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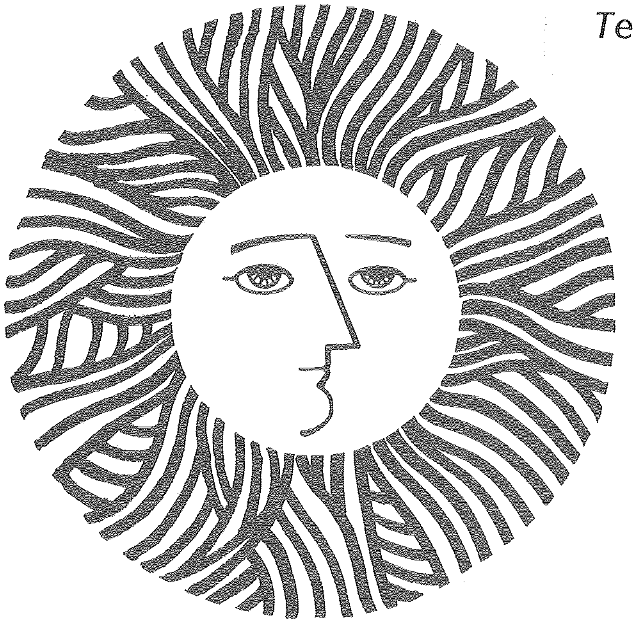
Elton J. Cairns and Earl H. Hietbrink

January 1981



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ELECTROCHEMICAL POWER FOR TRANSPORTATION

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1. INTRODUCTION

The use of electrochemical power in transportation vehicles is an old concept that has a good probability of again playing a significant role in the transportation industry. It is interesting to note that this is occurring almost a century after its initial success in the late 1800s and early 1900s. It is appropriate to include in this section some historical background of the rise and fall and subsequent rebirth of the electric vehicle; and a brief discussion of current transportation needs, and environmental and energy utilization issues that resulted in the renewed interest in applying electrochemical energy conversion technology to electric vehicle applications. Although energy utilization has evolved to be the most significant and important issue, the environmental issue will be discussed first in this section only because of its chronological occurrence.

The next part of the chapter is a review of passenger and commercial electric vehicle technology with emphasis on vehicle design and demonstrated performance of vehicles with candidate power sources being developed. This is followed by a discussion of electrochemical power source requirements associated with future electric vehicles that can play a role in meeting modern transportation needs.

The last part of the chapter includes first a discussion of how to identify candidate electrochemical systems that might be of interest in meeting electric vehicle power source requirements. This is then followed by a review of the current technological status of these systems and a discussion of the most significant problems that must be resolved before each candidate system can be a viable power source.

1.1. Historical Background

Scientists, engineers, entrepreneurs, and hobbyists have been intrigued by the concept of battery-powered transportation vehicles for well over a century. As early as 1837, the first practical electric carriage was constructed by Robert Davidson of Aberdein, Scotland.(1) The year 1888 is generally recognized as the beginning of the electric passenger car industry in the United

States with the introduction of an electric car by Frederick M. Kimball of Boston, Mass.(2) During the late 1880s and early 1900s, the electric vehicle was a serious contender, along with the steam engine vehicle and the internal combusion vehicle, in the technological race to replace the horse-drawn carriage as the dominant form of transportation. However, the electric vehicle technology could not keep pace with the rapid and exciting development of the combustion engine. Consequently, the combustion engine has played a dominant role in transportation and has also proved to be one of the most significant inventions of our time.

The annual production of electric vehicles in the United States reached a peak in 1916 when 10,000 electric vehicles were manufactured: 6000 passenger cars and 4000 commercial vehicles.(1) Since that time the manufacture of electric passenger vehicles was soon discontinued, but the commercial electric vehicle industry continued to develop. By the late 1960s, there were in the order of 45,000 electric vehicles being used as milk wagons, post office trucks, and delivery vans in England and Europe.(3) In the United States there were approximately 65,000 lift trucks and perhaps 100,000 golf carts but an insignificant number of trucks and delivery vans.(4)

The downfall of the electric passenger vehicle was attributed primarily to (1) its inability to keep pace with the increasing speed of the internal combustion engine vehicles, (2) the high cost of electricity relative to gasoline, and (3) the unavailability of electricity in the rural areas. It is worth noting that the cost of electricity varied from 7 to 12 cents per kilowatt-hour and the cost of gasoline was 3.2 to 4.0 cents per liter (5).

A resurgence of electric passenger vehicle activity began in the late 1950s and accelerated significantly in the early 1960s. This renewed interest was primarily motivated by a growing national concern over air pollution and secondarily by an advancing *Direct Energy Conversion* technology to meet the challenges of the *Space Age*. Simultaneous with the development of the fuel cell and advanced battery concepts for orbiting satellites and manned space vehicles, the environmentalists were advocating that the internal combustion engine be banned from our cities because it was the major contributor of pollutants to the atmosphere of our large metropolitan areas.

As the internal combustion engine was being developed to meet the environmental challenge of the 1960s, another motivating factor for increased electric vehicle activity began to emerge rapidly in the form of an ever-increasing demand for petroleum-based fuel and associated pressures causing crude oil prices to increase.

By 1970 the stage was set for a petroleum fuel "crisis," and in the early 1970s the price of crude oil more than doubled and the supply of crude oil was demonstrated to be controlled by world-wide political pressures in addition to traditional supply-demand economics. Since the electric vehicle can readily utilize nonpetroleum-based energy sources, such as coal and nuclear, the effect of the petroleum fuel "crisis" was a significant increase in electric vehicle development activities.

1.2. Modern Transportation Needs

A basic need to be met by any transportation system is to effectively transport people and goods from one point to another. Modern society has become dependent upon the predominant use of private automobiles and trucks to meet their transportation needs, not only effectively, but also very economically. This is particularly true in the United States where the automobile has had such a significant impact on individual life-styles as well as on the total development of the country. History has shown that as any country becomes more affluent, there is an increasing pressure to develop improved transportation concepts that result in a greater degree of individual freedom and mobility. This has resulted in the relatively rapid development of the private automobile, of various sizes and styles, with a unique versatility and capability of meeting changing demands resulting from growth in population and the individual desires of a highly mobile society.

The relatively rapid growth in the population of automobiles and light trucks has also resulted in a variety of problems and issues that are of considerable concern to modern society. These include highway safety, air quality, traffic congestion, noise, and an increasing worldwide concern over the need to conserve petroleum resources. However, in spite of the problems that plague the private automobile, its use in meeting personal transportation needs is expected to continue to increase throughout the world. In order to satisfy the constraints associated with the issues mentioned above, there is expected to be increased emphasis on the development of specialty vehicles, including electric vehicles, which would be effectively integrated into a total transportation system to meet future needs.(6) The use of the electric vehicle, in a small way, has already been initiated in the areas of personal transportation, public transportation, and delivery of goods and services. The trend is that these initiatives will continue with the greatest impact of the electric vehicle, over the near term, being made in the latter area.

1.2.1. Personal Transportation Characteristics

Statistics compiled and published by the Motor Vehicle Manufacturers Association of the United States, Inc.(7) show that private automobiles and trucks account for 90% of all personal travel in the United States. The distribution of this travel by purpose and related average trip length is presented in Table 1. The most significant information in Table 1 is the average trip length. Since the electric vehicle is limited in range between recharges, its scope of application to personal travel needs depends primarily on the trip length and the number of trips per day. (It is assumed that recharging will take place primarily during nighttime, off-peak hours.) Although the average trip length in Table 1 is relatively short, indicating that most personal travel could be accomplished with an electric vehicle, the randomness of travel in terms of the number and lengths of trips made on any given day must be taken

Table 1. PERSONAL TRAVEL IN THE UNITED STATES (7)

	Percentage Distribution		Average (One-Way) Trip Length
Purpose of Travel	Trips	Travel	(km)
Earning a Living	36.7	42.1	16.3
Family Business	31.3	19.5	9.0
Educational, Civic or Religious	9.4	5.0	7.5
Social and Recreational	22.6	33.4	21.0
All Purposes	100.0	100.0	14.2

Source: U.S. Federal Highway Administration, Nationwide Personal Study (1969) into account. This has been done in an analysis referred to in Ref. 8. The results of this work indicated that a vehicle range of 132 km would satisfy personal driving needs 95% of the days of the year based on total annual travel of about 16,295 km. Furthermore, if total annual travel continued to increase in the same manner that it did during the period 1963 through 1972, a range of about 160 km would satisfy the same needs until late in the 1990s.

1.2.2 Public Transportation Characteristics

The continuously increasing cost of owning and operating a private automobile results in an increased demand for effective public transportation vehicles, such as route buses and community vehicles. This area of transportation need has been primarily emphasized in Europe and, to some degree, in Japan. Although the desire for zero exhaust emissions and reduced noise in urban areas provides a strong incentive for the development of electric buses, other requirements, such as low cost, high daily use factor and, in some cases, long range are difficult to satisfy. As a general rule, these vehicles are used for 8-16 h and can travel up to 300 km per day.(9) Thus, in many cases, this area of need requires a vehicle designed for rapid battery exchange and the related use of battery exchange stations.

1.2.3. Delivery of Goods and Services Characteristics

Service and delivery vehicles are used for a wide range of applications in the urban and suburban areas throughout the world. These applications range from mail delivery and the distribution of goods to service vans which are used primarily by the utility industry. The desired vehicle characteristics are primarily low maintenance and low operating cost. In contrast to the privately owned automobile, the daily use of the delivery and service vehicle is quite well defined. Many of these vehicles are used as commercial fleets and are parked overnight near their point of daily use for normal recharging and servicing by experienced personnel. Although the range and payload requirements vary considerably for different applications, a majority of the needs can be met with a daily range of 60-120 km and a payload capability of 500 kg.(9,10)

1.3. Environmental and Energy Utilization Issues

An electric vehicle is normally thought of as a vehicle chassis that is powered by an electric motor which is driven by electrical power from a secondary battery. However, this simplified concept is not sufficient for a meaningful discussion of the environmental and energy utilization issues related to electric vehicles. Rather, the electric vehicle must be considered as a total system which includes the primary energy source, electric power generating plant, and the distribution network of electrical power, as shown in Figure 1.

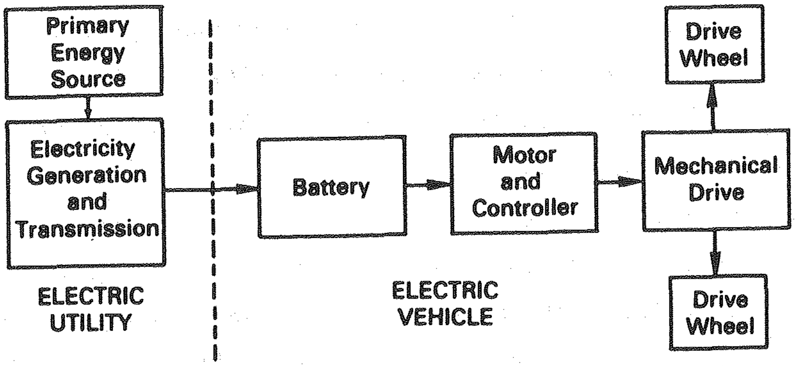


Fig. 1. Electric vehicle schematic.

In comparison, the combustion engine vehicle must also be considered as a total system which includes the primary energy source, a chemical fuel processing plant, and a fuel distribution network, as shown in Figure 2. These two vehicle systems are observed to be very similar in many aspects but also have a

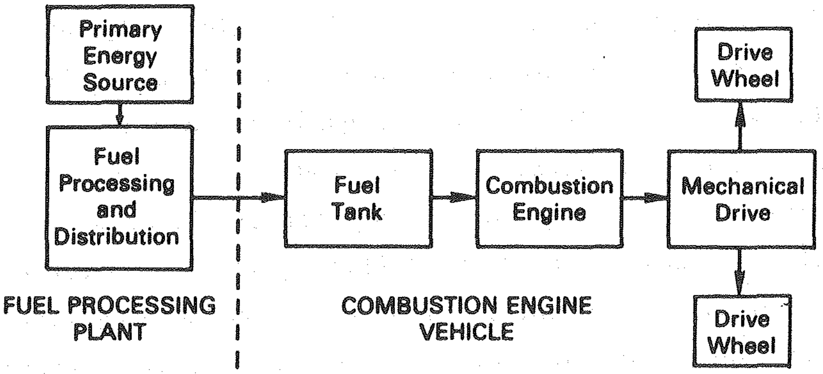


Fig. 2. Combustion engine vehicle schematic.

very distinct and important difference. It is noted that both systems include a Carnot-limited energy conversion step which is the efficiency-limiting step in the total process and is also the step in the process where there is direct interaction with the air and/or water environment. In the case of the electric vehicle system, this conversion step is carried out in a relatively small number of large stationary equipment installations as contrasted to being carried out at the point of vehicle usage in millions of small, mobile combustion engines. Although this might appear to be a rather subtle difference, it is a particularly important aspect of the environmental issues related to electric vehicles.

1.3.1. The Environmental Issue

The *environmental crisis* of the 1960s provided the incentive for renewed interest in electric vehicles. The automobile became the "target" of some environmentalists who singled it out as being a dominant source of carbon monoxide, and a major contributor to photochemical smog by virtue of it being a major source of nitrogen oxide and hydrocarbon contaminants.(11) As a consequence, a great deal of vehicle emission legislation was enacted in the United States during this period to reduce and control the effect of vehicle emissions on atmospheric contaminant problems. The most significant legislation was the passage of the Clean Air Act of 1963 and its subsequent amendments in 1965 and 1970 which provided for the establishment and enforcement of nation-wide ambient air quality and related vehicle emission standards. The goal of the Clean Air Act Amendment of 1970 was to establish a 90% reduction and control of hydrocarbon (HC) and carbon monoxide (CO) emissions, based on 1970 levels, by January 1, 1975 and a similar 90% reduction in nitrogen oxides (NO_x) from 1971 levels, by January 1, 1976. The vehicle emission standards associated with these goals were determined administratively to be 2.1 g/km (3.4 g/mile) for CO, 0.26 g/km (0.41 g/mile) for HC, and 0.25 g/km (0.4 g/mile) for NO_x. However, subsequent action by the Environmental Protection Agency and the 1977 amendments to the Clean Air Act resulted in an extension of the time for meeting these goals and a relegation of the 0.25 g/km NO_x standard to a research goal. A summary of the emission standards that have been in effect since 1968 and the new schedule through 1981 are shown in Table 2.(12)

Table 2. FEDERAL EMISSION STANDARDS

Year	HC	CO	NO_x
	[g/km (g/mile)]		
Prior to 1961 (Average Level)	9.4 (15.0)	56.2 (90.0)	3.1 (5.0)
1968	3.9 (6.3)	31.9 (51.0)	--
1970	2.6 (4.1)	21.2 (34.0)	--
1972	1.9 (3.0)	17.5 (28.0)	--
1973	1.9 (3.0)	17.5 (28.0)	1.9 (3.1)
1974	1.9 (3.0)	17.5 (28.0)	1.9 (3.1)
1975	0.9 (1.5)	9.4 (15.0)	1.9 (3.1)
1977	0.9 (1.5)	9.4 (15.0)	1.2 (2.0)
1980	0.26 (0.41)	4.4 (7.0)	1.2 (2.0)
1981 and beyond	0.26 (0.41)	2.1 (3.4)	0.6 (1.0)

The impact of exhaust emission controls on the aggregate emmisions from the automobile population is difficult to quantify. Heywood and Martin have examined several methodologies that have been used to make reasonable projections and have estimated the average vehicle urban emission rates (grams per vehicle mile) for the in-use urban vehicle population, as shown in Fig. 3,(13) which can be used to calculate aggregate emission rates for any urban area for different assumptions of total vehicle miles traveled per year. These estimates indicate that by the mid-1980s the full impact of exhaust emission controls could begin to be realized, depending on the rate at which old, higher-polluting automobiles are retired from the in-use automobile population.

Within the framework of emission control regulation, the environmental issue associated with electric vehicles results in the following concerns: (1) the effect of changing the nature and location of the pollution from the primary automobile exhaust emissions (CO, HC, NO_x) to the primary emissions from the smokestacks of electric power generating stations (SO_2, particulates, NO_x), and (2) the control and maintenance of pollution abatement devices.

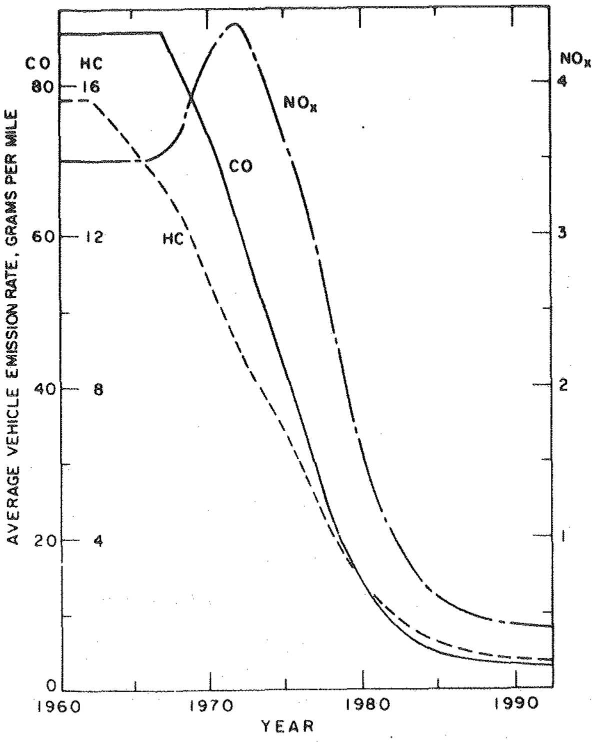


Fig. 3. Average vehicle urban emission rates for HC, CO, and NO$_x$, g/mile, baseline case, from Reference 13.

A significant issue related to the electric vehicle is the hazard of SO_2 and particulate emissions relative to CO and HC. There has recently been increased concern over the role that SO_2 plays in the production of sulfuric acid mist in the atmosphere. The rate of production of the acid increases with both increased humidity or SO_2 concentration.(14) The electric vehicle would contribute to this problem, although it is projected that the amount of electrical energy required by electric vehicles is a small fraction of total electrical demand.

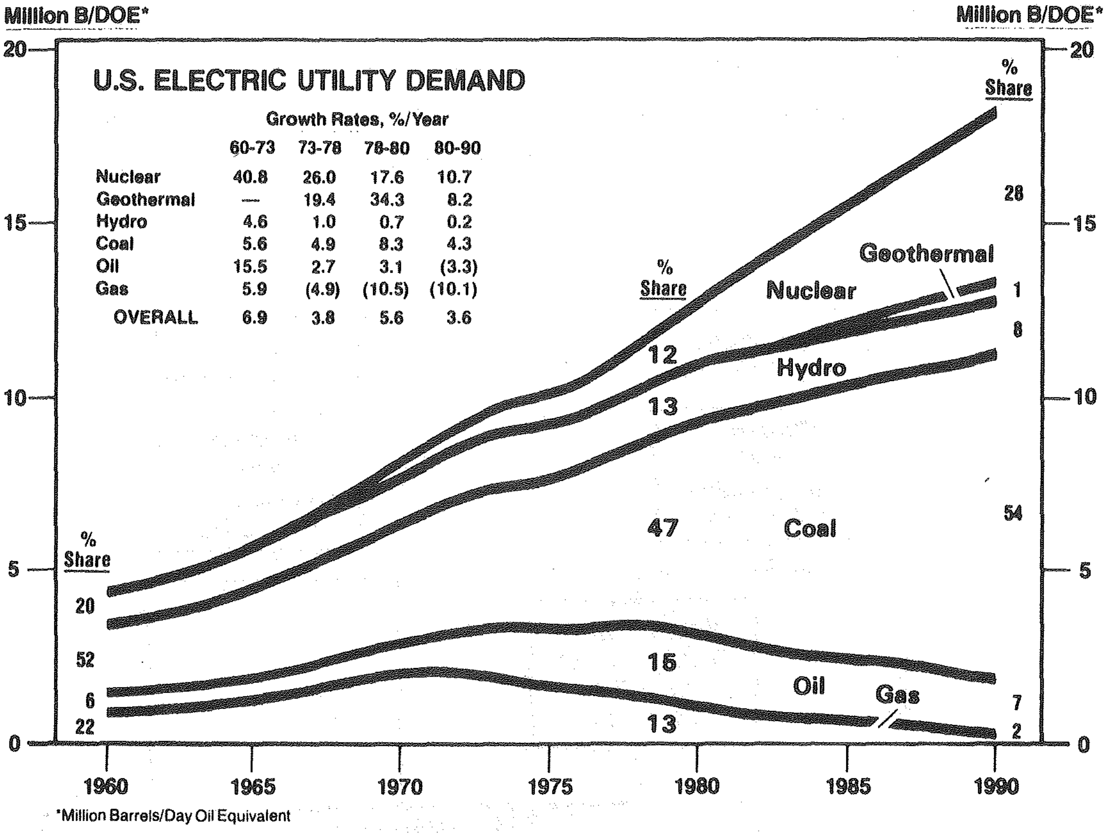
The emissions related to an electric vehicle are released from smokestacks high above the ground rather than at ground level from combustion engine vehicle exhausts. In general, this can mitigate the effect of a high concentration of contaminants, particularly CO, at ground level in highly congested areas. However, the position of the smokestack relative to the congested area and atmospheric conditions are key factors in this regard, and under unstable conditions the plume from the stack can touch down and, in fact, cause an increase in the concentration of emissions over a small area.(15)

Several models have been developed in order to analytically determine the atmospheric concentration of pollutants emitted from single sources either at ground level or from stacks.(16,17) A significant part of this effort has been spent on plume dispersion calculations, and the results have been rather widely used in the literature to imply a substantial advantage associated with the electric car in this regard.(18) However, the results can vary widely depending on the assumptions used. In addition, other considerations are quite often neglected, such as SO_2 interaction with vegetation, or more generally, the absorption or deposition of pollutants when the plume reaches the ground.

With regard to the control and maintenance of pollution abatement devices, it must be recognized that the use of fossil fuel in either power-generating plants or combustion engines, will require <u>effective</u> pollution abatement equipment in order to meet clean air standards. As a consequence, large amounts of capital are being invested in the development and application of pollution abatement technology. In this regard, the abatement equipment related to the electric vehicle is required on the power-generating plant and not on the vehicle itself. Thus, this equipment is apportioned over the total electrical energy demand, rather than over just that relatively small fraction of the demand associated with the electric vehicle.

1.3.2. Energy Resource Considerations

A very important aspect of electric vehicle use is that it could have a favorable impact on achieving effective utilization of relatively abundant nonpetroleum primary energy sources. The projection of energy resource utilization for electric power generation shown in Figure 4(19) illustrates that by 1990 82% of electrical energy in the United States will be generated from coal and nuclear energy in contrast to 7% from oil. Thus, on an aggregate basis, these sources are primarily providing the base load and oil is used during daily peak demand periods. Providing the electric vehicles are charged during off-peak hours, the result would be an increase in the use of coal and nuclear energy for transportation and a corresponding relief of the petroleum demand for transportation.



Growth Rates, %/Year

	60-73	73-78	78-80	80-90
Nuclear	40.8	26.0	17.6	10.7
Geothermal	—	19.4	34.3	8.2
Hydro	4.6	1.0	0.7	0.2
Coal	5.6	4.9	8.3	4.3
Oil	15.5	2.7	3.1	(3.3)
Gas	5.9	(4.9)	(10.5)	(10.1)
OVERALL	6.9	3.8	5.6	3.6

Fig. 4. Projected energy resource utilization to 1990.

In this regard, the gasoline (spark-ignition) automobile can also use coal or nuclear energy as a primary source by using a synthetic fuel prepared from either or both sources. As an aid in evaluating the relative effectiveness of the two approaches, a first step is to consider the overall production efficiency of producing gasoline or a synthetic fuel and electricity from each of the primary energy sources introduced above. Efficiency values representative of present-day processes and operations associated with the use of petroleum and coal are shown in Figure 5.(20) In the case of nuclear fuel, shown in Figure 6, there is essentially no available experience to refer to with regard to the manufacture and distribution of synthetic fuel. An efficiency of about 70% (probably a high value) was assumed for the preparation of a fuel such as hydrogen, ammonia or methanol. This value is higher, in fact, than the present efficiency of producing hydrogen from water by electrolysis. It will probably be 10-15 years before synthetic fuel production can satisfy even a few percent of the demand for petroleum fuels.

It is noted from Figures 5 and 6 that, for all practical purposes, the efficiency associated with producing electricity (∿30%) is essentially the same from all three energy sources. However, the production of a synthetic fuel from coal is significantly less efficient than the production of gasoline and this situation is even more pronounced in the case of nuclear fuel.

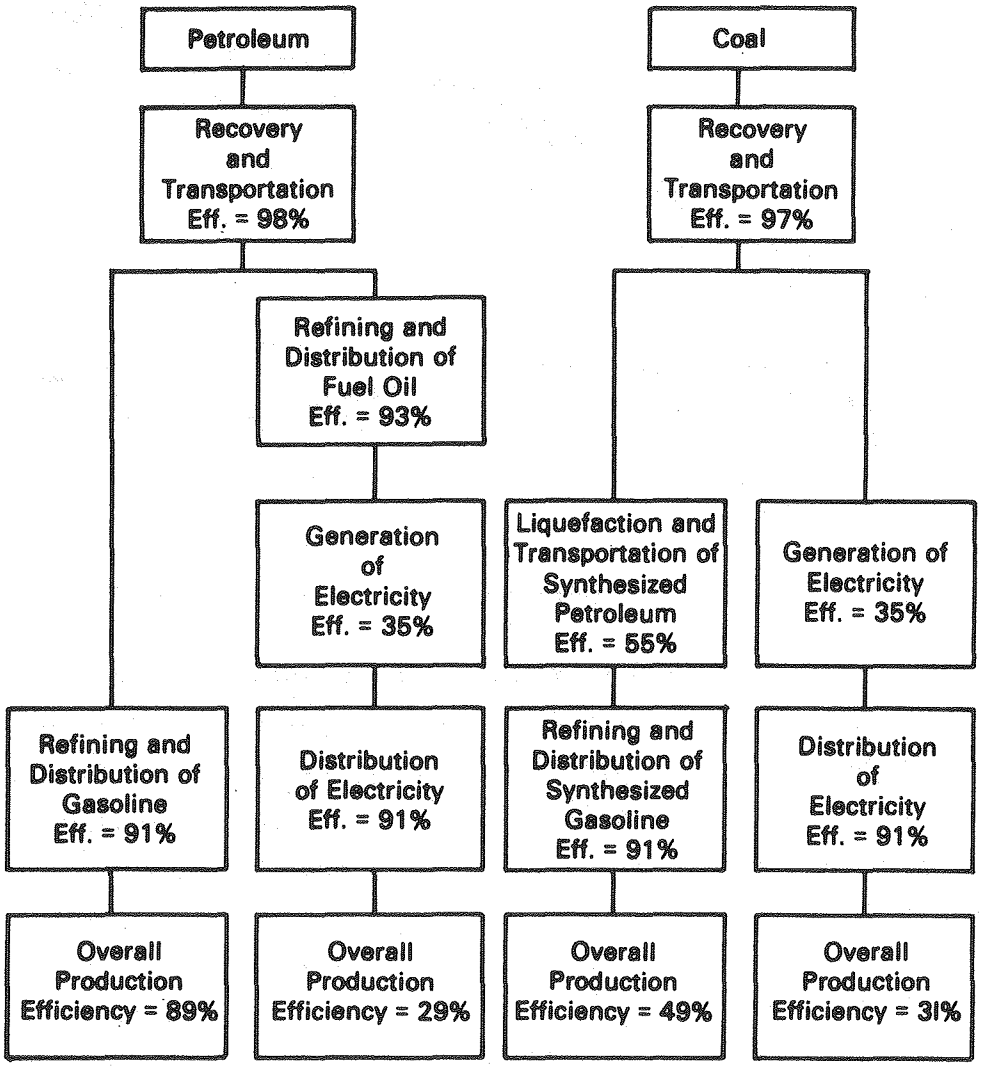


Fig. 5. Process efficiencies associated with the utilization of coal and petroleum.

