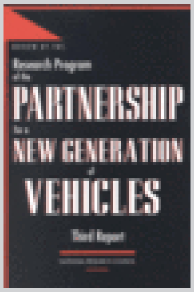

Review of the Research Program of the Partnership for a New Generation of Vehicles: Third Report

ISBN
978-0-309-05776-9

156 pages
6 x 9
PAPERBACK (1997)

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

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

THIRD 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

NATIONAL ACADEMY PRESS
Washington, D.C. 1997

NATIONAL ACADEMY PRESS • 2101 Constitution Avenue, N.W. • Washington, DC 20418

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This report and the study on which it is based were supported by Contract No. DTNH22-94-G-07414 from the National Highway Traffic Safety Administration, U.S. Department of Transportation. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the organizations or agencies that provided support for the project.

Library of Congress Catalog Number: 97-66882
International Standard Book Number: 0-309-05776-0

Available for sale from:

National Academy Press
2101 Constitution Avenue, N.W. Box 285
Washington, DC 20055
800-6242 or 202-334-3313 (in the Washington metropolitan area)
http://www.nap.edu

Printed in the United States of America

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Acknowledgments

The committee wishes to thank all the members of the Partnership for a New Generation of Vehicles who contributed significantly of their time and effort to this National Research Council study, whether by giving presentations at meetings, providing responses to committee requests for information, or hosting site visits. The committee also acknowledges the valuable contributions of organizations outside the Partnership for a New Generation of Vehicles, including those from outside the United States, who provided information on advanced vehicle technologies and development initiatives. Finally, the chairman wishes to recognize the committee members and the staff of the Board on Energy and Environmental Systems of the National Research Council for their hard work during the meetings and for their individual efforts in gathering information and writing sections of the report.

Acronyms

Ah	ampere hour
ARPA	Advanced Research Projects Agency
ATP	Advanced Technology Program
CIDI	compression ignition direct injection
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CRADA	cooperative research and development agreement
DISI	direct injected spark ignited
DME	dimethyl ether
DOC	U.S. Department of Commerce
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EGR	exhaust-gas recirculation
EPA	U.S. Environmental Protection Agency
GREET	greenhouse gases, regulated emissions and energy in transportation
HC	hydrocarbons
HEUI	hydraulic electronic unit injection

HEV	hybrid electric vehicle
HSDI	high speed direct injection
HVAC	heating, ventilation, and air conditioning
kWh	kilowatt hour
LEV	low-emission vehicle
MPFI	multi-port fuel injection
mV	millivolt
NASA	National Aeronautics and Space Administration
NDE	nondestructive evaluation
NO_x	nitrogen oxides
NSF	National Science Foundation
NRC	National Research Council
OBD	on-board diagnostics
OEM	original equipment manufacturer
PEBB	power electronic building block
PEM	proton exchange membrane
PEMFC	proton exchange membrane fuel cell
PM	particulate matter
PNGV	Partnership for a New Generation of Vehicles
ppm	parts per million
R&D	research and development
SIDI	spark ignition direct injection
SO_x	oxides of sulfur
SWRI	Southwest Research Institute
TACOM	Tank Automotive Command
ULEV	ultra-low emission vehicle
USABC	U.S. Advanced Battery Consortium
USCAR	United States Council for Automotive Research
VOCs	volatile organic compounds
VW	Volkswagen
ZEV	zero emission vehicle

Contents

List of Tables

Highlights

This is the third report of the National Research Council's 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 program between the federal government and the United States Council for Automotive Research (USCAR). 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 those of comparable 1994 family sedans. At the same time, these vehicles should maintain performance, size, utility, and cost of ownership and operation and should meet or exceed federal safety and emissions requirements. The intent of the program is to develop production prototype vehicles by 2004. The next major PNGV milestone, scheduled for the end of 1997, is selection of the most promising technologies.

The committee's major tasks were to examine research progress and state of development of energy converters (compression ignition direct injection engines [CIDI], gas turbines, Stirling engines, fuel cells) and energy storage technologies (batteries, flywheels, ultracapacitors) under consideration by PNGV, assess the relevance of ongoing research to the PNGV's goals and schedule, and address several broad program issues. As part of its effort, the committee continues to review the PNGV systems analysis activity that is essential to conducting vehicle performance and cost comparisons for alternative vehicle configurations incorporating different subsystem combinations and could guide the orderly selection and development of subsystem technologies with specific performance requirements for meeting the Goal 3 vehicle objectives.

TABLE H-1 Potential of PNGV Candidate Technologies and Assessment of Research Progress

Major Subsystems	Critical Technical Barriers	Likelihood of Meeting Technical Objectives[a]	Likelihood of Meeting Cost[b]	Likelihood of Meeting Schedule[c]	Overall Potential Regardless of Schedule[d]	Basic Needs	Overall Progress Since Last Review
Hybrid Drivetrain Power Sources							
CIDI	Combustion control NO_x catalyst	High	Medium	High	High	Resources	Modest
Fuel cell	Fuel processor/ reformer	Low	Low	Low	Medium	Breakthroughs	Modest to Good
Turbine	Structural ceramics Exhaust heat recovery	Low	Low	Low	Medium	Resources, focused R&D	Modest
Stirling	Heat Exchangers Leakage Control	Medium	Low	Low	Medium	Resources, focused R&D	Small
Energy Storage							
Lithium-ion battery	Scale-up System safety	High	Medium	Medium	Medium	Resources, focused R&D	Good
Nickel metal hydride battery	Efficiency Power density	Medium	Medium	Medium	Medium	Resources, focused R&D	Modest
Ultracapacitor	Efficiency Self-discharge Safety	Low	Low	Low	Low	Breakthroughs, resources	Small
Flywheel	Safety	Medium	Medium	Low	High	Resources, focused R&D	Small
Power electronics	Efficiency	Medium	Medium	High	High	Resources	Small

Note: This table represents a general committee judgment at an aggregate level of detail. The critical technical barriers are those that appear to be most challenging today and in many instances appear to require technical breakthroughs. See Chapter 4 for a more complete description of the key developments needed.

[a]Regardless of cost or schedule.
[b]Assuming the technical goals can be met.
[c]In achieving the technical goals.
[d]Overall potential over the long term of meeting the technical goals and cost.

MAJOR ACHIEVEMENTS AND BARRIERS

A number of achievements were realized by the PNGV in the past year, and progress has been made for a number of the technologies (see Table H-1). According to a presentation to the committee by the PNGV, the most important technical accomplishments in 1996 include:

- demonstration of a prototype fuel-flexible processor for a fuel cell with an 80 percent efficiency for the processor
- demonstration of a subscale, high-power, lithium-ion battery cell for 100,000 shallow cycles
- scale-up of a lean NO_x (nitrogen oxides) catalyst demonstrating 30 percent NO_x reduction
- fabrication of ceramic gas turbine scrolls and rotors using a process with high volume potential
- survival of a glass-fiber-reinforced, composite front-end structure design in a 35 mph barrier crash test
- development and construction of advanced technology demonstration vehicles, some of which incorporated requirements related to those of the PNGV, such as Ford's Synergy 2010, Chrysler's ESX, and General Motors EV-1

Despite significant progress in a number of critical areas, there continues to be a wide gulf between the current status of system and subsystem development and the performance and cost requirements necessary to meet major PNGV milestones. Some of the technical barriers to achieving PNGV objectives can probably be overcome with sufficient funding and management attention; others require inventions and very significant technical breakthroughs (see Table H-1). As stated in the committee's second report, the effort being expended on candidate technologies and systems is not consistent with the likelihood that each will meet performance goals within the program schedule. Work on many critical systems is inadequately funded and lacks integrated technical direction. The PNGV provided a list of major barriers to success. These barriers, which included a number of technical, production cost, funding, schedule, and other issues that need resolution, need to be overcome.

Based on the data provided, the committee believes that the following conclusions can be drawn:

- When incorporated in a vehicle, none of the energy converters/powertrains will come close to meeting the cost objectives within the time frame of the PNGV program.
- The CIDI engine is the energy converter with the highest potential for meeting the PNGV program performance requirements within the schedule and cost constraints. This position may be negatively affected should the Environmental Protection Agency promulgate more stringent exhaust emissions standards for diesel engines.

- The successful development of fuel cells, Stirling engines, and gas turbines that meet or approach the cost and performance requirements of the PNGV program is substantially beyond the current time frame of the program.
- Flywheels appear to have potential for providing energy storage as part of a hybrid vehicle once the safety and cost issues have been resolved. Their successful development is well beyond the time frame of the program.
- The successful development of ultracapacitors as storage devices is well beyond the time frame of the PNGV program.

The committee is not suggesting that development of these technologies should be terminated. However, it is most timely for the PNGV to reprogram funding and development efforts aggressively to be consistent with expected successful results within the current PNGV schedule through 2004. Investments in technology developments for the PNGV beyond that schedule should be continued, but with reduced and/or more highly focused effort. The committee's position is consistent with its first and second reports.

With regard to nontechnical aspects of the PNGV program, the institutional innovations and resulting technical organizations have advanced dramatically through the PNGV and appear beneficial to the goals of the program. In the committee's view, many previously isolated technology research programs have become much more focused and productive by uniting researchers and users and by developing clear technology goals. Materials and manufacturing teams have been formed and are apparently making impressive strides in support of program goals.

SYSTEMS ANALYSIS

During its second review, the committee expressed strong concern that the systems analysis effort had been significantly delayed by 12 to 18 months and that this delay was likely to jeopardize the technology "downselect" process scheduled for the end of 1997. That concern remains, although the committee notes that progress has been made since January 1996, when a contract was ultimately initiated to pursue aggressively the systems analysis effort. Progress to date has resulted in the creation of a rudimentary vehicle model and the initial development (or assembly from various sources) of models for the many vehicle subsystems and components. These subsystem models vary in quality from excellent representations (with substantial documentation) of some subsystems, such as internal combustion engines, to very generic, simplistic models for less understood subsystems like the fuel cell.

Although attention has been focused on creating systems analysis tools, little effort has been made to understand how the tools will be used by the PNGV technical teams (especially the vehicle engineering team) in studies necessary for the technology downselect process. Minimal participation by the vehicle engineering team has delayed the accurate establishment of optimal vehicle requirements. Also, interactions with the other technical teams appear to be minimal. This will affect the accuracy and usefulness of the subsystem models. In addition, establishing reliable models requires good validation data, but much of the available data are considered proprietary by potential providers.

TECHNOLOGY DOWNSELECT PROCESS

From the outset of the PNGV program in late 1993, the first major milestone was the 1997 technology downselect. This milestone was chosen on the basis that as a result of three to four years of studies and research and development clear technology "winners" would emerge. The winning technologies would obviously be those with the most potential to meet the PNGV goals. Conceptually, after downselect, the "losing" technologies would be dropped (or dramatically deemphasized), and most of the PNGV development effort would be directed toward the technologies selected as "winners." These efforts would result in the incorporation of the winning technologies in the concept vehicles and, later, in the production prototypes. However, the perception of what defines the winners and losers has changed. The initial focus was almost entirely on one part of Goal 3 (up to 80 miles per gallon fuel economy), along with the innovations and inventions that would be needed to make the technologies compatible with the Goal 3 car, but more traditional automotive considerations, such as cost, packaging, and system integration, are becoming equally important.

When all of these factors are taken into account, there will probably be no clear winners in the context of the original PNGV plan. This is not because of a lack of technical progress since there has been appreciable progress in virtually all, and very significant progress in some, technologies. Instead, it is related to the PNGV time frame and the realities of costs and manufacturing requirements. A primary downselect conclusion will be that some otherwise very promising technologies (fuel cells, gas turbines, Stirling engines, flywheels, and ultracapacitors) will not be fully demonstrable within the original PNGV time frame. Thus, the 1997 downselect will likely encompass, to a large degree, substantially improved and advanced versions of internal combustion engine and drivetrain technologies, batteries, vehicle structure, and manufacturing technologies. As a result, the nonconventional technologies run the risk of being discontinued or discarded in the downselect process, although it might well be in the national interest to continue their development under a longer-term, sustained program. Such a program would provide an insurance strategy in the event that the expected nearer-term technologies encounter unexpected barriers to implementation or fall short of fuel economy goals or if future societal goals change. Impressive advances have been made in several of the technologies that may not make the initial cut but that appear to offer important future societal benefits. Pursuing the more promising of these longer-term technologies for an extended period appears to be consistent with the original intent and goals (especially Goal 3) of a longer-term (initially defined as 10 years) PNGV program.

ADEQUACY AND BALANCE OF THE PNGV PROGRAM

Because of the lack of specific data that the committee requested from the PNGV (particularly current and future required funding), the committee found it extremely difficult to evaluate the adequacy and balance of funding to accomplish the PNGV Goal 3 objectives. The ultimate proof, of course, will be embodied in the timeliness of the 1997 technology downselect, the content and level of the performance achieved by the 2000 concept demonstration vehicles, and the performance and cost projections of 2004 production prototypes. However, as yet there are no clear criteria other than the PNGV Technical Roadmap and the generalities of Goal 3 objectives.

With appropriate focus and resources there still may be sufficient time in the current PNGV schedule to make some candidate technology systems viable (for example, the CIDI engine in conjunction with other subsystem improvements, [see Table H-1]). However, in the absence of a significant acceleration in their rate of development, progress beyond that achieved in the Department of Energy hybrid electric vehicle program is unlikely to make other fundamentally promising candidate technologies (such as fuel cells, gas turbines, Stirling engines, and some battery candidates) available within the PNGV time frame for demonstration of good performance in practical vehicles with acceptable risk.

The USCAR partners have decided to conduct independent vehicle demonstrations of the concept vehicles. Meeting the PNGV schedule with credible concept vehicles for 2000 will demand greatly increased efforts in 1997. Currently, the committee is not aware of what the PNGV would consider acceptable levels of performance for concept demonstration vehicles. The committee has requested this information from the PNGV.

The PNGV is experiencing severe funding and resource allocation problems that will preclude the program from achieving its objectives on its present schedule if they are not resolved expeditiously. In the absence of an acceptable and sustained resolution to this PNGV-wide problem in both government and industry, the PNGV's current objectives will no longer be tenable with respect to performance, cost, and schedule.

PNGV RESPONSE TO THE PHASE 2 REPORT

In the second report (issued in March 1996 following the second review of the PNGV research program), the committee offered a number of recommendations (see Appendix C) for the PNGV's consideration.

In addition to specific technology evaluations and recommendations, the committee offered six major recommendations:

- Strengthen and make more effective program management and technical leadership in both government and industry.
- Initiate and accelerate a comprehensive systems analysis program.
- Obtain and re-allocate federal and industry funding to activities with promising technological potential within the time horizon and needs of the program.
- Conduct comprehensive assessments and benchmark foreign technology developments relevant to the PNGV.
- Continue to address infrastructure issues as an integral part of the program.
- More fully involve other U.S. government agencies, such as the U.S. Department of Transportation, the National Aeronautics and Space Administration, the U.S. Department of Defense, and the Environmental Protection Agency, in the program.

The first five recommendations above were also made in the first committee report (NRC, 1994); the committee feels that insufficient attention or progress has been made in correcting these deficiencies since the first review. The slow rate of progress or lack of attention to the first three issues listed above may ultimately jeopardize the PNGV's ability to accomplish its goals.

SUMMARY

A recent Congressional Research Service report points out that relatively low U.S. gasoline prices do not create incentives for automobile purchasers to consider fuel economy to any great extent in their purchase decisions. With a lack of market forces that create incentives for car buyers to purchase vehicles with high fuel economy, it is difficult to realize the public benefits from improvements in fuel economy, such as health benefits from reduced urban ozone, "insurance" against sudden crude oil price shocks, reduced military costs of maintaining energy security, potential savings from reduced crude oil prices, improved balance of payments, and reductions in greenhouse gases from the transportation sector. The development of such a vehicle, as noted by the committee in previous reports, is extremely challenging. An ambitious goal stimulates rapid development of required technology and, even if a Goal 3 vehicle does not achieve the triple fuel economy level, it may still reach a level far above current levels.

To achieve the PNGV program objectives on the current schedule, the PNGV partners (USCAR and the federal government) should immediately develop a schedule of resource and funding requirements for each major technical task. This schedule should show current resources and funding applied to each major technical task and current resource shortfalls. Upon completion of this schedule, the PNGV partners should provide a strategy to obtain the necessary resources and funding.

Executive Summary

This is the third report of the National Research Council (NRC) Standing Committee to Review the Research Program of the Partnership for a New Generation of Vehicles (PNGV).[1] 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) that was initiated by President Clinton on September 29, 1993. The program has three goals:

Goal 1. Significantly improve national competitiveness in manufacturing for future generations of vehicles.

Goal 2. Implement commercially viable innovation from ongoing research on conventional vehicles.

Goal 3. Develop vehicles to achieve up to three times the fuel efficiency of comparable 1994 family sedans.

The Goal 3 vehicles should maintain or improve performance, size, utility, and total cost of ownership and operation of comparable 1994 family sedans and should meet or exceed federal safety and emissions requirements. The first major PNGV milestone, targeted for the end of calendar year 1997, is selection of the most promising technologies for the Goal 3 concept vehicles. (This is usually referred to as the technology "downselect" process.) Goal 3 vehicle schedules are to fabricate concept vehicles by 2000 and preproduction prototype vehicles by 2004.

[1]Hereafter referred to in this report as the committee.

During this third review, at the request of the U.S. Department of Commerce, the committee was charged with:

- critically evaluating the research progress and the state of development of energy converters (compression ignition direct injection [CIDI] engine, gas turbines, fuel cells, and Stirling engines), energy storage technologies (batteries, flywheels, and ultracapacitors), and electrical systems and power electronic technologies under consideration by the PNGV
- evaluating the PNGV efforts to overcome technical barriers identified in the committee's second report, progress the PNGV has made to maintain its current research schedule and milestones, and the efficacy of the future program to achieve the specified PNGV goals of performance, cost, and schedule
- assessing the relevance of ongoing research to the PNGV's goals and schedule
- examining the extent to which recommendations from the committee's first and second reports have been addressed by the PNGV

The committee was also charged with commenting on several broad program issues:

- the effort the government has initiated to anticipate infrastructure problems or issues that might arise upon introduction of the PNGV advanced vehicle
- the means by which PNGV might draw upon foreign automotive technology
- the process by which PNGV will make choices and reallocate resources in the downselect process now scheduled for the end of 1997
- the overall adequacy and balance of the PNGV technical program

This summary highlights the committee's principal findings and recommendations and addresses the following: (1) the PNGV's systems analysis efforts, which are needed to properly define performance requirements for the technologies under development towards Goal 3 objectives; (2) progress in technology development; (3) progress on goals 1 and 2; (4) broad program issues; and (5) important barriers to program success. The final section comments on PNGV's response to recommendations in the committee's two previous reports (NRC, 1994; 1996).

SYSTEMS ANALYSIS

Systems analyses are used for preliminary design studies as well as for performance trade-offs and cost comparisons for alternative vehicle configurations incorporating different subsystem combinations. An appropriately configured and validated set of systems analysis tools can allow an accurate determination of the requirements for the vehicle subsystems, such as energy converters, energy storage, and power electronics. If systems analyses are established at the outset of the program, they can guide the orderly selection and development of subsystem technologies with specific performance requirements for meeting the Goal 3 vehicle objectives.

During its second review, the committee expressed strong concern that the systems analysis effort had been significantly delayed by 12 to 18 months and that this delay was likely to jeopardize the technology downselect process scheduled for the end of 1997. That concern remains, although the committee notes that progress has been made since January 1996, when a contract was ultimately initiated to pursue aggressively the effort outlined in the PNGV Technical Roadmap. Progress to date has resulted in the creation of a rudimentary vehicle model and the initial development (or assembly from various sources) of models for the many vehicle subsystems and components. These subsystem models vary in quality from excellent representations (with substantial documentation) of some subsystems, such as internal combustion engines, to very generic, simplistic models for less understood subsystems like the fuel cell.

Although attention has been focused on creating systems analysis tools, little effort has been made to understand how the tools will be used by the PNGV technical teams (especially the vehicle engineering team) in studies necessary for the technology downselect process. Minimal participation by the vehicle engineering team has delayed the accurate establishment of optimal vehicle requirements. Also, interactions with the other technical teams appear to be minimal. This will affect the accuracy and usefulness of the subsystem models.

Establishing reliable models requires good validation data, but much of the available data are considered proprietary by potential providers. The lack of such data is hindering the efforts of the PNGV systems analysis team and, if not corrected, will further aggravate program schedules. Also, lack of government funding has necessitated reductions in technical efforts by the national laboratories, which will affect the realization of systems analysis objectives for fuel cells, batteries, ultracapacitors, and flywheels. Furthermore, cost and reliability models, which are critical to evaluating designs, are inadequate and significantly behind schedule.

The committee believes the foundation for the systems analysis part of the PNGV program has now been established. This belief is based on a detailed review of the technical approach and a demonstration of the systems analysis capabilities to the committee. However, the systems analysis work is at least a year behind schedule. If there is to be a truly meaningful downselect process in the 1997 to 1998 time frame, a reasonably reliable systems analysis of competing systems must be available before the end of that time period. Completing tradeoff studies by the end of 1997 to allow selection of the preferred vehicle concepts remains a major challenge, especially in light of insufficient funding.

Recommendation. The managers of the PNGV should conduct a program review with the leadership of the vehicle engineering team and systems analysis team to assess the capability of the existing projects to achieve program performance requirements for the technology downselect process. A corrective action plan should be formulated and implemented as a matter of some urgency. This will ensure that systems studies are designed and implemented to provide the necessary optimization and trade-off information to make the best choices. It would be logical for the systems analysis team to place a priority on enacting those models that appear to be sure contenders for the technology selection process in 1997.

Recommendation. The managers of the PNGV should define and obtain the necessary resources for conducting systems analyses in 1997 and 1998.

TECHNOLOGY ASSESSMENT

To achieve the Goal 3 fuel economy target, the efficiency of the combustion engine or fuel cell, averaged over a driving cycle, will have to be approximately double today's efficiency and will have to reach a level of at least 40 percent thermal efficiency. This is a very challenging goal. The candidate systems for the Goal 3 vehicle (as listed above in the committee's statement of task) have not changed during the past year.

Energy Converters

CIDI Engine

There has been limited progress during the last year in developing CIDI engines in the PNGV program, per se. However, the production of relatively advanced small-displacement CIDI engines in Europe, and ongoing work to improve them, indicates that the PNGV CIDI performance goals, with the possible exception of emissions, are potentially achievable. The 1995 engine characteristic targets established by the PNGV CIDI technical team have been met or exceeded in test engines. An adequate plan has been developed, and a technology road map applicable to CIDI has been completed. Research priorities have been established, and efforts to address them have begun.

The highest technology risk appears to be the ability to develop fuel management and after-treatment systems to meet uncertain federal exhaust emission requirements in 2004. The PNGV has an ongoing modest effort to reduce emissions both from the engine and through after-treatment. But funds are limited, and results are insufficient to date to assess a rate of progress.

The production cost of a CIDI engine appears to be an impediment to meeting the challenging goals set forth for 2004. It appears that the complex high pressure injection system, variable geometry turbocharger, and high cylinder pressures, combined with the need for lightweight, high strength materials will result in a substantial cost premium. Also, the testing of lightweight structures and cost-reduction features for the CIDI engine are at least a year behind schedule for the year 2000 concept vehicle.

Although, as noted above, there are significant risks that CIDI engines will not meet the PNGV goals, this technology is, by far, the best understood and most highly developed among the power plant technologies being pursued in the program. It is, therefore, highly likely that CIDI engine technology will be among the selected candidates for use in the year 2000 concept vehicles. This technology deserves substantial and focused program attention with adequate (increased) financial support.

Recommendation. The PNGV should expand efforts to devise lightweight, low-cost alternative CIDI engine structures, and additional resources should be made available.

Recommendation. The PNGV should immediately assess the possible effect of regulatory actions aimed at reducing the atmospheric level of fine particulate matter on the viability of passenger car CIDI engines, and the research and development program should be modified, if necessary. To help the Environmental Protection Agency (EPA) make decisions based on the best possible information, the EPA should be continually informed of decisions made by PNGV during the downselect process. Furthermore, the PNGV and EPA should work together to determine the trade-offs between vehicle performance and environmental standards and associated impacts on social benefits and costs.

Gas Turbines

Gas turbines represent a "promising" technology for hybrid vehicles; however, development is behind schedule, and major technical barriers remain. These barriers include the availability of suitable turbine materials that could withstand the high temperatures demanded for Goal 3 vehicles and the need for low-cost heat recovery devices (recuperators or regenerators). Also, there is still considerable uncertainty about critical design parameters for the subsystems because to date no comprehensive PNGV system studies have been completed for automotive gas-turbine powered vehicles.

Recent system studies indicate that gas-turbine powered vehicles have the potential to approach the thermal efficiency, weight, and volume requirements for an 80-mpg fuel economy level. However, these systems studies are primarily first-order analyses, and more detailed systems studies involving tradeoff analyses are necessary to identify promising systems and subsystem configurations. Gas turbine manufacturers have stated that they can meet or approach the PNGV objectives. This claim has not been proved. However, based on information presented by the manufacturers and the state and progress of turbine technology in general, the claim seems feasible given sufficient development time and adequate resources.

Significant progress has been made in the manufacture of high quality ceramic turbine components with complex shapes using processes with good potential for scale-up to the required manufacturing volumes. Impressive gains (e.g., shorter production times) have also been documented with the silicon nitride gelcast approach, but it is still far from what would be required to achieve a low enough production cost for automotive parts.

Despite the progress to date, especially in the critical areas of ceramic turbines and ceramic heat-recovery devices, even the most optimistic projections (for the development time required based on current funding levels) would put the gas turbine well beyond the time frame for a meaningful demonstration of the PNGV concept vehicle.

Recommendation. Gas turbine development should continue, and acceleration of the basic technology and systems and design optimization efforts should be considered. Some of the deficiencies and inconsistencies among the developers indicate that a better technical focus in areas such as bearings, overall system optimization, and manufacturing goals should be defined.

Stirling Engines

Stirling engine technology has been selected by General Motors for development in the U.S. Department of Energy (DOE) hybrid electric vehicle (HEV) program, which is in its initial engine evaluation. Much will be learned about the potential of the Stirling engine for possible application to the PNGV program through this program. Cost, manufacturing hurdles, and durability for automotive applications are not well understood at this time. Being an external combustion engine, the five heat exchangers required (heater head, regenerator, air pre-heater, gas cooler, and radiator) create the most uncertainty. Cold-start emissions also need to be determined. The DOE HEV program is expected to provide a benchmark regarding the performance of these components as well as an assessment of the critical issue of working fluid containment.

Recommendation. The PNGV should review results from the General Motors/DOE HEV program on an ongoing basis, and the potential use of a Stirling engine in a PNGV prototype vehicle should be assessed through appropriate vehicle systems, modeling, and packaging studies.

Fuel Cells

Current PNGV and worldwide efforts to develop fuel-cell power plants for cars focus on the proton-exchange-membrane (PEM) fuel cell, which is generally considered the most promising fuel-cell candidate for the HEV. Like other fuel-cell technologies, it operates best on hydrogen as a fuel. However, because an infrastructure for production, storage, and distribution of competitively priced hydrogen is not likely to be developed in the foreseeable future, the strategy of the PNGV program is to convert gasoline on board the vehicle to hydrogen for use by the fuel cell. This approach requires a fuel processor on board the vehicle to convert gasoline into a hydrogen-rich fuel stream with very high efficiency (i.e., to retain the fundamental efficiency advantage of electrochemical energy converters over combustion engines). Furthermore, the fuel stream entering the fuel-cell stack must be almost entirely free of carbon monoxide (CO) and other fuel-processing contaminant byproducts that can poison the noble metals used as the fuel-cell anode electrocatalysts.

The most challenging issues are: (1) developing a high efficiency, thermally integrated fuel processor for gasoline; (2) developing a method and/or system for reducing CO concentrations to very low levels in the hydrogen gas stream emerging from the fuel processor; (3) integrating and controlling a fuel processor and fuel-cell stack to achieve highly efficient operation over a wide range of power outputs; (4) finding a CO-tolerant electrocatalyst for the hydrogen anode in the fuel cell; and (5) achieving the stringent PNGV cost goals for the complete fuel-cell power plant with its integrated controls. Progress has been made in (1) developing fuel processors for potential use with gasoline, (2) attaining much improved performance levels in the electrochemical cell stack, as required to meet PNGV goals, and (3) developing and evaluating controls and ancillaries for efficient thermal and water management and for operation of fuel cells at the desired pressures.

Resolution of the major technical and cost issues will require more funding, time, and effort than are currently available; thus, the prospect of reaching PNGV goals on schedule is low. Present high costs of commercial phosphoric-acid fuel cells used for stationary power, and the high cost of the materials used for PEM fuel-cell components indicate that costs must be reduced by about two orders of magnitude to meet the PNGV targets. The committee is of the opinion that it is unlikely dramatic reductions can be obtained without significant technological developments and major breakthroughs. The PEM fuel-cell technology probably cannot be cost-competitive in the PNGV time frame or substantially thereafter.

Even though the PEM fuel cell appears to be beyond the PNGV time frame, it does offer high potential for very low emissions and high thermal efficiency. Because other fuels more compatible with fuel cells than gasoline, such as methanol or possibly hydrogen, may become commercially available in the long run, it seems important for PNGV program decisions to weigh the longer-term high efficiency and low-emissions potential of fuel cells powered by nongasoline fuels.

Recommendation. Development of automotive fuel-cell technology should be continued with emphasis on achieving breakthroughs in areas critical to achieving high efficiency, long life, and low manufacturing cost.

Recommendation. Because a high performance, compact, efficient, and low-cost gasoline fuel processor is a key to early automotive fuel-cell applications, high priority should be given to a 50-kW gasoline fuel processor. However, a demonstration project should be funded only if design studies can reliably indicate the attainment of the performance goals that have been set with respect to CO content and total system efficiency.

Energy Storage Devices

Batteries

During the last year, the PNGV battery program has progressed well, and the growing focus on electrochemical batteries as the most promising energy storage option for the hybrid vehicle seems appropriate to the committee. The PNGV program has refined the performance and cost criteria for HEV energy storage based on assumed vehicle powertrain response modes. Because these criteria are not based on detailed vehicle systems analysis of performance requirements and cost trade-offs, they should be used as guides rather than as hard rules for selecting and developing batteries for hybrid vehicles.

The committee concurs with the selection of the lithium-ion battery technology as the primary candidate for development of hybrid vehicle batteries. The first phase of this development, completed in 1996, benefited from a sound starting point and technical approach and has been successful. Plans for a second phase are to develop a battery system design that minimizes safety concerns under all operating conditions and has potential to approach the PNGV cost goals. The PNGV is also funding two efforts to develop nickel-metal hydride hybrid batteries. These efforts have not yet yielded results that permit assessment of the potential of this technology for the Goal 3 vehicle.

Battery requirements may be able to be relaxed based on a more detailed vehicle systems analysis. If so, this would expand the selection of possible battery types that may be applicable, including alternatives such as high-power versions of lead-acid batteries or nickel/cadmium batteries. At present the PNGV appears to rely on the DOE programs and evaluations of the three USCAR partners to advance and assess the potential of advanced lead-acid batteries for the HEV.

The plans for developing a more systematic hybrid vehicle battery design testing methodology and, presumably, a physical capability for testing, are most appropriate and deserve support of the PNGV, as does a program of fundamental research for the exploration of breakthroughs.

Recommendation. Development of the high-power lithium-ion battery should continue to the prototype module level, with early emphasis on safety under all foreseeable conditions. The control requirements for the safe operation of modules and batteries in the hybrid mode(s) should be determined, and development of potentially low-cost electric and thermal control systems should be initiated.

