Comparison of Alternative Energy Storage Systems for Automobiles: A Report (1982)

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A COMPARISON OF ALTERNATIVE ENERGY STORAGE SYSTEMS FOR AUTOMOBILES

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STORAGE VEHICLES PANEL
OR4 Committee on Advanced Energy Storage Systems
OR3 Energy Engineering Board
OR2 Commission on Engineering and Technical Systems
OR1 National Research Council

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

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PREFACE

The Committee on Advanced Energy Storage Systems of the National Research Council has been studying a number of important topics concerning the subject of energy storage since 1975, under contracts with the Energy Research and Development Administration (ERDA) and the Department of Energy (DOE). Several of these studies considered the applicability of various mobile storage system applications to automobiles. A 1976 Committee report, "Criteria for Energy Storage R&D,"[1] devoted a chapter to the prospects and problems of electric and flywheel systems in transportation applications. A 1979 report, "Hydrogen as a Fuel,"[2] contained a chapter on the possible automotive uses of hydrogen. Each report included a discussion of possible difficulties in gaining wide public acceptance of storage-powered vehicles because of their probable performance limitations compared with conventional cars powered by internal combustion engines (ICE).

Current programs for developing and demonstrating storage-powered vehicles and the corollary research and development programs for the necessary mobile storage systems are largely directed at rechargeable (i.e. secondary) battery systems. These programs were initiated when the principal impetus for storage vehicle development arose from urban pollution concerns and the technical prospects for alleviating such pollution through the deployment of battery-powered "commuter" cars. More recently, however, concern has arisen over the continued U.S. dependence on petroleum supplies in general and the cost and vulnerability of oil imports in particular. Thus, it now appears opportune to consider the effort that would be needed to develop general purpose automobiles capable of markedly reducing national petroleum consumption rates with minimum social and economic upheavals.

To have a significant impact on oil consumption, such replacement cars would need to be perceived by the public as suitable alternatives to conventional automobiles. Cars based on the rechargeable battery systems now under study may not be so viewed because of their limited driving range between lengthy charging periods, but some other less investigated storage concepts may have greater potential appeal. Accordingly, in late 1979 the Committee on Advanced Energy Storage

Systems established a Storage Vehicles Panel to compare the potential performance capabilities of passenger cars powered with rechargeable batteries with those from possible storage system alternatives.* This report presents the findings of the Panel together with their recommendations regarding desirable R&D programs for these latter storage systems.

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* The Panel considered hydrogen as an ICE fuel, including the storage issues associated with its portability, to have been adequately treated in Reference 2. Therefore, no further treatment of hydrogen vehicles is included in this study.

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SUMMARY

In the study of alternatives to internal combustion engines (ICE) as power sources for personal automobiles, rechargeable (secondary) batteries have received the bulk of the national research and development (R&D) resources. However, those batteries that are likely to become available for automotive use within the next decade have inherent shortcomings because the driving range of electric vehicles will be appreciably lower and initial costs will be higher than those of ICE vehicles. Accordingly, as long as there are no significant restrictions on the availability or use of ICE vehicles, it seems unlikely that electric vehicles powered by the batteries now under development will make substantial market penetrations, at least for the foreseeable future.

Vehicles powered by other types of storage systems may have a greater potential for penetrating the personal automobile market, however. This report reviews the performance potentials of systems such as primary batteries, fuel cells, and flywheel-transmission systems in comparison with secondary batteries.

Metal-air primary (non-rechargeable) batteries can be described that would be capable of powering automobiles for driving ranges of 1,000 miles or more with only brief intervening stops every few hundred miles for water addition and inert by-product removal. Experimental aluminum-air cells for such batteries have been demonstrated. However, there are difficult technical problems to be solved in the electrochemical systems of a practical battery before an adequate automobile power system can be postulated.

Fuel cells can also be described that could produce automobile driving ranges comparable to conventional cars, and such power systems have been demonstrated in elemental forms. Much R&D remains, however, before the practicality of fuel cells for automotive purposes can be assured.

Flywheel-transmission systems cannot be contemplated as independent alternatives to conventional power systems. They may, however, have important roles in improving the acceptability of any of

the electrochemical power systems, or of improving the fuel efficiency of conventional automobiles. The principal obstacle to such flywheel applications lies in the lack of a reliable, low cost continuously variable transmission for connecting the flywheel to the remaining power train.

This report outlines a number of areas of research that are recommended for attention (in addition to areas of basic research in support of the more promising rechargeable batteries) as part of a well-rounded investigation of ICE alternatives. Specifically, the following recommendations are made:

- Electrolytes and novel electrode structures should be investigated for lithium/sulfur batteries, and secondary lithium/sulfur dioxide cells should receive research attention.
- Cost and life problems of air electrodes for aluminum-air batteries should be studied, together with the potential impacts of large numbers of aluminum-air powered cars on the aluminum industry infrastructure. Existing research on aluminum-air batteries might be expanded following such studies.
- Improved materials for phosphoric acid fuel cell structures should be identified through research, as should electrolytes to improve the system start-up times and responses.
- Systems studies and fuel acceptability analyses for alkaline fuel cells should be conducted, and research should be directed to the solution of air electrode cost and life problems.
- Ongoing flywheel R&D programs should be continued, but with added emphasis on continuously variable transmissions and on overall flywheel-transmission system designs.

Because the R&D risks are high and the applications are distant, these research areas are appropriate for federal sponsorship if a federal research and development role is warranted in anticipation of potential future national transportation needs. If, on the other hand, the future availability of personal automobiles is judged to be wholly a marketplace decision, R&D in the suggested areas would appear to represent a prudent, though long-range, investment for the private sector to supplement electric vehicle R&D activities presently being conducted by industry.