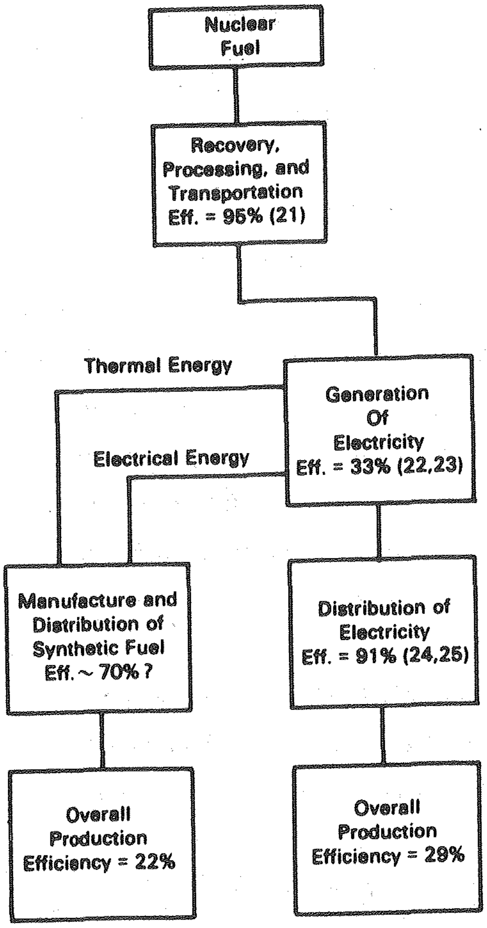


Fig. 6. Process efficiencies associated with the utilization of nuclear fuel.

The next step is to consider the utilization of the fuel and electricity to accomplish the movement of people and goods safely in urban traffic. The detailed designs of SI-engine and electric automobiles to carry out a specific mission of moving a certain payload through a specific driving profile is beyond the scope of this work. As a step in the proper direction, however, it is appropriate to state that for a given mission present-day electric urban automobiles are heavier than their SI-engine counterparts. In the case of current and near-term battery technology, such as lead-acid and zinc/nickel oxide batteries, the electric vehicle may be in the order of 50% heavier than the SI engine vehicle depending significantly on the desired range. The effect in terms of prime energy consumption would be to reduce the energy advantage of electric automobiles; however, the overall energy advantage, particularly for coal and nuclear energy utilization, would still be significant.

There is a limited amount of experimental data available for making a direct energy consumption comparison of electric and SI-engine automobiles of the same payload capability and performance, operating over the same driving cycle. This most meaningful comparison cannot be made with a high degree of confidence unless development and test activities are conducted for the purpose of obtaining directly comparable data. In an attempt to gain a reasonable perspective, a first-order comparison for a two-passenger commuter and a four-passenger sedan automobile is presented in Table 3. This table was constructed from the use of the overall production efficiency values for fuel and electricity from Figures 5 and 6, and from automobile design and energy utilization characteristics compatible with published results from analytical studies to compare the efficiency of energy utilization by electric and SI-engine powered automobiles. Thus, the prime source energy utilization values in Table 3 result from dividing the fuel and electricity utilization values in Table 3 by the corresponding efficiency values for the production of fuel and electricity from Figures 5 and 6. It is also noted that the automobile mass

Table 3. PRIME SOURCE ENERGY CONSUMPTION

	Automobile Characteristics(20,24,26)		Energy Used From Prime Source		
Automobile Type	Fuel or Electricity Utilization (kW·h/km)	Automobile Mass (kg)	Petroleum (kWh/km)	Coal (kWh/km)	Nuclear (kWh/km)
Spark Ignition:					
2 Passenger Commuter	0.49[a]	700	0.55	1.0	1.59
4 Passenger Sedan	0.62[a]	1050	0.70	1.27	2.04
Lead-Acid Electric:					
2 Passenger Commuter	0.31	1500	1.07	1.0	1.07
4 Passenger Sedan	0.51	2800	1.76	1.65	1.76
Zinc/Nickel Oxide Electric:					
2 Passenger Commuter	0.22	1050	0.76	0.71	0.76
4 Passenger Sedan	0.34	1650	1.17	1.1	1.17

[a] A value of 0.35 and 0.45 was used for the commuter and sedan respectively in the nuclear case to reflect an increase in the thermal efficiency of the SI engine for these synthetic fuels relative to the other cases.(27)

shown in Table 3 is associated with a two-passenger commuter automobile range of approximately 80 km and a four-passenger sedan automobile range of about 120 km. The results of Table 3 tend to confirm the energy advantage of the electric automobile with regard to the utilization of coal and nuclear energy; however, this is only significant with, at least, the near-term battery technology, such as zinc/nickel oxide. As the battery technology advances further, the electric automobile energy advantage will also become greater.

One additional consideration associated with the use of electric vehicles to achieve effective utilization of non-petroleum resources is the impact they would have on the electric power generation industry. This, of course, depends on several factors, such as:

(1) the energy consumption of the electric vehicle;
(2) the growth rate of the electric vehicle population;
(3) the electric vehicle battery charge mode; and
(4) the growth in the electric power-generating capacity.

The primary factors to be considered in determining the energy consumption is the vehicle mass, driving profile, accessory load, and component efficiencies. A summary of published energy consumption data is presented in Figure 7 in terms of kilowatt-hour per kilometer as a function of vehicle mass. The data points in the lower portion of Figure 7 represent the energy required from

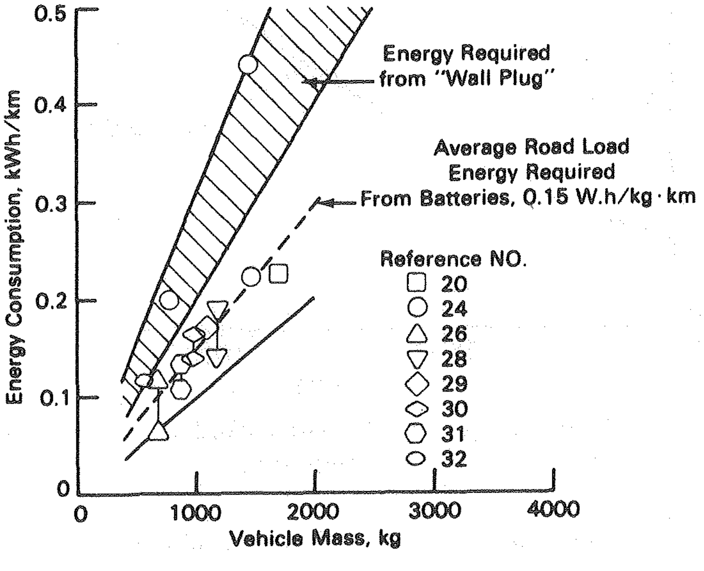


Fig. 7. Electric automobile energy consumption.

the battery power source to propel the vehicle over an urban driving profile. As a first approximation, these points lie reasonably close to a normalized value of 0.15 W·h/kg·km of vehicle mass. The upper crosshatched band represents a reasonable range of the energy required from the power-generating utility. This range of values reflects variation in accessory equipment load, battery charge and discharge efficiency, and the vehicle driving profile.

With regard to the growth rate of the electric vehicle population, one author's projection of the impact of two different rates relative to a specific projection of electric power-generating capacity is shown in Figure 8.(24). Curve *A* represents a hypothetical worst case; conditioned with the assumptions that total electrification of all vehicles would take place by year 2000 and have an average energy consumption of 0.425 kW·h/km, which represents a relatively heavy vehicle with current component efficiency technology.

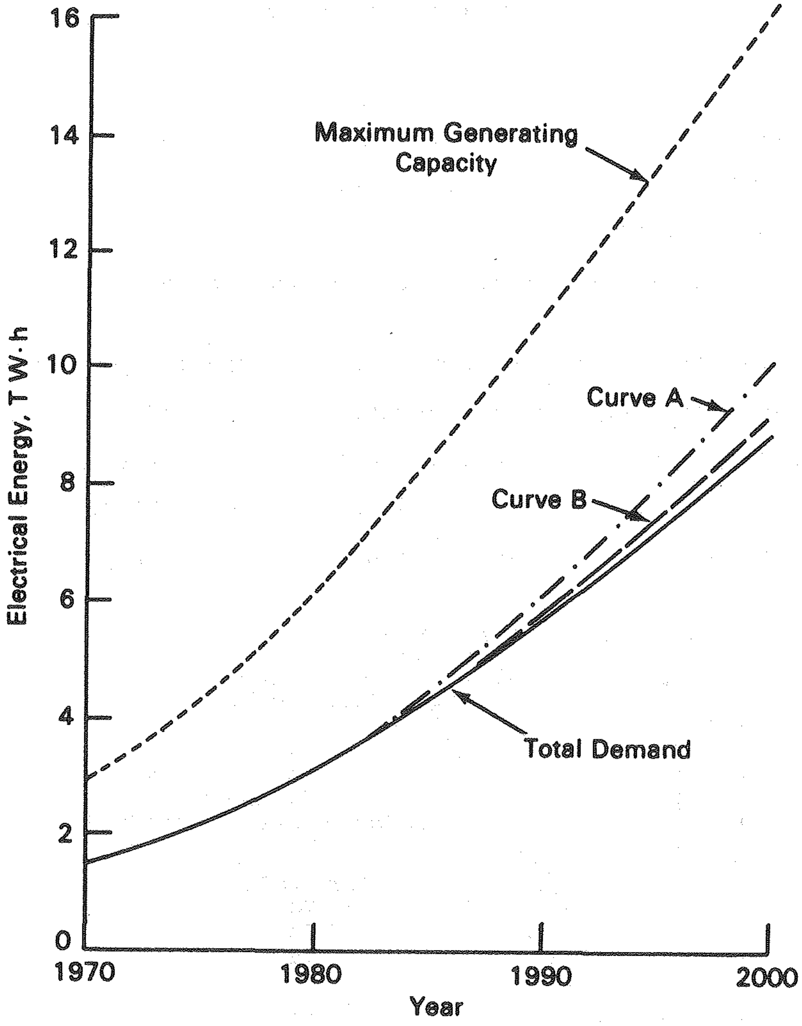


Fig. 8. Effect of electric automobiles on the electric power generation industry.

The impact of this condition was projected to be a 14% increase in total nonelectric vehicle nationwide demand by year 2000. Curve *B* represents a more probable growth rate where 40% of all vehicles would be electric by year 2000 and have an average energy consumption of 0.2 kW·h/km, which represents a smaller vehicle with improved component efficiency technology. The impact of this condition is projected to be only a 2.5% increase in total nonelectric vehicle nationwide demand by year 2000.

An important consideration relative to the impact of the small increase in electrical demand projected for electric vehicles is how the electric vehicle batteries will be charged. If they are charged rapidly (<2 h), then the relatively high power required could adversely impact the power industry, particularly during periods of peak load. However, it is most probable that electric vehicles will be limited to a slower charge (4-10 h) and that there will be economic incentives from the power industry to charge during the off-peak, nighttime hours. Under these conditions, the impact of electric vehicles on the power industry is considered to be a very favorable one.(33)

2. ELECTRIC TRANSPORTATION VEHICLES

A significant number of electric vehicles were built during the 1960s and 1970s. Most of these vehicles were demonstration or "test bed" vehicles which were primarily used to demonstrate technical feasibility of batteries and electric drive components and to obtain a first order evaluation of vehicle acceleration, speed, and range capabilities. However, there has been some effort aimed specifically at the development of a marketable product which has resulted in a relatively small number of passenger, utility, and public transport vehicles being manufactured and marketed in recent years. The market for these vehicles has included the individual consumer as well as various industries and institutions interested in evaluating vehicle performance and overall feasibility for specific applications. It is not intended here to present a complete compilation of the various electric vehicles and their design and performance characteristics. Such a compilation can be found in Ref. 34 and 35. Rather, the objective here is to emphasize specific automobiles and commercial vehicles that have had a significant effect on enhancing overall interest in electric vehicle development or are representative of recent developments in vehicle design, battery concepts, and drive train components for application to electric vehicles in the next decades.

2.1 Automobiles

The electric automobile development efforts are primarily aimed at increasing overall performance to a point where personal transportation needs can be met. As a minimum, the electric automobile has to have sufficient speed and acceleration capability to mix with other traffic on city streets and to have sufficient range to meet the daily driving needs. These performance characteristics are primarily affected by the automobile design, type of battery, drive motor, controller, and mechanical drive components. The use of regenerative braking can also have a significant effect as indicated later in this section.

2.1.1. Design Considerations

A variety of design concepts have been demonstrated by the many experimental automobiles that have been constructed. The most significant factors that must be considered include the gross vehicle mass (GVM), battery mass, location of batteries for appropriate distribution of GVM, front or rear wheel drive, passenger and cargo space requirements, aerodynamic drag and other features important to the customer, such as styling, safety, and practicality.

The battery mass is the prime factor affecting the GVM. This in turn is directly related to the range requirement. Increasing battery mass to enhance the range also results in an increase in basic structure mass to support the battery mass. This has become known as the mass compounding factor. A uniformly accepted value has not been established as yet; however, a range of 30% to 50% is not uncommon.(20) That is, for every 100 units increase in battery mass, an additional 30 to 50 units increase in structure mass should be added to the GVM. Modern electric automobile concepts result in a GVM ranging from about 750 kg for the two-passenger urban shopper shown in Figure 9 to about 1770 kg for the four-passenger sedan which is shown later in Figure 18. It is also noted that the battery mass usually varies from 20% to 40% of GVM with a maximum 25% to 30% being the most desirable from a design and handling point of view.(26)

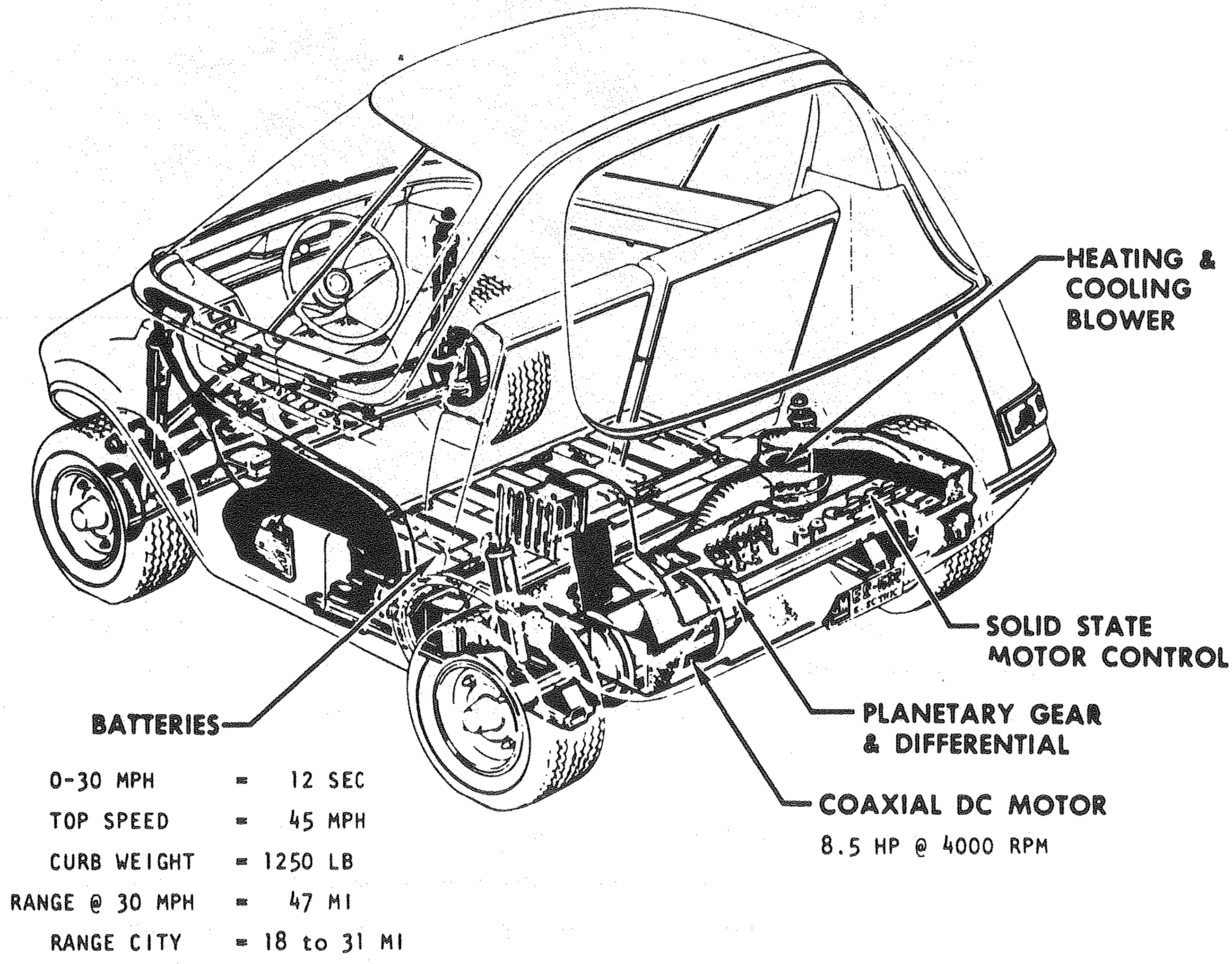


Fig. 9. General Motors 512 electric car.

With regard to the location of batteries, a common design concept is one where the batteries are packaged under the floor of the passenger or cargo compartment, as illustrated by the GM Electrovette in Figure 10. This approach is normally used when the electric automobile is designed within the constraints of an existing gasoline engine automobile chassis which, in this case, is the standard Chevette. At the present time, there is a significant

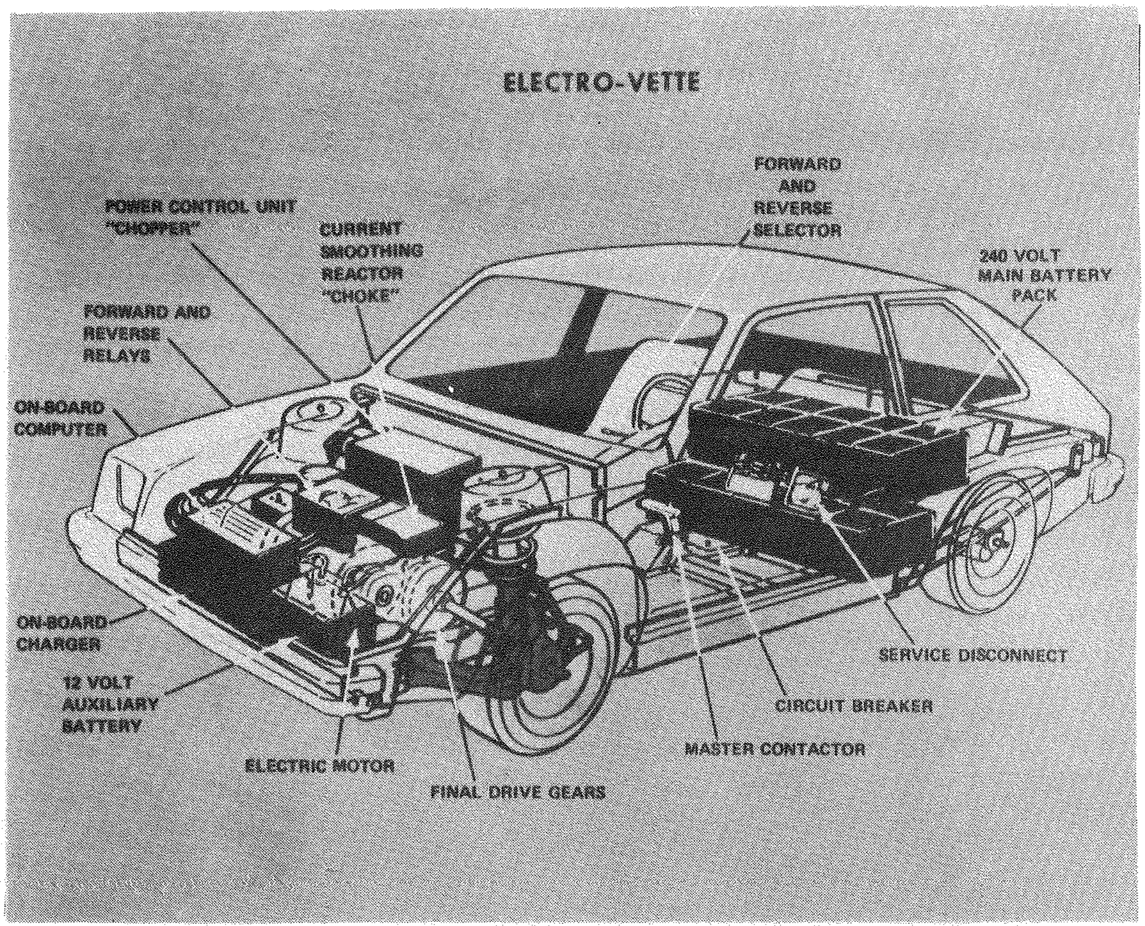


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Fig. 10. General Motors Electrovette.

cost and convenience advantage to this approach in that the cost advantage of high volume production components can be applied to the construction of a relatively small number of electric automobiles at this stage in their development.

Another design concept has become known as the "backbone" structure where the batteries are packaged in a tunnel which also becomes the longitudinal axis of the chassis as demonstrated in Figures 11 and 12. This concept usually includes a mechanism to allow the batteries to be easily removed from either the front or the rear for replacement or service. Although both of these automobiles make use of the same chassis concept, they demonstrate considerable variation with regard to other design features.

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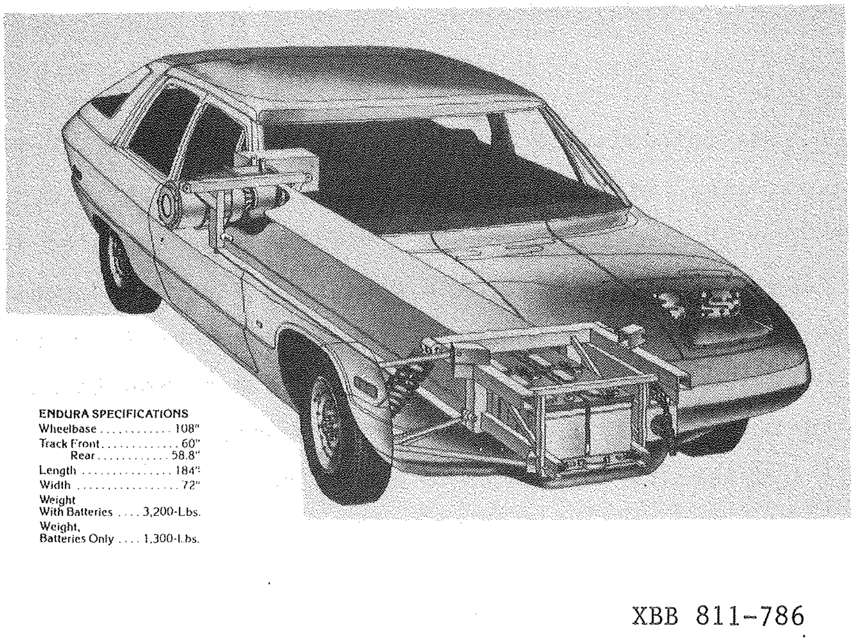
Fig. 11. Copper Electric Runabout (36).



ENDURA SPECIFICATIONS

Wheelbase	108"
Track Front	60"
Rear	58.8"
Length	184"
Width	72"
Weight With Batteries	3,200-Lbs.
Weight, Batteries Only	1,300-Lbs.

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Fig. 12. Globe-Union Endura (37).

The Runabout, described in Ref. 36, features a front-wheel drive and a seating concept wherein the rear-seat occupants face rearward. It was primarily designed for manufacturability, marketability, and serviceability, but also included good styling features with relatively low aerodynamic drag for improving range and performance. A fiberglass reinforced polyester is used as the body surface and structure material. This has advantages of reduced weight, manufacturing flexibility, and relatively inexpensive tooling for initial, low-volume production.

The Endura, described in Ref. 37, is designed with rear-wheel drive and has all four passenger seats facing the front. It was primarily designed to promote the feasibility of the electric automobile and to enhance their public acceptance. Thus, such design features as safety, practicality, and aesthetics were strongly emphasized in addition to minimizing air drag through aerodynamic design for good performance.

2.1.2. Battery Type

The lead-acid battery has been the most commonly used for electric automobiles primarily because it is the only battery available at a reasonable cost on a production basis. However, in recent years a number of demonstration vehicles have been constructed and tested with powerplants of alkaline batteries, such as zinc/nickel oxide, iron/nickel oxide, and metal/air (i.e., iron/air and zinc/air).

Figure 13 shows some initial work at General Motors Technical Center on electric automobile concepts, with the zinc/nickel oxide battery in mind.(38) Earlier GM work with the GM 512 car in Figure 9 verified the expected improvements in performance and range obtainable with this type of battery compared to the lead-acid battery (26). More than a factor of two improvement in range was demonstrated. Another zinc/nickel oxide battery-powered automobile is shown in Figure 14. The battery mass in this urban auto is only 17% of the GVM which allows greater flexibility in component packaging.(39)

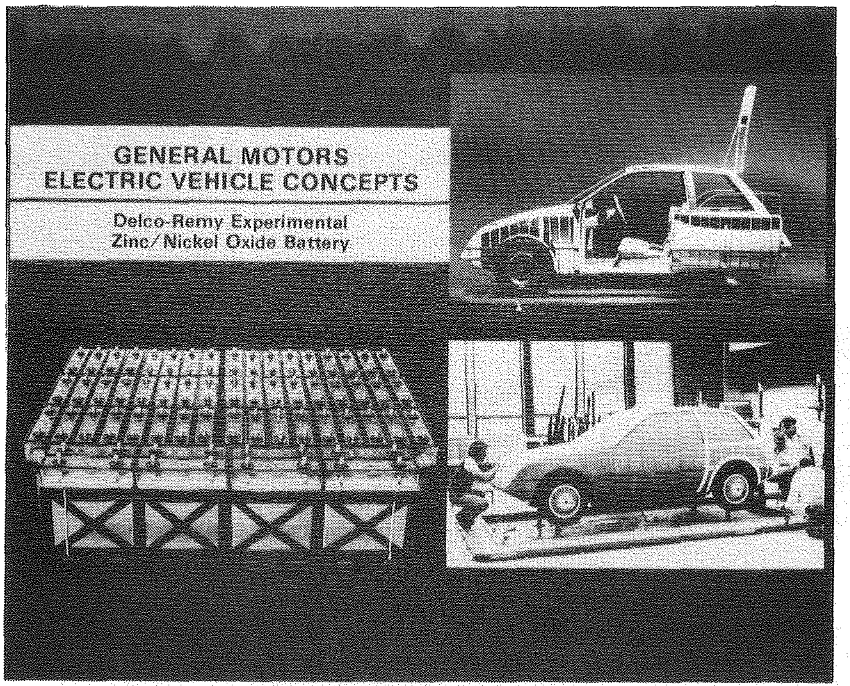

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Fig. 13. General Motors electric vehicle concepts (38).