Recommendation. The ongoing exploratory development of high-power nickel metal hydride batteries should be completed. Based on these data and test data from promising nickel metal hydride batteries available from other sources, the PNGV should determine whether this technology offers advantages over lithium-ion in hybrid applications and how these advantages might be captured for the Goal 3 vehicle.

Flywheels

Flywheels offer very attractive power-to-weight and power-to-volume characteristics for hybrid vehicles, both in delivering power and in recovering kinetic energy during braking. However, major issues related to safety, cost, and packaging remain to be resolved if flywheel subsystems are to become an integral part of HEV power sources.

Since the committee's second review, the PNGV flywheel technical team has planned a series of efforts starting in January 1996 and has made progress in defining a mission statement and constructing a development plan for the flywheel activity. The team is also involved in integrating other flywheel design and testing activities occurring outside of the PNGV. If funding of about $1.3 million can be made available for fiscal year 1997, a laboratory-scale flywheel subsystem is scheduled to be ready for testing by the end of 1997.

The committee concurs with the flywheel technical team's assessment that flywheel subsystems are unlikely to be integrated in the first concept vehicles. The committee believes that other activities outside of the PNGV, such as related work funded by the Advanced Research Projects Agency, have produced significant data that will be important to the technical team's evaluation of flywheel subsystems as part of the technology selection process in 1997.

Recommendation. After the appropriate vehicle systems analysis trade-off studies are completed, performance objectives for flywheel subsystems should be established that satisfy the requirements of the fast-response power plant vehicle system.[2] A plan should then be developed for the integration and evaluation of a flywheel subsystem into post-2000 concept vehicles.

Recommendation. The Advanced Research Projects Agency comprehensive flywheel failure-containment plan should be pursued, including the compilation of burst/collision failure test data from all available sources.

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[2]A fast-response power plant reacts very much like a conventional automotive engine.

Ultracapacitors

Ultracapacitors are potential energy storage devices for some hybrid vehicle configurations and have been proposed for limiting the surge current load on hybrid vehicle batteries. Ultracapacitors can deliver high specific power over short time periods and operate for many cycles, but their specific energy is well below that of batteries and the Goal 3 vehicle requirements. They also have a problem in that the projected cost for energy storage capacity is about two orders of magnitude higher than the PNGV cost goal. In addition, the requirement for more complex power conversion devices will add to the ultracapacitor system cost as compared with batteries.

The ultracapacitor projects are in an early stage of research and development. Current programs are behind schedule, and the milestones for 1996 have not been met. Given the state of development and the technical and cost barriers, it is highly unlikely that the ongoing projects will meet the PNGV performance, cost, and schedule goals. None of the ultracapacitor concepts currently under development appears capable of meeting the PNGV cost goals. Thus, it seems too early to attempt cell stack engineering scale-up. It would be appropriate at this stage to assess the progress being made in ultracapacitor development for other applications with the intention of determining needed research, development, and demonstration for hybrid vehicles. Additional systems studies using better models for capacitors, batteries, and the balance of system can provide a more realistic view of the long-term potential of ultracapacitors.

Recommendation. The PNGV should conduct appropriate systems studies to determine the prospects for ultracapacitors in hybrid vehicles in comparison with high power batteries and other energy storage devices, such as flywheels.

Recommendation: Ultracapacitor activities for application to hybrid vehicles should be limited to basic and applied research at universities, national laboratories, and industrial R&D centers, aimed at fundamental advances and breakthroughs.

Electrical and Electronic Power Conversion Devices

All of the PNGV HEV configurations (including vehicle subsystems and accessories) require electric motors/alternators, electric power inverters, sophisticated electronic and electric controllers, and electric power conversion and control devices to maximize efficiency. During this third review, major issues identified by the committee affecting the realization of the PNGV goals include the following: (1) no data were presented to the committee that would establish confidence that the goal for overall driveline efficiency can be increased to 80 percent from the estimated 70 percent based on current technology; (2) it appears that insufficient technical effort is being directed toward reducing the power requirements of vehicle electric and electronic subsystems (such as power steering, heating, ventilation, and air conditioning systems, cooling pumps) below the current potential demand of up to 30 percent of the vehicle drivetrain power; (3) the current cost of many of the electrical subsystems is estimated to be 50 percent to 300 percent above the PNGV targets; and (4) assigning targets to the individual components without the benefit of an overall vehicle system definition supported by systems analysis will not result in an overall optimization of vehicle performance and cost.

Overall the committee concluded that very little was accomplished by the PNGV electrical and electronics power conversion devices team during the past year. The PNGV Technical Roadmap power electronic building block milestone for 1995 was not met, and at the current rate of accomplishment, the second milestone, established for 1997, will also be missed. Furthermore, many tasks in the road map are not being addressed. The team has been without an appointed leader for most of the year, and the team has virtually no full-time participants. The committee also sensed that the PNGV appears to have placed an inadequate degree of urgency and importance on this team's activities. The committee believes that this effort is seriously behind schedule and could jeopardize the 1997 downselect process at its current pace.

Recommendation. The new leader of the electrical and electronic power conversion devices team should be full time in this role and should determine what is required to make up for lost time and establish the necessary schedule. The team leader should identify the staff necessary for effective team performance and commit them to team activities. One of the highest priorities for the new team leader should be the development of interfaces with the vehicle engineering team and the systems analysis team.

Recommendation. The impact of the schedule slippage on the technology downselect process should be reviewed immediately by PNGV management, and plans should be made for meeting schedules to support the overall PNGV effort.

MANUFACTURING NEEDS FOR GOAL 3

The manufacturing team is now well organized, well established, and is making progress. A manufacturing technology road map also has been formulated and will need continued refining as new needs are identified to meet the challenges of the Goal 3 product technologies. The manufacturing team members are active participants in the product technology teams and, as needs arise, are able to communicate these needs to government representatives, other consortia, universities, and suppliers. It is unlikely, however, that significant cost and production efficiency achievements will be available for the vehicle systems when the selection of technologies (the downselect) occurs at the end of 1997 for the year 2000 concept vehicle. The magnitude of cost offset for the new product technologies currently assumed to be candidates for the Goal 3 vehicles would seem to be well beyond what can be achieved by the projects in place in Goal 1 and by projects currently being considered for Goal 3.

Recommendation. A major portion of the manufacturing efforts for the Goal 3 vehicle should be directed towards identifying new manufacturing approaches for achieving significant cost reductions in all key system and subsystem areas.

GOAL 1

The PNGV manufacturing team has conducted a comprehensive review of potentially useful projects and identified 10 projects for joint action by the USCAR and the federal government. Nine of these projects are being actively pursued, and one still requires funding. The committee commends the work of the manufacturing team. Although some of the new production technologies that evolve from these efforts may result in significant cost and weight reductions, they may be precluded from being introduced because of high initial costs and associated financial risks.

Recommendation. For the technologies that will contribute cost and weight reductions for Goal 3 vehicles, industry and government should use a cost-shared approach to fund the initial tooling for proof-of-concept demonstration to reduce the financial risk to any one company. Investments for subsequent tooling for larger production runs would appropriately be made by individual companies.

GOAL 2

The Goal 2 projects selected are making significant progress under the mentoring of the PNGV manufacturing team. Although the projected cost and weight savings calculated for Goal 2 near-term projects are substantial, they are far below what will be required to make the Goal 3 vehicles feasible. It appears that all important areas are being addressed, but year-to-year progress and plans for 1997 do not indicate much improvement in the pace of development.

Recommendation. The PNGV should evaluate and prioritize its Goal 2 projects to identify those that contribute the most to near-term improvements in fuel efficiency and reduction in emissions and those that would enhance the manufacturing base needed to meet the cost goals of the Goal 3 technologies. Based on prioritization of potential improvements, resources and funding should be appropriately reallocated.

INFRASTRUCTURE

The committee's second report cited the importance of considering the impact of the PNGV program on the nation's infrastructure. For example, adoption of alternative PNGV power plants that use fuels such as methanol, dimethyl ether, or hydrogen to achieve the PNGV vehicle efficiency goals would require significant modification of the fuel production, transportation, storage, and retail distribution infrastructures. Indeed almost all aspects of bringing a Goal 3 vehicle to market have significant infrastructure implications. These range from raw material supply to manufacturing capability to production of the products and from environmental impact to ancillary support, such as highway systems and vehicle service, insurance, and maintenance.

The infrastructure analysis is an important tool for the PNGV program. As the PNGV continues to refine its technology knowledge base, it is important that the power plant configurations and fuel types being considered are accurately represented and evaluated with suitable infrastructure models as an integral part of the downselect process. Also, for simulation to remain a valuable tool, it is very important that the underlying assumptions of the model be continually re-evaluated, updated, and made transparent as new information becomes available.

During the past year, a research team from Argonne National Laboratory has continued the work reported to the committee during its second review in August 1995. The work involved further developing and testing their life-cycle energy and emissions model, GREET (greenhouse gases, regulated emissions, and energy use in transportation).

Recommendation. The infrastructure study should be continued. There should be a concerted effort to evaluate the GREET model relative to models developed for similar purposes by the oil industry and other agencies.

TECHNOLOGY DOWNSELECT PROCESS

From the outset of the PNGV program, the first major milestone was the 1997 technology downselect. This milestone was chosen on the basis that, as a result of three years of studies and research and development, clear technology "winners" would emerge. The winning technologies would obviously be those with high potential to meet the PNGV goals. Conceptually, after downselect, the "losing" technologies could be dropped (or dramatically de-emphasized), and most of the PNGV development effort would be directed toward the technologies selected as "winners." These efforts would result in the incorporation of the winning technologies in concept vehicles and, later, in production prototypes. However, the perception of what defines the winners and losers has changed. The initial focus was almost entirely on one part of Goal 3 (up to 80 miles per gallon fuel economy), along with the innovations and inventions that would be needed to make the technologies compatible with the Goal 3 car, but more traditional automotive considerations, such as cost, packaging, and system integration, are becoming equally important as decisions must be made on concept car designs.

When all of these factors are taken into account, there will probably be no clear winners in the context of the original PNGV plan. This is not because of a lack of technical progress since there has been appreciable progress in virtually all, and very significant progress in some, technologies. Instead, it is related to the PNGV time frame and the realities of costs and manufacturing requirements. Consequently, a primary downselect conclusion will be that some otherwise very promising technologies will not be fully demonstrable within the original PNGV time frame, especially nonconventional technologies, such as fuel cells, gas turbines, Stirling engines, flywheels, and ultracapacitors. Thus, the 1997 downselect will likely encompass, to a large degree, substantially improved and advanced versions of internal combustion engine and drivetrain technologies, batteries, vehicle structure, and manufacturing technologies. As a result, nonconventional technologies run the risk of being discontinued or discarded in the downselect process, although it might well be in the national interest to continue their development under a longer-term, sustained program. Such a program would provide an insurance strategy in the event that the expected nearer-term technologies encounter unexpected barriers to implementation or fall short of fuel economy goals or if future societal goals change.

In summary, the original downselect concept of winners and losers no longer appears tenable. The initial technology selections and decisions (especially by the government) on where to focus resources must be made on the basis of technology readiness in addition to performance potential and the likelihood of achieving program objectives as they currently exist or are modified. Impressive advances have been made in several of the technologies that may not make the initial cut but that appear to offer important future benefits. Pursuing the more promising of these longer-term technologies through an extended period appears to be consistent with the original intent and goals (especially Goal 3) of a longer-term (initially defined as 10 years) PNGV program.

Recommendation. The PNGV should continue to update systems studies and projections for longer-term technologies as new information becomes available to categorize their potential benefits more accurately.

Recommendation. The PNGV should continue R&D on technologies that appear to have the potential for making key contributions toward PNGV goals, even if they are beyond the 1997 downselect time frame. This recommendation is consistent with the committee's previous recommendations.

LEVERAGE OF FOREIGN TECHNOLOGY DEVELOPMENTS

In spite of recommendations by the committee in both previous reports that PNGV make "as a matter of urgency" more comprehensive assessments of, and benchmark foreign technology developments relevant to, the programs, there has been little visible response from the PNGV. The PNGV operational steering group, in response to the recommendation in the second report, indicated that this was being done routinely by several government agencies, as well as by each of the USCAR members (see Appendix D). However, only limited evidence of this type of activity was presented to the committee.

The committee does not doubt that the USCAR members have knowledge of many foreign technology activities. Clearly, it is in their best interest to do so. Moreover, the USCAR members, as well as their many suppliers, have access to such information through their foreign partners and operations. The committee also knows that several government agencies are tracking some aspects of foreign technology developments. However, it is not clear whether these pieces of information from many groups are synthesized and assimilated in any meaningful way to provide the opportunity for superior foreign technology introduction to the PNGV program.

One area of foreign technology development that is visible and will likely influence the PNGV program is development of the CIDI engine. It is an important part of the European automobile engine market, whose share is expected to increase, and offers substantial fuel economy benefits compared to state-of-the-art, multiport fuel-injection gasoline engines. This is a technology that is already in production or in the advanced stages of development by every major European engine manufacturer. It also appears that the technology is close to meeting the most severe European emission requirements (Euro IV). However, it is not clear how the major European and Japanese developments on the CIDI engine will affect the PNGV. This is a significant issue because the CIDI engine is clearly a leading candidate for approaching PNGV Goal 3 objectives. Some very limited information presented by the PNGV to the committee on European and Japanese developments in fuel cells, gas turbines, and batteries indicates no evidence of major breakthroughs that would significantly impact the PNGV.

Recommendation. The committee again recommends that the PNGV conduct and routinely update comprehensive foreign technology assessments. These assessments should be used to determine which, if any, of the technologies of interest to the PNGV could benefit from more knowledge of the foreign activities.

Recommendation. Because the CIDI engine is a major potential technology in the PNGV, the PNGV should make a special effort to determine to what extent European and Japanese developments are available to members of the USCAR.

MAJOR TECHNICAL ACHIEVEMENTS AND BARRIERS

A number of achievements were realized by the PNGV in the past year. According to a presentation to the committee by the PNGV, the most important technical accomplishments in 1996 include the following (Viergutz, 1996):

- demonstration of a prototype fuel-flexible processor for a fuel cell with an 80 percent efficiency for the processor
- demonstration of a subscale high-power lithium-ion battery cell for 100,000 shallow cycles
- scale-up of a lean NO_x (nitrogen oxides) catalyst demonstrating 30 percent NO_x reduction
- fabrication of ceramic gas turbine scrolls and rotors through a process with high-volume potential
- survival of a glass-fiber-reinforced, composite front-end structure design in a 35 mph barrier crash test
- development and construction of advanced technology demonstration vehicles, some of which incorporated requirements related to those of the PNGV, such as Ford's Synergy 2010, Chrysler's ESX, and General Motors EV-1

Despite significant progress in a number of critical areas, there continues to be a wide gulf between the current status of system and subsystem developments and the performance and cost requirements necessary to meet major PNGV milestones. Some of the technical barriers to achieving PNGV objectives can probably be overcome with sufficient funding and management attention; others require inventions and very significant technical breakthroughs. As stated in the second report, the effort being expended on candidate technologies and systems is not consistent with the likelihood that they will meet performance goals within the program schedule (NRC, 1996). Work on many critical systems is inadequately funded and lacks integrated technical direction.

The assessment of technical barriers to the development of major candidate subsystems presented in this report was used to construct Table ES-1. In the committee's view this table provides an approximate assessment of the broad potential for candidate technologies and a gross indication of the relative progress over the past year. The committee made a distinction between systems for which technical breakthroughs are needed to meet targets established by the PNGV and those for which incremental development with adequate resources (funding and staff) is likely to lead to required achievement. For each major subsystem, the committee identified the most critical barriers to meeting the PNGV performance and cost requirements, as well as the likelihood of meeting established schedules. These three factors were used to derive a first approximation of the overall potential to meet PNGV goals, regardless of the schedule, and to highlight program priorities.

At the committee's November 1996 meeting, the PNGV provided a list of major barriers to success and the program needs to overcome these barriers. These barriers are delineated in Table ES-2. As can be seen, there are a number of technical, production cost, funding, schedule, and other issues that need to be resolved.

TABLE ES-1 Potential of PNGV Candidate Technologies and Assessment of Research Progress

Major Subsystems	Critical Technical Barriers	Likelihood of Meeting Technical Objectives[a]	Likelihood of Meeting Cost[b]	Likelihood of Meeting Schedule[c]	Overall Potential Regardless of Schedule[d]	Basic Needs	Overall Progress Since Last Review
Hybrid Drivetrain Power Sources							
CIDI	Combustion control NO_x catalyst	High	Medium	High	High	Resources	Modest
Fuel cell	Fuel processor/ reformer	Low	Low	Low	Medium	Breakthroughs	Modest to Good
Turbine	Structural ceramics Exhaust heat recovery	Low	Low	Low	Medium	Resources, focused R&D	Modest
Stirling	Heat Exchangers Leakage Control	Medium	Low	Low	Medium	Resources, focused R&D	Small
Energy Storage							
Lithium-ion battery	Scale-up System safety	High	Medium	Medium	Medium	Resources, focused R&D	Good
Nickel metal hydride battery	Efficiency Power density	Medium	Medium	Medium	Medium	Resources, focused R&D	Modest
Ultracapacitor	Efficiency Self-discharge Safety	Low	Low	Low	Low	Breakthroughs, resources	Small
Flywheel	Safety	Medium	Medium	Low	High	Resources, focused R&D	Small
Power electronics	Efficiency	Medium	Medium	High	High	Resources	Small

Note: This table represents a general committee judgment at an aggregate level of detail. The critical technical barriers are those that appear to be most challenging today and in many instances appear to require technical breakthroughs. See Chapter 4 for a more complete description of the key developments needed.

[a]Regardless of cost or schedule.
[b]Assuming the technical goals can be met.
[c]In achieving the technical goals.
[d]Overall potential over the long term of meeting the technical goals and cost.

Based on the data provided, the committee believes that the following conclusions can be drawn:

- When incorporated in a vehicle, none of the energy converters/powertrains will come close to meeting the cost objectives within the time frame of the PNGV program.
- The CIDI engine is the energy converter with the highest potential of meeting the PNGV program performance requirements within the schedule and cost constraints. The CIDI engine may be negatively impacted if EPA promulgates more stringent exhaust emissions standards for diesel engines.
- The successful development of fuel cells, Stirling engines, and gas turbines that meet or approach the cost and performance requirements of the PNGV program is substantially beyond the current time frame of the program.
- Flywheels appear to have potential to provide energy storage needs of a hybrid vehicle once the safety and cost issues have been resolved.
- The successful development of ultracapacitors as storage devices is well beyond the time frame of the PNGV program.

The committee is not suggesting that development of these technologies be terminated. However, it is most timely for the PNGV to reprogram funding and development efforts aggressively to be consistent with expected successful results within the current PNGV schedule through 2004. Investments in technology developments for the PNGV that have a projected success beyond that schedule should be continued but should be reduced and/or more highly focused. This position is consistent with the committee's position in the first and second reports (NRC, 1994; 1996).

ADEQUACY AND BALANCE OF THE PNGV PROGRAM

Because of the lack of specific data requested by the committee from the PNGV, the committee found it extremely difficult to evaluate the adequacy and balance of funding to accomplish the PNGV Goal 3 objectives. The ultimate proof, of course, will be embodied in the timeliness of the 1997 technology downselect, the content and level of the performance achieved by the 2000 concept demonstration vehicles, and the performance and cost projections of 2004 preproduction prototypes. However, there are no clear criteria today other than the PNGV Technical Roadmap and the generalities of Goal 3 objectives.

With appropriate focus and resources there may still be sufficient time in the PNGV's current schedule to make some candidate technology systems viable (for example, the CIDI engine, in conjunction with other subsystem improvements [see Table ES-1]). However, in the absence of a significant acceleration in their rate of development, for other fundamentally promising candidate technologies

TABLE ES-2 PNGV's Presentation to Committee on Assessment of Major Barriers and Program Needs

Issue	Challenges and Issues	Recommendations by the PNGV
Technical	• control of particulates and NO_x from CIDI engines • compact fuel-flexible fuel processor for PEM fuel cells • flywheel safety • thermal management of lithium battery systems • high yield fabrication of complex ceramic componentry	Funding is required to support a sufficient level of effort for addressing the engineering research challenges.
Production cost	• low-cost lamination material and processing for electric motor rotors and stators • low-cost aluminum sheet, carbon fiber for structral applications and magnesium • low-cost power electronic building blocks and liquid coolants • low-cost high yield ceramic fabrication methods • low-cost high-pressure fuel injector and pump • low-cost electronic materials and fabrication processes for batteries and fuel cells • low-cost flywheel containment	Appropriate levels of effort required for technical cost challenges.
Funding	• cost-share requirements of high-risk DOE programs • inability to mobilize supplier resources • long lead-time from identification of R&D need to contract initiation • adminstrative complexity of government programs • difficulty in redirecting/influencing existing government programs • non-strategic distribution of resources	Policy change and active implementation needed by upper levels of government and industry management.

Schedule	• probability of meeting all performance and cost targets by 2004 is declining due to continued inadequate resource commitment • technology selection date broadened to pre-1997 and post-1997 data-driven events	There should be an emphasis on schedule of technology development at component level with later demonstraton at vehicle level.
	• recognition that concept vehicles pre-2000 and post-2000, with focus for 2000 on fuel economy benchmark demonstration • recognition that initial hybrid vehicle concept vehicles and design were introduced in 1996, for pre-1997, focus should be on: (a) lithium and NiMH battery systems (b) PEM gasoline-fueled fuel cell systems (c) double-layer capacitors would be eliminated For 1997, make decision on viability of current ceramic gas turbine designs. For 1998: (a) decide on viability of high-volume fabrication of ceramic components (b) decide on whether to proceed with next generation of ceramic gas turbine (c) decide on safety potential of lithium-ion battery system (d) resolve flywheel safety issue (e) assess CIDI emissions based on operating hardware	Adequate funding levels are required to meet engineering research challenges.
Other	• potential change in emissions regulations • potential requirement for zero emission vehicle range	Funding issues and regulatory environment need to be resolved.

Source: Viergutz (1996).

(such as fuel cells, gas turbines, Stirling engines, and some battery candidates), progress beyond that achieved in the DOE HEV program is unlikely to make these technologies available within the PNGV time frame for demonstration of good performance in practical vehicles with acceptable risk.

The USCAR partners have decided to conduct independent vehicle demonstrations of the concept vehicles. Meeting the PNGV schedule with credible concept vehicles for 2000 will demand greatly increased efforts in 1997. Currently, the committee is not aware of what PNGV would consider acceptable levels of performance for concept demonstration vehicles.

The appropriate role of the government during the demonstration phase needs to be considered. Government's role is normally expected to apply to longer-term objectives. There is no definable funding line in the Fiscal Year 1997 budget specifically to support the PNGV R&D activities and no way to rely on such funding in subsequent years. Thus, it is not clear to the committee at what level "PNGV-related" technology efforts being supported by the government will be continued in parallel with the industry's concept vehicle demonstrations to provide a basis for future advancements in Goal 3 vehicle technology at least through the year 2004. In the committee's view, relevant technology development specifically devoted to risks identified in the Goal 3 demonstration configurations merit meaningful federal support, that is, support consistent with program needs and objectives.

However, the PNGV is facing severe problems with funding and resource allocation. Unless these problems are resolved expeditiously, they will preclude the program from achieving its objectives on its present schedule. In the absence of acceptable and sustained resolution to this PNGV-wide funding and resource problem in both government and industry, PNGV's current objectives will no longer be tenable with respect to performance, cost, and schedule. Although the lack of sufficient funds is a major problem for most of the PNGV program elements, Table ES-2 indicates that there are also serious technical hurdles to be overcome. Even with adequate funding, these hurdles may prevent successful development and commercialization of the proposed systems within the PNGV time frame.

Recommendation. The PNGV partners (USCAR and the federal government) should immediately develop a schedule of resource and funding requirements for each major technical task. This schedule should show current resources and funding for each major technical task and current shortfalls. Upon completion of this schedule, the PNGV partners should provide a strategy to obtain the necessary resources and funding.

Recommendation. In the event that the PNGV (industry and government) does not obtain or chooses not to increase the resource levels and thereby accelerate the pace of development, the PNGV should reconsider the viability of current PNGV program objectives with regard to performance, schedule, and cost.

PNGV RESPONSE TO THE PHASE 2 REPORT

In the second report, issued in March 1996 following the second review of the PNGV research program, the committee offered a number of recommendations (see Appendix C) for the PNGV's consideration (NRC, 1996).

In addition to specific technology evaluations and recommendations, the committee offered six major recommendations:

- Strengthen program management and technical leadership in both government and industry and make management more efficient.
- Initiate and accelerate a comprehensive systems analysis program.
- Obtain and re-allocate federal and industry funding to activities with promising technological potential within the time horizon and needs of the program.
- Conduct comprehensive assessments and benchmark foreign technology developments relevant to the PNGV.
- Continue to address infrastructure issues as an integral part of the program.
- Increase the involvement of other U.S. government agencies, such as the U.S. Department of Transportation (DOT), the National Aeronautics and Space Administration (NASA), the U.S. Department of Defense (DOD), and the EPA.

The first five recommendations, above, were made in the first committee report (NRC, 1994); the committee feels that insufficient attention or progress has been made in correcting these deficiencies since the first review. The slow rate of progress or lack of attention to the first three issues listed above may ultimately jeopardize the PNGV's ability to accomplish its goals.

For those issues that the PNGV elected to respond to in its June 18, 1996, letter (see Appendix D), the committee considered the response to be to the point, well articulated, and understandable within the context of conducting a complex joint industry–government program. USCAR rejected the recommendations made by the committee on the issue of organization and management in the first and second reports. The committee addressed this issue in the previous reports; therefore, it did not address it in the current review. However, the timely results of the PNGV program will be a major indicator of the effectiveness of USCAR's organization and management structure.

The committee was also concerned that the PNGV response did not specifically respond to the committee's recommendations on structural materials and powertrain developments (see chapters 5 and 6 in the committee's second report [NRC, 1996]) and the broad evaluations of the potential for various technologies to meet the PNGV performance, cost, and schedule objectives as summarized in the committee's second report (included herein in Chapter 7 as Table 7-1). The committee recognizes that the program is in only its fourth year; however, a realistic evaluation of the potential of each technology should provide a guide for a more appropriate allocation of resources as recommended by the committee.

In the committee's view, DOD, DOT, NASA, and EPA need to be more supportive and integrated into the PNGV research program. The relevance of certain ongoing R&D programs funded by these agencies to the PNGV technical objectives supports this view. PNGV's response indicated that it was satisfied with the interagency participation to the extent that project resources permit such cooperation. While the committee understands this PNGV response, the level of support in terms of resources and funding is minimal in many areas.

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1

Introduction

This is the third report of the National Research Council's (NRC's) Standing Committee to Review the Research Program of the Partnership for a New Generation of Vehicles (PNGV); the first and second reports were issued in 1994 and 1996 (NRC, 1994; 1996). The committee was established in July 1994 to conduct independent annual reviews of the PNGV's research program, advise the government and industry participants on the program's progress, and identify significant barriers to success. The PNGV declaration of intent includes a requirement for an independent peer review "to comment on the technologies selected for research and progress made." To this end, this review was undertaken by the NRC at the written request of the under secretary for Technology Administration, U.S. Department of Commerce (DOC), acting on behalf of the 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 Chrysler Corporation, Ford Motor Company, and General Motors Corporation.[1] The PNGV was initiated on September 29, 1993, by President Clinton with the purpose of substantially improving the fuel efficiency of today's automobiles and enhancing the U.S. domestic automobile industry's productivity and competitiveness. The aims of the PNGV program are to improve automobiles over the next decade and 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

[1]The existence of USCAR, which predated the formation of PNGV, makes sense from the nation's point of view to support intercompany precompetitive cooperation in the face of intracompany international competition.

vehicles. At the same time, these vehicles should maintain performance, size, utility, and cost of ownership and operation and should meet or exceed federal safety and emissions requirements (The White House, 1993).

The PNGV goals and the considerations underlying them are articulated in the partnership's program plan, as follows (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/or 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 significantly increase 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.

Achieving significant improvements in automotive fuel economy, while maintaining consumer safety and emissions standards, could provide important benefits to the nation. As noted in a Congressional Research Service report for Congress, the number of workers employed directly and indirectly by the automotive industry in the United States is substantial, with motor vehicle manufacturers and suppliers representing an important component of the U.S. gross domestic product (Sissine, 1996). Hence, technology change can influence the kinds of cars that are driven as well as the health of the U.S. economy. The Congressional Research Service report further notes that in 1994, automobiles accounted for as much as 50 percent of atmospheric ozone in urban areas, 15 percent of U.S. emissions of the "greenhouse gas," carbon dioxide, and 37 percent of U.S. crude oil consumption, at a time when U.S. crude oil imports are greater than 50 percent of total U.S. consumption and represent a third of the U.S. trade deficit.

Higher gasoline prices and federal fuel economy regulations had been contributing causes to significant increases in the fuel economy levels of new cars, as well as the entire automotive fleet on the road during the late 1970s and 1980s; however, trends in the average fuel economy of all on-road (new and old) passenger vehicles showed a decline in the early 1990s from a peak in 1991 (Sissine, 1996). These trends are strongly influenced by relatively low U.S. gasoline prices, which do not create incentives for automobile purchasers to value fuel economy to any great extent in their purchase decisions. The lack of market incentives for car buyers to purchase vehicles with high fuel economy makes it difficult to realize the public benefits from improvements in fuel economy, such as health benefits from reduced urban ozone, "insurance" against sudden crude oil price shocks, lower military costs of maintaining energy security, potential savings from lower crude oil prices, improved balance of payments, and reductions in greenhouse gases from the transportation sector (Sissine, 1996; OTA, 1995). The PNGV strategy of developing an automobile with a fuel economy of up to 80 mpg, while maintaining performance, size, utility, and cost and meeting or exceeding safety and emissions standards, circumvents the lack of economic incentives for buying automobiles with high fuel economy. If the PNGV strategy is successful, the automotive buyer will purchase a vehicle with all the desirable consumer attributes, and, as part of the technical design, with greatly enhanced fuel economy. The development of such a vehicle, as noted by the committee in its previous reports, is extremely challenging. An ambitious goal stimulates rapid development of required technology and, even if a Goal 3 vehicle does not achieve the triple-level fuel economy, it may still reach a level far above current levels.

The projected increases in vehicle usage in nonindustrial and newly industrializing nations is expected to place a severe burden on world petroleum reserves and substantially increase airborne emissions. For example, Asia, excluding Japan, has 55 percent of the world's population and only 8 percent of the world's highway vehicles in use (AAMA, 1996). It is expected that the use of vehicles and the consumption of petroleum will increase dramatically in this region. This anticipated increase in vehicles provides an unusually large market opportunity for cost-effective, fuel-efficient products. The philosophic objectives of the PNGV program are aligned with meeting these two product needs to the benefit of the American automobile industry.

The PNGV concept is to bring together the extensive R&D resources of the federal establishment, including the national laboratories and network of university-based research institutions, and the vehicle design, manufacturing, and marketing capabilities of both the USCAR partners and suppliers to the automotive industry. Government funding for the PNGV will be used primarily for technology developments that involve high risk (Goal 3 and beyond). USCAR funding will be used mainly to develop technologies with clear, near-term market potential (goals 1 and 2).

Central to the organization and efforts of the PNGV are several technical teams responsible for R&D on the candidate subsystems, such as fuel cells, gas turbines, compression ignition direct injection engines (CIDI), and others. A manufacturing team, materials and structure team, and systems analysis team are also part of the PNGV organization (NRC, 1996). Technical oversight and coordination are provided by the vehicle engineering team. The PNGV technical teams need direction on vehicle system requirements. This direction should be provided by the vehicle engineering team and supported by systems analysis.