1

INTRODUCTION

The internal combustion engine (ICE) is currently the dominant means of propulsion for personal motor cars and has been so since early in the automobile era. However, extensive governmental and private sector research and development (R&D) is now underway on alternative propulsion systems. For any alternative systems to displace ICEs in significant numbers in the future, one or several of the following will have to occur:

- o ICE fuels cease to be readily available
- o The use of ICE cars is restricted
- o The automobiles powered by the alternative propulsion systems have operational characteristics and costs that are favorably competitive with ICE-powered cars in the judgment of the potential buyers.

For any of these circumstances, it would be preferable that R&D stress types of propulsion systems that offer the maximum opportunities for using domestic, plentiful, and societally acceptable energy sources. Additional objectives would depend on which of the above situations is predominant.

- o Only if ICE fuels (including synthetic fuels) are expected to be unavailable will any alternative propulsion system be better than none; and then only if such an unlikely circumstance is credible should extensive R&D be conducted to establish the widest range of feasible options, regardless of ICE comparisons.
- o If it seems more likely that the sale and use of ICE cars may be restricted but not eliminated (e.g., through strict urban pollution controls), then the R&D should focus more narrowly on alternative systems that offer operational characteristics that would minimize the societal impacts accompanying their introduction in large numbers.

- If it is anticipated that alternative propulsion systems will be adopted mainly on their competitive merits, then the R&D should be directed primarily toward system concepts offering characteristics that will be comparable with those of future ICE cars.

For the next several decades, comparative merits are most likely to influence the rate of adoption of ICE vehicle alternatives. Therefore, research should be directed at a broader range of propulsion systems that offer a greater likelihood of performance comparability with ICE cars than the secondary battery powered electric systems now under study.

It is not obvious what features of an automobile attract buyers. Experienced automobile makers have sustained huge losses, and even have been forced out of business, as a consequence of their inability to identify and satisfy the buying public's preferences. In general, however, an easily salable car could be expected to combine operational performance and cost characteristics that compare favorably to those of the competition.

The operational performance of alternative propulsion systems will almost certainly need to include an essentially uninterrupted driving range that will satisfy the user's perceived needs. The effective range of ICE-powered cars can be viewed as unlimited, if brief fueling stops are discounted. Most cars are designed with a fuel capacity that provides a range of 400-500 kilometers (250-300 miles) between refills. While statistical evidence suggests that such a range exceeds average driving requirements, there is no market evidence regarding the acceptability of significantly shorter ranges.

Acceleration also appears to be important. A successful alternative to the ICE-driven car will need to accelerate quickly enough for the driver to feel safe when operating the car in normal traffic. Whatever the acceptable level of acceleration, it should be achievable at all times. ICE-powered cars differ in their acceleration capabilities, but all have a first-order performance that is independent of the amount of fuel remaining in the tank or of the age of the vehicle. Alternative propulsion systems will need similar characteristics to be competitive.

The relative importance of cost in automobile marketing competitiveness is difficult to determine. Although advertisements frequently stress low first costs, few "stripped" minimum-cost cars are sold in any product line. For the most part, the foreign cars that have flooded the U.S. market have not been cheaper than the lowest cost American makes. The buyer seems willing to pay for options that offer added comfort, performance, or self-esteem. Frequently the added-cost options also increase the car's operating costs and thus add to life-cycle as well as initial costs. In light of this demonstrated buyer behavior, there is no basis for postulating that either first-cost or life-cycle absolute costs will be crucial to the competitiveness of comparable alternative automobile propulsion systems. On the other hand, it is unlikely that buyers will pay added costs for <u>lower</u> perceived vehicle performances unless there are offsetting perceived advantages.

Probably few automobile owners see themselves as playing a major role with respect to U.S. dependence on imported petroleum fuels. Nevertheless, non-ICE propulsion systems may have a certain amount of user appeal because they can offer a prospect for user independence from future gasoline shortages of the sort that this country experienced in 1974 and 1979. The extent of such an appeal will depend on the nature and availability of the alternative energy source and on the car owner's perception of his vulnerability to disruption by international events.

To make substantial market penetrations, it will be essential that an alternative propulsion system make only minor changes in the total national industrial infrastructure. Heavy capitalization requirements would inhibit--if not stifle--wide geographic deployment of new vehicle classes, and this would severely limit ultimate market possibilities.

Regardless of the expectations for the future that motivate R&D, it will be important that alternative propulsion systems be no more polluting than the ICE-powered vehicles they will be expected to displace. Furthermore, cars using alternative propulsion systems should be at least as safe as conventional cars.

2

RECHARGEABLE BATTERIES

Storage batteries have been used for vehicle propulsion for nearly a century. They have, however, consistently had an urban driving range between recharges (typically, 40-80 kilometers (km)) that has been too short for most general driving needs. This has been a direct result of the low energy density of the available batteries, 15-30 Watt-hours per kilogram (Wh/kg) for lead-acid batteries and about the same for iron/nickel oxide batteries.* In the last decade, renewed interest in electric vehicles--first as a means of reducing air pollution, then in response to the dwindling petroleum supply--has brought into focus the need for high-energy-density batteries to increase the driving range of electric vehicles.

