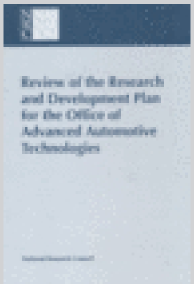

# Review of the Research and Development Plan for the Office of Advanced Automotive Technologies

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Committee on Advanced Automotive Technologies Plan, National Research Council

# Review of the Research and Development Plan for the Office of Advanced Automotive Technologies

Committee on Advanced Automotive Technologies Plan

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

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This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. The committee, on behalf of the NRC, wishes to thank the following individuals for their participation in the review of this report: L. Gary Byrd, consultant; Robert A. Frosch, Harvard University; Robert D. Hall, CDG Management; Trevor Jones, Echlin, Incorporated; Craig Marks, University of Michigan, Ann Arbor; Jerome G. Rivard, Global Technology and Business Development; and Daniel Sperling, University of California, Davis.

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

# Contents

# Executive Summary

The Office of Advanced Automotive Technologies (OAAT) within the U.S. Department of Energy (DOE) was established in 1996 to consolidate DOE's programs in automotive technology research and development (R&D) into an integrated program for light vehicles.[1] One of the first activities undertaken by OAAT was to develop a plan defining the scope, focus, and content of its Advanced Automotive Technologies Program for calendar years 1997 through 2001. The *Research and Development Plan for the Office of Advanced Automotive Technologies* describes the research that OAAT plans to undertake "to reduce the most serious technical barriers to the development of energy-efficient automotive technologies that could significantly reduce the nation's dependence on petroleum." The National Research Council formed the Committee on Advanced Automotive Technologies Plan in response to a request from the OAAT to conduct an independent review of the OAAT R&D plan.

## OVERALL APPROACH

The committee commends the OAAT on its R&D plan, which is a worthy attempt to integrate and coordinate research on advanced automotive technologies within DOE. In the committee's judgment, the technologies described in the plan generally offer important potential benefits to the nation in terms of reducing petroleum consumption[2] and adverse environmental effects from automobiles,

[1]Light vehicles are defined as passenger vehicles and light trucks under 8,500 lb. gross vehicle weight (GVW), in accordance with the Environmental Protection Agency's system of vehicle classification.

[2]Petroleum is a generic term for oil and liquid oil products, excluding natural gas.

even if the ambitious OAAT goals are not met. The plan emphasizes jointly funded partnerships among government agencies, the national laboratories, universities, and industry to develop and validate technologies. The committee encourages OAAT to continue these partnerships, which permit the federal government to stimulate technology development and create opportunities for the exchange of ideas between government and industry. In most cases, the OAAT plan is attentive to the different but complementary contributions of government and private sector R&D to technology development. In the committee's view, for the reductions in petroleum consumption and adverse environmental effects to be realized, the participation of industry in the implementation and commercialization of advanced automotive technologies is essential. However, the OAAT should fund only generic, precompetitive R&D that industry would not undertake on its own.

The technical section of the plan provides information on technical barriers and approaches to overcoming these barriers for vehicle systems and seven individual technology areas: advanced engines; fuel cells; high power energy storage; power electronics and electric machines; advanced automotive materials; alternative fuels; and electric vehicle batteries. The committee found the technical plan to be logical and well structured, with a clear progression from the technical barriers to the technical tasks. The technical barriers are, in general, appropriately defined in that they represent the most significant hurdles to technology development. However, the quality of the strategies for overcoming the technical barriers varies considerably. An important feature of the technical plan is the incorporation of "Go/No Go" decision points corresponding to potential technical "showstoppers." The committee considered the Go/No Go methodology to be sensible for high-risk R&D, although the decisive implementation of the Go/No Go approach will be essential for the overall success of the R&D portfolio.

The committee was unable to clarify the detailed relationship between the R&D described in the plan and two related programs, namely, the research programs of the Partnership for a New Generation of Vehicles (PNGV) and the U.S. Advanced Battery Consortium (USABC), whose projects include developing batteries for electric and hybrid vehicles. Although the plan states that "PNGV is larger than OAAT and OAAT is not strictly PNGV," OAAT activities are central to the PNGV automotive technology development. In fact, about 86 percent of OAAT funds for fiscal year 1997 were expended in PNGV, according to DOE representatives. A better explanation of the differences between OAAT and PNGV goals and of the relative time frames for these two programs would be helpful for the reader. For example, OAAT activities for 1997 to 2001 cannot be readily correlated with PNGV targets after 2001.[3]

[3]The PNGV expects to define, develop, and construct concept vehicles by the year 2000 and production prototypes by the year 2004.

A more detailed description of, and justification for, OAAT's targets as distinct from those of PNGV—such as increasing fuel efficiency from 80 miles per gallon (mpg) to 100 mpg—would give the reader a better perspective on OAAT's long-term objectives. A more detailed explanation of the relationships among the OAAT R&D plan, the USABC, and the proposed Advanced Battery Initiative (to be launched in 2000) would also be helpful.

The committee understands that the plan is a living document and that assimilating existing R&D programs and aligning them with OAAT objectives is an ongoing process. The committee also recognizes that the plan is required to respond to legislative directives, such as the directives in the Energy Policy Act of 1992, and must accommodate evolving political agendas. In this context, the committee offers some suggestions for improving both the content and presentation of the plan. The committee was mindful that for the plan to be effective it must be both technically robust and clearly communicated. The committee's major recommendations are provided in the executive summary. Additional recommendations, including those relating to individual technology areas in the plan, are given in the body of the report.

**Recommendation.** The relationship between the OAAT R&D plan and the PNGV and USABC programs should be explained clearly in the plan, particularly with regard to the different goals and objectives, budgets, and responsibilities for program management.

## GOALS AND OBJECTIVES

One of DOE's goals is to "enhance energy productivity."[4] The committee recognizes the benefits of this goal as part of a strategy for responding to possible energy supply shortages or more stringent environmental regulations, such as mandatory reductions in emissions of greenhouse gases to the atmosphere.

In keeping with DOE's goals, OAAT's goal is to develop technologies that will enable the introduction into the domestic market of vehicles with several times the fuel efficiency of current, comparable conventional vehicles. At the same time, these advanced technology vehicles will have to meet all future emissions regulations and be competitive with conventional vehicles in other ways (including costs). The OAAT goal includes a requirement for fuel flexibility, although it is not clear whether this requirement applies to individual vehicles or to the light-vehicle fleet as a whole. In the committee's view, the OAAT goal is commendable but will be very difficult to reach, especially for fuel-flexible

[4]Energy productivity refers to the amount of energy required to deliver a unit of service. For example, if the level of today's transportation services from gasoline-fueled vehicles could be attained using less gasoline, energy productivity would be increased.

vehicles. It would be helpful if the overall light-vehicle fleet were fuel flexible so that alternative fuels could gradually absorb some of the demand for petroleum. However, attaining the high performance needed to meet OAAT's challenging fuel efficiency goal and other targets will be less difficult if an individual vehicle is optimized for a well defined and well refined fuel and is not required to be fuel flexible.

The objectives of the OAAT plan specify fuel economy levels and dates for meeting technical targets and for marketing advanced vehicles. These objectives are very challenging, and the marketing objectives are probably not attainable without higher gasoline prices or other market incentives. In the committee's judgment, the plan should recognize the possibility that OAAT will fall short of meeting the stated objectives in the specified time. But the committee believes important benefits could be realized even if the objectives are not fully met. For example, fuel economy values of 40 or 60 mpg—as opposed to the target values of 80 and 100 mpg—would considerably reduce petroleum consumption.

Alternative fuels may help reduce the consumption of petroleum-based fuels in the United States. However, the OAAT role in enabling the efficient use of alternative fuels does not go beyond the pre-production development of new vehicle technologies and R&D related to the development of low-cost refueling facilities. Because at least two automotive companies are already producing ethanol-fueled vehicles, the committee considers the OAAT tasks related to ethanol-fueled vehicles to be inappropriate for federal government support. The committee also believes that the OAAT approach of progressing from E85 technology to E95 technology is not technically defensible.[5] Increasing the proportion of ethanol in the fuel from 85 percent to 95 percent offers negligible efficiency gains and aggravates the cold-start problem. In the case of vehicles fueled by compressed natural gas (CNG), the committee considers that some OAAT efforts are justified to address the problem of refueling, which now limits the market for CNG vehicles. In the committee's view, the cost and reliability of CNG refueling are more critical for market penetration than the cost of fuel tanks or vehicle range. The committee therefore suggests that OAAT change the priorities of the CNG technical barriers defined in the plan and focus its efforts on the most critical barrier, namely, the refueling infrastructure.

The committee supports setting target dates for achieving performance goals but questions OAAT's decision to set dates when vehicles will be "commercially viable" or "could be successfully marketed."[6] Dates when marketing becomes feasible are beyond OAAT's control and are strongly dependent on when

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[5]E85 fuel is made up of 85 percent ethanol and 15 percent gasoline. E95 has 95 percent ethanol and 5 percent gasoline.

[6]The Executive Summary of the plan includes dates for achieving performance objectives and marketing, but the Goals and Objectives section of the main report includes dates only for marketing.

advanced vehicles become "cost competitive" (see discussion of costs below) and when other market factors come into play.

**Recommendation.** The OAAT should modify its R&D plan to acknowledge the benefits of the partial attainment of goals and objectives.

**Recommendation.** The OAAT efforts related to ethanol-fueled vehicles should be eliminated from the R&D plan because these vehicles are already in production. In the event that legislative mandates require OAAT to continue some work on ethanol, further consideration of E95 should be eliminated from the plan because this fuel has little more to offer than E85, and it exacerbates the cold-start problem.

**Recommendation.** The priority of the technical barriers for CNG should be changed. The cost and reliability of fueling facilities and the related technical task should be given the highest priority. Substantial reductions in the cost of refueling facilities should be a major criterion for the 2001 Go/No Go decision to continue the development of CNG vehicles.

**Recommendation.** The dates indicating when advanced technology vehicles could be marketed should be either eliminated from the plan or qualified to indicate that they depend on many unknown, nontechnical factors.

## TECHNICAL TARGETS

The plan defines technical targets for each technology area. The dates by which the intermediate and final targets are to be achieved vary, but most of them fall between 1997 and 2006. The basis for technical targets is not clearly defined in the plan, which was of concern to the committee. For example, some of the targets for 1997 appear to be overly optimistic considering the current state of the technologies, which undermines the credibility of later targets. In some cases, the intermediate targets appear to reflect a steady rate of progress from today's technology toward the final targets. In other cases, the intermediate targets appear to require technology breakthroughs or reflect diminishing returns, although assumptions about rates of progress are not articulated in the plan. Representatives of OAAT explained to the committee that the technical targets are based on a combination of performance data and projections and will be refined as more data are generated. The committee also noted some inconsistencies in defining targets. Targets should be defined in a way that facilitates comparisons of components that perform the same function but are based on different technologies. For example, the cost and efficiency of a fuel cell power plant should include the reformer (if used), motor, and other necessary accessories so they can be compared to the cost and efficiency of a compression-ignition direct-injection (CIDI) engine and transmission.

**Recommendation.** To enhance the overall credibility of the plan, OAAT should do the following:

- clearly state the bases for the technical targets
- explain the proposed procedures for updating and refining targets as more data become available
- ensure that targets for the various technologies are defined consistently in terms of efficiencies and functional units

## COSTS

Throughout the plan, advanced technology vehicles are referred to as being cost competitive with conventional vehicles, but the term "cost competitive" is not clearly defined. The committee interprets "cost competitive" to mean that the overall cost of owning and operating an advanced vehicle over its life is equal to or less than the cost of a comparable conventional vehicle at a particular date. The cost of operations includes fuel and required service.[7] The term "comparable" implies that advanced and conventional vehicles will offer the same degree of customer satisfaction in terms of functionality, design, prestige, reliability, comfort, safety, etc. However, the two vehicles will not necessarily offer the same "societal benefits," such as reduced air pollution or less dependence on imported petroleum.

The PNGV Goal 3 states that advanced technology vehicles should "achieve up to three times the fuel efficiency of comparable 1994 family sedans with equivalent cost of ownership adjusted for economics." The committee believes this PNGV goal is unrealistic because many of the technologies under consideration are likely to increase the cost of advanced vehicles, even when adjusted for economics. Although changes in market conditions could make cost competitiveness easier to attain (petroleum prices could rise substantially or government mandated market incentives could be introduced), the committee believes that OAAT should set more realistic objectives for cost competitiveness. The plan might also indicate that some increase in cost over conventional vehicles at a specific date might be justified on the basis of broad societal benefits. Determining how much of an increase in vehicle cost might be justified on the basis of societal benefits is a public policy issue that falls beyond the scope of OAAT's mandate.

The committee found that the strategies for reducing the cost of technologies in the technical plan are generally inadequate, although there are some exceptions. The plan emphasizes performance rather than cost and offers few specific technical approaches for reducing the costs of various systems.

[7]Both the PNGV and the OAAT specify life-cycle costs in their planning documents. However, the committee notes that many customers are likely to interpret "cost competitive" as referring to the initial cost to purchase a vehicle.

**Recommendation.** To ensure that expectations of the cost competitiveness of advanced technology vehicles are realistic, the OAAT should clearly define "cost competitiveness" in terms of some future date when the overall costs of ownership and operation of comparable conventional vehicles might be considerably higher than they are today because of higher petroleum prices or new environmental regulations.

**Recommendation.** The OAAT should apply more effort to reducing the costs of advanced automotive technologies and should be more specific in explaining technical approaches to cost reduction for individual technologies.

## STRATEGIC APPROACH

Identifying technical barriers and establishing technical targets are necessary steps in the development of an R&D plan but do not in themselves constitute a strategy for achieving goals and objectives. OAAT needs to lay out specific technical strategies (and actions) for overcoming the barriers. In some instances, the technical road maps described in the plan simply state that barriers will be overcome. The committee was concerned that some of these statements relate to technology areas where necessary breakthroughs have not materialized despite significant R&D efforts over a period of many years (e.g., batteries, gas turbines, ceramic materials for gas turbines). Proposals from the larger technical community might yield some innovative solutions to overcoming the technical barriers defined in the plan.

Although the Go/No Go decision points in the technical plan are commendable, the committee believes OAAT must define the criteria for decision making more clearly. It is not clear from the plan what will be done if performance falls somewhat, but not hopelessly, short of the levels judged necessary to make a Go decision. In this context, the committee considers that the OAAT should use better systems analysis tools not only to configure vehicles to meet overall objectives, but also to establish performance requirements for component technologies and trade-offs as a basis for making Go/No Go decisions. These tools should include vehicle simulation models capable of comparing vehicle options on a consistent basis to clarify questions of relative performance and fuel economy. Simulation models should be verified with experimental results as they become available. The systems analysis must include all of the objectives, not just fuel economy. Costs, emissions, acceleration, safety, reliability, accessory loads, and other criteria must be considered in the optimization of a vehicle.

In addition to technology development related to family sedans, DOE has a separate program for sport utility vehicles and other projects for developing CIDI technologies. The plan does not include a comprehensive explanation of CIDI technology development by the government outside the OAAT program. The plan is also unclear as to how the OAAT program in general, and the CIDI program in particular, will relate to the light-vehicle market from 2004 to 2008, which could be quite different from today's market if the increase in the sales of pickup trucks, vans, and sport utility vehicles continues.

**Recommendation.** OAAT should define the technical approaches to achieving its objectives in terms of specific actions. Suggested approaches to overcoming technical barriers might be solicited from the larger technical community, particularly when innovations or nontraditional technologies are needed.

**Recommendation.** The OAAT plan should emphasize the development of improved systems analysis tools that incorporate all factors relevant to: (1) configuring the vehicle and making trade-off decisions; (2) setting priorities for resource allocation and technology selection; and (3) supporting Go/No Go decisions. Funding for systems analysis should reflect its overall importance to OAAT's R&D program.

**Recommendation.** Because the OAAT plan includes R&D for "light trucks under 8,500 lb. GVW," the requirements and technical targets for these vehicles should be included in the plan.

## SETTING PRIORITIES

The OAAT anticipates that the R&D described in the plan could be implemented within "plausible" budget levels, but the plan does not specify budget levels. The plan notes that "in the event that appropriated budget levels will not support all of the activities reflected in this plan, available funding will be concentrated on the highest-priority technical barriers in the development path of the subject technologies." No mention is made of prioritizing activities across technology areas.

In the committee's judgment, in the face of budget uncertainties, OAAT must set priorities both within and across technologies. The committee understands that some priorities are implicit in the plans for individual technologies (in the ranking of technical barriers, for example). OAAT representatives informed the committee that prioritization across technologies will be part of the PNGV technology selection process for concept vehicles to be constructed by the year 2000 and will involve extensive discussions with other interested parties.

