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ELECTROCHEMICAL POWER SOURCES FOR ELECTRIC HIGHWAY VEHICLES

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16. Abstract This report summarizes an assessment of electrochemical power sources (batteries and fuel cells) which are relevant to electric vehicle propulsion. The developments reported herein have taken place since a previous assessment on the same subject was completed by Arthur D. Little, Inc. in 1968 for the U.S. Department of Health, Education and Welfare.

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PREFACE

The work described in this report was performed by A.D. Little, Inc. for the Office of the Assistant Secretary for Systems Development and Technology, U.S. Department of Transportation, through the Department's Transportation Systems Center. This work is part of an effort at the Transportation Systems Center, sponsored by the Office of the Assistant Secretary for Systems Development and Technology, with the objective to obtain technical information to be used by the Department for matters relating to energy usage by the transportation sector.

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1. CONCEPT OUTLINE

This memorandum report summarizes technical developments in the field of electrochemical power sources (batteries and fuel cells) which are relevant to electric vehicle propulsion and which have taken place since the study carried out in 1968 for the U.S. Department of Health, Education and Welfare by Arthur D. Little, Inc. (ADL) under Contract No. PH 86-67-108. Limitations on time and budget have required us to base this report primarily on in-house information and have prevented verification of specific factual material with outside sources. However, we believe that the information provided is generally accurate.

The following abbreviations appear frequently in this report:

w/lb = watts per pound

wh/lb = watt-hours per pound

kw, kwh = kilowatt, kilowatt-hour

ah = ampere-hour.

2. OBJECTIVE

Electrochemical power sources are components of the prime mover system in the following types of electric vehicle:

Battery powered vehicles

Fuel-cell powered vehicles

Heat-engine battery hybrid powered vehicles

Fuel-cell battery hybrid powered vehicles

Battery-containing dual mode vehicles.

These types of vehicle are of interest for highway transportation because of the following considerations:

- Air Quality. Battery powered and dual mode vehicles have no noxious emissions (apart from possible small quantities of ozone from the electric motors) and the levels of emissions from fuel-cell powered vehicles and hybrid vehicles are likely to be much lower than those from conventionally powered vehicles.

- Fuel Supply. Use of electricity to power highway vehicles will lessen dependence on petroleum based fuels since electricity can be generated from a variety of fossil fuels and also from nuclear, hydro, and possibly solar sources. Fuel cells operate on a variety of specific fuels and will present new options in the consideration of fuel supply.

- Fuel Economy. The overall fuel conversion efficiency of electric vehicles, whether direct, hybrid, or dual mode, promises to be greater than that of conventionally powered vehicles.

- Noise Pollution. Electric vehicles promise to be quieter in operation than other types.

Existing types of commercially available battery do not possess the appropriate combination of energy density, power density, lifetime, and cost to provide electric vehicles with performance capabilities matching those of existing highway vehicles. While the effective energy densities of fuel cells can in principle be very high, the other parameters listed above are far from meeting the requirements of electric vehicles. Moreover, fuel cell technology is relatively immature. Further development of batteries and fuel cells with improved performance and cost parameters is therefore required for the advancement of electric vehicle technology.

3. PRESENT STATUS

Analysis of the energy and power requirements of highway vehicles carried out in ADL's 1968 report showed that a full-sized electric family automobile of average performance and with a range of 200 miles would require a battery power source with an energy density of about 100 wh/lb and a power density of about 60-80 w/lb. Other types of vehicle with lower performance specifications had correspondingly more modest requirements for their battery power sources, down to energy densities in the range of 20-40 wh/lb and power densities in the range of 30-40 w/lb. Vehicles with hybrid heat-engine battery or fuel-cell battery power sources, presumably having adequate energy densities, were found to require batteries with power densities in the range of 50-100 w/lb.

Developments in the battery and fuel cell field need to be reviewed im the context of the above requirements. In all cases low cost and long life are desirable characteristics.

Presented in Table I is an overview of the performance targets and development status of those batteries and fuel cells of interest for electric highway vehicles.

3.1. Conventional Batteries

The following commercially available conventional rechargeable battery systems may be considered for use in electric vehicles:[1]

Lead-acid
Nickel-cadmium
Nickel-iron
Silver-zinc
Silver-cadmium.

In the interval since the preparation of the 1968 report, only the lead-acid and nickel-iron battery systems, among conventional batteries, have developed further in directions relevant to electric highway vehicle applications.

