

GOVERNMENT INVOLVEMENT AND INTERFACES

A program like the PNGV that involves the intermingling of government and private-sector funds, as well as personnel, will always raise questions about the methods and extent of appropriate government participation. The committee has always held the view that the PNGV, as a whole, is a program of national importance because developments on advanced vehicles would not be pursued in response to market forces at this time. Therefore, government funding and participation are entirely appropriate. The committee has previously recommended that government participation be primarily directed towards high-risk, but potentially high-payoff, technologies. In essence, it is in the national interest that technologies be available to produce fuel-efficient vehicles with low emissions, even (and especially) if there is little market demand for them. The absence of market demand means the private sector would have little incentive to make the necessary huge investments in technology developments. The same logic applies to the development of manufacturing processes to make American manufacturing more globally competitive. R&D on advanced generic materials and processes are more feasible through industry/government cooperation than for individual companies.

Some technologies, such as the CIDI engine, are being developed by private industry, but for vehicles much less demanding than the PNGV vehicle. General emission, particulate emission, and noise requirements for military and industrial CIDI engines are much less stringent than they are for the PNGV vehicle. Combined with the relatively low production volumes expected for CIDI engines in the near term, individual companies would not be able to justify investing in R&D to meet PNGV targets. Thus, government participation in areas such as combustion chambers, injection systems, exhaust after-treatments, and even new fuels can be easily justified.

Some technologies have long-term potential, but only if one or more major obstacles can be overcome. The gas-turbine engine, for example, promises to be a small, lightweight, low-emission engine, but requires very high turbine temperatures and expensive turbomachinery. Further government involvement in the development of gas-turbine engines is probably not justified until low-cost, high-temperature (presumably) ceramic turbines become a possibility. The committee considers the development of a ceramic turbine material an enabling technology that does justify government support (NRC, 1997, 1998b). A similar case can be made for resolving the containment issue for flywheels. Fuel cells are in a different category because they have great long-term potential for meeting PNGV goals, and many of the major problems are generic; continued major government investment in these technologies can clearly be justified.

Government support for R&D related to the PNGV is provided by several federal agencies (see Table 4-1). Work directly relevant to PNGV and coordinated with PNGV technical teams is supported by DOE's OAAT. In fiscal year

1999, OAAT's expenditure comes to about $129 million, or 54 percent of the federal monies estimated to be supporting the PNGV program, either directly or indirectly. Total federal appropriations for fiscal year 1999, either directly relevant to the PNGV and coordinated with the PNGV technical teams (Tier 1), directly relevant to the PNGV but not coordinated with the technical teams (Tier 2), or indirectly related to PNGV or supporting long-term research (Tier 3) is about $240 million (Patil, 1998). PNGV research supported by OAAT (most of OAAT's activities) includes work on vehicle systems, fuel cells, batteries, advanced combustion engines, alternative fuels, and automotive materials technology. OAAT also has programs that are not part of PNGV, such as the development of electric-vehicle technology. At current funding levels, OAAT cannot expand its R&D beyond the PNGV technologies selected in January of 1998. Based on OAAT's R&D plan for technology development beyond 2004, OAAT believes that government funding should extend beyond PNGV's time horizon of 2004 (DOE, 1998).

Work directly relevant to the PNGV program but not coordinated with the PNGV technical teams is also supported by the National Institute for Standards and Technology, both through in-house activities and the Advanced Technology Program. The total level of funding was $19 million in fiscal year 1999. Activities by the Advanced Technology Program directly relevant to the PNGV program are R&D on lightweight materials, energy storage and conversion, advanced manufacturing, and individual projects on reducing mechanical losses, controlling emissions, developing alternative fuels, and improving crashworthiness.

Both the National Science Foundation, and to a lesser extent the Office of Science (formerly the Office of Energy Research) at DOE, support research indirectly related to the long-term goals of PNGV. In fiscal year 1998, the National Science Foundation funding was $47 million, and DOE Office of Science funding was $5 million. Considerable talent and R&D is also being provided by the national laboratories through DOE funding. About half of the research supported by the National Science Foundation is conducted at engineering research centers; the balance is carried out by individual principal investigators. A very small fraction of the work is conducted at corporate laboratories through the Small Business Innovative Research program. The U.S. Department of Transportation, the U.S. Department of Defense, the National Aeronautics and Space Administration, and EPA also have various projects that support or supplement PNGV activities.

Since the DOE OAAT is the principal source of federal support for the PNGV program, it is important that OAAT's program be properly focused. In a recent National Research Council review of the OAAT R&D program plan, OAAT was advised to fund only generic, precompetitive R&D that industry would not otherwise support (NRC, 1998b). An example of this type of research is the development of low-cost, high-performance fuel cells, fuel-cell stacks, and fuel reformers for liquid fuels (e.g., methanol to hydrogen). Fuel-cell systems continue to be the most attractive long-term source of power for automobiles of the future, but significant improvements in performance and cost for currently available technology must be made.

As part of supporting R&D related to the PNGV program, the OAAT must validate technologies developed with federal funding. To avoid competition with industry, OAAT has agreed to limit its validations to components and component systems, leaving the validation of systems performance in concept vehicles to industry. OAAT also conducts tests of systems models. The committee suggests that the criteria used by OAAT for validation be defined in close partnership with industry. The priorities for component and systems performance, and the degree to which trade-offs in performance demands can be made, should also be established with input from industry.

Government funds, line items or not, supporting PNGV are provided by a considerable number of departments and laboratories. Given the difficulties of achieving effective coordination among many different government agencies, the committee believes the program office at the U.S. Department of Commerce is doing a commendable job of promoting the interests of PNGV among government organizations and providing workable interfaces in its proactive support of the program.