The committee recognizes the difficulty of setting priorities, particularly across different technology areas. In some cases, a lack of adequate data to support decisions adds to the difficulties. Nevertheless, good management requires clear priorities, even if they are not articulated in the written plan, and the committee urges OAAT to be decisive in this regard. Extending timelines or cutting uniform percentages across the entire plan in response to budget reductions may be expedient temporary measures but are not effective long-term practices.

Changing the proportions of government/industry costs may be one way of accommodating reductions in federal funding although increasing the cost share of industry may cause industry partners to withdraw from programs they consider to be of low priority. The committee again emphasizes the importance of developing systems analysis tools to assess performance requirements and trade-offs in support of a technically robust set of priorities for R&D. The committee recognizes that judgment is required in balancing the many factors that influence priorities, but a rigorous analysis of technologies incorporating the latest technical discoveries should be the foundation for setting priorities.

**Recommendation.** To ensure implementation of the plan in the face of budget uncertainties, the OAAT should prioritize R&D both within and across technology areas.

# 1

# Introduction

For more than 20 years, the administration and Congress have expressed a strong desire to reduce the nation's dependence on foreign petroleum. In pursuit of this goal, beginning in 1974, Congress has enacted a number of laws authorizing the development of advanced automotive technologies and alternative fuels. For example, Section 2021 of the Energy Policy Act of 1992 (P.L. 102-486) directed the U.S. Department of Energy (DOE) to "conduct a five-year program . . . on cost effective technologies to reduce the demand for oil in the transportation sector for all motor vehicles, including existing vehicles, through increased energy efficiency and the use of alternative fuels." In September 1993, President Clinton initiated the decade-long Partnership for a New Generation of Vehicles (PNGV) program with the goals of (1) significantly improving U.S. competitiveness in manufacturing; (2) implementing commercially viable innovations from ongoing research on conventional vehicles; and (3) developing a vehicle with up to three times the fuel efficiency of comparable current vehicles while maintaining or improving current levels of performance, size, utility, and total cost of ownership and meeting or exceeding federal safety and emissions requirements (PNGV, 1995). Goal 3 of the PNGV includes the production of a concept vehicle by 2000 and preproduction prototypes by 2004. The PNGV program is a cooperative research and development (R&D) program between the federal government and the U.S. Council for Automotive Research (USCAR), which is made up of Chrysler Corporation, Ford Motor Company, and General Motors Corporation. DOE is one of eight federal agencies participating in the PNGV and is the largest federal participant in terms of R&D programs on advanced automotive technologies directly related to PNGV goals.

DOE's Office of Advanced Automotive Technologies (OAAT) was established in 1996 to consolidate the department's automotive technology R&D into an integrated program for light vehicles, namely, passenger vehicles and light trucks under 8,500 lb. gross vehicle weight (GVW). In addition to the development of piston and gas turbine engines, OAAT is also developing electric vehicles (EVs). The goal of the OAAT is to research, develop, and validate technologies that will enable the introduction into the domestic market of light vehicles that have:

- several times the fuel economy of current, comparable conventional vehicles
- fuel flexibility
- emissions that comply with regulatory limits projected to be in place when the vehicles are available for the marketplace
- other attributes, such as price, that render them competitive with conventional products (DOE, 1997)

One of the first steps undertaken by the OAAT was to develop a five-year plan defining the scope, focus, and content of its R&D program for calendar years 1997 through 2001. The *R&D Plan for the Office of Advanced Automotive Technologies* describes the research "to reduce the most serious technical barriers to the development of energy-efficient automotive technologies that could significantly reduce the nation's dependence on petroleum" (DOE, 1997). The spectrum of technologies addressed by OAAT pertain to advanced engines,[1] fuel cells, high power energy storage,[2] power electronics and electric machines, advanced automotive materials, alternative fuels, and batteries for EVs. The R&D plan includes: a description of the program goal and objectives; a detailed technical plan, with separate discussions of the status of each technology area, key technical barriers, strategies for overcoming technical barriers, and critical tasks and milestones for the development and validation of each technology; and a management plan detailing how the program will be managed and implemented. The technical plan emphasizes jointly funded partnerships with industry for developing and validating technologies. The federal OAAT budget for fiscal year 1997 was $125 million.

## ORIGIN AND SCOPE OF THIS STUDY

At the request of the director of the OAAT, the National Research Council (NRC) convened a committee under the auspices of the Board on Energy and Environmental Systems to conduct an independent review of the OAAT R&D

[1]The advanced engine technology area focuses on two power plants, the compression-ignition, direct-injection (CIDI) engine and ceramic gas turbines.

[2]Energy storage is essential for hybrid vehicles. Energy storage devices included in the OAAT R&D plan are high power batteries, ultracapacitors, and flywheels.

plan. In its review of the plan, the committee was asked to examine and provide comments on issues such as:[3]

- the goals, objectives, assumptions, priorities, and descriptions of potential benefits to the nation
- the strategies for overcoming identified technical barriers in high-priority technical areas
- the metrics for measuring progress in R&D
- the strategy for dealing with future budget uncertainties and allocating resources among technology areas
- the strategy for implementing and managing the plan in the light of anticipated budgets

The committee members included experts on engines, vehicles, and power trains; fuels and associated infrastructure; fuel cells, electrochemistry, and batteries; materials; power electronics and electrical engineering; management of R&D; and environmental and strategic planning. Biographical sketches of committee members are provided in Appendix A.

The committee noted that about 86 percent of OAAT funded R&D is contained in the PNGV program and that another NRC committee, the Standing Committee to Review the Research Program of the PNGV, has conducted three reviews of the PNGV program (NRC, 1994, 1996, 1997); a fourth review is under way. However, the present committee was not constrained in its review of the OAAT R&D plan by the findings, conclusions, or recommendations of these reviews. The present review was also conducted independently of an ongoing NRC study by the Committee to Review the U.S. Advanced Battery Consortium's (USABC) Electric Vehicle Battery R&D Project Selection Process. Approximately 14 percent of the OAAT funded R&D in fiscal year 1997 is contained in USABC, which includes the development of advanced batteries for future electric and hybrid vehicles.

The committee observed that one of the challenges faced by the OAAT in developing its R&D plan was assimilating R&D already funded by DOE (including parts of the PNGV and USABC programs) into a comprehensive program. In addition, the OAAT plan had to respond to a number of legislative directives from Congress and executive orders and regulations at the federal and state levels. The committee recognized that these constraints complicated OAAT's task of developing an R&D plan that is technically robust and strategically focused on high-level goals and that includes priorities for implementation in the face of budget uncertainties. Except for the potential benefits of the proposed R&D, the

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[3]The phrase "such as" in the statement of task implies flexibility. The exact contents of the DOE R&D plan were not known at the time the NRC submitted the study proposal to DOE. The committee, in reviewing the draft of the DOE plan, considered the issues specified in the statement of task, as appropriate, as well as other concerns that seemed important for improving the plan.

committee's analysis and recommendations do not address implicit questions of public policy, which were considered to be beyond the scope of the committee's task.

## STUDY PROCESS AND REPORT ORGANIZATION

The committee met twice over a two-month period. A major portion of the first meeting was devoted to presentations from OAAT personnel on the overall plan and on individual technology areas (see Appendix B). Although the committee had reviewed the plan prior to the first meeting, the organized and informative presentations by OAAT were extremely useful for clarifying some aspects of the plan, which, even after several readings, had remained confusing. In the committee's view, the plan cannot be effective unless it is communicated clearly to everyone involved in R&D, as well as to sponsors and decision makers. For this reason, the committee deemed it necessary to recommend improvements in the presentation of some material, as well as in technical content. In most cases, the committee's suggestions for improving the presentation of the plan are given in the body of the text. The recommendations address more substantive issues.

Chapter 2 addresses the OAAT R&D plan from an overall perspective. It includes the committee's assessment of and recommendations regarding goals and objectives, assumptions, benefits, priorities, strategies for overcoming barriers, metrics, and the influence of budget uncertainties. Chapter 3 addresses the detailed technical programs for vehicle systems and the seven major technology areas identified in the plan, namely, advanced engines, fuel cells, high power energy storage, power electronics and electric machines, advanced automotive materials, alternative fuels, and electric vehicle batteries.

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# 2

# Overall Evaluation

The R&D plan for the OAAT, *Energy Efficient Technologies for 21st Century Vehicles*, is a long-range planning document that addresses research needs for the development of energy-efficient light vehicles (DOE, 1997). The plan comprises four main sections: (1) Introduction; (2) Goal and Objectives; (3) Technical Plan; and (4) Management Plan. The technical plan is divided into eight sections, one section on vehicle systems and seven sections on individual technology areas, namely, advanced engines, fuel cells, high power energy storage, power electronics and electric machines, advanced automotive materials, alternative fuels, and electric vehicle batteries. R&D proposed for the technical areas will be conducted primarily by industry and the national laboratories, although small businesses and universities will also have an opportunity to participate. The committee's detailed assessment of the technical plan and related recommendations are provided in Chapter 3. The present chapter provides the committee's comments on the overall plan, as well as on the specific items in the statement of task, namely, goals and objectives, assumptions, potential benefits, strategies for overcoming technical barriers, metrics for measuring progress, priorities, and resource allocation and management in light of budget uncertainties. The chapter concludes with recommendations for improving the plan.

## GENERAL COMMENTS

The committee considers the OAAT R&D Plan (the plan) to be a commendable effort with the potential to result in long-term benefits to the United States in terms of reducing petroleum consumption and the adverse environmental effects from automobiles. In the committee's view, much of the research described in the plan is likely to be valuable, whether or not the ultimate goals and objectives in the plan are achieved. Cost-benefit issues relating to the development of advanced automotive technologies are discussed later in the context of potential benefits.

## Choice of Technologies

Technologies that could reduce petroleum consumption in personal automotive transportation are being thoroughly evaluated within the framework of an overall plan. The committee recognizes that the OAAT did not have complete control over which technologies were included in the plan; some were inherited from pre-existing programs, and some were included in response to congressional mandates. Nevertheless, the choice of technologies in the plan is generally consistent with assessments by other organizations (see, for example, OTA, 1995). The technologies that were omitted are generally considered less likely to be successful or are already being developed in the private sector (for example, steam engines, rotary engines, spark-ignited engines with variable valve timing, engines that run on liquefied petroleum gas, and continuously variable transmissions). The committee is not aware of any additional technologies with high promise that require OAAT funding.

## Research and Development Partnerships

The partnership approach to R&D outlined in the plan brings together the major automobile companies, suppliers, national laboratories, universities, the U.S. Department of Energy, and other federal government agencies to develop precompetitive automotive technologies. In the committee's view, the partnership agreements—including the sharing of program costs—are highly desirable because they concentrate the talents, motivations, and resources of the various partners on the OAAT goal and objectives. Therefore, the committee strongly supports the overall partnership concept embraced by OAAT.

In the course of product realization—from basic scientific research through the various phases of engineering to production and marketing—the appropriate roles of government and industry must be defined and adhered to. In the committee's view, private industry is unlikely to conduct most of the research on advanced automotive technologies described in the plan without government encouragement and support because of the high technical risk, the long time lag before benefits are likely to be realized, and the lack of market incentive. (For example, consumers attach little importance to fuel efficiency as long as fuel prices are low.) Nevertheless, the potential benefits to society could be significant. Therefore, government involvement, especially in the early stages of preproprietary research and engineering development, will be necessary. However, as the commercialization of a product approaches, the government role will no longer be necessary, and private industry should take over. Developing production prototypes, manufacturing the product, and marketing are obvious roles for industry, which has considerably more expertise and experience than the federal government in these areas. Commercial—as well as societal—benefits also come into play in the manufacturing and marketing stages.

The dividing line between government and industry roles in technology development is not easy to define and becomes even less distinct when industry and government share the associated costs. The committee suggests that the OAAT approach this "grey area" very carefully. In the committee's judgment, the OAAT plan assigns an inappropriate role to government in some technology areas where industry is either already doing proprietary work on its own (e.g., ethanol-fueled vehicles and CIDI engines) or is likely to undertake proprietary work in the expectation of a return on its investment. Nevertheless, the committee considers that the funding and coordination of precompetitive R&D by the OAAT are important for the overall success of developing high-risk automotive technologies with high potential payoffs.

### Scope of the Program and Relationship to Other Programs

In the committee's view, the relationship of the OAAT program and the PNGV program should be clarified in the plan. The OAAT should explain that more than 85 percent of its program is implemented in PNGV and that most of the rest is implemented in USABC. OAAT should then explain who directs the R&D and how. OAAT goals and objectives that differ from those of other programs must be clarified. For example, the PNGV Goal 3 is to develop vehicles with "up to three times the fuel efficiency of comparable 1994 sedans" (generally said to be 80 miles per gallon [mpg]). The corresponding OAAT objective is to develop and validate "automotive technologies which will enable the achievement of 80 mpg in a six-passenger sedan." The OAAT should explain why the words "up to" were omitted, given that vehicles with fuel efficiencies of 40 or 60 mpg would considerably reduce petroleum consumption. The PNGV program is scheduled to end in 2004 with the development of production prototype vehicles, and the OAAT plan covers the five years from 1997 through 2001. It is not clear from the plan what will happen between 2001 and 2004 or how the OAAT plan relates to technical targets and objectives of PNGV after 2001.

The scope of the OAAT plan includes "automobiles and light trucks (pickups, mini-vans, and sport utility vehicles) under 8,500 lb. GVW [gross vehicle weight]."[1] However, the plan does not directly address light trucks. The experience of committee members has shown that there are significant differences in the targets and technologies for passenger cars and light trucks. This opinion is supported by a statement from the NRC Standing Committee to Review the

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[1]Light vehicles are defined as passenger vehicles and light trucks under 8,500 lb. GVW in accordance with the Environmental Protection Agency's system of vehicle classification.

Research Program of the PNGV, "As decisions to narrow the technology focus are made, care must be taken not to discard technologies that are not suited for a midsized car but are capable of providing improvements that meet Goal 3 requirements in a different segment of the light-duty vehicle fleet." By the same token, some technologies suited for midsize cars may not meet the requirements for light trucks. Consequently, the OAAT plan must either address the requirements for light trucks specifically or eliminate them from the plan. The committee believes eliminating them would be a serious mistake, however, because light trucks, many of which are heavier and consume more fuel than most passenger cars, have become an important part of the market.[2] In the course of its assessment of CIDI engine technologies (see Chapter 3), the committee determined that DOE's Office of Heavy Vehicle Technologies (OHVT) has a CIDI program for the sport utility market. A better explanation of how R&D in the OHVT relates to R&D in the OAAT would be helpful for the reader.

The committee acknowledges that the strategic plan of DOE's Office of Transportation Technologies (OTT), within which the OAAT is located, addresses some issues related to fuel supply and infrastructure for advanced technology vehicles (DOE, 1996b). However, omitting these issues from the OAAT plan raises some concerns because problems in these areas could be "showstoppers" for some technologies, especially for alternative fuels and electric vehicles. Therefore, fuel supply and infrastructure must be taken into consideration in OAAT's systems studies.

## GOALS AND OBJECTIVES

The committee recognizes that DOE's goal of increasing energy productivity would strengthen the U.S. economy and improve living standards; reduce the country's vulnerability to sudden changes in energy prices and supplies; and reduce the adverse environmental effects associated with energy production, delivery, and use. The committee also acknowledges the desirability of slowing the rate of growth of petroleum consumption, provided this can be done without serious adverse effects. In the committee's judgment, the possible adverse economic, social, and other consequences of reducing the rate of growth of petroleum consumption could outweigh the benefits, depending on how the reduction was accomplished.

Energy productivity would be increased if the level of today's transportation services from petroleum-fueled vehicles could be maintained using less petroleum, notably by increasing vehicle efficiency. In addition, the rate of growth of

[2]Total U.S. sales of new light trucks (including sport utility vehicles) increased from about 20 percent of the passenger automobile and light truck market in 1976 to about 40 percent in 1994 (DOE, 1996a). Preliminary sales data indicate that the market share for new light trucks in 1997 had increased to 46 percent (Automotive News, 1997).

petroleum use would decrease if alternative fuels or electric vehicles came into widespread use. Therefore, the OAAT has set a goal of researching, developing, and validating technologies that will enable the introduction to the domestic market of vehicles with several times the fuel efficiency of current, comparable conventional vehicles and/or alternative fuel sources.[3] Advanced technology vehicles will have to meet all future emissions standards and will have to be competitive with conventional vehicles in other ways. In the committee's view, these are commendable goals although the probability of success appears to be small, at least within the time frame defined in the plan. (The target is an 80 mpg, six-passenger sedan that could be successfully marketed by 2008.)