3.1.1. Lead-Acid

The introduction of several new consumer oriented battery powered vehicles, such as electric garden tractors and rider lawn mowers, together with the continued popularity of electric golf carts, has stimulated further development of a type of lead-acid battery intermediate in quality and cost between automotive starter (SLI) batteries and industrial traction batteries. Designed to give optimum service at a 2-hour discharge rate, these batteries can, with careful maintenance, give up to 2 years of service (300-400 cycles) in vehicle applications. At low discharge rates, they possess energy densities of 16-18 wh/lb. Batteries of this type are manufactured by (among others) Gould, Inc., Electric Fuel Propulsion Corp., and ESB, Inc. They are similar in construction to SLI types but have somewhat thicker grids made of a modified lead alloy. Polypropylene containers and through-the-partition (TTP) connectors are

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1. The alkaline-manganese system possesses limited rechargeability but its poor cycle life and performance capabilities make it unsuitable for application in electric vehicles.

TABLE I. ELECTROCHEMICAL POWER SOURCES FOR ELECTRIC HIGHWAY VEHICLES

Class	System	Expected Performance(1) wh/lb	Expected Performance(1) w/lb	Development(2) Status	Principal Problems
Conventional	Lead-acid	18-20	20-30	****	low energy density
	Lead-acid (for hybrids)	5?	100-150	*	lifetime?
	Nickel-iron	20-25	50?	**	cost, maintenance?
High Temper-ature alkali metal	Sodium-sulfur	80-100	80-100	**	ceramic fragility
	Lithium-sulfur	>100	>>100	*	selection of construction materials
	Lithium-chlorine (Carb-Tek^R)	50	>>100	**	low cycle life
Metal-air	Iron-air	40-50	10-20	***	cathode corrosion
	Zinc-air	40-50	10-20	**	low cycle life
Other	Zinc-chlorine	80-100?	?	**	information not available
	Zinc-bromine	20		**	low energy density
	Nickel-zinc	20-25	>100	**	low cycle life, cost
Fuel Cells	Reformed-hydrocarbon	--	10-15	***	too heavy for vehicles
	Methanol	--	50-100	***	need catalyst for methanol

Footnotes:

1. Energy density and power density refer to maximum values attainable, respectively, at very low discharge rates and for short high-rate discharge periods.
2. Development status:
   **** commercially available
   *** batteries tested
   ** cells tested, some batteries
   * cells under development

used. ESB has under development a new type of positive plate for this class of battery, in which the active material is held sandwiched between latticed grids. This design is reported to improve the energy density at high discharge rates.

An industrial quality lead-acid battery with improved performance has been developed by A. B. Tudor,[1] the Swedish battery company. Using TTP connectors and polypropylene cases with monobloc construction, energy densities of 17 wh/lb have been achieved at a 6-hour discharge rate. These batteries have tubular positive plates and a life expectancy of 5-6 years (1500-2000 cycles).

There has been significant activity also in the development of lead-acid batteries with improved high discharge rate capability for use in hybrid electric vehicles. Experimental batteries designed specifically to maximize power density are being developed at Tyco Laboratories, Inc., and in a joint program by Gould and TRW; both programs are sponsored by the Environmental Protection Agency. Progress so far indicates that power densities in the range of 100-150 wh/lb should be attainable in batteries having a reasonable lifetime (2 years or more).

3.1.2. Nickel-Iron

Some interesting work on the nickel-iron system has been carried out by Westinghouse Electric Corporation. By means of new techniques for electrode fabrication, particularly the employment of metal fiber substrates for the cell plates, the energy density obtainable from batteries has apparently been doubled (from about 10 to about 20 wh/lb) and the high rate discharge capability has also been considerably improved. The poor charge efficiency of the nickel-iron system remains, however, and maintenance requirements (water addition) of the batteries are consequently high. The Westinghouse work is internally funded, and no further information is publically available.

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1. wholly owned subsidiary of AGA A. B. (see also Section 3.2.2.).

3.2. Batteries Under Development

The two main approaches towards the development of batteries with higher energy density are by the use of electrochemical couples which contain either alkali metal anodes or air cathodes. Due to the reactivity of water with alkali metals, the former approach necessitates a non-aqueous electrolyte; this may be a molten salt, an electrolytically conductive ceramic, or an organic liquid. The molten salt and ceramic electrolytes, on which almost all present development work is focused, require operating temperatures of 250°-600° C. Interest in alkali metal organic electrolyte systems was initially discouraged by the extremely poor cycle life obtained. Recent major improvements in the technology of lithium-organic electrolyte primary batteries (for instance, the lithium-sulfur dioxide and lithium-cupric sulfide systems) may, however, restimulate activity in this field.