Recommendations

Recommendation. The U.S. Department of Energy Office of Advanced Automotive Technologies should continue to focus its support on generic, precompetitive research and development that industry would not undertake on its own.

Recommendation. The criteria used by the U.S. Department of Energy Office of Advanced Automotive Technologies to validate components and component systems should be established with the full cooperation and participation of industry.

5

PNGV's Response to the Phase 4 Report

In its previous four reviews, the National Research Council Standing Committee to Review the Research Program of the PNGV made a number of recommendations, which were documented in published reports (NRC, 1994, 1996, 1997, 1998a). In the fourth report, the committee made both specific recommendations for each of the technologies under development and general recommendations for the program as a whole. Appendix C contains a letter from the PNGV to the committee chairman documenting the responses by the PNGV to the major recommendations contained in the Executive Summary of the fourth report (NRC, 1998a). (The responses indicated below can be found in Appendix C.) Although for the most part, the PNGV has been responsive to these recommendations, the committee still has some concerns about the extent to which the PNGV has responded to the following five recommendations:

> **Recommendation from Fourth Report.** *The PNGV should continue to refine its detailed cost of ownership analyses of hybrid vs. non-hybrid vehicles. If the economic and performance benefits of the hybrid vehicle do not exceed or warrant its additional costs, the concept demonstration vehicle program should be expanded to include non-hybrid vehicles to accelerate the development and commercial introduction of economically viable technologies.*

> **PNGV Response.** We agree the hybrid technologies are one of the most challenging aspects of the PNGV effort, but probably essential to meeting the ultimate three-fold fuel economy stretch target. Most PNGV

technologies (light-weight, efficient power sources, low rolling resistance and aero, new fuels, etc.) are applicable to both hybrid and nonhybrid vehicles.

The committee believes that the analysis presented during this Phase 5 review on vehicle cost and cost of ownership is still inadequate as a guide to the selection of specific technologies to meet affordability requirements. Of course, the USCAR partners are engaged in making cost analyses that are proprietary to each company. Nevertheless, without compromising proprietary concerns, the committee urges the PNGV to work vigorously to develop a detailed assessment of the costs and benefits of the HEV compared to a nonhybrid vehicle.

Recommendation from Fourth Report. *Systems analysis and computer modeling are essential tools for making system trade-offs and optimizing performance. The PNGV should create detailed, rigorous cost and design reliability models as soon as possible to support ongoing technology selection. These models should be continuously upgraded as new information becomes available.*

PNGV Response. As the PNGV program progresses, the focus is evolving from a technology/performance priority toward a greater emphasis on cost, reliability and manufacturing in addition to performance. We agree that many of the technology programs have now reached the point where "affordability" will be given greater priority. Each of the Technical Teams has been assigned cost targets and is addressing the "affordability" challenges. We will report on the status of this work at the fifth PNGV Review. PNGVSAT includes both a design reliability model and cost trade-off model that will be exercised more fully as the designs mature. Warranty and reliability continue to be major automotive industry focuses.

Recommendation from Fourth Report. *Because cost is a significant challenge to PNGV, the USCAR partners should continue to conduct in-depth cost analyses and to use the results to guide new development initiatives on components and subsystems.*

PNGV Response. We agree. This is being done on both a collaborative basis through the Tech Teams and proprietary basis at the companies.

The PNGV has still not presented detailed, rigorous cost and design-reliability models to the committee, and the committee found little evidence that reliability models have been created for the vehicle system. The cost data presented during this review appeared to be gross variance data without detailed analysis.

Establishing a confidence level in these data is difficult without a more detailed vehicle subsystem breakdown. The committee notes, however, that the individual companies have undertaken detailed cost studies, and the committee urges that the PNGV also conduct in-depth cost analyses (without compromising the proprietary information of individual companies).

> **Recommendation from Fourth Report.** *The government should significantly expand its support for the development of long-term PNGV technologies that have the potential to improve fuel economy, lower emissions, and be commercially viable.*

> **PNGV Response.** Fundamental work at the National Science Foundation, the Department of Defense and Department of Energy is addressing long-term PNGV technical needs.

The PNGV response to the recommendation did not convince the committee that the issue is being addressed adequately. The committee recognizes that each federal agency has its own mission and may not be able to increase activities that would directly benefit the PNGV research program. The committee is aware that the DOE OAAT program engages in R&D that is directly relevant to the PNGV and that the appropriations for fiscal year 1999 have been increased for some of the longer range technologies, such as fuel cells, but not enough to confront the challenges facing the development of these technologies.

In general, the committee believes the PNGV has been responsive to most of the recommendations for the individual technology development areas. The PNGV has responded well to all of the committee's recommendations in the fourth report on 4SDI engine development, as well as to the recommendations on fuel cells. The remaining two power plants that had been under development, the gas-turbine and Stirling engines, have now been discontinued. The development of ultracapacitors and flywheels as energy-storage devices have also been discontinued.

During the review of battery developments in the fourth review, the committee's recommendations included the following one below:

> **Recommendation from Fourth Report.** *The PNGV should update the storage requirements and goals by means of subsystem models integrated with the overall system analysis. In addition to specific energy, test results should be reported on energy efficiency and specific power over well defined test protocols and compared to the refined goals.*

The committee believes that the response by the PNGV during its presentations on battery developments and in answers to committee questions has been inadequate, as evidenced by the absence of data on energy efficiency and the paucity of data on specific power (except by special committee requests) in the current review. PNGV's review of targets, based on systems integration, consisted of lowering the goal for regenerative pulse power for the dual-mode hybrid vehicle, an inconsequential change. The PNGV also discovered inconsistencies in the targets for dual-mode operation compared to power-assist operation, but nothing was done to correct them.