The performance goals alone represent severe challenges, and the likelihood of success from a marketing standpoint will be small unless conventional vehicles become much more costly to purchase and operate than they are today. This opinion is supported by the findings and conclusions of the NRC Standing Committee to Review the Research Program of the PNGV, which noted that "there continues to be a wide gulf between the current status of system and subsystem development and the performance necessary to meet major PNGV milestones" (NRC, 1997). The PNGV review committee also concluded that, when incorporated into a vehicle "none of the energy converters/power trains will come close to meeting the cost objectives within the time frame of the PNGV program." The PNGV Goal 3 (up to 80 mpg) is less demanding than the corresponding OAAT objective (80 mpg) in a six-passenger sedan. The goal of the PNGV is to develop production prototype vehicles by 2004.

The OAAT goal includes a requirement that vehicles be fuel flexible, apparently to allow the use of alternative fuels. In the committee's judgment, this requirement is ill-advised if it applies to individual vehicles, although it would be helpful for the overall transportation system to be fuel flexible so that alternative fuels could gradually meet more of the demand. Individual fuel-flexible vehicles would have advantages in a time of transition from gasoline to alternative fuels but would make meeting all other performance requirements more difficult. Attaining the high performance needed to meet the challenging fuel efficiency goal and other targets will be less difficult if individual vehicles are optimized for a well defined and well refined fuel. Electric vehicles are not addressed specifically in the OAAT goal, although they are included in the objectives and technical plan.

Several terms in the OAAT's stated goal for fuel efficiency (80 mpg) should be changed. "Cost" is a better term than "price" because price is determined by many nontechnical factors. "Fuel efficiency" is less ambiguous than "fuel economy," particularly in reference to alternative fuels. "Gasoline equivalent fuel consumption per mile" might be even better because it provides a better perspective

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[3]Alternative fuels include ethanol, compressed natural gas (CNG), dimethyl ether, and, in the case of electric vehicles, coal and nuclear fuel.

on energy productivity than targets expressed in mpg.[4] For example, reducing fuel consumption by going from 50 mpg to 100 mpg would save only half as much fuel as going from 25 mpg to 50 mpg.

The plan should include a preamble to the objectives explaining that fuel efficiency numbers refer to a six-passenger sedan as a test bed for the advanced technologies but that the technologies (with some adaptations) could be applicable to other light vehicles under 8,500 lb. GVW, for which the numbers for fuel efficiency would be different. As the committee noted earlier, the plan should be changed to include a list of the target fuel efficiencies for light vehicles other than automobiles and a discussion of the differences in technology requirements for light trucks and automobiles.

The terms "commercially viable," "could be successfully marketed," and "could be marketed" used in the OAAT objectives must be defined better. It is not clear whether or not the three expressions are synonymous. In the committee's view, the expression "technically capable of being marketed" might be more appropriate in all three cases. Even this phrase should be qualified unless fuel procurement and infrastructure requirements, which are not included in the plan, are taken into account in system studies to define marketability. The committee agrees that dates when performance goals will be achieved should be specified but has concerns about using dates to specify when vehicles will be "capable of being marketed."

Dates when the marketing becomes feasible are beyond OAAT's control and depend on the timing of a variety of market factors coming into play. In this context, a report from the Office of Technology Assessment (OTA) notes that the extent to which a U.S. technological lead in advanced automotive technologies will be translated into early commercialization "will depend on future government policies as well as how the vehicles perform and how much they cost relative to steadily improving conventional vehicles of the same generation" (OTA, 1995).[5] An important criterion for marketability is cost competitiveness, but it is impossible to predict when the price of gasoline or diesel fuel will rise to the level that would make advanced technology vehicles cost competitive. As OTA noted, "the cost effectiveness of fuel economy technologies and customer preference for efficient vehicles will vary with gasoline prices."

The dates for meeting the 80 mpg and 100 mpg performance targets and for marketing the associated technologies in the Executive Summary and the Goal and Objectives section of the plan differ. For example, the Executive Summary refers to the development and validation "by 2004" of technologies that will

[4]The energy content of gasoline is generally influenced by the energy content of additives present in significant volumes, such as oxygenates. Any determination of gasoline equivalent fuel consumption needs to take into account the variability in energy content due to additives.

[5]Future government policies might address air quality and potential global climate change through revised emissions standards.

enable the achievement of 80 mpg in a six-passenger sedan that could be successfully marketed by the year 2008. The Goal and Objectives section of the plan makes no reference to the milestone in 2004, although it does refer to the 2008 milestone for successful marketing. Similarly, a milestone in 2011 (in the Executive Summary) for the development and validation of technologies that "use nonpetroleum-based fuels and achieve zero emissions while obtaining 100 mpg" does not appear in the Goal and Objectives section. The committee considers objectives relating to technology development and validation to be more relevant to the OAAT plan than objectives relating to marketability, which is out of OAAT control and strongly dependent on a range of market factors. Thus, the omission of the technology development and validation milestones from the Goal and Objectives section of the plan should be rectified.

The plan includes separate objectives relating to the use of compressed natural gas (CNG) and ethanol as alternative fuels. The objective for CNG refers to the use of this fuel in conventional automobiles "to achieve full range and performance capability by 1999," although no target is specified for fuel economy.[6] In the committee's opinion, reductions in CNG refueling costs and the convenient availability of quality fuel are more critical for market penetration than vehicle range. The objective for ethanol requires "80 mpg (gasoline equivalent) in demonstration automobiles by 2008." Given that at least two automotive companies are already producing ethanol-fueled vehicles that use substantially less petroleum than conventional vehicles, the committee does not believe the OAAT should be pursuing incremental improvements in vehicle performance. (These concerns are addressed in detail in the section of Chapter 3 on alternative fuels.) Dimethyl ether (DME) is not mentioned explicitly in the objectives although technology relating to its use is included in the section of the technical plan on alternative fuels.

## ASSUMPTIONS

The plan implies that industry will determine when advanced technology vehicles will be marketed. The underlying assumption is that something, somehow, some time will produce a "market pull" that will enable advanced technology vehicles to be commercialized. The basis of this assumption is not stated, but it appears to involve a significant rise in petroleum prices either as the result of a world shortage or some other political or economic event, or because of increased concerns about the environmental impact of air pollution and global climate change. Thus, advanced technology vehicles, which are likely to be more costly than current conventional vehicles, might become cost competitive at some time in the future.

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[6]The absence of a fuel economy target for CNG-fueled vehicles appears to be inconsistent with the goal of achieving "several times the fuel economy of current, comparable conventional vehicles."

The committee's experience indicates that most readers of the plan are likely to conclude that the term "cost competitive," which is used throughout the plan, means competitive with today's comparable conventional vehicles. PNGV Goal 3 targets a total cost of ownership and operation comparable to the cost of a 1994 family sedan when adjusted for economics. The OAAT plan is less explicit about cost targets, referring to light vehicles with "attributes, such as price, that render them competitive with conventional products." In the committee's view, almost every technology in the plan is likely to increase the cost of the vehicle, in some cases significantly.

A statement in the body of the plan explains that "competitive cost" means "competitive at the time the vehicles are marketed." Therefore, the committee interpreted "competitive cost" to mean that the overall cost of ownership and operation of an advanced vehicle over the vehicle life would be equal to or less than the cost of a conventional vehicle at some given date in the future. In the committee's view, the term "cost competitive" should be explained clearly prior to the discussion of the technical plan to avoid the misconception that advanced technology vehicles are likely to be cost competitive with comparable conventional vehicles in today's market. The economics of synthetic fuel production provide a useful analogy. Synthetic fuels have the potential to be cost competitive if petroleum prices rise because of disruptions in the supply, as they did during the oil crisis of the 1970s. However, synthetic fuels are not cost competitive with petroleum at today's prices, despite considerable efforts to improve production technology and reduce costs.

## POTENTIAL BENEFITS

In the committee's view, the National Needs section of the plan provides a satisfactory description of the potential benefits to society of advanced automotive technologies. However, a prioritization of the benefits would be helpful. The plan should state whether reducing petroleum consumption is the major focus or whether energy efficiency, economics, air pollution from hydrocarbons, carbon monoxide, and oxides of nitrogen, and global climate change are equally important. The distinction is important because advanced technologies may have different effects on overall energy consumption and emissions over the fuel cycle and may also increase costs.

The plan should also acknowledge that benefits are subject to diminishing returns as technologies are refined and that reductions in petroleum consumption resulting from gains in fuel efficiency could be overwhelmed by the increase in vehicle miles traveled (VMT). Records show that VMT has increased for all vehicle classes in the United States, and continued increases in VMT are projected for the next 20 years, although at a slower rate than during the period from 1970 through 1993 (DOE, 1996b). Fuel efficiency gains are likely to be offset somewhat by an increase in VMT in response to the lower net fuel cost per mile.[7] The different time frames for reductions in petroleum consumption and the possible environmental benefits of advanced automotive technologies should also be discussed. In this context, distinguishing between air pollution and global climate change would be helpful for clarifying their short-term and long-term characteristics and their relative priorities.

Although the National Needs section of the plan identifies benefits that could accrue from the implementation of advanced automotive technologies, it does not include a discussion of related costs. In the committee's view, a discussion of cost-benefit issues would enhance the credibility of the plan and create realistic expectations about advantages and costs. Unfortunately, projections of petroleum prices have been notoriously unreliable in the past and will probably remain so in the future. The future need for advanced automotive technologies and the costs of those technologies are uncertain. Developing technologies as an insurance policy against future needs is a legitimate pursuit, but the costs of this insurance policy must be weighed against the likelihood of the need. In the committee's opinion, the potential impact on the U.S. economy of disruptions in petroleum supplies, the potential costs of air pollution and global climate change, and the relatively modest costs of the proposed R&D, justify the OAAT plan as an insurance policy.

One point that is not adequately addressed in the plan is that a higher than "competitive" cost for advanced automotive technologies might be justified by the societal benefits, such as less air pollution, a reduced threat of global climate change, enhanced national security, or a lower trade deficit. There is a strong likelihood that, unless petroleum prices rise or there are other market incentives, the plan's goal for cost competitiveness may not be achieved within the time frame of the plan, or in the foreseeable future thereafter.

Nevertheless, some societal benefits of advanced automotive technologies could be provided immediately. Important environmental benefits, for example, could be gotten for incremental increases in cost. The American public is already paying for certain air pollution controls and safety features that are included in the price of automobiles.[8] The public must be convinced, however, that the social benefits justify further increases in cost.

Determining how much of an increase in vehicle cost is justified on the basis of societal benefits is a public policy issue that falls beyond the scope of OAAT's mandate. Nevertheless, some mention of cost-benefit issues in the plan would put the proposed R&D in a broader social context and would be particularly helpful for those responsible for making public policy decisions.

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[7]As the price of gasoline increases and the cost per mile of transportation services rises, consumers respond by reducing miles traveled (NRC, 1992).

[8]Estimates of anticipated price increases for new cars as a result of Tier I emissions controls to meet the Clean Air Act Amendments of 1990 vary widely from a few hundred dollars to $1,600 per car (NRC, 1992).

## STRATEGIES FOR OVERCOMING TECHNICAL BARRIERS

The committee found that the structure of the technical plan was excellent, with a logical flow from goals and objectives to technical targets and barriers to proposed technical approaches, which encompass technical tasks, milestones, and Go/No Go decision points. The technical barriers are particularly well identified throughout the plan and, with a few exceptions, accurately identify the most significant hurdles to development in each technology area. The barriers appear to be suitably prioritized, at least in terms of inclusion (or not) in the plan. In presentations to the committee (see Appendix B), DOE representatives indicated that the barriers are listed in order of importance for each technology, but this is not explained in the plan.

Defining barriers and establishing targets, however, do not by themselves constitute a meaningful R&D plan. Although the technical barriers are well defined, the strategies for overcoming them vary considerably. In some cases, the technical approaches do not identify courses of action but simply repeat the barrier in different words. For example, "seeking lower cost material" is not a satisfactory description of a technical approach to overcoming the barrier of high-cost materials. In other cases, the approach details activities rather than defines a strategy. For the plan to be credible, specific courses of action must be identified, especially for overcoming technical barriers that have persisted for many years despite considerable efforts to overcome them. If strategies for overcoming barriers are not available, OAAT might request proposals from the larger technical community (similar to requests issued by the NRC's Innovations Deserving Exploratory Analysis [IDEA] program). The IDEA program funds projects—each less than $100,000—for technology development and demonstration related to intelligent transportation systems, highways, and mass transit.[9] A similar approach to overcoming the technical barriers defined in the OAAT R&D plan might result in some innovative solutions and nontraditional technologies.

In general, the committee found that the subject of reducing the costs of the various technologies is not addressed adequately in the technical plan. The emphasis throughout is on performance (principally fuel efficiency), and few effective technical strategies are suggested for reducing costs (see further discussions in Chapter 3). However, cost will be a crucial factor in industry's decision to market advanced automotive technologies.

## METRICS FOR MEASURING PROGRESS

The intermediate targets, milestones, and Go/No Go decision points provide an excellent set of metrics for measuring progress. The committee particularly

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[9]The NRC allocates project funds provided by the Highway Trust Fund through the U.S. Department of Transportation.

commends OAAT for including Go/No Go decision points. However, the criteria for determining if milestones have been met are not always clear. Nor is it clear how intermediate targets were set, in particular whether they correspond to a steady rate of progress, require breakthroughs, or reflect diminishing returns. The dates for meeting the intermediate targets differ from one technology to another, but the reasons for these differences are not explained.

During discussions at the first committee meeting, representatives of OAAT explained that the technical targets are based on a combination of performance data and projections and will be refined as more data are generated. The evolving nature of the targets is not adequately described in the plan. The committee is also concerned that targets for various technologies are not always defined on the consistent basis necessary to facilitate comparisons of components that perform the same function but are based on different technologies. For example, the cost and efficiency of a fuel cell power plant should include the reformer (if used), motor, and other necessary accessories for comparison to the cost and efficiency of a CIDI engine and transmission.

For the plan to be successful in the face of budget constraints, OAAT must establish specific criteria for making Go/No Go decisions and adhere to them. OAAT should specify actions that will be taken if fuel efficiency or other targets are not met, but progress toward meeting them has been made. Will significant progress that does not meet the targets trigger a No Go decision?

## PRIORITIES

The priorities of the various technologies are not evident in the plan. Without knowing what the priorities are, how they were derived, and the criteria on which they were based, the committee was unable to comment in detail on OAAT priorities, as requested in the statement of task. Nevertheless, the committee assumed that the inclusion or exclusion of specific technologies from the plan was indicative of general priorities. On this basis, the committee believes that most of the technology areas selected for further R&D are appropriate (see discussion in Chapter 3).

During the oral presentations, OAAT representatives indicated to the committee that priorities are implied in the plans for individual technologies, notably in the ranking of technical barriers. The OAAT staff also informed the committee that prioritization across technologies will be part of the PNGV technology selection process for concept vehicles to be constructed by the year 2000, which will involve extensive discussions with interested parties. The committee recognizes that setting priorities, particularly across technology areas, is difficult and requires judgment. In some cases a lack of adequate data to support decisions adds to the difficulty, and priorities may need to be revised as more data are obtained. The committee recognizes that it may not be desirable to articulate priorities in the plan if they are likely to change more frequently than the rest of the plan. The situation with budget levels is somewhat analogous. Because the plan is a long-range planning document, explicit budget levels are not defined in the plan. Nevertheless, the committee emphasizes that good management requires that OAAT establish clear priorities, even if they are not articulated in the written plan.

Criteria that might be used to set priorities include potential payoffs, probabilities of success, levels of risk, whether a technology is on a critical path (a showstopper), and the likelihood that industry would develop the technology without government funding. The committee believes the development of improved systems analysis tools for assessing performance requirements and trade-offs would support the establishment of technically robust priorities. Vehicle systems R&D requirements are discussed in more detail in Chapter 3.

## RESOURCE ALLOCATION AND STRATEGIES FOR MANAGING THE PLAN

The plan does not include budget figures to indicate the allocation of resources to different activities. The budget information in Table 2-1 was provided to the committee by the OAAT staff. The committee concluded that in FY 1997 about 86 percent of OAAT funds was expended in the PNGV program and about 14 percent in the USABC program. However, the OAAT funding comprises only part of the total funding for PNGV and USABC. Thus, the expenditures listed in the OAAT budget do not represent the total distribution of resources in the different technology areas and give an incomplete picture of OAAT's technology priorities. The OAAT budget request for FY 1998 showed a 17 percent increase over the total FY 1997 appropriations. Increases in individual technology areas were primarily for R&D on fuel cells, high power energy storage, and hybrid propulsion systems.

A statement in the Preface declares that the plan, "is not tailored to explicit budget levels" although the activities described in the plan "have been conceived to be implemented within realistic, plausible budget levels." The plan also notes that "in the event that appropriated budget levels will not support all of the activities reflected in the plan, available funding will be concentrated on the highest-priority technical barriers in the development path of the subject technologies." No mention is made of prioritizing activities across technology areas, thereby suggesting that work would continue in all eight technology areas but at reduced levels.