Several candidate systems with higher specific energies are in various stages of R&D. Batteries can be grouped into three categories according to their stages of development:

- <u>Exploratory.</u> This includes any applied research necessary to characterize a single experimental "laboratory cell"[3] prior to the time that transition to engineering or product development is underway.
- <u>Product Development.</u> This term is used to denote a spectrum of activities, including engineering design of full-size cells and batteries, life testing of components, development of manufacturing methods and equipment, pilot line installation and operation, application engineering, and market development.
- <u>Production.</u> This category comprises batteries that can be purchased in quantity on the open market.

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*McAlevy has shown the direct relationships between storage system energy density (Wh/kg) and vehicle range, and between storage system power density (W/kg) and vehicle power demands, in several papers.[4-6]

CHARACTERISTICS OF RECHARGEABLE BATTERIES

The Panel has prepared its best estimates of secondary battery performance in Tables 1-3. Table 1 lists values of the most important parameters that characterize golf car lead-acid production batteries for electric vehicles (EV). These are the only widely used rechargeable propulsion batteries in production today. Thus, their performance is the baseline from which improvements are measured. In addition to values of energy and power density, the table indicates the number of discharge cycles that the batteries can be expected to undergo before failure (life cycles), and the current cost per kilowatt-hour of energy stored.

TABLE 1 Electric Vehicle Batteries in Production

Type Battery	Energy Density[a] (Wh/kg)	Power Density[b] (W/kg)	Discharge Life (cycles)	Cost ($/kWh)
Lead-Acid (Golf Car)	30	75	150-250	55

[a] Measures for steady state discharge over three hours have been chosen, since these are most readily available.

[b] At 50 percent state of charge

SOURCE: Panel estimates.

Similar data on electric vehicle (EV) batteries in the product development phase are given in Table 2. A distinguishing feature of these battery systems is that all have received some testing in electric vehicles. However, the values given are largely based on independent testing at the National Battery Testing Laboratory. (This table does not list cost estimates for the batteries. Present estimates all lie within the $75-125 range, but lack the accuracy to justify their use as performance discriminators.)

It is important to note that the increase in energy density of the battery systems in Table 2 over the golf car lead-acid battery is not much more than a factor of 2.5 for any of the batteries. There is even less increase if the improved lead-acid batteries of Table 2 are taken as the baseline. The maximum driving range that has been achieved by an electric vehicle using improved golf car lead-acid batteries is from an electric test vehicle (ETV-1) using 30 Wh/kg

Globe-Union EV2-13 batteries. This was 148 km at a constant 72 km/hr (45 mph), and only 119 km on the standardized Society of Automotive Engineers (SAE) J227a/d driving cycle used to compare vehicles. By extrapolation, a range of about 320 km is the best that might be expected from a similarly sized "product development" battery.

TABLE 2 Electric Vehicle Batteries in Product Development

Type Battery	Energy Density (Wh/kg)	Power Density (W/kg)	Discharge Life (Cycles)	Estimated Available[a] Year
Improved Lead-Acid	38-42	105	800	1982
Zinc/Nickel Oxide	65-70	130	150+	1982
Iron/Nickel Oxide	45-50	110	1000+	1981
Zinc/Chlorine	60-70	60	1400	1982

[a] Forecast year of availability of limited numbers for evaluation in electric vehicles.

SOURCE: Panel estimates.

Table 3 gives performance measures for several rechargeable batteries in exploratory stages of development. Because of the early battery stages, some of the performance estimates are not as reliable as those in Tables 1 and 2. Two batteries, sodium/sulfur and lithium/iron sulfide, are subjects of major programs. However, the sodium/sulfur battery is being developed in the United States primarily for utility applications, not for electric vehicles. Accordingly, it is not categorized as being in product development. The lithium/iron sulfide battery is on the verge of making the transition to product development. The last obstacle to be overcome is a demonstration of adequate cycle life. However, the gain in energy density is not remarkable, and the practical driving ranges of vehicles equipped with the reference size lithium/iron sulfide battery will be 240 to 320 km at a maximum. This is still less than for comparable ICE vehicles.

OPTIONS FOR THE FUTURE

As shown in Table 3, the lithium/iron disulfide and lithium/iodine batteries offer about a 50 percent increase in energy density when compared with lithium/iron sulfide, the best of the batteries receiving substantial R&D support. However, these research programs are in the exploratory stage. Substantial corrosion problems must be overcome, and exploratory work on large cells has just begun. Accordingly, only uncertain projections as to performance, life, and cost can be made. If R&D goals are achieved, the resulting EVs may have a range of 500 km or more--comparable to that of ICE vehicles.

TABLE 3 Electric Vehicle Batteries in Exploratory Stages

Type Battery	Energy Density (Wh/kg)	Power Density (W/kg)	Discharge Life (cycles)	Expected Development Year
Sodium/Sulfur[a]	100+	100+	400	1983
Lithium Aluminum/ Iron Sulfide[a]	100	120	400	1983
Lithium Silicon/ Iron Disulfide	180	120	700	1986
Bipolar Lead-Acid[b]	50	150	?	1990?
Zinc/Bromine[b]	65	80	2000?	1985
Lithium/Iodine[c]	180	250	1000	?
Iron/Air	120	120	?	?

[a] These are major programs in which cell and battery testing are major factors. However, classification in product development is not yet justified (see text).

[b] No Department of Energy program of EV battery R&D for these batteries.

[c] Extrapolations from small cells.

SOURCE: Panel estimates.