PNGV continues to make meaningful progress in many technical areas and to allocate resources to the most promising technologies for the concept vehicles. Although the USCAR partners are also focusing more of their resources on the development of the concept vehicles, they have also been working on other experimental vehicles.

In several previous reports, the committee concluded that insufficient resources have been allocated for the PNGV program to meet the objectives of Goal 3. The committee still believes the program will require additional resources to meet the severe development challenges that lie ahead.

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Appendixes

APPENDIX A

Biographical Sketches of Committee Members

Trevor O. Jones, *chair*, is chair and chief executive officer (CEO) of Biomec, Incorporated, a biomedical device company. He was formerly vice chairman of the board of Echlin, Incorporated, a supplier of automotive components primarily to the after-market. He is also chairman and CEO of International Development Corporation, a private management consulting company that advises automotive supplier companies on strategy and technology. He was chair, president, and CEO (retired) of Libbey-Owens-Ford Company, a major manufacturer of glass for automotive and construction applications. Previously, he was an officer of TRW, Incorporated, serving in various capacities in the company's Automotive Worldwide Sector, including vice president of engineering and group vice president, Transportation Electronics Group. Prior to joining TRW, he was employed by General Motors in many aerospace and automotive executive positions, including director of General Motors Proving Grounds; director of the Delco Electronics Division, Automotive Electronic and Safety Systems; and director of General Motors' Advanced Product Engineering Group. Mr. Jones is a life fellow of the American Institute of Electrical and Electronics Engineers and has been cited for "leadership in the application of electronics to the automobile." He is also a fellow of the American Society of Automotive Engineers, a fellow of the British Institution of Electrical Engineers, a fellow of the Engineering Society of Detroit, a registered professional engineer in Wisconsin, and a chartered engineer in the United Kingdom. He holds many patents and has lectured and written on the subjects of automotive safety and electronics. He is a member of the National Academy of Engineering (NAE) and a former commissioner of the National Research Council (NRC) Commission on Engineering and Technical Systems.

Mr. Jones has served on several other NRC study committees, including the Committee for a Strategic Transportation Research Study on Highway Safety, and chaired the NAE Steering Committee on the Impact of Products Liability Law on Innovation. He holds an HNC (Higher National Certificate) in electrical engineering from Aston Technical College and an ONC (Ordinary National Certificate) in mechanical engineering from Liverpool Technical College.

Alexis T. Bell (NAE) is professor of chemical engineering and dean of the College of Chemistry, University of California, Berkeley. The focus of his research is on heterogeneous catalysis and the relationship between catalyst composition and structure and catalyst performance on the molecular level. He is a recipient of the Curtis W. McGraw Award for Research, American Association of Engineering Education; the Professional Progress Award, American Institute of Chemical Engineers; the Paul H. Emmett Award in Fundamental Catalysis, the Catalysis Society; and the R.H. Wilhelm Award in Chemical Reaction Engineering, American Institute of Chemical Engineers. He is a fellow of the American Association for the Advancement of Science (AAAS). He received his Sc.D. in chemical engineering from the Massachusetts Institute of Technology.

Harry E. Cook (NAE) received his Ph.D. in materials science from Northwestern University. He is a recipient of the Robert Lansing Hardy Medal and the Ralph R.Teetor Award, as well as awards from the American Institute of Mining and Metallurgical Engineers. He is also a fellow of the Society of Automotive Engineers and the American Society of Metals. His career in the automotive industry began with the Ford Motor Company as a senior research engineer and culminated as the director of automotive research with Chrysler Motors. Currently, Dr. Cook is head, Department of General Engineering at the University of Illinois at Champaign-Urbana. His research includes work on phase transformations, friction and wear, automotive product development, and competitiveness.

David E. Foster is professor of mechanical engineering and director, Engine Research Center, University of Wisconsin, Madison. The Engine Research Center has won two center of excellence competitions for engine research and has extensive facilities for research on internal combustion engines, mainly diesels. Dr. Foster's interests include thermodynamics, fluid mechanics, internal combustion engines, combustion kinetics, and emissions formation. He is a recipient of the Ralph R. Teetor Award and the Forest R. McFarland Award of the Society of Automotive Engineers. Professor Foster is active on a number of committees of the Society of Automotive Engineers. He has conducted research in many areas related to internal combustion engines. He has a Ph.D. in mechanical engineering from the Massachusetts Institute of Technology.

Norman A. Gjostein (NAE) is currently clinical professor of engineering, University of Michigan-Dearborn, where he teaches courses in materials engineering. He retired from Ford Research Laboratory as director, Manufacturing and Materials Research Laboratory, which includes research in advanced materials, manufacturing systems, and computer-aided engineering. He has directed a variety of advanced research programs, including the development of lightweight metals, composite materials, sodium-sulfur batteries, fiber-optic multiplex systems, and smart sensors. He has pioneered studies in surface science and discovered a number of new surface structures still under investigation today. He is a member of the NAE and a fellow of the Engineering Society of Detroit (ESD) and the American Society of Metals (ASM). He has received ASM's Shoemaker Award and ESD's Gold Award. He has a B.S. and M.S. in metallurgical engineering from the Illinois Institute of Technology and a Ph.D. in metallurgical engineering from Carnegie-Mellon University.