According to the schedule for Goal 3 described in the PNGV Program Plan, the PNGV expects to assess system configurations for alternative vehicles and narrow its technology choices by the end of 1997, with the intent of defining, developing, and constructing concept vehicles by 2000 and producing preproduction prototypes by 2004 (PNGV, 1995). (This technology selection process is usually referred to as the technology "downselect" process.) Each USCAR partner—Chrysler, Ford, and General Motors—will develop concept vehicles separately, drawing from the spectrum of technologies developed under the PNGV. It has also been decided that the PNGV will not design and build a concept car. Although the 1997 technology selection process will focus on choosing the technologies most likely to result in concept and production prototype vehicles that meet the Goal 3 requirements, other longer-range technologies will continue to evolve. As they evolve, they may be incorporated into the concept vehicles, as appropriate. The technology areas being addressed by the PNGV include advanced lightweight materials and structures; energy efficient 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); more-efficient electrical systems; and systems that efficiently recover and utilize exhaust energy and braking energy.

For the third PNGV peer review, several committee members from the second review were rotated off the committee, and additional members were added to provide the expertise necessary for an in-depth review and analysis of the technology developments in the program, notably in the areas of energy conversion and energy storage technologies. (See Appendix A for biographical information on committee members.) Given the critical nature of developing advanced energy conversion devices (CIDI engines, gas turbine engines, Stirling engines, and fuel cells) and energy storage devices (batteries, flywheels, or ultracapacitors) to meet the high fuel economy target set by Goal 3, the committee undertook to examine the development program for these technologies in greater detail than in the previous review. The committee also reviewed the PNGV efforts and progress in power electronics and systems analysis and continued to review progress on goals 1 and 2. The committee was charged with:

- Critically evaluating the research progress and the state of development of energy converters (CIDI engines, fuel cells, and gas turbines) and energy storage (batteries, flywheels, and ultracapacitors) under consideration by the PNGV. The evaluation focused on PNGV efforts to overcome technical barriers identified in the committee's second report, progress the PNGV has made to maintain its current research schedule and milestones, and the efficacy of the future program to achieve the specified PNGV goals of cost, performance, and schedule.

The committee was also charged with addressing and commenting on the following areas based on presentations by the PNGV to the committee:

- the overall adequacy and balance of the PNGV technical program
- the process by which the PNGV will make choices and reallocate resources in the downselect process now scheduled for the end of 1997
- the means by which the PNGV might draw upon foreign automotive technology
- the effort the government has initiated to anticipate infrastructure problems or issues that might arise upon introduction of the PNGV advanced vehicle

The committee was not charged with the review of materials developments due to government funding limitations; however, this area is extremely important to the ultimate success of achieving Goal 3 objectives.

Based on its review, the committee prepared this third peer review report containing its conclusions and recommendations. In addition to two extensive committee meetings, subgroups of the committee received detailed presentations on the various technologies under consideration (Appendix B contains a list of meetings, presentations, and other data-gathering activities by the committee.)[2] Some of the material was presented to the committee as USCAR proprietary information under an agreement signed by the National Academy of Sciences, the USCAR, and the U.S. government (represented by the DOC).

As noted in the second report (NRC, 1996), the committee started its work with the explicit understanding that the vision, goals, and target dates for the PNGV had been articulated by the president and that the appropriate R&D programs had been launched. On the premise that the PNGV will be seriously pursued by its partners, the committee sees its charge as one of providing independent advice to help the PNGV achieve its goals. Therefore, the committee has sought to identify strengths and actions that could enhance the program's chance for success. The committee has studiously avoided making judgments on the value of the program to the nation at this time and has accepted the goals as given, noting that unlike Goal 3, goals 1 and 2 are open-ended and do not have quantitative targets and milestones.

The committee's objective continues to be to review the R&D program as presently configured and assess the PNGV program's progress and potential for

[2]The committee formed the following subgroups: (1) Nonelectrochemical Storage Devices, (2) Electrical Systems and Systems Analysis, (3) Batteries and Ultracapacitors, (4) Fuel Cells, (5) Compression Ignition Direct Injection Engines, (5) Gas Turbine Engines, and (6) Stirling Engines. See committee list for members of subgroups.

achieving its goals. During this third review, the presentations sought by the committee have been aimed at (1) a more detailed understanding of PNGV progress, efforts, and technical barriers and plans for future development of energy converter and storage technologies; (2) key research challenges and priorities; (3) alignment of the program architecture with the goals, schedule, and milestones; (4) metrics for measuring progress; (5) resources deployed in fiscal year 1996 and planned for subsequent years; and (6) the effectiveness of the technical leadership within the PNGV.

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2

Goals 1 and 2

This chapter provides a brief overview of PNGV activities and discusses general progress toward goals 1 and 2. As noted in the committee's second report, goals 1 and 2 have no quantitative objective; therefore, the committee is providing only qualitative comments on its brief review of these PNGV goals. Goal 1 is to improve significantly national competitiveness in manufacturing by improving the productivity of the U.S. manufacturing base by significantly upgrading U.S. manufacturing technology. Goal 2 is to implement commercially viable innovations from ongoing research on conventional vehicles. As part of this goal, technological advances that can improve fuel efficiency and reduce emissions of standard vehicle designs, while maintaining safety standards, are being pursued. Achievement of goals 1 and 2 forms an important enabling base for Goal 3 technologies, such as establishing commercially viable manufacturing methods. The projects pursued for goals 1 and 2 will supplement Goal 3 technology development and will provide useful supporting information for subsequent actions by the USCAR and the federal government.

GOAL 1

In the first two years of the PNGV program, progress toward Goal 1 included (1) forming a manufacturing team to monitor joint projects, (2) completing a comprehensive review of potential projects, and (3) identifying 16 high-potential projects for joint action by the USCAR and the federal government. Cost is a major area of competition among the automotive companies; therefore, most companies invest in technology and its implementation independently, and the results are not shared. Under the auspices of the PNGV, precompetitive technology-development projects can be pursued jointly, presumably at a lower total cost than if they were conducted individually by an automotive company. Joint programs are also attractive investments for government and suppliers because of their broad potential application when all three U.S. automotive companies are committed to a technology. The PNGV presentations to the committee indicated that 10 precompetitive projects have been selected. All three automotive companies will work together on these projects through the PNGV (Hartfield, 1996; Joseph, 1996). However, USCAR funding is currently still being sought for one of the projects.

Plans for 1996

The manufacturing team planned to solidify its relationships with outside suppliers and initiate work on the 10 projects selected in 1996. The projects were chosen for their potential to satisfy manufacturing needs with major cost reductions and productivity increases. The team planned to make progress on data generation and validation for a number of projects and to complete experimental designs and model evaluations for other projects. Three projects were to be identified and initiated by the end of 1996.

Progress in 1996

The PNGV Goal 1 projects are managed by various organizations outside of the PNGV. The manufacturing team monitors and "mentors" these projects. Four projects are managed by the National Center for Manufacturing Systems, in Ann Arbor, Michigan. Three of the projects are partially funded by the government under the National Institute of Science and Technology Advanced Technology Program (ATP); the other seven are self-funded by industry, including the automotive companies, suppliers, and others. In at least one case, an ATP proposal that was not selected for government funding was of such great interest to the PNGV that it was fully funded by industry.

The 10 Goal 1 projects include a broad range of topics, which are briefly described below:

1. Springback predictability. Develop and validate a three-dimensional computer code for accurate springback prediction for high-strength steel and aluminum sheet forming.
2. Intelligent resistance welding. Improve the quality and consistency of resistance spot-welding for steel and aluminum.
3. Feature-based modeling. Develop a standard feature definition for exchange among different computer-aided design systems.
4. Powder paint. Develop a powder clearcoat-paint material technology to reduce paint material costs and emission-abatement system costs.

5. Laser welding of aluminum. Develop the fundamentals of a process to produce good joint integrity for automated laser welding of automotive components with high aluminum content.
6. Aluminum die casting. Improve aluminum die-casting process efficiencies.
7. Dry machining of aluminum. Develop a process for dry machining of aluminum without the use of coolants.
8. High-throughput hole making. Improve tool holders for high-speed cells and develop new tooling materials and designs to improve machining productivity.
9. Leak-test technology. Evaluate four technologies for leak detection and location.
10. Ergonomics for hand tools. Establish comprehensive ergonomic-based techniques, information, rules, and guidelines for powered hand tools that support their selection, use, and design (funds are currently being sought).

Of the nine active PNGV projects, three were initiated in the fall of 1996. Experimental designs and model evaluations are being completed for three others. The remaining three (powder paint, laser welding of aluminum, and aluminum die casting) are at the data-generation and validation stage.

Plans for 1997

The manufacturing team will continue to pursue plans for the 10 projects. No additional projects are currently planned. At a minimum, all of the projects will generate data from designed experiments in 1997. Some projects will be completed in 1997, and the data will be validated.

Assessment

The committee believes that the ATP provided an excellent focus for projects of value to the PNGV. The proposal process defined promising development programs for a broad range of technologies to allow competition for up to 50 percent funding by the government. Teams of users, suppliers, and technologists were created during competition for these awards. If additional government funding is invested in Goal 1 projects, the ATP approach, which includes flexible project solicitation and selection, would be a good model. The committee believes the projects currently selected have a high potential for contributing to the Goal 1 objectives. The committee commends the work of the manufacturing team and encourages its continued progress. The committee also recognizes that 7 of the 10 projects are being self-funded through the USCAR because of a lack of government support. Ultimately, the three USCAR partners will be strongly motivated to implement these technologies to achieve the cost reduction and productivity they will make possible. However, the high initial cost of tooling to demonstrate these new production technologies could be a barrier to their introduction.

Recommendation

Based on its review of Goal 1 plans and progress, the committee makes the following recommendation.

Recommendation. For the technologies that will contribute cost and weight reductions for Goal 3 vehicles, a cost-shared approach between industry and government should be used to fund the initial tooling for proof-of-concept demonstration to reduce the financial risk to any one company. Investments for subsequent tooling for larger production runs would be made by individual companies.

GOAL 2

The committee indicated in its second report that some progress had been made in pursuit of Goal 2 through the USCAR consortia and cooperative research and development agreements (CRADAs) with the national laboratories. The committee considers continuation of this progress essential for determining the viability of several Goal 3 technologies.

Plans for 1996

The intent of the Goal 2 program is to pursue advances that can lead to increased efficiency in standard vehicle designs prior to Goal 3 schedules. Throughout the research program, the USCAR partners have committed to apply those commercially viable technologies resulting from this research that would be expected to increase vehicle fuel efficiency significantly and reduce emissions. As various components or subsystems are determined and validated as part of the Goal 3 effort, they can be programmed into earlier production release by the USCAR partners.

Progress in 1996

The number of projects defined and in various stages of implementation give evidence that significant progress was achieved in 1996. The technology sources for these projects derive from a variety of efforts, including collaborative industry–government developments, R&D directed towards Goal 3 and early breakthrough technology, proprietary R&D by individual companies, USCAR projects, and relevant government R&D. The committee reviewed details of 29 projects currently under consideration or development by all of these sources. Sixteen collaborative R&D projects relate to engine-support systems, and 13 relate to automotive materials. The projects that are purported to have a benefit of "breakthrough enabling technology" are discussed here because they should impact both near-term and Goal 3 product needs.

PNGV stated that projects dealing with "engine-support systems" have breakthrough benefits; five of these projects deal with vehicle system components, and two deal with manufacturing process improvements. The following projects relate to vehicle system components:

- Lean NO_x catalyst. Develop catalyst technology to reduce NO_x (nitrogen oxides) in lean-burn exhaust gas.
- On-board diagnostics (OBD-II) subsystem analysis. Develop a methodology to assess and improve the performance of the OBD system.
- Exhaust-constituent sensor. Develop exhaust gas sensors capable of measuring future low emission levels.
- High-durability spark delivery. Develop improved sparkplug and insulator materials for increased life at higher firing potential and power and on increased dielectric strength.
- Plasma treatment of the exhaust. Determine the feasibility of plasma-based technologies using catalytic material to achieve simultaneous hydrocarbon (HC) oxidation and NO_x reductions under lean-burn conditions.

The following projects are related to improvements in manufacturing processes:

- Super-plastic formed stainless steel. Design exhaust components for unique energy conservation designs using super-plastic stainless steels.
- Rapid prototyping using spray-formed tooling. Develop a cost-effective, commercially viable spray-forming process for rapid production of net-shaped dies and tooling and demonstrate the process with both simple and complex model fabrication.

Eight projects deal with automotive materials that are designated as having technology-breakthrough benefits. These projects combine manufacturing methods and processes, as well as material types and characteristics, as briefly described below:

- Low-cost aluminum-sheet production. Develop a continuous-cast process to reduce the cost of aluminum sheet alloy by 25 percent by the year 2000.
- High-volume composite manufacturing. Develop and demonstrate high-volume, low-cost liquid molding technology for large, lightweight components.
- Crash energy management of composite structures. Develop the technology to apply structural composites for crash and energy management and on associated design tools.

- Adhesive bonding technologies. Develop attachment technologies for composite structures.
- Slurry preforming. Establish a water slurry process for high-volume, low-cost, fiber preforming for liquid molding of large complex structures.
- Manufacturing methods for fiber preforms. Develop and demonstrate high-volume, low-cost, fiber-preforming technology for liquid molding of large complex components.
- Full-field nondestructive evaluation (NDE) testing. Develop and demonstrate production-capable, full-field, NDE test methods for bonded composites.
- Low-cost powder metallurgy for particle-reinforced aluminum. Develop a process to manufacture powder metallurgy components using particle-reinforced aluminum composite materials.

Plans for 1997

Plans for 1997 for the 15 breakthrough technology projects described above fall into two categories: (1) working with industrial partners to commercialize and continue R&D activities; and (2) continuing the testing, evaluation, and validation of the process technology inside the PNGV. The latter category involves the projects on exhaust-constituent sensors, high-durability spark delivery, plasma treatment of exhaust, low-cost aluminum sheet, high-volume composite manufacturing, crash energy management of composite structures, and adhesive bonding technologies. The former category includes the projects on lean NO_x catalyst, OBD-II, super-plastic process improvement, rapid prototyping, slurry preforming, full-field NDE, and low-cost powder metallurgy. Activities for the other 14 projects for Goal 2 are primarily aimed at the progressive development of the individual original equipment manufacturer (OEM) product and manufacturing plans. The engine-support systems projects on fuel/combustion optimization, NDE testing for part integrity, intelligent welding, in-cylinder air/fuel mixing, sensor- and actuator-manufacturing process, and powder metal machining are well under way. Feasibility has been confirmed for virtually all of them. In the automotive materials area, projects on rapid tooling for metal-mold processes, laser welding of aluminum sheet metal, deformation and environmental degradation of structural composites, optimization of cast light metals, and environmentally friendly free-machining steel will be incorporated in the product process within two years. As of now, feasibility is confirmed for all projects except the free-machining steel project.

Assessment

The PNGV evaluated more than 80 projects. Those selected are achieving significant progress under the mentoring of the manufacturing team. The committee reviewed the individual product plans and accomplishments of the OEMs and found significant calculated cost and weight savings for near-term products. As substantial as they appear, however, the projected aggregate benefit of the near-term, competitive actions might be about 10 percent of the total weight and cost savings required to make any one of the proposed Goal 3 technologies feasible. Since goals 1 and 2 will produce an important enabling base for Goal 3, especially in manufacturing, the breakthrough technologies must result in the necessary cost and weight reductions. This requires ensuring efficient use of the optimum combination of materials in the PNGV vehicles, using the most productive manufacturing process and creative approaches for concurrent development of product designs, and implementing required manufacturing methods for production (concurrent engineering). It appears that all the important areas are currently being addressed; however, year-to-year progress and plans for 1997 do not indicate much improvement in the pace of development. It is expected that more resources will be directed toward the critical projects as technologies are selected for incorporation into the concept vehicle and projects are re-prioritized.

Recommendation

Based on its review of Goal 2 plans and progress, the committee makes the following recommendation.

Recommendation. PNGV should evaluate and prioritize its Goal 2 projects to identify projects that would contribute the most to near-term improvements in fuel efficiency and reduction in emissions and would enhance the manufacturing base needed to meet the cost goals of the Goal 3 technologies. Based on this prioritization of potential improvements, resources and funding should be appropriately reallocated.

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3

Systems Analysis

PROGRAM DESCRIPTION AND REQUIREMENTS

Systems analysis, along with vehicle, subsystem, and component modeling, is believed to be absolutely necessary to ensure that the best technologies are selected and that overall vehicle performance is optimized. The PNGV Technical Roadmap emphasizes this point in Section III-A and clearly states (PNGV, 1996):

> The role of systems analysis in the PNGV is to support component, systems, and vehicle development by providing the analytical capability to efficiently and accurately assess competing technologies, and vehicle concepts against Goal 3 objectives and vehicle performance requirements. This will enable an objective evaluation of risk, benefit, and cost, in order to focus on the best options, with the least expenditure of resources.

A vehicle systems model can be very powerful when comparing the relative performances of selected vehicle configurations. A good example is the optimization of hybrid electric vehicle (HEV) performance. The hybrid vehicle has two very significant advantages that contribute to fuel economy: (1) the possibility of recovering some fraction of the braking energy and (2) the ability to run the selected power plant in a restricted, more efficient load and speed range. Conversely, the disadvantage of the hybrid vehicle is that it is a much more complex and costly system than a conventional vehicle with an internal combustion engine. These advantages and disadvantages must be considered in any trade-off analysis.

Systems analysis provides the tools to determine how fuel economy, cost, and emissions can be optimized within the overall vehicle performance requirements. This information can then be translated into performance requirements for energy storage. System analysis, along with effective modeling tools, is the only way to ensure optimization of vehicle performance. Systems analysis also provides the opportunity to study trade-offs and make appropriate design compromises, and it leads to the specification of necessary characteristics for the interacting energy conversion, energy storage, and control technologies embodied in a vehicle. It is also extremely important for setting research, development, and engineering targets.

In its second report, the committee made the following recommendations (NRC, 1996):

- The PNGV should assess the impact on the overall program schedule of the delay in implementing systems analysis and vehicle engineering tasks and the need for remedial action. Priority projects must be identified and implemented by the technical teams as soon as possible.
- The PNGV should formalize the subsystem evaluation and selection process without delay, and performance criteria should be provided to the PNGV technology teams. The systems analysis must be an iterative process that continually receives new information, updates models, and provides updated results from optimizations and tradeoff studies to system, subsystem, and component designers.
- Overall vehicle system and subsystem analysis driving component developments should be under the control of a USCAR technical director.

The committee voiced a strong concern that the systems analysis effort had been significantly delayed 12 to 18 months, primarily because of a lack of funding. The committee believed this would jeopardize the downselect process scheduled by the end of 1997.

CURRENT STATUS

The PNGV systems analysis team, led by the USCAR, finalized a contract with TASC and Southwest Research Institute (SWRI) in January 1996, and the effort outlined in the PNGV Technical Roadmap has been aggressively pursued during the past year. The statement of work specified initial system studies to identify, quantify, and rank a selected set of alternative vehicle configurations. This requires developing analytic methods and tools for comprehensive analysis of the identified new vehicle technologies and performing trade-off studies to select the final preferred vehicle configuration. The systems analysis team, along with the vehicle engineering team, identified nine vehicle configurations for benchmarking (see Table 3-1).

A rudimentary vehicle model has been created, and the team is currently developing models for the many subsystems and components that are being evaluated. These models are key elements in assuring that the 1997 technology downselect process can be accomplished with high confidence in the accuracy of

TABLE 3-1 Systems Analysis Benchmarking Configurations

Configuration	Fuel Converter	Motor	Transmission	Energy Storage
Conventional	SIDI		Automatic	
Series	CIDI	PermMag	Gear Reduction	NiMH
Parallel	SIDI	AC Induction	Manual	Li-ion
Series	Fuel Cell	PermMag	Gear Reduction	Li-ion
Series	Gas Turbine	AC Induction	Gear Reduction	Li-ion
Conventional	CIDI		Manual	
Parallel	CIDI	PermMag	Automatic	Li-ion
Parallel	SIDI	AC Induction	CVT	Flywheel
Parallel	SIDI	PermMag	CVT	Ultracapacitor

NOTE: CIDI (compression ignition direct injection); SIDI (spark ignition direct injection); PermMag (permanent magnet); CVT (continuously variable transmission); NiMH (nickel metal hydride); Li-ion (lithium-ion battery).

Source: Viergutz (1996).

predicted technology performance. The current modeling status varies, from highly accurate models for technologies like internal combustion engines that are well known to the automotive industry, to very generic, simplistic models for technologies that are not well developed, such as fuel cells. Some subsystems being evaluated clearly will not be ready for inclusion in the concept vehicle architecture.

All models must be extensively validated, and this is being accomplished by taking known performance characteristics from several sources. The automotive companies and SWRI have provided this validation, where possible. The process is complicated by proprietary vehicle simulation capability that includes the effects of cold starts, environmental conditions, crashworthiness, vehicle duty cycle, emissions, and fuel economy. Scaling and sizing of the subsystems and components still represent a significant challenge, and this must be accomplished for each vehicle configuration. Cost and reliability models are very weak. Control strategies are only starting to be developed, with the University of Michigan and Oakland University providing support.

Only very gross model benchmarking for the conventional and series hybrid-vehicle configurations has been accomplished to date. One of the major issues is how to achieve effective interaction with the other PNGV technical teams, especially the vehicle engineering team. Vehicle requirements are the responsibility of the vehicle engineering team. These requirements must be constantly matured and refined. The first significant workshop involving the technical teams was held in September 1996. The workshop was a major milestone, and it should start the effective dialogue needed to develop representative and accurate subsystem and component models. Templates for each subsystem must be developed in cooperation with the technical teams, and this will require considerable time and funds to achieve the accuracy necessary to ensure high-fidelity vehicle trade-off studies. It appears to the committee that effective interfaces have not been established with the subsystem teams. The tools being developed must be presented to the technical teams for a critique, which will lead to a more effective use of the models. In this case, the systems analysis team must determine users' real needs.

ADEQUACY OF THE PROGRAM

A significant problem regarding funding for 1997 was outlined to the committee. During 1996, \$2.4 million was spent with contractors. A Phase 2 and Phase 3 program are planned for 1997 and 1998. Each phase will cost approximately \$2.5 million. The 1997 funding will address the technology downselect, which is critical to meeting overall program timing. A source for this funding has not been identified. During the review of the systems analysis part of the PNGV program, the committee concluded that the Phase 1 expenditure of \$1.8 million was excessive. The PNGV program managers should review the planned Phase 2 and Phase 3 proposals to ensure that the work planned is consistent with the proposed expenditures. The importance of this work requires that the PNGV strive to maximize what can be accomplished with limited budgets. An additional issue is the inadequate funding provided by the Department of Energy to the national laboratories to support systems analysis. Considerable know-how and developed technology are available at the national laboratories. These assets could be major contributors to achieving successful subsystem and vehicle models.

None of the funding issues outlined above has been addressed. Without focused management action and resource allocation, this vital systems analysis effort will be interrupted or fall further behind schedule. Achieving the original planned milestone of completing the trade-off studies by the end of 1997 to allow selection of the preferred vehicle concept appears to be a major challenge. The loss of effectively more than a year in starting the system analysis effort has resulted in very late development of the required vehicle, subsystem, and component models; thus providing little timely support or guidance to the technical teams. Requirements based on the model studies should have been communicated early in the program; however, this is only beginning now. Serious problems could result from the fact that technology teams may not be developing technology centered on the PNGV vehicle design requirements.

The committee believes that the system analysis part of the program has now been established with a credible foundation. This is based on the detailed review of the technical approach and a demonstration of the PNGV systems analysis capabilities that are under development. Timing, however, is going to be a major challenge, along with providing the necessary funding.

The committee regards the following as significant issues:

- All analytic models are very rudimentary at this time. Validity and fidelity must be established. Lack of validation data is hindering the efforts of the systems analysis team. Unfortunately, a lot of these data are considered proprietary by potential providers. Program timing is thereby being threatened.
- Cost and reliability models, which are critical to evaluating designs, are insufficient and are significantly behind schedule.
- Attention to date has been focused on creating a systems analysis tool, and the necessary models. Little effort has been made to understand how the technical teams, especially the vehicle engineering team, will use the tool in the studies necessary for the technology downselect process. Interaction with the technical teams is minimal and significantly behind schedule.
- Participation by the vehicle engineering team has been minimal. This affects the accurate establishment of vehicle requirements.
- No funding source for 1997 and 1998 has been identified.
- Anticipated support from the national laboratories has been seriously curtailed by lack of government funding. This affects the realization of validation data for fuel cells, batteries, flywheels, and ultracapacitors.

RECOMMENDATIONS

Based on its review of the current status of the PNGV program, the committee makes the following recommendations.

Recommendation. The managers of the PNGV should conduct a program review with the leadership of the vehicle engineering team and the systems analysis team to assess the capability of the existing projects to meet program needs for the technology downselect process. A corrective action plan should be formulated and implemented as a matter of some urgency. This will ensure that systems studies are designed and implemented to provide the necessary optimization and trade-off information to make the best downselect choices. It would be logical for the systems analysis team to place a priority on creating those models that appear to be sure contenders for the technology selection process in 1997.

Recommendation. The managers of the PNGV should define and obtain the necessary resources for conducting systems analyses in 1997 and 1998. As part of this process, a detailed assessment of the 1996 $1.8 million TASC/SWRI contract should be conducted. The selected contractor should provide detailed work plans and expenditures for each task along with expected results.

Recommendation. The USCAR management should make a concerted effort to overcome the barrier of proprietary rights, at least to the extent necessary to ensure validation of the systems analysis models.

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4

Powertrain Developments

CANDIDATE SYSTEMS

A key measure of the ultimate success of the PNGV will be its ability to integrate R&D programs that collectively improve the efficiency of converting fuel into motive power for automobiles. This improvement must take place within the very stringent boundary conditions of size, reliability, durability, safety, and affordability of today's cars. At the same time, it must meet even more stringent emissions and recyclability levels and use components capable of being mass produced and maintained in a manner similar to current powertrains.

In order to achieve the Goal 3 fuel economy target (up to three times the fuel efficiency of today's comparable vehicles), the efficiency of the combustion engine (e.g., a CIDI, Stirling engine, or gas-turbine engine) or fuel cell, averaged over a driving cycle, will have to be approximately double today's efficiency to achieve at least 40 percent thermal efficiency (see Appendix E). This is a very challenging goal, considering all of the constraints noted above.

The candidate systems and subsystems have not changed during the past year. They are as follows:

- four-stroke CIDI engines
- gas turbines
- Stirling engines
- fuel cells
- reversible energy-storage devices[1]
- electrical and electronic power-conversion devices

[1]Reversible in this context means that the device can both accept and provide energy, not that it is reversible in a thermodynamic sense.

HEVs use an energy storage device to modify the fluctuating demands on the primary power plant. This modification allows the engine or fuel-cell peak power output to be reduced and provides an opportunity for improved efficiency by both restricting the power fluctuations and recovering some of the vehicle's kinetic energy during braking operations. The PNGV is sponsoring research on batteries, flywheels, and ultracapacitors for this purpose.

Committee members reviewed each of these R&D programs in considerable depth to assess the status of each, the progress that has been made, and the developments required for the future. The PNGV Technical Roadmap has been updated for most of these technologies, and it provides a good summary of the program goals. However, following in-depth reviews, the committee members almost all reported that the people in charge of performing the technical work had very limited information about the detailed requirements that would be imposed by a vehicle installation. This lack of information reflected a major concern for all of the candidate technologies, with the possible exception of the CIDI engine; namely, the systems analysis work and packaging studies that would provide this information have fallen significantly behind schedule. This lack of direction to the individual technical teams makes it difficult for them to focus their efforts. This basic flaw in the program cannot help but reduce R&D effectiveness and efficiency.

FOUR-STROKE COMPRESSION IGNITION DIRECT INJECTION ENGINES

Traditional passenger car diesel engines exhibit 15 percent to 30 percent better fuel economy, 10 percent to 20 percent lower carbon dioxide (CO_2) emissions, nearly zero evaporative emissions, and very low cold-start emissions when compared with similar gasoline engines. However, CIDI engines also suffer from size, weight, noise, and cost penalties that have limited their market acceptance in passenger cars unless their purchase is encouraged by a substantial fuel cost differential. Eliminating these disadvantages, while retaining or increasing the superior fuel economy of these engines, represents major challenges on several fronts.

Program Status and Progress

During the past year, the CIDI engine has been selected as the most promising of the four-stroke, direct-injection PNGV engine candidates for either standalone or hybrid vehicle use, and a technology road map applicable to CIDI engines has been completed. Research priorities have been established, and five high priority areas are being addressed through dedicated research programs. A workshop was held in which individuals from industry, academia, and government discussed and prioritized the critical technologies necessary for CIDI engines to meet the PNGV objectives. Also, the PNGV USCAR participants and the U.S. heavy-duty diesel-engine industry have established communications and agree that there are several areas of common interest including:

- understanding combustion fundamentals
- combustion gas after-treatment
- fuel-composition effects on engine performance

The five high priority CIDI research areas identified by the CIDI technical group are:

- lightweight engine architectures
- dimethyl ether (DME) as an alternate fuel for CIDI engines
- combustion-related processes
- lean NO_x catalysis
- alternative CIDI fuels assessment (including diesel reformulation)

The focus on combustion and DME is related to concerns about particulate emissions from CIDI engines. New cooperative programs, initiated in 1996, address critical aspects of each area. Other programs, most notably those involving fuel injection technology and lean NO_x catalysis, were already in place. The OEMs are supporting several in-house CIDI development programs, primarily through their European subsidiaries, but also in the United States. These projects involve both development of subsystems (fuel delivery, turbochargers, and engine- and emission-control strategies) and prototype vehicles through the HEV programs, which will serve as a test bed for the new technologies. CIDI hybrids are under contract at both Ford and Chrysler, with different delivery schedules. Because the HEV programs preceded PNGV, these hybrid vehicles are required to double fuel economy rather than meeting the PNGV Goal 3 vehicle target of tripling fuel economy.

Technical Targets

The critical characteristics of a CIDI engine, suitable for application to a Goal 3 vehicle, are shown as a function of PNGV milestone targets in Table 4-1. The last column shows that the 1995 targets have been met or exceeded in both test engines and some production engines. Passenger car diesel engines typically weigh 20 percent to 40 percent more than their gasoline counterparts. Table 4-1 shows a need to reduce the engine specific weight (usually referred to as specific power) by 26 percent and increase the displacement specific power (power density) by 29 percent in the 1995 to 2004 time frame. A production Volkswagen engine, which includes a variable geometry turbocharger and intercooler, is within 5 percent of the specific power goal but has made no progress toward the power specific weight goal. This indicates the need for radically new materials or construction techniques that can reduce the weight of CIDI engines. Using a turbocharger and intercooler also adds to the packaging challenge. Compared to the

TABLE 4-1 CIDI Engine Critical Characteristics versus PNGV Milestone Targets

Characteristic	Units	1995 Target	1997 Target	2000 Target	2004 Target	1996
Best brake thermal efficiency	%	41.5	43	44	45	42.5[a]
Displacement specific power[d]	kW/L	35	40	42	45	42.6[a] 45[b]
Power specific weight[d]	kW/kg	0.50	0.53	0.59	0.63	0.49[a]
Cost per kW	$/kW	30	30	30	30	30
Durability	1,000 miles	150	150	150	150	150
NVH (reduction in one meter noise)	dBA	–10	–10	–10	–10	–10[c]
FTP 75 NO_x Emissions in 2,500-lb ETW vehicle	g/mile	0.6	0.4	0.3	0.2	0.6 0.4[b]
FTP 75 PM Emissions in 2,500-lb ETW vehicle	g/mile	0.08	0.06	0.05	0.04	0.08 0.04[b]

Note: Based on data in Table III.F-1 in PNGV (1996).
Acronyms: NVH (noise, vibration and harshness); FTP (federal test procedure); PM (particulate matter); ETW (emissions test weight)

[a]Volkswagen production engine.
[b]Prototype single-cylinder.
[c]Current estimate for prototype hybrid.
[d]Displacement specific power is also referred to as power density; power specific weight is more commonly referred to as specific power.

gasoline engine, these components suggest an initial cost penalty of perhaps $800 to $1,200 in addition to the undetermined added cost of a sophisticated electronic fuel-injection system. The need for these added components makes keeping the cost to $30/kW (shown in Table 4-1) a major challenge.