In the committee's judgment, the absence of clear priorities is a serious problem that could jeopardize the implementation of the plan within anticipated budget constraints. Priorities among the various technology areas and programs are necessary for the allocation of resources and the selection of technologies for further development, especially in the likely event of budget reductions.

Extending timelines in the face of budget reductions is generally not a good practice, nor is a uniform, across-the-board percentage reduction, although both of these procedures may be acceptable temporary measures. A better practice in

TABLE 2-1 OAAT Budget

| Technology Area | FY 1997 Appropriation ($ thousands) |
|---|---|
| Vehicle Systems | |
| Hybrid propulsion systems (including analyses) | 38,850 |
| Advanced vehicle competitions | 850 |
| Subtotal | 39,700 |
| Advanced Heat Engines | |
| Piston engines | 7,600 |
| Gas turbines | 5,000 |
| Propulsion system materials | 6,500 |
| Subtotal | 19,100 |
| Fuel Cells | |
| Systems development | 12,150 |
| Component R&D | 4,500 |
| Reformer and storage | 4,500 |
| Subtotal | 21,150 |
| High Power Energy Storage | |
| High power batteries | 5,135 |
| Ultracapacitors | 2,165 |
| Flywheels | 700 |
| Subtotal | 8,000 |
| Power Electronics and Electric Machines | 3,000 |
| Advanced Automotive Materials | |
| Lightweight materials | 13,871 |
| Subtotal | 13,871 |
| Alternative Fuels | 2,370 |
| Electric Vehicle Battery | |
| Advanced battery development | 15,320 |
| Exploratory technology research | 2,500 |
| Subtotal | 17,820 |
| TOTAL | 125,011 |

most cases is to select projects for further work based on clear priorities and put others on hold or eliminate them. Another possibility would be to adjust industry's share of the costs. A refusal by industry to increase its cost share would be a clear indication of its judgment of the likely success and marketability of the technology.

In their presentations to the committee, OAAT representatives indicated that decisions about priorities, technical barriers, and the directions of R&D are made after numerous discussions internally within DOE and, importantly, with representatives of industry and the national laboratories. The committee believes this approach is appropriate in view of the subjective nature of predicting technology development.

## RECOMMENDATIONS

**Recommendation.** The relationship between the OAAT R&D plan and the PNGV and USABC programs should be explained clearly in the plan, particularly with regard to the different goals and objectives, budgets, and responsibilities for program management.

**Recommendation.** The OAAT should modify its R&D plan to recognize the benefits of the partial attainment of goals and objectives.

**Recommendation.** The OAAT should seek to limit its funding of R&D to areas where industry is not already doing, or is not likely to do, proprietary work on its own.

**Recommendation.** Because the OAAT plan includes R&D for "light trucks under 8,500 lb. GVW," the requirements and technical targets for these vehicles should be included in the plan.

**Recommendation.** Requirements for fuel procurement and infrastructure should be included in systems studies and should be factored into decisions regarding the viability of the various advanced automotive technologies.

**Recommendation.** The dates indicating when advanced technology vehicles could be marketed should be either eliminated from the plan or qualified to indicate that they depend on many unknown, nontechnical factors.

**Recommendation.** To ensure that expectations of the cost competitiveness of advanced technology vehicles are realistic, the OAAT should clearly define "cost competitiveness" in terms of some future date when the overall costs of ownership and operation of comparable conventional vehicles might be considerably higher than they are today because of higher petroleum prices or new environmental regulations.

**Recommendation.** The concept of developing advanced automotive technologies as an insurance policy against disruptions in oil supplies or more stringent environmental regulations should be clearly articulated. Cost-benefit issues and the time frames in which benefits (increased energy efficiency, reduced petroleum consumption, reduced air pollution, and reduced emissions of greenhouse gases) may be realized should be discussed in the plan.

**Recommendation.** The OAAT should apply more effort to reducing the costs of advanced automotive technologies and should be more specific in explaining the technical approaches to cost reduction for individual technologies.

**Recommendation.** OAAT should define the technical approaches to achieving its objectives in terms of specific actions. Suggested approaches to overcoming technical barriers might be solicited from the larger technical community, particularly when innovations or nontraditional technologies are needed.

**Recommendation.** To enhance the overall credibility of the plan, OAAT should do the following:

- clearly state the bases for the technical targets
- explain the proposed procedures for updating and refining targets as more data become available
- ensure that targets for the various technologies are defined consistently in terms of efficiencies and functional units

**Recommendation.** To ensure implementation of the plan in the face of budget uncertainties, the OAAT should prioritize R&D both within and across technology areas.

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# 3

# Evaluations of Individual Technology Areas

The committee's assessment of the individual technology areas in the OAAT R&D plan and related recommendations are presented in this chapter. The order of presentation follows the sequence in the plan. Following a brief introduction to each technology area, the committee has commented on the strengths and weaknesses of the proposed R&D and has recommended improvements, as appropriate. The recommendations address not only the technical content of the plan, but also the clarity and consistency of the presentation.

## VEHICLE SYSTEMS

The Vehicle Systems section of the plan attempts to define the requirements for subsystems of the overall vehicle system necessary to meet the OAAT goals and objectives. The proposed approach involves computer modeling of the overall vehicle system, based on the development and validation of subsystem models incorporated into the overall vehicle system models. The approach also involves the design and development of complete test-bed vehicle systems for validating system models, demonstrating that vehicle performance objectives can be met, and validating subsystem and component technologies.

### Comments

The vehicle systems area is crucial to the overall plan and deserves the prominent position it is given in the presentation. Systems analyses are necessary for configuring a vehicle to meet performance objectives. They are also necessary for setting priorities among technologies as a basis for allocating resources and selecting technologies, as well as for making Go/No Go decisions. In FY 1997, 31 percent of the OAAT budget ($38.85 million) was allocated for vehicle systems.

The committee was not able to determine how much of the vehicle systems budget is devoted to systems analysis and how much to hardware development. The PNGV program devotes approximately $2.5 million each year to systems analysis (NRC, 1997). The committee believes that, at the present stage of development, systems analysis and supporting validation (if they can be provided quickly) are among the most important activities described in the plan because the results are needed to support decisions about future directions for technology development. The allocation of funds should reflect the crucial importance of systems analysis.

In the committee's judgment, the technical tasks and milestones for the vehicle systems area are well thought out and appropriately directed toward modeling, simulation, and validating hardware for the complete vehicle. Nevertheless, these tasks and milestones are incomplete because they focus almost exclusively on fuel economy targets (50 mpg, 80 mpg, and 100 mpg) and pay little attention to costs, emissions, and other targets. Costs, emissions, acceleration, noise, vibration and harshness, drivability, safety, aerodynamics, rolling resistance, reliability, accessory loads (which can have a large impact on overall power requirements), and other criteria must also be considered in the optimization of a vehicle or in a decision to terminate research. Cost, in particular, could be considered a trade-off with societal benefits, or even with fuel economy, if the trade-offs were consistent with the goals and objectives of the plan. The plan should clarify how these trade-offs, as well as factors other than fuel economy, would be included in the analyses. More complex models will be required for these analyses than the very simplified models described in the technical approach to vehicle systems.

Unfortunately, the plan devotes so much space to the status and targets of the PNGV vehicle systems technology that the OAAT plan is somewhat neglected. In the discussion of technical barriers, too, the real barriers to system integration are given less attention than subsystem barriers. The presentation of the vehicle systems R&D plan suggests that the focus is on propulsion systems, with less consideration given to other systems and components. For example, the proposed approach focuses on advanced engines, does not even mention fuel cells or electric batteries, and does not include fuel type as a primary factor in vehicle system design. The transition from first generation to second generation test-bed vehicles, which aims to ensure that only the most cost-effective integrated systems are developed, is not clearly described.

The description of the vehicle systems R&D does not clarify whether the OAAT plans to focus on hybrid or conventional vehicle configurations. In contrast to conventional power trains, which have a single power source, hybrid power trains have a primary power source and a secondary power source that provides onboard energy storage. With a hybrid configuration, the primary energy converter can be smaller than in a conventional vehicle and can operate at loads and speeds that optimize efficiency, independent of the vehicle's immediate needs. In addition, a significant portion of the kinetic energy can be recovered as the vehicle decelerates. Regenerative braking is mentioned in the plan, but no strategy for overcoming related barriers is identified. In addition, the costs and benefits of regenerative braking, as opposed to alternative approaches to improving fuel efficiency (such as lightweight materials), are not addressed.

The decision to focus on either a hybrid or nonhybrid vehicle is a systems issue that should be addressed in the vehicle systems section of the plan. The development of advanced power plants depends on this decision, but most power plant development described in the plan appears to be oriented toward a hybrid vehicle. In the committee's judgment, conventional (nonhybrid) vehicles should not be excluded at this time, particularly in light of the cost constraints described in the OAAT goal (advanced technology vehicles will have to be competitively priced compared with conventional vehicles.) The need for two power sources in a hybrid vehicle is likely to increase the overall cost and complexity of the power plant compared to conventional power plants. The increased complexity raises concerns about reliability because there are more possibilities of design flaws and failures. The committee urges OAAT to develop systems analysis tools to support decisions regarding vehicle configuration, including the decision to focus on hybrid or conventional power trains.

Background information presented orally to the committee provided a much clearer picture of OAAT's plans in the area of vehicle systems than the written description in the plan. Incorporating the information provided by the DOE staff in its verbal presentations would greatly enhance the vehicle systems section in the plan.

### Recommendations

**Recommendation.** The OAAT plan should emphasize the development of improved systems analysis tools that incorporate all factors relevant to (1) configuring the vehicle and making trade-off decisions; (2) setting priorities for resource allocation and technology selection; and (3) supporting Go/No Go decisions. Funding for systems analysis should reflect its overall importance to OAAT's R&D effort.

**Recommendation.** The plan should include a thorough analysis of the trade-offs between hybrid and conventional (nonhybrid) vehicle configurations, including the relative reliability of hybrid and nonhybrid systems.

**Recommendation.** The written presentation of the section on vehicle systems should be revised to include more background information.

## ADVANCED ENGINES

The focus of the OAAT R&D plan for advanced engines is on CIDI (compression-ignition direct-injection) and gas turbine engines. Some work on spark-ignited, lean-burn engines is included but is slated to end in 1999. Industry is expected to continue work on the development of spark-ignited engine technology.

### Compression-Ignition Direct-Injection Engines

The OAAT plan for R&D on advanced automotive piston engines involves working with the U.S. automotive industry to solve the major technical barriers associated with the CIDI engine. The major focus is on reducing emissions without compromising efficiency. Other technical objectives include increasing specific power by making the engine lighter. If the CIDI engine does not meet Environmental Protection Agency (EPA) emissions standards, it would have to be eliminated from further consideration for advanced technology vehicles.

One area of activity in the OAAT plan encompasses several cooperative research and development agreements (CRADAs) between national laboratories and industry on oxides of nitrogen ($NO_x$) catalysts and nonthermal plasma technologies. CRADAs include the development of sensors and controls to measure and control emissions. Technologies for controlling particulates, fundamentals of exhaust gas recirculation (EGR), the development of CIDI models, and R&D on fuel systems are also being pursued.

A second area of activity on CIDI engines described in the OAAT plan is R&D funded under the Hybrid Propulsion System Development Program, which was initiated by DOE with Ford in 1993 and with Chrysler in 1996. This program is focused on building and testing small displacement, lightweight, turbocharged, direct-injection engines for parallel hybrid propulsion systems.[1] Ford is working with the FEV Engine Technology Corporation to design and develop a 1.2-liter, four-cylinder engine. FEV is responsible for engineering the top end (i.e., cylinder head, ports, piston cup design, and EGR) and the combustion system. Ford is responsible for the bottom end of the engine (i.e., cylinder block, crank train, sleeves, connecting rods, oil and water pumps, starter, and alternator), as well as for after-treatment. The first Ford/FEV development engine was on the test stand in Aachen, Germany, in the summer of 1997, and five technologies have been selected for further development.[2] Work will focus on three areas, emissions

[1]In a parallel hybrid propulsion system, the engine supplies some power directly to the drive wheels through a mechanical transmission, which is supplemented by electrical machines and an electrical power source. In a series hybrid propulsion system, all of the engine power is transmitted to the drive wheels through electric machines.

[2]The following technologies were chosen for development: high pressure, common rail, fuel injection system; variable geometry, turbocharged boosting system; aluminum engine material; re-entrant bowl, swirl-supported combustion system; and active, lean $NO_x$ catalyst after-treatment.

control; noise, vibration and harshness; and power density and engine weight. Chrysler is working with the Detroit Diesel Corporation to develop a three-cylinder engine, which is at the detailed design stage. The engine technologies being developed by FEV/Ford and Chrysler/Detroit Diesel may be suitable for conventional vehicle drivetrains, as well as for hybrid systems.

Under the Hybrid Propulsion System Development Program, and aside from the CIDI effort, OAAT is also funding some work on a Stirling engine[3] at General Motors and Stirling Thermal Motors for a series hybrid system. In this case, General Motors is supporting the hardware development, and OAAT is funding only the vehicle systems analysis.

A third area of CIDI R&D within DOE—but outside of OAAT—is a major ongoing project within the OHVT (Office of Heavy Vehicle Technologies) directed toward the development of diesel engines for light trucks, sport utility vehicles, and heavy-duty vehicles. Industry participants are Caterpillar, Cummins, and Detroit Diesel. OAAT coordinates and co-sponsors cross-cutting projects with OHVT.

### *Comments*

The committee believes that the development of a CIDI diesel engine is important to meeting the goal articulated in the OAAT plan. The CIDI engine could be used in a wide range of light-duty vehicles, assuming emissions standards; noise, vibration, and harshness goals; and targets for power density, specific power, and cost can be met as a result of R&D by government and industry. The marketability of the CIDI engine will be strongly influenced by the price and availability of both gasoline and diesel fuel. Fuel prices will be affected by any necessary modifications, such as sulfur removal, an increase in cetane number, or a reduction in aromatic content. Thus, engine and fuels development should not be treated independently.

One aspect of the OAAT plan that needs to be clarified is the basis for the technical targets for the performance of CIDI diesel engines. Targets for peak efficiency, peak power, specific power, emissions, and power density are given in the vehicle systems section. More detailed performance targets, as well as cost targets, are given in the discussion of R&D on advanced automotive piston engines. But neither the basis for the targets nor the relationship between the two sets of targets is clear. For example, it is not clear whether the "peak efficiency" in the discussion of vehicle systems corresponds to "best brake thermal efficiency" or "best full-load thermal efficiency" in the discussion of advanced

[3]The Stirling engine is an external combustion, reciprocating piston engine that is typically very quiet and relatively vibration free. It has been used successfully for stationary solar-to-electricity energy conversion and for some submarine and satellite applications (NRC, 1997).

engines. It is also not clear which, if any, of these efficiencies correspond to the efficiency used to generate the design space for achieving the 80 mpg target. In other words, if the goals are met, where will the CIDI engine option fall in the design space and what will the corresponding requirements be for mass reduction and regenerative braking?

The objectives for the CIDI engine program are to validate $NO_x$ emission levels of 0.3 grams/mile (g/mile), emissions of particulate matter of 0.05 g/mile,[4] and to be cost competitive, although the targets do not appear to call for reductions in engine costs. The technical targets call for substantial improvements in specific power and durability, and the technical barriers list "cost" and "operational shortcomings (acceleration, odor, and noise, vibration, and harshness)," in addition to emissions, but the technical tasks appear to address only the problem of emissions.

The Executive Summary states that the plan includes light vehicles, i.e., automobiles and light trucks (pickups, minivans, and sport utility vehicles) under 8,500 lb. GVW. The committee found, however, that the programs in the OAAT plan are directed almost exclusively toward automobiles, although in the case of CIDI engines, light trucks might be the easiest market to penetrate. If present trends continue, light trucks will dominate the market sometime between 2004 and 2008 (NRC, 1992; DOE, 1996), and much of the OAAT enabling R&D might be applicable to these vehicles. As the committee discovered, OHVT has a program directed toward the sport utility market. Even though this program is not covered in the OAAT plan, it could be described in a background discussion that would put the OAAT program in a broader context. A better description of how R&D funded by OHVT and R&D outside the government will complement the OAAT program would also be helpful.

The distinction between government and private sector roles in R&D on CIDI engines is of concern to the committee. Many of the CIDI engine technical tasks in the OAAT plan—for example, R&D on CIDI fuel systems, spark-ignited combustion, advanced integrated emission control, and technology validation—are already being pursued by industry independently. Therefore, it is not clear to the committee why the government should be a partner in these activities.

The plan should distinguish between government's role in facilitating R&D and industry's role in the final development of a marketable product. The need to develop an after-treatment system to control emissions of $NO_x$, particulate matter, hydrocarbons, and carbon monoxide, which the plan identifies as the most important breakthrough technology required to make CIDI diesel engines competitive with spark-ignited engines, is a case in point. The after-treatment system will be technically sophisticated, involving sensors, controls, catalysts, and

[4]The newly announced emissions level of "down to 0.01 g/mile" for particulate matter will be a major challenge for the CIDI program, as well as a potential challenge for advanced spark-ignition engines.

advanced materials to support complex physical and chemical processes. The research to achieve this breakthrough is high risk, particularly if the cost targets are to be met, but has a high potential payoff.