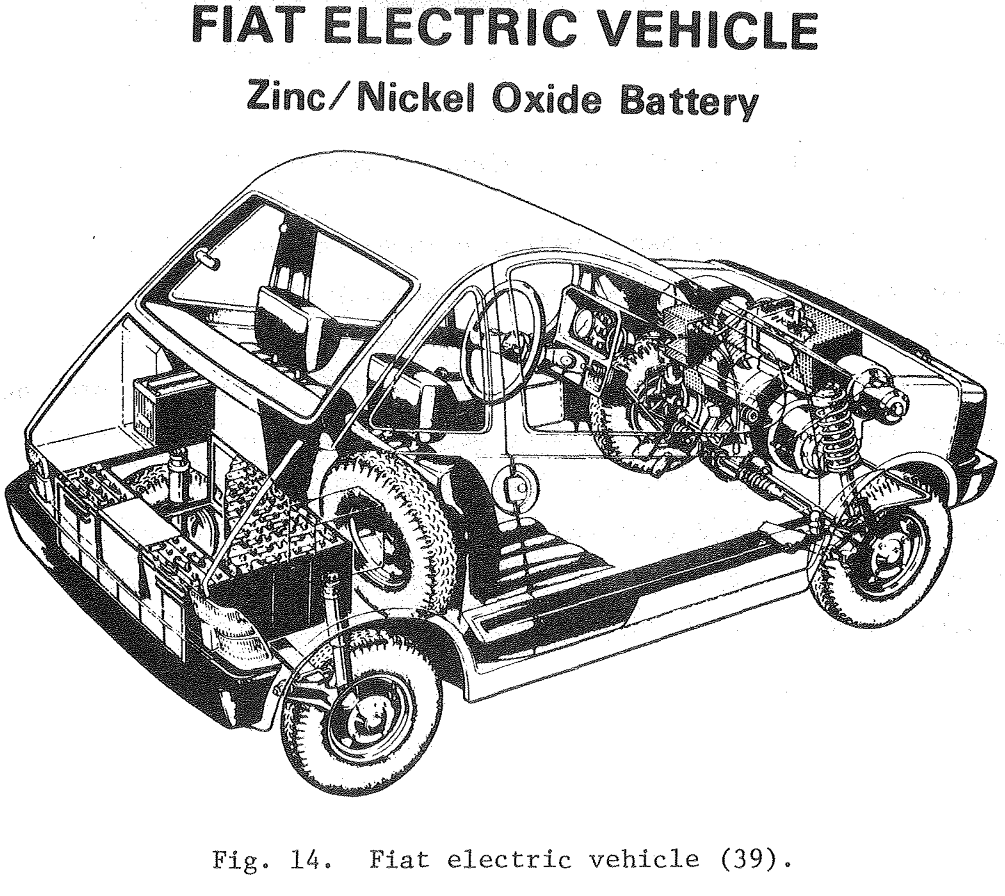

Fig. 14. Fiat electric vehicle (39).

The iron/nickel oxide battery has been investigated for use in a variety of vehicles by the Westinghouse Corporation. Figure 15 shows this battery installed in the trunk compartment of a conventional automobile.(40) An off-vehicle heat exchanger and pump system was used with this battery pack to provide cooling and gas separation during recharge.

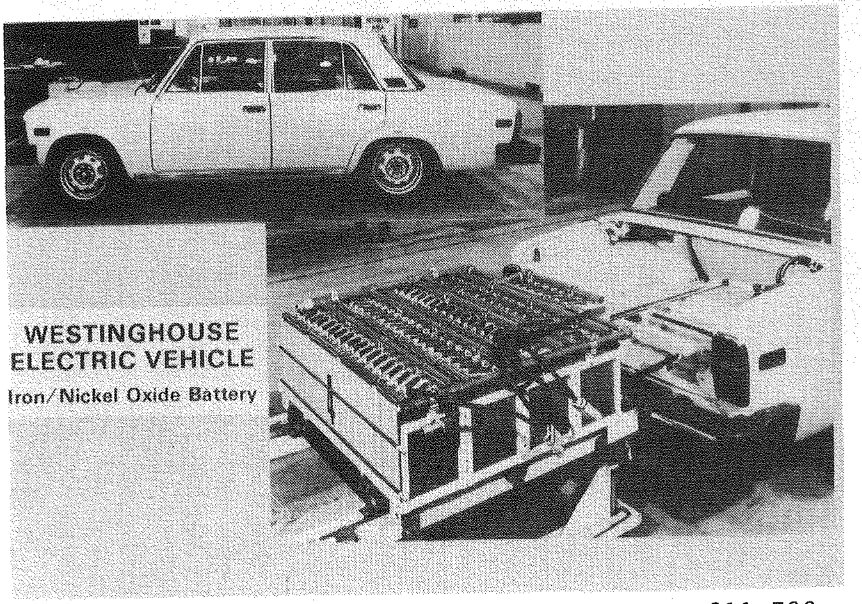

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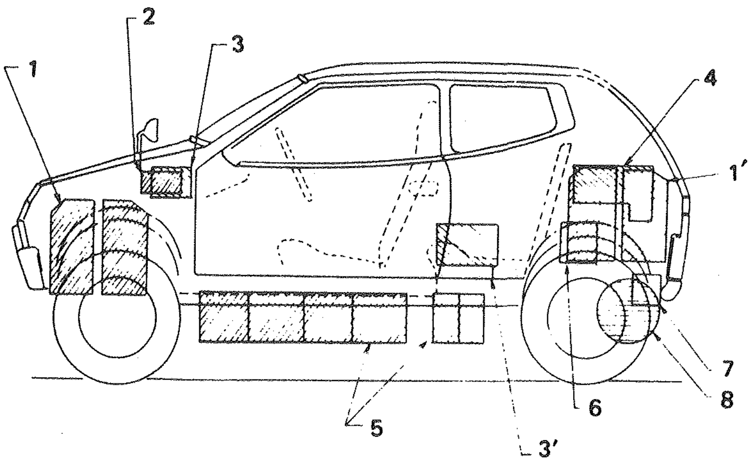
Fig. 15. Westinghouse electric vehicle (40).

Metal/air batteries have been evaluated in experimental vehicles in Japan.(41) Due to the low-specific power capability of the metal/air systems, a hybrid power source is required wherein the metal/air battery provides the energy for cruising, and a high power battery, such as lead-acid, provides power for acceleration. The installation of a hybrid system comprised of iron/air and lead-acid batteries in a lightweight electric passenger car is shown in Figure 16. Reported test results for this system indicate that a range of about 260 km can be obtained at a constant speed of 48 km/h.(41) It should be noted, however, that the total battery mass is about 37% of the GVM.



1	Iron-air storage batteries (4)	4	Controller
1′	Iron-air storage batteries (4)	5	Lead-acid storage battery
2	Battery charger	6	Power module
3	Contactor box (1)	7	Reactor
3′	Contactor box (2)	8	Electric motor

Fig. 16. Toyota EV1H electric passenger car (41).

In addition to the battery concepts demonstrated here, there are other advanced concepts that are of interest for future electric vehicle applications. These are included in a detailed discussion of electrochemical power source technology in Section 5.

2.1.3. Overall Electric Drive System

The electric automobile drive system consists of an integrated design package including an electric motor and associated controller and related power-train components. Variations in drive systems result primarily from trade-offs between cost, efficiency, and driving comfort. Within this framework, five conventional motor and control concepts have been evaluated by Bader and Stephan, and the results are included in Table 4.(42) The d-c series-wound motor has been commonly used primarily because its torque-versus-speed characteristics are such that a transmission is not necessarily required. The use of a transmission in any electric drive system is usually based on the need to enhance the torque at low speeds for improved acceleration and hill-climbing capability. Thus, the advantage of using a transmission becomes greater as the top speed and grade requirements increase.(43)

Table 4. CONVENTIONAL MOTORS AND CONTROL CONCEPTS FOR ELECTRIC AUTOMOBILES

Motor Description	Control Concept	Characteristics
Direct Current Series-Wound	Variable Resistor	Low Cost Low Efficiency
Direct Current Series-Wound	Battery Switching	Low Cost Low Driving Comfort
Direct Current Series-Wound	Electronic Chopper	Advanced Efficiency High Cost
Direct Current Shunt-Wound	Separate Electronic Choppers in Both Armature and Field Circuits	High Efficiency High Cost
Direct Current Shunt-Wound	Electronic Chopper in Field Circuit and Variable Resistor in Armature Circuit	Low Cost Reduced Efficiency and Driving Comfort

The function of the controller is to maintain the desired speed of the automobile under various road-load conditions by controlling the motor voltage. Advances in the field of power electronics have provided a more efficient means of doing this with so-called chopper circuits relative to using a variable series resistor or switching batteries into various parallel and series combinations. The chopper also provides smooth control over a wide range of motor speed. The most commonly used solid state controllers have utilized silicon controlled rectifiers (SCR's) as the major element in the control circuit to switch the batteries in or out of the circuit to obtain pulsed d-c with pulse width modulation. This approach is illustrated by the simplified schematic and the associated wave forms in Figure 17. The voltage applied to the motor can be varied continuously by controlling the conduction time of the switching SCR or transistor S_1. The inductor L_1 absorbs the difference between the motor voltage and the chopped voltage V, while diode D_1 provides a current path when S_1 is open. The current from the battery, I_b, is drawn in pulses as shown in

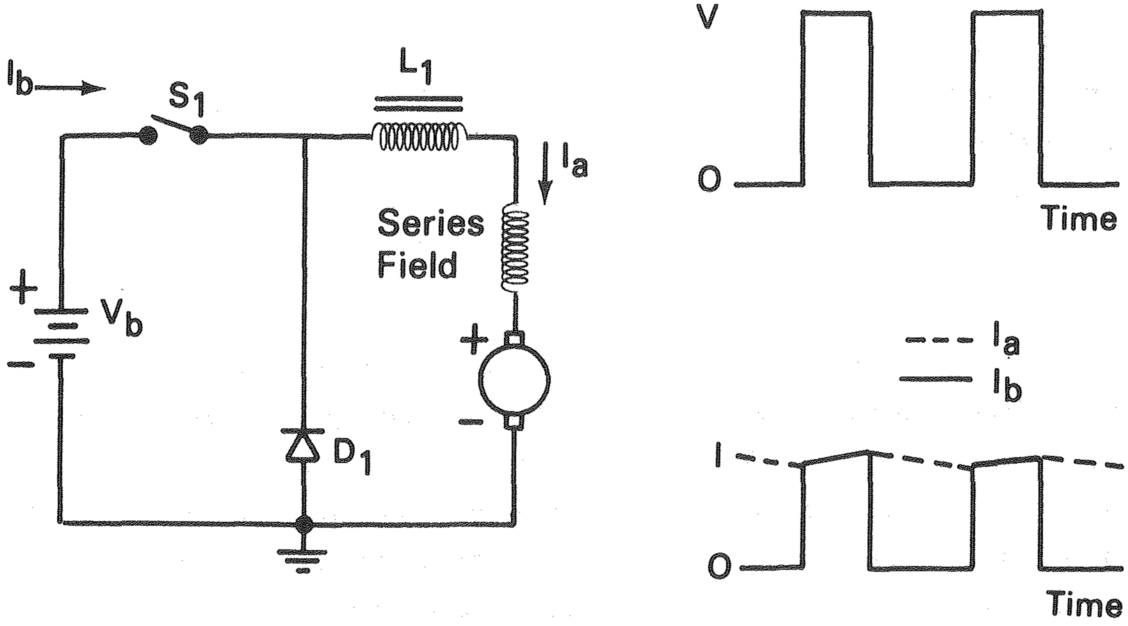


Fig. 17. Armature chopper schematic and related waveforms.

Figure 17, which has the effect of increasing the I^2R loss in the battery, relative to an unchopped current, unless an additional filter is added between the battery and the controller.

With continuous improvements in power electronics, more consideration has been given to the trade-offs between a d-c series-wound motor and the separately excited d-c shunt-wound motor where the armature and the field currents are separately controlled. With this concept, the armature current is chopped only at low speeds to provide smooth acceleration and is not chopped at the higher speeds. Speed control is accomplished at the higher speeds by means of a chopper in the field circuit. This control concept is characterized by a relatively higher efficiency at cruise speed. In addition, it is easier to add regenerative braking capability, particularly in the field control range. This can be a significant advantage in that the effect of regenerative braking is reported to increase the range in urban electric automobiles by as much as 15%.(44) However, this advantage must be traded off against the increased cost to provide this capability.

With regard to future electric drive developments, there continues to be an interest in evaluating the potential advantages of a-c drives as advances in microprocessors and other solid state technologies continue to develop.(45,46)

Beyond that, there is some promise of reduced weight and additional increases in performance if development efforts now under way on the disc-type permanent magnet motor are successful.(47)

2.1.4. Demonstration of Modern Technology

The United States Department of Energy is funding a Near Term Electric Vehicle Program with the general objective of showing that the electric vehicle concept is a promising near-term candidate for commercialization. In this regard, the four-passenger automobile concepts shown in Figures 18 and 19 have been designed to meet the performance objectives in Table 5 and are currently being developed for performance testing in late 1979.

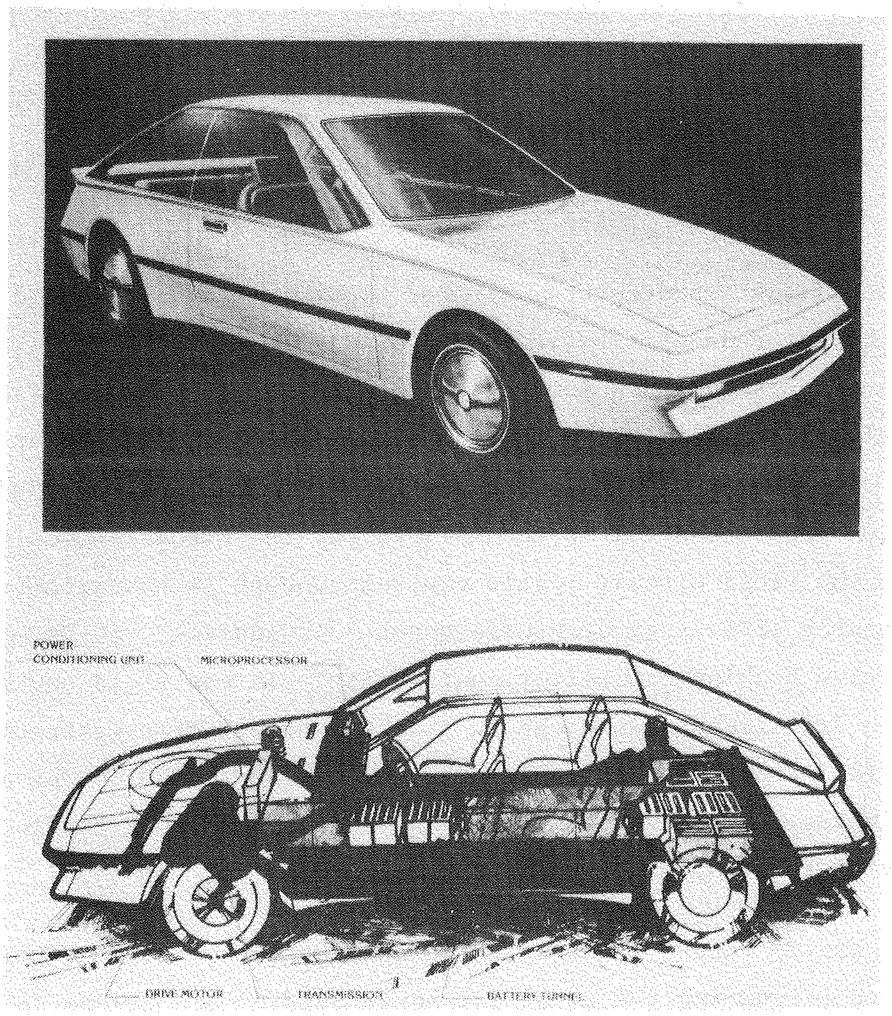


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Fig. 18. General Electric/Chrysler electric vehicle.

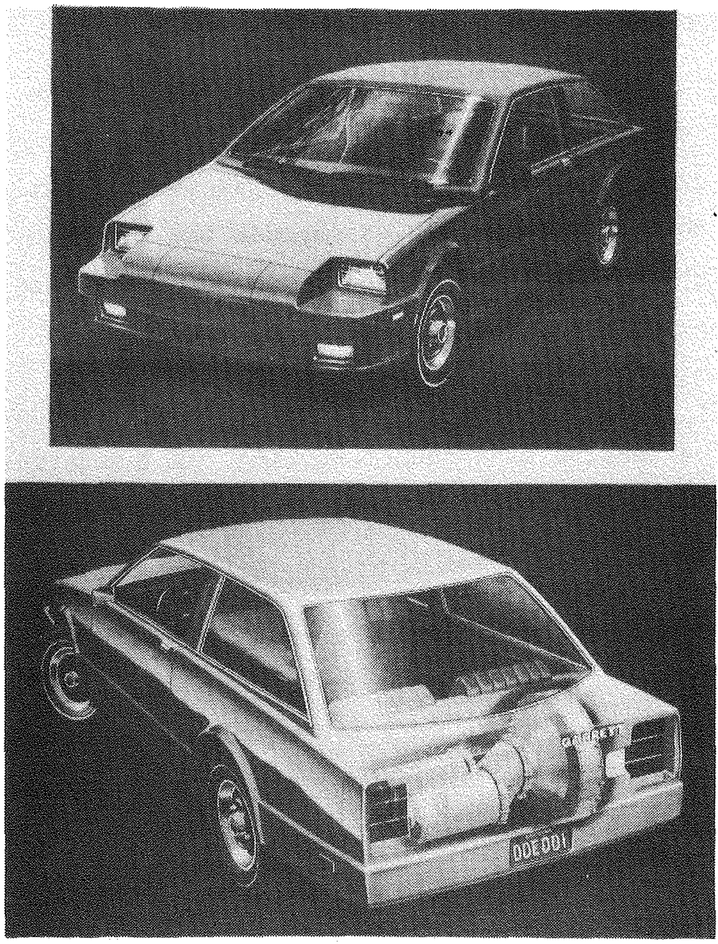

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Fig. 19. Garrett hybrid vehicle.

Table 5. NEAR-TERM DOE ELECTRIC VEHICLE PERFORMANCE OBJECTIVES (48)

Min passenger capacity	4 adults
Max curb weight	Open
Min urban range, km	121
Max electric recharge energy in urban driving, kW·h/km	0.32
Max recharge time, h	6
Safety features	Meet Federal Motor Vehicle Safety Standards
Min ambient temperature range, °C	-29 to +52
Min top speed, km/h	97
Min acceleration time, s (0-48 km/h)	9
Min merging time, s (40-89 km/h)	18

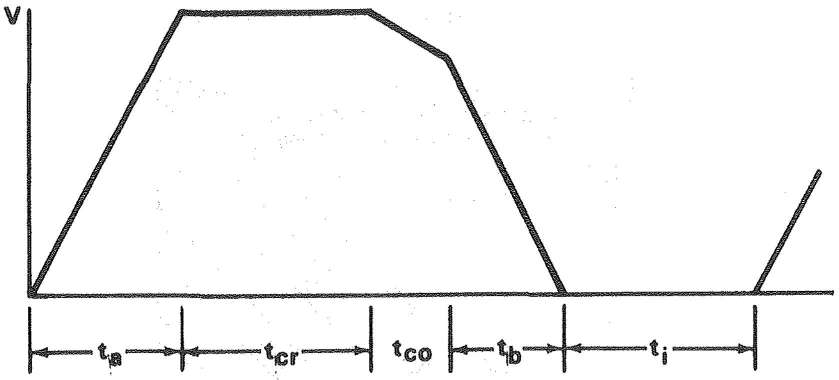
In view of the objectives in Table 5, it is reasonable to conclude that these vehicles will demonstrate much of the latest technology in body and chassis design and drive train components that has been discussed in the previous paragraphs. Both of these vehicles include the "backbone"-type chassis structure, lightweight materials in the body and structure, and a lead-acid battery power source.

The GE/Chrysler vehicle demonstrates a significantly reduced aerodynamic drag as a result of extensive wind-tunnel testing. Regenerative braking is also incorporated in the separately excited, d-c, shunt-wound propulsion motor which drives the front wheels.

The Garrett vehicle demonstrates the use of a flywheel in the drive train to provide the peak power required for acceleration and to extend the effectiveness of regenerative braking to very low speeds. The flywheel is connected to the rear wheels through a continuously variable electromechanical transmission, and the main d-c drive motor is a separately excited design developed specifically for this system.

2.1.5. Overall Performance Characteristics

At this relatively early stage in the development of the electric automobile, it is difficult to define state-of-the-art performance in terms of maximum cruise speed, acceleration capability, urban range, and energy consumption with any reasonable level of confidence. This situation exists primarily because of the following reasons: (1) most of the electric automobiles reported in the literature are one-of-a-kind developmental vehicles representing differing levels of technology and design objectives, and (2) very little test data have been reported on these vehicles where the tests have been conducted in accordance with any standardized driving schedule, such as the SAE J227a schedules shown in Figure 20.



	SAE J227a SCHEDULE			
TEST PARAMETER	**A**	**B**	**C**	**D**
Maximum Speed V, km/h	16 ± 1.5	32 ± 1.5	48 ± 1.5	72 ± 1.5
Acceleration Time t_a, s	4 ± 1	19 ± 1	18 ± 2	28 ± 2
Cruise Time t_{cr}, s	0	19 ± 1	20 ± 1	50 ± 2
Coast Time t_{co}, s	2 ± 1	4 ± 1	8 ± 1	10 ± 1
Brake Time t_b, s	3 ± 1	5 ± 1	9 ± 1	9 ± 1
Idle Time t_i, s	30 ± 2	25 ± 2	25 ± 2	25 ± 2
Total Time, s	39 ± 2	72 ± 2	80 ± 2	122 ± 2

Fig. 20. SAE J227a driving cycle schedules (49).

The performance results presented in the following paragraphs are taken primarily from the results of two studies conducted for the United States Energy Research and Development Administration.(35,50) The results reported in Ref. 35 are actual test results of selected automobiles to determine state-of-the-art performance. The results reported in Ref. 50 are based on literature values that were, in most cases, then used as a basis for calculating specific performance characteristics using a computer simulation of electric vehicle performance.

The maximum cruising speed and the acceleration capability of an electric automobile are primarily determined by the drive train design and the specific power capability of the battery. The maximum cruising speed for the automobiles tested in Ref. 35 varied primarily over a range of 60 to 80 km/h for automobiles with a curb mass in the range of 500 to 1500 kg, respectively. With regard to acceleration capability, it was determined that about two-thirds of the automobiles tested were able to accelerate from 0 to 48 km/h in from 7 to 13 s.

The urban driving range (e.g. for the SAE J227a "C" schedule) that is typical of present-day electric automobiles is illustrated in Figure 21.

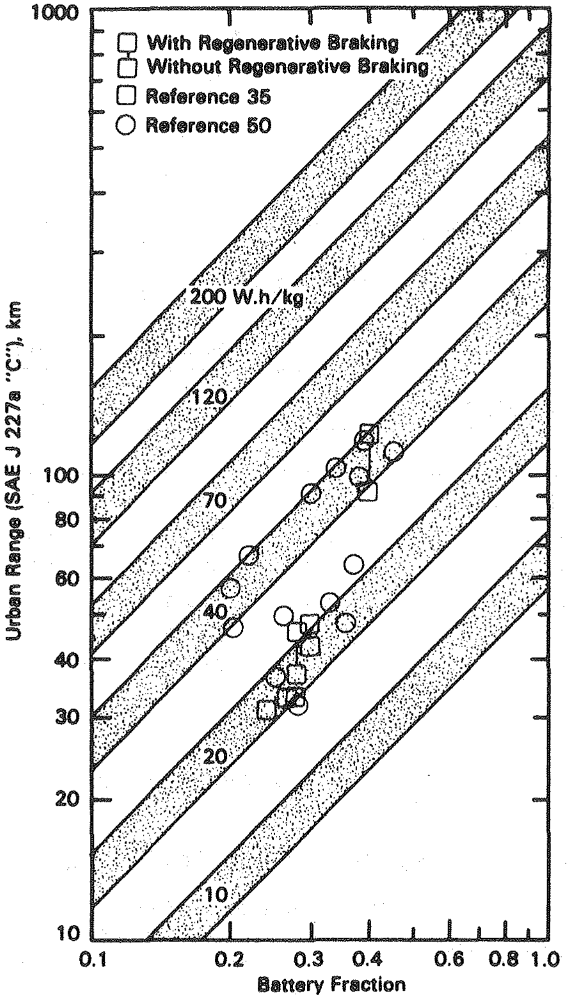


Fig. 21. Typical urban range (SAE J227a "C") of present-day electric automobiles.

These results demonstrate the effect of different ratios of battery mass to GVM from one automobile to another and also the effect of the specific energy of the battery power source. The specific energy bands define the urban range that can be expected from a power source when the specific energy of the power source is known for discharge conditions corresponding to urban driving requirements (see Figure 34, 30-35 W/kg). The width of the band allows for variation in road-load requirements from 0.13 to 0.17 W•h/kg•km. The results of Figure 21 illustrate that with lead-acid battery technology and a battery fraction between 0.25 and 0.3, the maximum urban range that can be obtained with state-of-the-art technology is about 80 km.

The energy consumption results shown in Figure 22 are representative of the same electric automobiles that provided the data base for the urban range results in Figure 21. For most electric automobiles with a GVM in the range of 750 to 1500 kg, the energy consumption from the "wall plug" is approximately 0.2 to 0.35 kW·h/km. However, it was noted in Ref. 35 that the limited data available from actual user experience with electric automobiles normally indicated about twice the energy consumption of the test results. This increase was speculated to be partly due to variations in road and climate conditions, driver's skill, and nonoptimum charging techniques and facilities.

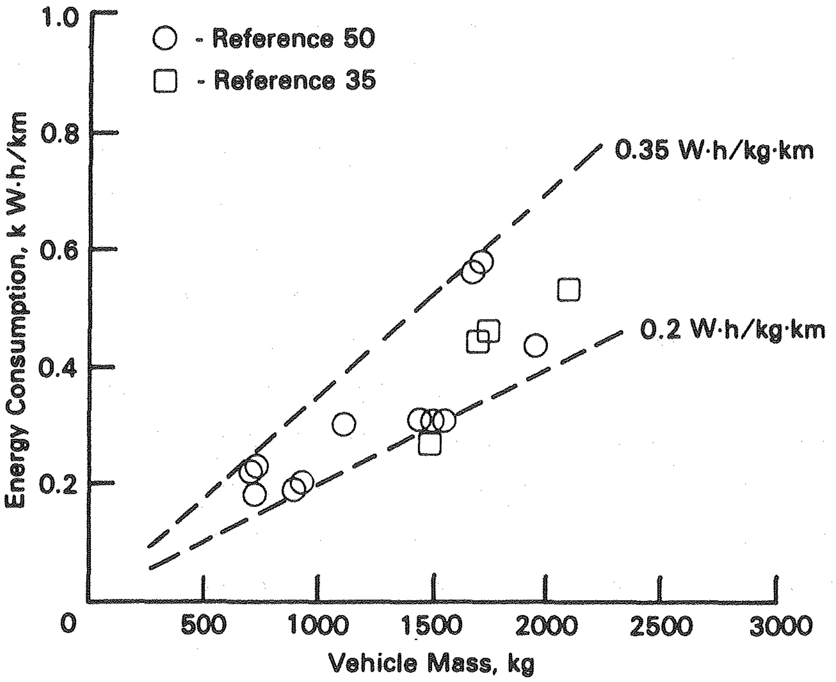


Fig. 22. Typical energy consumption (SAE J227a "C") of present-day electric automobiles.