3.2.1. High-Temperature Alkali Metal Batteries

Development work on high-temperature alkali metal batteries has concentrated mainly on the sodium-sulfur, lithium-sulfur, and lithium-chlorine couples, especially the sodium-sulfur system.

With one exception, all of the sodium-sulfur battery programs use beta-alumina ceramic electrolytes, mostly in the form of tubes 1-2 cm in diameter, typically of 0.5-1.0 mm wall thickness and 10-20 cm in length, although some work has been done with electrolytes in the form of discs. Programs of this type are being carried out at the Ford Motor Company and General Electric in the United States (with investigation of the electrolytic properties of the ceramic being made at TRW and elsewhere), at the laboratories of British Rail and the Electricity Council in the United Kingdom, at CGE in France, and in a joint program by Yuasa and Toshiba in Japan. Individual cells have power outputs in the range of 30-50 watts. Lifetimes of up to 800 cycles (generally one hour charge--one hour discharge at current densities in the range of 0.25-0.50 amp/cm^2) have been obtained, but the average cell lifetime, which is limited by the physical and electrical properties of the ceramic, is only on the order of 100 cycles. In some of these programs (including Ford, Yuasa, the Electricity Council, and British Rail), batteries with outputs of up to 2 kw have been operated, primarily for demonstration purposes and only for tens of cycles.

A different approach is being taken by the Dow Chemical Company which, in its sodium-sulfur cells, uses a glass with high sodium oxide content, spun in the form of thin-walled hollow fibers (50 microns in diameter and 8 microns in wall thickness). Each glass fiber is filled with a thin filament of sodium; the cell consists of large numbers of fibers immersed in a tank of molten sulfur. Although the glass is much less conductive than beta-alumina, the fibers provide a large surface area. Their small diameter results in the added advantage that if a fiber breaks it is automatically sealed off by formation of solid sodium sulfide. While the Dow approach seems to hold much promise, we understand that only about 60 cycles of operation have been demonstrated so far in experimental cells of 50 ah capacity. Typical current densities through the glass fibers are 2-4 milliamps/cm^2.

The most important lithium-sulfur program is that under way at the Argonne National Laboratory. So far it has focused on the development of single cells with cross-sectional area of up to about 30 cm^2. The largest cells built have capacities of about 25 ah. Cycle lives approaching 2000 cycles (one-hour charge, one-hour discharge) have been attained in unsealed cells but calendar life is presently no better than the half year or so taken up by the cycling experiments. Similar programs of smaller scope are in progress at North American Rockwell Corporation and at ESB. Preliminary work is also reported to be going on at Westinghouse and at the Admiralty Materials Laboratory in the United Kingdom, although the objective of the latter is the development of a primary battery for use in torpedo propulsion.

General Motors Corporation has carried out considerable development work on rechargeable lithium-chlorine cells. Difficulty in obtaining reasonable lifetime at the cathode is believed to have caused GM to cut back somewhat on these activities, but work still continues, motivated by the enormously high power output (up to 5 watts/cm^2 of electrode surface) obtainable with this system.

A lithium-chlorine program which holds more promise of practical hardware is the Carb-Tek battery development at Sohio. In the Carb-Tek system lithium is deposited on charge as an alloy in aluminum, while the chlorine, instead of being evolved as a gas, forms an addition compound with various inorganic compounds contained in a high surface area carbon cathode. Fully sealed Carb-Tek cells have been constructed in a range of capacities up to 30 ah. At the present stage of development, cycle life is limited primarily by the buildup of leakage current, but over 500 cycles have been attained in single cells. A battery of 12 cells, weighing 12 lb (without insulation) and having an output of 264 wh, has been operated for 100 cycles. From the standpoint of engineering development, the Carb-Tek system appears today to be the most advanced of the high-temperature alkali metal batteries.