The committee found no evidence in the plan of a major, directed effort to synthesize particulate traps, reducing and oxidizing catalysts, plasmas, and fuel additives into a complete emission control system. This is an area where the government, as a partner, should insist on a systems approach to planning R&D. A clear delineation should be established between the required research and the ultimate development and production of a product, and the OAAT should fund only the generic research, which includes systems research as well as component research. The ultimate development and production of a practical system should be done by industry in a competitive environment. The exploratory research for CIDI engines described in the plan does not cover the fundamentals of after-treatment, which are very complex when combined into a system. This is an example of the lack of systems-level planning in OAAT's R&D program on CIDI engines.

The major materials obstacle to meeting the weight reduction goals for a CIDI engine is the lack of a castable material that has many of the characteristics of grey cast iron but is substantially stronger. The goal of weight reduction is clearly defined in the PNGV plan but not in the OAAT plan. No clear research directions are defined in the OAAT plan for making the engine lighter, thereby increasing its specific power. Nor is there a discussion of the candidate materials, such as compacted cast iron, spheroidized cast iron, and aluminum alloys, that might meet the requirements for castability, damping, recycling, and cost, as well as weight reduction.

### *Recommendations*

**Recommendation.** The plan should describe the OHVT sport utility program and other government and industry CIDI programs and explain how they complement OAAT's R&D on CIDI engines.

**Recommendation.** The plan should give a better explanation of how the OAAT program for the CIDI diesel engine will be managed in anticipation of a continuing market shift from automobiles to pickups, vans, and sport utility vehicles.

**Recommendation.** The OAAT plan should clearly identify CIDI engine projects that primarily involve generic research, which should be funded by government, and projects that involve incremental improvements in technology or are closely tied to the development of commercial products, which should be left to private industry.

**Recommendation.** The plan should include a brief description of the sources of and bases for the technical performance targets for CIDI diesel engines and should clarify the various ways the term "efficiency" is used.

**Recommendation.** The OAAT should ensure that its program includes a major engineering effort to integrate particulate traps, reducing and oxidizing catalysts, plasmas, and fuel additives, as well as advanced materials, sensors, and controls, into a complete after-treatment system to control emissions. The program should include both hardware development and modeling.

**Recommendation.** The plan should define the materials and manufacturing approaches to be used in CIDI engine designs that aim to reduce weight and increase specific power.

## Turbines

Automotive-scale (40 to 60 kW) gas-turbine power unit technology is being developed as a power plant option for use in hybrid vehicles. Gas turbines have the advantage of producing low emissions (except for $NO_x$), and they can be used with different fuels. The technical goal of OAAT R&D on gas turbines is to develop an efficiency of 38 percent or more at 25 percent load for a hybrid vehicle fuel economy of 80 miles per gallon equivalent (mpge). The stated objectives are to validate ceramic components by 1999 and to validate 80 mpge in a hybrid vehicle by 2002. Four major technical barriers are identified: efficiency, especially at part load; cost, especially in ceramic component fabrication; durability and reliability, especially for ceramic components; and $NO_x$ emissions, especially for cold starts and transients. The goal of the materials R&D program related to gas turbines is the development of durable, high temperature, high strength ceramic materials and associated manufacturing technologies.

### *Comments*

Gas turbine engines have characteristics that can potentially contribute to the OAAT goal of developing propulsion systems for light vehicles with improved fuel economy, low emissions, and alternative fuel capability. More than a half-century of development, primarily for commercial and military aircraft, has resulted in a mature technology and gas turbine engines with power-to-weight ratios, emission characteristics, and fuel flexibility superior to current spark-ignited and compression-ignition automotive engines. The peak thermal efficiency of these larger gas turbine engines also exceeds the thermal efficiency of spark-ignited engines and is comparable to the best current compression-ignition engines. However, these efficiencies have not been demonstrated in smaller engines (less than 100 kW) that are compatible with automotive requirements. These efficiencies appear to be extremely difficult to achieve because of the problems of developing small aerodynamic turbomachinery components and the necessity for high turbine inlet temperatures (NRC, 1997). Aircraft and military gas turbines are also extremely expensive and do not have operational-envelope characteristics compatible with automotive driving-cycle requirements. Specifically, part-load efficiency in aircraft and military gas turbine engines is typically poor; response time is slow compared to automotive needs; and the rotational speed of appropriately sized engines is at least an order of magnitude greater than automotive spark-ignited and compression-ignition engines, which puts severe performance demands on mechanical transmissions and electric machines.

Aircraft-type gas turbine engines achieve high thermal efficiencies largely by operating at high turbine inlet temperatures (1,200°C to 1,400°C). The high temperatures are possible because of the combination of high-temperature superalloys and intricate air cooling passages internal to the turbine blades. Both of these features are much too expensive for automotive engines. Therefore, the approach proposed in the OAAT R&D plan is to use cast ceramic turbine components that can withstand the high turbine temperatures.

The development of a technology for producing high quality, low cost ceramic turbine components will be necessary, but not sufficient, for producing automotive propulsion systems that meet OAAT objectives. One area of concern, for example, is that engines that operate at high temperatures might produce unacceptable levels of $NO_x$ emissions. Even if the high temperatures can be reached, the target efficiencies can only be achieved if very effective regenerators or recuperators are used to recover waste heat.

High rotational speeds and slow response times essentially dictate that a gas turbine engine in an automobile will require a hybrid configuration, specifically a series hybrid configuration. Consequently, a high-speed, high-efficiency generator (or alternator) must be developed as an integral part of the gas turbine engine.

Six of the seven technical barriers to the development of gas turbines and engine system materials are entirely or primarily associated with ceramic components, and seven of the eight technical tasks are entirely or primarily associated with the development and manufacture of ceramic components. The implication is that overcoming problems with ceramics would all but eliminate the technical barriers to a hybrid vehicle turbine. However, this inference may not be justified because there may be other technical barriers, such as:

- high efficiency, low cost compressors and burners
- high efficiency, high speed, low cost generators or alternators
- low cost control systems
- low cost means of powering accessories
- low cost, highly effective, lightweight, low volume regenerators or recuperators
- a means of providing high engine efficiency at low engine load
- the minimization or elimination of high fuel consumption under no-load conditions (idling or decelerating)
- casing materials, tolerance requirements, balance, bearings, start-up and shutdown systems, sound generation
- issues relating to fatigue and engine life in an automotive application

It is also likely that, if the target combustion temperatures are achieved, $NO_x$ production will emerge as a major technical barrier.

In the committee's judgment, the technical barriers identified in the plan and the tasks to resolve them are generally reasonable and appropriate. Unfortunately, the goals and objectives for turbines do not mention cost, which is included in the technical targets for the turbine but not for the ceramic components. The dates for meeting the technical targets and milestones must surely be questionable, given that the technical approach to low cost ceramic components has not been defined and that breakthroughs appear to be necessary. Other important technical areas are not addressed, raising the possibility that even if a ceramic turbine could be developed, the engine could still be far from successful.

*Recommendations*

**Recommendation.** The technical approach to producing low cost, durable, and reliable ceramic components should be better defined in terms of specific technical (as opposed to administrative) paths.

**Recommendation.** The plan should specify major technical barriers to the development of automotive gas turbines besides the development of high temperature, low cost ceramic components. The following objectives and tasks should be added to the plan:

- address other areas where costs may be unacceptably high, such as compressors, burners, control systems, bearings, and housings
- establish a more definitive approach to achieving very high efficiencies at 25 percent power
- establish a more definitive approach to reducing $NO_x$ levels, if necessitated by increased combustion temperatures
- define an approach to developing a high efficiency, low cost alternator
- establish criteria for acceptable engine life

## FUEL CELLS

Fuel cells are being investigated as a potential alternative to the internal combustion engine in automobiles. Fuel cell vehicles offer the potential of higher energy efficiency than vehicles powered by internal combustion engines because they use a near isothermal electrochemical reaction as opposed to a combustion process. Like combustion engines, fuel cells can use a variety of hydrogen-rich fuels (hydrogen, methanol, gasoline, ethanol, and other hydrocarbons) from fossil or renewable sources. If an onboard fuel reformer is used, there could be emissions of sulfur and carbon monoxide (CO), although these are likely to be very low because the fuel cell/reformer system contains catalysts that are degraded by sulfur and CO. Issues associated with the production of a clean fuel remain to be resolved. The use of any hydrocarbon fuel in a fuel cell will result in emissions of carbon dioxide ($CO_2$). Thus, hydrogen fuel cells have zero or near zero undesirable emissions, although with a reformer generating hydrogen from a carbon-containing fuel, they have greenhouse gas emissions ($CO_2$).

Proton exchange membrane (PEM) fuel cells are the current technology of choice for road vehicles. They offer the potential for low cost mass production, as well as higher power density and more rapid start-up time (because of low-temperature operation) than other types of fuel cells. Nevertheless, the power density and start-up time for PEM fuel cells are poor when compared to internal combustion engines. The OAAT program (like most other fuel cell vehicle development programs around the world) has focused on PEM technology (NRC, 1997).

All fuel cells being considered for automotive applications require hydrogen fuel. Because a hydrogen infrastructure is not widely available, hydrogen must be produced from a readily available fuel source. Therefore, the OAAT program has focused primarily on a hydrocarbon fuel with an onboard fuel processor to convert it to a hydrogen-rich gas that can be used by the fuel cell. OAAT has also supported some research on onboard hydrogen storage and direct methanol fuel cells.

In addition to research on fuels for fuel cells, the OAAT program supports research on fuel cell stack systems (the reduction of catalyst loadings, CO poisoning of catalysts, stack materials and manufacturing, thermal and water management, balance of plant integration), fuel processors (CO cleanup, system integration and efficiency, start-up and transient operation, thermal management), and hydrogen storage. In addition, OAAT supports R&D on integrated 50 kW fuel cells and fuel processor systems. Industry-led teams are developing three integrated automotive fuel cell power systems that run on hydrogen, methanol, and gasoline, respectively. Demonstrations of all three of these systems are scheduled in the next several years.

## Comments

The committee identified four major strengths of the proposed fuel cell R&D program. First, the research priorities are focused on the most important technical issues: fuel cell stack performance, fuel cell component cost and manufacturing, fuel processor development, system integration, and hydrogen storage. Second, technical barriers are clearly identified, and the approaches to overcoming them are generally good. A detailed, cogent research program is set forth.

Third, the program is keeping open the hydrogen option (by supporting studies on hydrogen storage) and is also supporting an ongoing small program with the Defense Advanced Research Projects Agency (DARPA) on direct methanol fuel cells. However, the main thrust of the OAAT program is the development of onboard fuel processors that operate on gasoline, methanol, ethanol, or natural gas. The OAAT program is well coordinated with the DOE Hydrogen Program, and in the committee's judgment, this coordination should be continued. Finally, a program to develop three PEM fuel cell systems (fueled with hydrogen, methanol and gasoline) is planned. This program should provide much needed data for evaluating options for systems that combine fuel processors and fuel cells.

The committee also identified weaknesses in the R&D on fuel cells. First, international developments in fuel cell vehicles, notably by Daimler-Benz, Toyota, and Ballard, should be considered in the plan. Second, a variety of fuels (methanol, ethanol, gasoline, and natural gas) are listed as possibilities for fuel cell automobiles, but the potential of each option has not been adequately evaluated from a systems perspective. Systems studies should compare vehicle efficiencies for various fuel options. Questions to be addressed include whether, when using natural gas, the onboard fuel processor and compressed gas storage tank would be too bulky to fit in the vehicle and would render vehicle efficiency targets extremely difficult to achieve because of the extra weight. Systems studies to clarify performance and cost goals for fuel cell vehicle components should be continued and expanded, especially to compare alternative fuels and fuel processors and to compare fuel cells to other power plants. The experimental and systems integration studies for the next few years should help establish the viability of fuel cell vehicles.

The written presentation of the OAAT plan is somewhat confusing. The objectives refer to a peak power level of "40 kW net" without explaining the term "net." Also, the technical targets are for "40 kW peak power (continuous)" although the technical tasks all refer to a 50 kW system. In the vehicle systems section of the plan, it appears that corresponding peak power requirements for the gas turbine and the CIDI engine are 50 kW and 55 kW, respectively.

One objective is that fuel cells be "cost competitive with internal combustion engines" (with no caveats about when they are marketed), although the technical targets indicate a 5.7-fold reduction in stack system costs and a 6-fold reduction in integrated fuel cell power system costs. However, cost reduction strategies are not discussed in detail in the technical approach or technical tasks.

## Recommendations

**Recommendation.** To establish the potential of fuel cells, the plan should identify clearly the need for vehicle systems studies based on updated, consistent assumptions, and experimental data, as they become available, to model vehicle components. Adding economic factors to vehicle systems models will help identify key areas for development.

**Recommendation.** International developments in fuel cell technologies should be closely monitored by OAAT, and the plan should be modified as necessary to take these developments into account.

**Recommendation.** The plan should recognize the need for periodic re-examinations of fuels and fuel infrastructures, in coordination with other DOE alternative fuels programs.

**Recommendation.** Adequate funding should be provided over the next few years for experimental and systems integration work to elucidate the potential performance of fuel cell vehicles.

## HIGH POWER ENERGY STORAGE

A lightweight, compact, high power energy storage device is one of the critical pacing component technologies for a viable hybrid propulsion system. A storage device is necessary for load leveling the primary power source and for recovering kinetic energy for regenerative operation. The OAAT has determined that three devices, advanced high power batteries, ultracapacitors, and flywheels, have the potential to meet these requirements. The plan identifies energy storage requirements for hybrid vehicles with both fast-response and slow-response engines.[5] The requirements were derived from an analysis of 80 mpg vehicle systems, but the two types of engine are not further identified, and the vehicle configurations are not described. Thus, it is not clear what functions the high power energy storage devices are expected to provide—regenerative braking, load leveling, acceleration capability, or hill-climbing capability. The reasoning for the choice of devices is not clear either. An explanation of the "Minimum" and "Desired" columns in the table of energy storage requirements for hybrid vehicles would be helpful.

### Recommendation

**Recommendation.** The plan should include a discussion of the hybrid vehicle configurations in which the high power energy storage devices would be used and should confirm that hybrid vehicles would meet all OAAT objectives.

### High Power Batteries

High power batteries for hybrid vehicles must have high specific power with power-to-energy ratios greater than 10 kW/kWh. In contrast, batteries for EVs (electric vehicles) require high energy storage but relatively low power-to-energy ratios of 2 to 3 kW/kWh. Advanced batteries are being developed in the USABC (U.S. Advanced Battery Consortium) program[6] and in European and Japanese

[5]A fast-response engine, such as a diesel or spark-ignited engine, is capable of following a rapidly changing load. A slow-response engine, such as a gas turbine or Stirling engine, is not capable of following a rapidly changing load schedule.

[6]The USABC (formed in 1991) is a partnership among Chrysler Corporation, Ford Motor Company, and General Motors Corporation, with participation by the Electric Power Research Institute and battery manufacturers. Through a cooperative agreement, the U.S. Department of Energy is matching industry funding. The main goal of USABC is to establish a manufacturing capability for advanced batteries in the United States.

industry and government programs (NRC, 1997). Although USABC's original focus was on batteries for EVs, the scope of its activities has been expanded to include high power batteries and ultracapacitors for hybrid vehicles being developed in the PNGV program. At present, only nickel-metal hydride and lithium-ion systems appear to have the potential to meet both the requirements for hybrid vehicles and the PNGV (and OAAT) schedules (NRC, 1997).

*Comments*

Of the three technologies presently being considered for high power energy storage (batteries, ultracapacitors, and flywheels), high power batteries appear to be the most realistic in the short term. However, major technical problems for high power batteries remain, many of which are addressed in the OAAT R&D plan.

The OAAT plan for high power batteries is explicitly aimed at satisfying requirements for a hybrid vehicle with a slow-response engine. The reason for choosing this configuration should be explained in the plan, and a brief description of a possible system would be helpful for the reader. Batteries designed and developed for slow-response power systems may not meet the requirements for fast-response engines and vice versa (NRC, 1997).

The list of technical barriers in the plan is commendably frank and clear.[7] The description of the technical approach, however, is weak in that it mentions the use of "innovative materials and processing" but does not indicate whether the materials exist or whether other approaches to overcoming the technical barriers might be possible. The list of technical tasks is reasonably clear, although it would be helpful if the individual tasks that fall within the contracts awarded to four commercial contractors (SAFT America, Inc., SRI International, Yardney Technical Products, Inc., and VARTA) were designated. The tasks for which contributions from the national laboratories are expected should also be identified.