2.2. Commercial Electric Vehicles

There is a relatively strong interest in the electric vehicle industry to develop vehicles for fleet operation. The types of vehicles that appear to be of greatest interest are (1) the utility vehicle, such as the postal service vehicle, (2) the delivery or service van, and (3) the passenger bus for public transport. The prime incentive for the development of electric commercial vehicles is to reduce the cost of owning and maintaining the vehicle fleet that is necessary to perform a desired service. The second incentive is that these vehicles operate primarily in urban areas where the eliminations of exhaust emission and the reduction of noise are desirable objectives.

The primary need to obtain a low total operating cost means that the design emphasis must be on high reliability for low maintenance, high efficiency for reduced energy costs, and sufficient performance and range capability to perform the desired service. For these reasons, the commercial vehicles do not necessarily represent the latest innovations in electric vehicle component technology as much as they represent the application of the most mature technology to the development of a marketable product. Thus, most of these vehicles make use of an existing production-line body and structure, a d-c series or shunt-wound propulsion motor, a solid-state chopper controller, limited regenerative braking, and a lead-acid power source.

2.2.1. Utility Vehicle

The relatively small utility vehicle which is used in the United States Postal Service represents the largest on-the-road electric vehicle fleet in the United States. This fleet includes 31 Harbilt and 352 AM General DJ-SE delivery vehicles operating primarily in Southern California. The AM General vehicle is shown in Figure 23, and its design and performance characteristics are listed in Table 6. The electric powertrain for this vehicle, consisting of batteries, controller, motor, and charger are supplied by Gould, Inc. It has been reported that this vehicle appears to be cost effective in this application and with continued success there could be a need in the United States Postal Service for about 5000 of these vehicles per year.(51)

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Fig. 23. AM General DJ-5E postal service vehicle (51).

Table 6. AM GENERAL DJ-5E DESIGN AND PERFORMANCE CHARACTERISTICS

GVM, kg	1955
Payload, kg	306
Battery Mass, kg	586
Cargo Space, m^3	1.7
Acceleration time, s (0-48 km/h)	20
Gradeability:	
Speed on 10% grade, km/h	22.4
Range, km:	
Constant Speed of 48 km/h	48
Postal Cycle	40
Energy Consumption, W·h/kg·km	0.4-0.5

2.2.2. Delivery and Service Van

The standard size electric delivery and service van is being developed by several groups in Europe and Japan as well as in the United States. The GVM of these vehicles is usually in the range of 2600 to 3700 kg with a payload ranging from 500 to 1000 kg. The greatest interest for delivery applications is reported to be in the higher end of this range.(52)

The entry of General Motors Corporation Truck & Coach Division into this area is considered to be a significant indication that commercial electric vehicles can be developed into marketable products. The initial GMC vehicles being produced represent a conversion of a standard GMC van to electric propulsion and are aimed at satisfying the needs of limited-range service vehicles, such as telephone installation and repair trucks illustrated in Figure 24. The design and performance characteristics of this vehicle are listed in Table 7 and are quite typical of the overall developments in this field.

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Fig. 24. GMC battery-powered commercial van.

Table 7. GMC DESGN AND PERFORMANCE CHARACTERISTICS (53)

GVM, kg	3682
Payload, kg	682
Battery Mass, kg	1137
Lead-Acid Battery Mounting	Single pack under vehicle
Safety	Full FMVSS Compliance
Drive Train	Direct current series motor with chain drive gear reduction and solid state continuous electronic speed control
Brakes	Vacuum assist hydraulic with electrical regeneration
Acceleration time, s (0-48 km/h)	12
Grade Limit, %	20
Top Speed, km/h	80
Range on SAE J227a "C," km	64

Energy economy data for the GMC van in actual service are not presently available. A very limited amount of data for delivery vans in actual service is reported in Ref. 35 where energy economy at the "wall plug" is reported to be in the range of 0.25 to 0.3 W•h/kg•km.

The limited range obtained with lead-acid batteries significantly limits the scope of the electric delivery van applications. One approach to getting around this problem has been to design the vehicle to allow for a rapid exchange of the battery pack, as is illustrated by the Lucas Industries Limited (United Kingdom) conversion of the Bedford CF van shown in Figure 25.

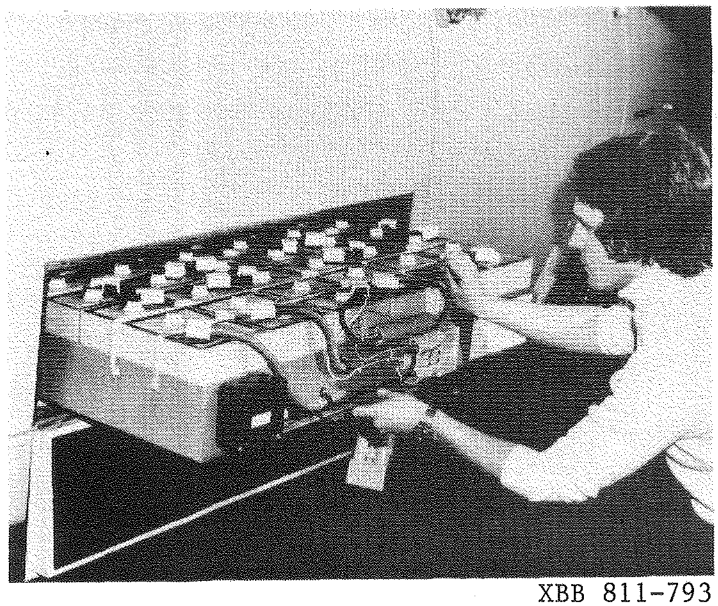

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Fig. 25. Bedford CF van and slide-in battery pack (52).

Advanced battery technology is, of course, a more desirable approach to extending the range and broadening the scope of application of electric vans. The zinc/nickel oxide battery is a near-term candidate that would double the range of the electric van relative to lead-acid.(53) The van in Figure 26(54) illustrates the installation of zinc/nickel oxide batteries for demonstration purposes by Energy Research Corporation. Beyond this, the fuel cell and the high temperature battery are potential long-term candidates. In this regard, it is noteworthy that the hydrogen/oxygen fuel cell powered van shown in Figure 27(55) was constructed and tested by General Motors in the late 1960s and that the sodium/sulfur battery powered van shown in Figure 28 was demonstrated by the Electricity Council Research Center in the United Kingdom in the early 1970s. The development status of these advanced concepts is discussed later in Section 5.

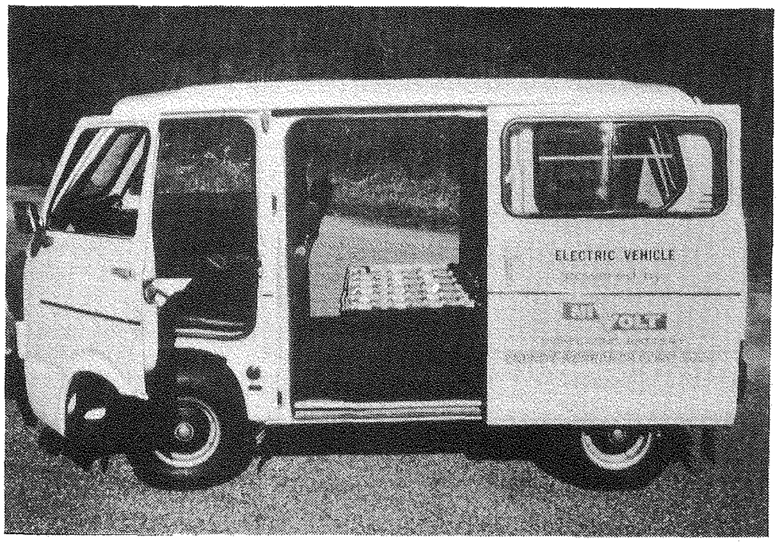

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Fig. 26. Zinc/nickel oxide battery-powered van (54).

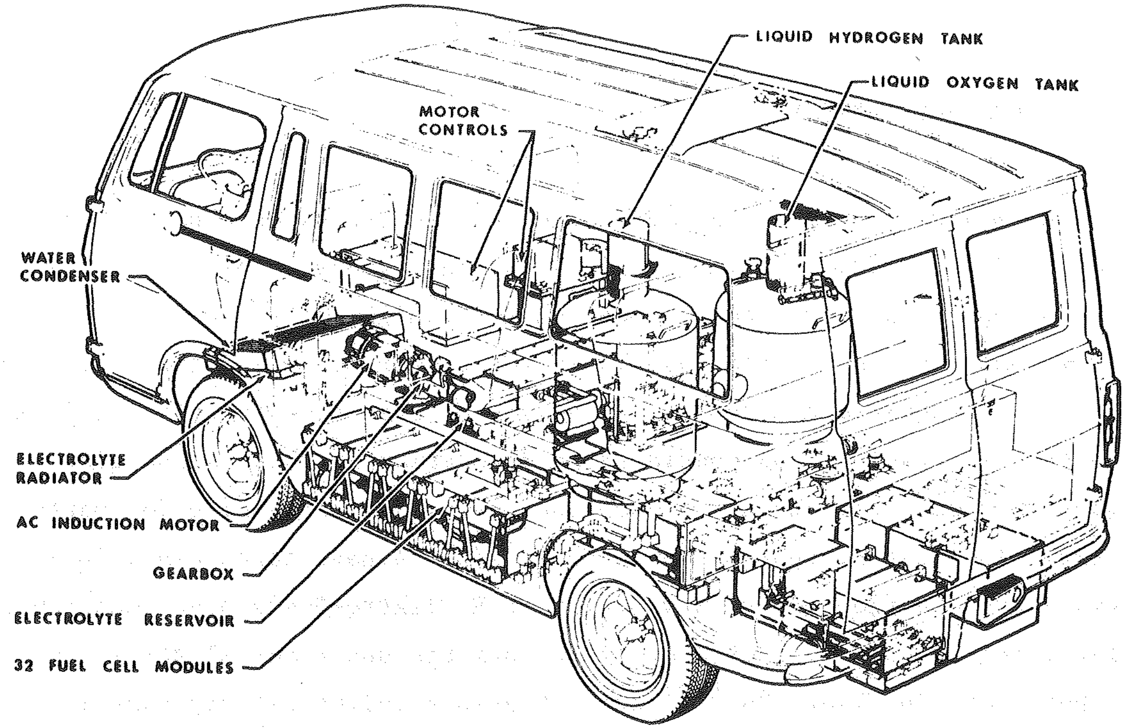

Fig. 27. Cutaway view of General Motors Electrovan (55).

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Fig. 28. Bedford van powered by a sodium/sulfur battery (35).
(Courtesy of Lewis Laboratories, NASA.)

2.2.3. Passenger Buses

The major portion of the development of electric buses has taken place in Europe and in Japan. The important operational requirements are high reliability, low operating cost and, in most cases, a high daily use factor with a relatively small amount of time available for battery charging and vehicle servicing. These requirements result in the use of proven components, maximum use of regenerative braking, and considerable innovation in battery charging techniques to reduce the amount of time the bus is out of service for battery recharge. The most noteworthy development efforts have taken place in West Germany where a fleet of twenty M.A.N. SL-E Elektro-Buses have been running in a large-scale evaluation of overall performance under actual service conditions. The bus shown in Figure 29 (56) demonstrates a unique battery containment and exchange concept wherein the batteries are contained in a trailer pulled behind the bus rather than being built into the bus chassis. Battery exchange is accomplished automatically during a five-minute rest period that the drivers are given between runs.

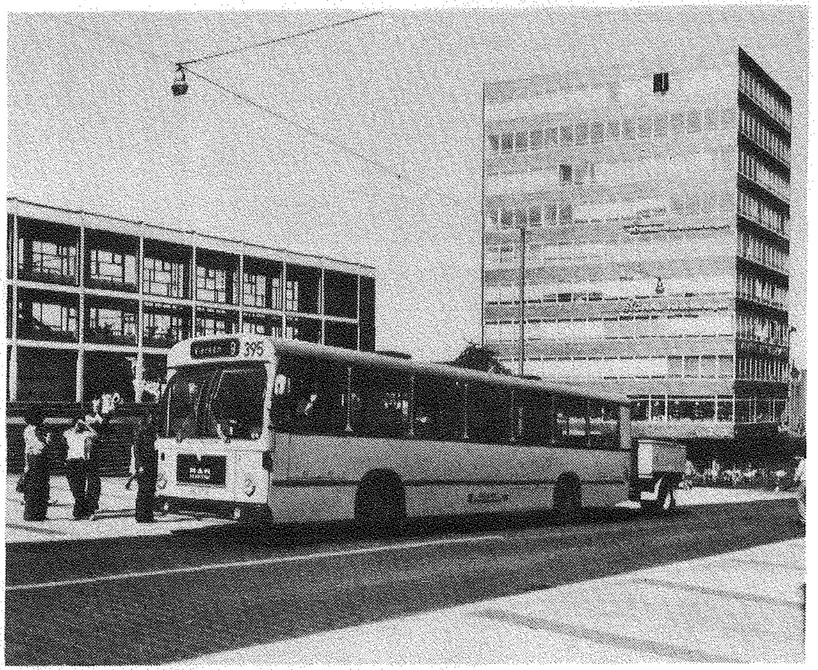

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Fig. 29. SL-E Electrobus in route operation (56). (Courtesy of Electric Vehicle News.)

Overall performance data for the SL-E Elektrobus are reported in Ref. 56. The bus has a GVM of 16,000 kg and half of the busses were built with separately-excited d-c motors and the other half with series-wound motors. The effect of regenerative braking was much more significant with the separately-excited motor in that the energy required from the battery was about 16% less than for the series-wound motor. The overall average energy economy (from the "wall plug" for all of the busses in actual service was reported to be 2.35 kWh/km or about 0.15 W•h/kg•km based on the 16,000 kg GVM.

3. ELECTROCHEMICAL POWER SOURCE REQUIREMENTS

The characteristics of electrochemical power sources that are of primary concern in electric vehicle applications are peak specific power, average specific energy, durability, and cost. The peak specific power must be interpreted to be a power level that can be sustained for at least 10-20 s, and the average specific energy is the specific energy obtained by discharging at a specific power that represents an average of actual discharge conditions in a vehicle. This is typically a value of about 32 W/kg for an urban commuter type vehicle. In order to define specific power and energy requirements for the electrochemical power source, it is necessary to evaluate the power required to propel the vehicle. This can be done with sufficient accuracy for purposes of this discussion by the analytical treatment in the following paragraphs.

3.1. Vehicle Propulsion Power Calculations

The vehicle propulsion power requirement can be obtained from the product of vehicle velocity and the summation of the resistive forces for acceleration, aerodynamic drag, rolling resistance, and moving up a grade.

The force required for acceleration is represented by the relation

$$F_a = M_v \, dV/dt \qquad (1)$$

where, F_a = acceleration force, N
M_v = vehicle mass, kg
V = vehicle velocity, m/s
t = time, s

This relation applies only to linear acceleration; whereas, some parts of the vehicle require rotational acceleration (such as the wheels, driveshaft, and motor). Tenniswood and Graetzel concluded that the force required for rotational acceleration is approximately 10% of that required for linear acceleration for the speed range 0 to 80 km/h.(57) The total force required for both linear and rotational acceleration is then given by the relation

$$F_a = 1.1\ M_v\ dV/dt \tag{2}$$

The retarding effect of the aerodynamic drag force can be calculated from

$$F_d = \rho_A\ C_D\ A_f\ V^2/2 \tag{3}$$

where, F_d = aerodynamic drag force, N
ρ_A = air density, kg/m^3 (1.2255 kg/m^3 at 15°C and 760 mm Hg)
C_D = air-drag coefficient, dimensionless
A_f = frontal area of vehicle, m^2

The coefficient of aerodynamic drag is determined by the design of the vehicle. Although the value can be in the order of 0.30 for highly streamlined cars, the average value for cars is closer to 0.5. The range of values for trucks is normally 0.5 to 0.7.

The resistive force due to the rolling resistance of the tires is typically approximated by the quadratic expression(58)

$$F_r = M_v\ g\ K\ (1 + 4.7 \times 10^{-3}\ V + 1.3 \times 10^{-4}\ V^2) \tag{4}$$

where, F_r = rolling resistance, N
g = gravitational constant, 9.80665 m/s^2
K = rolling resistance constant, dimensionless

The rolling resistance constant, K, is primarily a function of the type of tire and the amount of inflation. The value of the constant varies over a range of about 0.008 for truck tires and radial ply automobile tires at high pressure to approximately 0.015 for normal automobile tires at low pressure. A typical value for an urban electric commuter automobile would be in the order of 0.012.

The resistive force associated with climbing a grade is defined as the downhill component of the force due to gravity and is expressed as

$$F_g = M_v g \sin \theta \tag{5}$$

where θ is the angle of the grade.

Where it is common to express the grade as a percent, then

$$\theta = \text{Arctan } (\% \text{ grade}/100) \tag{6}$$

The power that must be provided to propel the vehicle can now be obtained by multiplying the sum of Eqs. (2), (3), (4), and (5) by the vehicle velocity. This results in the expression

$$P_p = V (F_a + F_r + F_g + F_d) \tag{7}$$

which is, by substituting Eqs. (2), (3), (4), and (5), the equation

$$P_p = M_v V [1.1 \, dV/dt + gK (1+4.7 \text{x} 10^{-3} V + 1.3 \text{x} 10^{-4} V^2) + g \sin\theta] + \rho_A C_D A_f V^3/2 \tag{8}$$

where, P_p = propulsion power at the wheels, W

It is noted that the propulsion power is a function of the vehicle design and also the manner in which the vehicle is driven. Thus, to define P_p, it is necessary to specify a driving profile, which defines vehicle velocity as a function of time. Calculations of this type have been reported in the literature for different driving profiles using typical electric vehicle design parameters.$^{(28,58)}$

Some of the pertinent results of those calculations are summarized in Table 8. The peak power and energy requirements shown in Table 8 will be referred to later in this section in the discussions of battery power and energy requirements.

In addition to the total propulsion power requirements shown in Table 8 for specific driving profiles, it is of interest to look at the contribution to the total power of each of the resistive forces in Eq. (7). Since the power required

Table 8. COMPARISON OF DRIVING PROFILE POWER AND ENERGY REQUIREMENTS (28,58)

Driving Profile	Maximum Speed (km/h)	Average Speed (km/h)	Number of Stops (per km)	Peak Power[a]/ Vehicle Mass (W/kg)	Energy[a]/ Vehicle Mass·km (W·h/kg·km)
EPA Urban	92	32	1.5	24.2	0.10
SAE J 1082 Urban	48	25	2.5	25.0	0.09
SAE J 227 Residential	48	33	0.7	13.3	0.08
SAE J 227 Metropolitan	72	39	0.6	17.5	0.10

[a] Requirements at the wheels of an automobile with a mass ranging from 1000 to 2000 kg.

to accelerate the vehicle and to overcome rolling resistance and grade forces is proportional to the vehicle mass in each case, these contributions are plotted in Figure 30 as a function of vehicle speed. The power required for acceleration in Figure 30 is based on a simplifying assumption that dV/dt in Eqs. (2) and (8) is a linear function of vehicle velocity. That is,

$$dV/dt = C_a - 0.1\ V \qquad (9)$$

where, C_a = initial acceleration, m/s^2

It can be illustrated that this is a reasonably good approximation of the actual acceleration characteristics of present-day combustion engine vehicles and that combustion engine compacts will typically fall in the range from $C_a = 2.7$ to $C_a = 3.1$. The velocity versus time characteristics associated with the values of C_a plotted in Figure 30 are given in Table 9. It is noted that the values of $C_a = 1.8$ and $C_a = 2.2$ are representative of the acceleration required for the SAE J 227a "C" and "D" driving schedules respectively, which are shown in Figure 20. As mentioned above, the value of $C_a = 2.7$ represents the minimum acceleration required for mixing with existing traffic on urban streets.

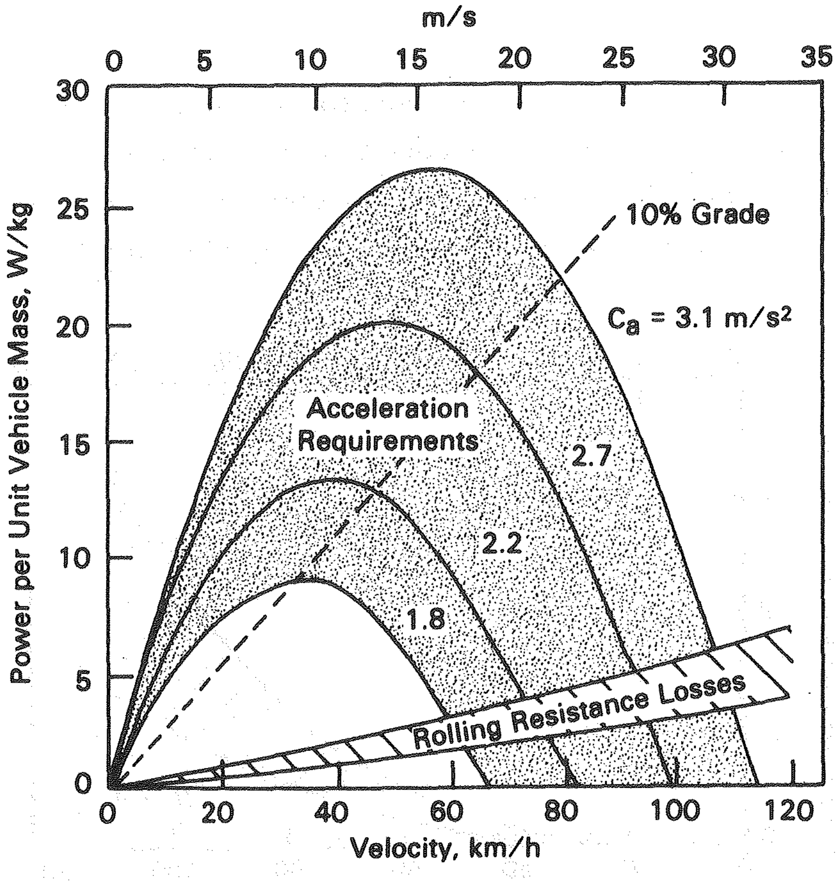

Fig. 30. Power per unit vehicle mass required for acceleration and to overcome rolling resistance and grade forces.

Table 9. LINEAR ACCELERATION CHARACTERISTICS

Initial Acceleration (C_a)	Time to Reach 13.4 m/s (48 km/h) (s)	Velocity After 20 s (m/s)	(km/h)
1.8	14	15.6	(56)
2.2	9	19.2	(69)
2.7	7	23.2	(83)
3.1	5.6	26.8	(96)

The power required to overcome the aerodynamic drag force is not a function of vehicle mass but is directly proportional to the frontal area of the vehicle. Thus, this contribution to the total power is plotted in Figure 31 in terms of power per unit of frontal area as a function of vehicle velocity.

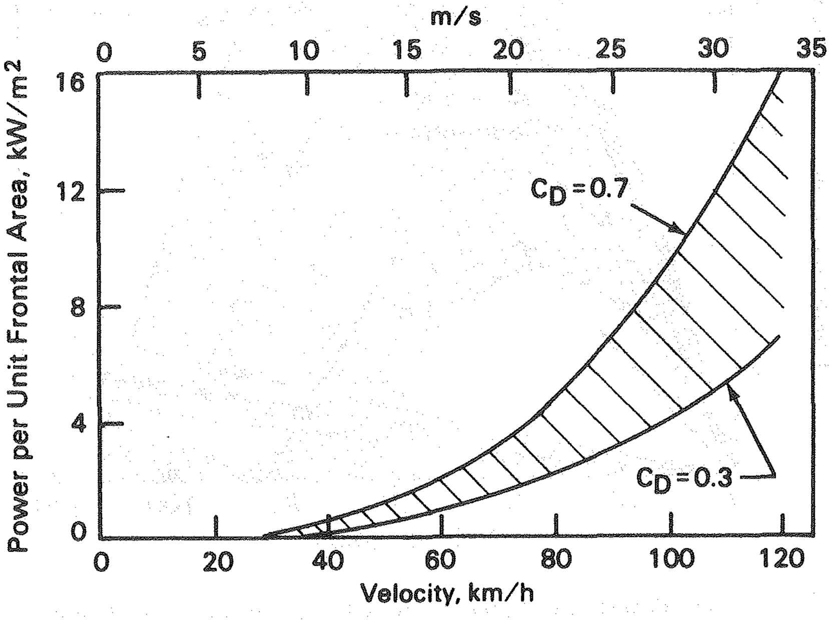

Fig. 31. Power per unit frontal area to overcome aerodynamic drag.

The results shown in Figures 30 and 31 are useful in that they can easily be applied to any vehicle, without the need of a large-scale computer, to approximate the maximum power required at the wheels of the vehicle as a function of aerodynamic drag coefficient, rolling resistance constant and the initial value of linear acceleration.

3.2. Battery Power Requirements

The total power required from the power source includes the power delivered to the wheels for propulsion, as defined by Eqs. (7) and (8) plus the losses resulting from electrical and mechanical inefficiencies in the powertrain and the power required to operate the accessory load. Thus, the power delivered by the battery power source is

$$P_b = P_p/\eta_m \cdot \eta_e + P_{acc} \qquad (10)$$

where, P_b = battery output power, W

η_m = mechanical efficiency of the drive train

η_e = electrical efficiency of the drive train

P_{acc} = accessory power required from the battery

The accessory power includes the power required for heating and air conditioning, power steering, power brakes, lights, windshield wipers, etc. The most significant of these is the power that would be needed for air conditioning. It has been reported that a value of 1.3 kW would be a reasonable air conditioning power requirement for limited-range commuter electric vehicles.(59) Other authors(58) have reported a minimum accessory load without air conditioning to be about 250 W and approximately 3000 W with air conditioning.

With regard to the inefficiencies of the drive train, the mechanical efficiency, η_m, is usually rather high and in the order of 93% to 95%. The electrical efficiency, η_e, of the motor and controller varies considerably with vehicle speed over a range of about 65% at low speeds to as high as 80% at high speeds. In view of this, an average value of 70% is a reasonable value for the product of $\eta_m \cdot \eta_e$ in Eq. (10).