David F. Hagen spent 35 years with Ford Motor Company, where his position prior to retirement was general manager, alpha simultaneous engineer, Ford Technical Affairs. Under his leadership, Ford's alpha activity, which involves the identification, assessment, and implementation of new product and process technologies, evolved into the company's global resource for leading-edge automotive product, process, and analytic technologies. Mr. Hagen led the introduction of the first domestic industry feedback electronics, central fuel metering, full electronic engine controls, and numerous four-cylinder, V6, and V8 engines. Based on his work on Ford's modern engine families, he was awarded the Society of Automotive Engineers E.N. Cole Award for Automotive Engineering Innovation in 1998. Mr. Hagen received his B.S. and M.S. in mechanical engineering from the University of Michigan. He is a fellow of the Engineering Society of Detroit and a member of the Society of Automotive Engineers. He is currently serving on the Visionary Manufacturing Committee of the National Research Council, the board of the School of Management, University of Michigan-Dearborn, and the engineering advisory boards of both Western Michigan University and the University of Michigan-Dearborn.

John B. Heywood is Sun Jae Professor of Mechanical Engineering at Massachusetts Institute of Technology and director of the Sloan Automotive Laboratory. Dr. Heywood's research interests have focused on understanding and explaining the processes that govern the operation and design of internal combustion engines and their fuel requirements. His major research activities include engine combustion, pollutant formation, and operating and emissions characteristics and fuel requirements of automotive and aircraft engines. He has been a consultant to Ford Motor Company, Mobil Research and Development Corporation, and several other industrial and government organizations. He has received the U.S. Department of Transportation 1996 Award for the Advancement of Motor Vehicle

Research and Development, as well as several awards from the Society of Automotive Engineers (SAE), among others. He has a Ph.D. in mechanical engineering from the Massachusetts Institute of Technology and an Sc.D. from Cambridge University. He is a fellow of SAE and a member of the National Academy of Engineering.

Fritz Kalhammer is consultant for the Electric Power Research Institute's (EPRI's) Strategic Science and Technology Group. He was co-chair of the California Air Resources Board's Battery Technical Advisory Panel on electric vehicle batteries. More recently, he chaired a similar panel to assess the prospects of fuel cells for electric vehicle propulsion. He has been vice president of EPRI's Strategic Research and Development and established the institute's programs for energy storage, fuel cells, electric vehicles, and energy conservation. Before joining EPRI, he directed electrochemical energy conversion, storage, and process research and development at Stanford Research Institute (now SRI International), conducted research in solid-state physics at Philco Corporation, and conducted research in catalysis at Hoechst, in Germany. He has a Ph.D. in physical chemistry from the University of Munich.

John G. Kassakian is professor of electrical engineering and director of the Massachusetts Institute of Technology (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. He is on the board 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 National Academy of Engineering, a fellow of the IEEE, and has received 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 Hing Chuen Kung is professor of chemical engineering at Northwestern University and was director of the Center for Catalysis and Surface Science. His research includes surface chemistry, catalysis, and chemical reaction engineering. His professional experience includes work as a research chemist at E.I. du Pont de Nemours & Co., Inc. He is a recipient of the P.H. Emmett Award from the North American Catalysis Society, the Japanese Society for the Promotion of Science Fellowship, John McClanahan Henske Distinguished Lectureship of Yale University, and Olaf A. Hougen Professorship of the University of Wisconsin, Madison. He has a Ph.D. in chemistry from Northwestern University.

Craig Marks is president of Creative Management Solutions. He is also adjunct professor in both the College of Engineering and the School of Business Administration at the University of Michigan and co-director of the Joel D. Tauber Manufacturing Institute. Dr. Marks is also president of the Environmental Research Institute of Michigan. He is a retired vice president of technology and productivity for AlliedSignal Automotive, where he was responsible for product development; manufacturing; quality; health, safety, and environment; communications; and business planning. Previously, in TRW's Automotive Worldwide Sector, Dr. Marks was vice president for engineering and technology and later vice president of technology at TRW Safety Restraint Systems. Prior to joining TRW, he held various positions at General Motors Corporation, including executive director of the engineering staff; assistant director of advanced product engineering; engineer in charge of power development; electric-vehicle program manager; supervisor for long-range engine development; and executive director of the environmental activities staff. He is a member of the National Academy of Engineering and a fellow of the Society of Automotive Engineers. Dr. Marks received his B.S.M.E., M.S.M.E., and Ph.D. in mechanical engineering from the California Institute of Technology.

John Scott Newman is professor of chemical engineering at the University of California, Berkeley. His research experience is in the design and analysis of electrochemical systems, transport properties of concentrated electrolytic solutions, and various fuel cells and batteries. He has received the Young Author's Prize from the Electrochemical Society, the David C. Grahame Award, the Henry B. Linford Award, the Olin Palladium Medal, and he is a member of the National Academy of Engineering. He is author of *Electrochemical Systems*, which has been translated into Japanese and Russian. He has a Ph.D. in chemical engineering from the University of California, Berkeley.

Jerome G. Rivard is president of Global Technology and Business Development, which advises business and universities on global business approaches to automotive electronics. He previously held a number of senior management positions with the Bendix Corporation and Ford Motor Company, including vice president for the Allied Automotive Sector of Bendix Electronics Group; group director of engineering for Bendix Electronic Fuel Injection Division; manager of the Bendix Automotive Advanced Concepts Program; and chief engineer for the Electrical and Electronics Division of Ford. Mr. Rivard built an engineering group with skills in electronics, electromechanical devices, fluid-flow control, combustion and power production, and control systems integration. He applied a systems approach to technical discipline management and adopted financial management systems to plan and control engineering projects effectively for maximum return on investment. Mr. Rivard is a member of the National Academy of Engineering and a fellow of the Institute of Electrical and Electronic Engineers and the Society of Automotive Engineers. He received his B.S.M.E. from the University of Wisconsin.