3.2.2. Metal-Air Batteries

At the time of publication of the 1968 report, considerable activity and optimism surrounded the development of metal-air batteries for application in electric vehicles. Various technical difficulties have caused the termination of most of those programs, including the zinc-air developments at Gulf Energy and Environmental Systems (formerly General Atomic), Joseph Lucas, Ltd. of the United Kingdom), and Leesona, Inc., and the sodium-air program at North American Rockwell. General Motors, however, continues a relatively small program on zinc-air batteries.

An interesting program at Sony (Japan) has demonstrated a 3-kw zinc-air battery which is novel in that it uses powdered zinc suspended in aqueous alkali as the anode active material. The zinc oxide formed on discharge is collected in a tank and subsequently reconverted to zinc powder in an external electrochemical reactor.

The most important program current active in metal-air batteries is the iron-air development at AGA A.B. of Sweden. The Swedish group has modified the tendency of the iron electrode to passivate at high current densities by incorporating other elements in it. An improved technology has also been developed for making air cathodes from pressed nickel powder, the catalyst being silver. The aqueous potassium hydroxide electrolyte is pumped through the cells and is protected from contamination with atmospheric carbon dioxide by scrubbers in the air supply to the cathodes. The system also includes a make-up water supply to replenish losses by evaporation and electrolysis. Batteries being tested in the laboratory now have lifetimes of about 500 cycles; battery life is limited by corrosion and catalyst loss or deactivation at the cathode, caused by the oxygen evolved there on recharge.

AGA A.B. has built a large iron-air battery with a capacity of about 30 kwh and has used it to power a small truck. This battery has demonstrated an energy density of 35 wh/lb (including auxiliaries) at low discharge rates, and the incorporation of improvements already achieved in the laboratory will soon raise this to 45 wh/lb.

3.2.3. Other Types of Battery Under Development

A number of other battery systems are under development or investigation for possible application in electric vehicles. While none has the potential high energy and power density of the high-temperature alkali metal systems, some have potential comparable to that of metal-air systems, and all, if brought to maturity, would provide better performance than conventional rechargeable batteries.

Of considerable interest is the recently announced zinc-chlorine battery being developed by Occidental Petroleum. This system has a recirculating electrolyte of aqueous zinc chloride and stores the chlorine under refrigeration as crystals of chlorine octahydrate. Little information has been released, but what is available indicates that a battery large enough to power a compact car would demonstrate an energy density of about 60-80 wh/lb.

A chemically related system is the zinc-bromine battery with an aqueous zinc bromide electrolyte, under development at the Zito Company. Batteries with a nominal capacity of 1 kwh have already demonstrated 1000 cycles of operation and several thousand cycles may be possible. However the energy density of these batteries is only 20 wh/lb, hardly greater than that of lead-acid batteries. Their attractiveness is based on their potentially high cycle life, their ability to be left idle for long periods without deterioration, and the non-hazardous nature of their electrolyte.

Also employing zinc anodes is the nickel-zinc battery, which has a prospective energy density of about 20-25 wh/lb. While this energy density is not much of an improvement over that of lead-acid batteries, the nickel-zinc battery does have excellent high rate discharge characteristics and might be useful in hybrid powered vehicle systems. Programs are being, or have been, carried out at Energy Research Corporation, Eagle Picher, Inc., Yardney Electric Corp., and North American Rockwell. The maximum cell size reported is 25 ah, and lifetimes of more than 300 cycles at 65% depth discharge have been demonstrated in laboratory tests on single cells. Hitachi, Ltd., of Japan is reported to have built cells of over 100 ah capacity with similar cycle lives.

Two other electrochemical couples, aluminum-chlorine and nickel-hydrogen have been given preliminary investigation for potential application in high-energy batteries. Work at Tyco Laboratories on the aluminum-chlorine system with a melt of aluminum chloride and alkali metal chloride as electrolyte showed that this system offers some promise in view of its relatively low (for a molten salt electrolyte system) operating temperature, 130-150° C, and its favorable anode electrode kinetics. To be weighed against these advantages is the very sharp dependence of electrolyte melting point on composition; for a practical battery, this would lead to requirements for excessive quantities of electrolyte, which would lower the energy density.

Most of the interest in the nickel-hydrogen system has been generated at the laboratories of Comsat, Inc., and at Tyco Laboratories. An outgrowth of earlier work, primarily at Electro Optical Systems (now a division of Xerox Corporation) and at Allis-Chalmers Manufacturing Company, on reversible hydrogen-oxygen fuel cells, the system uses a sintered nickel positive electrode similar to those of sealed nickel-cadmium cells and contains the hydrogen at pressures of up to 1000 psi in a reinforced fiberglass container. While energy densities of up to 40 wh/lb are postulated, the energy density based on volume is not so favorable. Cells with capacities of up to 10 ah have been built so far.