A final consideration in determining the specific power requirement of the battery is the amount of vehicle mass that is allocated to the battery power source. This is normally expressed as a fraction of gross vehicle mass and ranges from about 0.2 to 0.4. A maximum value in the range of 0.25 to 0.3 has been reported to be the most acceptable from the point of view of vehicle design and handling.(26)

A plot of battery specific power versus fraction of gross vehicle mass allocated to the battery power source for various acceleration characteristics is shown in Figure 32. The bold lines represent the peak power from Figures 30 and 31 at 0% grade, divided by the drive train efficiency of 70%. The broken lines are based on the peak power defined by specific driving profiles in Table 8. Since the increased aerodynamic drag of vans and light trucks is somewhat offset by a decrease in the rolling resistance constant

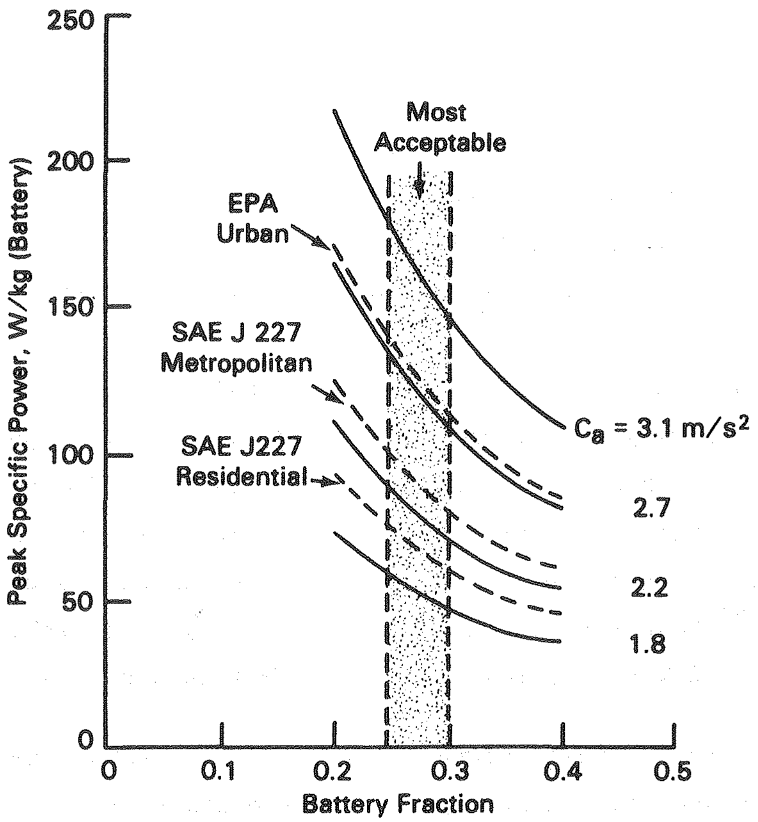

Fig. 32. Battery peak specific power requirement for various acceleration characteristics vs. battery mass fraction.

relative to passenger vehicles, the curves of Figure 32 represent a reasonable approximation for these vehicles as well as for passenger vehicles. It can be seen from Figure 32 that in order to have a passenger vehicle with reasonable performance as defined by the EPA Urban cycle or an initial linear acceleration of $C_a = 2.7$, a battery specific power in the range of 120 to 150 W/kg is necessary. In the case of delivery trucks, a reduced acceleration capability is acceptable in many applications; however, a mass fraction no greater than 0.25 is preferred to allow for a greater payload. In these applications, the lower curves in Figure 32 indicate that a battery specific power as low as 60 to 80 W/kg could be considered.

3.3. Battery Energy Requirements

The battery specific energy requirement is primarily defined by the range requirement of the vehicle. It is also important that this range be defined over a selected driving profile, in contrast to constant speed conditions, so that the efficiencies of the system and the effects of the driving schedule come into play and result in a more realistic measure of the energy required from the battery. A convenient approach to illustrating the relationships between vehicle range and battery specific energy is shown in Figure 21 of Section 2. In this plot, the range over urban driving conditions is plotted versus battery fraction for various values of battery specific energy. The specific energy lines are based on an energy requirement from the batteries of (0.15±0.02) W·h/kg·km which is a typical value for various urban driving profiles as indicated by the energy requirements shown in Table 8. The band is used to allow for reasonable variation in vehicle design parameters and drive train efficiencies.

There appears to be reasonable agreement that a commuter passenger vehicle should have an urban range of at least 150 km.(8,26,38) From Figure 21, it is concluded that for a reasonable battery fraction in the range of 0.25 to 0.3, a battery specific energy of at least 70 W·h/kg is required. With regard to many of the delivery and service vehicle applications, it has been indicated that a range in the order of 100 to 120 km would be quite adequate.(53) Thus, for these applications a minimum specific energy of 60 W·h/kg could be of interest.

3.4. Durability and Cost Requirements

The subject of electrochemical power source requirements would not be complete without some consideration of the durability and cost requirements. The key factor here is operating cost in that the cost of the batteries is usually considered to be a cost item that is amortized over the number of kilometers driven before the batteries are replaced. This brings into focus the concept of durability in that the amortized battery cost is inversely related to durability or cycle life. This issue is further complicated by the fact that the battery cycle life is a function of how the battery is used which is discussed in more detail in the next section.

Due to the lack of good information regarding the total operating costs of electric vehicles, it is rather meaningless to define objective requirements for durability and battery cost. However, the significant factors that come into play can be discussed, at least in general terms.

It is reasonable to postulate that the operating cost of an electric vehicle would have to be competitive with the operating cost of a conventional combustion engine vehicle. The operating cost of an electric vehicle can be expressed as

$$C_{eo} = C_b + C_e + C_{me} + C_{ev} \tag{11}$$

where, C_{eo} = total electric vehicle operating cost, \$/km

C_b = amortized battery cost, \$/km

C_e = cost of electricity, \$/km

C_{me} = amortized maintenance cost of electric power train, \$/km

C_{ev} = amortized electric vehicle (less batteries) ownership cost, \$/km

The related expression for a combustion engine vehicle would be

$$C_{co} = C_f + C_{mc} + C_{cv} \tag{12}$$

where, C_{co} = total combustion engine vehicle operating cost, \$/km

C_f = cost of fuel, \$/km

C_{mc} = amortized maintenance cost of combustion engine power train, \$/km

C_{cv} = amortized combustion engine vehicle ownership cost, \$/km

A comparison of Eqs. (11) and (12) leads to the following assumptions:

1. C_e will be less than C_f since the cost of electricity is not expected to increase as much as the cost of gasoline or synthetic fuels.

2. C_{me} will be less than C_{mc} primarily because of the relative simplicity of the power train and fewer parts.

3. C_{ev} will be less than C_{cv} since C_{ev} does not include battery cost, whereas C_{cv} includes the combustion engine cost. All other factors, such as insurance, body maintenance, tires, etc., should be similar.

The operating cost of the electric vehicle will be competitive if C_b is less than or, at most, equal to the savings realized by these assumptions. Thus,

$$C_b \leq (C_f - C_e) + (C_{mc} - C_{me}) + (C_{cv} - C_{ev}) \tag{13}$$

Since C_b is directly proportional to the battery cost (\$/kWh) and inversely proportional to durability (cycle life) as illustrated in the following section, the battery cost requirement can be expressed as

$$\text{Battery Cost (\$/kWh)} \leq K \cdot \mathit{durability}\, [C_{co} - (C_e + C_{me} + C_{ev})] \tag{14}$$

where, K = constant relating to the energy consumption of the electric vehicle and the depth-of-discharge of the battery power source.

durability = number of charge-discharge cycles

The expression above emphasizes the significance of the battery durability and the reliability of the electric power train with regard to battery cost. In general, the proponents of electric vehicles are optimistic that if the above assumptions prove to be reasonably valid and if the battery durability is in the order of 300 to 500 cycles at 80% to 100% depth-of-discharge, then the resulting battery cost requirement approaches a value that could be realized in production quantities.

4. IDENTIFICATION OF CANDIDATE POWER SOURCES FOR ELECTRIC VEHICLES

As discussed above, the success of an electric vehicle requires more than an electrochemical power source of acceptable performance; it must also have adequate durability, and acceptable cost. It is not difficult to build a battery of acceptable performance <u>or</u> acceptable durability <u>or</u> acceptable cost.

Even combinations of any two of these three requirements can be achieved. So far, it has been possible to achieve satisfactory battery performance and durability and cost in only a few electric vehicle applications. Currently, these applications are limited to a few specialized industrial, commercial, and recreational vehicles, such as fork lift trucks, mining vehicles, personnel carriers, and golf carts. All of these vehicles have modest performance and range requirements, such that Pb/PbO_2 batteries have been acceptable.

4.1. Battery Performance

When the performance and range needs for electric automobiles are taken into consideration, it is clear from the previous sections of this chapter that a power source capable of providing more than 100 W/kg acceleration power, and more than 70 W·h/kg energy storage capability is necessary if a range of 150 km is to be achieved. As a first step, it is of interest to identify those candidate systems that show promise (or hope) of providing adequate performance and range for electric automobile use. Next, this list can be reviewed with materials cost and availability criteria in mind, yielding a group of candidate systems for further consideration.

In the first step of identifying those candidate electrochemical systems that might be of interest, it is useful to separate the candidate systems into two groups: batteries, and fuel cells. This grouping is important because in batteries, at least one of the reactants is stored within each cell, and the specific energy of the system tends to be a performance-limiting factor. In fuel cells, neither reactant (fuel or oxygen from air) is stored in the cell, and the specific power of the system tends to be a performance-limiting factor. Most of the discussion to follow will be concerned with batteries, because they are much closer to being practical for electric automobiles than are fuel cells.

With regard to candidate couples for batteries, it is useful to consider the maximum amount of energy per unit mass of reactants that might be provided by a given electrochemical couple. This energy is called the theoretical specific energy, and is useful in focusing attention on the electrochemical couples that might provide batteries of high specific energy. Under ideal conditions

The list of couples that could be assembled from the above groups of reactants is impressively long. However, when practical chemical and electrochemical considerations are applied, such as compatibility with an electrolyte common to the positive and negative electrode reactants, the list becomes more manageable. Such a list is given in Table 10, showing the negative electrode reactant, electrolyte, and positive electrode reactant for each candidate couple. A number of reactants have been eliminated for reasons of cost (Ag, Cd, Hg), availability (Ag, Cd, Hg), health and environmental reasons (Cd, Hg, Se, F_2), and others.

Table 10. CANDIDATE CELLS FOR ELECTRIC AUTOMOBILE BATTERIES

Ambient-Temperature Cells

Aqueous Electrolytes	Non-Aqueous Electrolytes
$Pb/H_2SO_4/PbO_2$	$Li/LiClO_4/TiS_2$
$Zn/ZnCl_2/Cl_2$	
$Zn/ZnBr_2/Br_2$	
Zn/KOH/NiOOH	
$Zn/KOH/MnO_2$	
Zn/KOH/Air	
Fe/KOH/NiOOH	
Fe/KOH/Air	
Al/KOH/Air	

High-Temperature Cells

Molten Salt Electrolytes	Solid Electrolytes
Li/LiCl-KCl/S	$Na/\beta\text{-}Al_2O_3/S$
LiAl/LiCl-KCl/FeS	$Na/Na_{1+x}Zr_2Si_xP_{3-x}O_{12}/S$
$LiAl/LiCl\text{-}KCl/FeS_2$	Na/Na-glass/S
$Li_4Si/LiCl\text{-}KCl/FeS$	$Na/\beta\text{-}Al_2O_3/SbCl_3$ in $NaAlCl_4$
$Li_4Si/LiCl\text{-}KCl/FeS_2$	

To provide some perspective in comparing the candidate cells to one another, the theoretical specific energy values have been calculated for the couples of Table 10, and a number of others, using Eq. (15). The results are shown in Figure 33. Note the iso-emf lines. Other considerations being equal, it is advantageous to choose cells with a high emf, because resistive

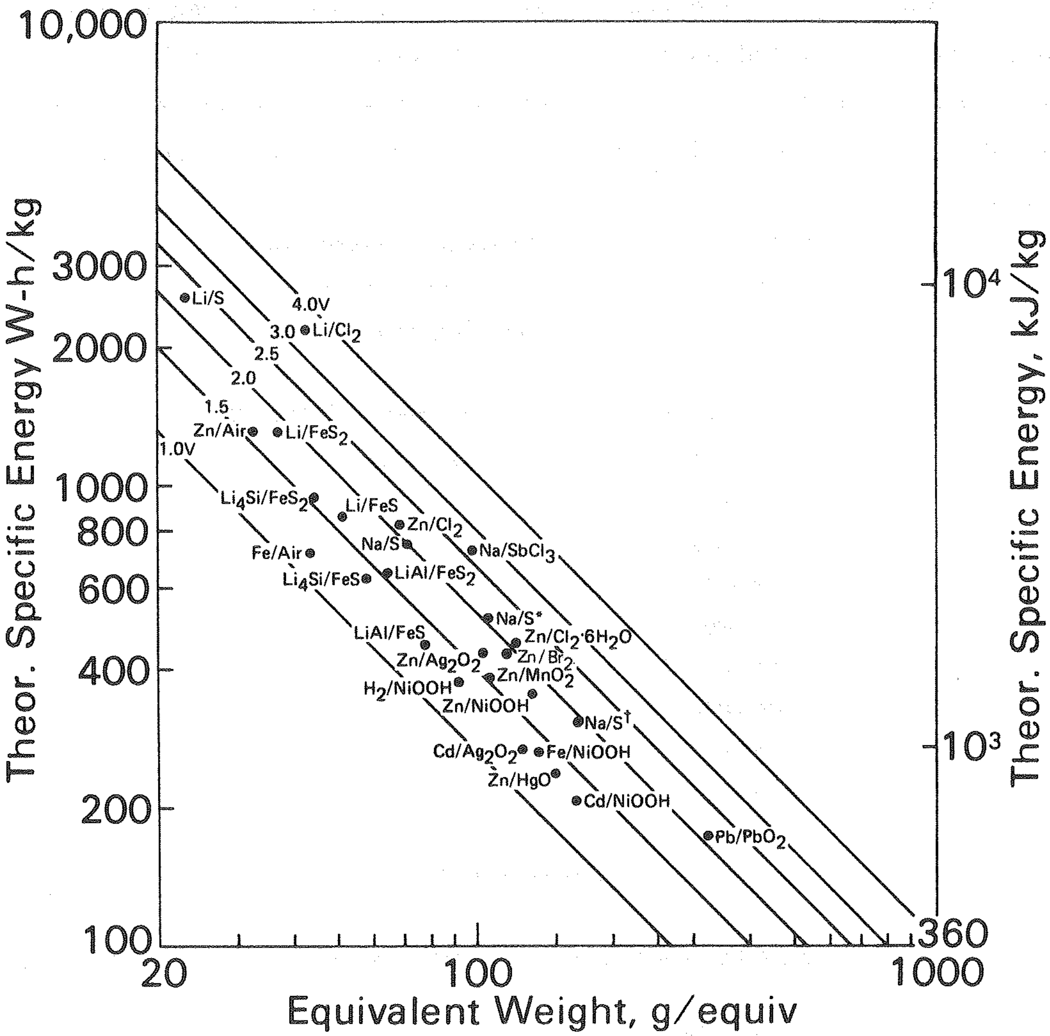

Fig. 33. Theoretical specific energy of candidate cells for electric vehicle batteries.

(and some other) losses tend to be a smaller fraction of the cell voltage for higher-emf cells. Also, a smaller number of cells in series connection is needed to provide a reasonable power system voltage (e.g., 100 V).

How does one use Figure 33 in assessing the specific energy that might be obtained from a cell of practical design and construction? A reliable set of guidelines is: multiply the theoretical specific energy by 0.2 to 0.25 for cells with solid reactants, and by 0.15 for cells with an air electrode. These multipliers apply for systems developed to provide reasonable cycle life, at a minimum weight.

The results of the considerations above indicate that the specific energy values above 100 W·h/kg are expected to be obtainable mostly with high-temperature cells using alkali metal electrodes. In a number of situations, it may be appropriate to compromise the specific energy for the convenience of ambient-temperature operation. This may be particularly appropriate for personal-use electric vehicles that are not operated every day.

The theoretical considerations above have allowed for the elimination of a number of cells from further evaluation, on the basis of specific energy, reactant cost, availability, and hazards. The next steps in comparing and selecting cells require experimental results, largely because the complex science of electrochemical cell design is not sufficiently advanced to allow accurate predictions of specific power, cycle life, and cost.

A simple but useful reflection of the relationship between the specific energy (W·h/kg) and the specific power (W/kg) of various batteries is shown in Figure 34. The lines curve toward lower specific energies at higher specific powers for a number of reasons, including higher voltage losses (resistive and other) at higher power levels and lower active material utilizations at higher power levels. Design improvements to make these curves more nearly vertical usually add weight, and cause the low specific power ends of the curves to shift to the left. The cell and battery design optimization process is a complex one, and requires a detailed knowledge of the motor and controller characteristics, and a map of the required vehicle performance.

The specific power required for reasonable acceleration is shown as 120 W/kg in Figure 34. All candidate batteries must have this capability for 10-20 s for each major acceleration, over most of the capacity of the battery (zero to 75 or 80 percent depth of discharge) and over most of its range of operating temperatures. As discussed earlier in this chapter, the specific

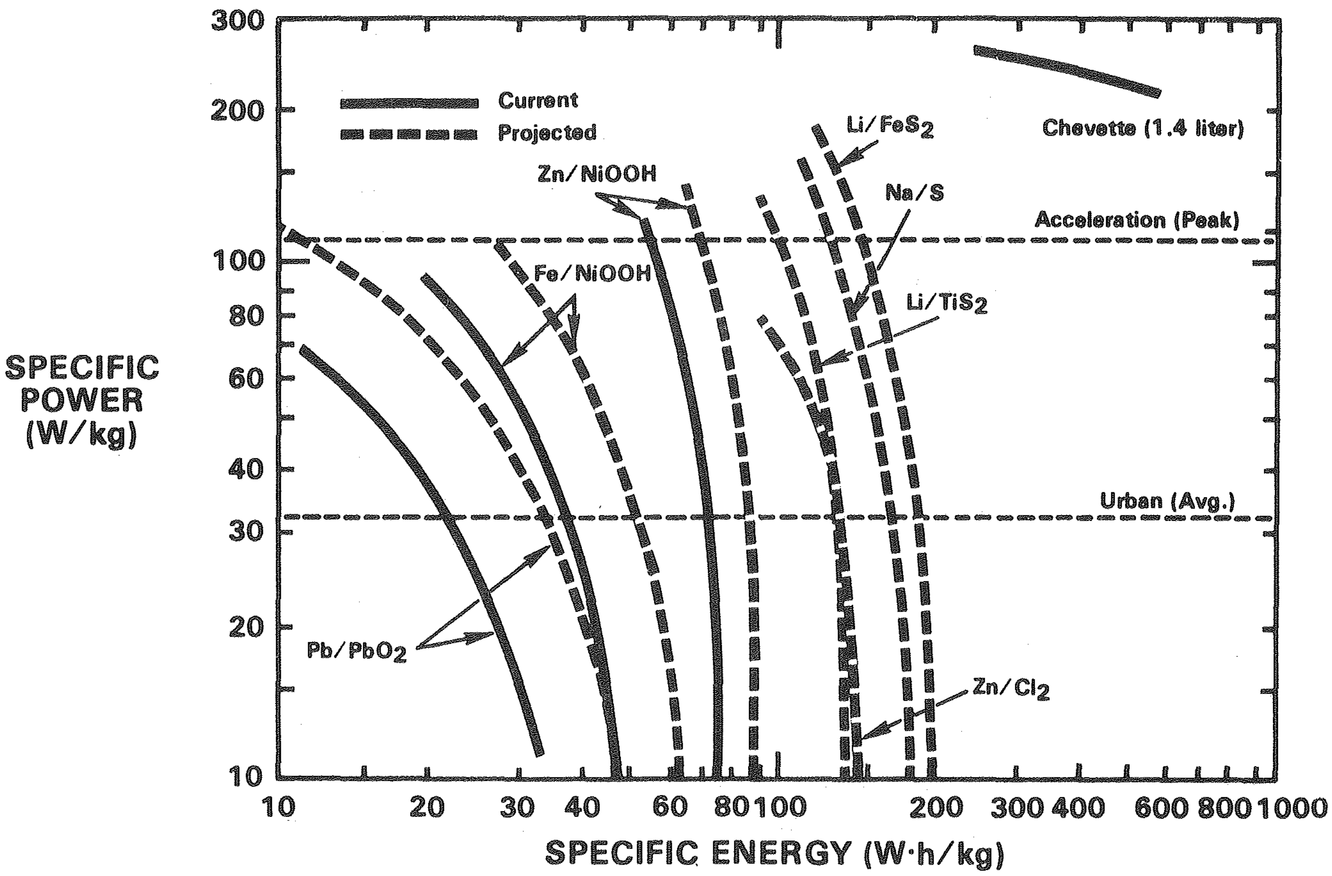

Fig. 34. Specific power *vs*. specific energy for electric vehicle battery candidates (50,70,76,90,85,128, 129).

energy determines the range of the vehicle as shown in Figure 21. Use of the specific energy at 32 W/kg (average specific power) from Figure 34 in conjunction with Figure 21 allows the estimation of the urban range of an electric automobile with any of the candidate batteries. Obviously the curves of Figure 34 which lie to the right give longer ranges; all candidates for automobile propulsion must have curves that extend above 120 W/kg for good acceleration. The curves of Figure 34 allow the preliminary selection of batteries based on performance issues alone. Durability and cost of the batteries are also very important considerations.

4.2. Battery Durability

Battery durability (or cycle life) is most simply expressed in terms of the number of charge-discharge cycles to which the battery can be subjected before a specified loss in energy delivery capability has occurred. As might be expected, the cycle life is a function of the conditions under which the battery is cycled. A partial list of variables (aside from design and construction parameters) influencing cycle life is given in Table 11. With this long list of important variables, it is not surprising that there is great scatter and uncertainty in the literature as to the values of cycle life under various conditions for even the most well-established cells (Pb/PbO_2 and Cd/NiOOH). There are very few data concerning the quantitative effect of the variables of Table 11 on the cycle life of any cells or batteries.

Table 11. SOME VARIABLES AFFECTING BATTERY CYCLE LIFE

- Temperature
- Depth of discharge
- Manner of discharge
    1. Constant current
    2. Constant Power
    3. Constant resistive load
    4. Variable current (driving profile)
    5. Variable power (driving profile)
    6. Chopped current
- Extend of charge (and overcharge)
- Manner of charge
    1. Constant current
    2. Constant voltage
    3. Constant-limited constant voltage
    4. Pulsed current
    5. Charge, rest
- Mechanical movement
    1. Vibration
    2. Shock
    3. Tilting or rocking
    4. Flow conditions
- Cell interconnections
    1. Series connections
    2. Parallel connections
    3. Ladder networks
- Maintenance procedures
    1. Water or electrolyte addition
    2. Periodic special discharging or recharging
    3. Periodic resting

The most commonly reported cycle life data for cells and batteries correspond to operation at room temperature, at depths of discharge less than 50%, carried out at constant current corresponding to less than 10 W/kg with no mechanical movement, and some sort of maintenance. If any cell interconnections are used, they are almost always simple series connections of no more than a few cells. A few data are available for the cycle lives of cells currently under development, and a scattering of data for various designs of Pb/PbO_2 cells and batteries. These are summarized in Figure 35,(38) plotted as the logarithm of the cycle life vs. percent depth of discharge. For most of the data, the cycle life was reported as the number of cycles before failure to deliver the fraction of the design capacity indicated by the percent depth of discharge (DOD). In the case of 100% depth of discharge data, the reported cycle life usually represents the number of 100% DOD cycles to a given discharge cutoff voltage (e.g., 1.4 V per cell) executed before a loss of 20% or 25% of the design capacity is experienced.

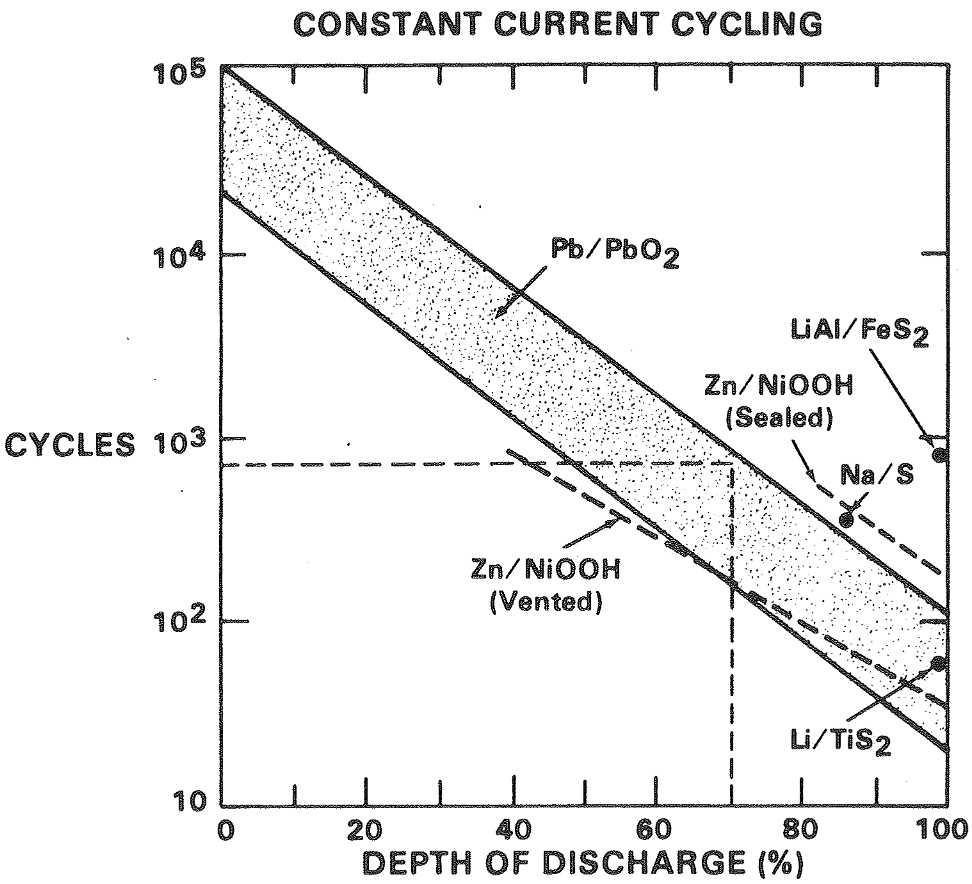

Fig. 35. Constant current cycles vs. depth of discharge (128,129,133).

At the present time, the exact shapes of the curves of Figure 35 are unclear because of the paucity of the data. If they are straight lines, then there is a depth of discharge for which the specific energy throughput is a maximum. The specific energy throughput is defined as follows:

$$\mathrm{SET} \equiv n \times \mathrm{SE} \times \mathrm{DOD} \tag{16}$$

where, SET = specific energy throughput, the amount of energy passed through the cell or battery in its lifetime, per unit of battery mass, W·h/kg

n = cycle life, the number of cycles before failure

SE = specific energy, W·h/kg

DOD = depth of discharge; fraction of the total energy withdrawn from the cell or battery on each discharge

If the relationships in Fig. 35 are straight lines, then the following equation applies:

$$\log n = \log n_1 - b\,(1 - \mathrm{DOD}) \tag{17}$$

where, n_1 = cycle life at DOD = 1

b = slope.

The maximum energy throughput then lies at the point:

$$\mathrm{DOD}_m = \frac{-1}{2.303b} \tag{18}$$

Values for DOD_m, n_m/n_1, and $\mathrm{SET}_m/\mathrm{SET}_{n_1}$) are given below for various slopes:

$-b$	DOD_m	n_m/n_1	$\mathrm{SET}_m/(\mathrm{SET}_{n_1})$
3	0.1448	368	53.3
2	0.217	36.8	8.0
1	0.434	3.68	1.6

In the case of an energy throughput which is independent of DOD, there is simply an inverse relationship between n and DOD:

$$n/n_1 = 1/\mathrm{DOD} \tag{19}$$

A few data points exist which indicate that for some Pb/PbO_2 cells, a relationship applies that is intermediate between Eq. (17) (with $b = -2$) and Eq. (19). Limited data for other systems are consistent with Eq. (17) for DOD >0.5, with $b \simeq -2$. The relationship between cycle life and depth of discharges remains an open issue, but an important one, because it may be feasible to increase significantly the energy throughput by operating at less than 100% DOD, as shown in the last column of the table above. This means that the distance that the electric automobile can be driven before replacing the battery may be increased very significantly by recharging the battery before it is completely discharged.