Vernon P. Roan is 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. He is also the director of the University of Florida Fuel Cell Research and Training Laboratory (since 1994). He was previously a senior design engineer with Pratt and Whitney Aircraft. Dr. Roan has more than 25 years of research and development experience. He is currently developing improved modeling and simulation systems for a fuel-cell bus program and works as a consultant to Pratt and 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 electric and hybrid vehicle programs. He has 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 regarding the status and outlook for fuel cells for transportation applications. Dr. Roan received his B.S. in aeronautical engineering and his M.S. in engineering from the University of Florida and his Ph.D. in engineering from the University of Illinois.

Appendix B

Letter from PNGV (October 14, 1998)

PNGV[SM]

PARTNERSHIP FOR A NEW GENERATION OF VEHICLES

October 14, 1998

Mr. Trevor Jones
Chair, Standing Committee to Review the
Research Program of PNGV
National Research Council
2101 Constitution Avenue N.W.
Room # HA 270
Washington, D.C. 20418

Dear Trevor,

We want to thank you and the other Standing Committee members for your thoughtful and very helpful review of the Partnership for a New Generation of Vehicles.

Attached are our comments on the major recommendations from the 4th report. We agree with many of your recommendations and we will be ready to discuss these with you at the upcoming 5th Review.

You also made a number of recommendations concerning the individual technology areas. The PNGV Technical Teams will address each of your recommendations during their discussions with you at the upcoming 5th Review.

Again we appreciate receiving your valuable input as we progress through the challenges of developing the PNGV technologies and advancing towards our goals.

Sincerely,

Vince Fazio
PNGV Director
Ford

George Joy (DOC)
PNGV Secretariat

Ron York
PNGV Director
General Motors

Steve Zimmer
PNGV Director
Chrysler

Attachment

Peer Review 4 Recommendations and Response

1) **RECOMMENDATION:** *In light of the published improvements in gasoline direct-injection (SIDI) engines, it would be prudent for the PNGV partners to continue to assess developments in this technology against PNGV targets and the CIDI engine, whether or not the gasoline direct-injection (SIDI) engine is chosen as a potential PNGV power plant.*

   We agree and are continuing SIDI research. We would also like to point out that four-stroke direct injection engines, which include both the SIDI and CIDI engines were the engines chosen during the Technology Selection process. For example, it would be more appropriate for Table ES-1 to show four-stroke direct injection engines in place of only CIDI engines. The SIDI effort has been expanded under the "1210" CRADA work at the National laboratories. The SIDI alternative continues to be pursued, although most of the work involves proprietary efforts by the companies. Finally, the proposed FY99 PNGV budget for the Department of Energy includes support for key research that would benefit the SIDI engines. It should be pointed out that lean SIDI has NOx and particulate challenges similar to CIDI.

2) **RECOMMENDATION:** *The relationship between the criteria for technology selection and the critical requirements of Goal 3 should be made more explicit to facilitate the proper distribution of resources for an ongoing, well structured research and development program.*

   We believe the relation between Technology Selection and Goal 3 criteria is explicit, as fuel economy, emissions, and performance were the key criteria used. However, as the acceptance criteria (such as emissions requirements) continue to be refined, some flexibility in technology options needs to be maintained.

3) **RECOMMENDATION:** *The PNGV should continue to refine its detailed cost of ownership analyses of hybrid vs. non-hybrid vehicles. If the economic and performance benefits of the hybrid vehicle do not exceed or warrant its additional costs, the concept demonstration vehicle program should be expanded to include non-hybrid vehicles to accelerate the development and commercial introduction of economically viable technologies.*

   We agree the hybrid technologies are one of the most challenging aspects of the PNGV effort, but probably essential to meeting the ultimate three-fold fuel economy stretch target. Most PNGV technologies (light-weight, efficient power sources, low rolling resistance and aero, new fuels, etc.) are applicable to both hybrid and non-hybrid vehicles.

4) **RECOMMENDATION:** *The PNGV should devote considerably more effort and resources to the exhaust-gas aftertreatment of oxides of nitrogen and particulates. PNGV should consider greatly expanding its efforts to involve catalyst manufacturers.*

   We agree with your recommendation and resources are being expanded. The proposed FY99 Department of Energy budget includes significant new funding in this area. The DOE has initiated programs to help the supply industry fund development of large-scale devices for evaluation. The catalyst industry has been working on lean NOx and NOx trap technologies for years, and

Response to Recommendation # 4 Cont'd.

PNGV is utilizing their efforts. The catalyst supply industry is being linked to the ongoing lean NOx catalyst effort at the National Laboratories. Progress is being made and we will report on the status of this work at the fifth PNGV Review.

5) **RECOMMENDATION:** *The PNGV should propose ways to involve the transportation fuels industry in a partnership with the government to help achieve PNGV goals.*

We agree with your recommendation. Both the Government (DOE lead) and Auto Industry have initiated technical dialogue to engage the Fuels Industry. Work is underway jointly to evaluate new and reformulated fuels. We will report on the status of this work at the fifth PNGV Review.

6) **RECOMMENDATION:** *PNGV's choices of energy conversion technologies should take full account of the implications for fuel development, supply, and distribution (infrastructure), as well as the economics and timing required to ensure the widespread availability of the fuel.*

We agree all the components of the system need to be considered. However, at this stage of program, given the very challenging fuel economy and emission goals of the program, it may be difficult to find the appropriate solution without considering new fuels. The current fuels infrastructure should not be a program constraint at this point in the program.