Even though significant improvements are being made as the more advanced systems are developed, the standard ICE engine plus fuel tank offers a formidable target in terms of specific energy and specific power as shown in Figure 1.[7] There is a large gap between the energy densities of the batteries and the theoretical specific energy for gasoline (13,000 Wh/kg). The practical specific energy of a gasoline-engine automotive power system is only about 300 Wh/kg in current practice, but this can be increased by enlarging the fuel tank. This value might be attained by a lithium/sulfur (Li/S) battery and electric drive, if the Li/S battery had an energy density

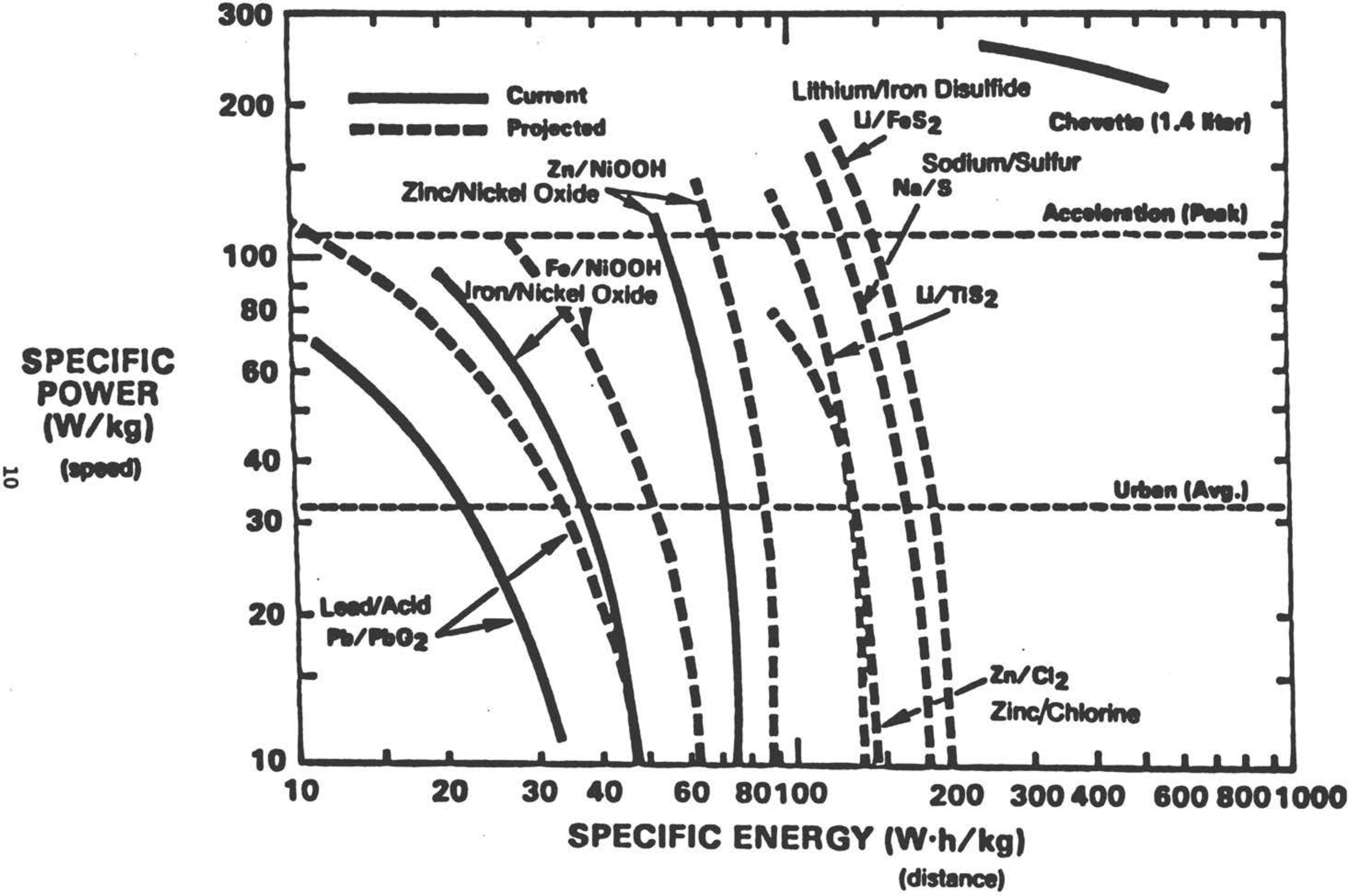

FIGURE 1 Power-energy relationships.

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of 20 percent as much as the theoretical 2600 Wh/kg (520 Wh/kg). Thus, even though no battery system currently being developed can provide the range of the existing ICE automobile, there is the hope that advanced systems such as Li/S may be able to provide the same range in the future.

The practical limitations on the achievable specific energy of a battery are set by a number of considerations.[8] These include:

- Less than full utilization of active materials (usually no more than 70-80 percent),and less than reversible cell voltage
- The weight of electrolyte and separators
- The weight of current collectors, connectors, etc.
- The weight of the cell case.

All of the above, taken in combination, result in practical specific energies that are no more than 20-25 percent of the theoretical value for cells with solid electrodes, and 15-20 percent for cells with one gas consuming electrode.

Areas of investigation that should enhance the rate of progress toward achieving very high specific energies include:

- Research on electrolytes suitable for use with the Li/S couple. These could include solid electrolytes to operate at either ambient or elevated temperatures.
- Novel electrode structures for use with sulfur that could provide high utilization and low weight.
- Novel electrode structures for use with lithium, in either the solid or liquid form.