Fuel economy targets for the CIDI engine have been moderated in recognition of the likelihood of having to meet the increasingly stringent emissions standards shown in Table 4-2. The CIDI team believes that the most technically challenging aspect of the CIDI program will be meeting the NO_x emission standards; however, possible stringent fine-particulate standards could also become a significant barrier for diesels. (Note that recently EPA issued a proposed rule for an atmospheric air-quality standard for fine particulates.) The PNGV should discuss with the EPA the likelihood of more restrictive particulate emission standards and their potential effect on the PNGV program. Intensive development of both in-cylinder combustion control and exhaust-gas after-treatment will be required

TABLE 4-2 PNGV Emission Targets and Standards

Species g/mile	1997 Target	2000 Target	2004 Target	Tier 1	Tier 2	LEV	ULEV
NO_x	0.4	0.3	0.2	1.25[a]	0.2	0.3	0.3
Particulate matter (PM)	0.06	0.05	0.04	0.1[a]	—	0.08	0.04
Carbon monoxide (CO)			1.7	4.2	1.7	4.2	2.1
Hydrocarbons			0.125	0.31	0.125	0.09	0.055

Note: LEV (low emission vehicle); ULEV (ultra-low-emission vehicle). Tier 1 and Tier 2 refer to standards for 10 years or 100,000 miles under the Clean Air Act Amendments of 1990.

[a] For California, the NO_x standard is 1.0 g/mile, and PM is 0.08 g/mile. The European standards for PM, which are based on a different driving cycle than U.S. standards, are (or are proposed to be) Euro II, 0.10 g/mile; Euro III, 0.04 g/mile; and Euro IV, 0.025 g/mile.

to reduce emissions from the CIDI engine, including reducing NO_x emissions. In-cylinder combustion control will require a sophisticated, high-pressure, fuel-injection system that is matched to the engine's in-cylinder flow field over the entire operating range of the engine. Exhaust-gas after-treatment will require the development of lean NO_x catalysts, NO_x traps, or plasma-aided catalysts.

Current Program Elements

Emissions After-Treatment

Two types of reductants have been considered for lean catalysis: urea (or ammonia) and hydrocarbons. Urea reduction of NO_x is a well-known technology developed for treatment of exhaust from stationary sources. However, the technology has not been tested under highly variable vehicle operating conditions, which would require a sophisticated control system to avoid ammonia in the exhaust as a result of incomplete conversion of injected urea. The possible formation of ammonium sulfate particulates and the need to refill a reservoir tank of urea solution also may hamper consumer acceptance of this technology.

Diesel fuel can also be used as a hydrocarbon reductant for NO_x; it can be injected into the exhaust stream. Like the use of urea, the injection technology must be developed for optimal operation with minimal fuel consumption. At present, noble metal (e.g., platinum [Pt], and rhodium [Rh]) catalysts are the most promising, but control of nitrous oxide (N_2O) emissions, formation of metal sulfates, and prevention of emission of unburned hydrocarbons are still significant issues. Laboratory data suggest that the Tier II target could be met by matching the operating temperature window of the catalyst and the exhaust-gas temperature, but at a 1 percent fuel penalty.

NO_x trap technology uses an alkaline earth oxide to trap NO_x by reacting with it to form metal nitrate when the engine is running lean. Periodically, the engine runs fuel-rich, and the temperature of the exhaust increases. Then the metal nitrate is decomposed to release NO_x, which is treated by a catalyst, such as the proven three-way catalyst. The long-term stability of such a system has yet to be demonstrated. The formation of stable metal sulfate and carbonate could cause severe degradation of the performance of such a device.

Plasma-assisted catalytic removal of NO_x is a new technology that has the potential to remove NO_x and particulate matter (PM) simultaneously. The technology has not been tested commercially. In the PNGV CIDI Workshop of May 22–23, 1996, in Detroit, Michigan, it was reported that for this technology to be successful the required power must be reduced. It was also reported that the NO_x removal rate needs to be increased while restraining the formation of nitric acid, ozone, and other atmospheric contaminants. Many of the research results have not been reported; therefore, the current status of and progress made with this technology is not clear.

Laboratory test data presented to the committee by USCAR for the newest Volkswagen engine indicate that the Tier 0, and possibly the low-emission vehicle (LEV) PM standard can be met without exhaust after-treatment. However, the more stringent ultra-low-emission vehicle (ULEV), or Euro III standard, will probably require an oxidation catalyst. Because of the trade-off between PM and NO_x, it is unlikely that these standards can be met by engine modification alone; an after-treatment device will be necessary. Catalytic oxidation devices to reduce PM emissions are currently used successfully on some heavy-duty trucks.

A lean NO_x cooperative research and development agreement (CRADA) was formed in 1994 involving the USCAR partners and five government laboratories, supported by the Department of Defense (DOD) and the U.S. Department of Energy (DOE). The government budget for Fiscal Year 1996 was $293,000 from the DOE Office of Defense Programs technology transfer initiative, and $950,000 from DOE. Unfortunately, because of late appropriation of the DOE funds, there was a nine-month stoppage of research at Sandia National Laboratories and Lawrence Livermore National Laboratory. The Fiscal Year 1997 request from DOE is for $840,000 and the emphasis of the research will be on methods to coat catalysts onto a monolith support and on production of full-size converters for testing and optimizing the reductant. No PNGV funds have been allocated for catalyst R&D because there are strong business incentives for companies to pursue proprietary research in this area. Catalyst suppliers worldwide, as well as Ford, General Motors, Cummins, and other engine manufacturers, both in the United States and abroad, are supporting intensive R&D of lean NO_x reduction technology.

High-Pressure Fuel-Injection Systems and Combustion Fundamentals

Significant advancements in the fuel-injection system's ability to control the fuel injection rate to match it to in-cylinder combustion processes are required for the CIDI power plant to be successful in the PNGV concept car and prototype. The concept engine will probably use more sophisticated electronically controlled injectors than are currently used. Two high-pressure fuel-injection configurations are under consideration: a hydraulically actuated common rail and a hydraulically intensified fuel injection system. They are referred to as the common rail and the hydraulic electronic unit injector (HEUI) types. Both are capable of providing an injection pressure independent of engine speed. This characteristic yields engines with relatively high low-end torque, which results in very good driving characteristics. Using a very high pressure common-rail injection system and large amounts (35 percent) of exhaust-gas recirculation (EGR), led a European contractor, AVL, to conclude that engine emissions eventually may be able to achieve the ULEV NO_x standard (Meurer, 1996).

The injection system must be capable of optimizing the injection rate shape and increasing the tolerance for EGR. A small pilot injection at varying times prior to the main injection has shown promise both for controlling combustion and reducing noise. However, as the EGR tolerance of the engine is increased, through increased injection-pressure and injection-rate-shape control, the carbon monoxide (CO) and unburned hydrocarbon emissions are also increased. These emissions are not a problem in current CIDI designs, but they may become a problem as regulations become more stringent and engine operation is extended into the operating range projected for the PNGV concept vehicles. The development of these injection systems for a concept engine is being pursued cooperatively between the USCAR participants and injection system manufacturers. Both types of injection system are being aggressively developed, and the prognosis is good for successful deployment to an engine in the required time frame.

In 1996 the PNGV program established a 4-year combustion CRADA, with an initial allocation of $700,000/yr, plus matching funds from industry, to address the in-cylinder combustion processes of fuel injection, air-fuel mixing, combustion, and emission formation. The CRADA objective is to provide "the technological understanding required to develop a new CIDI diesel engine which meets the efficiency and emissions standards of a PNGV vehicle." Participants are Sandia National Laboratories, Wayne State University, and the Engine Research Center of the University of Wisconsin, Madison. Optical diagnostics will be performed on a single-cylinder engine at Sandia; engine bench testing will be performed at Wayne State University; and modeling will be done at the Engine Research Center at the University of Wisconsin, Madison. The CRADA is just starting, and initial results are expected by the second half of the 1998 calendar year.

Structural Engine Design and Manufacturing

The Tank Automotive Command (TACOM) of DOD and USCAR initiated a program to investigate alternative engine architectures and lightweight materials leading to procurement, development, and pre-prototype engine testing in 1997. The requested funding of $2.44 million for 1997 is not yet firm, and if it is held at a carryover level of $450,000, such lack of funding would seriously hamper progress. Concept designs being developed by Ricardo Engineering Ltd. are now focused on the possible use of magnesium for the engine block (Talwar, 1996).

A specific manufacturing issue has surfaced related to the need for extremely close tolerances within the injection system; namely, the capability to make 0.10 mm diameter fuel injector holes consistently, compared to today's limit of 0.15 mm. A number of design and manufacturing approaches, for both affordability and weight reduction, are suggested throughout the program status documents. However, the benefits projected for these actions are not quantified with respect to their contribution to the cost or weight objectives, nor are these elements visible in the PNGV work plans.

Assessment of the Program

The relatively advanced small-displacement CIDI engines in production in Europe, together with programs put in place through the PNGV and by individual companies to improve these engines, make the PNGV CIDI performance goals seem potentially achievable. [2] The highest technology risk appears to be the ability to develop a combustion system and after-treatment system to meet an uncertain set of exhaust emission requirements in 2004. The PNGV program has put in place a modest effort to address both engine-out emissions reduction and after-treatment, but the funds are minimal, and results to date are insufficient to assess a rate of progress. However, substantial commercial programs are under way to address these issues.

The cost and weight objectives of a CIDI engine that will meet the challenging goals for 2004 appear to be major obstacles. Ideas have been proposed for novel engine architectures, systems integration, reduced parts count, and manufacturing improvements to address these problems. However, it seems likely that the sophisticated high pressure injection system, variable geometry turbocharger, and high cylinder pressures, combined with the need for lightweight, high strength materials will continue to bring a substantial cost premium for this engine. It also

[2] A presentation to the committee by AVL indicated a significant increase in fuel economy afforded by CIDI diesel engines (Herzog, 1996). Using data from production engines, by normalizing the weights of several vehicles to 1,000 kg (2,200 lb), AVL showed a CIDI fuel economy of 57.4 mpg as compared to 31.4 mpg for the multi-port fuel injection (MPFI) spark-ignited gasoline engine. This is an 83 percent increase in fuel economy as compared to state-of-the-art fuel injection gasoline engines. It should be noted, however, that these fuel economies are for the "1/3 Euromix" driving cycle, which is said to be less severe than the American federal urban driving cycle used for EPA fuel-economy estimates. They do not properly express efficiency differences, since the higher heating value of diesel fuel is not reflected in the normalization process; also the process may not properly reflect other vehicle differences.

appears that the proof-of-concept demonstration of lightweight structures and cost-reduction features for the CIDI are lagging the year 2000 concept vehicle schedule by a year or more. Obviously, further delays will be incurred unless funding is significantly increased from the 1996 level.

In spite of the significant risks of not meeting the PNGV goals as noted above, it is clear that CIDI technology is, by far, the best understood and most highly developed of any power plant technology being considered in the program. Because it is almost certain to be one of the final candidates for use in the year 2000 concept vehicles, the CIDI technology program needs to be more focused and needs a substantial increase in financial support.

Recommendations

Based on its review of the program status and progress for CIDI engines, the committee makes the following recommendations.

Recommendation. The PNGV should expand efforts to devise lightweight, low-cost alternative CIDI engine structures, and additional resources should be made available.

Recommendation. The PNGV should immediately assess the possible effect of regulatory actions aimed at reducing the atmospheric levels of fine PM on the viability of passenger car CIDI engines, and the research and development program should be modified, if necessary. To help the EPA make decisions based on the best possible information, the EPA should be continually informed of decisions made by the PNGV during the downselect process. Furthermore, the PNGV and EPA should work together to determine the trade-offs between vehicle performance and environmental standards and associated impacts on social benefits and costs.

GAS TURBINES

Gas turbine engines have some attributes that make them potentially successful as a Goal 3 vehicle engine and other attributes that will make realizing this potential very difficult. The low-pressure, excess-air, continuous-flow combustion provides very low levels of untreated emissions and a broad multifuel capability. The all-rotating machinery leads to low levels of vibrations and noise. The continuous flow, annular flow path, and high rotational speeds result in high power-to-weight and power-to-volume ratios for the "core" of the engine. Furthermore, the dominance of the gas turbine engine in commercial and military aircraft has generated an enormous amount of R&D, which has resulted in significant technological advances. However, for more than 40 years, substantial efforts to develop the gas turbine for automotive applications have been unsuccessful for several reasons. Most notable are (1) achieving sufficiently efficient aerodynamic turbomachinery components, which becomes more difficult as their size is reduced; (2) attaining high enough turbine inlet temperatures; (3) developing efficient means to recover a portion of the turbine exit thermal energy; and (4) developing materials, manufacturing techniques, and designs capable of meeting cost requirements.

The "core" of the gas turbine engine generates hot, high-pressure gas that is expanded through one or more turbines to produce work. These engines lose efficiency very rapidly if the main shaft speed is allowed to decrease in partial-power operations. A single-shaft turbine engine can attain a relatively high efficiency over a very limited speed range. Therefore, automotive gas-turbine engines have generally required at least two turbines operating on separate shafts, which make the engine bulkier and more expensive. However, for a series hybrid vehicle, the engine speed is independent of the vehicle speed, the engine-speed range can be reduced, and the single-shaft arrangement may be adequate, depending on the hybrid-vehicle control strategy. Idle fuel consumption of gas-turbine engines is much higher than for similar-output reciprocating engines, so systems optimization is critical.

High temperature gas at the turbine exit in an automotive gas turbine represents lost thermal energy, making regenerators or recuperators essential for efficient operation. These devices are heat exchangers that transfer some of the turbine exit thermal energy to the compressor discharge flow. However, they are large and heavy and thus detract from the power-to-weight and power-to-volume advantages of the engine "core."

Turbine-engine size can be reduced and thermal efficiency improved dramatically by increasing turbine inlet temperatures. Cycle studies have shown that to approach the thermal efficiencies required for a Goal 3 vehicle it is necessary for this temperature to approach 2,500°F, although there is some indication that it may have to be limited to less than 2,300°F to limit NO_x emissions. These temperatures exceed, by several hundred degrees, those possible with even the most exotic uncooled metal turbines. Even if they did not, the cost of these exotic materials and their fabrication would prohibit automotive usage. The alternative is to develop a ceramic material with the potential to meet both the cost and high temperature objectives.

Program Status and Progress

Previously Identified Barriers

In its second report, the committee reported that gas turbines represent a promising technology for hybrid vehicles and that considerable progress had been made in the previous year, especially in turbo-alternator design, bearings, combustors, heat recovery, and controls. However, the committee also reported that progress was behind schedule and there were major technical roadblocks (NRC, 1996). Foremost among the roadblocks was the lack of a turbine material that could withstand high temperatures, that was capable of being precision-formed to provide efficient aerodynamics, and that could be mass produced at low cost. It also appeared that little had been accomplished with respect to systems studies at the vehicle or power plant levels. To some extent, this clouded the actual magnitude of the technical barriers because the requirements and trade-offs were largely unknown.

Progress toward Removing Barriers

Some completed systems studies give better indications of the more desirable configurations and the projected performance parameters. The single shaft, turbo-generator configuration has been chosen, thereby limiting the vehicle application to a series hybrid. This configuration uses an all-electric drive system, in contrast to the parallel hybrid, where there is a direct mechanical link between the engine and the drive wheels. Some systems studies have projected better drive-train efficiency for the parallel hybrid. If this is confirmed, the challenge of enhancing gas turbine efficiency will be increased. The systems studies presented to the committee were very preliminary, and there was no evidence that systems trade-offs had been made.

The Allison engine design is complete, and the Teledyne Ryan design is well under way. Both designs appeared reasonable, although probably optimistic, in their projected goals. The designs have different target characteristics based upon two different hybrid-vehicle performance and control strategies. The Teledyne design power is 55 kW to 60 kW and its efficiency at one-third power, required to meet the Goal 3 vehicle fuel economy target, is 43 percent. Comparable values for the Allison design are 40 kW and 38 percent. The most optimistic projections would put attainable efficiencies at least several points lower than these values. Although many component tests have been run supporting the plausibility of the projections, the necessary resources have not been applied to iterative component and subsystem developments to indicate that these levels of performance can be maintained for the complete engine system.

Ceramic Turbine Progress

The single most critical component yet to be demonstrated is a suitably sized, efficient ceramic turbine, capable of being mass produced. The committee found that significant progress has been made by Kyocera-Vancouver and AlliedSignal Ceramics in making high-quality ceramic components with complex shapes and using processes with high potential for scale-up to automotive volumes and cost. Extruded regenerator rotors, integral turbine rotors, and scrolls have all shown new capabilities which, although beset by tooling and startup yield problems, have produced quality engine parts and have supported successful component durability demonstrations. Previously, precision silicon-nitride parts were made by hot isostatic pressing, which is impractical for large-volume production. Today, laboratory-scale parts can be produced in 10 minutes using a gelcast process, a much better time frame than the 8 hours required by the previous procedure. However, yield and consistency for this process have yet to be established. Some silicon-nitride components have been manufactured using this process and have been installed on an experimental basis in engines running at metal temperatures (approximately 2,000ºF), primarily to improve wear. A silicon-nitride diesel engine turbocharger rotor for use in automotive engines has been in large-scale production by Kyocera for several years.

Other Components

Two turbine engine manufacturers reported combustor tests results confirming an ability to meet California ULEV standards, and two other manufacturers are pursuing catalytic combustors with still lower emission potential. Thus it appears that emissions will probably not represent a significant barrier. Three turbine engine manufacturers developed air bearings. They reported engine or dynamic rig testing results that meet engine requirements. This indicates that the cost and parasitic losses associated with conventional oil lubrication systems can be eliminated. Although air bearings are not an enabling technology, they do represent a very desirable feature for minimizing engine cost and complexity.

Heat-recovery devices have also shown considerable progress. In particular, the Corning extruded design appears to offer a low-cost alternative, and its 500-hour test has begun to demonstrate the required durability and performance capability. An effective, low-cost, heat-recovery device is an enabling technology for the turbine, and progress in this area is impressive. However, high-volume cost, long-term durability, and performance characteristics still must be demonstrated. Adapting low-cost, automotive-type electronic control systems that can meet gas turbine requirements is also meeting with success.

Assessment of the Program

Considerable progress in the last year has moved the gas turbine closer to being a successful PNGV engine candidate. Gas-turbine manufacturers project that they can meet or approach the PNGV weight, volume, and efficiency goals. They also believe turbogenerators can meet other constraints, including operability, emissions, noise and vibration, and durability. These projections have not yet been validated, but given sufficient time and resources, they may be realized.

A ceramic turbine is necessary to meet or approach the efficiency goals. Even though impressive progress has been documented with the silicon-nitride gelcast approach, it is still not clear that this process can meet automotive parts-manufacturing requirements and costs. Considerable time will be required to demonstrate durability and repeatability of manufacture. Also, the efficiency and durability of such turbines at the required temperatures have yet to be demonstrated. Another major factor relative to the PNGV time frame is that there are no testbed engines for testing and integrating into the vehicle. A workable design and workable components are not enough to demonstrate effective system integration in a vehicle.

In summary, much progress has been made, but even the most optimistic projections for the required development time puts the gas turbine well beyond the time frame for PNGV concept vehicle demonstrations.

Recommendations

Based on its review of the program status and progress for gas turbines, the committee makes the following recommendations.

Recommendation. Development of the gas turbine engine should continue, and acceleration of the basic technology and systems and design optimization efforts should be considered. Some of the deficiencies and inconsistencies among the developers indicate that a better technical focus in areas such as bearings, overall system optimization, and manufacturing goals should be defined.

Recommendation. A testbed for the gas-turbine engine should be made available for vehicle integration studies.

Recommendation. Potential goal 1 and 2 applications of some of the gas-turbine engine technologies, such as oil-less bearings, gelcast parts, and extruded ceramics, should be explored for other automotive applications.

STIRLING ENGINES

The Stirling engine is an external-combustion, reciprocating-piston engine. This power plant has been under development for more than 40 years and has been used successfully for stationary solar to electricity energy conversion, as well as for some submarine and satellite applications. It was selected by General Motors for development as part of the DOE HEV program. This engine is expected to have performance, size, weight, and emission parameters similar to those projected for the PNGV ceramic gas turbine. Stirling engines are typically very quiet and are relatively vibration free. The engine being used by General Motors was built by Stirling Thermal Motors, a company with extensive experience with engines of similar size for use in solar electricity generation. The uncertainty about having ceramic turbine components in time to meet deadlines of the DOE HEV program, together with the higher predictability that the Stirling Thermal Motors design can be successfully adapted, were the primary factors in General Motors' decision to continue engine development.

Program Status and Progress

A 40-kW, four-cylinder, swashplate Stirling engine and alternator unit was delivered to General Motors in September 1996, and preliminary testing has begun. Packaging has not been optimized, and this initial unit does not meet specific power targets for a PNGV vehicle. Although steady-state emissions are expected to be very low (the burner is very similar to that for a gas turbine), little is known about emissions during start-up. Thermal efficiency is expected to meet the DOE HEV requirements, but the engine-head temperature would have to be increased or the heat-rejection temperature decreased to approach the requirements for a PNGV vehicle. The Stirling engine cycle efficiency is very sensitive to the temperature available for heat rejection, making radiator effectiveness a key system design parameter.

Stirling engines typically operate with either hydrogen or helium as the working fluid that is sealed within the engine. Performance is substantially better with hydrogen, which is currently being used in the General Motors engine; however, the use of hydrogen increases the difficulty of eliminating leakage past seals and from permeation through hot metal surfaces.

Assessment of the Program

This program is at a relatively early stage of development. Much will be learned about the potential of the Stirling engine for possible PNGV application through the current hybrid program. Cost, manufacturing hurdles, and durability for automotive applications are not well understood at this time. Because this is an external-combustion engine, the performance of the five heat exchangers (heater head, regenerator, air preheater, gas cooler, and radiator) creates the most uncertainty. Cold-start emissions also need to be determined. The HEV program will provide a benchmark for the performance of these components, as well as an assessment of the critical issue of working-fluid containment. The potential of this power plant in the PNGV program will be much easier to assess when this information is available.

Recommendation

Based on the review of the program status and progress for Stirling engines, the committee makes the following recommendation.

Recommendation. The PNGV should review results from the General Motors/DOE hybrid vehicle program on an ongoing basis, and the potential of using a Stirling engine in a PNGV prototype vehicle should be assessed through appropriate vehicle systems, modeling, and packaging studies.

FUEL CELLS

Fuel cells hold the promise of converting fuel to power for vehicle propulsion much more efficiently and with lower emissions than combustion engines. The proton-exchange-membrane fuel cell (PEMFC) is the best candidate among established fuel cell technologies for a hybrid vehicle. It can operate at about 80°C and its efficiency, specific power, and power density (operating on a hydrogen fuel) approach the goals of the PNGV program. Like other fuel cell technologies, it operates best on hydrogen as a fuel. However, because an infrastructure for the production, storage, and distribution of competitively priced hydrogen is not likely to be developed in the foreseeable future, the strategy of the PNGV program is to convert hydrogen on board the vehicle to hydrogen for use by the fuel cell. Pollutant emissions from PEMFCs should be extremely low because high-temperature combustion processes are not involved and the fuel (e.g., gasoline) must be processed into a hydrogen-rich fuel stream with extremely low levels of carbonaceous compounds (except carbon dioxide) to be compatible with PEMFC electrocatalysts. However, the requirement that fuel be converted completely and with very high thermal efficiency poses difficult technical challenges for the fuel-processing subsystem, especially if gasoline is the primary fuel. Incompatibility of fuel cell electrocatalysts with CO in the output fuel stream from the fuel processor remains an important issue. An electrocatalyst that yields a higher fuel cell efficiency with lower noble metal loadings but retains high activity in the presence of CO from the reformer would remove a significant barrier to progress. Subsystem integration and plant engineering (i.e., water, thermal, and air management, and operation under pressure) also require extensive development efforts. Major advances are needed in manufacturing at the component, subsystem, and system levels to reduce greatly the weight, volume, and especially the cost of fuel-cell power plants if the goals of the PNGV program are to be met.

The PNGV targets for 2004 include the following: energy efficiency of 80 percent for the fuel processor and 57 percent for the fuel-cell stack; power densities of 0.75 and 0.50 kW/L for the fuel processor and stack, respectively; and costs of $10 and $35 per net peak kW, respectively. These goals do not include the volume or costs of energy storage or the power-conditioning subsystems. In addition, a durability of 5,000 h is sought, along with a warm-up time of about 1 min and a transient response to changes in load within 10 s for the fuel processor and 1 s for the stack. To meet durability and efficiency goals with currently available electrocatalysts, the CO content of the fuel stream passing from the fuel processor to the stack is targeted to be less than 10 ppm at steady state and less than 100 ppm for transients.

Program Status and Progress

Fuel Processing

The achievement of efficient, compact on-board fuel processing is one of the most challenging problems in developing practical automotive fuel-cell power plants. Successful development requires low CO content (preferably below 1 ppm) to avoid poisoning the anode catalyst of the fuel-cell stack; low processing temperatures to minimize warm-up time, thermal-insulation requirements, and thermal inefficiencies that arise when fuel and hydrogen-rich product streams are heated and cooled; high degrees of thermal integration and fuel utilization to avoid compromising the overall energy efficiency of the fuel-cell system; and reduced capital costs. These challenges are greater if gasoline is the fuel. Although fuel processing of methanol requires temperatures in the range of 200°C to 300°C, gasoline reformers will need to operate at about 700°C to achieve practical conversion rates while avoiding deleterious deposition of carbon on the catalyst.

Up to now, the PNGV fuel-processor development efforts have taken advantage of the earlier development of reformers and fuel processors for alcohol fuels under the DOE HEV program. Now part of the PNGV program, these developments include a successful laboratory prototype (6-kW equivalent) of a single reactor combining partial oxidation and steam reforming of methanol (at Argonne National Laboratory) and a complete 50-kW equivalent ethanol fuel processor comprising reactors for partial oxidation, steam reforming, and CO shift to hydrogen and carbon dioxide (at Arthur D. Little, Inc.). These fuel processors appear capable of meeting (or even exceeding) PNGV goals for specific power and power density, and they are projected to meet cost goals when operating on alcohol fuels. However, infrastructure constraints have led the PNGV to stipulate gasoline as the primary fuel. Gasoline is more difficult to process than alcohol fuels because of its more complex composition and chemistry and because it contains potential catalyst poisons such as sulfur. Efforts at Argonne National Laboratory and Arthur D. Little to process gasoline are now beginning. The efficacy, efficiency, and durability of these fuel-processor technologies when operated with gasoline are yet to be established, as is their effectiveness in reducing CO to the required levels, and the dependence of the fuel processor efficiency on part-load and transient conditions.

Electrochemical Cell Stack

In programs funded under the DOE HEV program, now part of PNGV, and by the OEMs outside of the PNGV program, several fuel-cell power plants in the 10-kW to 30-kW range have been developed, built by subcontractors to Chrysler, General Motors, and Ford, and operated with methanol or hydrogen fuels.

Typically, these prototype units fell about 40 percent short of the PNGV goal for power density and a few percentage points short on efficiency. Work at Los Alamos National Laboratory (LANL) on the important electrocatalyst poisoning issue shows that small amounts of air (about 2 percent) added to the fuel stream fed to the electrochemical cell can raise the CO tolerance level to about 100 ppm. Although it compromises the overall efficiency somewhat, this approach may make the requirements of the fuel-cell stack compatible with the capabilities of the fuel processor. Because CO tolerance is an electrocatalyst property, exploration and development of improved fuel electrode electrocatalysts for CO tolerance should continue to be pursued albeit at a low level given the high technical risk. This work should proceed in parallel with alternative approaches, such as the LANL preferential-oxidation technique, to achieve CO levels at the electrocatalyst surface sufficiently low to be compatible with the limitations of present materials and technology.

Currently used proton-conducting membranes perform adequately, and thinner membranes of lower resistance are becoming available. Membrane costs are high, but this is not considered as critical as achieving an acceptable overall efficiency and producing a system that can meet performance targets. The need to develop lower-cost materials and fabrication techniques for bipolar plates is being addressed.

Control and Ancillary Systems

In addition to the fuel processor and the cell stack, auxiliary systems are needed for water management, thermal management, fluid-flow control, and safety. Appropriate water-transport management and hydration control are critical to membrane performance and life. Even in a fuel cell power plant, more than 50 percent of the fuel energy is released and must be removed as heat. These needs translate largely into engineering and design problems. These should be put on a schedule and priority commensurate with the time needed to deal with the most critical issues, which include catalyst poisoning, fuel-processor performance on gasoline, and overall system efficiency.

Costs

The PNGV cost goal for the entire fuel-cell power plant is $50/kW. Because commercial phosphoric acid fuel cells presently cost more than $1,000/kW on a larger, less constrained scale, major efforts will have to be made to find low-cost component materials and to develop low-cost manufacturing methods for PEMFCs. Substantial cost reduction can be anticipated to accrue from high-volume production using automated processes (for fabricating key components like bipolar plates, membranes, and electrodes, and for assembly of cell stacks), but reliable overall cost estimates must await the resolution of the costs of materials for the aforementioned components necessary to achieve efficiency and durability for operation with gasoline as the fuel, and the conceptualization and cost estimation of manufacturing practices for all key components and subsystems. It is not clear to the committee whether and how the cost goals can be achieved because no analyses of materials, components, or manufacturing costs were presented to the committee.

International Developments

Ballard Power Systems, Inc., in Canada, is a leader in developing PEMFC technology for vehicles. Ballard is collaborating with General Motors on the PNGV program and with Daimler Benz (in Germany) to develop power plants for minivans and passenger cars. Ballard also has a program to develop power plants for buses. All of these systems use either pure hydrogen or hydrogen produced from the on-board processing of methanol.

The Toyota Motor Company recently demonstrated a PEMFC-powered vehicle using hydrogen, stored onboard as a hydride, as the fuel. Toyota has also investigated electrocatalysts (Pt-Ru) for CO tolerance. Siemens in Germany and De Nora in Italy have also designed and constructed PEMFC power plants (rated at 1 kW to 10 kW) for defense and vehicle applications. The existence of fuel-cell development and demonstration programs does not mean that fundamental issues—from gasoline fuel-processor performance to electrocatalyst and membrane performance to overall system efficiency and cost—have been resolved. At the present time, U.S. research laboratories are in the forefront of fundamental and applied research investigations to advance PEMFC technology, and International Fuel Cells, a subsidiary of United Technologies, appears to be only behind Ballard in technology development and demonstration.