7) **RECOMMENDATION:** *PNGV and the USCAR partners should continue to make safety a high priority as they move toward the realization of the concept vehicles.*

Safety continues to be a high priority and was a consideration during the Technology Selection process . Meeting all applicable safety standards is a requirement for any production program. For example, we recognize and are working on the challenges of crash worthiness, high voltage, new fuels, and battery safety.

8) **RECOMMENDATION:** *Systems analysis and computer modeling are essential tools for making system trade-offs and optimizing performance. The PNGV should create detailed, rigorous cost and design reliability models as soon as possible to support ongoing technology selection. These models should be continuously upgraded as new information becomes available.*

As the PNGV program progresses, the focus is evolving from a technology/performance priority toward a greater emphasis on cost, reliability and manufacturing in addition to performance. We agree that many of the technology programs have now reached the point where "affordability" will be given greater priority. Each of the Technical Teams has been assigned cost targets and is addressing the "affordability" challenges. We will report on the status of this work at the fifth PNGV Review. PNGVSAT includes both a design reliability model and cost trade-off model that will be exercised more fully as the designs mature. Warranty and reliability continue to be major automotive industry focuses.

9) **RECOMMENDATION:** *Because of their high efficiency and low emission potential, fuel-cell systems for transportation could become vitally important to the United States. U.S. government and industry investments in research and development should, therefore, be continued at current levels or even be increased for an extended period.*

Response to Recommendation # 9 Cont'd.

We agree. The anticipated FY99 Department of Energy budget includes a $10 million increase for fuel cell R&D for a total of $34 million.

10) **RECOMMENDATION:** *Because cost is a significant challenge to PNGV, the USCAR partners should continue to conduct in-depth cost analyses and to use the results to guide new development initiatives on components and subsystems.*

We agree. This is being done on both a collaborative basis through the Tech Teams and proprietary basis at the companies.

11) **RECOMMENDATION:** *Government and industry policy makers should review the benefits and implications of PNGV pursuing a parallel strategy to achieve a 60+ MPG non-hybrid vehicle at an early date and should establish goals, schedules, and resource requirements for a coordinated development program.*

The PNGV collaborative research and development efforts are targeting technologies that can be applied broadly across the light-duty vehicles. The automotive industry partners are evaluating the opportunities for the PNGV technologies in a variety of configurations in their light-duty vehicle designs. At present, the only known near-term non-hybrid solution in the 60-mpg range requires a CIDI engine. As discussed above, the evolving future emission requirements and the availability of new fuels are issues that may present challenges to the viability of this as a near-term solution. The SIDI engine alternative probably can not meet a 60-mpg fuel economy target without hybridization, and also has emission challenges.

12) **RECOMMENDATION:** *The PNGV should assess the implications of the growing vehicle population of light trucks in the U.S. market in terms of overall fuel economy, emissions, and safety. Wherever possible, the PNGV should develop strategies for transferring technical advances to light trucks.*

The PNGV collaborative research and development efforts are targeting technologies that can be applied broadly across the light-duty vehicles. The automotive industry partners are evaluating the opportunities for the PNGV technologies in a variety of configurations in their light-duty vehicle designs. The PNGV technologies, in general, can be applied to light trucks for significant fuel economy improvements. Some of the ongoing efforts have addressed issues specifically related to light truck needs. For example, the Automotive Composite Consortium (ACC) is developing a composite pickup box. The utility and performance requirements of light trucks and SUV's will probably limit the extent of benefits. For example, it may not be possible to downsize the engines as much as is the case for passenger cars. PNGV is determining whether any unique technologies are required for SUVs and light trucks.

13) **RECOMMENDATION:** *The government should significantly expand its support for the development of long-term PNGV technologies that have the potential to improve fuel economy, lower emissions, and be commercially viable.*

Fundamental work at the National Science Foundation, the Department of Defense and Department of Energy is addressing long-term PNGV technical needs.

14) **RECOMMENDATION:** *The PNGV should expand its liaison role for the exchange of technological information among federal research programs that are relevant to automotive technologies and should accelerate the sharing of results among the participants in the PNGV on long-term, high-payoff technologies applicable to automobiles.*

We agree and progress is being made to strength the program links. The Department of Energy and the National Laboratories continue to be the major sources of program funding and technology input for the core portion of the PNGV program. In the future, the focus will be on strengthening the involvement of the Environmental Protection Agency, the National Institute of Standards and Technology, the Department of Transportation and the National Science Foundation.

Appendix C

Statement of Task

In the Phase 5 review the Standing Committee to Review the Research Program of the Partnership for a New Generation of Vehicles will address the following tasks:

(1) In light of recommendations from the fourth review, for each of the major technology selection focus areas (i.e., four-stroke direct injection engines, fuel cells, energy storage, electronic and electrical systems, and materials), examine the overall adequacy and balance of the PNGV research and development efforts to meet the program goals and requirements (i.e., technical objectives, schedules and rate of progress necessary to meet the requirements).

(2) Examine the ongoing systems analysis effort and the process by which it is guiding the PNGV to make decisions on R&D directions.

(3) Examine the efforts and progress towards PNGV's long-range component and system-level cost and performance goals.

(4) Examine ongoing PNGV-related efforts in the areas of vehicle emissions research and advanced materials research, and the process by which results are targeting both long-range and shorter-range PNGV goals.

(5) Review the government efforts to provide interfaces among different government agency R&D activities in support of PNGV.