3

PRIMARY BATTERIES

Primary batteries have been used in the past for propulsion of specialized military systems, such as torpedoes, and they have been under investigation for potential automotive applications as part of electrochemical R&D programs. The effort in this area has included the demonstration of the feasibility, at least in the laboratory, of an aluminum-air cell.[9-14] Both aluminum (Al) and lithium (Li) have been investigated for use in a primary cell with an air electrode. However, the following comments apply specifically to the aluminum-air battery.

THE ALUMINUM-AIR BATTERY

The high heat of combustion of aluminum, combined with the fact that the proposed battery uses oxygen directly from the air, suggests that it should have an outstanding energy/weight ratio. Indeed, present experimental cells have yielded 4 to 4.5 kWh/kg of aluminum. These figures are well above the corresponding energy/weight figures for gasoline and even diesel engines (0.2 to 0.3 kWh/kg), but may be reduced by as much as an order of magnitude in complete, operational systems.[15]

In contrast to simple hydrocarbon oxidation reactions, the aluminum cell involves a series of reactions. Together, these equate to the overall reaction:

$$(1)\quad Al + 3/2\ H_2O + 3/4\ O_2 \longrightarrow 1/2\ (Al_2O_3 + 3\ H_2O)$$

The advantage of this process is that the product of the reaction, hydrargillite (Al_2O_3), is a stable solid which is currently the main feedstock of the aluminum industry and can, therefore, be safely recycled.

To develop preliminary cost and performance figures, a team from the Lawrence Livermore National Laboratory (LLNL)[13] selected an automobile operating mode in which the aluminum would be replaced every 1600 km and the hydrargillite would be removed every 400 km.

Estimates of energy efficiency and consumption were developed relative to two ICE vehicles, the gasoline-powered X-Body car and the diesel Rabbit, for 50 percent urban and 50 percent freeway driving. The aluminum consumption is proportional to the vehicle weight and range; for these two examples it corresponded to a constant 31,000 kg-km range per kg of aluminum consumed. It was determined that for equal weight vehicles, 1 kg of aluminum fuel would be the range equivalent of 2.3 liters of gasoline (0.61 gal) or 1.6 liters of diesel fuel (0.42 gal).

For any trip, the automobile would start with aluminum and water having a combined weight that is 2.4 times the weight of the required aluminum. It would complete the trip with 3.3 times the aluminum weight in the form of hydrargillite. The cell performance quoted earlier, 4 to 4.5 kWh/kg of aluminum, is now degraded by an average factor of 2.85, and becomes 1.4 to 1.6 kWh/kg of on-board materials.

This arithmetic is oversimplified, and it should be noted that only the aluminum is to be paid for--both for the material and its installation in the cell. Water is universally available at negligible cost, and the final product has a recoverable value of some 20 percent of the original aluminum cost.[14] (The current value of hydrargillite is estimated at about $100 per ton.)

The air cathode is presently envisioned as being fabricated of carbon, probably with a silver catalyst. Both the cost and the probable lifetime of the air cathode are highly uncertain, but clearly it will be a major component of the total cost of the battery. Currently a 2-year life is being assumed, without much supporting evidence. Fuel cell air cathodes have lasted more than 10,000 hours under steady, continuous loading, but there are no data on lifetime under the highly intermittent duty cycle of the automobile. The assumption of a 2-year life in the automobile would imply a lifetime of only 500 hours under these conditions.

It is possible that an electrocatalyst of platinum, instead of silver, will be necessary to achieve a reasonable lifetime, and this could more than double the cost of the cathode. An additional problem is the possibility of oxidation when the power is off; in stationary fuel cells, the cathodes are flooded with an inert gas during off-power periods to prevent this.

The achievement of an effective operational air cathode has still a considerable way to go. It is recommended that a much greater fraction of the total R&D effort should be concentrated on experimental work in this area. The investigations should encompass not only the properties of alternative electrocatalysts but also the carbon/graphite chemistry of the cathode materials and the optimization of the cathode structure.

Impact on Industry

A high performance vehicle that travels 16,000 km per year would need 816 kg of replacement aluminum each year. A fleet of 18 million such cars would absorb the entire output of the present aluminum industry. Thus, if the aluminum-air powered vehicle were to become a significant fraction of the total number of automobiles manufactured in the United States, then a dedicated refueling industry would be necessary.* That aluminum would need to be provided by the aluminum industry, using electricity as a power source. Unfortunately, current aluminum manufacturing processes were established in an era of low electric power costs.[13,14] Thus, more modern plants with higher production efficiency would be desirable.

An evaluation has been carried out of the overall energy use based on current Hall-Heroult and Alcoa processes.[13] This calculation, assuming 36 percent efficiency of electric power generation from coal, does not take additional credit for the plant modernizations in terms of the aluminum-air vehicle. The primary energy consumed in the preparation of fuel for aluminum-air powered cars compared with corresponding figures for gasoline or diesel fuel derived from crude oil or coal for ICE powered cars is:

		Primary energy kWh/km
Aluminum-air	Hall-Heroult process	1.7 - 1.9
	Alcoa process	1.1 - 1.4
Gasoline	From crude oil	1.0
	Syngas from coal	1.5 - 1.7
Diesel fuel	From crude oil	0.8
	Synfuel from coal	1.2 - 1.4

An analysis of the long-term trend of aluminum production in response to increasing cost of electricity indicates that current plants operating at 15-17 kWh/kg of aluminum output should be replaced by cells operating near the maximum efficiency point of 11-12 kWh/kg; additional detailed improvements could further reduce electrical energy requirements by 15-25 percent.**

There could be a substantial effect on the energy supply industry. As implied earlier, a fleet of 18 million aluminum-air powered vehicles

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* Such levels of consumption might raise some concerns about the security of aluminum as a fuel supply vis-a-vis petroleum, since a substantial increase in the importation of bauxite would be required.