3.3. Fuel Cells

Only two major fuel cell hardware development programs are presently active. These are the TARGET program at Pratt & Whitney Aircraft division of United Aircraft Corporation and the joint program between Alsthom (a Division of the French Company, CGE) and Standard Oil of New Jersey.

The TARGET program is aimed primarily at the development of a stationary fuel cell to operate on natural gas. It is based on technology involving reaction of an unpurified (i.e., carbon dioxide containing) fuel made by steam reforming hydrocarbons in an aqueous phosphoric acid electrolyte cell operating at 130° C. A standard module, rated at 12.5 kw and weighing about 1600 lb with auxiliaries, is now being installed in about 40 different locations for field testing and is reported to have a life expectancy of more than five years. The fuel cell itself is reported to have an operating point of 250 milliamps/cm^2 at 0.6 volts per cell, using electrodes having a catalyst loading of 0.25 milligrams of platinum/cm^2. A weight reduction of the 12.5-kw module to 1100 lb (12 w/lb), believed to be possible, might make the system interesting for application in heavy vehicles.

The Alsthom fuel cell system has a remarkably compact design, in which fuel, oxidant, and electrolyte are pumped at high velocity through narrow cells, the corrugated walls of which are coated with catalysts. Operating on hydrazine and hydrogen peroxide as fuel and oxidant, this cell can achieve a power density of about 50 w/lb. Systems with power outputs of up to 100 kw have been assembled wtih components built on a production line basis. However, the applicability of this fuel cell to electric vehicles will depend very largely on whether low-cost (non-noble metal) catalysts can be developed that will allow it to operate on methanol and air instead of hydrazine and hydrogen peroxide.

A systematic five-year program with this objective is now underway. Results to date are encouraging, but it is too early to tell whether the goal will be achieved.

In the mid-1960's, large-scale proggrams to develop vehicle-oriented fuel cell hardware were undertaken by Union Carbide, on hydrogen-oxygen alkaline-electrolyte fuel cells, and by Shell Oil Company, on a variety of systems. Shell has built a 5-kw alkaline-electrolyte fuel cell operating on steam-reformed methanol and a 0.5-kw acid-electrolyte fuel cell using methanol directly. Shell's efforts are presently concentrated on a search for improved non-noble metal catalysts for use in direct methanol fuel cells.

The West German government is coordinating a substantial fuel cell development program, covering acid-electrolyte and alkaline-electrolyte hydrogen-oxygen fuel cells, and acid electrolyte direct methanol fuel cells. While the program is clearly relevant to electric vehicles, much of the work is under military sponsorship, and details of its status are not available. Organizations participating in this activity include Siemens, Varta, AEG, Bosch, and the Battelle-Institut (Frankfurt).

3.4. Support Level

Estimates of the level of financial support for vehicle-oriented electrochemical R&D are somewhat unreliable because of (1) the difficulty of isolating, within a broad research program, those expenditures which apply specifically to vehicle-oriented research and (2) the proprietary nature of most information on expenditures by the private sector and by governments outside the United States. The estimates in Table 2 are largely subjective, based on our impressions of the scale of the various current R&D activities.

The Conventional Batteries category in the table consists mainly of lead-acid development efforts but also includes the work on nickel-iron batteries. Much of the former is interwoven with developments aimed at the improvement of lead-acid starter batteries, and its contribution to electric vehicle development may therefore be exaggerated.

TABLE 2

SUPPORT-LEVEL FOR VEHICLE-ORIENTED ELECTROCHEMICAL R&D

	Estimated 1972 Expenditures ($ millions)	
	United States (federal and private)	All Other Non-Communist Countries
Conventional Batteries (3.1)	1.0 - 1.5	1.0 - 2.0
Batteries Under Development (3.2)		
High-Temperature Alkali Metal (3.2.1)	1.5 - 2.5	1.0 - 1.5
All Others (3.2.2 and 3.2.3)	1.5 - 2.0	0.5 - 1.5
Fuel Cells[1] (3.3)	8.0 - 12.0	4.0 - 8.0

1. Fuel cell expenditures are largely oriented toward stationary applications and include much work on systems engineering. Much of the technology, however, should later be adaptable to electric vehicle requirements.