Sponsor(s): U.S. Department of Transportation

Date of Statement: 07/07/98
Date of Previous Statement: 06/30/97

Appendix D

Committee Meetings and Other Activities

1. **Committee Meeting, October 26–28, 1998, Southfield, Michigan**
The following presentations were made to the committee:

Opening Remarks
Trevor Jones, Committee Chair
Bill Powers, Ford Motor Company, for USCAR
George Joy (U.S. Department of Commerce), Chair, PNGV Government Technology

Discussion of Peer Review IV: Comments and Recommendations
PNGV Executive Committee

Affordability
Chris Sloane, General Motors

Systems Analysis, Engineering, and the Decision Process
Mutasim Salman, General Motors

Vehicle Engineering
Bill Todd, General Motors

Materials
Andy Sherman, Ford Motor Company

Manufacturing
Chuck Rice, DaimlerChrysler

Fuels/Combustion/Aftertreatment: General Discussion
Jim Spearot, General Motors

U.S. Department of Energy Fuels Program
Bob Kirk, U.S. Department of Energy

4SDI Technical Team
Rich Belaire, Ford Motor Company; Loren Beard, DaimlerChrysler; Dick Blint, General Motors

Electrical/Electronics Technical Team
Bob Malcolm, DaimlerChrysler; David Hamilton, U.S. Department of Energy

Battery Technical Team
Harold Haskins, Ford Motor Company

Fuel Cell Technical Team
JoAnn Milliken, U.S. Department of Energy

Summary of Highlights
Al Murray, Ford Motor Company

Progress and Schedule
Chris Sloane, General Motors

Major Challenges, Funding Balance, and Adequacy
Owen Viergutz, DaimlerChrysler

Accounting for Results of Federal R&D Investments in Technology Development
Pandit Patil, U.S. Department of Energy

2. Committee Subgroup Visit to Ford for Proprietary Review of PNGV-related Concept Vehicle Activities, December 1, 1998, Dearborn, Michigan

3. Committee Subgroup Visit to DaimlerChrysler for Proprietary Review of PNGV-related Concept Vehicle Activities, December 8, 1998, Auburn Hills, Michigan

4. Committee Subgroup Visit to General Motors for Proprietary Review of PNGV-related Concept Vehicle Activities, December 11, 1998, Milford and Troy, Michigan.

5. Committee Meeting, December 14–16, 1998, Washington, D.C.
The following presentations were made to the committee:

Impact of Automotive Fuels Changes on the Fuels Industry
Bob King, Sun Oil Company

The Impact of California LEV-2 Emissions Standards on High Fuel Economy Goal 3 Vehicles
Tom Cackette, California Air Resources Board

Highlights of Government Agency Present and Future Support for PNGV
John Gudas, National Institute of Standards and Technology
Louis Martin-Vega, National Science Foundation
Dan Petonito, U.S. Department of Defense
Laszlo Backh, Environmental Protection Agency
Pandit Patil, U.S. Department of Energy

Validation and Testing the Results of Federally Funded R&D
Pandit Patil, U.S. Department of Energy

Appendix E

List of Recommendations

CHAPTER 2 VEHICLE SUBSYSTEMS

Recommendation. The 4SDI team should continue its program plan but should provide a more quantitative means of assessing progress and technical status relative to targets. In particular, the program should focus on exhaust-gas after-treatment and the development of performance or fuel specifications for a clean diesel fuel.

Recommendation. The 4SDI technical team should develop projections of the performance of compression-ignition direct-injection and gasoline direct-injection power-train systems, especially comparisons of the estimated emissions and fuel economy for each system. These projections would be a first step toward the quantification of trade-offs between emissions and fuel economy based on current and emerging state-of-the-art technologies.

Recommendation. Because one of the objectives of the PNGV program is to develop a vehicle that will be competitive in a global market and because fuel economy is a stronger market force in Europe and Asia than in the United States, the PNGV should continue development of the compression-ignition direct-injection engine.

Recommendation. PNGV should re-examine its fuels selection for fuel cells, taking into account the anticipated technical difficulties and cost implications of using gasoline as the onboard fuel.

Recommendation. PNGV should focus on improving stack performance without the use of a multi-atmosphere pressurization system.

Recommendation. PNGV should evaluate and compare reasonably optimized fuel-processor systems for different fuels to determine if the fuel-flexible or multifuel processing systems would be cost effective and would provide acceptable performance compared to systems optimized for a single fuel.

Recommendation. The PNGV should update its energy-storage requirements and goals by means of subsystem models integrated with overall system analysis. In addition to specific energy, test results should be reported for energy efficiency and specific power over well defined test protocols and compared to the refined performance goals.

Recommendation. The PNGV should decide whether safety issues with lithium-ion batteries will preclude their introduction for energy storage in hybrid electric vehicles.

Recommendation. The PNGV should conduct life-cost and performance-cost trade-off studies, as well as materials and manufacturing cost analyses, to determine which battery technology has the best prospects and most attractive compromises for meeting capital and life-cycle cost targets.

Recommendation. Because limited progress is expected on the flywheel device, the PNGV considers it a post-2000 technology. Given that no money has been allocated for flywheel development in PNGV's fiscal year 1999 budget, the PNGV should follow through on monitoring developments in other flywheel programs.

Recommendation. The PNGV should review its power-electronics and motor cost targets for 2004 to determine if they are realistic based on known and projected technology. Because of the reliance of other vehicle systems on power electronics, the PNGV must have a high level of confidence that its cost projections can be met.

Recommendation. The PNGV should conduct a thorough analysis of the electrical-accessory loads to ensure that targets for supplies of electrical energy are consistent with system needs.

Recommendation. The committee continues to believe that fabricated aluminum sheet should be the primary candidate for the body-in-white and closure panels for the year-2000 concept vehicles. The development of the low-cost continuous-casting process of aluminum sheet should be given a high priority in terms of resources and technical support. In addition, low-cost processes to overcome the cost penalty associated with the manufacturing and assembly of parts from aluminum sheet should be pursued.