** See Appendix C of reference 13 for further discussion.

would double the size of the aluminum manufacturing industry. This could necessitate the development of a dedicated aluminum electrode industry, perhaps with its own special generating plants.

The most serious change required would be a new distribution system to recycle material from the aluminum plant to the automobile. The gasoline tank in the average corner filling station would need to be replaced with storage for 20,000 kg of aluminum electrodes and 66,000 kg of hydrargillite, if roughly the same monthly rate of energy supply were to be maintained. Since 66 tonnes is excessive for road transport, there would be frequent shipping between plant and filling station, and, probably, more fuel transport vehicles on the road than is now the case.

ALTERNATIVES TO ALUMINUM

The air cathode, when sufficiently developed for use in a vehicle, will offer the possibility of operation with other anode materials as alternatives to aluminum. Mention has been made of earlier experiments with lithium; zinc also has comparable electrochemical characteristics, although it will require some additional weight. Since a major utilization of the aluminum-air vehicle would require a significant increase in the size of the aluminum industry, it would be expedient to examine whether alternative metals offer advantages at this high level of utilization.

Hybrid Vehicles with Aluminum-Air Batteries

In common with other storage batteries, the performance of the aluminum-air powered vehicle shows significant improvement when it is coupled with a suitable flywheel for load leveling and regenerative braking. For urban driving, range gains approaching 15 percent for the same battery capacity appear possible. Other hybrid arrangements, for example with a secondary battery, can also be envisioned. At this stage in the development of the aluminum-air battery, however, a serious examination of these hybrid alternatives is not recommended. Their relative advantages are so dependent upon the comparative costs and lifetime of the aluminum-air cell, that research on aluminum anodes and air cathodes needs to be carried much further before meaningful comparisons can be made.

4

FUEL CELLS

PRESENT STATUS

The fuel cell is periodically proposed as a power source for various types of vehicles. In addition to its use in special military applications, there have been several demonstrations of fuel cell powered trucks, vans, tractors, golf carts, and other vehicles.[8] In these vehicular demonstrations, fuel cells have generally had specific power values too low for rapid acceleration and high top speed, and the fuel cell systems were bulky and complex. Long start-up times were a problem in some cases.

Progress in the development of fuel cells continues, and with recent advances in fuel cells for stationary applications they are once again being examined for vehicular applications. The specific power and lifetime have increased and the projected cost has been reduced, but major improvements are still required before fuel cells have a chance of providing power for automobiles.

In a device so far from commercial exploitation, calculated cost figures tend to be optimistic. The available reports come up with costs only about 20 percent above ICEs. This estimate is considered to be low. A substitute for platinum would make a sizable improvement. Attempts to assess lifetime costs are premature because of the dependence on the fuel needs and the efficiency of fuel utilization. With a major development effort, fuel cells for transportation might be available for field evaluation in 5 years, with advanced versions perhaps 10 years later. However, the current emphasis on larger stationary systems will delay progress to about 10 years for the early versions and 15 for the advanced.

The fuel consumption would be approximately 56 kilometers per liter (km/l), or 24 miles per gallon (mpg) for the present versions and perhaps 66 km/l (28mpg) for advanced versions. Two major fuel cell developments are candidates for vehicle propulsion: the phosphoric acid fuel cell which has been the focus of the recent development in the United States; and the alkaline fuel cell which is being developed abroad.

PHOSPHORIC ACID FUEL CELLS

The phosphoric acid fuel cell is the most common acid-electrolyte fuel cell because concentrated phosphoric acid is very stable and has a low vapor pressure, permitting operation at elevated temperatures (up to about 250°C). Operation at high temperatures allows more rapid electrode reactions, reducing the amount of electrocatalyst required for a given power. As might be expected, serious materials problems are associated with the use of hot phosphoric acid under both reducing and oxidizing conditions. Some of the materials that can be used are certain forms of carbon, polytetrafluoroethylene, silicon carbide, platinum, and a very few others.

The development of phosphoric acid fuel cells and steam reformers for use in stationary applications is being carried out by United Technologies.[15] Many of the improvements that have been made are applicable to a vehicular fuel cell system composed of a methanol reformer (to provide hydrogen for the fuel cell) and a hydrogen-air fuel cell. Methanol is considered to be an attractive fuel because it can be prepared by a number of processes, is easily stored as a liquid, and is easily reformed to produce hydrogen by the following reaction:

$$CH_3OH + H_2O \longrightarrow 3H_2 + CO_2 \tag{2}$$

Carbon dioxide (CO_2) is relatively inert in the fuel cell, but carbon monoxide (CO) and sulfur compounds must be avoided because they poison the platinum electrocatalyst.

The potential application of the phosphoric acid fuel cell with a methanol reformer to automobile propulsion raises a number of important issues for consideration:

- <u>Power Density</u>. For acceleration, the power density needed is at least 150 W/kg (assuming the fuel cell system is 20-25 percent of the vehicle test mass). The average power density required is about 35 W/kg. These figures are difficult, but not impossible, for present phosphoric acid fuel cell technology to attain, especially for pressurized operation (several atmospheres) at temperatures slightly above 200°C.[13]

- <u>Cost.</u> The electrocatalyst cost of $1500-$2800 per vehicle is too high. The complete power plant for a 1500 kg automobile should cost about $2000.