The network chart for R&D on high power batteries, which summarizes tasks, milestones, and decision points, shows that research was begun in 1996 with a Go/No Go decision point on the construction of 50-volt (V) modules early in 1997. But the report does not reference the results of the 1996 decision, which was apparently a Go decision. The results of completed tasks to develop initial test procedures and cell models are not included either. If the research to date has resulted in a decision to focus primarily on nickel-metal hydride and lithium-ion batteries, this decision should to be clearly stated. For example, the first technical task ("assess electrode feasibility") includes the selection of baseline electrochemical couples, a task that must have been completed if nickel-metal hydride

[7]The highest priority technical barriers for high power batteries are power-to-energy ratio, models, cost, cycle life, and state-of-charge/self-discharge.

and lithium-ion batteries have been selected as of mid-1997. A brief account of the couples that were considered and rejected could bolster the reader's confidence in the selection procedures. Nevertheless, in the committee's view, nickel-metal hydride and lithium-ion technologies are the most promising battery options for meeting high power energy storage requirements for hybrid vehicles. The choice of either nickel-metal hydride or lithium-ion batteries will probably be made in the marketplace.

The four phases in the technical approach should be identified in the R&D network chart to enable the reader to judge the logic and appropriateness of the plan. The chart shows R&D continuing to 2006, several years after the USABC will have expired. The plan should explain how work that is presently under the auspices of USABC would be continued in an advanced battery initiative.

It appears to the committee that although the technical performance targets for high power batteries are very challenging, they may well be reached eventually.[8] However, the cost targets seem unlikely to be met without remarkable breakthroughs. For example, the production cost for a unit cell is targeted to decline from $750/kWh in 1997 to $120/kWh in 2006.

### *Recommendations*

**Recommendation.** The technical approach to improving the performance and lowering the cost of high power battery systems should be described in more detail.

**Recommendation.** The basis for selecting the nickel-metal hydride and lithium-ion batteries should be described, and descriptions of other battery systems that were considered should be added. The results of other completed tasks should be summarized.

**Recommendation.** The plans for continuing work on high power batteries beyond the scheduled expiration of USABC in 2000 should be explained.

**Recommendation.** Brief descriptions and comparisons of the properties and capabilities of high power batteries and electric vehicle batteries should be included in the plan.

## Ultracapacitors

Ultracapacitors are included in the OAAT plan because of their potential for storing high-density electrical energy in future generations of electric or hybrid vehicles. One feature that makes ultracapacitors particularly attractive for this

[8]Targets are for the battery unit cell, a 50-V module, and a 400-V subsystem.

role is that, like batteries, they are entirely passive. In other words, they have no moving parts to wear out.

Ultracapacitor technology is relatively new and has emerged as a serious candidate for peak power delivery in electric-based vehicle propulsion systems only in the past decade. Major technical progress has been made during this time at both university and industrial research centers. Most of this work has addressed double-layer capacitors that utilize the high electrical capacitance exhibited by particle-solution interfaces in new types of carbon materials with high surface area.

Work sponsored by DOE on double-layer ultracapacitors for transportation applications has included industrial partnerships with Maxwell Laboratories, Inc., and SAFT America, Inc. Double-layer ultracapacitor modules of up to 48 V with power densities of 1 kW/kg have been achieved in experimental cells. Despite this progress, the OAAT has concluded that double-layer ultracapacitor technology is fundamentally incapable of meeting the long-range, high power energy storage requirements for PNGV. As a result, the OAAT plan projects a major shift in future investments from double-layer capacitor technology to pseudocapacitor technology.

Pseudocapacitors are based on electrochemical reduction-oxidation (redox) reactions that utilize faradaic charge transfer mechanisms. Although the underlying physical principles have been known for some time, the development of pseudocapacitors for peak power delivery in electric propulsion systems is very immature compared to the development of double-layer capacitors. During the course of presentations to the committee (see Appendix B), the OAAT staff justified the selection of pseudocapacitor technology on the basis of its reported potential of providing significantly higher levels of power and energy density consistent with PNGV Goal 3 requirements.

The OAAT plan comprises long-range research focused on laboratory demonstrations of new pseudocapacitor cells and modules over the next five years. The OAAT acknowledges that this research carries a high technical risk but justifies this risk on the basis of the high potential payoff. The plan calls for the development of experimental unit cells by 2000, followed by higher-voltage (50 V) modules by 2002. The key technical barriers identified in the plan (in order of decreasing priority)[9] are power-to-energy ratio and cost, followed by lifetime, internal electrical resistance, and voltage matching.

*Comments*

Because significant technical progress has been made in the development of ultracapacitors in recent years, the committee considers that ultracapacitors should continue to be an active part of the OAAT advanced technology portfolio. The

[9]Priorities are not specified in the plan, but OAAT staff informed the committee that the technical barriers are listed in order of decreasing priority.

technical barriers outlined in the plan are generally well founded and appropriate. However, the committee notes that focusing on the power-to-energy ratio as the principal technical barrier is misleading because high power density and high energy density are both critical ultracapacitor characteristics. The plan should avoid suggesting that energy density can be sacrificed in favor of power density. The OAAT should also consider whether safety should be included as a technical barrier in view of the burst and rupture failure modes in some experimental ultracapacitor units.

The basis for OAAT's decision to abandon double-layer capacitor technology in favor of pseudocapacitor technology is given very little attention in the plan. This significant shift raises two questions: whether the decision to drop double-layer capacitor technology is justified on technical grounds; and whether the decision to direct future DOE investments into pseudocapacitor development is the best technical alternative for the long term.

Independent information available to the committee suggests that double-layer capacitor technology is not likely to achieve the aggressive long-range PNGV targets for energy or power density without significant new breakthroughs (IEEE, 1996). This information is therefore consistent with OAAT's decision. However, two questions remain to be answered. First, are the PNGV long-range targets for power and energy density justifiable on the basis of vehicle system requirements? Second, what are the prospects for breakthroughs in the area of double-layer capacitor materials and processes that might allow this technology to achieve significantly higher performance in the future? In the course of the committee's conversations with OAAT staff, it was not clear that either of these questions had been adequately addressed.

One justification for selecting pseudocapacitors for future OAAT investment is credible technical evidence that energy storage based on electrochemical redox couples has the potential for higher energy density (although lower power density) than electrostatic charge separation, which is the basis for double-layer capacitor technology (Conway, 1991). However, it is not clear that the potential performance advantages of pseudocapacitors can be realized because pseudocapacitors, which are close relatives of electrochemical batteries, have the well known performance problems of large bulk-storage batteries—such as limited cycle lifetime. These problems have not been solved despite huge investments in R&D by government, industry, and universities over a period of several decades. Thus, it is not clear that researchers will be able to avoid or overcome essentially identical problems with pseudocapacitors in the next several years. It is possible that pseudocapacitor technology looks attractive today in comparison to the more developed double-layer capacitor technology because the limitations are still poorly understood.

Given the time and resource constraints on the present study, the committee was unable to gather sufficient detailed technical information to make a definitive judgment on OAAT's decision to abandon double-layer capacitors in favor of pseudocapacitors. However, the committee believes that the OAAT's decision has significantly raised the risk level of the OAAT ultracapacitor program and that steps should be taken to ensure that resources are appropriately allocated in the coming years.

*Recommendations*

**Recommendation.** The OAAT should critically review its ultracapacitor technology targets to satisfy itself that the performance targets are justifiable on the basis of vehicle system requirements.

**Recommendation.** The OAAT should immediately initiate a review of the state of the art of alternative ultracapacitor technologies and determine whether the decision to concentrate future investments on pseudocapacitor technology is technically defensible. The basis for this decision should then be clearly articulated in the plan.

**Recommendation.** The principal technical barrier, identified as "power-to-energy ratio," should be modified to reflect the fact that power density and energy density are both critically important for future ultracapacitor systems.

## Flywheels

A number of diverse applications for flywheels are being investigated by companies and agencies outside OAAT, and OAAT's role appears to be largely monitoring these outside investigations. OAAT's R&D on flywheels is an enabling technology program primarily concentrated on overcoming the technical barrier of safety, especially on the problem of containment in case of rotor failure. The objectives include developing analytical models and standardized tests for rotor failure and containment systems, and the technical tasks are all directed toward overcoming the containment problem. The milestones include Go/No Go decisions in 1998 and 2001. In some cases, the containment problem is being approached more empirically by organizations outside OAAT.

*Comments*

The plan states that the flywheel is "well suited for meeting the fast-response engine requirements," but the reasoning behind this statement is not provided. The role of the flywheel in the vehicle system is not clearly articulated in the plan; it could be only to recover braking energy (regenerative braking), or it could serve other functions, such as improving acceleration, load leveling the engine, and improving hill-climbing ability. It is not clear whether the flywheel system will help meet the 80 mpg objective and still permit climbing a seven-mile-long hill at speed. If the flywheel is only intended to provide regenerative braking capability, what fraction of the braking energy can it be expected to recover? The committee would like to see the OAAT plan focus on vehicle systems studies that show the merits of different configurations of flywheel hybrid vehicle systems and the inherent trade-offs.

The flywheel containment issue is an appropriate concern, and the related modeling studies and test procedures that have been developed are valuable contributions to solving the problem. However, there is a trade-off between safety and containment requirements on the one hand and power and energy storage requirements on the other. Thus, OAAT should conduct systems analyses to justify the identification of containment as the highest priority technical barrier.

In the absence of adequate vehicle systems studies, the committee is concerned that the flywheel energy storage system may not be a viable system for a highly efficient, cost competitive vehicle even if the containment barrier can be overcome. In addition, OAAT's technical targets for power-to-energy ratio, specific energy, energy density, cycle life, and production cost are all very far from current levels, and OAAT has no program for meeting these targets. The cost estimates seem unrealistic to the committee, particularly in view of the likely cost of the necessary power electronics and motor.[10] In the context of overall vehicle requirements, OAAT systems analyses should try to determine whether flywheel subsystems can actually meet OAAT's objectives, including cost.

The committee noted that a number of technical barriers are associated with flywheel systems that are not mentioned in the plan, including bearings, vacuum maintenance, the cost and size of power electronics, gyroscopic effects, motor/generator optimization, and manufacturing processes.

### *Recommendations*

**Recommendation.** The viability of various configurations of flywheel energy storage systems, in terms of fuel savings, weight, cost, emissions reduction, and other criteria, should be assessed as part of OAAT vehicle systems analyses. The results should be used to support the Go/No Go decision regarding flywheel procurement in the fourth quarter of 1998.

**Recommendation.** High costs and the need for vehicle system integration studies should be considered high priority technical barriers, together with containment in case of rotor failure.

[10] The table of technical targets for flywheels lists production costs in $/unit. The definition of a "unit" should be provided. Technical targets for 1997 and 2000 require doubling specific energy, an increase in energy density of 60 percent, and a five-fold increase in cycle life. Production cost must be halved by 2000 and halved again by 2004.

**Recommendation.** The OAAT plan should include a description of the flywheel energy storage subsystem, including the motor/generator and power electronics, and its physical integration into a vehicle system.

## POWER ELECTRONICS AND ELECTRIC MACHINES

Power electronics and electric machines are critical technologies for meeting OAAT fuel efficiency objectives for all of the candidate hybrid or EV (electric vehicle) configurations. In particular, all of the candidate vehicle power trains that include adjustable-speed electric motors as key subsystems will require the best available power electronics and electric machines technology to meet the demanding system performance and fuel efficiency targets. In addition, other advanced technology subsystems, including gas turbines and flywheels, depend critically on high-speed electric machines and their associated power electronic converters for use in automotive systems. Unfortunately, modern power electronics have not yet been incorporated into many consumer products, including automobiles, because of chronic problems with reliability, ruggedness, and high cost.

The section of the OAAT plan devoted to power electronics and electric machines identifies the major technical objectives as increasing power density and efficiency and lowering cost. Technical targets specify quantitative values for power density, efficiency, and cost at roughly three-year intervals for the next decade. The plan provides a ranked list of seven technical barriers on which the technical approach is based.

The OAAT's planned technical approach is closely aligned with the multi-agency power electronic building block (PEBB) development program led by the Office of Naval Research, which is already under way. The purpose of the aggressive PEBB program, which involves manufacturers of semiconductors, is to develop new power semiconductor devices and modules that integrate many of the inverter functions into low cost compact units with high power density. The OAAT plan also incorporates parallel multi-year materials R&D programs in both the electric machines and power electronics areas that will be defined at the end of 1997 based on the results of an ongoing assessment of the materials needed for hybrid vehicle power electronics and EVs.

### Comments

The committee concurs with OAAT's identification of improvements in power density, efficiency, and cost as major objectives. The importance of major reductions in production costs for power electronics cannot be overemphasized. The current cost of power electronics typically overshadows the cost of electric machines by at least a five to one margin. The plan's objectives specify an 8-fold reduction in the costs of power electronics by 2004; the milestones indicate a 10-fold cost reduction by 2000; and the technical target is a 25-fold cost reduction by 2004. These inconsistencies should be resolved. Regardless of the inconsistencies, however, none of the cost targets will be easy to reach, partly because of materials costs, but mostly because of the problems of manufacturing and packaging posed by bulky passive components and nonstandardized inverter designs. Unfortunately, little attention is paid to these problems in the plan.

Power electronics must be more rugged and reliable to withstand the harsh automotive under-hood environment, which combines high temperatures and vibration. These requirements should be identified as explicit objectives in the plan. For example, electrolytic capacitors, which are major components in most inverter designs, are typically limited to a maximum temperature of 85°C and are major contributors to inverter failure rates. The reader is referred to the third report of the NRC Standing Committee to Review the Research Program of the PNGV for further discussion of the requirements for and research on automotive power electronics and electric machines (NRC, 1997).

It appears that most of OAAT's expenditures in the area of power electronics and electric machines will be devoted to R&D on power electronics rather than on electrical machines, although the proposed resource allocations are not stated. In the committee's view, a decision to focus R&D investments on power electronics is appropriate, given that, in general, the cost of power electronics today greatly exceeds the cost of electrical machines. The OAAT also plans to devote a portion of its program effort to exploring new approaches to reducing the cost of high performance motors. The committee considers this an appropriate approach.

The technical strategy is not completely defined in the present plan. Unfortunately, this is unavoidable because R&D on materials can not be specified until the assessment of materials needs has been completed at the end of 1997. Therefore, the committee cannot make specific comments or recommendations regarding the materials R&D portion of the power electronics and electric machines program. In general, however, the committee considers that the materials R&D effort should include investigation of manufacturing techniques that have the potential to reduce the costs of motors.

The second major portion of the technical approach is participation by the OAAT, through an interagency agreement with the Office of Naval Research, in the multi-agency PEBB development program mentioned above. Unfortunately, the OAAT, which contributes less than 15 percent of the PEBB program's annual budget, is a relatively minor participant in this program. The committee is concerned that not enough attention is being paid in the PEBB program to the key issue of cost reduction in deference to the aggressive power density and performance objectives. As a stakeholder in the PEBB program, OAAT should become a strong advocate for focusing on the cost reductions necessary to meet OAAT's objectives.

### Recommendations

**Recommendation.** The technical objectives for power electronics and electric machines should explicitly include more reliable and environmentally rugged power electronics to meet automotive requirements. Consistent with these objectives, the list of technical barriers should be expanded to include the constraints on operating temperatures imposed by critical passive components, such as electrolytic capacitors.

**Recommendation.** The technical barriers should be modified to specify the manufacturing limitations of current power electronics, which are at least as important as materials in driving up the costs of power converters.

**Recommendation.** After an expert review within the power electronics community, the materials R&D plan, which is scheduled for completion at the end of 1997, should be incorporated into the master five-year plan.

**Recommendation.** The OAAT, as a stakeholder in the multi-agency PEBB program, should ensure that more program resources are devoted to reducing the cost of power electronics.

## ADVANCED AUTOMOTIVE MATERIALS

Lightweight materials in the drivetrain, body, and chassis will be necessary for the OAAT to meet its goal of vehicle fuel economy. Although not all of the technical targets are specified in the systems analyses described in the plan, the weight reduction targets are well defined. Four areas are targeted, namely, a 50 percent weight reduction in both body and chassis, a 10 percent weight reduction in the hybrid power train (as it exists today), and a 55 percent weight reduction in the fuel system.

### Comments

The timelines in the plan for the development of materials and materials processing technologies will require much more rapid progress than has been made in the past. Therefore, it would be useful if strategies were more clearly defined to provide some assurance that the goals might be achieved. Using aluminum and polymer matrix materials in sheet and body structures has been demonstrated, but only at very high costs and after long and extensive efforts. Strategies for producing high volume, low cost components made of these materials have not been identified. Consistent with its earlier comments about government and industry roles in R&D partnerships, the committee considers that the government involvement in advanced automotive materials development should be limited to generic research that supports innovative approaches to overcoming technical barriers. OAAT should not fund industry work on incremental improvements in materials technology.