The battery durability issue currently represents one of the most important unknowns with regard to the economic viability of electric automobiles. It is essential that much more information be gathered about the effects of all of the variables of Table 11 on cell and battery life, especially temperature (and temperature gradients), depth of discharge, manner of discharge (driving profile), extent and manner of charge, mechanical movement (during discharge), cell interconnections, and maintenance. The equipment for such testing is expensive, and the time required is long. It is not surprising that these data are slow to appear.

4.3. Battery Cost

The cost of batteries suitable for use in electric automobiles is highly uncertain because none of the commercially-available batteries has been optimized for this application. At this time, it is only possible to bracket the costs of some types of batteries, and to set goals for others that are in earlier stages of development. As indicated above, the life of batteries is also very uncertain, causing the very important amortized cost of the battery to be in a highly unsatisfactory state of knowledge. A large amount of testing and field experience will be required before the amortized battery cost ($/km) will be known with reasonable confidence.

Something must be said about battery cost, in spite of the lack of information, because this subject is central to the viability of the electric automobile (and other electric road vehicles). As one point of reference, the present cost of Pb/PbO_2 traction batteries is about \$100/kW·h.(38) If this battery has a cycle life of 300 at 80% DOD, then the amortized cost (for the battery in a 1000 kg vehicle) is:

$$\text{Amortized Cost,\$/km} = \frac{\text{Battery Cost (\$kW·h) x 0.15 W·h/kg·km x 1000 kg}}{\text{n x DOD}} \qquad (20)$$

$$= \frac{100 \times 0.15}{300 \times 0.8} = 0.0625 \text{ \$/km}$$

Note that the battery fraction does not enter this calculation, except as it may indirectly affect n x DOD. Therefore, to a good approximation, the amortized battery cost is insensitive to the battery fraction. (The range of the vehicle, however, is directly proportional to the battery fraction.) The amortized battery cost calculated above is significantly higher than present gasoline costs (it is equivalent to about \$2.70/gallon), hence battery amortization cost goals well below 0.06 \$/km are advisable.

In the absence of firm cost information for electric vehicle batteries of various types, it is of some interest to review the cost goals for the battery development programs being funded by the Department of Energy (DOE).(38) These goals are set in terms of \$/kW·h. We have converted these into \$/km, and \$/battery for a 250 kg battery in a 1000 kg vehicle:

$$\text{\$/Battery} = \text{\$/kW·h x kW·h/kg x 250 kg} \qquad (21)$$

The cost goal figures are summarized in Table 12.

Most of the cost goals in Table 12 are reasonably close to 1¢/km for a 1000 kg vehicle, with a battery fraction of 0.25. This is certainly an ambitious goal, corresponding to \$50/kW·h or less, and a cycle life of about 1000. Ambitious as it is, this low cost may be a prerequisite to widespread use of electric automobiles. Considerably higher costs for batteries to be used in commercial vehicles (such as vans) or buses can be tolerated. It is likely that commercial electric vans will be in use in the U.S. with acceptable economics within the next few years.

Table 12. BATTERY GOALS

Battery Type		State of Art	$/kW·h	Cycle Life	% DOD	W·h/kg at 32 W/kg	$/ Battery[a]	$/km[b]
Pb/PbO$_2$	(124)	Now	∿90	300	80	25	562	0.056
		Improved	50	800	80	40	500	0.012
		Advanced	40	1000	80	50	500	0.075
Fe/NiOOH	(125)	Now	120	100+	100	50	1320	0.018-
		Advanced	60	1000+	100	60	900	0.0090-
Zn/NiOOH	(126)	Now	180	300	75	70	3150	0.12
		Improved	110	500	75	75	2062	0.044
		Advanced	55	1000	75	90	1238	0.011
Zn/Cl$_2$	(127)	Now	--	100	100	70	--	--
		Improved	75	500	100	130	2438	0.023
		Advanced	50	500	100	130	1625	0.015
Li/TiS$_2$	(128)	Now	--	50	100	40	--	--
		Advanced	50	500	80	130	1625	0.019
Na/S	(129)	Now	--	∿300	80	80	--	--
		Advanced	35	1000	80	170	1488	0.0066
Li/FeS$_2$	(129)	Now	--	700	100	170	--	--
		Advanced	35	1000	100	200	1750	0.0053

[a] For a 250 kg electric automobile battery

[b] $$\$/\text{km} = \frac{\text{Battery Cost (\$kW·h)} \times 0.15\ \text{W·h/kg·km} \times 1000\ \text{kg}}{\text{DOD} \times \text{Cycle Life}}$$

The performance and cycle life goals were included with the cost goals in Table 12 to emphasize the point that it is necessary to simultaneously meet goals in all three areas before expecting to find acceptance in the marketplace. These goals for each of the batteries serve as a useful reference point against which to compare the status of the systems ("Now" in Table 12) to be discussed individually below.

4.4. Fuel Cells

The idea of using fuel cells as a high-efficiency source of pollution-free electrical power has been attractive for a very long time. The interest in fuel cells for vehicle propulsion relates to the ability to carry enough fuel to give the vehicle a range of hundreds of kilometers, but with greater efficiency than existing automobiles, and with the advantages of smooth, quiet, low-pollution, electrical propulsion. Unfortunately, there have been many scientific and engineering problems preventing the use of fuel cells in applications that could be served by any other means. Fuel cells were used in the space program because they alone possessed the combination of specific energy and specific power to meet the needs of the Gemini and Apollo missions. Continued research and development efforts have made it possible to construct and operate a few fuel-cell powered vehicles for demonstration purposes. These vehicles have included a farm tractor, golf carts, an army truck, and a full-performance van.(60) Also, hybrid systems of fuel cells (for range) plus batteries (for power) have been demonstrated, one in an electric car.(61)

The results of the above demonstrations have served to emphasize the problems that remain to be solved before fuel cell systems might be practical for some classes of electric vehicles. One of the major technical problems with regard to vehicle fuel cells is that of the fuel. The only fuel cells with performance capabilities within the range of acceptability for vehicle use must have hydrogen as the fuel, and the hydrogen must be free of carbon monoxide (at least in the 100 ppm range) and sulfur. This presents a significant problem with regard to on-board storage or preparation of hydrogen. Storage of hydrogen in tanks is bulky, heavy, and presents safety problems; storage as the hydride is also heavy,* and expensive. Preparation on board from carbonaceous fuels is bulky, complex, and slow to start up. The storage and/or preparation of hydrogen on the vehicle adds to the system weight and volume to the extent that the overall system specific power is low (<100 W/kg max.) and the power density is low (<100 W/L max).

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*Hydrogen storage as a metal hydride is interesting, but presently-known alloys are expensive, and only store 1% or 2% hydrogen by weight. The kinetics of storage and release under vehicle operation conditions is problematical.

The lifetime of some fuel cells is probably more than adequate for vehicle propulsion, but the projected cost still is very high compared to a goal of \$100/kW average, or about \$25/kW peak. Cost reduction will result in large measure from system simplification. As progress in fuel cell system engineering is made, vehicle applications come closer to realization. In the meantime, battery-powered electric vehicles can be expected to find wider application.

5. ELECTROCHEMICAL POWER SOURCE TECHNOLOGY

5.1. Ambient-Temperature Batteries

Inspection of Table 10 reveals that the ambient-temperature batteries can be divided into groups according to the state of the reactants: solid, liquid, or gaseous. The batteries will be discussed in that order. Additional information on many of the batteries can be found in Chapter 5 of this volume.

The lead-acid cell ($Pb/H_2SO_4/PbO_2$) operates with the following overall reaction:

$$Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O \tag{22}$$

which serves as the basis for the computation of the theoretical specific energy of 175 W·h/kg. This cell has proven to be the most widely-used rechargeable cell of all. It is relatively inexpensive and has met a wide variety of needs, in spite of its low specific energy (20-40 W·h/kg at 10 W/kg), and its loss of capacity at low temperatures (Fig. 36).

The current interest in electric automobiles, and the government-sponsored electric vehicle demonstration program have enhanced the incentive to optimize the design of the lead-acid battery for this application. The result is a design that is lighter-weight than that for industrial traction batteries, but more robust than that for starting, lighting, and ignition (SLI) applications. The performance and cycle life of the electric vehicle (EV) battery represent a compromise between the above two types, resulting from weighing the conflicting requirements of high specific energy, high specific power, long cycle life at great depth of discharge, little or no maintenance, and low cost.

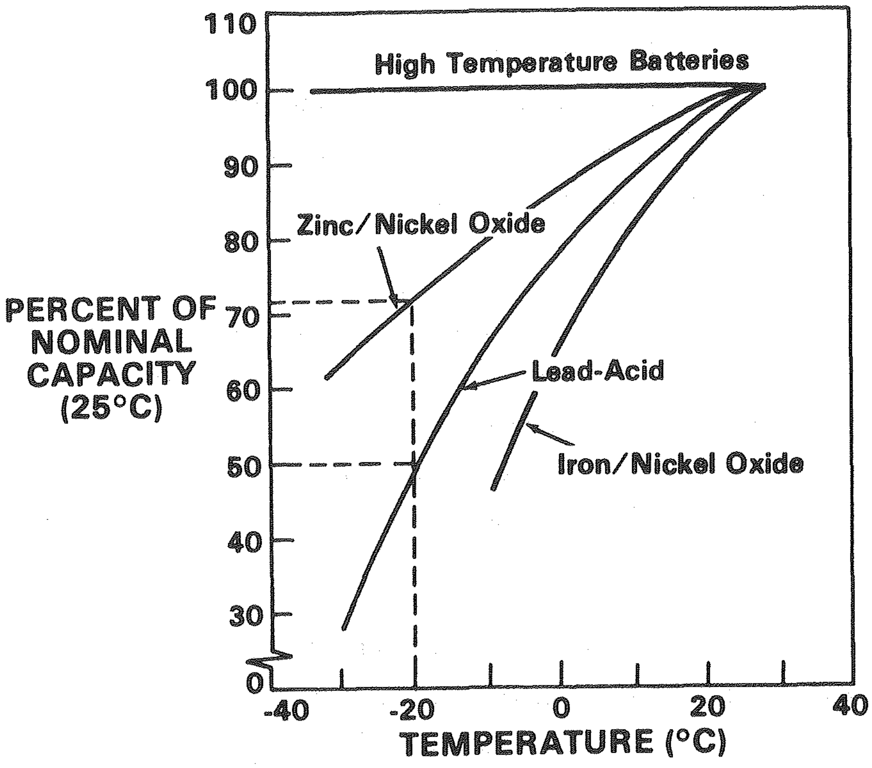

Fig. 36. Constant current discharge corresponding to average specific power for urban driving (32 W/kg), (130, 131, 132).

The cell design variables that are adjusted to meet the needs of a given application include the design of the current collectors, (62,63) the amount of active material in excess of that theoretically required, the thickness of the electrodes, the porosity and pore size distribution of the active material, the composition and amount of the electrolyte, the separator(s), the cell terminals, and the cell case. In addition to these variables, the design of a complete vehicle battery must take into account cell interconnections (series, parallel, ladder, etc.), and temperature control requirements.

As the development of the lead-acid cell for electric vehicles has progressed, a number of problems have been encountered. One of the common problems with rechargeable cells is the evolution of gases, especially during recharging. In the Pb/PbO_2 cell, both hydrogen and oxygen are evolved, resulting in a potential fire hazard and loss of water from the electrolyte. This problem was ameliorated by removing antimony as an alloying agent from the lead alloy current collector of the PbO_2 electrode, and replacing it with calcium. A sufficiently low rate of gas evolution resulted that a maintenance-free design was made practical. A vented battery case is used, allowing for the escape of the much smaller amounts of gases; however, water addition is unnecessary for the life of the battery.

The internal resistance of Pb/PbO_2 cells has been high enough that a significant loss of specific energy occurs at specific power levels needed for automobile propulsion. Some improvement has been made by the use of new polyvinyl chloride, and other polymeric separators of high porosity. Additional improvement is necessary because the internal resistance is still relatively high.

The present performance of Pb/PbO_2 batteries is such that electric vehicles having about 25% of their test mass as battery can accelerate from 0 to 50 km/h in about 10 seconds, and demonstrate an urban driving range of 50-60 km. This may correspond to 100 km or more at a constant 50 km/h. Typical top speed capabilities are 80-90 km/h. These values are consistent with the discussion of present electric vehicle performance information presented earlier in this chapter.

The cycle life of EV Pb/PbO_2 cells has been too low for electric automobile applications: generally 300 or fewer cycles at 80% DOD. This is one of the key areas requiring improvement. The issues that must be dealt with include the adhesion of the PbO_2 to the current collector, and the cohesion of the PbO_2 to itself. Corrosion of the positive-electrode current collector is also a life-limiting factor.

The cost of Pb/PbO_2 EV batteries can probably be decreased to acceptable values near \$50/kW·h for designs yielding more than 300 cycles at 80% DOD, and a specific energy of about 40 W·h/kg at 30 W/kg. Table 13 summarizes the situation for the Pb/PbO_2 battery, the standard against which the status of all other rechargeable cells is compared.

Table 13.

$Pb/H_2SO_4/PbO_2$

$Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$

E = 2.095 V; 175 W·h/kg Theoretical

Status		References
Specific Energy	22–40 W·h/kg @ 10 W/kg	64
Specific Power	50–100 W/kg @ 10 W·h/kg	65
Cycle Life	300+ @ 10 W/kg, 60% DOD[a]	64,65
Cost	\$35–\$50/kW·h	66,65
Recent Work		
Replace Sb with Ca in positive current collector		64
Maintenance-free cells		64
Use $4PbO \cdot PbSO_4$ instead of $PbO + Pb_3O_4$ in positive		64
PVC separators		64
Problems		
Sealing of cells (gassing)		
Corrosion of positive current collector		
Cohesion and adhesion of PbO_2		
High internal resistance		
Heavy		

[a] Depth of discharge as percent of nominal (or rated) capacity

The iron/nickel oxide cell (Fe/KOH/NiOOH) may employ either of the following overall reactions, depending on the design:

$$3Fe + 8NiOOH + 4H_2O \rightarrow Fe_3O_4 + 8Ni(OH)_2 \qquad (23)$$

$$Fe + 2NiOOH + 2H_2O \rightarrow Fe(OH)_2 + 2Ni(OH)_2 \qquad (24)$$

Reaction 23 takes place in two stages, yielding two voltage plateaus, 1.37 V and 1.05 V, with a theoretical specific energy of 284 W·h/kg. If the cell is constructed to operate according to Reaction 24, with only the 1.37 V plateau, then the theoretical specific energy is 267 W·h/kg.

The iron/nickel oxide cell has a long history; it is the famous Edison cell, used for the propulsion of electric cars developed by Henry Ford and Thomas Edison.(67) The rapid advances in gasoline engine performance prevented widespread use of electric automobiles, and the iron/nickel oxide cell found other applications. The classical constructions of this cell have involved heavy, bulky electrodes, resulting in low specific energies, in the same range as those for Pb/PbO_2, but at a higher cost. The cycle life has been excellent -- 1000–3000 cycles, and the cells have been rugged.(68)

In recent years, a number of laboratories have announced improvements in the weight and performance of both the iron electrode(69,70-72) and the nickel oxide electrode.(70-72) Some of the announcements include current collectors prepared from inexpensive steel wool, sintered to form a high-porosity plaque, into which is placed the electrochemically active material, Fe or $Ni(OH)_2$. The high specific area iron can be prepared by hydrogen reduction of an iron oxide; the $Ni(OH)_2$ can be precipitated in place by an electrochemical method from a nitrate solution, or can be prepared separately and then added to the porous current collector.

Cells prepared using the electrode technology described above have demonstrated specific energy values up to about 52 W·h/kg at 17 W/kg, and peak specific power values of 125 W/kg at 50% DOD. Cycle life data are still being gathered (presently in excess of 100 cycles, 100% DOD,(72)) but projections based on the earlier electrode designs(70,71) are 1500 cycles at 80% DOD. The continuing problems that are inherent to the Fe/NiOOH cell include gas evolution during charge (H_2 and O_2) and on open-circuit (H_2). Significant efforts have been invested in the reduction of the hydrogen evolution rate at the iron electrode. Evidently, removal (or avoidance) of impurities in the iron significantly reduces, but does not eliminate hydrogen formation, both a source of inefficiency, and a safety issue. Accompanying hydrogen evolution during charge is the evolution of heat at a rate that makes electrolyte circulation to a heat removal system advisable,(71,72) and complicates the system. One positive feature of the electrolyte circulation system is the opportunity to add make-up water to the electrolyte at a single point. The overall impact of the hydrogen evolution problem is to reduce the energy storage efficiency to 50%-55%, compared to 70%-80% for some other batteries. Another area requiring effort in the further development of the Fe/NiOOH system is the loss of energy storage capability at reduced temperatures. For example, a loss of about 40% of the capacity when the temperature is reduced from 25°C to 0°C.(72) Table 14 summarizes the status of the Fe/NiOOH system.

A significant amount of experience has been gained during the last several years on the use of Fe/NiOOH batteries in electric vehicles.(70-72) (See Figure 15.) The vehicle performance has been as expected based on the battery

Table 14.

Fe/KOH/NiOOH

$Fe + 2NiOOH + 2H_2O \rightarrow Fe(OH)_2 + 2Ni(OH)_2$

E = 1.37 V; 267 W·h/kg Theoretical

Status		References
Specific Energy	35-52 W·h/kg @ 10 W/kg	70,71,72,73
Specific Power	25-125 W/kg @ 10 W·h/kg	72,73
Cycle Life	100+ ? @ 10-25 W/kg, 80% DOD	72
Cost	~$500	72
Recent Work		
Improved Fe and NiOOH electrodes with higher specific energy		74,75
Problems		
H_2 evolution during recharge; cannot be sealed		73
Heat evolution		
Low efficiency, 50%-55%		72,73
Capacity loss at low temperature, 60% @ 0°C		72,73
High rate of self-discharge, with H_2 evolution; loss of 10% of charge in <100 h		72

performance information presented above. Vehicle ranges of 80 km in urban driving are consistent with 50 W·h/kg. The durability projection of 1500 cycles is very attractive; the cost projections are in the range of $350-500/kW·h for pilot quantities; it is too early to speak with confidence about ultimate costs. Clearly, a factor of 7-10 reduction should be the goal.

The zinc/nickel oxide cell (Zn/KOH/NiOOH) is in some ways similar to the iron/nickel oxide cell, but offers a higher specific energy, and has different problems. The overall cell reaction:

$$Zn + 2NiOOH + H_2O \rightarrow ZnO + 2Ni(OH)_2 \qquad (25)$$

corresponds to a theoretical specific energy of 373 W·h/kg, and a cell voltage of 1.74 V. If this cell can be effectively produced in a compact configuration, then a very attractive specific energy of 90-95 W·h/kg may be achieved (23% of theoretical).

The zinc electrode has received a great deal of effort to improve its cycle life capabilities. It has suffered from a complex set of problems, which can be summarized in four categories:(76) dendrite formation, zinc redistribution (shape change), densification, and passivation. The relatively high solubility of zinc-containing species in the KOH electrolyte has been a major contributing factor to the difficulty in extending the cycle life, because it contributes to all of the four problems above, except (possibly) for passivation.

The problem of dendrite formation has been reduced (but not totally eliminated) by the use of separators with extremely small pores (30-100 Å), such as cellophane, fibrous sausage casing, microporous polypropylene, and inorganic/organic composites. The rate of zinc redistribution has been reduced by the careful design of cells for uniform current distribution, the use of inorganic/organic separators, and proprietary additives to the zinc.

An important issue for EV batteries is that of maintenance. If the cells can be sealed, then no water or electrolyte addition should be required. It has been possible to reduce the amount of hydrogen evolution from the zinc electrode by the addition of one or two percent of metals with a high hydrogen overvoltage such as Hg or Pb,(77) so that sealed Zn/NiOOH cells can be operated successfully.(76,78) The oxygen formed at the NiOOH electrode during recharge can be recombined with zinc either by means of a porous oxygen reduction electrode (connected to the zinc electrode) or by direct reaction with the zinc electrode. Either of these options can be readily incorporated into the cell design, permitting sealed operation. Sealed cells have exhibited specific energies as high as 70-75 W·h/kg(76) in 125 A·h EV-sized cells.

As indicated in an earlier section of this chapter, several different electric vehicles, varying from small, 2-passenger autos to vans have been evaluated with Zn/NiOOH batteries. Typically, these vehicles exhibit urban driving ranges of about twice that found for Pb/PbO_2 vehicles, or 110-120 km under urban driving conditions, and more at steady speeds below 80 km/h.(54)

The status and current problems for the zinc/nickel oxide cell are summarized in Table 15. The establishment of pilot lines for the production of EV-sized cells and batteries is currently under way. Within the next year or

Table 15.

$Zn/KOH/NiOOH$

$Zn + 2NiOOH + H_2O \rightarrow ZnO + 2Ni(OH)_2$

$E = 1.74$ V; 373 W·h/kg Theoretical

Status		References
Specific Energy	55-75 W·h/kg @ 30 W/kg	76,78,79,54, 77,30,80
Specific Power	80-150 W/kg @ 35 W·h/kg	76,78,79,54, 77,81
Cycle Life	100-200 @ 25-50 W/kg 80% DOD	30,80,82 76,78,79,54, 77
Cost	>$100/kW·h	
Recent Work		
Inorganic separators (e.g., K_2TiO_3, ZrO_2, others)		30,80,82
Sealed cells		78,30,80
Nonsintered electrodes		78,30,80
Problems		
Sealing of cells - O_2 evolution and recombination		
Shape change and densification of zinc electrode		
Separators		

two, there should be a reasonable amount of information on the performance of such cells and batteries, and perhaps some cycle-life information as well. It will be important to know if the energy throughput has a maximum at an intermediate depth of discharge.

The ambient-temperature batteries using liquid reactants that may be candidates for use in certain types of electric vehicles are the zinc/halogen batteries: $Zn/ZnO_2/Cl_2$ and $Zn/ZnBr_2/Br_2$. Both of these systems rely on the storage of the halogen external to the cells, and, therefore, require a flow system to supply the halogen reactant (dissolved in electrolyte) to the electrodes.

The zinc/chlorine cell (83-85) operates according to the overall reaction:

$$Zn + Cl_2 \cdot 6H_2O \rightarrow ZnCl_2 + 6H_2O \qquad (26)$$

The reversible potential is 2.12 V, and the theoretical specific energy is 461 W·h/kg when the chlorine is stored as the hexahydrate. In some cases, the octahydrate is used, corresponding to a theoretical specific energy of 401 W·h/kg. The use of solid, ice-like chlorine hydrate as a storage medium increases the safety of the system, since the Cl_2 partial pressure is low. A refrigerator is required to form and store the hydrate (at about 9°C).(84,85) A schematic diagram of the system is shown in Figure 37.

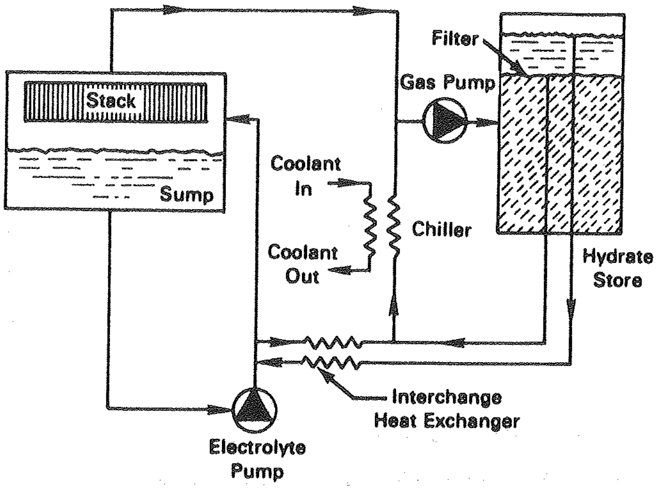

Fig. 37. Flow schematic for an electric vehicle battery system.

The electrodes are prepared from graphite: porous for the flow-through Cl_2 electrode, and solid for the Zn electrode. During charge, a dense zinc deposit is formed on the graphite substrate, with the aid of additives to the electrolyte. Low-hydrogen-overvoltage impurities, including iron, must be absent, to avoid hydrogen formation. Chlorine gas is formed at the porous carbon electrode, is swept out of the cell, and pumped to the $Cl_2 \cdot 8H_2O$ formation area, held at a few degrees centigrade. During discharge, the processes are reversed, with Cl_2-saturated electrolyte being pumped through the porous graphite electrodes. No separators are used, and the flow patterns in combination with the electrochemical consumption of dissolved chlorine are arranged to minimize direct reaction of dissolved chlorine with zinc. After every few cycles, it is necessary to discharge all of the zinc in order to avoid dendritic zinc deposits on recharge.

[Corrected Page 73; Third Sentence]

A one kilowatt-hour system has operated for over 1000 cycles, with some electrolyte maintenance. Other systems as large as 50 kW·h, 40 kW have been constructed and operated at efficiencies in the range of 55%. These larger systems have demonstrated a specific energy of 71 W·h/kg* @ 18 W/kg and 57 W·h/kg @ 57 W/kg. Because of the many components and the plumbing required, the density of the system is low: only 1.17 kg/L (vs. a typical value of 2 kg/L for batteries with solid reactants).

An advantage of this system is the inexpensive reactants. Disadvantages include the inefficiencies associated with hydrogen formation, direct reaction of chlorine with the zinc, system complexity, corrosion problems of the acidic chlorine-chloride flowing electrolyte, and safety issues. The status of this system is summarized in Table 16.

Table 16.

$Zn/ZnCl_2/Cl_2$

$Zn + Cl_2 \cdot 6H_2O \rightarrow ZnCl_2 + 6H_2O$

E = 2.12 V; 461 W·h/kg Theoretical

Status		References
Specific Energy	71 W·h/kg @ 18 W/kg	83,84
Specific Power	60 W/kg	83,84
Cycle Life	1000+ with maintenance	84
Cost	>$100/kW·h	
Recent Work		
Graphite for Cl_2 electrode		84
Additives for Zn deposition		85,87,88,89
System components		90
Photocatalytic H_2 recombination		83,84
50 kWh systems being tested		84
Problems		
Low efficiency (<60%)		85
H_2 formation		
Bulky		
Complex		
Low specific power		
Need for Zn stripping		85
System component reliability		

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*About 17% of theoretical.

It appears unlikely that Zn/Cl_2 systems will be used in automobiles, but they could find application in larger vehicles.