Source: ADL estimates.

The High-Temperature Alkali Metal category includes the programs on sodium-sulfur, lithium-sulfur, and lithium-chlorine batteries. Outside of the United States, expenditures in this category are almost entirely for sodium-sulfur battery development.

The All Other category includes the zinc-chlorine, zinc-bromine, nickel-zinc, and nickel-hydrogen programs in the United States, the iron-air program in Sweden, and various activities in Japan. It should be noted that the nickel-zinc and nickel-hydrogen work is only indirectly related to electric vehicle application.

The estimates for fuel cell expenditures are large in comparison with those for batteries because they include much work on systems engineering and the development of auxiliaries. As noted in the table, most fuel cell work is directed at stationary applications but the technology might later be adapted for vehicles.

3.5. Contributors

Organizations active in electrochemical R&D related to electric vehicles are listed below, grouped according to the types of system they are working on. An attempt is also made to estimate the magnitude of the various programs (with the same caveats as in the previous section) by the following classification:

*** a major effort involving annual expenditures above $250,000

** intermediate effort at the $100-250,000 annual level

* preliminary, largely exploratory program involving annual expenditures of less than $100,000.

Conventional Batteries

Gould***	Furukawa** (Japan)
Westinghouse Electric***	Japan Storage** (Japan)
ESB**	Lucas** (U.K.)
Globe-Union**	Matsushita** (Japan)
Tyco Laboratories**	RWE** (Germany)
Electric Fuel Propulsion*	Tudor** (Sweden)

Conventional Batteries (continued)

Eltra*
General Battery*
General Motors*

Varta** (Germany)
Yuasa** (Japan)
Bosch* (Germany)
Chloride* (U.K.)
Marelli* (Italy)

High Temperature Alkali Metal Batteries

Argonne N.L.***
Dow**
Ford**
General Electric**
General Motors**
North American Rockwell**
Sohio**
ESB*
Westinghouse*

British Rail*** (U.K.)
Electricity Council*** (U.K.)
Yuasa-Toshiba*** (Japan)
CGE** (France)
Admiralty Lab.* (U.K.)

All Other Batteries

Occidental Petroleum***
Zito***
Energy Research **
ESB**
General Motors**
Eagle Picher*
Tyco Laboratories*

AGA*** (Sweden)
Hitachi** (Japan)
Matsushita** (Japan)
Sony** (Japan)

Fuel Cells

United Aircraft***

Alsthom***
Combined German Program***
Shell**

4. OUTLINE OF TECHNICAL PROBLEMS

The technical problems involved in developing various electrochemical power sources need to be reviewed in the context of the performance and cost objectives which have been set for them. Thus, for example, while most of the high-temperature alkali metal batteries have potential for meeting the power and energy density requirements of full-size, full-performance automobiles, interest in lead-acid batteries related to their application (1) in limited-performance battery powered vehicles and (2) as the energy storage component of full-performance hybrid vehicles. Like all batteries each system has its own combination of performance and cost parameters, either achieved or projected, which makes it especially suitable for some specific class of application.

4.1. Conventional Batteries

4.1.1. Lead-Acid Batteries

The main problem with the lead-acid system is its low energy density, resulting primarily from the high density and equivalent weight of lead. Improvements are being made by reducing the amount of lead in the grids, increasing active material utilization, and optimizing the design of the battery. The use of thinner grids, however, increases the likelihood of grid corrosion and premature battery failure. Claims of improvements in energy density must therefore be assessed against their effect on battery lifetime.

In the development of high-power-density lead-acid batteries, which generally use plates composed of thin layers of active material supported on plastics, the main problem is to achieve adequate life. This problem is aggravated by the higher operating temperatures which result from high rates of charge and discharge.

4.1.2. Nickel-Iron

Although the energy density of the nickel-iron battery appears capable of exceeding that of the lead-acid battery, it is still low. In addition, the battery is substantially more expensive, and the low charge efficiency leads to a burdensome maintenance requirement.

4.2. Batteries Under Development

4.2.1. High-Temperature Alkali Metal Batteries

The universal problem with all high-temperature alkali metal batteries is to find construction materials which have adequate physical and electrical properties and lifetime, at an acceptable cost. A secondary problem is that of scaling up laboratory techniques into production technology.