Assessment of the Program

PNGV and worldwide progress in automotive fuel-cell technology have been impressive in a number of important areas, especially in improving the power density of the fuel-cell stack and in lowering the projected costs. Nevertheless, PNGV's PEMFC technology targets are unlikely to be technically achievable by 2004 and cannot be expected to be cost-competitive with state-of-the-art automotive power source technology before 2010 to 2015.

By 2004, the PNGV technical goals for fuel-cell-stack power density and specific power could be met by using thinner membranes and bipolar plates and by paying careful attention to stack design and construction. No fundamental scientific breakthroughs will be needed. A substantial breakthrough will be required to obtain electrocatalysts with long-term stability, low noble-metal content, and high CO tolerance. However, this must be recognized as a very high-risk endeavor. In the absence of electrocatalyst breakthroughs and considerable reduction of the production costs for some key components (e.g., bipolar plates), the inherent cost of the system will remain high, and the overall efficiency may not meet PNGV goals. Durability of key components and subsystems has not been demonstrated under conditions of anticipated use, including, most importantly, use of gasoline as fuel. Refinement and demonstration of gasoline fuel processor technology are required.

A high degree of system integration will be needed to realize the fuel cell's potential for higher efficiency compared to heat engines. For example, if the fuel processor has an 85 percent thermal efficiency, the fuel stack reaches 55 percent efficiency, the energy-storage (battery) system returns 95 percent of its input energy, and conversion of electrical to mechanical energy reaches 81 percent efficiency, the fuel-cell system would have an overall efficiency of only 36 percent. This is below the projected values of 37 percent for gas turbines and 43 percent for CIDI engines. Therefore, one important conclusion is that fuel-cell stack and electrical/mechanical conversion efficiencies need to be targeted for significant improvements if fuel cells are to offer meaningful efficiency advances.

Recommendations

Based on its review of the fuel-cell program and status, the committee makes the following recommendations:

Recommendation. Development of automotive fuel-cell technology should be continued because of the inherent potential of fuel-cell power sources for very high efficiency and near-zero emissions. However, PNGV program emphasis in the coming years should be on achieving major advances and/or breakthroughs in areas critical to achieving high efficiency, long life, and low manufacturing costs rather than on prematurely demonstrating prototypical power sources with less-than-competitive performance.

Recommendation. A consistent systems analysis should be conducted that (1) determines the overall efficiency of vehicles using a fuel cell with a gasoline reformer and compares it to vehicle power sources using other advanced energy-conversion systems, (2) clearly identifies areas where significant improvements are needed, and (3) establishes realistic targets and the most promising technical approaches to attain these targets.

Recommendation. Because a high-performance, compact, efficient, low-cost gasoline fuel processor is the key to automotive fuel-cell applications in a gasoline-fuel scenario, high priority should be given to advancing fuel-processor technology, validating it in an engineering prototype (e.g., 50-kW), and integrating it with a prototype fuel-cell stack.

Recommendation. Electrocatalyst, membrane, and bipolar-plate durability tests should be run on small cells with simulated gasoline-reformate fuel to determine the prospects of retaining high efficiency, electrocatalyst specific activity, and tolerance to poisons and degradation processes over the longer term.

Recommendation. Efforts to develop more cost-effective materials and high technology automated techniques for manufacturing and assembling key fuel-cell components, such as bipolar plates, membranes, electrodes, end-plates, and sealants, should have higher priority than costly and possibly premature efforts to demonstrate integrated fuel-cell power plants in parallel efforts.

BATTERIES

Technical Targets

Batteries, especially some of the advanced batteries currently under development for electric vehicle propulsion, have the potential to meet the energy storage requirements of HEVs. The PNGV Technical Roadmap compares HEV requirements to those set for electric vehicles (see Table 4-3).

The HEV targets for battery specific energy (60 Wh/kg) and energy density (75 Wh/l) exclude lead-acid and nickel-cadmium batteries from consideration. Advanced batteries are being developed in the U.S. Advanced Battery Consortium (USABC) program and in European and Japanese industrial and government

TABLE 4-3 Battery Target Comparison

Characteristic	Units	EV Targets	Hybrid Targets
Power Density	W/L	600	2,000
Specific Power	W/kg	400	1,600
Energy Density	Wh/L	300	75
Specific Energy	Wh/kg	200	60
Cycle Life			
DE = 5% [a]		—	300,000[a]
DE = 50% [b]	Cycles	—	120,000 [b]
DE = 80% [c]		1,000	1,000 to 2,000 [c]
Lifetime	yr	10	10
Cost	$/kWh	100	150

Note: Based on Table III H.1 in PNGV (1996).

The committee offers the following comments on cycle life characteristics and targets:

[a]The target of 300,000 cycles at 5 percent depth of discharge does not appear to relate to any operating modes or conditions that can be expected for batteries used in hybrid vehicles.

[b]The target of 120,000 cycles at approximately 50 percent depth of discharge is meaningful only if the charge and discharge excursions from this state are specified, for example, 3 percent of capacity.

[c]From the comparison with electric-vehicle battery targets, DE can be inferred to stand for depth of discharge.

efforts, but only the nickel-metal hydride and lithium-ion systems appear to have potential for attaining hybrid targets and meeting the PNGV time table. However, neither the capabilities of these battery systems for meeting the specific power and power density requirements nor the number of shallow cycles delivered had been established when the PNGV high-power-battery development program began.

The PNGV Technical Roadmap correctly identifies achievement of high power-to-energy ratios, long cycle life, retention of cell balance in a series-connected multiple battery, very high charge-discharge efficiency, and affordability (low cost) as the major development challenges for the PNGV battery program. The road map also indicates that developing a battery technology to meet these objectives will require significant, and possibly major, modifications in current battery designs and manufacturing methods.

Because of delays in developing the PNGV systems analysis and modeling programs (see Chapter 3), definitive energy-storage subsystem requirements for hybrid batteries based on appropriate trade-off studies have not been established. The road map does, however, recognize the differences in battery requirements imposed by power plants with significantly slower response times to power demands than conventional automobile engines. Batteries designed and developed for "slow-response" power systems may not be able to meet the "fast-response" requirements and vice versa. Table 4-4 shows these requirements. This distinction expands the range of capabilities for HEV batteries and increases the number of battery types that might qualify for at least one of the hybrid applications. Even lead-acid and nickel-cadmium batteries might eventually be able to meet the "fast-response" requirements.

TABLE 4-4 PNGV Design Targets for Short-Term Energy Storage

Characteristic	Units	Fast Response	Slow Response
Discharge pulse power (18 s)	kW	25	65
Peak regenerative power (10 s)	kW	30	70
Discharge power density	kW/L	0.78	1.6
Discharge specific power	kW/kg	0.63	1.0
Cost	$/kW	12	7.7
Durability (100 Wh)	cycles	50,000	120,000
Lifetime	yr	10	10
Operating temperature	°C	–40 to 52	–40 to 52
Survival temperature	°C	–40 to 66	–40 to 66

Note: The fast-response power plant is assumed to react very much like a conventional automotive engine, responding very quickly to vehicle power demands. The slow-response engine puts a much greater demand on the energy storage system for instantaneous high-power delivery.

Source: Kizer (1996).

Between January and May 1996, the PNGV awarded Phase 1 contracts through USABC for initial exploration of three different battery types. Four organizations received contracts: SAFT (conventional lithium-ion); Yardney and VARTA (nickel metal hydride); and SRI International (novel lithium-ion concept). All of the technologies except the SRI lithium-ion technology are well developed and involve established developers and manufacturers.

SAFT Lithium-Ion Program

Status and Progress

The SAFT technology meets all major HEV battery target performance goals except for cost, including goals for energy density, power density, and cycle life, at the 0.85-Ah cell level. The project is on schedule and within budget. Capability was demonstrated for 120,000 shallow cycles with less than 20 percent capacity loss and, more importantly, with only a small increase in cell impedance. Also, basic feasibility was established for scaling the technology up to the 10-Ah cell size envisioned for HEV applications. Refinements in electrical and thermal design and in charging control are still needed, and safety under all conceivable operating conditions must be demonstrated. Safety requirements will be the focus of a follow-on program to develop a 50-volt module. Priority objectives include analyzing failure modes and effects and developing a potentially low-cost electric/electronic battery-control system from existing technology. A key issue is whether cell-level current control is likely to be required (as for consumer-product and electric vehicle batteries) or whether a combination of quality control in cell manufacturing and the shallow charge/discharge hybrid-battery duty cycle (around intermediate states of charge) will permit less elaborate and, thus, less expensive control strategies and equipment.

Assessment

Achieving the PNGV production cost goal of $150/kWh for a 3-kWh battery will be extremely difficult. Several developers project that electric-vehicle versions of lithium-ion batteries (less expensive than HEV versions because they are larger in scale and lower in specific power) will cost more than the PNGV target even if produced in volume (1 to 2 million kWh/year). SAFT currently projects a cost well in excess of the target for 3-kWh lithium-ion hybrid systems that include adequate provisions for electric and thermal management. The main uncertainties and risks regarding the timely availability of prototype 50-volt modules arise from the required combination of high levels of safety and the potential for low production costs.

Yardney and VARTA Nickel Metal Hydride Programs

Status and Progress

Initial explorations of the potential of nickel metal hydride battery technology for hybrid duty are nearing completion, but only very limited performance and cycle life data are available. To date, the Yardney program (started in April 1996) has demonstrated that small (0.44 Ah) test cells can deliver 10,000, one-minute pulse discharges and that the cell coulombic efficiency promises to meet the PNGV target at low states of charge. However, the power density projected for a battery using this technology is only 0.33 kW/kg. The VARTA program, begun in May 1996, has demonstrated capability for more than 60,000 shallow cycles, but other performance results were not available for committee review.

Assessment

The nickel metal hydride system should be a good candidate for developing high-power batteries because electric-vehicle versions have already demonstrated energy densities approaching those of lithium-ion as well as comparable peak-power capability and deep-cycle life. Cell and battery safety are more easily achieved with nickel metal hydride than with lithium batteries because of less reactive battery materials and the ability of cells to sustain overcharge safely and without damage. Meeting efficiency and cost goals will be more difficult, however, because of the nature of the electrochemistry (including the relatively low cell voltage) and the materials involved.

It is not clear whether the current programs will be able to demonstrate battery performance and cycle life close to those needed to meet PNGV goals. It is also unclear whether the program's nickel metal hydride batteries will approach, much less exceed, the very promising performance reported by DAUG (a battery-development organization owned jointly by Daimler-Benz and Volkswagen in Germany) for prototype, full-scale nickel metal hydride cells developed for hybrid applications. Cost remains a major concern. The inherently less expensive electric-vehicle nickel metal hydride batteries are projected to cost at least $250/kWh to $300/kWh unless there is a materials breakthrough. Therefore, meeting the PNGV goal of $150/kWh seems quite unlikely.

SRI International Lithium-Ion Program

Status and Progress

The SRI concept differs from the concept of other lithium-ion cells. SRI uses a noncarbon anode (negative electrode) host material and a nonflammable solvent base for the electrolyte. These features and the nearly 2 V less-negative anode potential should considerably reduce safety concerns although at the expense of reduced energy-density and power-density potential. Since June 1996, SRI has been fabricating and testing small laboratory cells. The ability of these cells to deliver and absorb 10 s current pulses at the nominal 15 C rate (discharge of the nominal capacity in 1/15 of an hour) has been established, but the battery power density projected from cell data appears limited to about 0.4 kW/kg. No cycle life information was made available.

Assessment

Even after the current SRI program has been completed, this battery technology will be in a much earlier development phase than other systems. Key cell and battery materials, design, engineering, manufacturing, safety, and system aspects are not yet developed to the point where a prototype program could be initiated with a definable probability of success. If results of the current program indicate that performance, cycle life, and cost requirements might ultimately be met, the next step should be designing, fabricating, and evaluating small engineered cells. Availability of SRI production prototype battery modules in time for the Goal 3 prototype vehicle appears unlikely. Also, because larger amounts of active materials and larger electrode areas are required to achieve the same energy and power levels as more conventional lithium-ion batteries, the SRI technology is likely to have higher production costs.

Assessment of the Overall Program

The PNGV battery program has benefited from DOE's long-term support of battery R&D and from the more recent, major commitments by DOE and its industrial partners to the USABC electric-vehicle battery program. As a result, the PNGV can draw on the services of a substantial number of capable industry and government people with relevant technical and management experience to define and direct its high-power battery development program. In addition, the PNGV had a "running start" because the program was based on battery technologies with proven promise and battery developers who performed well in the USABC program. Together with the battery R&D and testing capabilities established by DOE at several national laboratories, this combination of government and industrial capabilities is more than adequate to define, manage, and technically support the PNGV battery program.

The PNGV criteria provide a reasonable guide for identifying candidate HEV battery systems. With the identification of "slow" and "fast" primary vehicle powertrain response modes, a useful refinement of the criteria has been made. However, the impact of this refinement is not yet reflected in the program's technical strategy. Given that the vehicle systems analysis and its link to the storage subsystem model are not yet fully developed, the PNGV storage system criteria appear to be based on somewhat arbitrary and restrictive assumptions for performance requirements. Therefore, these criteria should be used as guidelines rather than as rules for selecting candidates.

The importance of PNGV's modeling and systems analysis and its impact on battery/storage system selection, development, and integration, argue for a continuing, systematic refinement of modeling and analysis of batteries as integral parts of hybrid vehicle power systems. However, the PNGV Phase 2 battery program plan does not appear to include a corresponding line item, and it is unclear whether adequate resources will be available for modeling, systems analysis, and high-power battery testing. Adequate resources for these critically important activities are essential.

Testing developmental and prototype batteries in ways that realistically simulate the operating conditions of batteries in hybrid power systems will become an essential part of the PNGV battery program when prototype cells and modules are available not only from the PNGV but also from other development programs. The testing methods and plans presented during the committee's review seem appropriate for this task, but no corresponding task and budget line item was shown in the program plan.

The extensive PNGV compilation of worldwide advanced battery development organizations and technologies does not identify any programs aimed specifically at hybrid applications. Leading international battery developers such as SAFT (France), VARTA (Germany), and Matsushita/Panasonic and Sony (Japan) undoubtedly are exploring high-power versions of their systems. However, no major program or product has emerged. One possible exception is DAUG's successful development of a 14-Ah nickel metal hydride high power cell technology, but DAUG does not appear to have immediate plans for commercializing this technology. Thus, the hybrid/high power battery developments funded under the DOE HEV program and PNGV represent leading-edge efforts to achieve the challenging technical targets for power density, shallow cycle life, and high "round-trip" efficiency with potentially affordable battery systems. If the PNGV battery program in Phase 2 results in prototype modules that meet the proposed technical targets, the United States almost certainly will have the lead in hybrid/high power batteries.

PNGV funds for the Phase 1 efforts undertaken in 1996 appear to have been adequate, although relying on a single contractor to explore conventional lithium-ion technology is somewhat risky. Funding for the SAFT, Phase 2 lithium-ion module development effort appears adequate, mostly because of SAFT's large (50 percent) cost share. It is not clear whether or not sufficient funding will be available to fund appropriate follow-on development efforts at Yardney, VARTA, or alternative developers. Testing and critical evaluation of several nickel metal hydride technologies against refined PNGV targets probably could be accomplished relatively quickly and with a modest budget. Similarly, an effort to establish the advantages and limitations of the SRI technology on a meaningful scale of technology could be carried out with a modest budget. These actions should considerably enhance the program focus and the probability of success in Phase 2.

Assuring a high probability that the most promising battery systems are selected and production prototypes are developed that meet the PNGV performance, cycle life, safety, and cost goals will require substantially higher funding levels in the future. It seems likely that a meaningful share of the funding required for each system (on the order of $60 million to $150 million for the critical prototype and pilot-plant phases) will have to be provided by PNGV over the next five to seven years.

Recommendations

Based on its review of battery-development programs, the committee makes the following recommendations.

Recommendation. Development of the high-power lithium-ion battery should continue until the prototype module level is reached, with early emphasis on ensuring safety under all foreseeable conditions. The control requirements for safe operation of modules and batteries in the hybrid mode should be determined, and development of potentially low-cost electric and thermal control systems should be initiated.

Recommendation. The ongoing exploration of high-power nickel metal hydride batteries should be completed. Based on data and test data from promising nickel metal hydride batteries available from other sources, the PNGV should determine whether this technology offers advantages over lithium-ion batteries in hybrid applications and how these advantages might be captured for the PNGV Goal 3 vehicle.

Recommendation. Modest efforts should be supported to explore the potential of other battery systems (such as the SRI concept) that show promise of providing superior performance, safety, enhanced cycle life, and/or lower cost. This support should be provided at least until the capabilities of the lithium-ion and/or nickel metal hydride batteries to meet PNGV goals can be predicted with confidence.

Recommendation. Continued efforts should be supported to (1) develop storage subsystem and vehicle subsystem models that provide realistic performance, cycle life, and cost targets that establish a capability for conducting trade-off analyses; and (2) establish a testing methodology and a physical capability for evaluating high power batteries for hybrid electric vehicles both from within the PNGV program and externally.

FLYWHEELS

Flywheels have very attractive power-to-weight and power-to-volume characteristics of the "core" system (compared to batteries) both in delivering power and in accepting the high power developed during vehicle braking. However, serious problems related to safety, cost, and size must still be solved.

Technical Targets

A detailed vehicle systems analysis, with appropriate vehicle subsystem trade-offs, has not been performed to define flywheel requirements for a PNGV hybrid vehicle. Nevertheless, the PNGV flywheel technical team has assumed parameters in order to specify its application to vehicles designed with either a fast-response or slow-response power plant. The fast-response power plant is assumed to react very much like a conventional automotive engine, responding very quickly to vehicle power demands. This type of power plant places the least demand on the flywheel system. The slow-response engine puts a much greater demand on the flywheel for the delivery of instant high power. This demand requires a much larger and more costly flywheel system. The flywheel objectives metrics for both types of power plants are shown in Table 4-4.

Program Status and Progress

There is a high probability that the design performance objectives shown in Table 4-4 can be achieved for the basic flywheel system because material specifications and performance characteristics are well known. However, because of the potential for catastrophic flywheel failure, safety considerations require that a containment structure be included. Requirements for this structure have not yet been determined; therefore, the ultimate cost, volume, and overall system weight cannot be determined at this time.

Progress during 1996

The PNGV flywheel technical team has put together a mission statement and a technical plan. Objectives of the technical plan include developing automotive-applications requirement guidelines and action plans for testing, identifying high-leverage issues, developing a scalable model, and reviewing the feasibility of other mechanical energy storage systems (e.g., hydraulic) and progress documentation. The team is also monitoring flywheel design and testing efforts being pursued for other applications. For example, the University of Texas Center for Electromechanics at Austin is developing a flywheel system for a bus with AlliedSignal and another project, funded by the Advanced Research Projects

Agency (ARPA) and the Houston Metropolitan Transit Authority, to develop a safety containment system.

Plans for 1997

Program guidelines and vehicle test data are not expected to be available until the end of 1997. The action plan for the test protocol is scheduled for completion by May 1997. The University of Texas Center for Electromechanics plans to mount a flywheel system on an advanced technology transit bus by the end of 1997, and they will complete a substantial number of flywheel burst-containment tests by May of 1997. The Federal Railroad Administration is testing composite flywheels that are one-third of the full design size making them comparable to the bus requirements. The ARPA flywheel safety program will provide a fundamental understanding of composite flywheel behavior and will develop rational means for developing safe designs. Containment of failures will be pursued through (1) careful design to avoid flywheel failure, (2) detection of initial failure potential and shutdown of the flywheel system to minimize failure loads, and (3) barriers to contain and mitigate potential damage.

Assessment of the Program

The PNGV flywheel technical team believes it is unlikely that flywheel subsystems will be able to support the first PNGV concept vehicles; but, if estimated funding of $1.3 million for Fiscal Year 1997 is made available, they should have a laboratory-scale subsystem by the end of 1997. The committee concurs with the team's assessment, while noting that other activities have produced significant data on flywheels systems that can assist in the downselect decision. These activities include the Trinity model flywheel from Lawrence Livermore National Laboratory, the Unique Mobility flywheel contracted by Ford Motor Company, and the Satcon work on the flywheel for the Patriot Vehicle at Chrysler. Containment cost and weight remain significant issues that are, as yet, undefined in terms of total vehicle system requirements.

Recommendations

Based on its review of the program and progress for flywheel development, the committee makes the following recommendations.

Recommendation. After appropriate vehicle system trade-off studies have been conducted, performance objectives should be created that satisfy the requirements of the fast-response power plant vehicle system, and a plan should be developed for evaluating and integrating a flywheel subsystem in post-2000 concept vehicles.

Recommendation. The ARPA comprehensive flywheel failure containment plan should be pursued, including collecting burst/collision failure test data from all available sources.

ULTRACAPACITORS

Technical Targets

Ultracapacitors are in the same category as flywheels—they are compatible only with the power-assist (fast-response engine) type of HEV configuration. The technical targets for ultracapacitors are essentially the same as those of the flywheel. The goal of the projects, sponsored mainly by DOE, is to develop high-power ultracapacitors that meet or exceed the energy storage requirements for fast-response engines.

Program Status and Progress

Several laboratories in the United States and other countries are examining the prospects for using ultracapacitors to provide pulse power for military applications, but there is little evidence of R&D abroad of ultracapacitors for use in the HEV. However, carbon-based, aqueous electrolyte ultracapacitors have been developed and commercialized in Japan for other applications, such as providing instantaneous power to high-speed computers during power failure.

The ultracapacitors being developed for the HEV are of the electrochemical type, the active material being high-surface-area carbon, a noble metal oxide, or a conducting polymer. Of these types, ultracapacitors using carbon in an aqueous electrolyte are the most highly developed. However, the cell potential for this type of device is only 1 V, compared with 3 V for a cell with an organic electrolyte. General Electric Company is developing ultracapacitors of the latter type for the Ford HEV program. Based on the testing of unpackaged single cells, they project the following performance characteristics at 2.75 V: specific energy of 4.1 Wh/kg, energy density of 5 Wh/L to 7 Wh/L, specific power (to half maximum voltage) of 1,100 W/kg, and power density of 1,500 W/L. Maxwell Laboratory, Inc. is developing this same type of cell and has built 24-V modules and determined temperature effects and cycle life performance. At a constant power (1,100 W/kg) the performance was found to be better at a higher temperature, but there was a problem with an increased self-discharge rate. There is also some loss in energy after about 60,000 charge/discharge cycles. Sixteen cell modules (electrode area 200 cm^2) are being built.

Ultracapacitors using noble metal oxides and conducting polymers have the advantage of achieving a high specific power (2,000 W/kg to 4,000 W/kg); their drawback is having lower values of specific energy. Ultracapacitors with p-doped and n-doped conducting polymers, have demonstrated a value of 10 Wh/kg (the

PNGV goal for 2004 is 15 Wh/kg) for the specific energy. Los Alamos National Laboratory has demonstrated a very high specific power (about 10 kW/kg) with devices of this type. The Army Research Laboratory at Fort Monmouth, New Jersey, has obtained promising results with a new electrolyte, which is benign and exhibits a high specific conductivity, high solubility, high electrochemical stability, and the ability to work satisfactorily over a wide range of temperature (–40ºC to 70ºC). In addition, Small Business Technology Transfer and Small Business Innovation Research Phase I awards were made in 1996 for innovative research on electrode structures, "wet" electrochemical ultracapacitors, and solid-state ultracapacitors, including thin-film dielectrics.

Assessment of the Program

Ultracapacitor projects are in an early stage of research and development. Their only potential applicability in the PNGV program is in conjunction with fast-response engines. The current programs are behind schedule, and the milestones for 1996 have not been reached. Developing ultracapacitors for energy storage in an HEV is a high risk, high payoff project. It is unlikely that the ongoing projects will be able to meet the PNGV timing, performance, and cost goals for the following reasons:

- Even though the specific power and power density could reach high values, the energy density is likely to remain low.
- For this application, the ultracapacitors must have a time constant of less than 100 ms. The high capacity needed for a high specific power and a relatively high energy density makes it very difficult to have such a low time constant because the equivalent series resistance will have to be of the order of a few ohms.
- The current costs of materials and fabrication processes are very high; to meet the PNGV cost goal for this energy storage device ($150/kWh), these costs will have to be reduced by two orders of magnitude.
- Self-discharge rates, particularly of the carbon ultracapacitors, are relatively high; although 100,000 to 200,000 cycles have been demonstrated in small cells, there is a significant loss in capacity after about 50,000 cycles.

The prospects for developing batteries (particularly the high performance nickel metal hydride and lithium-ion batteries) that meet the PNGV technical goals for energy storage, both for the slow-response and fast-response engines, are excellent. The ultracapacitor technology will require at least 10 times the current level of financial support for a period of 10 to 15 years to reach the same state of development. A considerable amount of research is needed just to identify the type of ultracapacitor that might attain the performance level required for an energy-storage device for the HEV. It is premature to carry out scale-up and cell-stacking tasks for the HEV application. Because ultracapacitors may be used in other applications, for which there are ongoing investigations, the PNGV should follow the progress of these programs and then analyze the needed research, development, and demonstration for the HEV at a later date.

Recommendations

Based on its review of ultracapacitor programs and progress, the committee makes the following recommendations.

Recommendation. PNGV should conduct appropriate systems studies to determine the prospects for ultracapacitors in HEV applications in comparison with high power batteries and other energy storage devices, such as flywheels.

Recommendation. Work on ultracapacitors for HEV applications should be limited to basic and applied research studies at universities, national laboratories, and industrial R&D centers and should be directed toward making fundamental advances and breakthroughs.

ELECTRICAL AND ELECTRONIC POWER-CONVERSION DEVICES

Program Description and Requirements

All of the PNGV vehicle configurations involving electric motor drives, energy recovery, flywheels, or fuel cells require electric motors/alternators, power electronic inverters, and sophisticated electronic controllers. There are other vehicle subsystems and accessories, such as power steering and heating, ventilation, and air conditioning (HVAC) systems, that also require electric power control. During its second review, the committee noted that the PNGV Technical Roadmap demonstrated a good awareness of the state of the art for these devices and had established appropriate and challenging targets for performance, efficiency, weight, and cost. The milestones in the PNGV Technical Roadmap show the overall electric driveline efficiency improving from today's estimated 70 percent to 80 percent in 10 years, and the weight decreasing by 47 percent. The cost of the electronic converter/controller must be reduced by 85 percent, and the cost of the electric motor must be reduced by 80 percent. The committee commented that these are very ambitious goals. The committee did not conduct an in-depth review of the technologies during its second review and did not make specific recommendations.

Current Status

The following assessment is based on presentations on October 10, 1996, by the PNGV electrical and electronics power conversion devices team to the committee subgroup on electrical and systems analysis. The PNGV–USCAR partners have varying degrees of experience in developing and producing power electronic converters and controls, and electrical motors and alternators of the type necessary for a Goal 3 vehicle. They are actively exploring various types of electric motor configurations, including induction, permanent magnet, switched reluctance, and synchronous reluctance. It was stated to the committee that power electronic converters available for demonstration today are approximately twice the weight required to meet the needs of a Goal 3 vehicle. Members of the team have some recent experience working with qualified semiconductor manufacturers in the development and fabrication of insulated-gate bipolar transistors (IGBTs) for high-power applications and a very preliminary understanding of the producibility of IGBT power converters and their associated production costs.

PNGV–USCAR recognizes the importance of reducing vehicle accessory loads, such as HVAC loads, to reduce overall vehicle electrical loads. Moreover, they believe that the trend toward higher accessory loads in response to consumer demand will continue. This will make the challenge of reducing accessory loads even greater by the year 2004. PNGV needs to develop plans and allocate resources to address this issue.

The PNGV–USCAR partners have made progress in understanding the effect of system requirements on the system architecture and primary components. The PNGV vehicle-defined need for 0.5-g vehicle acceleration will determine the configuration and size of the electric drive motors.

The vehicle requirements for this subsystem have not been adequately defined for all vehicle configurations under consideration. The interface with the vehicle engineering team and the system analysis team has not been effectively established. It appears to the committee that this team is relying heavily on other electric-vehicle and HEV programs to guide their efforts in developing technology for the Goal 3 Vehicle. Chrysler is using its experience with the Patriot concept HEV; General Motors is using its experience from the Impact concept electric vehicle and the production of the EV-1; and Ford is using experience from the Ecostar and other advanced vehicle studies. Chrysler, Ford, and General Motors also have government-sponsored contracts to demonstrate HEV technology in concept vehicles. These programs provide the technology base for collaboration on electric motors, power converters, and other related components. It must be pointed out that these applications can provide background, but the PNGV requirements demand very specific design and development considerations in order to meet the performance targets.

The DOE-funded HEV programs require the three OEMs to explore alternative HEV architectures. These include both parallel and series hybrid vehicles. Two of the partners (Ford and General Motors) selected parallel architectures for their HEV assumptions; the other partner (Chrysler) selected a series configuration.

Chrysler received its HEV contract during the past year while General Motors and Ford have had contracts for a longer period. The partners have organized technical steering groups that share information generated from the individual HEV programs. DOE and PNGV should make sure that detailed data developed in the HEV program is universally and uniformly shared with USCAR partners on a periodic basis. The technical steering groups have identified responsibilities, and members have collaborated on identifying cost, weight, and size targets for components. The steering groups have also developed various technical performance measures for the high-priority components, and they are assessing the state of existing technology. Analytic results are emerging, and limited test data are available from the partners' electric-vehicle and HEV efforts.

The Chrysler Patriot program was targeted at a racing-technology vehicle; therefore, its requirements were quite different from those of a passenger vehicle. What was learned during development of the Patriot vehicle is useful to the PNGV program, especially in the design of the power controller. It must be noted, however, that manufacturability and cost were not major considerations in the Patriot vehicle program.

The committee also reviewed an Office of Naval Research and DOE program, known as the Power Electronic Building Block (PEBB). This program is dedicated to developing new technologies to advance the state of the art in power electronics control. The goal of the program is to reduce the cost and weight of electric-propulsion systems while achieving a high degree of functional integration, efficiency, and reliability. Semiconductor development is a major part of this program. The committee questions the direct applicability of this program to PNGV requirements. The focus is on large packages containing multiple die, which are very expensive from both a device and system-manufacturing point of view. The cost constraints for automotive design will require optimum design for manufacturing and assembly where both weight and space must be minimized.

In the course of the committee's review of this program, very little data on component and subsystem performance relative to PNGV requirements were presented. Both Ford and General Motors have made good progress in developing components that could contribute to the PNGV in their HEV programs. The new General Motors drive-motor design is an advance over currently available components, and the packaging density is impressive. These advances should lead to some design baselines and should provide needed cost and reliability data. General Motors' Impact vehicle could also provide basic cost data for a production vehicle.

The PNGV–USCAR partners identified and ranked the highest priority areas for component technology development. These include electric motors and alternators, power control electronics, HVAC, and electric/electrohydraulic power steering. High performance efficiency for these subsystems and components is vital and a high priority because they greatly affect the overall efficiency of an HEV configuration. If the HEV configuration is selected for a Goal 3 vehicle, overall system performance will be significantly affected by the design and integration of the power electronics and electrical subsystems.

Typically, accessory loads, such as HVAC, power steering, wipers, cooling pumps, instrumentation, and the antilock braking system, can increase the demand for engine power by approximately 30 percent (Malcolm, 1996). Although the team presented limited descriptive material on these systems and their impact on fuel economy, it is clear that the power required by these loads must be reduced, and this will require a well-directed active effort by the PNGV team to achieve maximum efficiency. An aggressive cost-reduction program is also mandatory. For example, the electric or electrohydraulic steering subsystem cost must be reduced by a factor of three to meet the vehicle cost objectives (Piccinato, 1996).