Another liquid-reactant system similar in many ways to the Zn/Cl_2 battery is the Zn/Br_2 battery. The zinc electrode uses a graphite or titanium substrate, behaves very similarly to the zinc electrode in the Zn/Cl_2 cell, and has the same problems. The bromine electrode is made of catalyzed titanium or graphite, and serves to reduce Br_2 to Br^- on discharge. On recharge, the Br_2 can be stored as complex polybromide ions such as Br_3^- and Br_5^-, provided that they are prevented from contacting the zinc electrode (e.g., by use of a cation exchange membrane separating the electrodes(86)). Another alternative is to store the Br_2 as a tetra alkyl ammonium complex, which has the properties of an oil which forms a separate phase and can be stored outside the cell.(91)

Individual, small cells (3.2 W·h) without the tetra alkyl ammonium bromide complex have been operated with maintenance for 1800 cycles at efficiencies of 60% to 80% (no subtraction of the parasitic power required was made). Larger cells (32 W·h) have cycled up to 600 times, with some shorting caused by zinc dendrites, and small systems of 1.2-2.5 kW·h (91,92) have been operated with relatively low efficiencies of 40%-65%. It is clear from the experience with small systems that overall, there are many similarities to the Zn/Cl_2 system. There may be some advantages to the ambient-temperature storage that is feasible with bromine.

The low density of the Zn/Br_2 system, caused by the circulating streams and external storage make it unlikely that electric automobiles will be a practical application. Perhaps larger vehicles with more volume available for the power plant, and lower performance requirements will be a future application. Current emphasis with the Zn/Br_2 system is for stationary energy storage. The status and problems are summarized in Table 17.

Table 17.

$Zn/ZnBr_2/Br_2$

$Zn + Br_2 \rightarrow ZnBr_2$

E = 1.82 V; 430 W·h/kg Theoretical

Status		References
Specific Energy	61 W·h/kg @ 12 W/kg	92
Specific Power	73 W/kg peak	92
Cycle Life	200 @ 90% to 100% DOD (1800 for small cells)	91,92
Cost	>$100/kW·h	
Recent Work		
Prototype battery of 2.5 kW·h tested		92
Complexing of bromine		
Problems		
Complete discharge every few cycles is required		86,91,92
Zinc dendrites--uneven current distribution		
Flowing electrolyte--complex system		86,91,92
Low efficiency: 65% W·h		91,92
High self-discharge rate: 50% in 50 h		92
Poor Zn adherence; Zn dendrites		92
Corrosion by bromide-bromine solutions		
Recharge of bromine electrode		86,91,92
Safety		
Low kW·h/L		

Cells with gaseous reactants are exemplified by the metal/air couples, which tend to have higher specific energies than those with liquid reactants because there is no need to carry along a supply of air. In the calculation of the theoretical specific energy, however, appropriate allowance should be made for the weight added to the system by the oxygen in the reaction products. The three metal/air systems that are under active investigation involve iron, zinc, or aluminum electrodes, which react in alkaline (KOH or NaOH) electrolyte according to the following overall reactions, with the standard cell emf's and theoretical specific energies shown:

Reaction	EMF	Theoretical Specific Energy
$Fe + \frac{1}{2}O_2 + H_2O \rightarrow Fe(OH)_2$	1.2 V	720 W·h/kg
$Zn + \frac{1}{2}O_2 \rightarrow ZnO$	1.6 V	1310 W·h/kg
$Al + \frac{3}{4}O_2 + \frac{3}{2}H_2O \rightarrow Al(OH)_3$	2.7 V	2790 W·h/kg

The metal/air cells represent the first group discussed in this chapter that is generally unable to operate at practical current densities at cell voltages within 0.1 - 0.2 V of the reversible value. A major portion of this voltage inefficiency is caused by the air electrode, and has been the subject of major efforts at improvement for many years. An air electrode capable of acting as an anode during recharge, and a cathode during discharge would be very useful in both the iron/air cell and the zinc/air cell, but operation during recharge tends to cause damage to the electrode structures and electrocatalysts, rendering them less active for oxygen reduction. Generally speaking, cycle lives for these bifunctional air electrodes at practical current densities (>0.05 A/cm^2) have been less than 100.* This difficulty has led to the attempted use of a third electrode for oxygen evolution during recharge. Third electrodes have proven to be impractical, and have added unreasonably to system complexity (and cost). Other approaches include metal anode replacement, removing the recharge requirement from the air electrode.

All of the metal-air systems are rather bulky and complex, making them unpromising for automobile applications. There is a possibility for use in vans, buses or industrial vehicles, if the fundamental problems of voltage efficiency and rechargeability can be solved.

The Fe/KOH/air system probably has reached the most advanced state of development of any of these three systems, in terms of electric vehicle propulsion, since it has been used in a demonstration industrial vehicle.(93) The iron electrode has the advantages pointed out in connection with the Fe/NiOOH cell: It is very rugged, has a long cycle life, and probably can be produced at an acceptable cost. The current inefficiency of the iron electrode is less of a disadvantage in the Fe/air cell, because no balancing of state of charge against the air electrode is required. The relatively low voltage of the iron/air cell is a disadvantage because it contributes to a low efficiency (about 45% now), and

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*There have been occasional reports of 200 and 500 cycles, but firm supporting data for these reports have not been published.

requires that more series-connected cells be used to meet a given voltage requirement (the operating voltage is 0.7 - 0.8 V per cell).

System specific energies of 90 W·h/kg have been reported,(93) with cycle lives of about 200. The status of the iron/air system is summarized in Table 18. Work continues at a few laboratories in the U.S.A. and Europe.

Table 18.

Fe/KOH/Air

$$Fe + \frac{1}{2}O_2 + H_2O \rightarrow Fe(OH)_2$$

E = 1.2 V; 720 W·h/kg Theoretical

Status		References
Specific Energy	90 W·h/kg @ 10 W/kg	93
Specific Power	30 W/kg @ 40 W·h/kg	93,94
Cycle Life	200 @ ∿20 W/kg	93,94
Cost	>$100/kW·h	93,94
Recent Work		
Improved Fe and air electrodes		93,94
Systems of several kilowatts built for vehicles		93
Additives to reduce H_2 gassing		93
Problems		
Maintenance of water balance		93,94
H_2 evolution during charge		
Self-discharge		93
Low specific power		
High internal resistance		
Low efficiency: <45%		95

The zinc/air cell has received more attention than iron/air, probably because of its higher cell voltage and higher specific energy. The problems of the air electrode are the same as for other metal/air systems. The cycle lives of the zinc electrodes tend to be the same as for the bifunctional air electrodes. In some cases, the replacement of the zinc electrode has been practiced as a means of "mechanically" recharging the battery. The advantages of this are that the zinc electrode is not recharged *in situ*, and thus does not suffer from dendrite formation, shape change, etc. In addition, the air electrode is not required to operate as an anode, thus providing for a greatly extended life.

Primary zinc/air batteries of this sort have included interesting design variations, such as a circulating zinc powder slurry electrode,(96,97) which can be replaced, or recharged electrically in a separate cell.(97)

Prototype zinc/KOH/air systems of several kW·h capability have been constructed and operated,(98) but no lifetime information has been made available. The status of the zinc/air battery is shown in Table 19.

Table 19.

Zn/KOH/Air

$Zn + \frac{1}{2}O_2 \rightarrow ZnO$

E = 1.6 V; 1310 W·h/kg Theoretical

Status		References
Specific Energy	70-90 W·h/kg @ 20 W/kg	97
Specific Power	80 W/kg peak	97
Cycle Life	<100	99
Cost	>$100/kW·h	
Recent Work		
Improved circulating zinc electrodes		97
Improved air electrodes		97
Multicell batteries built (∿3 kW)		100
Zinc recharge unit		97
Problems		
Complex system		
Rechargeable air electrodes		96,100
Control of zinc in slurry		96
Wetting		
Carbonation		
Short Life		
Low efficiency: 35%-40%		
Low W·h/L		

The final metal/air system for consideration here is the Al/air system, which uses an aqueous alkaline or neutral electrolyte such as KOH, NaOH, or NaCl. The theoretical specific energy and the reversible potential are very high, as shown above. Because of the spontaneous reaction of aluminum with air and water, however, an oxide film is formed which causes very high overvoltages (∿1 V). Also, current inefficiency results from the direct chemical reaction of aluminum with water. Various measures have been taken to reduce these difficulties. The addition of 0.2% of Ga, In, or Tl reduces the anodic overvoltages of Al by 0.5 to 0.7 V in 2M NaCl,(101) allowing current densities as high as 1 A/cm^2. In another approach, the 0.05M $Na_2Sn(OH)_4$ has been used in 6M NaOH, with proprietary Al alloys.(102) The reaction product is $Al(OH)_3$ which can be precipitated as crystals of $Al_2O_3 \cdot 3H_2O$ (hydrargillite). The plan (102) is to remove this precipitate from the battery and send it to an electrolyte plant for conversion to new aluminum anodes. Because of the high overvoltages, and the logistics, the efficiency and suitability of this system for vehicle use are not attractive. No cell stacks, batteries, or systems have been reported yet; the status is summarized in Table 20.

Table 20.

Al/NaOH/Air

$$Al + \frac{3}{4}O_2 + \frac{3}{2}H_2O \rightarrow Al(OH)_3$$

E = 2.7 V; 2790 W·h/kg Theoretical

Status *(Lab cells only)*		References
Current Density	0.1 A/cm^2	
Voltage	1.4 V typical	
Cycle Life	Not rechargeable	
Cost	Too early	

Recent Work

Aluminum alloys of higher performance (In, Ga, Tl)

Electrolyte additives (e.g., $Na_2Sn(OH)_4$)

Removal of $Al(OH)_3$ as precipitate (Hydrargillite)

Problems

Not electrically rechargeable

Control of precipitate formation

Low efficiency

Logistics

Air electrode

Low W/L

Low performance at low temperatures

Last of the candidate ambient-temperature batteries for vehicle propulsion to be discussed is the one with a nonaqueous electrolyte: Li/$LiClO_4$ - dioxolane/TiS_2. This is one of the very few ambient-temperature nonaqueous systems that claims to be rechargeable. In fact, a cycle life of 260 has been reported for a laboratory cell(103) The overall reaction is:

$$xLi + TiS_2 \rightarrow Li_xTiS_2 \tag{27}$$

The lithium intercalates into the TiS_2 reversibly, yielding a positive electrode with a long cycle life and a low overvoltage at low, but probably acceptable current densities (7.5 mA/cm^2). When x is 1.0, then the theoretical specific energy is 490 W·h/kg.

Because lithium is highly reactive, and readily reduces many materials forming lithium compounds, it is very difficult to obtain stable, inert, sufficiently pure nonaqueous solvents for use in lithium cells. Next, there must be adequate solubility of a stable lithium electrolyte. Lithium perchlorate has been used in diosalane, but this combination is not stable with lithium and explosions have resulted. Research on safer electrolytes and solvents is progressing, but compromises on cycle life have been necessary, bringing the value down to 100 cycles.

In spite of the above difficulties, small cells (up to 20 A·h) have been constructed and tested. Utilizations of TiS_2 have been 55% to 82%, depending on current density. A factor of ten excess lithium is used. The laboratory-cell results have been used in design calculations for performance projections which indicate that large (400 A·h) cells might achieve 120 W·h/kg (24% of theoretical) at 30 W/kg. This system is still in the early stages of development, and should be watched with interest, especially to determine if the safety issues can be adequately handled. Table 21 serves to summarize the information on the Li/TiS_2 cell. The potential advantages of this type of system include: high specific energy for long vehicle range, completely sealed cells (therefore no maintenance), and ambient-temperature operation.

Table 21.

$Li/LiClO_4/TiS_2$

$xLi + TiS_2 \rightarrow Li_xTiS_2$

E = 2.2 V (average); 490 W·h/kg Theoretical for x=1

Status		References
Specific Energy	120 W·h/kg @ 30 W/kg projected	103
Specific Power	100 W/kg peak projected	103
Cycle Life	100-260 *(lab cells)*	
Cost	>$100/kW·h	

Recent Work

- New solvents--more stable
- New electrolytes--more stable

Problems

- Safety
- Seals
- Low conductivity of electrolyte
- Low specific power
- Many parts per cell
- Lithium rechargeability
- Overcharge and overdischarge problems
- Manufacturability--water and air are contaminants

5.2. High-Temperature Batteries

In contrast to ambient-temperature batteries, most of which have aqueous electrolytes, high-temperature batteries have nonaqueous electrolytes, either molten salts or ionically conductive ceramics. This is the case because aqueous electrolytes have very high vapor pressures at the operating temperatures for high-temperature batteries (usually 300°C - 500°C). Following the practice for ambient-temperature batteries, systems with solid reactants will be discussed first, followed by those with liquid reactants.

A family of molten-salt electrolyte systems that has evolved from early work on lithium/LiCl-KCl/sulfur cells(104) is that of lithium alloy/LiCl-KCl/ metal sulfide cells. Several combinations of lithium-alloy negative electrodes have been investigated, however only two or three have received significant development effort, especially for use in electric vehicles. The overall cell reactions, emf values, and theoretical specific energies are summarized below:

$$2LiAl + FeS \rightarrow Li_2S + Fe + 2Al \qquad 1.3\ V,\ 458\ W{\cdot}h/kg$$

$$4LiAl + FeS_2 \rightarrow 2Li_2S + Fe + 4Al \qquad 1.75, 1.3\ V,\ 650\ W{\cdot}h/kg$$

$$Li_4Si + FeS_2 \rightarrow 2Li_2S + Fe + Si \qquad 1.75, 1.3\ V,\ 944\ W{\cdot}h/kg$$

All of the above cells make use of a molten-salt electrolyte comprised of about 60 m/o LiCl-40 m/o KCl, which melts near 350°C. Typical operating temperatures are near 450°C. This temperature requires a high-performance insulation and thermal control system, in order to minimize thermal losses, especially during idle periods and to maximize overall system efficiency.

These cells have demonstrated very long cycle lives (105,106) (∿700 and more), with modest capacity losses (105,106) (∿20%). The reactants are inexpensive, making these cells attractive from a potential cost viewpoint.

One advantage of high-conductivity molten salts is the design flexibility they offer in meeting the high specific power required of electric vehicles. The electrodes can be thicker, and of much higher capacity per unit area (e.g., 0.3 $A{\cdot}h/cm^2$ vs. 0.03 $A{\cdot}h/cm^2$) than those of ambient-temperature cells. This means fewer electrodes are needed per unit energy and power, reducing manufacturing costs.

The electrodes can be prepared by simple powder mixing and pressing operations in a dry atmosphere. Compact cells (105,106) require small interelectrode distances and thin, corrosion-resistant, strong separators. Boron nitride cloth has been used as the separator in most of the work on these systems; however, it is extremely expensive (∿5000/m^2). Recently, BN felts have been used with acceptable results, and much more acceptable cost projections (∿\$25/m^2).

The need for isolation of lithium alloys from air and moisture makes necessary the use of hermetically sealed systems with electrical feedthroughs.

Systems containing many cells of only two or three electrodes each would require too many expensive feedthroughs to be cost effective. Therefore, recent efforts have included work on multielectrode cells(105,107) and bipolar batteries.(108) The development of Li_4Si as a successful, high-performance electrode has halved the weight of the negative electrode, compared to LiAl.(109)

The inconvenience of having a high-temperature battery in a vehicle must be offset by significant advantages such as the high specific energy available from the Li_4Si/FeS_2 cell,(106) the long cycle lives, and the potential for low cost. If these advantages are not preserved in the finally-developed battery, then advanced ambient-temperature systems will certainly continue to hold strong interest for automobile propulsion.

The continued development of $Li\text{-}M/FeS_x$ cells for transportation applications will require careful attention to maximizing specific energy (>125 W/kg), cycle life (1000 cycles), calendar life (3 years, minimum), and minimizing cost (<$100/kW·h). The current problems include raising the specific energy of the LiAl/FeS cell, avoidance of internal shorting, development of feedthroughs, improved corrosion-resistant current collectors for the FeS_2 and FeS electrodes, lower-cost separators and thermal control systems for batteries (see Tables 22 and 23 for a summary). Even though much work remains to be done before these systems are ready for application, demonstration EV batteries are being constructed, and will be evaluated in vehicles during the next two years.

The only high-temperature cells with liquid reactants that now appear to be candidates for vehicle propulsion are two versions of the sodium/sulfur cell. The most vigorously-developed version uses a beta-alumina ($Na_2O \cdot xAl^2O^3$, $x = 5$ to 11) ceramic electrolyte, and the other uses a Na_2O-containing glass electrolyte. Both cells rely on the same overall reaction:

$$2Na + 3S \rightarrow Na_2S_3 \qquad (28)$$

which has an average emf of 2.0 V, and a theoretical specific energy of 758 W·h/kg. The product, written as Na_2S_3 above, is not meant to represent a compound, but merely the overall composition of the sulfur electrode at the point defined as 100% DOD. This point is so defined because farther discharge will cause the undesirable precipitation of solid Na_2S_2 from the liquid sulfur-rich positive electrode.

Table 22.

LiAl/LiCl-KCl/FeS

$2LiAl + FeS \rightarrow Li_2S + Fe + 2Al$

E = 1.33 V; 458 W·h/kg Theoretical

Status		References
Specific Energy	50-90 W·h/kg @ 30 W/kg	105,107
Specific Power	60-100 W/kg, peak	105
Cycle Life	300 @ 100% DOD	105,107
Lifetime	∿5000+ h	107
Cost	>$100/kW·h	
Recent Work		
Multielectrode cells		105,107
LiCl-rich electrolyte		107
BN felt separators		107
Batteries of 320 A·h cells		107
Charging equipment		107
Problems		
Low specific energy		
Low voltage per cell		
Cell shorting major failure mode		
Electrolyte leakage		
Agglomeration of Li-Al with cycling		
High separator cost		
Leak-free feedthroughs		
Thermal control		

Table 23.

$Li_4Si/LiCl-KCl/FeS_2$

$Li_4Si + FeS_2 \rightarrow 2Li_2S + Fe + Si$

E = 1.8, 1.3 V; 944 W·h/kg Theoretical

Status		References
Specific Energy	120 W·h/kg @ 30 W/kg	106
	180 W·h/kg @ 7.5 W/kg	106
Specific Power	100 W/kg peak	106
Cycle Life	700 @ 100% DOD	106
Lifetime	∿15,000 h	
Cost	>100/kW·h	
Recent Work		
Bipolar cells		108
Li-Si electrodes		106
BN felt separators		105,107
70 A·h cells		

Problems

- Materials for FeS_2 current collector
- Leak-free feedthroughs
- High internal resistance
- Low-cost separators needed
- Thermal control

A very attractive feature of Na/S cells is their inherent simplicity, and the idea that the electrodes, being liquid, should not change with cycling. If combinations of materials that are pure and stable in contact with one another are used, these cells should last a very long time. The basic materials of which the cell is made are mostly inexpensive: Na, S, Na_2CO_3. Al_2O_3, C. The electronic conductor for use with the sulfur electrode may be relatively costly (Cr-coated steel?). Most versions of this cell are tubular. The $Na_2O \cdot xAl_2O_3$ electrolyte is prepared in the shape of a closed-end tube, as shown in Figure 38. Cells with sodium inside the electrolyte tube, and outside of it have been evaluated. In the U.S.A., the sodium-inside design is predominant.

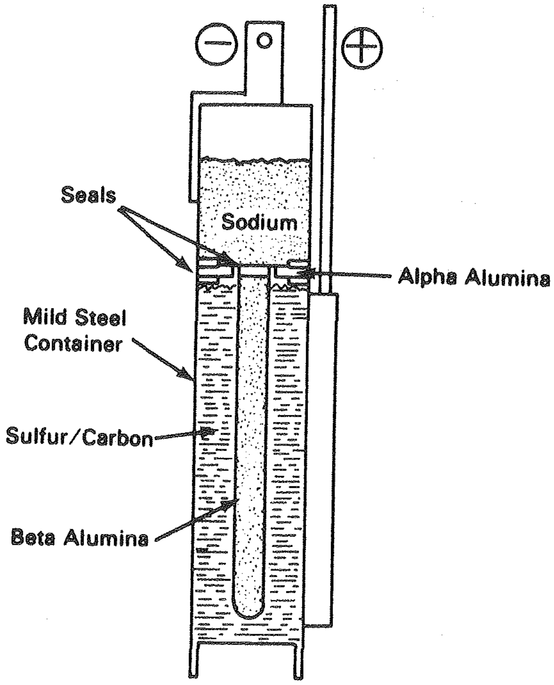

Fig. 38. Sodium/sulfur cell.

Cells of the beta-alumina type with capacities of up to about 170 A·h have been operated,(110-112) and a few multikilowatt-hour batteries have been demonstrated, one in an electric van, in England.(113) Other similar demonstrations are imminent. Table 24 indicates that the specific energy of single Na/S cells is in some cases above 100 W·h/kg, and the cycle life can be over 1000. The lifetime needs to be raised to at least 25,000 h. Recent efforts have been

Table 24.

$Na/Na^+Solid/S$

$2Na + 3S \rightarrow Na_2S_3$

$\bar{E} = 2.0$ V; 758 W·h/kg Theoretical

Status		References
Specific Energy	85-140 W·h/kg @ 30 W/kg	114,111,112
Specific Power	60-130 W/kg, peak	114,115
Cycle Life	200-1500	110,111,116
Lifetime	3000 - 15,000 h	116,117,113
Cost	>$100/kW·h	
Recent Work		
Batteries ∿10 kW·h		
C_6N_4 additive to S		116,113
Ceramic (TiO_2) electronic conductors		116
Shaped current collectors		
Tailored resistance current collectors		110
Sulfur-core cells		114
$Na_{1+x}Zr_2Si_xP_{3-x}O_{12}$		111
Thermocompression bonded seals		110
Problems		
Corrosion-resistant material for contact with S		
Low-cost seals		
Low-cost electrolyte		
Specific power is low		
Thermal cycling		

devoted to the several problem areas indicated, especially improving the capabilities of the sulfur electrode, the corrosion resistance of the container, and the seals. Major efforts are devoted to the preparation of the beta alumina, and the cost reduction of the process.

The approach of using an electrolyte comprised of many thousands of hollow glass fibers (of high resistivity) has been showing increasing promise. The fibers are sealed into a common header, in contact with the sodium reservoir, as shown in Figure 39. Cells of this design, having a nominal capacity of 6 A·h have shown a durability of up to 400 cycles; some 40 A·h cells have been constructed and are under test. The current life-limiting problem is gradual sagging of the glass header, resulting in breakage of the glass fibers.

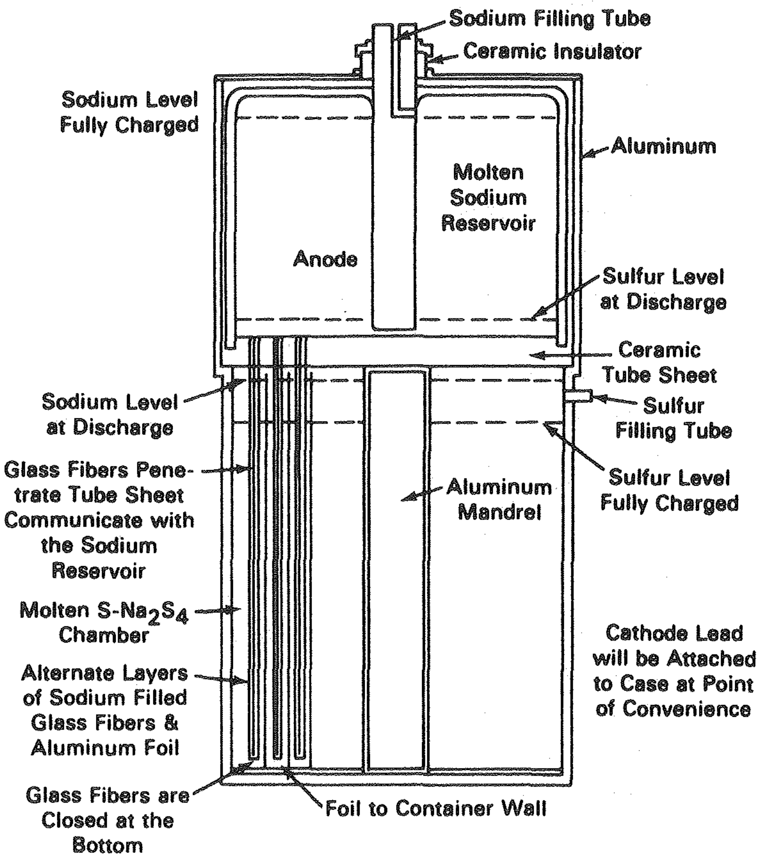

Fig. 39. The DOW sodium/sulfur hollow fiber cell.

All of the sodium/sulfur cells have been of cylindrical design, causing the energy per unit volume to be lower than it overwise might be. This may result in batteries that are very bulky for automotive use.

Sodium/sulfur cells are very sensitive to thermal cycling, and frequently fail upon freezing and reheating. This problem is one of the fundamental issues that is unresolved.

If progress on high-temperature batteries continues at the present pace, several major electric vehicle demonstrations will take place before 1985. If these are highly successful, some commercial applications may follow.

5.3. Fuel Cells

For many years, fuel cells* have been a hope for clean, efficient conversion of the chemical energy of a (conventional) fuel directly into the most useful form of energy: electricity. Hundreds of millions of dollars have been invested in fuel-cell research and development efforts around the world, but the practical fuel cell for commercial or consumer application still is in the future. The performance of fuel cell systems has steadily improved with time, to the point where it is marginally acceptable for a number of uses. The lifetime, and especially the cost require a great deal of improvement.

By far, the greatest fraction of fuel-cell development effort has been oriented toward stationary applications, where high specific power is not required, and higher (than acceptable for vehicle systems) cost is acceptable. From time to time, however, fuel cells are re-evaluated for use in electric vehicles. A recent evaluation(118) of the applicability of present-day fuel cell technology to electric vehicles has indicated that the most appropriate system for development is a fuel cell -- battery hybrid, arranged according to the diagram in Figure 40. The fuel cell is designed to meet the maximum cruising power requirements, and the battery is designed to provide additional power for acceleration. The battery also provides all power during the time required for fuel cell system startup (up to 15 min).

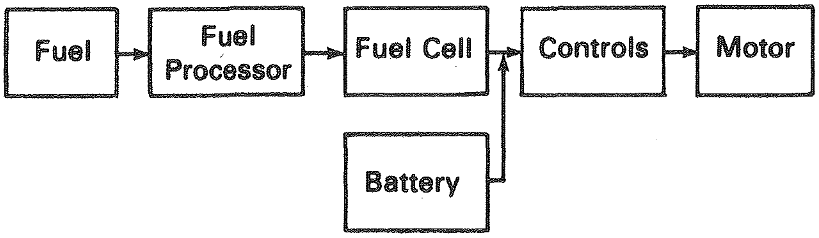

Fig. 40. Proposed electric propulsion system diagram.

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*For a more complete discussion of fuel cells, see Chapter 2 of this volume.

The fuel cell that is technologically the most advanced, and is closest to being manufactured in quantity is the phosphoric acid electrolyte cell, with thin, porous PTFE-bonded gas diffusion electrodes comprised of platinoid electrocatalysts (≤ 1 mg/cm^2 total) supported on graphite, held against a thin, inert, absorbent matrix containing the electrolyte.(119-121) These cells operate best on hydrogen, or CO- and sulfur-free hydrogen-rich fuel streams. The optimum operating temperature is 150°C - 200°C; sometimes pressurized operation (ca. 3 atm) is used to increase the current density.(119)

Recently, electrocatalyst loadings have been reduced below 1 mg/cm^2 (total of both electrodes), and methods for reducing the rate of surface area (therefore, performance) loss have been sought. Single cells have reached lifetimes greater than 20,000 h.(119) Development efforts on stationary systems continue; little is being done toward vehicle propulsion. The status shown in Table 25 reflects the situation with regard to the H_3PO_4-electrolyte cell being developed for stationery applications. Before fuel cell or fuel cell-battery hybrid vehicle propulsion is appropriate (other than for demonstration purposes), it will be important to reduce the system volume (a power density of 100 W/L is probably necessary), provide for rapid startup (<5 min), improve system response to follow driving profiles, greatly reduce system complexity, and greatly reduce system cost.