The strategy outlined in the plan for reducing the cost of light metals, aluminum (Al), magnesium (Mg), and titanium (Ti), does not appear to be well thought out. Considerable efforts over many decades by major metal producers, the Bureau of Mines, many universities, and others to improve methods and reduce costs have not resulted in breakthrough technologies for the production of light metals. The cost of a metal is governed by the cost to produce it from its ore.[11] Iron (Fe) is a relatively low cost metal for three main reasons: it is abundant in nature; iron ores are rich in iron and easily beneficiated; and iron oxide can be reduced by carbon at relatively low temperatures (about 700°C). Light metals are generally found in the form of very stable oxides. Although aluminum is more abundant than iron in the earth's crust, aluminum ores are much more difficult to process. The free energy of formation of aluminum oxide is much greater than that of iron oxide, and as a result, reducing aluminum oxide by carbon requires temperatures near 2,000°C. Consequently, the aluminum reduction process is performed electrolytically and is much more costly than the reduction process for iron oxides. As a result, the cost per pound of aluminum ingot is roughly ten times the cost of pig iron. Mg and Ti are reasonably abundant in the earth's crust, although less abundant than Fe or Al, but their ores are low grade (Mg is mined from seawater in the United States) and reducing them to the metallic state is much more complex. Magnesium ores are processed electrolytically or using the Pidgeon process; the Kroll process is used to process Ti.

The OAAT program goal is to produce a car that is 85 percent recyclable; present vehicles are about 80 percent recyclable. However, current vehicles contain substantial quantities of plain carbon steel and grey cast iron, materials that can be easily recycled and are eagerly sought as feedstock by mini-mills and foundries. If lightweight materials (high strength steels, Mg, Al, Ti, and composites) are used extensively in future vehicles, the recycling problems will be much more challenging. For the goal of 85 percent recyclability to be considered realistic, programs must be developed for the easy separation of components made from different materials and for recycling alloyed and polymer-based materials, all of which will be challenging tasks.

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[11]The energy requirements (and related costs) for recycling metals are much lower than for primary production. For example, steel requires about 31 gigajoule (GJ)/ton to produce and 8.7 GJ/ton to recycle. Comparable figures for aluminum are 270 GJ/ton for production and 16.5 GJ/ton for recycling. Although about 50 percent of steel and 40 percent of aluminum come from recycled materials, the supply of recycled materials is not sufficient to meet total demand. Thus the original cost of primary production is a major component of material cost, and efforts to reduce this cost must focus on the primary production process.

### Recommendations

**Recommendation.** Strategies for making very rapid progress in materials development and processing technologies should be described in more detail to enhance their credibility.

**Recommendation.** The proposed program to reduce the costs of light metals should be examined in terms of basic thermodynamic principles to establish a comparison with the cost of producing iron and iron alloys.

**Recommendation.** A program should be defined to address the challenges of recycling vehicles that contain relatively large quantities of high strength steels, Mg, Al, Ti, and composites to meet the goal of 85 percent recyclability.

## ALTERNATIVE FUELS

The strategic plan of the OTT (Office of Transportation Technologies), and the supporting R&D by the OAAT, are intended to reduce transportation energy or fuel consumption in the United States, including petroleum consumption.[12] Alternative fuels have the potential to displace substantial amounts of petroleum, as well as to improve fuel efficiency and lower emissions, if the cost barriers associated with vehicles, fuels, and infrastructure can be overcome. These cost barriers vary depending on the fuel, but none of the alternatives is competitive with today's gasoline or diesel fuel. In response to legislation, such as the Alternative Motor Fuels Act of 1988 and the Energy Policy Act of 1992, original equipment manufacturers have begun to produce vehicles that run on alternative fuel. At present, these vehicles account for only 0.1 to 0.2 percent of total highway fuel usage.

The OAAT R&D plan for alternative fuels acknowledges that the commercialization of some alternative fuels has already begun; the plan is oriented toward technologies where further research or development is needed to remove critical barriers. The fuels under consideration in the plan are CNG (compressed natural gas), ethanol, and DME (dimethyl ether). Natural gas and ethanol have already been developed as alternatives to gasoline and diesel fuel, and commercial vehicles that can operate on these alternatives are already available. In contrast, technology for DME-fueled vehicles is relatively immature.

Parallel to the efforts described in the OAAT plan, the OTT is conducting a fuels study to determine which fuels are most likely to be commercialized in the twenty-first century. This study, which is expected to be completed in 1998, will be used to prioritize future work by OTT.

[12]"Petroleum" is defined as conventional liquid fuels made from crude oil.

## Compressed Natural Gas

*Comments*

Using CNG in light-duty vehicles reduces petroleum consumption. Liquefied, as opposed to compressed, natural gas is better suited to heavy-duty vehicles. OAAT plans to develop technologies that will enable CNG vehicles to be "similar to" gasoline vehicles in cost, range, refueling convenience, safety, and acceptance level. Thus, in the committee's judgment, OAAT has correctly identified the existing shortfalls in CNG technology. A major strength of the proposed plan is the interactive R&D involving both the fuel and vehicle industries, as well as academia, which will be doing fundamental research. The main weaknesses of the plan relate to the ambitious objectives (300 mile vehicle range and 50 percent reduction in the cost of refueling stations) to be achieved within a short period of time and the relative priorities assigned to the technical barriers.

Natural gas is one of the few alternative fuels that currently has an operating cost advantage over gasoline. This cost advantage is the primary driver for fleet operators to purchase CNG vehicles, although some, if not all, of the advantage would disappear if natural gas were taxed in the way gasoline is. Even today, the lower fuel cost only offsets the higher vehicle cost if the vehicle operates in a high mileage fleet. The average retail customer does not drive enough miles per year to offset the higher vehicle cost.

One of the major barriers to retail customer acceptance of the CNG vehicle is the high initial cost of the vehicle, primarily because of the high cost of the fuel tanks. This cost would come down if the volume of production went up. The volume will remain small, however, until the retail market has been penetrated, which will only happen if there is adequate refueling infrastructure. The establishment of a low cost, widely available refueling infrastructure is unlikely because the cost of a CNG fast-fill refueling station is too high. The OAAT R&D plan estimates that the cost of a CNG refueling station is five times the cost of a gasoline facility. Therefore, even if the targeted 50 percent reduction in refueling station cost could be achieved through better compressor designs and materials and improvements in some of the other refueling technologies mentioned in the plan, the economic barrier to CNG market penetration would remain.

The refueling infrastructure issue could be addressed by retail customers using small, slow-fill compressors to refuel vehicles in their garages overnight. However, there are significant safety concerns associated with this concept, and the capital cost of the equipment (several thousand dollars) would be difficult for the average retail customer to amortize. If the equipment were leased by the gas company to the customer, the equipment cost would be reflected in an increased fuel cost, and CNG would probably not be competitive with gasoline. Without the advantage of lower fuel cost, it is doubtful that customers would be interested in CNG-fueled vehicles. Therefore, in the committee's judgment, technical tasks that address the cost and reliability of CNG refueling should be given the highest priority in the OAAT plan. Without a substantial reduction in the cost of refueling infrastructure, the market for CNG vehicles will be too small to support the OTT fuel strategy plan.

The increased use of CNG in light vehicles would reduce petroleum consumption but would not significantly reduce energy use. Therefore, the plan should state clearly that the CNG program is not aimed at 80 mpge fuel economy. Although natural gas is widely available, an increase in the use of CNG as a vehicle fuel in the United States would probably result in increased imports, as well as higher prices and higher road use taxes. Thus, the advantages of CNG in reducing petroleum consumption would be offset by increased imports and higher prices, and there would be very little reduction in overall energy use.

Environmental issues associated with the use of CNG need to be considered from a broad perspective. $CO_2$ emissions from CNG vehicles are lower than from equivalent gasoline vehicles (Leiby et al., 1996). However, increased methane emissions are associated with the CNG distribution system, and methane is a greenhouse gas with a higher temperature effect than $CO_2$. Thus the overall impact of CNG use on global climate change should be considered. The committee urges OAAT to adopt a systems perspective when addressing questions relating to the use of alternative fuels.

Lean-burn combustion, in principle, can increase fuel efficiency, but the operating limits—such as air-to-fuel ratio—consistent with maintaining vehicle performance have not been defined. Fuel-lean operation would also increase $NO_x$ emissions. The current $NO_x$ catalyst depends on the presence of CO (carbon monoxide) for the reduction reaction. If an engine is operated fuel-lean, the amount of CO present is too low for the catalyst to work, and the $NO_x$ emissions are too high to meet current air quality standards. Consequently, CNG engines must be operated at stoichiometric air-to-fuel ratios.

The plan should explain how a targeted 10 percent improvement in efficiency will produce a 150 percent increase in range, which is another target. If these targets are met by changing the design to increase the tank volume without decreasing vehicle cargo capacity, the proposed technical approach and costs should be described. The descriptions of technical tasks generally do not include descriptions of the technical approaches to overcoming barriers. Because safety is also identified as a concern, related work should be described, and work being conducted outside OAAT should be cited. The plan targets safety improvements that will make CNG as safe as, or safer than, reformulated gasoline but does not describe related technical approaches or tasks.

*Recommendations*

**Recommendation.** The priority of the technical barriers for CNG should be changed. The cost and reliability of fueling facilities and the related technical task should be given the highest priority. Substantial reductions in the cost of refueling facilities should be a major criterion for the 2001 Go/No Go decision to continue the development of CNG vehicles.

**Recommendation.** Technical tasks relating to onboard fuel storage, especially the cost of fuel tanks and vehicle range, should remain in the plan and should be assigned second and third priorities, respectively. A detailed technical description of the technologies that might enable achievement of a 300- or 380-mile vehicle range should be included.

**Recommendation.** The plan should address the issue of controlling $NO_x$ emissions in vehicles with more efficient, fuel-lean combustion.

**Recommendation.** Technical approaches to safety concerns raised by the increased use of natural gas should be included in the plan.

**Recommendation**. The plan should affirm the need for a systems approach, including life cycle analyses, to evaluate the trade-offs associated with the use of alternative fuels, such as CNG. Issues that should be addressed in a systems evaluation include the impact of the increased emissions of methane (a greenhouse gas) associated with natural gas vehicles and the related infrastructure.

## Ethanol

*Comments*

Ethanol is a renewable, nonpetroleum fuel. About 97 percent of all the ethanol produced in the United States today comes from ethylene derived from petroleum,[13] so the use of ethanol from this source would have little effect on petroleum consumption or energy efficiency. However, ethanol can also be made from biomass and thus has the potential to reduce petroleum consumption and $CO_2$ emissions, depending on the biomass source and production process. Methanol can also be a renewable fuel made from biomass, and the production process is less expensive than for ethanol. Neither methanol nor ethanol made from biomass, however, is cost competitive with alcohols produced in a chemical plant.[14]

Costs associated with ethanol use are being addressed by DOE's Office of Fuels Development and are not addressed in the OAAT R&D plan, which focuses on technical issues associated with ethanol-fueled vehicles. But the current

[13]Most ethanol used for fuel is currently produced from biomass, but ethanol for chemical purposes is produced from ethylene.

[14]Almost all of the methanol produced in the United States today is made from natural gas.

federal subsidy for ethanol produced from biomass should be a consideration in the large scale use of ethanol. Because fuel subsidies and taxes are subject to adjustments that reflect changing public policy, analyses of alternative fuels should be based on real costs rather than prices as much as possible.

The plan correctly states that a fully optimized, dedicated alcohol-fueled vehicle has the potential to increase fuel efficiency. High efficiency vehicles are being produced in Brazil, for example, where hydrous ethanol is widely available commercially. Use of hydrous rather than anhydrous ethanol reduces fuel costs because the fuel production process does not require a water-removal step. Evaporative emissions are not a problem for vehicles that use high levels of alcohol fuels. At present, dedicated alcohol vehicles are not being produced in the United States because of the lack of refueling stations for dedicated vehicles (there are only 35 ethanol and 65 methanol stations in the United States). Fuel-flexible vehicles, which are being produced in the United States, have lower performance and are less fuel efficient than vehicles fully optimized for a single alcohol fuel.

The plan also correctly states that ethanol-fueled vehicles have problems with cold starts, which is attributed to low vapor pressure (ethanol has a vapor pressure of only 2.3 psi). No mention is made of the fact that ethanol, unlike gasoline, has a single boiling point (72°C). The ethanol vehicles presently being produced in the United States are designed to use E85 (85 volume percent ethanol and 15 volume percent gasoline, with a vapor pressure of about 6.9 psi). Although the cold start performance with E85 is better than with pure ethanol, it still does not meet the same specifications as gasoline.[15] In the committee's judgment, further improvements in the cold start of E85 should be undertaken by the vehicle manufacturer. In general, the committee does not consider it appropriate for the OAAT to support the incremental improvement of ethanol-fueled vehicles, given that these vehicles are currently in production by at least two automotive manufacturers (Ford and Chrysler). Technologies for ethanol-fueled vehicles are well beyond the stage of precompetitive R&D. Because the OAAT plan for ethanol does not address innovative, high-risk approaches to making ethanol commercially competitive with gasoline, the committee sees no need for government funding of the proposed R&D.

The plan states that the successful resolution of the cold start problem with E85 technology "will allow research to progress to neat ethanol (E95)[16] in the future, which would provide greater energy and emissions benefits." Almost all

[15]The physical properties of methanol are better for cold starts (4.6 psi, with a boiling point of 65°C), and M85-fueled vehicles have met industry standards for cold starts (M85 consists of 85 percent methanol and 15 percent gasoline).

[16]E95 is composed of 95 volume percent ethanol and 5 volume percent gasoline. The terminology used in the plan is confusing because E95 is variously referred to as "neat ethanol" and "near-neat ethanol." The committee prefers to avoid use of the term "neat," which can be confusing when discussing hydrous and anhydrous ethanol.

of the efficiency gains and other high performance attributes of alcohol-gasoline mixtures can be achieved with a 50-50 mix, making the gains in changing from E85 to E95 negligible (Nichols et al., 1987). In fact, increasing the proportion of ethanol above 85 volume percent reduces the vapor pressure and aggravates the cold start problem. Therefore, in the committee's judgment, there is no justification for moving to E95.

*Recommendations*

**Recommendation.** The OAAT efforts related to ethanol-fueled vehicles should be eliminated from the R&D plan because these vehicles are already in production. In the event that legislative mandates require OAAT to continue some work on ethanol, further consideration of E95 should be eliminated from the plan because this fuel has little more to offer than E85, and it exacerbates the cold start problem.

## Dimethyl Ether

*Comments*

DME could be a good substitute for diesel fuel in compression-ignition engines; it has a high cetane number and inherently low particulate emissions. However, methanol also has inherently low particulate emissions, and DME is normally made from methanol. On the one hand, the additional processing step from methanol to DME increases the costs and requires more energy. On the other hand, DME has a higher volumetric energy density than methanol, and thus has advantages for onboard fuel storage, as well as for reducing the volume of liquid that has to be handled during fuel distribution. (DME is a liquid only when it is stored and distributed under pressure.) The committee suggests that the plan include a more detailed description of the advantages of DME over methanol and the trade-offs between the two fuels. The discussion should assume that methanol or DME fuels would be made from cheap natural gas from remote sources and shipped to the United States. It should also be noted that Detroit Diesel has already produced a methanol-fueled compression-ignition engine.

The characteristics of DME are similar to those of propane, and therefore a DME distribution and refueling system is expected to be much like the system for propane or liquefied petroleum gas (LPG). Moderate fuel tank pressures would be required (nominally 160 psi for LPG) for onboard storage of DME as a liquid rather than as a gas.

The plan acknowledges that the technologies for producing and using DME are in the very early research stage in the United States and that cost, reliability, durability, safety, and other performance parameters have not been well defined. OAAT plans to use some ongoing work at the OHVT (Office of Heavy Vehicle

Technologies) and the Tank Automotive Command to help in its initial development of a fuel injection system for light-duty vehicles. The committee suggests that OAAT also take into account the results of work in progress on DME outside the United States.

Even though technical barriers for DME cannot be defined, OAAT must provide some justification for including this fuel in the plan. The OAAT objectives in the Goal and Objectives section of the plan mention CNG and ethanol but not DME. The committee speculated that DME might be included under the objective that addresses "automotive technologies that use non-petroleum-based fuels that achieve zero emissions while obtaining 100 miles per gallon." If this is correct, OAAT must indicate how DME-fueled vehicles might achieve the OAAT objectives of 80 or 100 mpge. The committee noted that the reduction in incremental vehicle cost of $1,500 to $600 indicated in the technical targets for DME does not appear to meet the OAAT goal of a vehicle that is "competitive with conventional vehicles."

### *Recommendation*

**Recommendation.** The plan should state that DME is made from methanol and should include an analysis of the technical and economic trade-offs between using methanol and DME (made from methanol) as compression-ignition engine fuels.