The group working on regenerative braking has identified a number of barriers to the development of a practical system. Of these, the efficiency of the energy storage device is critical. The battery technology now available cannot accept a high charging current efficiently. Questions concerning over-charging and depleting batteries as a storage device remain unaddressed. The efficiency goal for regenerative braking is 75 percent, without considering energy storage efficiency; current efficiency is estimated at 35 percent. There are many constraints to efficient braking-energy regeneration, and recovering the energy at low vehicle speeds is a significant challenge.

The team did not review or discuss the awareness of global technology. In Japan and Europe, for example there are several electric-vehicle and HEV programs in various stages of development. The team should make an effort to capitalize on all applicable technology.

Assessment of the Program

The committee concluded that very little was accomplished overall by the electrical and electronics power conversion devices team during the past year. The report given to the committee subgroup in October 1996 was virtually the same as the status reported at Vice President Gore's symposium in the spring of 1996. It should be noted that the team did not have an appointed leader for most of the year, and the committee believes the team lacks an overall sense of urgency. The PNGV Technical Roadmap details four PEBB milestones. The first PEBB milestone, scheduled for 1995, has been missed. At the current rate of accomplishment, the second milestone, established for 1997, probably will be missed. The third and fourth milestones are scheduled for 2000 and 2002.

Many tasks described in the PNGV Technical Roadmap are not being addressed. For example, no trade-off format with well defined requirements has been established to support the downselect process in 1997. The committee was informed at its November 11–13, 1996, meeting that a part-time team leader had been selected. The question of adequate funding was not addressed by the team. The committee had requested that this be reviewed and can only assume that it is not an issue.

Although the team did not specifically identify barriers to progress, the committee concluded that the following major issues could constitute barriers:

- Overall driveline efficiency is currently estimated to be 70 percent. The PNGV goal is 80 percent. No data were presented to establish a confidence factor in achieving the goal.
- Today's electric/electronic subsystems, such as power steering and HVAC, and accessories, such as wipers, cooling pumps, instrumentation, and antilock braking systems, require electric power equal to approximately 30 percent of the PNGV vehicle drive power. This level of power must be reduced. Sufficient, directed technical effort is necessary to achieve the required efficiency.
- Costs of motors and alternators, the power controller, vehicle electrical subsystems, and accessories are estimated at from 50 percent to 300 percent above the individual subsystem targets. No plan of action to achieve these targets was presented.
- The committee has a major concern about the overall process of assigning attribute targets to individual components without the benefit of a top-down, overall system definition supported by a systems analysis. Optimization of overall vehicle performance can be achieved only by this approach. Evaluation of the differences among the power plants is especially important.

Recommendations

Based on its review of electrical and electronic power conversion device programs and progress, the committee makes the following recommendations.

Recommendation. The new electrical and electronic power conversion devices team leader should function full time and should determine how to make up for lost time and establish a schedule for the team. The team leader should identify the staff necessary for effective team performance and should commit them to the team's activities. One of the highest priorities for the new team leader should be developing interfaces with the vehicle engineering and the systems analysis teams.

Recommendation. The impact of the team's schedule slippage on the technology downselect process should be reviewed immediately by the PNGV, and plans should be made to meet schedules that support the overall PNGV effort.

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5

Major Manufacturing Considerations for Goal 3

The manufacturing team is working with the PNGV technology teams to ensure that the manufacturing R&D meets the near-term and long-term needs of the PNGV. As addressed in Chapter 2, the near-term goal (Goal 1) is to improve significantly the manufacturing competitiveness of the USCAR partners. In the longer term Goal 3 R&D program, the manufacturing team is working with the technology teams to develop viable concept vehicles by the year 2000 and cost-effective preproduction prototypes by the year 2004.

PLANS FOR 1996

The objective of the 1996 plans was to mobilize the USCAR partners' manufacturing community through the formation of teams, propose projects, and develop a manufacturing technology road map. The objective for the latter part of the year was to identify manufacturing technologies that would improve the global competitiveness of the partners and would meet the technology needs of Goal 3 vehicles.

PROGRESS IN 1996

The manufacturing team has been firmly established and will play a substantial and critical role in meeting the cost, weight, performance, productivity, and other requirements to make any of the proposed Goal 3 technologies viable. Near-term projects have been defined that can improve the partners' competitiveness in manufacturing, the objective of Goal 1. A manufacturing technology road map has been formulated, but it will have to be refined as new manufacturing technologies are identified to meet the challenges of Goal 3 product technologies. The manufacturing team members are active participants in the product technology teams and, as needs arise, are able to communicate them to government representatives, other consortia, universities, and suppliers. The manufacturing team believes it has identified all known product technology needs at this time; it is still identifying needs for improvements in specific manufacturing processes.

The highest priority manufacturing needs include the following:

- Fuel Cells. New or improved processes are required for metal bipolar plates, injection molding of graphite/polymer plates, catalyst application, and sealing and adhesives applications. Modeling high-speed, automated manufacturing and assembly and evaluating of real-time quality control/nondestructive evaluation methods for all components are also required.
- Gas-Turbine Engines. Significant producibility and affordability issues must be addressed. In this last year, the PNGV has made significant progress in fabricating precision ceramic components suitable for the extremely high inlet temperatures required for the Goal 3 turbine-engine application. Most recently a new gelcast technology was developed that allows parts to be made in 2 percent of the traditional time. Proof of length of life at high temperatures is still required. Another manufacturing goal is to demonstrate high-volume manufacture of a low-cost, high-yield product that can be reliably joined to other ceramic or metal materials. Furthermore, the targets for raw-material (silicon nitride) cost at acceptable availability levels is a significant challenge. Demonstration of a high-volume engine assembly that takes precision, balance, and material handling into account is also needed.
- CIDI Engine. Fuel-injection-system performance is critical in support of engine efficiency and emissions control. Machining of small injector holes at a high-volume rate, as well as affordably producing other precise injector pump components, are the significant tasks. Improvements in the process for aluminum cylinder head and cylinder block, bore and valve seat treatment, are also required.
- Flywheels. A low-cost process for carbon-fiber fabrication with excellent and consistent quality characteristics is essential. Low-cost bearings, design of a method to evacuate the high-speed housing, and a means to balance the high-speed flywheel are other requirements.
- Electrical and Power Electronics. Refined manufacturing processes will be needed, and lightweight materials will be mandatory. Casting and machining processes for ultimate structural weight reduction must be achieved. The use of rare-earth magnets will challenge manufacturing forming and handling processes. High electrical power levels will require sophisticated designs for lead attachment and bonding for which manufacturing processes will be critical to reducing costs. Cooling

requirements will require the machining and casting of complex cooling packages. New motor construction designs and integrally casting a copper squirrel cage for induction motors are also significant areas to be addressed. Very little progress has been made in producibility and affordability. The PNGV team estimates that the cost for the electrical and electronic components for driveline and power control are 50 to 300 percent higher than Goal 3 target levels. Simultaneous design for performance optimization and manufacturing cost reduction must be achieved.

- Battery and Ultracapacitors. New processes are required for thin-film coatings of large battery plates, carbon manufacturing to reduce costs and improve energy densities, and reliable and affordable sealing.
- Vehicle Systems. Modeling and simulation of the entire vehicle assembly process will be performed to improve logistics, flexibility, and operator variability and to improve the cost of all manufacturing phases (for example, individual, subassembly, and assembly operations). Improvement in manufacturing of both composite and aluminum materials is required. Computer models are desired for composites to predict manufacturing variability effects on material performance. Reduced cycle time and the use of intelligent process controls are also required. Improvements required for aluminum relate to joining methods (for example, adhesive bonding, welding, or mechanical), aluminum forming methods to reduce cycle time and achieve predictability and reliability, and developing different approaches for reducing the feedstock cost of the aluminum.

PLANS FOR 1997

During 1997, the PNGV will initiate projects to address the needs identified in 1996. The formation of specific project teams will be completed, and funding will be obtained. Close communication will be maintained with the product technology teams so objectives can be adjusted in response to new developments.

ASSESSMENT

The manufacturing team is now clearly organized and is making progress. Each USCAR partner has assigned at least one full-time, dedicated person and one full-time equivalent (several part-time people) to this goal. Many more individuals are involved on a part-time basis, and there is substantial support from suppliers, government, and universities. It is unlikely, however, that significant cost reductions and efficiency improvements will be available during the technology downselect process at the end of 1997. Critical manufacturing proofs, however, may be achieved in time to validate the feasibility of technologies, such as high-temperature ceramics for gas-turbine engines or precision injectors for diesel engines.

The cost reductions required to offset the likely higher cost of the new product technologies currently assumed as candidates for the Goal 3 vehicles seems to be well beyond what can be achieved through the current projects in Goal 1 and those currently forming for Goal 3. It appears to the committee that the work in progress and work planned will not be sufficient to meet the very demanding requirements of the Goal 3 objective. A major portion of the effort should be directed toward "clean-sheet-of-paper" approaches rather than what seems to be incremental process improvement. One example of this would be engine construction in a mono-block configuration. This is quite different, but not radical, from today's construction. Although there is a possibility that the mono-block configuration would require one-third fewer parts and result in lower costs, the PNGV seems to have relegated this configuration to the periphery; that is, the manufacturing needs assessment for the CIDI suggests only tentative support for a mono-block approach. The committee believes that the manufacturing team needs to take a stronger initiative in identifying and pursuing new approaches to manufacturing technologies to accomplish the significant cost reductions that are going to be needed to achieve Goal 3. The committee fully supports the funding requests associated with initiating and continuing the efforts of the project teams.

RECOMMENDATION

Based on its review of the manufacturing team's progress and plans for 1997, the committee makes the following recommendation.

Recommendation. A major portion of the manufacturing efforts for the Goal 3 vehicle should be directed toward identifying new manufacturing approaches for lowering costs significantly in all key system and subsystem areas.

6

Outstanding Program Issues

Five primary aspects of the PNGV program are considered in this chapter: (1) the government's efforts to anticipate infrastructure issues; (2) the downselect process and post-downselect issues; (3) leverage of foreign technology developments; (4) major achievements and technical barriers; and (5) the balance and adequacy of the PNGV program.

INFRASTRUCTURE

The committee's second report cited the importance of considering the impact of the PNGV program on the nation's infrastructure (NRC, 1996). For example, adoption of alternative PNGV power plants that use fuels such as methanol, DME, or hydrogen would require significant modification of the entire fuel production, transportation, storage, and retail-distribution infrastructure. There are significant infrastructure issues in almost all aspects of bringing a PNGV product to market. These range from supplies of raw materials to manufacturing capability to production to environmental impact to ancillary support, such as highway systems and vehicle service and maintenance. In its second report, the committee made three recommendations relative to the issues of infrastructure (NRC, 1996):

- The PNGV must continue to address infrastructure issues as an integral part of its program. A careful assessment of infrastructure issues associated with alternative technologies should be an essential part of the technology-selection process scheduled for 1997.
- The PNGV should perform a study to establish the energy balance, in-use environmental effects, and resource requirements, as well as the production

and distribution costs, for fuels other than gasoline or diesel fuel being considered for use in Goal 3 vehicles.
- The PNGV should immediately involve the Department of Transportation's National Highway Traffic Safety Administration in identifying, addressing, and resolving the safety issues raised by Goal 3 vehicles.

During the past year a research team from the Energy Systems Division of the Argonne National Laboratory continued its study of infrastructure issues. This was a continuation of the work reported to the committee during its second review in August 1995. The work involved further developing and running their life-cycle energy and emissions model, GREET (greenhouse gases, regulated emissions, and energy use in transportation). The GREET program is a documented and peer-reviewed simulation (Wang, 1996). In fact, the results of the first phase of the GREET study have been accepted for presentation at the 29th International Symposium on Automotive Technology and Automation to be held in Florence, Italy (Wang and Johnson, 1996). Documentation of the work presented to the committee at its November 1996 meeting will be available in January 1997.

A necessity for the infrastructure studies, and also a significant challenge, is to include in the analysis the impact of all processes associated with changes in the vehicle system. For example, petroleum-based fuel may be displaced by using electric vehicles; however to correctly assess the impact this would have on air quality requires that any pollution from the power station used to recharge the electric vehicle also be taken into account. That is, the environmental impact of manufacturing the electric vehicle and pollution from its power source must be included in the analysis. The basis of all comparisons in these infrastructure studies must be made on a "well-to-wheels" or "cradle-to-grave" framework. All of the infrastructure study results presented to the review committee by the Energy Systems Division were on a total system, or process, basis.

In exercising a life-cycle energy and emission predictive simulation, it is important to realize that the results are sensitive to the process-energy and emission assumptions used in the submodels of the simulation. In the results presented to the committee, it was assumed that the PNGV Goal 3 fuel economy and emission targets had been met. Two different PNGV market penetration scenarios were hypothesized: a low market share (approximately 30 percent of new vehicles being sold in the year 2030 being PNGV vehicles) and a high market share (approximately 60 percent of new vehicles being sold in the year 2030 being PNGV vehicles). Even though the PNGV vehicles in the model were assumed to meet the PNGV fuel economy and emissions goals, the accounting of different power plants and manufacturing processes yielded different mixes and quantities of exhaust emissions. For example, a hydrogen fuel cell will have lower NO_x emissions than a CIDI engine, even though the CIDI meets the NO_x emission standards; or different fuels may have different propensities for evaporative emissions.

If the hydrogen in the fuel cell were to be obtained from photovoltaic processes, the impact of the fuel on air quality would be low, but the financial cost would be high. In addition, it was assumed that non-PNGV vehicles being sold during the simulated time interval were also improving because they were meeting increasingly stringent air quality emission standards. The predictions include all processing, that is, the entire fuel cycle from “well-to-wheels”; therefore, the model includes many assumptions about processing efficiency, emissions release, and manufacturing capabilities.

In the infrastructure analysis there was also an implicit assumption that the new, more efficient vehicles were being purchased by the general public, as opposed to being restricted to corporate or government fleet operations. In this case, replenishing the stored energy of the vehicle by refueling must be as convenient as it is now with conventional gasoline-fueled vehicles. This has significant infrastructure implications. Whereas there may be current programs with alternate fuels in controlled fleet tests that show great potential, there could be significant infrastructure issues in making such power plants available to the public at large before there are “refueling capabilities” nationwide. There is a strong desire to implement the transition to more fuel efficient and environmentally friendly vehicles on a timeline and via a process that avoids dislocations. One purpose of the infrastructure studies is to assess the best way to implement changes and to identify processes that may cause undue hardship to the public so that dislocations can be kept to a minimum.

In an attempt to assess the viability of the model’s underlying assumptions and evaluate the results of the model’s predictions, representatives from Amoco Oil Company were asked to act as informal advisors and offer feedback as the work progressed. In addition, where possible, the results of the simulation were compared to other publicly available infrastructure models. This was challenging because each such study had its own specific focus, which differed from the focus of this assessment. For example, a study by Exxon focused on performance, energy security, domestic production, fuel costs, and consumer receptiveness for four specified fuels. The results from the Exxon study were quite different from what is required of this PNGV infrastructure analysis. However, where sufficient data were presented, it was possible to check for consistency in underlying assumptions within the different models. Two studies conducted by Arthur D. Little, Inc., were sufficiently similar to the PNGV infrastructure analysis to allow specific comparisons to be made between assumptions of the submodels. The assumptions about energy efficiencies of upstream production activities and the capital cost of production and distribution between the PNGV assessment and those of Arthur D. Little, Inc. were consistent.

The results of the simulation enabled assessments to be made of the capital investments for fuel production and distribution facilities, the impact of fuel-cycle energy and emissions, and the manufacturing effects of substituting lightweight materials. To date, the impact of PNGV Goal 3 vehicles on infrastructure related to production, maintenance, repair, recycling and insurance of the actual vehicles, or road and vehicle noise, and safety have not yet been addressed. A total of 12 combinations of fuels and power systems and four lightweight materials were evaluated. The 12 vehicle configurations considered were (1) reformulated gasoline—stand-alone spark-ignition engine and hybrid vehicle; (2) diesel—stand-alone compression ignition and hybrid vehicle; (3) dimethyl ether—stand-alone CIDI and hybrid vehicle; (4) methanol—stand-alone spark-ignition engine, hybrid vehicle, and fuel cell; (5) ethanol—stand-alone spark-ignition, hybrid vehicle, and hydrogen fuel cells. The four lightweight materials considered were ultralight steel, aluminum, magnesium, and polymer composites.

The model predictions indicated that the oil industry would have time to adjust to the change in demand for fuel brought on by a growing fleet of vehicles with triple the fuel economy of today's vehicles.[1] It also indicated that all of the fuel scenarios would entail moderate incremental capital costs in transition to the year 2015, with gradually increasing costs to the year 2030. Hydrogen was an exception in the 2030 time frame. The analysis predicted hydrogen would have a disproportionately large incremental cost by that year. The reason for the large increase in the projected cost is that it was assumed that hydrogen from the fuel cells would be obtained from photovoltaic devices by the year 2030. In terms of the impact of energy and carbon monoxide, the predictions indicated that petroleum and hydrogen require the least total energy use, that renewable fuels use the least fossil fuel, and that renewable fuels produce the least carbon dioxide.

Summary

The effects of various fuels and power plants on pollutant emissions are summarized below:

Volatile Organic Compounds

- Fuel cells offer the greatest benefit.
- Diesel fuel is similar to alternative fuels.

Carbon Monoxide

- Fuel cells offer the greatest benefit.
- Diesel fuel and dimethyl ether promise significant CO reductions.
- Alcohol fuels increase CO emissions.

Oxides of Nitrogen

- Hydrogen fuel cells offer the greatest benefit.
- Diesel and DME fuels could increase emissions.

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[1]The committee notes that the transition of the nation's fuel infrastructure, if it occurred, would be gradual. It would be difficult for production and distribution facilities for alternative fuels to be widely available in the United States soon after production of the first alternative-fueled vehicles.

Particulate Matter

- Fuel cells provide the most reduction.
- Emissions reductions also occur with reformulated gasoline, DME and methanol.
- Diesel fuel and ethanol fuel use increase particulate emissions.

Sulfur Oxides

- Renewable fuels provide the greatest emissions reduction.
- Reformulated gasoline and diesel fuel provide some reductions, but not as much as dimethyl ether and methanol.

The effects of incorporating lightweight materials into the vehicles is summarized below:

Ultralight Steel Autobody

- Using the existing infrastructure is an advantage.

Aluminum

- Foreign aluminum jobs would mostly replace U.S. steel jobs.
- New production capacity would be needed to use lower cost technologies.
- Vehicle ownership cost may increase due to potentially higher repair costs.

Magnesium

- Production capacity would need to be doubled or tripled.
- Significant increase in energy is required for production.

Polymer Composites

- Transition issues are significant because the carbon-fiber business is a small-volume specialty industry.
- Fabrication technologies are in their infancy.
- Low capital investment is needed, but a more highly skilled labor pool is required.

Recycling

- This is a major issue for all alternatives to steel.

The infrastructure analysis is an important tool for the PNGV program. As the PNGV continues to refine its technology knowledge base and push toward downselect scenarios, it is important for power plant configurations and fuel types to be accurately represented in an infrastructure scenario and evaluated with the infrastructure model. Infrastructure analysis should be an integral part of the downselect process. Also, for the simulation to remain a valuable tool, it is very important that the underlying assumptions of the model continually be re-evaluated and updated as new information becomes available. The model is only as good as its assumptions, and as new technologies emerge, the underlying assumptions of the model may change.

Recommendations

Based on its review of infrastructure issues, the committee makes the following recommendations.

Recommendation. The infrastructure study should be continued. There should be a concerted effort to evaluate the GREET model relative to models developed for similar purposes by the oil industry and other government agencies.

Recommendation. The GREET model should be used with specific engine and fuel configurations in various downselect scenarios.

TECHNOLOGY DOWNSELECT PROCESS

The PNGV program was launched in September 1993, with the first major milestone scheduled for the end of 1997. The program plan was for the PNGV to select technologies for the concept vehicles that will be designed, developed, and fabricated by the year 2000. In its second report, the committee stated that technical challenges were "daunting" and "inventions and breakthroughs" would be needed before certain technologies could be considered as viable options for selection in 1997. The committee also recognized the difficulty in anticipating inventions and breakthroughs and concluded that it would not be appropriate to try to classify technologies as "winners or losers" prior to 1997. The process of identifying the technologies that are considered to be viable options in 1997 has been referred to as the downselect process. Conceptually, the 1997 downselect process occurs after a three-year period of intense investigation of candidate technologies with potential winners emerging within the PNGV time frame. However, many factors enter into the determination of a potential winner, including the fact that individual technologies do not stand alone; each technology must interact with the rest of the system. Among the more obvious winning factors are the contributions towards meeting the fuel-efficiency, emissions, and consumer-cost goals. However, other factors needed to meet Goal 3 vehicle requirements, such as packaging, weight contributions, and interactions with other components, have become more important as systems studies have finally begun to influence subsystem and component designs. In support of the downselect process, the PNGV should assure that its Technical Roadmap is current in all respects. Another major factor now being more seriously considered is market readiness.

When all factors are considered, the result is that there will likely be no clear winners in all areas of importance. Indeed, the most important downselect conclusion that can be made at this time is that there are some promising technologies that simply cannot be ready for consideration in 1997. Thus, some of the technologies that still promise some very desirable characteristics must be considered as beneficial even though their development schedule stretches beyond 1997.[2] Another important observation is that the combination of technologies that can meet the 1997 downselect time frame are likely to fall significantly short of Goal 3 fuel efficiency and cost targets unless substantial advances are made in the very near future. Even though the downselect will not occur in quite the fashion that it was initially envisioned, it will accomplish most of the original program objectives. Technologies have been successfully analyzed to determine, in much more detail than was previously possible, specific advances needed to meet PNGV goals, and important strides have been made towards these advances. This has resulted in a steady decrease in the number of "inventions" needed; however, in some cases, estimates of development time and effort needed to become viable concept- and production-vehicle candidate technologies have been increased. Thus, it is likely that the more nonconventional technologies, such as fuel cells, gas turbines, Stirling engines, flywheels, and ultracapacitors, will require development beyond the current program time frame. The 1997 downselect will probably encompass mostly substantially improved and advanced versions of internal-combustion engine and drivetrain technologies, vehicle structure, and manufacturing technologies.

Although the visible focus of the PNGV has been and will continue to be on Goal 3, specifically a car with fuel economy of up to 80 miles per gallon, other important aspects of the program should be recognized. Clearly, the most positive results of the program achieved under the PNGV umbrella should be retained and nurtured. These positive results include both institutional and technological advances with the potential for yielding long-term benefits for American industry and for the public at large.

POST-DOWNSELECT ISSUES

Numerous and often impressive technological advances have been made in the areas of potential vehicle hardware (Goal 3) and potential improvements in manufacturing capabilities and national competitiveness (Goals 1 and 2). For example, with the exception of a very small group of people, very few of whom are in the automotive industry, the practical application of fuel-cell technology was virtually unknown when the PNGV began. Furthermore, some of the characteristics

[2]For decisions on allocating resources, the candidate technologies might be categorized as (1) power plants that would meet technological goals at the end of 1997 with expectation that they would be used in a concept vehicle in year 2000; (2) power plants that will not reach concept engine status by the end of 1997 but are far enough along to recommend continued development; and (3) power plants with characteristics sufficiently attractive that a strong basic R&D program should be continued.

of fuel cells, such as power density and projected costs, were far from PNGV requirements. However, recent advances in materials and stack technology have demonstrated high efficiency and emission advantages of fuel cells that might make them a more realistic longer-term option for automotive applications, but not in a time frame compatible with Goal 3.

The PNGV has helped to focus automotive fuel cell development. This technology is in the category that has longer-term potential national benefits, making continued R&D clearly desirable. A similar statement can be made about gas turbines, partly as a result of progress towards achieving practical ceramic turbines and recuperators, oil-less bearings, and automotive-type electronic controls. Similar advances have been made in other technologies that might not make the Goal 3 time frame but that have demonstrated significant long-term potential benefits. These technologies include flywheels, ultracapacitors, and some of the advanced lithium batteries. Continuing the development of longer-term technologies also provides an insurance strategy in case the nearer-term technologies encounter significant development barriers or future societal needs change. Thus, it is clearly in the best interest of the nation to continue the R&D on many of the PNGV technologies that are longer term than the 1997 schedule. They have higher risk of failure, and development probably would not be continued without substantial government support.

The institutional innovations and resulting technical organizations have advanced dramatically through the PNGV and appear to be extremely beneficial to the goals of the PNGV. The committee has observed a rapid increase in the number of technical teams, which involve a mix of OEMs, suppliers, government agencies, national laboratories, and universities. The result is an increase in the number of accomplishments. Many, if not most, of the technical issues being probed by these technical teams are high-risk areas that probably would not have been undertaken by a single OEM or supplier and that would have been very difficult to address in a national laboratory or other isolated environment. The formation of these technical teams has, therefore, made the best use of combined national laboratory, government agency, private industry, and, to a limited extent, university resources to help advance technologies, materials, and processes. These advances will not only make the American automotive industry more competitive, they will also be available for many other industries.

It is the committee’s view that many previously existing, but isolated, technology research programs have become much more focused and productive by uniting researchers and users and developing clear technology goals. This has resulted in rapid advances in potentially valuable new technologies and a more efficient use of public and private resources, which should be continued. In an effort to meet weight and cost goals, materials and manufacturing technical teams have been formed and are apparently making impressive strides in support of goals 1, 2, and 3. These efforts should also be continued.

Summary

The concept that a single downselect process can occur in 1997 to eliminate all but the winning technologies no longer appears to be tenable. The initial technology selections and decisions in the downselect process (especially by the government) on where to focus resources must be made on the basis of readiness in addition to performance and the likelihood of achieving program objectives (as they currently exist or are modified). However, impressive advances have been made in several of the technologies that may not make the initial downselect date but that appear to promise important benefits. Pursuing the more promising of these longer-term technologies through an extended period appears to be consistent with the original intent and goals (especially Goal 3) of a longer-term (initially defined as 10 years) PNGV program. Continuing to update systems studies on these technologies will provide a foundation for their continuing development.

Recommendations

Based on its review of the technology downselect process, the committee makes the following recommendations.

Recommendation. The PNGV should continue to update systems studies and projections for longer-term technologies as new information becomes available to categorize their potential benefits more accurately.

Recommendation. The PNGV should continue R&D on technologies that appear to have the potential for making important contributions towards meeting PNGV goals, even if they are beyond the 1997 downselect time frame. This recommendation is consistent with the committee's previous recommendations.

Recommendation. The PNGV should continue to form cooperative R&D interinstitutional technology teams.

LEVERAGE OF FOREIGN TECHNOLOGY DEVELOPMENTS[3]

In its first and second reports, the committee recommended that, as a matter of urgency, the PNGV should conduct more comprehensive assessments and benchmark foreign technology developments relevant to the program (NRC, 1994; 1996). In the response to this recommendation, the PNGV Operational Steering Group indicated that this effort is already under way (Appendix D). They responded, "Each of the members of USCAR and several government agencies

[3]It was not the committee's task to analyze foreign technology developments. However, the committee summarized some foreign activities in Chapter 4, and comments on PNGV activities are included in this section.

routinely evaluate worldwide automotive technology developments." However, only limited evidence of this type of activity was presented to the committee.

Indeed, beyond anecdotal statements, no technology and competitiveness issue perceived by the committee to be important has received less apparent attention than evaluating, utilizing, and leveraging foreign technologies. The key word is "apparent." Not only do all of the OEMs, and many suppliers, have foreign operations and partners, but clearly it is in their best interests to monitor competitive foreign activities in relevant technologies. However, little information was presented to the committee to indicate that PNGV was receiving any substantial benefit from foreign technology developments. The TASC overview presentation to the committee at its November 1996 committee meeting was very superficial. Apparently, this was because of minimal funding (six man-months) (Hardy, 1996). The information presented was no more than information available in the automotive press or at international automobile shows.

One area of foreign technology development is well known and will probably influence downselect decisions. This is the development of direct-injection internal-combustion piston engines. The CIDI engine, in particular, is receiving a lot of attention because of significant improvements in fuel economy as compared to the multiport fuel-injection (MPFI) spark-ignited engine. It is projected that use of CIDI engines will increase from 5 percent of all European automotive engines to about 25 percent by the year 2000 (Herzog, 1996). This is not surprising considering the high cost of fuel in Europe, the lower fuel tax for diesel oil in some countries, and the significant increase in fuel economy afforded by this engine. In addition, the major European automobile makers are either already producing the CIDI diesel engine or plan to do so in the very near future. However, the fuel-system costs of the CIDI are about three times those of MPFI gasoline systems, and overall engine costs are about 40 percent higher (Herzog, 1996). Furthermore, even though the advanced engines can meet current European and American standards, technologies have not yet been developed that can simultaneously meet both particulate and NO_x emission requirements for Euro IV or California ULEV standards. Because of intense efforts to develop the CIDI engine in Europe, it is likely that the emission problems will be resolved, at least to the extent of meeting Euro IV requirements.

In parallel with CIDI diesel engine developments, significant activity is being directed towards direct-injected, spark-ignited (DISI) gasoline engines, particularly in Japan. During its second PNGV review, the committee was advised by USCAR that "current and past efforts aimed at direct-injection (stratified charge) spark-ignition engines have demonstrated significant increases in thermal efficiency over homogeneous-charge counterparts; however, they will likely fall short of this target. Severe emissions and durability challenges have hampered implementation of this approach." (See Appendix E of the committee's second report [NRC, 1996]). The USCAR position was maintained in the current review.

As noted in Chapter 4, automotive fuel cells are also receiving considerable attention worldwide, but they clearly represent a much longer-term technology option. Ballard, a Canadian company, and Daimler-Benz are working on the development of fuel cell vehicles, but most of their efforts have been directed towards hydrogen-fueled systems, and hydrogen still faces major obstacles to becoming an accepted automotive fuel.

Many of the major automotive manufacturers in Europe and Japan have ongoing programs for fuel-cell vehicles that included demonstration vehicles. However, most use pressurized hydrogen, thus limiting both range (about 100 miles) and general acceptability. A major obstacle for foreign (as well as American) automotive fuel-cell-powered vehicles is the availability of an acceptable fuel-processing system that would permit the use of hydrocarbon fuels such as gasoline while retaining the major virtues of a hydrogen-fueled vehicle.

Other vehicle technology programs worldwide have been initiated or expanded, especially in Europe, apparently in reaction to the existence to the PNGV program. The concern seems to be more about market competitiveness with the United States than about increasing fuel efficiency. There are several European "camps" of technological approaches that include electric and hybrid vehicles as well as those advancing more conventional technologies. Volvo, for example, has pursued gas turbine hybrids, especially for larger cars.[4] BMW and Daimler-Benz are pursuing longer-term developments with the fuel cell. And others, such as Fiat, Renault, and Volkswagen are pursuing advances in more near-term technologies such as the CIDI engine and continuously variable transmissions.

The Japanese are (1) making significant advances in batteries, especially lithium batteries; (2) continuing to be active in the development of fuel cells; and (3) developing several hybrid vehicle concepts. According to TASC, there has been no appreciable effect in Japan due to the PNGV (Hardy, 1996). In fact, TASC reported a drop-off in the level of advanced-vehicle development in the last year or so.[5]

Summary

There is evidence of foreign technology development in essentially the same areas as in the United States, but there is no specific evidence of major

[4]The committee believes it is likely there are major proprietary gas turbine and related ceramics programs in Japan, but little information was presented.