- <u>Energy Source Efficiency.</u> Propane can be converted to electricity in a current reformer plus fuel cell system with about 35 percent efficiency. With advanced fuel cells the conversion can run up to 45 percent efficiency. Coal can be converted to methanol using current processes at about 50 percent efficiency, but the methanol reformer-fuel cell reaction to make electricity is only about 70 percent efficient, so that overall efficiency falls to about 35 percent. Thus, the generation of electricity in a fuel cell using coal-derived methanol is equivalent to that of current propane fuel cell cycles.

- Start-up Time. The phosphoric acid fuel cell operates near 200°C and is not self-starting from ambient temperatures. An external source of heat is required, and start-up time is presently estimated to be 15 minutes. This is a particular problem for short-trip urban driving.
- Transient Operation. Almost all fuel cell performance and life testing has been performed under essentially steady state operating conditions. Little is known about the ability of a fuel cell plus reformer system to accommodate transients that are characteristic of vehicle operation.
- Materials Problems. Corrosion of carbon catalyst supports has been a significant problem in these fuel cells and appears to be a major life-limiting factor. Loss of phosphoric acid and reformer operation and life are also critical problems.
- Bulkiness and complexity are significant problems.

It can be concluded that advanced phosphoric acid fuel cells may have acceptable performance for some types of vehicles, but the projected cost is still much higher than can be tolerated for automobiles. System lifetime is a major area of uncertainty. In addition, the problem areas listed above require greater attention.

ALKALINE FUEL CELLS

During the mid-1960s, fuel cells for space applications received great emphasis, and the majority of the fuel cell systems developed were based on alkaline electrolytes (usually potassium hydroxide (KOH)). Alkaline fuel cells are capable of operating at higher current densities (largely because of higher performance air electrodes) than phosphoric acid fuel cells. They also are capable of operating at room temperature and therefore start up almost instantaneously. Corrosion problems are less severe and electrocatalyst requirements are more modest than for the phosphoric acid cell.

An inconvenience associated with the use of alkaline electrolytes is the necessity of removing CO and CO_2 from the fuel and oxidant. For this reason, it is inappropriate to use methanol or other organic fuels. Other possibilities are hydrogen, cracked ammonia, or hydrazine. Hydrogen cannot be readily stored in an inexpensive light-weight system, hydrazine is toxic and expensive, but ammonia is an item of commerce and is handled as a liquid in bulk quantities. Ammonia could be carried as an automotive fuel and cracked to form nitrogen and hydrogen on a simple hot tungsten filament in the following reaction:

(3) $$2NH_3 \longrightarrow N_2 + 3H_2$$

The product stream can be fed directly to an alkaline fuel cell; the nitrogen passes through as an inert gas. For the oxidant, air is used, but the CO_2 (30ppm) must be removed by passing it over sodium hydroxide (NaOH) or KOH supported on an inert packing material. A fuel cell-battery hybrid automobile has already been demonstrated using an alkaline electrolyte cell and a CO_2 scrubber, with tank hydrogen as the fuel.

Alkaline-electrolyte fuel cell hardware is not available for automotive uses; only aerospace systems have been operated in any significant numbers. These have demonstrated operating lives of 5,000 to 10,000 hours of continuous operation on hydrogen. The cell performance is high with power densities of 500 mW/cm^2 at 0.8 V.

From the viewpoints of potentially lower cost and demonstrated higher performance relative to the phosphoric acid fuel cell, the alkaline fuel cell should be given serious consideration in any development of fuel cell powered vehicles. The main strategic question to be answered is whether ammonia can be an acceptable fuel for vehicles.

RELATION OF FUEL CELL TO OTHER ENERGY SOURCES

The fuel cell is not directly competitive with batteries for vehicle propulsion. Electricity from nuclear or coal-fired powerplants could only be the primary source of fuel cell energy if hydrogen or ammonia were the on-board fuels. The other potential fuels are still either derived from petroleum or produced from synthesis gas, which is produced from coal. Once the synthesis gas is produced, the fuel cell is competing with motor fuels that can be produced from the same synthesis gas.

Hydrogen as a fuel would be economically non-competitive and would very much limit the driving range. Very cheap hydrogen would change the economics; but by the same token, a cheap source of hydrogen would reduce the cost of refining both petroleum and synthetic motor fuels as well as encourage the use of hydrogen-fueled internal combustion engines.[2]

5

FLYWHEEL-TRANSMISSION SYSTEMS

PRESENT PROGRAM

Current research and development on flywheels and their transmission systems is part of the Mechanical Energy Storage Technology (MEST) project at Lawrence Livermore National Laboratory (LLNL). The objectives of MEST are as follows:

- To develop, demonstrate, and evaluate mechanical energy storage technology for vehicular and fixed-base applications
- To carry out the RD&D activities in a manner that maximizes the commercialization potential of the technology.

To pursue these objectives, LLNL has established an in-house project team that both conducts in-house research and contracts with outside organizations for R&D. The project has been organized into two primary areas: applications and basic technology. Two applications areas are being considered; transportation and fixed-base. The technology work is divided into three tasks: (1) fiber composite materials, (2) flywheel rotor and containment, and (3) advanced components. The in-house activities of LLNL are limited to work on fiber composite materials and flywheel rotor technology.

A sense of the extent of activity can be obtained by noting that in fiscal year 1980, of 59 individual R&D activities, 44 were subcontracts to private industry, 12 to universities or university-related laboratories, and 3 were performed within LLNL.