## ELECTRIC VEHICLE BATTERIES

The primary motivation for the EV is to improve urban air quality and reduce petroleum use. The large scale replacement of internal combustion engine powered vehicles by EVs would have a substantial impact on petroleum consumption because the electricity required to recharge the batteries would be supplied by central power stations, which (in the United States) use petroleum for only a small percentage of their total electricity production. The impact of EVs on total energy consumption is uncertain and would depend on the overall efficiency of the EV and its supply of electricity over the fuel cycle, from fuel source to EV recharging station. Increased demand for electricity from central power stations to power EVs could have adverse environmental effects. For example, coal-fired power plants produce air emissions, including greenhouse gases, as well as solid waste.

EVs introduced into the market to date have not met with great success, primarily because of their high cost and the need to recharge them frequently, which restricts their range. The key to market success for the EV has always been battery technology. USABC has sponsored the development of nickel-metal hydride, sodium-sulfur, and lithium-ion battery technologies to meet mid-term (1997) goals. Meeting the long-term (2000) goals has focused on lithium-polymer technology. The OAAT R&D plan focuses on battery development, which is being conducted through USABC.

## Comments

The background information in this section of the plan should explain that the long-term goals specified by the USABC in 1991 were revised in 1996 and that the revised goals are reflected in the plan. Given the important historical role of the USABC in EV battery development, it would be helpful for OAAT to explain and justify the proposed replacement of the USABC, which is expected to end in 2000, with an advanced battery initiative. Such programmatic changes can result in a loss of momentum.

In the committee's judgment, the progress in the development of EV batteries is praiseworthy, and the new goals and technical tasks identified by the USABC seem to be appropriate, as does the division of goals into "mid-term" and "long-term" categories. However, to put the proposed R&D in context, a list of all the battery technologies investigated in the USABC program should be given, together with some explanation as to why certain technologies, such as sodium-sulfur, were dropped by USABC. The attention to safety and to the extensive testing of existing systems in the plan is appropriate.

The USABC goals for EV batteries indicate a price of less than $150/kWh in the mid-term (1997) and less than $100/kWh (with a desired goal of $75/kWh) in the long term (2000). These prices assume an annual production of 10,000 units of 40 kWh each. However, the technical target in the plan for nickel-metal hydride batteries is $300/kWh for 20,000 units/year in 1997 and $150/kWh for 20,000 units/year for lithium-polymer batteries in 2000. The discrepancies between the USABC goals and the OAAT technical targets have to be explained. OAAT must also explain how these costs will make EVs competitive with conventional vehicles. In the committee's opinion, the target cost will be difficult to attain, and the proposed technical approach for reducing cost is not adequately defined ("have each developer conduct ... efforts to reduce production cost").

Some work being done on EV batteries is well under way and appears in the milestones as almost completed. OAAT should update the plan and include progress reports to date.

It is not clear why safety and disposal appear in the same heading in the list of technical barriers for lithium-polymer batteries. If there is an implicit link between safety and disposal, it should be identified. The technical barriers for the lithium-polymer battery are formidable. For example, anode and cathode materials that will ensure stable capacity during battery cycle life are not available, and the chemical and electrochemical stability of the electrolyte are inadequate to support long cell life. The tasks that address the technical barriers are too vague to be meaningful. For example, unless safety issues involved in the disposal of lithium-polymer batteries are identified, the value of the related R&D cannot be properly evaluated.

The section headed Materials Research consists of a single sentence referring to an exploratory technology research program. In the committee's judgment, this perfunctory treatment fails to reflect the importance of materials development, which is the focus of the technical tasks. If the research in question is to develop advanced materials beyond those addressed in the Advanced Automotive Materials section of the OAAT R&D plan, this should be explained.

## Recommendations

**Recommendation.** The OAAT should describe its plans for the transition to a new program when the USABC program ends in 2000.

**Recommendation.** The cost targets and technical approach to reducing the cost of EV batteries should be explained in more detail.

**Recommendation.** The tasks for addressing the technical barriers of lithium-polymer batteries should be more specific, and the metrics for assessing progress should be stated.

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# Acronyms

| | |
|---|---|
| CIDI | compression-ignition direct-injection |
| CNG | compressed natural gas |
| CO | carbon monoxide |
| $CO_2$ | carbon dioxide |
| CRADA | cooperative research and development agreement |
| DARPA | Defense Advanced Research Projects Agency |
| DME | dimethyl ether |
| DOE | U.S. Department of Energy |
| EGR | exhaust gas recirculation |
| EPA | Environmental Protection Agency |
| EV | electric vehicle |
| GVW | gross vehicle weight |
| IDEA | National Research Council's Innovations Deserving Exploratory Analysis program |
| IEEE | Institute of Electrical and Electronic Engineers |
| LPG | liquefied petroleum gas |
| mpge | miles per gallon equivalent |
| $NO_x$ | nitrogen oxide |
| NRC | National Research Council |

| | |
|---|---|
| OAAT | Office of Advanced Automotive Technologies (U.S. Department of Energy) |
| OHVT | Office of Heavy Vehicle Technologies (U.S. Department of Energy) |
| OTA | Office of Technology Assessment |
| OTT | Office of Transportation Technologies (U.S. Department of Energy) |
| PEBB | power electronic building block |
| PEM | proton exchange membrane |
| PNGV | Partnership for a New Generation of Vehicles |
| redox | reduction-oxidation |
| R&D | research and development |
| USABC | U.S. Advanced Battery Consortium |
| USCAR | U.S. Council for Automotive Research |
| V | volt |
| VMT | vehicle miles traveled |

# APPENDICES

# APPENDIX A

# Biographical Sketches of Committee Members

**William Agnew** (*chair)* (NAE) retired as director of programs and plans for General Motors (GM) Research Laboratories in 1989. From 1944 to 1946, Dr. Agnew served in the Manhattan District, U.S. Army Corps of Engineers, at the Los Alamos Laboratory. He attended Purdue University from 1946 to 1952. From 1952 to 1989, he held a number of positions at GM Research Laboratories, including department head of fuels and lubricants; head of the Emissions Research Department; technical director of the Engine Research, Engineering Mechanics, Mechanical Research, Fluid Dynamics, and Fuels and Lubricants departments; and technical director of the Biomedical Science, Environmental Science, Societal Analysis, and Transportation Research departments. His technical expertise spans internal combustion engines, gas turbines, engine performance, automotive air pollution, and automotive power plants. He has a Ph.D. in mechanical engineering from Purdue University.

**Robert Aldrich** is president of Pridtronics, Inc., a manufacturer of energy storage devices, and chairman of Tailored Energy, Inc., an energy services company that provides on-site products to commercial and small industrial customers. His previous positions include group vice president of the Business and Finance Division and vice president of the Integrated Energy Systems Division of the Electric Power Research Institute; research and development projects director, Niagara Mohawk Power; and director, Life and Materials Science Center, Syracuse University Research Corporation. Dr. Aldrich has been a member of various professional organizations, including the Presidents Association and International Council of the American Management Association, and a member of the Board of Advisors at Syracuse University. He has extensive experience in energy conversion technologies, fuel cells, materials science, and R&D management. He received his Ph.D. in solid state science and technology from Syracuse University.

**Fred C. Anson** (NAS) is Elizabeth W. Gilloon Professor of Chemistry, Division of Chemistry and Chemical Engineering, California Institute of Technology, where he has been a faculty member since 1957 and was chair of the Division of Chemistry and Chemical Engineering from 1984 to 1994. He has been a fellow of the American Association for the Advancement of Science and the recipient of a number of awards, including the David C. Grahame Award from the Electrochemical Society, the Alexander von Humboldt Award from the Fritz Haber Institut der Max Planck Gesellschaft, and the C.N. Reilley Award in Electroanalytical Chemistry. He has conducted research in a number of areas related to fuel cells and batteries. He received his Ph.D. from Harvard University.

**Robert Epperly** is president of Epperly Associates, Inc., a consulting firm. From 1994 to 1997, he was president of Catalytica Advanced Technologies, Inc., a company that develops new catalytic technologies for the petroleum and chemical industries. Prior to joining Catalytica, he was general manager of Exxon Corporate Research and director of the Exxon Fuels Research Laboratory. After leaving Exxon, he was chief executive officer of Fuel Tech N.V., a company that develops new combustion and air pollution control technology. Mr. Epperly has authored or co-authored more than 50 publications on technical and managerial topics, including two books, and has 38 U.S. patents. He has extensive experience in fuels, fuel cells, engines, catalysis, air pollution control, and R&D management. He received an M.S. degree in chemical engineering from Virginia Polytechnic Institute.

**Anthony J. Finizza** is the chief economist at Atlantic Richfield Company, a position he has held since 1985. His responsibilities include monitoring alternative fuel vehicle developments and energy/economic studies. Prior to 1985, he was regional vice president of Data Resources, Inc. (1970 to 1975) and vice president and economist of Northern Trust Company (1968 to 1970). Dr. Finizza has contributed his expertise to various professional organizations, including the International Association for Energy Economics, of which he was president in 1996. He received his Ph.D. in economics from the University of Chicago.

**Thomas M. Jahns** is drives program manager at GE Corporate Research and Development. He is currently on a two-year research sabbatical as a senior lecturer and co-director of the Massachusetts Institute of Technology (MIT)/Industry Consortium on Advanced Automotive Electrical/Electronic Components and Systems, where he directs and is actively engaged in research on new electrical system architectures and advanced accessory subsystems for future automotive vehicles. He has been manager of the Power Electronics Control Program at

General Electric Corporate Research and Development and was a senior engineer at Gould Corporate Laboratories. He is a fellow of the Institute of Electrical and Electronic Engineering (IEEE), and has served as president of the IEEE Power Electronics Society, and chair of the Industrial Drives Committee of the IEEE Industry Applications Society. He has a Ph.D. in electrical engineering from MIT.

**John H. Johnson** is Distinguished Presidential Professor, Department of Mechanical Engineering-Engineering Mechanics, at Michigan Technological University (MTU) and a fellow of the Society of Automotive Engineers. His experience spans a wide range of analysis and experimental work related to advanced engine concepts, emissions studies, fuel systems, and engine simulation. Before joining the mechanical engineering faculty at MTU, he was project engineer at the U.S. Army Tank Automotive Center and chief engineer at Applied Engine Research at International Harvester Company. He was chair of the MTU Mechanical Engineering Department from 1986 to 1993. Dr. Johnson has served on many committees related to engine technology, engine emissions, and health effects for the Society of Automotive Engineers, the National Research Council, the Combustion Institute, the Health Effects Institute, and the Environmental Protection Agency. He is also a consultant for a number of government and private sector institutions. He received his Ph.D. in mechanical engineering from the University of Wisconsin, Madison.

**Parker D. Mathusa** is director of the Energy Resources, Transportation and Environmental Research Program at the New York State Energy Research and Development Authority. He is responsible for establishing research programs and policies to develop new energy technologies and environmental mitigation measures that will contribute to New York state's energy supply needs, with a focus on renewable energy resources, advanced transportation technologies, and environmental products. His previous positions include chief of utility research and demand management, New York State Public Service Commission, where he developed a comprehensive R&D program for electric and gas utilities, and engineering positions at Yankee Atomic Electric Company and Bechtel Corporation. He has a B.S. in physics from SUNY-Albany and an M.S. in engineering management from Northeastern University.

**Phillip Myers** (NAE) is emeritus distinguished research professor and former chairman of the Department of Mechanical Engineering at the University of Wisconsin, Madison, and a fellow of the American Society of Mechanical Engineers. He was the president of the Society of Automotive Engineers in 1969 and has served on numerous National Research Council committees, including the Committee on Fuel Economy of Automobiles and Light Trucks and the Committee on Toxicological and Performance Aspects of Oxygenated Motor Vehicle Fuels. His research interests include internal combustion engines, combustion processes, and fuels. He has a Ph.D. in mechanical engineering from the University of Wisconsin, Madison.

**Roberta Nichols** (NAE) is retired from Ford Motor Company. From 1979 to 1995, she held several positions at Ford, including manager of the Electric Vehicle (EV) External Strategy and Planning Department, North American Automotive Operations; manager of EV External Affairs, EV Planning and Program Office; manager of the Alternative Fuels Department and the environment and safety engineering staff; and principal research engineer of the Alternative Fuels Department, Scientific Research Laboratory. She was also a member of the technical staff at The Aerospace Corporation from 1960 to 1979, as well as a consultant for the state of California. She is a fellow of the Society of Automotive Engineers, a recipient of the National Achievement Award from the Society of Women Engineers, and a recipient of the Clean Air Award for Advancing Air Pollution Technology from the South Coast Air Quality Management District. Her expertise includes alternative fuel vehicles, EVs, internal combustion engines, and new sources of energy. She has a Ph.D. in engineering and an M.S. in environmental engineering from the University of Southern California and a B.S. in physics from the University of California-Los Angeles.

**Joan Ogden** has been a research scientist at the Center for Energy and Environmental Studies at Princeton University since 1985. Most of her work has involved technical and economic assessments of new energy technologies, including renewable fuels, the use of hydrogen as an energy carrier, and applications of fuel cell technology in transportation. For two years, she was chair of the Solar Fuels and Transportation Division of the American Solar Energy Society. Dr. Ogden has published more then 60 technical articles on energy topics and a book, Solar Hydrogen. She received her Ph.D. in physics from the University of Maryland.

**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. His research involves spark-ignition engines and diesel engines operating with many alternative fuels, advanced concepts for both types of engines, and fuel-cell powered vehicles. He has served as a consultant to the Jet Propulsion Laboratory, monitoring electric and hybrid vehicle programs, and is now a consultant to Pratt and Whitney on advanced gas turbine engines. Dr. Roan is a member of the NRC Standing Committee to Review the Research Program of the Partnership for a New Generation of Vehicles. He has a Ph.D. in engineering from the University of Illinois.

**Dale Stein** (NAE) is president emeritus of MTU (Michigan Technological University) and a retired professor of materials science. He has held positions at MTU, the University of Minnesota, and the General Electric Research Laboratory. He is the recipient of the Hardy Gold Medal of the American Institute of Mining, Metallurgical and Petroleum Engineers and the Geisler Award from the American Society of Metals (Eastern New York Chapter) and was an elected fellow of the American Society of Metals and the American Association for the Advancement of Science. He has served on numerous National Research Council committees and has been a member of U.S. Department of Energy's Energy Research Advisory Board. Dr. Stein is an internationally recognized authority on the mechanical properties of engineering materials. He received his Ph.D. in metallurgy from the Rensselaer Polytechnic Institute.

**John Wise** (NAE) is retired vice president of research, Mobil Research and Development Corporation. He has also been vice president of planning, manager of exploration and production R&D, manager of process and products R&D, director of the Mobil Solar Energy Corporation, and director of the Mobil Foundation. He was on the Board of Directors of the Industrial Research Institute, was active in the World Petroleum Conference, and was co-chair of the Automotive/Oil Industries' Air Quality Improvement Research Program. Dr. Wise's expertise is on fuels, catalysis, R&D management, and the effects of fuels and engines on emissions. He received a Ph.D. in chemistry from MIT.

# APPENDIX B

# Committee Meetings and Other Activities

**First Committee Meeting, July 14–16, 1997, Washington, D.C.**

The following presentations were made to the committee:

Overview of the Office of Advanced Automotive Technologies (OAAT)
*Pandit Patil, Director, OAAT*
Introduction to the OAAT R&D Plan
*Bob Kirk, Deputy Director, OAAT*
Vehicle Systems
*Robert Kost, OAAT Systems Team Leader*
Gas Turbines
*Tom Sebestyen, OAAT Program Manager, Gas Turbine Engines*
Compression-Ignition Direct-Injection (CIDI) Engines
*Pat Davis, OAAT Program Manager, CIDI Engines*
Fuel Cells
*Donna Lee, OAAT Program Manager, Fuel Cells*
Alternative Fuels
*John Garbak, OAAT Program Manager, Alternative Fuels*
High Power Energy Storage
*Ray Sutula, OAAT Energy Management Team Leader*
High Power Batteries
*Ray Sutula, OAAT Energy Management Team Leader*
Ultracapacitors
*Susan Rogers, OAAT Program Manager, Ultracapacitors*
Flywheels
*Tien Duong, OAAT Program Manager, Flywheels*

Power Electronics and Electric Machines
*David Hamilton, OAAT Program Manager, Power Electronics and Electric Machines*
Advanced Automotive Materials: Lightweight Materials
*Joe Carpenter, OAAT Program Manager, Advanced Automotive Materials*
Electric Vehicle Batteries
*Ken Heitner, OAAT Program Manager, Electric Vehicle Batteries*

**Second Committee Meeting, September 4–5, 1997, Washington, D.C.**

The following presentation was made to the committee:

Flywheel Technology for Hybrid Vehicles
*David Eisenhaure, President, Satcon Technology*