Difficulties arise in the choice of materials for cell containers, current collectors, separators, and seals. In the lithium-sulfur and lithium-chlorine systems, active material solubility in the electrolyte can cause self-discharge. In the sodium-sulfur battery, a major problem is posed by the mechanical fragility of the beta-alumina ceramic in the thicknesses required to give an acceptably low internal resistance. Seals are a source of difficulty in all programs.

In the Sohio lithium-chlorine (Carb-Tek) battery system, power density is very high (>500 w/lb) but the energy density is probably limited to about 50 wh/lb by the mass of the aluminum and carbon current collectors.

4.2.2. Metal-Air Batteries

The energy densities potentially attainable in metal-air systems are generally in the range of 40-80 wh/lb, which makes them of considerable interest for electric vehicles. Power densities, however, are quite limited, primarily by the capabilities of the air electrode, and probably will not exceed 20-30 w/lb. The main technical problems with this type of battery are (1) limited cycle life due to corrosion of the cathode on recharge and (2) passivation of the anodes at high discharge rates.

4.2.3. Other Types of Battery

The zinc-chlorine battery is believed to experience difficulties resulting from the volatility of the halogen and from side reactions at the cathode which take place on recharge. The primary handicap of the zinc-bromine battery is its limited energy density, while the main problem with the nickel-zinc system is its limited cycle life due to structural problems at the zinc anode. The nickel-zinc battery will also probably cost more than other types.

The narrow liquid range of the molten salt electrolyte used in the aluminum-chlorine cell has already been mentioned as a problem which may limit this system's potential. The nickel-hydrogen battery is also at too early a stage for final comment, but it will be rather costly and its projected energy density, 40 wh/lb, will be less favorable on a volume than on a weight basis because of the bulkiness of the gas container.

4.3. Fuel Cells

The two most appropriate classes of fuel cell for vehicular application appear to be the reformed hydrocarbon acid electrolyte and direct methanol acid (or neutral) electrolyte types. In each case, the primary technical problem is to develop low-cost, long-life catalysts for both anode and cathode. Noble metals, particularly platinum, are the most effective catalysts but are expensive. They must either be replaced by lower-cost substitutes or made effective at lower concentrations.

If fuel cells are to be used for vehicle propulsion, their power density must probably also be greatly improved. A possible alternative would be to use them in conjunction with high-power-density batteries.

Low-cost fuel cells using alkaline electrolytes have been developed which use hydrazine as a fuel. Unfortunately, no method has yet been devised for the low-cost synthesis of hydrazine.

5. RECOMMENDED ACTION

Greater investment by the federal government in R&D relating to electrochemical power sources seems a recommendation to be made from this review. Present efforts appear underfunded in relation both to the magnitude of the technical problems and to the significance of the technology to the transportation field. The private sector cannot be expected to increase its contribution very much in view of (1) the questionable return on investment due to the political, social, and economic uncertainties surrounding the future of electric vehicles and (2) the exceptionally long lead times involved in electrochemical research.

6. RANK

Of the various classes of electrochemical power source, the high-temperature alkali metal battery development programs seem most deserving of increased support, in view of (1) their potential for achieving the high power and energy densities required by highway vehicles and (2) the relatively unexplored state of their technology. However, the technical difficulties of high-temperature operation and the hazards associated with the use of alkali metals must not be underestimated.

Fuel cell development would appear to be second in order of merit because of the fuel cell's high effective energy density and its greater compatibility with existing systems of vehicle fuel distribution. Part of this effort on fuel cells might be directed at the catalyst problem and part at the problem of hydrazine synthesis.

Also meriting support are the metal-air and other batteries, which should be evaluated on the basis of their potential as power sources for limited-capability vehicles. The importance of this type of vehicle to transportation may well increase over the next few decades.

The lead-acid battery is already a well-established commercial system, and its improvement can probably be left largely to private capital.

7. ESTIMATED EFFORT, SCHEDULE AND COST

At least four high-temperature alkali metal battery systems are presently under active development--the lithium-sulfur battery, two types of sodium-sulfur battery (ceramic and hollow glass fiber) and the lithium-chlorine (Carb-Tek) battery (the latter having somewhat limited potential for energy density improvement). On the basis of recent experience, it seems likely that a budget of $1.0 million per year is close to the minimum for any viable development program in this field. A reasonable course might be to invest this amount annually in each of the four systems for a three-year period to determine more clearly their relative merits.