[5]The committee did not conduct an analysis of efforts in Japan. However, it was recently reported in *Automotive News* that Toyota's president stated: "We haven't been able to determine which is better—trying to improve the current internal-combustion engine or developing alternative engines. So we're devoting efforts equally on both sides. Research spending used to be equal to 4 percent to 5 percent of sales, but recently it has been approaching 6 percent. That is related to our research efforts on alternative vehicles" (Treece, 1996). According to *Automotive News*, Toyota "devoting an additional 1 percent of sales to research on alternative engines would amount to $800 million" annually.

breakthroughs that could significantly affect the PNGV. There is evidence, however, of considerable effort and continuing advances in the European CIDI programs. There is also evidence that the Japanese have made major strides in advanced battery development (especially lithium batteries) and commercialization (especially lithium-ion batteries for consumer applications, such as laptop computers, video cameras, and cellular phones). These significant advances could affect the development of a hybrid vehicle.

Recommendations

Based on its review of foreign technology developments, the committee makes the following recommendations.

Recommendation. The committee again recommends that the PNGV should conduct and routinely update comprehensive assessments of foreign technology. These assessments should be used to determine which, if any, of the PNGV technologies of interest could benefit from more knowledge. In each important technology area, significant progress or significant barriers to development should be identified. The assessments and their evaluation should then be used to consider redirecting PNGV efforts, if appropriate. USCAR members and government agencies may already be doing this, but it is not clear to the committee that this information is being used in any meaningful way to benefit PNGV or that it is even accessible to the individual technology developers who might need it.

Recommendation. Because the CIDI engine is a potential major technology in the PNGV, a special effort should be made to determine to what extent European and Japanese developments are available to members of the USCAR.

MAJOR TECHNICAL ACHIEVEMENTS AND BARRIERS

A number of significant achievements were realized by the PNGV in 1996. According to a presentation to the committee by PNGV, the most important technical accomplishments in 1996 include the following (Viergutz, 1996):

- demonstration of a prototype fuel-flexible processor for a fuel cell with an 80 percent efficiency for the processor
- demonstration of a subscale high-power lithium-ion battery cell for 100,000 cycles
- scale-up of a lean NO_x catalyst demonstrating 30 percent NO_x reduction
- fabrication of ceramic gas turbine scrolls and rotors through a process with high volume potential
- survival of a glass-fiber-reinforced composite front-end structure design in a 35 mph barrier crash test
- development and construction of advanced technology demonstration

TABLE 6-1 Potential of PNGV Candidate Technologies and Assessment of Research Progress

Major Subsystems	Critical Technical Barriers	Likelihood of Meeting Technical Objectives[a]	Likelihood of Meeting Cost[b]	Likelihood of Meeting Schedule[c]	Overall Potential Regardless of Schedule[d]	Basic Needs	Overall Progress Since Last Review
Hybrid Drivetrain Power Sources							
CIDI	Combustion control NO_x catalyst	High	Medium	High	High	Resources	Modest
Fuel cell	Fuel processor/ reformer	Low	Low	Low	Medium	Breakthroughs	Modest to Good
Turbine	Structural ceramics Exhaust heat recovery	Low	Low	Low	Medium	Resources, focused R&D	Modest
Stirling	Heat Exchangers Leakage Control	Medium	Low	Low	Medium	Resources, focused R&D	Small
Energy Storage							
Lithium-ion battery	Scale-up System safety	High	Medium	Medium	Medium	Resources, focused R&D	Good
Nickel metal hydride battery	Efficiency Power density	Medium	Medium	Medium	Medium	Resources, focused R&D	Modest
Ultracapacitor	Efficiency Self-discharge Safety	Low	Low	Low	Low	Breakthroughs, resources	Small
Flywheel	Safety	Medium	Medium	Low	High	Resources, focused R&D	Small
Power electronics	Efficiency	Medium	Medium	High	High	Resources	Small

Note: This table represents a general committee judgment at an aggregate level of detail. The critical technical barriers are those that appear to be most challenging today and in many instances appear to require technical breakthroughs. See Chapter 4 for a more complete description of the key developments needed.

[a]Regardless of cost or schedule.
[b]Assuming the technical goals can be met.
[c]In achieving the technical goals.
[d]Overall potential over the long term of meeting the technical goals and cost.

vehicles, some of which incorporated PNGV related requirements, such as Ford's Synergy 2010, Chrysler's ESX, and General Motors EV-1

Despite significant progress in a number of critical areas, there is still a gulf between the current status of system, subsystem, and component developments and the performance and cost requirements necessary to meet major PNGV milestones.[6] Some of the technical barriers to achieving PNGV objectives can probably be overcome with sufficient funding and management attention; others require inventions and very significant technical breakthroughs. As reported in the committee's second report (NRC, 1996), the effort being expended on candidate technologies and systems is not consistent with the likelihood that they will meet performance goals within the program schedule. Funding for some critical systems is inadequate, and the work lacks integrated technical direction.

The assessment of technical barriers to the development of major candidate PNGV subsystems presented in this report was used as a basis for constructing Table 6-1. In the committee's view, this table provides an approximate assessment of the broad potential for candidate PNGV elements and a gross indication of progress in the past year. The committee made a distinction between systems for which technical breakthroughs are needed to meet PNGV targets and those for which incremental development with adequate resources (funding and staff) is likely to lead to the required achievement. For each major subsystem, the committee identified critical barriers to meeting PNGV performance and cost requirements, as well as the likelihood of meeting PNGV schedules. These three factors were used to derive a first approximation of the overall PNGV potential regardless of the PNGV schedule and to highlight program priorities.

At the committee's meeting in November 1996, PNGV provided a list of major barriers to success. The PNGV needs to overcome these barriers, which are delineated in Table 6-2.

A number of technical, production cost, funding, schedule, and other issues need to be resolved. Based on the data provided, the committee believes that the following conclusions can be drawn:

- When incorporated into a vehicle, none of the energy converters will come close to meeting the cost objectives within the time frame of the PNGV program.
- The availability of fuel cells, Stirling engines, and gas turbines that meet the cost and performance requirements of the PNGV program is substantially beyond the current time frame of the program.
- The CIDI engine is the energy converter with the highest potential of meeting the PNGV program performance requirements. This may change

[6]These milestones include technology selection in 1997, design and construction of concept vehicles by 2000, and the availability of production prototypes in 2004.

TABLE 6-2 PNGV's Presentation to Committee on Assessment of Major Barriers and Program Needs

Issue	Challenges and Issues	Recommendations by the PNGV
Technical	• control of particulates and NO_x from CIDI engines • compact fuel-flexible fuel processor for PEM fuel cells • flywheel safety • thermal management of lithium battery systems • high yield fabrication of complex ceramic componentry	Funding is required to support a sufficient level of effort for addressing the engineering research challenges.
Production cost	• low-cost lamination material and processing for electric motor rotors and stators • low-cost aluminum sheet, carbon fiber for structral applications and magnesium • low-cost power electronic building blocks and liquid coolants • low-cost high yield ceramic fabrication methods • low-cost high-pressure fuel injector and pump • low-cost electronic materials and fabrication processes for batteries and fuel cells • low-cost flywheel containment	Appropriate levels of effort required for technical cost challenges.
Funding	• cost-share requirements of high-risk DOE programs • inability to mobilize supplier resources • long lead-time from identification of R&D need to contract initiation • adminstrative complexity of government programs • difficulty in redirecting/influencing existing government programs • non-strategic distribution of resources	Policy change and active implementation needed by upper levels of government and industry management.

Schedule	• probability of meeting all performance and cost targets by 2004 is declining due to continued inadequate resource commitment • technology selection date broadened to pre-1997 and post-1997 data-driven events	There should be an emphasis on schedule of technology development at component level with later demonstraton at vehicle level.
	• recognition that concept vehicles pre-2000 and post-2000, with focus for 2000 on fuel economy benchmark demonstration • recognition that initial hybrid vehicle concept vehicles and design were introduced in 1996, for pre-1997, focus should be on: (a) lithium and NiMH battery systems (b) PEM gasoline-fueled fuel cell systems (c) double-layer capacitors would be eliminated For 1997, make decision on viability of current ceramic gas turbine designs. For 1998: (a) decide on viability of high-volume fabrication of ceramic components (b) decide on whether to proceed with next generation of ceramic gas turbine (c) decide on safety potential of lithium-ion battery system (d) resolve flywheel safety issue (e) assess CIDI emissions based on operating hardware	Adequate funding levels are required to meet engineering research challenges.
Other	• potential change in emissions regulations • potential requirement for zero emission vehicle range	Funding issues and regulatory environment need to be resolved.

Source: Viergutz (1996).

if EPA promulgates more stringent exhaust emissions standards for diesel engines.

- Flywheels appear to have potential for energy storage once the safety issues have been resolved. Their successful development is well beyond the time frame of the program.
- The successful development of ultracapacitors as storage devices is well beyond the time frame of the PNGV program.

The committee is not suggesting that the development of the technologies listed above should be terminated. However, PNGV should reprogram development efforts and funding to be consistent with expected results within the current PNGV schedule through 2004. Investments in technology developments that may be successful beyond that schedule may be continued but should be more highly focused on solving specific problems.

ADEQUACY AND BALANCE OF THE PNGV PROGRAM

Because of a lack of specific data the committee requested from the PNGV, an evaluation of the adequacy and balance of this complex technology development was difficult. Evaluating the PNGV requires a specific understanding and knowledge of three major elements: (1) the selection of technologies to be developed to satisfy a set of delineated goals and objectives, (2) a detailed schedule of activities and needed accomplishments, and (3) the required resources and funding to accomplish the tasks in a timely manner. A measure of progress generally encompasses comparing accomplishment of individual tasks directed towards the goals and objectives with the resources expended. Complex technology programs involving and requiring technical breakthroughs and inventions are the most difficult to schedule, manage, and evaluate.

The committee feels that the technologies selected for development are appropriate and that no major technology has been overlooked or omitted. The PNGV Technical Roadmap provides major technical objectives against a macro schedule within a specific time frame. The committee had great difficulty considering resources and funding, the third major element in an evaluation of adequacy and balance of the program. In general, PNGV presenters frequently stated that inadequate (and at times zero) resources were available to achieve program objectives. However, in the majority of cases the PNGV was unable when requested to inform the committee of current spending or to estimate underfunding. The committee has repeatedly requested this funding and resource information from the PNGV only to be informed that it is being compiled. As of the completion of this report, this information had still not been provided.

The committee found it extremely difficult to evaluate the adequacy and balance of funding to accomplish the PNGV Goal 3 objectives. The ultimate proof, of course, will be in the 2000 concept demonstration vehicles and the 2004 prototypes, but no clear criteria exist as to what should be expected at the end of the third year of PNGV. An evaluation is further obscured by several factors. The overall funding required to meet Goal 3 has not been presented to the committee and has not been defined. Detailed program and technology plans have been generated by USCAR for some candidate components, but none of the component plans identified specific resource and funding requirements. Consequently, there is no funding plan against which the PNGV program can be evaluated.

The first three to four years of the PNGV provide time for technology development and risk reduction, leading to selection in 1997 of technologies with performance and risk levels consistent with concept vehicle demonstration in 2000. Most new and sophisticated power plant and materials technologies, such as those required by a vehicle with up to tripled fuel economy, generally require more than three or four years to develop. Consequently, it is necessary for the PNGV to use technologies that were developed before the PNGV was established. Most of the candidate technologies were under development and partly funded by the government prior to the PNGV (i.e., fuel cells, gas turbines, advanced batteries, advanced materials, low-emission combustion, advanced motor/generators, etc.); others were under development by the international automobile industry (e.g., CIDI). As technologies show promise toward contributing to the accomplishment of PNGV Goal 3, it is reasonable to expect that the PNGV will accelerate or modify their development to meet unique requirements or to reduce risks.

The government has identified approximately $300 million for efforts that are "PNGV-related." These efforts were primarily directed toward energy conservation, materials, and research programs that had been planned and funded before the PNGV was initiated and were authorized for a variety of reasons under the mission statements of eight different U.S. government departments and agencies. Although "PNGV-related" funding deals with technologies being considered to meet PNGV goals, much of the funding is focused on technologies and time frames that do not coincide with the specific goals of the PNGV. Instead, funding is being directed to nearer-term or farther-term technologies or to technologies that address national needs other than the need to reduce light-duty vehicle fuel consumption.

The committee was informed that some redirection of ongoing government R&D programs to meet PNGV requirements has taken place; however, numerous observers stated that no new money has been appropriated specifically for the PNGV in government budgets, and no line item has been established in the budget. USCAR stated at the committee's November meeting that they would like to see government funds available to PNGV-related technology doubled. The USCAR partners' company budgets attributable to the PNGV are vague and similarly subject to interpretation. The USCAR primarily reports their expenditures on jointly funded projects and committed cost-sharing against government programs.

Many ongoing programs are described under the PNGV initiative and, although some new technology programs can be identified and a very substantial effort is being expended on PNGV technical management and system studies, it is not clear how much of the new funding has been motivated by improving vehicle fuel efficiency. Also, industries conduct independent technology programs that can contribute to meeting PNGV Goal 3 objectives but are in areas they consider to be proprietary. Because car companies generally do not report the accomplishments on these independent proprietary programs, their funding and impact cannot be assessed by the committee. Thus, the PNGV operates under two serious constraints: (1) insufficient access to data already known to USCAR principals regarding advanced technology, and (2) the nonexistence of a sufficient R&D database to guide reliable choices for the future.

Summary

Even if it is concluded that the formation of the PNGV has not resulted in major and appropriate increases in funding and a rapid acceleration in improved fuel-efficiency-related R&D, the committee believes the PNGV has provided major benefits in focusing government and industry on a common objective. USCAR personnel have conducted joint evaluations of the candidate technologies and placed themselves in a position to make informed decisions on which technologies to include in their concept vehicles. Government personnel—both laboratory researchers and project managers—have become more familiar with the real-world requirements of the automotive industry and, in many cases, have adjusted their programs to be more practical. The automotive industry, suppliers, government personnel, and academia have become more aware of the need for greater fuel efficiency in light vehicles, and everyone is committed to working toward the 10-year PNGV program objectives.

Because applied resources have not increased significantly and the rate of development for relevant technologies has not increased sufficiently, a number of candidate technologies will not be able to meet the PNGV time schedule with acceptable risk. In the opinion of the committee, these are likely to include gas turbines, Stirling engines, fuel cells, some battery candidates, and flywheels. However, with appropriate focus and resources, the CIDI hybrid configuration, in combination with lightweight structures and loss reduction technologies, might come close to meeting the PNGV program goals and schedule.

Has the balance of funding been appropriate? The committee believes that some useful redirection has been experienced in government programs, considering the constraints on rapid change to government-funded programs and the multiple constituencies and needs that these programs address. In many cases, major changes were precluded by the congressional appropriation language and/or government contracting commitments. The USCAR partners have decided to conduct independent vehicle demonstrations of the concept vehicles. The development and construction of demonstration vehicles is a normal OEM activity; each OEM is experienced in conducting complex programs in a disciplined fashion against a fixed schedule. To meet the schedule for 2000 with credible concept demonstration vehicles will require greatly increased efforts in 1997. Each company needs to select demonstration technologies and initiate development and risk-reduction efforts on the advanced components in the specific configurations and envelopes of each selected vehicle design. Assignment of project personnel, increased technical leadership, increased management attention, and increased funding will all be required. Decisions on these matters are expected to be made as part of the 1997 downselect process. In this regard, the committee has been particularly concerned that not enough system studies have been conducted. Currently, the committee is not aware of what PNGV would consider acceptable levels of performance for concept demonstration vehicles.

The appropriate role of the government during the demonstration phase needs to be considered and defined. Government's role is normally expected to apply to longer-term objectives. There is no definable funding line in the Fiscal Year 1997 budget specifically to support PNGV R&D and no guarantee of funding in subsequent years. Thus, it is not clear to the committee at what level PNGV-related technology efforts being supported by the government will be continued in parallel with the industry's concept-vehicle demonstrations to provide a basis for future advancements in PNGV vehicle technology on a continuing basis, at least through the year 2004. It is the committee's view that relevant technology development specifically devoted to reducing risks identified in the PNGV demonstration configurations merit meaningful federal support, that is, support consistent with program needs and objectives.

However, PNGV is experiencing severe funding and resource allocation problems that must be resolved immediately to achieve Goal 3 objectives and to keep the program on schedule. The committee requested that PNGV provide the priorities and required resource and funding levels. In the absence of an acceptable, sustained resolution of the PNGV-wide funding and resource problem, the committee recommends that PNGV's objectives be restructured to reflect more realistic performance, cost, and schedule objectives. In addition to the lack of sufficient funds for most of the PNGV program elements, there are also some serious technical hurdles that, even with adequate funding, may prevent the successful development and commercialization of the proposed systems within the PNGV time frame. Remaining technical hurdles are shown in Table 6-2.

Recommendations

Based on its review of the adequacy and balance of the PNGV program, the committee makes the following recommendations.

Recommendation. The PNGV partners (USCAR and the federal government) should immediately develop a schedule of resource and funding requirements for each major technical task. This schedule should show the current level of resources and funding applied to each major technical task and current shortfalls.

Upon completion of this schedule, the PNGV partners should provide a strategy to redirect R&D and to obtain the necessary resources and funding.

Recommendation. In the event that PNGV (industry and government) does not obtain and/or chooses not to increase the resource levels and thereby accelerate the pace of development, the PNGV partners should reconsider the viability of current PNGV program objectives with regard to performance, schedule, and cost.

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7

PNGV Response to the Phase 2 Report

After the previous reviews by the NRC Standing Committee to Review the Research Program of the PNGV, the committee made a number of recommendations (see Appendix C). The committee's first report, issued in the fall of 1994, was a broad overview in coverage and perspective (NRC, 1994). The committee offered a number of additional recommendations for the PNGV's consideration in its second report, issued in March 1996, following the phase 2 review of the PNGV research program (NRC, 1996). Some of the recommendations in the first report were reiterated in the committee's second report. The committee considered the broad priorities and underlying concepts of the program goals to be reasonable and credible but noted that for the program goals to be met or closely approached, well-managed, adequate resources had to be devoted to the program in a timely manner.

In addition to specific technology evaluations and recommendations, the committee offered the following six major recommendations in the previous reports:

- Make program management and technical leadership of both government and industry activities more effective.
- Initiate and accelerate a comprehensive systems analysis program.
- Obtain and re-allocate federal and industry funding to activities consistent with promising technological potential within the time horizon and needs of the program.
- Conduct comprehensive assessments and benchmark foreign technology developments relevant to the PNGV.
- Continue to address infrastructure issues as an integral part of the program.

TABLE 7-1 Potential of PNGV Candidate Technologies in the Committee's Second Report

Major Subsystems	Critical Technical Barriers	Cost[a]	Likelihood of Meeting Schedule[a]	Overall Potential Regardless of Schedule[b]	Basic Needs
Hybrid Drivetrain Power Sources					
CIDI	NO_x catalyst	Low	High	High	Resources
Fuel cell	Fuel processor/ reformer Fuel storage	High	Low	Medium	Breakthroughs
Turbine	Structural ceramics Exhaust heat recovery	High	Low	Medium	Breakthroughs
Energy Storage					
Battery	High cycle life	Medium	Medium	Medium	Resources, focused R&D
Ultracapacitor	Efficiency Self-discharge Safety	Medium	Medium	Medium	Breakthroughs, resources
Battery/ ultracapacitor	Integration Safety	Medium	Medium	High	Breakthroughs, resources
Flywheel	Safety	High	Medium	Medium	Resources, focused R&D
Power electronics	Efficiency	High	High	High	Resources
Lightweight Structural Materials					
Composite	High-volume manufacture Crashworthiness	High	Low	Medium	Resources, focused R&D
Aluminum	High-volume manufacture Joining	Medium	High	High	Focused R&D
Steel	Weight	Low	Medium	Medium	Focused R&D

[a] High cost is a barrier, as is low likelihood of meeting the PNGV schedule.
[b] Long-term potential beyond 2004.

Source: Table H-1 in NRC (1996).

- Involve other U.S. government agencies, such as the U.S. Department of Transportation (DOT), the National Aeronautics and Space Administration (NASA), the DOD, and the EPA, more fully.

It should be noted that recommendations 1 through 5 were made in the first report (NRC, 1994). The committee feels that insufficient attention or progress has been made in ameliorating these deficiencies since the 1994 review. The continued lack of progress or specific attention, especially to recommendations 1 through 3, may ultimately jeopardize meeting the PNGV program goals.

The PNGV responded to the committee's recommendations in a letter from its Operational Steering Group, dated June 18, 1996. The committee also received a letter response from the DOT on March 25, 1996, stating that it concurred with the report's recommendations. These letters are included in Appendix D.

The committee discussed the response letters with the PNGV at its September 1996 meeting in Dearborn, Michigan, and assessed the PNGV's actions to implement the committee's recommendations. The committee considered the PNGV responses in its June 18, 1996, letter (Appendix C) to be specific, well articulated, and understandable within the context of a complex joint industry–government program, with one exception—the USCAR position on organization and management. USCAR rejected the committee's recommendations on organization and management in the first and second reports. Because the committee had addressed this issue in the two previous reports, it did not address it in the current reviews. The timely achievement of technical progress and the effective use of critical resources within the PNGV program will serve as a measure of the effectiveness of the USCAR's organization and management structure.

The committee was also concerned that the PNGV response did not specifically address the committee's concerns about structural materials and powertrain developments. (See Chapter 5, "Structural Materials," and Chapter 6, "Powertrain Developments," in NRC, 1996). The committee was also concerned about the lack of response regarding evaluations of the potential for various technologies to meet the PNGV performance, cost, and schedule objectives as summarized in Table H-1 of the committee's second report, and included in this report as Table 7-1 (NRC, 1996). The committee recognizes that the program is only in its fourth year; however, a realistic evaluation of the potential of each technology should provide a guide for a more appropriate allocation of resources, as recommended by the committee. This issue is particularly important in light of the PNGV's extremely difficult objectives, tight time frame, and limited financial resources.

In the first report the committee recommended that the PNGV "make an analysis and divide all technologies related to Goal 3 into two categories: current PNGV and post-PNGV technologies" and identified the need to address infrastructure issues as "an integral part of the PNGV program systems analysis" (NRC, 1994). These recommendations continue to be favorably viewed by the program managers. The committee believes that the program would benefit significantly if (1) the major technologies the PNGV is pursuing were critically examined in light of current PNGV and post-PNGV technologies, and (2) the infrastructure issues were directly addressed as an integral part of the PNGV's technology trade-off studies and its decision-making process for 1997 technology selection. The PNGV has stated that the infrastructure implications "are not part of the PNGV charter. However, the federal government, through other programs, continues to analyze infrastructure issues and is trying to assure that these efforts align with PNGV progress." The committee fully accepts this position and is impressed with the initial results of the analysis; however, it is important that the petroleum industry be involved in PNGV fuel-related activities (see Chapter 6).

In keeping with recommendation 6 from the second report, it is the committee's view that the DOD, DOT, NASA, and EPA still need to be more supportive and integrated into the PNGV research program. The relevance of certain ongoing R&D programs funded by these agencies to the PNGV technical objectives supports this view. The June 1996 PNGV response indicated satisfaction with the level of interagency participation to the extent that budgets permitted such cooperation. Although the committee understands this response, the level of support in terms of resources and funding is minimal in many areas. The DOT letter (Appendix C) addressed the committee's recommendation that "the PNGV should immediately involve the DOT's National Highway Traffic Safety Administration in identifying, addressing, and resolving the safety issues raised by Goal 3 vehicles." The March 1996 DOT letter stated that "funding was requested to develop advanced computer models and to obtain the computing capacity necessary to evaluate the crashworthiness characteristics of alternate vehicle designs and new lightweight materials, such as advanced composites proposed for use in the PNGV program." The letter further stated that "despite a strong effort on the part of the Department to secure funding for these initiatives in fiscal year 1996, Congress specifically denied this request on the basis that it was premature at this stage in the PNGV effort." The committee does not accept the position that such studies are premature at this stage because the crashworthiness of a vehicle depends on its structural design and materials. Also the weight of the vehicle will vary, depending on the design and the materials, and this is strongly related to fuel economy.

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APPENDICES

APPENDIX A

Biographical Sketches

STANDING COMMITTEE TO REVIEW THE RESEARCH PROGRAM OF THE PARTNERSHIP FOR A NEW GENERATION OF VEHICLES (PHASE 3)

Trevor O. Jones, *chair,* (NAE) is chairman of the board of Echlin, Incorporated, a major supplier of automotive after-market parts; chairman and chief executive officer of International Development Corporation, a private management consulting company; and chairman, president and CEO (retired) of Libbey-Owens-Ford Co., 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 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 member of the National Research Council's (NRC's) Commission on Engineering and Technical Systems. Mr. Jones has served on NRC study committees, including the Committee for a

Strategic Transportation Research Study on Highway Safety, and chairs the NAE Steering Committee on the Impact of Products Liability Law on Innovation. He holds an HNC in electrical engineering from Aston Technical College and an ONC in mechanical engineering from Liverpool Technical College.

R. Gary Diaz is former senior vice president of manufacturing and engineering for Case Corporation, with responsibility for providing general management and directing the leadership of global product development and production for an agricultural and construction equipment company. He previously held a number of positions with General Dynamics Land Systems, including division vice president and general manager, Development and Integration Business Unit; vice president, Research Engineering and Logistics; director, Engineering Programs; and engineering manager, Advanced Ground Vehicle Technology. Mr. Diaz participated extensively in the development of the M1A2 Abrams tank; notably, the technology base for system sensors, electronics, communications, and software. He also managed product development and engineering for the advanced amphibious assault vehicle and the heavy assault bridge. Mr. Diaz received his B.S. in mechanical engineering and his M.S. in engineering from the University of Florida.

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 interest include thermodynamics, fluid mechanics, internal combustion engines, combustion kinetics, and emissions formation. He is recipient of the Ralph R. Teetor Award and the Forest R. McFarland Award of the Society of Automotive Engineers. Professor Foster is active in a number of committees of the Society of Automotive Engineers. He has conducted research in a broad array of areas related to internal combustion engines. He has a Ph.D. in mechanical engineering from the Massachusetts Institute of Technology.

David F. Hagen is director and president of the Michigan Center for High Technology in Detroit. He spent 35 years with Ford Motor Company, where his most recent 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 4-cylinder, V6, and V8 engines. Mr. Hagen received his B.S. and M.S. in mechanical engineering from the University of Michigan. He serves on the boards of the Engineering

Society of Detroit and the School of Management, University of Michigan-Dearborn, and on the Engineering Advisory Boards of both Western Michigan University and the University of Michigan-Dearborn.

Simone Hochgreb is an associate professor in the Department of Mechanical Engineering, Massachusetts Institute of Technology. Her research focuses on fundamental and applied problems in combustion and chemical kinetics, with particular focus on applications to transportation, internal-combustion engines, and pollutant emission formation. She has been awarded the Society of Automotive Engineers' Teetor Award, the General Electric Career Development Award, and the Bradley Foundation Career Development Chair. She holds a Ph.D. from the Department of Mechanical and Aerospace Engineering, Princeton University (1991).

Fritz Kalhammer was co-chair of the California Air Resources Board's Battery Technical Advisory Panel on electric vehicle batteries, and is part-time coordinator for the Electric Power Research's (EPRI's) Strategic Development group. He has been vice president for EPRI research and development and established the Institute's research and development programs for energy storage, fuel cells, and electric vehicles; managed the electrochemistry program at Stanford Research Institute (now SRI International); and has worked for Philco Corporation and Hoechst in Germany. He has a Ph.D. in physical chemistry from the University of Munich.

John G. Kassakian (NAE) is professor of electrical engineering and director of Massachusetts Institute of Technology's (MIT's) Laboratory for Electromagnetic and Electronic Systems. His expertise is in the use of electronics for the control and conversion of electric 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 within 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), and the IEEE Centennial Medal (1984). He has an Sc.D. in electrical engineering from MIT.

Harold Hing Chuen Kung is professor of chemical engineering at Northwestern University and director of the Center for Catalysis and Surface Science. His research includes surface chemistry and physics, catalysis, and chemical reaction engineering. His professional experience includes work as a research chemist at E.I. du Pont de Nemours & Co., Inc., and he is the recipient of the P.H. Emmett

Award from the Catalysis Society. He has a Ph.D. in chemistry from Northwestern University.

Craig Marks (NAE) is president, 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. He is a retired vice president of technology and productivity for Allied Signal Automotive with responsibility 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 served as the 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 NAE and a fellow of the Society of Automotive Engineers. Dr. Marks received his BSME, MSME, 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 in 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, and the Olin Palladium Medal. He has a Ph.D. in chemical engineering from the University of California, Berkeley.

Jerome G. Rivard (NAE) is president of Global Technology and Business Development, advising 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 NAE and a fellow of the Institute of Electrical and Electronic Engineering and the Society of Automotive Engineers. He received his BSME 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 nearly 30 years. 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 for both types of engine. Together 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 served as a consultant to the Jet Propulsion Laboratory, monitoring electric and hybrid vehicle programs. Dr. Roan received his B.S. in aeronautical engineering, his M.S. in engineering from the University of Florida, and his Ph.D. in engineering from the University of Illinois. 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.

Supramaniam Srinivasan obtained his B.S. in chemistry from the University of Ceylon and his Ph.D. in physical chemistry from the University of Pennsylvania. He is internationally recognized for his contributions in electrochemistry, electrochemical energy conversion and storage, with emphasis on hydrogen energy technologies and bioelectrochemistry. Dr. Srinivasan established electrochemistry/electrochemical technology laboratories at the State University of New York-Downstate Medical Center, Brookhaven National Laboratory, Los Alamos National Laboratory, Institute for Hydrogen Systems at the University of Toronto, and Texas A&M University. While at Brookhaven National Laboratory, he played a major role in initiating the "Fuel Cells for Transportation Program," sponsored by the U.S. Department of Energy. He has more than 200 publications, including a book, chapters in books, reviews, and journal articles. Dr. Srinivasan has been an invited or keynote speaker at several national and international meetings. In 1996, Dr. Srinivasan received the Energy Technology Division Research Award from the Electrochemical Society. He is currently a visiting professor in chemistry at the Université de Poitiers, France, and is engaged in research on direct methanol fuel cells.

F. Blake Wallace is retired chairman and chief executive officer, Allison Engine Company. He has been involved in engineering and management of high technology gas turbines with United Technologies (Pratt and Whitney), Allied Signal (Garrett), General Electric (Aircraft Engine Group), and Allison. From 1983 to 1993 he rebuilt the Allison Division of General Motors and served as vice president of General Motors Corporation. He has a bachelors degree in mechanical engineering from the California Institute of Technology and a masters and Ph.D. in engineering science from Arizona State University.