Recommendation. The best long-term candidate—beyond year 2000—is the hybrid-material body-in-white, featuring thin carbon fiber-reinforced polymer sheet, sandwich panels, and aluminum front ends. The development program for low-cost carbon fiber should be continued for longer term applications beyond Goal 3. A low-cycle-time process and better recycling methods should also be pursued.

Recommendation. The PNGV materials technical team should endeavor to decrease the gap between the PNGV targets for weight savings and the actual identified weight savings for the power-train and chassis subsystems.

CHAPTER 3 SYSTEMS ANALYSIS

Recommendation. PNGV management should take steps to ensure the effective use of systems analysis by all technical teams and to expedite the validation of the PNGV models. The USCAR partners, which are effectively using individual proprietary models to guide the designs of their concept vehicles, should provide validation support to the PNGV models.

Recommendation. Without compromising proprietary considerations, the PNGV should conduct in-depth cost analyses and use the results to guide subsystem and vehicle-affordability studies.

Recommendation. The allocation of total vehicle cost among the various subsystems and components should be redone in light of development experience of the last five years to ensure that the cost targets, which have remained relatively static, are realistic.

CHAPTER 4 CROSSCUTTING ISSUES

Recommendation. The PNGV and USCAR partners should continue to make vehicle crashworthiness a high priority as they move toward realization of the concept vehicles.

Recommendation. A comprehensive mechanism should be established to help define feasible, timely, compatible fuel and power-plant modifications to meet the PNGV goals. This mechanism will require extensive cooperation among automotive and fuels industry participants at all levels of responsibility, but also among technical and policy members of relevant government organizations.

Recommendation. The federal government agencies involved in the PNGV program should review how future emissions requirements (especially NO_x and particulates), fuel economy, CO_2 emissions, as well as fuel quality, will affect the choice of the CIDI engine as the most promising short-term combustion-engine technology; a program plan that responds to that assessment should be developed. The PNGV, especially the U.S. Department of Energy and the Environmental Protection Agency, should work closely with the California Air Resources Board on these issues. Once the systems model has been validated, it would be an appropriate tool to use in quantifying the necessary trade-offs.

Recommendation. Future committee reviews should focus on the progress of manufacturing projects toward meeting the needs of the Goal 3 technical teams in development of component and subsystem technologies.

Recommendation. Future reviews of the PNGV program should not include evaluations of progress towards Goal 2. Instead, the three USCAR partners should make nonproprietary information available to the public.

Recommendation. The U.S. Department of Energy Office of Advanced Automotive Technologies should continue to focus its support on generic, precompetitive research and development that industry would not undertake on its own.

Recommendation. The criteria used by the U.S. Department of Energy Office of Advanced Automotive Technologies to validate components and component systems should be established with the full cooperation and participation of industry.

Appendix F

United States Council for Automotive Research Consortia

The U.S. automotive industry, through USCAR, has implemented collaborative projects that directly or indirectly support PNGV objectives. These USCAR consortia include:

- Low Emissions Technologies R&D Partnership
- Automotive Materials Partnership
- Supercomputer Automotive Applications Partnership
- CAD/CAM[1] Partnership
- Natural Gas Vehicle Technology Partnership
- Advanced Battery Consortium
- Vehicle Recycling Partnership
- Auto/Oil Quality Improvement Research Program
- Environmental Research Consortium
- Low Emissions Paint Consortium
- Electrical Wiring Component Applications Partnership

[1]CAD = computer-aided design; CAM = computer-aided manufacture.

Acronyms

ADL	A.D. Little
ANL	Argonne National Laboratory
AIPM	automotive integrated power module
BIW	body-in-white
CAFE	corporate average fuel economy
CARAT	Cooperative Automotive Research for Advanced Technologies
CARB	California Air Resources Board
CFRP	carbon fiber-reinforced polymer
CIDI	compression-ignition direct-injection
CO	carbon monoxide
CRADA	cooperative research and development agreement
DIATA	direct-injection, aluminum-block, through-bolt
DOE	U.S. Department of Energy
EE	electrical and electronic power systems team
EPA	Environmental Protection Agency
FTP	federal test procedure
GDI	gasoline direct injection
GM	General Motors Corporation

GFRP	glass fiber-reinforced polymer
HEV	hybrid electric vehicle
IFC	International Fuel Cell Company
IGT	Institute of Gas Technology
LANL	Los Alamos National Laboratory
LEV	low-emission vehicle
LLNL	Lawrence Livermore National Laboratory
MEA	membrane-electrode assembly
NO_x	nitrogen oxides
NVH	noise, vibration and harshness
OAAT	Office of Advanced Automotive Technology (U.S. Department of Energy)
ORNL	Oak Ridge National Laboratory
PEM	proton exchange membrane
PNGV	Partnership for a New Generation of Vehicles
PNNL	Pacific Northwest National Laboratory
POX	partial oxidation
ppm	parts per million
PrOx	preferential oxidation
R&D	research and development
RFP	request for proposal
SBIR	Small Business Innovative Research
SCAQMD	South Coast Air Quality Management District
SIDI	spark-ignited direct-injection
SNL	Sandia National Laboratory
SOC	state of charge
SULEV	super ultra LEV
SWRI	Southwest Research Institute
ULEV	ultralow emission vehicle
USAMP	United States Automotive Materials Partnership
USCAR	United States Council for Automotive Research
UTC	United Technologies Corporation
4SDI	four-stroke direct-injection