A decision might then be taken to continue development at least through the engineering prototype stage with one, or preferably two, systems. The estimated time and cost for this continued development activity might be in the range of a further 5 years at an annual budget of $2-5 million for each continuing program.

Fuel cell programs are of even more long-range nature, with emphasis needed on the catalyst problem, the development of low-cost construction techniques, and the low-cost synthesis of hydrazine. Encouragement should be given to R&D in these three areas, with a total allocation of perhaps $1-2 million annually. However, it must be recognized that the work is likely to be characterized by slow progress rather than sudden breakthroughs. Progress might be reviewed every three years to redetermine the ranking of the effort.

For the other battery systems, support should be provided on a more circumstantial basis and in relation to the specific promise and potential application of each candidate system. A general fund of perhaps $1-2 million might be made available for support of the three or four most promising systems. Decisions about escalation of support for those which were fulfilling their earlier promise might be taken at three-year intervals.

8. IMPACT ON RESOURCES

The electrochemical couples employed in high-temperature alkali metal batteries utilize sodium or lithium as anodes and sulfur or chlorine as cathodic oxidants. With the possible exception of lithium, all these elements are in unquestionably abundant supply and offer no conceivable problem of availability. According to a recent statement by the President of the Foote Mineral Company, the world's largest supplier of lithium and its compounds, existing proved reserves of lithium in the United States are also fully adequate for conversion of all highway vehicles to lithium battery power. Thus, the basic active materials of high-temperature batteries present no problems to national resources. Materials of construction, on the other hand, may present some difficulties. Such elements as tantalum, niobium, and tungsten, used in experimental cells, cannot be used in large-scale production for reasons of both cost and availability. The future viability of high-temperature batteries may well depend on the degree of success achieved using substitute materials such as graphite, aluminum, and stainless steel.

The availability of lead appears to be reasonably adequate for prospective use in high-power lead-acid batteries of the type required by hybrid electric vehicles. Such vehicle systems are estimated to need about 100 lb of lead per vehicle, which is only about ten times the amount presently needed for starter batteries alone. Since other uses for lead (e.g. anti-knock compounds and paints) are declining rapidly, the lead industry would need to expand only some two or three times to cover the entire anticipated vehicle need. This is partly because lead for the battery requirement is recyclable, while the declining uses are consumptive. Reserves of lead are possibly not adequate for complete conversion to lead-acid batteries as vehicle power sources, but in view of their low energy density, this would not in any case be practicable.

Among the other elements used in batteries, production and reserves of both nickel and zinc appear insufficient for their employment in batteries to power the entire vehicle population. Reserves would be adequate, however, for use in hybrid electric vehicle applications.

In the case of fuel cells, and to some extent also for the cathodes of metal-air batteries, requirements for noble metal catalysts, particularly platinum, may make a serious impact upon the reserves of these elements. These extensive large-scale applications of platinum-catalyst fuel cells will be possible only if the efforts made to increase their effectiveness are successful.

With regard to fuel resources, conversion to battery or fuel cell power for vehicles will certainly have beneficial effects, since electricity can be generated from nuclear, hydro, and even solar sources as well as from a wide variety of fuels. The fuel requirements of fuel cells will of course depend on the specific technology developed but should at least allow a greater range of options than is presently available in our petroleum-based highway transportation system.

9. ENVIRONMENTAL AND ECOLOGICAL IMPACT

Conversion to battery or fuel cell vehicles should be of considerable benefit to air quality, particularly in urban areas. Electric vehicles have essentially no noxious emissions, and the level of emissions from fuel-cell powered and hybrid powered vehicles are likely to be much lower than those from conventionally powered vehicles.

The quieter operation of electric vehicles will be an added environmental benefit.

Set against these benefits is the potential increase in air pollution due to fossil fuel consumption by an increased number of central electricit generating stations, installed to meet the increased demand for electricity The trade-off should, however, be highly favorable since control technology can be applied more effectively and less expensively to such large stationa sources.

10. CONCLUSIONS AND RECOMMENDATIONS

The power, energy, cost, and lifetime requirements of power sources for electric highway vehicles cannot adequately be met by existing battery and fuel cell technology. The importance of electric highway vehicles to transportation can only grow in the future and increased emphasis on research and development in electrochemical and related technology appears mandatory. The slowness with which progress is made in these fields is unfortunate politically, but should not be allowed to obscure the necessity for taking steps now which will ensure the availability of adequate technology in the future.