Activities for the future include the following:

- Continued transportation application studies with increasing emphasis on heat engine-flywheel systems
- Fixed-base applications focusing primarily on residential and small-scale industrial or commercial energy storage systems.

- Fiber composite materials technology with a view toward characterizing fiber and matrix materials; continued work on long-term behavior studies
- Rotor and containment technology; cyclic behavior and manufacturing and economic studies; development of containment concepts
- Advanced component technology, focusing on development and operation of test facilities and on continuously variable transmissions.

TECHNOLOGY NEEDS

Flywheels have a demonstrated capability of improving fuel economy for urban driving in transportation applications and for load leveling and storing energy available from intermittent sources in stationary applications. Flywheel technologies that can exploit these capabilities to the maximum need to be developed and demonstrated so that this option can become a reality. Small light-weight flywheels, especially for transportation applications, are becoming possible as a consquence of developments in composite materials. (Heavier flywheels that can store more energy also have a number of potential applications, one of which could be wayside energy storage as part of a national railroad electrification program.)

The advantages of flywheels in vehicles is heavily dependent on the drive cycle. The greatest pay-off will be for drive cycles with large numbers of stops and starts. For constant speed highway type driving, the flywheel constitutes a penalty because of the additional weight. In order for the flywheel to be economically feasible, the initial cost must be offset by the fuel savings over the life of the vehicle.

The LLNL program seems well-designed to address these issues. The present program has among its goals the development by 1984 of a rotor having 88 Wh/kg at failure (with operation designed for 44-55 Wh/kg) and an energy storage capacity of approximately 1 kWh. The goal is for rotor and containment weights of about 50 kg each. These seem reasonable and desirable goals. The program also contains plans for the installation of developmental flywheels in a passenger vehicle.

The Panel recommends that emphasis be given to the following areas of investigation:

- <u>System Design</u>. Past work has been properly focused primarily on component development; further work is needed in this area. However, as component problems become solved, attention needs to be given to flywheel system design that comprises, for example, trade-offs between rotor and containment so that the two are designed together.

- <u>Continuously Variable Transmission (CVT)</u>. The Panel concurs that flywheel rotors and their containment must be demonstrated in practice. However, the key to applications lies in the development of an efficient and producible CVT. This is a formidable problem and should receive increasing attention.

- <u>Manufacturability</u>. Emphasis should be given to the development of flywheel designs that are easy to manufacture and can be produced cheaply. Although it is recognized by the LLNL program, the Panel would like to emphasize that this is an area of considerable importance.

- <u>Component Technology</u>. The LLNL program appears to be cognizant of the work that needs to be done in this area and has a well- designed program for carrying out the necessary investigations.

6

CONCLUSIONS AND RECOMMENDATIONS

Among the potential propulsion system alternatives to internal combustion engines (ICE) for personal automobiles, rechargeable (secondary) batteries, which offer a great range of options for using primary energy sources, have received the bulk of national R&D resources. However, the batteries that might be developed to a preproduction stage within the next decade seem to have inherent shortcomings, including higher first costs and appreciably lower driving ranges than those offered by ICE powered vehicles. Accordingly, unless the use of ICE vehicles is curtailed for some reason, it is unlikely that rechargeable electric vehicles will make a significant market penetration in the foreseeable future. Therefore, such vehicles will probably have only a minor impact on petroleum fuel use and on pollution abatement.

In light of these shortcomings, it is recommended that other storage vehicle alternatives be investigated (in addition to secondary batteries) to establish realistic performance potentials and to determine if health or safety hazards would preclude their use in automotive systems. R&D on metal-air primary batteries, fuel cells, flywheels, and continuously variable transmissions is proposed. The following areas are specifically recommended for emphasis in the investigation of ICE alternatives for personal automobiles:

1. Secondary battery systems with a potential for an energy density above 200 Wh/kg. One example is the lithium/sulfur cell for which research on electrolytes (molten salt and solid) and novel electrode structures might be very rewarding. Another specific electrochemical couple deserving research emphasis is secondary lithium/sulfur dioxide.

2. Metal-air primary batteries. The existing research on aluminum-air batteries might be expanded, but only after key issues are resolved, such as the cost and life problems of air electrodes and the acceptability of the major alterations in the aluminum industry fuel-supply infrastructure that a substantial utilization of such batteries would entail.

3. Phosphoric acid fuel cells. Expected efficiency improvements justify research on key issues, even though the fuel supply options are limited and may be petroleum based. Particular issues of importance include the identification of improved materials for structures, and the identification of electrolytes to improve system start-up times and responses.

4. Alkaline fuel cells. Systems study and fuel acceptability analyses are merited. A research and development project should be put in place only if the results are encouraging. Problems of air electrode cost and life will require research emphasis.

5. Flywheel-transmission technology. The successful application of metal-air batteries and/or fuel cells in energy storage vehicles may require a flywheel adjunct to handle acceleration and regenerative braking situations. Accordingly, the ongoing flywheel programs should be continued, but with emphasis on continuously variable transmissions and on overall system designs.

To the extent that fuel shortages or pollution concerns may generate a future national requirement for personal automobiles to be powered by systems other than conventional internal combustion engines, these recommended research areas are believed appropriate for federally sponsored R&D. If adequate solutions to the kinds of problems that have been identified are forthcoming, the vehicles that could become available should minimize the societal impacts that might accompany the necessary replacement of conventionally powered cars.

To the extent that non-ICE vehicle systems can be expected to remain as optional choices of the driving public, R&D in the suggested areas would appear to represent a prudent investment for the private sector as a supplement to ongoing electric vehicle R&D activities.

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