APPENDIX B

Committee Meetings and Other Activities

1. **Committee Meeting, September 9–11, 1996, Dearborn, Michigan**
The following presentations were made to the committee:

Orientation of PNGV for New Committee Members
Robert Chapman, Chair, PNGV Government Technical Task Force, DOC
Peter Rosenfeld, Director, USCAR–PNGV

National Research Council (NRC)—Phase 3 PNGV Review Committee Objectives
Trevor Jones, Committee Chair

PNGV Committee Review of PNGV Response to Phase 2 Report
Trevor Jones, Committee Chair

Opening Remarks and Review of PNGV Response to Phase 2 Report
Trevor Jones, Committee Chair
Robert Chapman, U.S. Department of Commerce
William Power, Vice President, Ford

PNGV Program Overview [T.O. Jones, Session Chair]
Robert F. Mull, USCAR–PNGV
Pandit Patil, PNGV, DOE

Energy Conversion Technology Review [Craig Marks, Session Chair]
Compression Ignition Direct Injection Engines, *Al Murray, USCAR–PNGV*
Fuel Cells, *Christine Sloane, USCAR–PNGV*
Gas Turbines, *Christine Sloane, USCAR–PNGV*

Energy Storage Technology Review [S. Srinivasan, Session Chair]
Electrochemical, *Christine Sloane, USCAR–PNGV*
Electromechanical, *Al Murray, USCAR–PNGV*
Other technologies under consideration

Power Electronics/Electrical Systems [Jerry Rivard, Session Chair]
Owen Viergutz, USCAR–PNGV

Enabling Technology Review [Jerry Rivard, Session Chair]
Systems Analysis, *Owen Viergutz, USCAR–PNGV*
Materials, *Al Murray, USCAR–PNGV*
Manufacturing, *Owen Viergutz, USCAR–PNGV*

Vehicle Engineering Review [David Hagen, Session Chair]
Owen Viergutz, USCAR–PNGV

Technology Down-Select Process/Status [T.O. Jones, Session Chair]
Ron York, USCAR–PNGV
Ed Wall, PNGV, DOE

DOE/Industry Hybrid Electric Vehicle Overview: Performance and Cost Projections versus Requirements [T.O. Jones, Session Chair]
Robert Kirk, PNGV, DOE

2. Committee Subgroup Visit on Nonelectrochemical Storage Technologies, University of Texas Center for Electromechanics (UT-CEM), October 7, 1996, Austin, Texas

The following presentations were made to committee members Dave Hagen (subgroup chair), Craig Marks and Jerome Rivard, and NRC staff member James Zucchetto.

Introduction, *Al Murray, Ford*

PNGV Flywheel Technical Team Activities, *Tom Kizer, Chrysler*

Performance and Cost Metrics, *Tom Kizer, Chrysler*

Overview of Flywheel Technology Status, *Dave O'Kain, Oak Ridge National Laboratory (ORNL)*

Ford/Unique Mobility Flywheel, *Mike Tamor, Ford*

Flywheel Development Program and Plan, *Dave O'Kain, ORNL*

UT-CEM Flywheel Development and Safety/Containment Program Overview, *Joe Beno, UT-CEM*

UT-CEM Hybrid Vehicle Flywheel Battery Design and Status, *Richard Hayes, UT-CEM*

Composite Rotor Technology, *Richard Thompson, UT-CEM*

Flywheel Containment Issues and Approaches, *Mark Pichot, UT-CEM*

UT-CEM Burst Test Results, *Richard Thompson, UT-CEM*

UT-CEM Overview and Tour, *Alan Walls, UT-CEM*

3. Committee Subgroup Visit on Electrical Systems and Systems Analysis, Chrysler Technology Center, October 10–11, 1996, Auburn Hills, Michigan

The following presentations were made to committee members Jerome Rivard, R. Gary Diaz, Trevor Jones (October 11), and John Kassakian and NRC staff member Dev Mani.

October 10

Opening Remarks, *Owen Viergutz, Chrysler*

Chrysler Patriot/HEV Program, *Robert Malcolm, Chrysler*

Ford HEV EE Program, *Allan Gale, Ford*

GM HEV EE Program, *Balarama Murty, General Motors*

DOE/ONR, *David Hamilton, DOE*

Motors and Power Electronics, *Allen Gale, Ford*

HVAC and Electric Steering, *Peter Piccinato, Chrysler*

Starting and Charging, *Anson Lee, Ford*

Regenerative Braking, *Linos Jacovides, General Motors*

October 11

Systems Analysis Overview, *M. Salman, General Motors*

Software Demonstration, *Rick Berthiaume, TASC, Inc.*

Models, *Scott Mitchell, SWRI*

Vehicle Requirements and Flowdown of Requirements to Subsystems and Components, *Richard Swiatek, Chrysler*

Testing Plans, *Tom Kenney, Ford*

Trade-off Study, *Tom Kenney, Ford*

Approach and Input to "Downselect" Process, *M. Salman, General Motors*

Future Plans and Issues, *M. Salman, General Motors*

Wrap Up, *M. Salman, General Motors*

4. Committee Subgroup Visit on Batteries, SAFT and the Holiday Inn, Baltimore-Washington Airport, October 16, 1996

The following presentations were made to committee members Supramaniam Srinivasan (subgroup chair), Fritz Kalhammer, John Newman, and Vernon Roan and NRC staff member James Zucchetto.

Introduction, *Christine Sloane, General Motors*

SAFT Review of Battery Developments, Progress, and Prospects, *Guy Chagnon, SAFT*

SAFT Tour of Pilot-Scale Operations

Development of Technical Targets, *Harold Haskins, Ford*

Battery Technology Assessment, *Russ Moy, Ford*

Ultracapacitor Technology Assessment, *Tim Murphy, Idaho National Engineering Laboratory (INEL)*

VARTA Nickel/Metal Hydride, *Russ Moy, Ford*

Yardney Nickel/Metal Hydride, *Harold Haskins, Ford*

SRI Lithium-Ion Battery, *Bernie Heinrich, Chrysler*

SAFT Lithium-Ion Battery, *Tim Murphy, INEL*

Test Methods and Plans, *Tim Murphy, INEL*

Modeling Support for Systems Analysis, *Harold Haskins, Ford*

Phase 2 Plans and Resource Requirements, *Harold Haskins, Ford*

5. Committee Subgroup Visit on Fuel Cell Technology, Hartford Airport Ramada Inn and International Fuel Cell Corporation (IFC), October 17, 1996

The following presentations were made to committee members Supramaniam Srinivasan (Fuel Cells and Electrochemical Systems subgroup chair), Simone Hochgreb, Fritz Kalhammer, Harold Kung, John Newman, and Vernon Roan and NRC staff member James Zucchetto.

Introduction and Technical Targets, *Christine Sloane, General Motors*

Technical Challenges and Progress Assessment, *Swathi Swathirajan, General Motors*

DOE Programmatic Overview, *Steve Chalk, DOE*

Fuel Cell Stack R&D at Ford, *Gie Oei, Ford*

Direct-Hydrogen-Fueled Proton Exchange Membrane Fuel Cell Vehicle, *Tim Rehg, Allied Signal*

GM Fuel Cell Program, *Swathi Swathirajan, General Motors*

National Laboratory Fuel Cell Stack R&D Overview, *Jim Miller, Argonne National Laboratory*

National Laboratory Fuel Processing R&D Overview, *Romesh Kumar, Argonne National Laboratory*

Foreign Investment & Programs (handout), *Jim Miller, Argonne National Laboratory*

Arthur D. Little Reformers for Fuel Cells in Transportation, *Jeff Bentley and Bill Mitchell, A.D. Little*

Tour and Discussion at International Fuel Cells Corporation

6. Presentations on the Compression Ignition Direct Injection (CIDI) Engine, Ford Scientific Research Laboratory, October 22, 1996

The following presentations were made to committee members Craig Marks (CIDI subgroup chair), David Foster, David Hagen, Simone Hochgreb, and Harold Kung and NRC staff member James Zucchetto.

Introduction, *Dave Foulkes, Ford; Tom Asmus, Chrysler; and Roger Krieger, General Motors*

Roadmap and Metric Assessment, *Dave Foulkes, Ford*

CIDI Research Priorities, *Roger Krieger, General Motors*

Overall 1996 and 1997 Funding, *Al Murray, Ford; Pat Sutton, DOE; Charles Gray, EPA; Walt Bryzik, DOD*

Fuel Injection Systems, *Peter Meurer, AVL*

Evaluation of Dimethyl Ether, *Peter Meurer, AVL*

Individual Presentations by Each Automotive Company to PNGV Committee Members Only:
Ford, Dave Foulkes
General Motors, Roger Krieger
Chrysler, Tom Asmus

Hybrid Electric Vehicle/CIDI Sharing, *Dave Foulkes, Ford; Tom Asmus, Chrysler*

Lightweight Engine Structures, *Chris Talwar, Ricardo*

Lean NO_x Catalyst CRADA, *Dick Blint, General Motors*

Combustion CRADA, *Paul Miles, Sandia National Laboratory*

Alternative Fuels Evaluation, *Karl Hellman, EPA*

Aftertreatment, *Bob Hammerle, Ford*

Wrap-up and Questions, *Dave Foulkes, Ford*

7. Presentations on Gas Turbine Technology, Crown Plaza Hotel, Detroit Airport, October 24, 1996

The following presentations were made to committee members Vernon Roan (Gas Turbine subgroup chair), D. Gary Diaz, Craig Marks, and Blake Wallace and NRC staff member, James Zucchetto

Introduction, *Jerry Skellenger and Christine Sloane, General Motors*

Overview of Automotive Gas Turbine R&D Programs, *Jerry Skellenger, General Motors*

Technical Targets for Gas Turbine Power Systems, *Rich Belaire, Ford*

Structural Ceramics: Status and Challenges, *Dave Stinton, Oak Ridge National Laboratories*

Progress in Fabrication of Ceramics, *Barry Draskovich, Allied Signal*

DOE Enabling R&D, *Dave Stinton, Oak Ridge National Laboratory*

Progress in Fabrication of Ceramics, *Barry Draskovich, Allied Signal*

Assessment of Technical Issues, *Jerry Skellenger, General Motors*

Teledyne Ryan Aeronautical Turbo-Generator Development Program, *Ted Exley, Teledyne Ryan*

Ceramic Gas Turbine Development Progress Up-Date, *Craig Heathco and Phil Haley, Allison Engine Company*

Objectives and Priorities for Next Phase of R&D, *George Fenske, Argonne National Laboratory*

8. Committee Meeting, November 11–13, 1996, Washington, DC

The following presentations were made to the committee:

Future High Speed Diesel Engines for Passenger Cars, *Peter Herzog, AVL*

Broad PNGV Progress Issues, *Mary Good, U.S. Department of Commerce*

Achievements and Progress on Goal 2, *George Joseph, PNGV–USCAR*

Achievements and Progress on Goal 1 and Major Manufacturing Development Needs Including Resource Requirements, *Susan Hartfield-Wunsch, PNGV–USCAR*

Significant Infrastructure Considerations, *T.R. Lakshmanan, Bureau of Transportation Statistics, Larry Johnson, Argonne National Laboratory, Dick John, Volpe National Transportation Center*

Advanced Vehicle Technology Competitions, *Shelley Launey, DOE*

Assessment and Incorporation of Foreign Automotive Technology Developments in PNGV Program, *Keith Hardy, TASC Automotive*

Update on "Downselect" Process, *Ron York, PNGV–USCAR*

Major Impediments to Program Success and Suggested Resolutions, *Owen Viergutz, Al Murray, Christine Sloane, PNGV–USCAR*

9. Presentation on the Stirling Engine, December 10, 1996

The following presentation was made to committee members Craig Marks (Stirling Engine subgroup chair) and Trevor Jones, committee chair.

Overview and Update on Stirling Engine Activities
Jerry Skellenger, General Motors

APPENDIX C

Recommendations from the Phase 2 Report

The following is a list of recommendations from the committee's Phase 2 report.

STRUCTURAL MATERIALS

Recommendation. The systems analysis effort recently initiated by the PNGV should be used to drive the optimization of materials usage for the various vehicle components based on part configuration trade-offs and on incorporation of data on manufacturing costs, structural effectiveness, recyclability, and other properties.

Recommendation. The USCAR should continue to use the process it has developed—incorporating its substantial leverage through integrated industry programs—to pursue the very promising developments in steel and aluminum materials made by materials suppliers and trade associations. The development of innovative manufacturing processes for aluminum and steel should be encouraged and accelerated.

Recommendation. The PNGV should establish an integrated product design program to provide better evidence for the advantages and viability of using polymer-based composites for automotive body structures. The program should:

- Develop computerized feature-based design and decision support tools to enable an integrated product design evaluation of the cost effectiveness of composites for vehicle structural applications.
- Validate the projected cost of \$3 to \$5/lb at high-volume through production process pilots.

- Address the development of a database and models to establish the crashworthiness of composite structures.
- Take into account relevant experience with composites in the aerospace industry.

The approach adopted to date by the PNGV (materials workshops, white papers, etc.) should be pursued on an accelerated schedule as a basis for establishing the above program.

POWERTRAIN DEVELOPMENT

Recommendation. The PNGV should devote substantial additional resources to the DICI hybrid powertrain in view of its relatively high potential to meet PNGV Goal 3 objectives.

Recommendation. The PNGV should develop a powertrain systems analysis methodology to aid in the evaluation of the potential gains and probability of success for various technologies.

Recommendation. The PNGV should perform vehicle packaging studies soon for each powertrain system that is likely to remain a candidate past 1997. Such studies would establish realistic size and shape goals for the component development programs.

Recommendation. The PNGV should perform a study to establish the energy balance, in-use environmental effects, and resource requirements, as well as production and distribution costs, for any fuels other than gasoline or diesel fuel being considered for use in Goal 3 vehicles.

Recommendation. PNGV should continue to develop flywheel and generator technologies.

Recommendation. On a stand-alone basis, batteries still appear to be the best near-term candidates for energy storage, and PNGV should fund development of the most promising battery system consistent with this potential.

Recommendation. PNGV should focus its ultracapacitor R&D on the most promising technologies, and serious efforts should be devoted to the investigation of a battery/ultracapacitor hybrid storage device.

INFRASTRUCTURE

Recommendation. The PNGV must continue to address infrastructure issues as an integral part of its program. A careful assessment of infrastructure issues associated with alternative technologies should be an essential part of the technology selection process scheduled for 1997.

Recommendation. The PNGV should immediately involve DOT's National Highway Traffic Safety Administration in addressing and resolving the safety issues raised by Goal 3 vehicles.

SYSTEMS ANALYSIS

Recommendation. The PNGV should assess the impact on the overall program schedule of the delay in implementing systems analysis and vehicle engineering tasks, and the need for remedial action. Priority projects must be identified and implemented by the technical teams as soon as possible.

Recommendation. The PNGV should formalize subsystem evaluation and selection process without delay, and performance criteria should be provided to the PNGV technology teams. The systems analysis must be an iterative process that continually receives new information, updates models, and provides updated results from optimizations and tradeoff studies to system, subsystem, and component designers.

Recommendation. Overall vehicle system and subsystem analysis driving component developments should be under the control of a USCAR technical director.

PROGRAM ORGANIZATION AND MANAGEMENT

Recommendation. The committee still strongly recommends that the partners in USCAR appoint a single technical director as a way of benefiting from the leverage of an integrated organization in pursuit of PNGV goals.

Recommendation. The committee reiterates its earlier recommendation that senior management at DOC and DOE install a management structure with appropriate authority and responsibility as soon as possible and ensure strong, capable staffing. This structure should include a chief technical officer to provide technical direction to the wide array of government technical activities. The role of the chief technical officer becomes even more critical in the absence of a single USCAR technical program director.

Recommendation. The PNGV needs to have a better calibration of the state of development and predictions for commercial availability of foreign technology.

Recommendation. As a matter of urgency and in accordance with the committee's recommendation in its first report, the PNGV should conduct more comprehensive assessments and benchmark foreign technology developments relevant to the program. If warranted by the results of such analyses, PNGV should reassess its research priorities.

Recommendation. To be successful, a complex development program such as PNGV must have well defined plans and objectives, adequate resources, and the support of sufficient funding. It is incumbent upon both USCAR and the government to ensure that adequate resources for the PNGV program are provided in a timely manner and used efficiently in overcoming the critical barriers to achieving PNGV goals.

APPENDIX D

Letters from PNGV and the U.S. Department of Transportation Regarding Phase 2 Report

THE DEPUTY SECRETARY OF TRANSPORTATION
WASHINGTON, D.C. 20590

MAR 25 1996

Mr. Trevor Jones
Chairman of the National Research Council Advisory Group
on the Partnership for a New Generation of Vehicles
National Research Council
2101 Constitution Avenue, NW - Room HA-270
Washington, DC 20418

Dear Mr. Jones:

I have reviewed the second report of the National Research Council's (NRC) Standing Committee to Review the Research Program of the Partnership for a New Generation of Vehicles (PNGV) and concur with the report's recommendations.

In particular, the U.S. Department of Transportation (US DOT) supports the Committee's recommendation that "The PNGV should immediately involve the DOT's National Highway Traffic Safety Administration (NHTSA), in identifying, addressing, and resolving the safety issues raised by Goal 3 vehicles."

The Department has been committed to providing technical support to the PNGV initiative and holds to that position. Within the Department, NHTSA has been designated as the focal point for PNGV. In fiscal year 1996, NHTSA requested $5 million to support PNGV. Funding was requested to develop advanced computer models and to obtain the computing capacity necessary to evaluate the crashworthiness characteristics of alternate vehicle designs and new lightweight materials such as advanced composites proposed for use in the PNGV program. These evaluations would ensure that the PNGV vehicles meet existing and anticipated safety standards, and that the overall safety of the future vehicle fleet is not compromised. It was also proposed that NHTSA assess the specific requirements and costs associated with developing the physical infrastructure to support these new vehicles--including vehicle and component manufacturing repair and refueling. And finally, DOT proposed a National Research Council Peer Review study of the conceptual designs developed by the program. It was planned that NHTSA, with technical support from the US DOT Volpe National Transportation Systems Center, would also create a comprehensive knowledge base and conduct analyses of the impact of this new vehicle on the U.S. economy, transportation system, and motor vehicle industry.

Despite a strong effort on the part of the Department to secure funding for these initiatives in fiscal year 1996, Congress specifially denied this request on the basis that it was premauture at this stage in the PNGV effort.

In fiscal year 1997, however, NHTSA is again requesting $5 million for PNGV. I am hopeful that your group's recognition of the need for NHTSA involvement will help us convince the Congress to provdie The research proposed in the fiscal year 1997 budget ensures that the PNGV-developed vehicles will meet existing and anticipated safety standards and that the overall crash and other safety attributes are not compromised by their light weight or the use of new advanced materials. If funded, NHTSA plans to develop advanced computer models to evaluate the crashworthiness of conceptual designs; conduct research in the area of advanced composites; provide the required PNGV infrastructure analysis; and provide a peer review of conceptual designs.

We are aware of the PNGV timetable, and recognize that analytical capability is needed before January 1998 for sufficient confidence in the safety of specific PNGV technologies to move forward with concept vehicles and production prototypes on schedule. The US DOT's key fiscal year 1997 milestone will be to develop the analytical capability required to support the PNGV program.

Please contact me if you would like to discuss the Department's commitment and most recent efforts to support the Partnership for a New Generation of Vehicle program.

Sincerely,

Mortimer L. Downey

UNITED STATES DEPARTMENT OF COMMERCE
The Under Secretary for Technology
Washington, D.C. 20230

JUN 18 1996

Mr. Trevor O. Jones
Chairman
Standing Committee to Review
the Research Program of the
Partnership for a New Generation of Vehicles
National Research Council
2101 Constitution Avenue, NW
Washington, D.C. 20413

Dear Mr. Jones:

Both the government and industry members of the Partnership for a New Generation of Vehicles (PNGV) have reviewed your second report on our research program. We were pleased by the general tone of the findings. The Committee's confirmation of our overall program strategy and the scope of our technical work is appreciated. In particular we are reassured by your belief that the technologies being pursued are relevant and appropriate to the Partnership's objectives. The Committee's recognition that our technical teams are organized effectively and are working well is also gratifying. We certainly agree the PNGV has a significant challenge to meet in a relatively short time frame. Our goals were purposely set high to accelerate the advance of automobile technology.

The NRC report contained a number of important findings and recommendations. The partnership has studied these carefully and believe all provided helpful perspectives. Our intent is to respond to most of the major recommendations and enter into a more detailed dialogue during the next review.

There are some peripheral aspects that we have only begun to explore for which the Committee's recognition and guidance are appreciated. These include the need for global technology benchmarking and the importance of anticipating the impact of new PNGV technologies on the automobile industries'--and even the nations'--infrastructure.

With regard to the recommendation that research funding be focused on the most promising technologies, we can report that some steps have been taken on the government side to facilitate this. First, the Office of Management and Budget has assumed a stronger role in the allocation and tracking of PNGV-related projects. Additionally, industry representatives are participating more actively in budget planning with OMB and Congressional staffs. The actual shifting of resources will follow the technology selections process. This is expected to commence this summer and continue, as per the original schedule, through the end of 1997. We are developing procedures for this process and expect to review them with the Committee before they are implemented. An ability to redeploy funds will certainly be needed for this process to be most effective. Although there are numerous constraints imposed on the government with regard to handling funding, there now appears to be some mechanisms for shifting funding that offer promise. We will report our progress on this to you at the next review.

Comments on other, more specific, committee recommendations are contained in the enclosure.

The PNGV team greatfully acknowledges the willingness of the Peer Review panel to contribute their time and experience to the review of the PNGV program. We are pleased with the growing level of interaction between our organizations in both formal and informal sessions and believe that this process will advance our efforts measurably. The Peer Review Committee's recommendations are important guidance to us as we seek to achieve the very ambitious goals of the program. We look forward to the next interaction with you.

Mary L. Good

Francois Castaing
Executive Vice President
Chrysler Corporation

John McTague
Vice President Technical Affairs
Ford Motor Company

Arvin Mueller
Vice President and Group Executive
NAO Vehicle Development & Technical Operations
General Motors Corporation

Enclosure

cy: Dr. J. Gibbons, Director, OSTP
Operational Steering Group

PNGV RESPONSE TO RECOMMENDATIONS BY THE NATIONAL RESEARCH COUNCIL'S PEER REVIEW

RECOMMENDATION: PNGV needs systems analysis tools to support 1997 technology selection.

PNGV RESPONSE: Systems analysis is one of the important approaches to model vehicle and subsystems decision making. Each company has its own systems modeling team to guide technology decisions. In addition, there is an independent, effective analysis underway funded by the government. This analysis allows for the integration of the systems as a whole without having to overcome proprietary issues of each company. We have an effective analysis underway and will ensure that it continues; the government is committed to funding this effort on an ongoing basis. We are holding to our schedule and we have not changed our technical goals.

The industry has always recognized the essential role of systems analysis in achieving vehicle and component development objectives as evidenced by a considerable and growing dedication of resources to modeling and computer analysis of vehicle designs. Discussions with the federal agencies involved in the systems analysis effort have reaffirmed that PNGV systems analysis will remain a priority. All of our plans described in Technical Roadmaps reflect its importance.

As we described to the Committee, the OEM's have sophisticated proprietary modeling tools which have been used in support of the Hybrid Electric Vehicle development programs. Since the last Peer Review, the PNGV systems analysis activity has made substantial progress in developing a joint cross-calibrated vehicle modeling tool for trade studies. Existing component models have been acquired from the federal labs and industry and, where needed, component models have been created or modified using the OEM's proprietary modeling capabilities. Verification of vehicle models is planning for this Summer, with initial trade studies scheduled for this Fall.

RECOMMENDATION: Assess and benchmark foreign technology developments; U.S. not in clear leadership position in developing critical technologies for PNGV-type vehicles.

PNGV RESPONSE: We agree on the importance of assessing the bench marking foreign technology developments and will continue to benchmark domestic and foreign technologies whenever they may reside. There are pockets of technology around the world that may be ahead of the United States; there are pockets of technology where the U.S. is ahead. While no country or region has collected necessary integration capabilities to meet full vehicle development objectives, we believe we have a very powerful tool with PNGV to create a leadership position in the development of the critical technologies.

The industry relies on established integral technology assessment processes as an important foundation to support our goals. This includes actively surveying the spectrum of technology developments both through our global supplier networks and through foreign subsidiaries.

2

RECOMMENDATION: Three auto companies should have more integrated industry organization to better leverage strengths.

PNGV RESPONSE: We believe we have a well integrated industry organization, as evidenced by 13 consortia and 10 technical teams, doing pre-competitive work. We appreciate the spirit of the Peer Review comments and will continue to seek means to improve industry's management process. Diverse and sometimes proprietary efforts of the three partners and their numerous suppliers complicate the management challenge

RECOMMENDATION: Industry should appoint single technical director

PNGV RESPONSE: The industry believes that appointment of the technical teams, using similar operating techniques and working in parallel with established USCAR consortia, has proven to be an effective and workable mechanism to balance the program's complex and proprietary issues and represents the best opportunity for success within our timeframe. We are collaborating in a pre-competitive environment to understand fundamental automobile technologies but we are competitive when it comes to bring vehicles to market. Given the nature of our relationship and the results of working together to develop the broad spectrum of technologies, appointing a single technical director would only serve to add another layer of bureaucracy and inevitably slow our progress.

RECOMMENDATION: The federal government should establish a Chief Technical Officer.

PNGV RESPONSE: Since the Peer Review Committee met with PNGV official last year, the government has expanded its management team to include a Chief Financial Officer for PNGV. He resides in the Office of Management and Budget. This official will address the committee's concerns about the project's ability to focus funding in necessary technical areas. Also, a government Technical Council has been established to improve the oversight and support to the Technical Teams. This has been accomplished via an expansion of the previous Technical Oversight Principals and the establishment of a permanent chair for the council.

RECOMMENDATION: Need more effort regarding infrastructure issues.

PNGV RESPONSE: This is not part of the PNGV charter. However, the federal government through other programs, continues to analyze infrastructure issues and is trying to assure that those efforts align with PNGV progress. Argonne National Laboratory has recently released a report on these issues and will continue to do this analysis. A report to the Committee is planned.

The importance of developing appropriate infrastructure programs necessary to support the technologies required by a breakthrough vehicle is recognized. At the inception of PNGV, lead responsibility for developing all infrastructure mechanisms was assigned in the Declaration of Intent to the government partner. This allocation of duties was necessary to allow the auto industry to pursue technologies that it was best suited to address, leaving the government to lead in the development, in parallel, of collaborations or associations with those industries most informed on infrastructure issues. The auto industry, meanwhile, will make every effort to keep all parties informed of developments that may have an impact on vehicle support systems.

RECOMMENDATION: Need more involvement from DOT, NASA, EPA and DOD

PNGV RESPONSE: All these agencies are fully committed to the success of this project and are participating to the extent that their budgets will allow.

The principal difficulty with the involvement of DOT and NASA is a lack of funding appropriated by Congress. These agencies are committed to the PNGV goals, made budget requests to support these goals, and actively support PNGV to the extent their appropriated budget permit. However, their PNGV line items were deleted by Congress in the appropriations process. These agencies are continuing to discuss the importance of these issues with the appropriations committees.

EPA is using a significant portion of its limited research budget to address technical issues related to PNGV and emissions, as well as other PNGV issues. Its regulatory responsibilities are, of course, dictated by the statutory requirements of the Clean Air Act, and EPA is carrying out those responsibilities. The joint industry-government parameters for the PNGV vehicles include a requirement that the vehicles meet Tier II Clear Air Act standards.

DOD's research is in support of its military mission. DOD is nevertheless important to PNGV because, in several areas, its mission-oriented research is also directly relevant to PNGV goals. Light weight and fuel efficiency are important to military vehicles just as they are to the civilian passenger fleet. DOD research in these areas is available to the PNGV project. Examples of other overlapping areas of research include DARPA's hybrid vehicle projects and the Office of Naval Research's work on electric power systems.

Industry, the Administration, and many members of Congress understand the need for this program. We will continue to educate lawmakers on the important of PNGV and the unique collaborative effort it represents to strengthen U.S. competitiveness, improve environmental quality, and provide greater energy security for our nation.

RECOMMENDATION: The federal government portion of PNGV's R&D must be sufficiently funded.

PNGV RESPONSE: PNGV is jointly funded by the federal government and the three major domestic auto makers. Government's proper role is to fund long-term, high risk basic research. The companies have a complementary role, but their R&D is more focused on work that is more likely to be commercially viable in the near term. The Administration believes that government support of long-term, high-risk R&D to assist in the development of fuel efficient vehicles is vital to reaching important economic and environmental public policy goals, particularly given the lack of near-term market pull for such vehicles. Maintenance of a government research budget adequate to support the realization of PNGV goals is a matter of the highest priority for the Administration. The budget as submitted consistently reflects this, and increases in PNGV spending, have been requested since the beginning of the program.

The PNGV budget received the same level of priority within the Administration during the 1997 budget cycle. In addition, the government expanded its management team to include an OMB official appointed as Chief Financial Officer for PNGV. This official will ensure maximum value for the government's expenditures. During the last budget cycle there were strenuous efforts by some members of Congress not only to reduce spending generally, but specifically to reduce drastically the government's spending on long-range R&D. The Administration believes this is short-sighted, and ignores the historic value to the country of such spending, which traditionally has enjoyed bipartisan support. Notwithstanding such congressional efforts generally, the Administration and the industry worked closely with those members of Congress responsible for appropriations in the areas important to PNGV to explain the value of the requested expenditures. While we were unable to obtain the level of spending requested in all cases, expenditures on PNGV-related research were held relatively constant in a year in which the vast majority of R&D spending was severely reduced. Government and industry are working together to get the maximum value from those expenditures and we are examining each agency's projects to assure maximum efficiency.

APPENDIX E

Brief Background on Powertrains

The following is an excerpt from Chapter 6, Powertrain Developments, of the committee's second report, to provide the reader background on powertrains and series and parallel hybrid vehicle configurations (NRC, 1996).

Even when combined with reductions in vehicle mass, aerodynamic drag, tire rolling resistance, and other energy-saving vehicle design parameters, the PNGV technical team estimates that achieving the Goal 3 fuel economy target (up to three times fuel efficiency of today's comparable vehicle) will require a power plant with at least 40 percent thermal efficiency (PNGV, 1996). Achieving this efficiency by incremental improvements to current gasoline engines is unlikely. Therefore, a variety of alternative energy conversion devices and drivetrain components are being considered by the PNGV. None of these alternatives is, at present, suitable for passenger car application without further development. Moreover, many combinations are possible; therefore, system tradeoff analyses must be performed to fully understand the fuel efficiency potential of each. For instance, adding hybrid and regenerative braking driveline[1] components reduces the power plant efficiency gain needed for the PNGV Goal 3 vehicle but increases the size, weight, complexity, and cost of the complete powertrain. This kind of first-order qualitative analysis has resulted in the powertrain technologies listed below. These technologies are currently being pursued by PNGV for Goal 3 vehicles, all of which will operate as hybrid systems.

The powertrain technologies being pursued by the PNGV for Goal 3 vehicles are as follows:

[1]The term driveline (or drivetrain) typically refers to the transmission system from engine output shaft to driven road wheels.

- four-stroke DICI engines
- gas turbines
- Stirling engines
- fuel cells
- reversible energy-storage devices (namely, batteries, flywheels, and ultracapacitors)
- electrical and electronic power-conversion devices

Hybrid powertrain systems are attractive to increase powertrain efficiency for two reasons. When combined with a suitable energy-storage device, these systems allow the possibility of recovering a significant portion of the kinetic energy of the vehicle as it decelerates. They also allow the primary energy converter (engine or fuel cell) to be smaller and to operate under load and speed conditions that are independent of the vehicle's immediate needs. This reduces its size and permits its efficiency to be optimized. In addition, this arrangement allows an engine to operate at a speed and load that are independent of the vehicle, and increases the feasibility of using power plants that would otherwise be unsuitable for passenger vehicles. Emissions can also be reduced significantly, especially at startup when the car can start without the engine.

Both series and parallel hybrid configurations are being considered. In the series configuration, all of the engine power is transmitted to the wheels through electric machines. In a parallel configuration, the engine supplies some power directly to the drive wheels through a mechanical transmission, and this is supplemented by electrical machines and an electrical power source. Continuously variable transmissions allow the relationship between engine speed and vehicle speed to be changed at will and are candidates for the parallel hybrid application. It appears that little or no work with respect to continuously variable transmissions is being conducted on behalf of the PNGV program in the United States. However, foreign firms are continuing to develop such transmissions. The committee, therefore, believes that these developments should continue to be incorporated into the PNGV agenda.

REFERENCES

NRC. 1996. Review of the Research Program for a New Generation of Vehicles, Second Report. Board on Energy and Environmental Systems and Transportation Research Board. Washington, D.C.: National Academy Press.