Table 25.

$H_2/H_3PO_4/Air$

$$CH_3OH + H_2O \rightarrow CO_2 + 3H_2 \text{ (reformer)}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \text{ (fuel cell)}$$

$E = 1.23$ V; 6094 W·h/kg[a] Theoretical

Status		References
Specific Power	27-25 W/kg	118
Power Density	12-35 W/l	118
Efficiency	40%	
Lifetime	4000 - 6000 h (est.)	118
Cost	>$100/kW·h	118
Recent Work		
Lower electrocatalyst loadings		120,122
Methods to reduce catalyst sintering rate		120,123
Operation at elevated pressures		119
Scaleup for megawatt stationary systems		119
Compact reformers for hydrocarbons		
H_3PO_4 inventory control		122
Problems		
Low specific power and power density		
Slow system startup		
Slow system response		
System complexity		
System cost		
Corrosion of catalyst substrate		
Catalyst area loss		

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[a] Based on methanol weight only; the oxygen is taken from the air and not carried; the water is assumed to be recovered from the exhaust.

6. SUMMARY AND CONCLUDING REMARKS

We have attempted, in only one chapter, to present an introduction to electrochemical power for transporation, with emphasis on such important items as the potential advantages of electric vehicles in shifting some of the transportation energy demand away from petroleum, and toward other primary sources of energy, while retaining the individual freedom that accompanies the operation of one's own vehicle. In addition, it has been shown that gains in overall efficiency and effectiveness of primary energy use can be made if electric vehicles are used instead of conventional vehicles operating on synthetic fuels from coal or nuclear sources. Electric vehicles also offer opportunities for extremely low pollution.

The current situation for electric vehicles has been presented. Basically, only low-performance, short-range (<80 km in urban traffic) vehicles are now in use or available; higher range and performance require better power sources. Several vehicles with next-generation batteries such as Fe/NiOOH and Zn/NiOOH have been demonstrated to have the expected higher performance and longer range. The cycle life and cost issues for these higher-performance batteries are still being addressed. Pilot lines are being constructed, and the cost and durability of electric vehicle batteries in pilot production quantities will be asesssed. Even advanced, high-temperature Na/S and Li-M/FeS_x batteries have been and are being tested in vehicles. Also fuel cell systems, both alone and as fuel cell-battery hybrids have been evaluated in vehicles. The high-temperature batteries and fuel cell demonstrations were for technical feasibility only. The system performance, lifetime, and cost figures are still well outside of acceptable limits.

In reviewing the status of the individual candidate electrochemical power systems, it has become clear that meeting the performance, durability, and cost goals simultaneously represents a significant, but very important challenge. Each system reviewed has its own strong points and deficiencies. Several of the systems of intermediate specific energy seem to have fewer remaining problems than the very high specific energy systems, and are therefore expected to find application in vehicles soon -- within the next several years. Table 26 shows that such batteries as Fe/NiOOH and Zn/NiOOH have acceptable

Table 26. CANDIDATE POWER SOURCES FOR ELECTRIC VEHICLES

System	Cell Voltage	Theor. W·h/kg	Status W·h/kg[a]	W·h/l	W/kg[b]	Efficiency	Cycle[c] Life	Range[d] km	Remarks
$Pb/H_2SO_4/PbO_2$	2.1	175	20–40	45–90	80	70	300	35–65	Bench mark. Available now.
Fe/KOH/NiOOH	1.4	267	50	90	125	50–60	100+[e]	85	Low efficiency, gassing.
Zn/KOH/NiOOH	1.7	373	75	140	150	75	200+	125	Better cycle life needed.
$Zn/ZnCl_2/Cl_2$	2.1	461	70	~80	60		1000[f]	115	Complex, bulky, safety ?, maintenance.
$Zn/ZnBr_2/Br_2$	1.8	430	60	~60	75	65	200+	100	Complex, bulky, safety ?.
Fe/KOH/Air	1.2	720	90	~90	30	45	200	150	Low efficiency, bulky.
Zn/KOH/Air	1.6	1310	70–90	70–90	80	35	MR[g]	115–150	Not rechargeable, bulky.
Al/NaOH/Air	2.7	2790	N.A.	N.A.	N.A.	~35	MR	—	Not rechargeable, low efficiency.
$Li/LiClO_4/TiS_2$	2.2	490	(120)[h]	(170)	(100)	~75	100+	(200)	Safety ? Cycle life ?.
LiAl/LiCl-KCl/FeS	1.3	458	50–90	75–130	60–100	~70	300+	85–150	Thermal control needed.
$Li_4Si/LiCl\text{-}KCl/FeS_2$	1.8,1.3	944	120	180	100	~75	700	200	Thermal control needed.
$Na/\beta\text{-}Al_2O_3/S$	2.0	758	85–140	100–165	60–130	~75	200–1500	140–235	Thermal control needed.
$H_2/H_3PO_4/Air$	1.0	[i]	[i]	[i]	25–75	N.A.	40	400+[j]	Complex, bulky, Expensive

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[a] At 30 W/kg.

[b] Peak specific power, at least 15 s.

[c] At least 80% DOD.

[d] 25% of vehicle test weight allocated to batteries. Urban driving profile, 0.15 kW·h/km.

[e] Cycle lives of up to 1500 were demonstrated for earlier electrode designs.

[f] This cycle life for 1 kW·h system with electrolyte maintenance.

[g] MR = mechanically rechargeable. The anodes are replaced periodically. Life data not available.

[h] Figures in parentheses are projections based on lab cells of low specific energy.

[i] Depends on amount of fuel carried -- may be as high as ~6100, in principle.

[j] Typical range for fuel-carrying vehicle.

specific power and power density values. The Fe/NiOOH battery (in the prior version) has demonstrated long cycle life (∿1500 cy), and has been tested in several vehicles. Its main problems are low efficiency, hydrogen formation, and the requirement of electrolyte circulation during recharge. With cost reduction to below \$100/kW·h, it could find application in commercial vehicles with a range of about 85 km. The Zn/NiOOH battery offers an urban driving range well above 100 km, with a high energy per unit weight and volume. Improved cycle life (>300 needed) is essential, as is a cost of <\$100/kW·h. The cycle life of the zinc electrode remains the most important problem.

The batteries with flowing reactants (Cl_2, Br_2, air) in Table 26 all have low efficiencies, low power per unit volume, and are complex relative to batteries with solid reactants, making them less attractive, other things being equal. They do, however, offer attractive specific energies. One of these systems may find application in commercial vehicles.

High-temperature batteries offer the highest performance, and possibly the longest cycle life, with the inconvenience of special thermal control requirements. These systems require several years of additional development and attention to materials and sealing issues.

Fuel cells remain elusive to the electric vehicle application. Their volume and complexity must be reduced, and the fuel (H_2) storage problem must be solved. Of course, all of this must be done concomitant with a greatly reduced cost (to <\$100/kW average). Progress continues; fuel cells should not be eliminated from possible future use in electric vehicles. Perhaps 10 or 15 more years of development will be required before they can be used in specialized and commercial vehicles.

Overall, the prognosis is positive with regard to more extensive use of electric vehicles, and the development of electrochemical powerplants which yield significantly higher performance and longer range than is possible with Pb/PbO_2 batteries. As this happens, more attention will be focused upon the electrochemical problems that remain to be solved, and the opportunities for significant contributions from electrochemists and electrochemical engineers.

REFERENCES

1. Selected Dates in History of Electric Vehicles, Edison Electric Institute Bulletin, Vol. 36, p. 105, Apr. 1968.

2. J. H. Wherry, Automobiles of the World, Chilton Book Co., 1968, p. 713.

3. N. H. Tomblin, Electric Vehicle Development in the United Kingdom, Proc. of the First International Electric Vehicle Symposium, Nov. 5-7, 1969, Phoenix, AZ, p. 509.

4. A. A. Tullio, G. R. Fagan, and E. Hines, A Progress Report on Electric Vehicles, Edison Electric Institute Bulletin, Vol. 36, p. 238, Aug. 1968.

5. Proceedings of the National Electric Automobile Symposium, Sponsored by Santa Clara Valley Engineers' Council, San Jose State College, San Jose, CA, Feb. 24 & 25, 1967, p. 38.

6. H. J. Young, Electric Vehicles: Economics and Experience, SAE Publication 690115, Detroit, MI, Jan. 13-17, 1969.

7. 1973/74 Automotive Facts and Figures, Motor Vehicle Manufacturers Association of the United States, Inc., Detroit, MI (1974).

8. H. J. Schwartz, The Computer Simulation of Automobile Use Patterns for Defining Battery Requirements for Electric Cars, Fourth International Electric Vehicle Symposium, Düsseldorf, 1976.

9. T. Merkle and E. Zander, Basic Requirements for the Various Items of Equipment for Supplying Energy to Electrically Driven Road Vehicles From the Point of View of the User, Fourth International Electric Vehicle Symposium, Düsseldorf, 1976.

10. M. C. Attendu and J. H. Beaudet, Electric Delivery Vans Above the 45th Parallel in North America, Fourth International Electric Vehicle Symposium, Düsseldorf, 1976.

11. The Sources of Air Pollution and Their Control, U.S. Department of Health, Education, and Welfare, Public Health Service Publication No. 1548, U.S. Government Printing Office, Washington, D.C., Dec., 1966.

12. Technology Assessment of Changes in the Future Use and Characteristics of the Automobile Transportation System, Vol. II, p. 150, Congress of the United States, Office of Technology Assessment, Washington, D.C., Feb., 1979.

13. J. B. Heywood and M. K. Martin, Aggregate Emissions From the Automobile Population, SAE Publication - 740536, Chicago, IL, June 17-21, 1974.

14. H. E. Hesketh, Understanding and Controlling Air Pollution, Ann Arbor Science Publishers, Inc., 1972.

15. A. Venkatram and J. Kurtz, Short-Term Dispersion From Tall Stocks, Proceedings of the Ninth International Technical Meeting on Air Pollution Modeling and its Application, Number 103, North Atlantic Treaty Organization, Toronto, Canada, August 28-31, 1978.

16. H. C. Perkins, Air Pollution, McGraw Hill, Inc., 1974.

17. F. Pasquill, Atmospheric Diffusion, John Wiley & Sons, New York, 1974.

18. J. T. Salihi, The Electric Car--Fact and Fancy, IEEE Spectrum, Vol. 9, pp. 44-48, June 1972.

19. U.S.A.'s Energy Outlook 1979-1990, Exxon Company, U.S.A., Dec. 1978.

20. D. C. Sheridan, J. J. Bush, and W. R. Kuziak, Jr., A Study of the Energy Utilization of Gasoline and Battery-Electric Powered Special Purpose Vehicles, SAE Publication - 760119, Detroit, MI, Feb. 1976.

21. K. A. Hub, Private Communication to E. J. Cairns, Dec. 11, 1973, based on an Argonne National Laboratory Report, Social Cost Study for Alternate Means of Generating Power for 1980 and 1990, Mar. 1973.

22. M. S. Mashikian, Detroit Edison Co., Private Communication to E. H. Hietbrink, Jan. 17, 1974.

23. Nuclear Power 1973-2000, Office of Planning and Analysis, United States Atomic Energy Commission, U.S. Government Printing Office, Washington, D.C., WASH-1139(72), UC-80, Dec. 1972.

24. J. T. Salihi, Energy Requirements for Electric Cars and Their Impact on Power Generation and Distribution Systems, IEEE Transactions on Industry Applications, Vol. 1A9, No. 5, Sept./Oct., 1973.

25. D. P. Grimmer and K. Luszczynski, Lost Power, Environment, Vol. 14, No. 3, April, 1972, pp. 14-56.

26. Ming-Chih Yew and D. E. McCullock, Small Electric Vehicle Considerations in View of Performance and Energy Usage, Proc. of the 11th IECEC, Vol. 1, AIChE, NY, Sept. 12-17, 1976.

27. R. F. Stebar and F. B. Parks, Emission Control With Lean Operation Using Hydrogen-Supplemented Fuel, SAE Publication - 740187, Detroit, MI, Feb. 1974.

28. A. W. Liles and G. P. Fetterman, Jr., Selection of Driving Cycles for Electric Vehicles of the 1990's, Proc. of the 11th IECEC, Vol. 1, AIChE, NY, Sept. 12-17, 1976.

29. M. Klein, An Analysis of Electric Vehicle Mission, Design, Energy Impact and Cost, Proc. of the 11th IECEC, Vol. 1, AIChE, NY, Sept. 12-17, 1976.

30. E. J. Cairns and J. McBreen, Industrial Research, June, 1975, p. 56.

31. R. S. McKee, B. Borisoff, F. Lawn and J. F. Norberg, Sundancer: A Test Bed Electric Vehicle, SAE Publication - 720188, Detroit, MI, Jan., 1972.

32. S. F. Powel III, N. Rosenburg, The Advisability of Regulating Electric Vehicles for Energy Conservation, Transportation Systems Center, National Technology Information Service, Springfield, VA, Report No. DOT-TSC-OST-76-37, p. 4-46.

33. E. Hines, M. S. Mashikian and L. J. Van Tuyl, Effect of Electric Vehicles on the Power Industry, SAE Publication - 690441, Chicago, IL, May 1969.

34. Recommended Performance Standards for Electric Vehicles, Arthur D. Little, Inc., SAN/1335-1, Prepared for the Energy Research and Development Administration, Final Report on Work Performed Under Contract No. EY-76-C-03-1335, C-79954, Oct., 1977.

35. State-of-the-Art Assessment of Electric and Hybrid Vehicles, HCP/M1011-01, UC-96, Feb., 1978, Prepared by National Aeronautics and Space Administration, Lewis Research Center, National Technical Information Service, U.S. Dept. of Congress, Springfield, VA, sponsored by U.S. Dept. of Energy under Interagency Agreement EC-77-A-31-1011.

36. D. K. Miner, M. A. Pocobello and D. A. Armstrong, The Copper Electric Runabout, Fifth International Electric Vehicle Symposium, Publication 784103(E), Philadelphia, PA, Oct. 1978.

37. J. R. Pierson, Road and Range Testing of High Voltage Lead-Acid Powered Electric Vehicles, Fifth International Electric Vehicle Symposium Publication - 783303(E), Philadelphia, PA, Oct. 1978.

38. J. L. Hartman, E. J. Cairns and E. H. Hietbrink, Electric Vehicles Challenge Battery Technology, Proceedings of the Fifth Energy Technology Conference, Washington, D.C., Feb. 27, 1978.

39. Fiat Electric Vehicles, Electric Vehicle Brochure, Fiat Public Relations Dept., International Electric Vehicle Exposition and Conference, McCormick Place, Chicago, IL, April, 1977.

40. J. T. Brown, Westinghouse E-180 Nickel-Iron Oxide Vehicle Battery, Brochure and Data Sheets, Westinghouse Research and Development Center, Pittsburgh, PA, Jan. 1978.

41. S. Matsumoto, The Status of Electric Vehicles in Japan, The International Electric Vehicle Exposition and Conference, McCormick Place, Chicago, IL, Apr. 26-29, 1977, Paper No. 7748.

42. C. Badar and W. Stephan, Electric Vehicles in Germany--Present and Future, SAE Publication - 780087, Detroit, MI, Feb. 27-Mar. 3, 1978.

43. F. T. Thompson, Advanced Electronic Control System for Electric Vehicles, Proceedings of International Conference on Automotive Electronics and Electric Vehicles, Sept. 20-22, 1976, Dearborn, MI, SAE Catalog Number: P-68, IEEE Catalog Number: 76CH1146-OUT.

44. D. K. Miner, Range Improvement from Regenerative Braking on the Copper Electric Town Car, The International Electric Vehicle Exposition and Conference, McCormick Place, Chicago, IL, April 26-29, 1977, Paper No. 7756.

45. A. M. Bueche, Advanced Motor Developments, Proceedings of International Conference on Automotive Electronics and Electric Vehicles, Sept. 20-22, 1976, Dearborn, MI, SAE Catalog Number: P-68, IEEE Catalog Number: 76CH1146-OVT.

46. D. Pohl and H. Ch. Skudelny, Induction Motor Drives for Electric Vehicles - An Alternative to Usual D. C. Drives?, The Fifth International Electric Vehicle Symposium, Publication - 782104 (E), Philadelphia, PA, Oct. 2-5, 1978.

47. P. Campbell, The Permanent Magnet Disc Armature Motor - An Evaluation of its Advantages Compared with Conventional Electric Vehicle Drives, The Fifth International Electric Vehicle Symposium, Publication - 782102(E), Philadelphia, PA, Oct. 2-5, 1978.

48. The Second Annual Report to Congress for Fiscal Year 1978, Electric and Hybrid Vehicle Program, U.S. Dept. of Energy, DOE/CS-0068, Jan. 1979, National Technical Information Service, U.S. Dept. of Commerce, Springfield, VA 22161.

49. Electric Vehicle Test Procedure--SAE J227a, Society of Automotive Engineers, Inc., 1976.

50. J. Brennand, R. Curtis, H. Fox and W. Hamilton, Electric and Hybrid Vehicle Performance and Design Goal Determination Study, ERDA Contract No. EY-76-C-03-1215, General Research Corp., GRC Publication No. CR-1-734, SAN/1215-1, Santa Barbara, CA, Aug. 1977.

51. D. P. Crane and J. R. Bowman, United States Postal Service Electric Vehicle Program, Fourth International Electric Vehicle Symposium, Düsseldorf, 1976.

52. G. G. Harding, High Performance Electric Commercial Vehicles for City Use, SAE Publication - 760073, Detroit, MI, Feb. 1976.

53. P. O. Larsen, Commercial Electric Vehicle Program at General Motors, Presentation to Battery Council International, New Orleans, LA, Mar. 1979.

54. M. Klein, A. Charkey, H. Vaidyanathan and S. Viswanathan, Performance Characteristics of Nickel-Zinc Electric Vehicle Battery, 14th Intersociety Energy Conversion Engineering Conference, Boston, MA, Aug. 1979.

55. C. Marks, E. A. Rishavy and F. A. Wyczalek, Electrorian--A Fuel Cell Powered Vehicle, SAE Publication - 670176, Detroit, MI, Jan. 1967.

56. H. Hagen and R. Zelinka, The M. A. N. Electrobus Experience Gained in Large-Scale Tests, Fourth International Electric Vehicle Symposium, Düsseldorf, 1976.

57. D. M. Tenniswood and H. A. Graetzel, Minimum Road Load for Electric Cars, SAE Publication - 670177, Detroit, MI, Jan. 1967.

58. M. L. Kyle, H. Shimotake, R. K. Steunenberg, F. J. Martino, R. Rubischko and E. J. Cairns, Lithium/Sulfur Batteries for Electric Vehicle Propulsion, 1971 Intersociety Energy Conversion Engineering Conference, Boston, MA, Aug. 3-5, 1971.

59. L. E. Unnewehr, Electric Vehicle Systems Study, Third International Electric Vehicle Symposium, Washington, D.C., Feb. 1974.

60. E. J. Cairns and R. R. Witherspoon, Batteries, Primary--Fuel Cells, Kirk/Othmer Encyclopedia of Chemical Technology, Sept. 26, 1977.

61. K. V. Kordesch, J. Electrochem. Soc., 118, 815 (1971).

62. N. E. Bagshaw, K. P. Bromelow and J. Eaton, The Effect of Grid Conductivity on the Performance of Tall Lead-Acid Cells, Power Sources 6, D. H. Collins, editor, Academic Press, NY, 1977.

63. W. Tiedemann, J. Newman and F. DeSua, Potential Distribution in the Lead-Acid Battery Grid, Power Sources 6, D. H. Collins, editor, Academic Press, NY, 1977.

64. A. C. Simon and S. M. Caulder, Proc. of the Symposium and Workshop on Advanced Battery Research and Design, Argonne National Lab., Argonne, IL, March 1976, ANL 76-8.

65. N. J. Maskalick, J. T. Brown and G. A. Monito, Proc. of the 10th IECEC, IEEE, NY, 1975.

66. D. L. Douglas, Proc. of the Symposium on Power Systems for Electric Vehicles, Columbia Univ., NY, April, 1967.

67. T. A. Edison, German Patent No. 157290, (1901) and U.S. Patent No. 678722 (1901).

68. S. U. Falk and A. J. Salkind, Alkaline Storage Batteries, Sponsored by the Electrochemical Society, Inc., New York, NY, John Wiley & Sons, Inc. Publishers, New York, NY, 1969.

69. Power Sources 5, Research and Development in Non-Mechanical Electrical Power Sources, Proceedings of the 9th International Symposium held at Brighton, Sept. 1974, Sponsored by the Joint Services Electrical Power Sources Committee, D. H. Collins, editor, 1975.

70. J. D. Birge, J. T. Brown, W. Feduska, C. C. Hardman, W. Pollack, R. Rosey, and J. Seidel, Performance Characteristics of a New Iron-Nickel Cell and Battery for Electric Vehicles, Power Sources 6, D. H. Collins, editor, Academic Press, NY, 1977.

71. R. E. Vaill and R. Rosey, Applications and Developments of W Iron-Nickel Battery Systems, Presented at MIDCON/77 Electrical and Electronics Exhibition, Nov. 1977.

72. R. Rosey, Westinghouse Iron-Nickel Battery Development, Presented at the Joint ACS/CSJ Chemical Congress, Honolulu, Apr. 1979.

73. S. U. Falk and A. J. Salkind, Alkaline Storage Batteries, John Wiley & Sons, NY, 1969.

74. E. Buzzelli, The Electrochemical Society Meeting, Dallas, Texas, Oct. 1975.

75. E. Buzzelli, private communication, 1976.

76. E. J. Cairns, Zinc/Nickel Oxide Cells: Status and Projections, Extended Abstracts of the Electrochemical Society Meeting, Atlanta, GA, 77-2, Oct. 1977.

77. J. McBreen and E. J. Cairns, The Zinc Electrode, Advances in Electrochemistry and Electrochemical Engineering, Vol. 11, H. Gerischer and C. W. Tobias, editors, 1978.

78. E. J. Cairns, Zinc/Nickel Oxide Cells, Presentated at International Society Electrochemical Meeting, Budapest, Aug. 1978, Extended Abstracts, p. 1190.

79. O. Von Krusenstierna, High Energy, Long Life-Zinc Battery for Electric Vehicles, in Power Sources 6, D. H. Collins, editor, Academic Press, New York, 1977, p. 303.

80. A. Charkey, in Proc. of the 10th IECEC, IEEE, NY, 1975, p. 1126.

81. F. P. Kober and A. Charkey, Power Sources 3, D. H. Collins, editor, Oriel Press, Newcastle, England, 1971.

82. R. G. Gunther, Presented at the Electrochemical Society Meeting, Washington, D.C., May 1976, Abstract No. 2.

83. C. J. Warde, P. C. Symons, C. C. Whittlesey and H. A. Catherino, 100 MWh Zinc-Chlorine Peak-Sharing Battery Plants, in Proc. 13th IECEC, SAE, Warrendale, PA, 1978, p. 755.

84. C. H. Chi, P. Carr and P. C. Symons, Modeling of Zinc-Chloride Batteries for Electric Vehicles, in Proc. 14th IECEC, ACS, Washington, D.C., 1979, p. 692.

85. P. C. Symons and M. J. Hammond, Evaluation of a 1 kWh Zinc-Chloride Battery System, Energy Development Associates Report to EPRI, EM-249, Sept. 1976.

86. F. G. Will, The Zinc-Bromine Battery: Possible Candidate for Electric Vehicles and Load Leveling, in Proc. of the 12th IECEC, ANS, Hinsdale, IL, 1977, p. 250.

87. P. C. Symons, Preprint No. 730253, Society of Automotive Engineers, NY, 1973.

88. P. C. Symons and H. K. Bjorkman, Jr., Presented at AIChE Meeting, Detroit, MI, June, 1973.

89. P. C. Symons, Presented at the Society for Electrochemistry Meeting, Brighton, England, Dec. 1973.

90. P. C. Symons, in Proceedings of the 3rd International Electric Vehicle Symposium, Washington, D.C., Feb. 1974.

91. R. A. Pott, A Zinc-Bromine Battery for Energy Storage, in the Proc. of the 14th IECEC, ACS, Washington, D.C., 1979, p. 683.

92. G. Clerici, M. de Rossi and M. Marchetto, Zn/Br Battery, Power Sources 5, D. H. Collins, editor, Academic Press, New York, 1975, p. 167.

93. O. Lindstrom, Power Sources 5, D. H. Collins, editor, Academic Press, NY, 1975.

94. H. Cnoblock, D. Groppel, D. Kükl, W. Nippe and G. Siemsen, Power Sources 5, D. H. Collins, editor, Academic Press, NY, 1975.

95. E. S. Buzzelli, C. T. Liu, W. A. Bryant, Iron-Air Batteries for Electric Vehicles, Proc. of the 13th IECEC, SAE, Warrendale, PA, 1978, p. 745.

96. A. J. Appleby, J. P. Pompon and M. Jacquier, Proc. of the 10th IECEC, IEEE, NY, 1975, p. 811.

97. A. J. Appleby, J. Jacquelin and J. P. Pompon, SAE Publication No. 770381, Feb. 1977.

98. N. P. Yao, in Proceedings of the Symposium and Workshop on Advanced Battery Research and Design, Report No. ANL-76-8, Argonne National Lab., Argonne, IL, Mar. 1976.

99. A. J. Appleby and J. P. Gabano, Current Status and Prospects of the Zn-Air and Na-S Batteries in France, Proceedings of the Symposium and Workshop on Advanced Battery Research and Design, Report No. ANL-76-8, Argonne National Lab., Argonne, IL, Mar. 1976.

100. H. Baba, SAE Transactions, Paper No. 710237, 1971.

101. A. R. Despic, D. M. Dracic, S. K. Zecevic and T. D. Grozdic, Problems in the Use of High-Energy-Density Aluminum-Air Batteries for Traction, Power Sources 6, D. H. Collins, editor, Academic Press, NY, 1977.

102. J. F. Cooper and E. L. Littauer, Mechanically Rechargeable Metal-Air Batteries for Automotive Propulsion, Proc. of the 13th IECEC, SAE, Warrendale, PA, 1978, p. 738.

103. L. H. Gaines, R. W. Francis, G. H. Newman and B. M. L. Rao, Ambient Temperature Electric Vehicle Batteries Based on Lithium and Titanium Disulfide, Proc. of the 11th IECEC, AIChE, NY, 1976.

104. E. J. Cairns and H. Shimotake, High-Temperature Batteries, Science, 164, 1347 (1969).

105. F. J. Martino, T. W. Olszanski, L. G. Bartholme, E. C. Gay and H. Shimotake, Advances in the Development of Li-Al/FeS Cells for Electric Automobile Batteries, Proc. of the 14th IECEC, ACS, Washington, D.C., 1978, p. 660.

106. E. J. Zeitner and J. S. Dunning, High Performance Lithium/Iron Disulfide Cells, Proc. of the 13th IECEC, SAE, Warrendale, PA, 1978, p. 697.

107. Argonne National Lab., Proceedings of the Annual Department of Energy Review of the Lithium Metal Sulfide Battery Program, June 20-21, 1979.

108. T. G. Bradley, Bipolar Lithium/Iron Disulfide Cells, Proc. of the 13th IECEC, SAE, Warrendale, PA, 1978, p. 717.

109. E. J. Cairns and J. S. Dunning, High-Temperature Batteries, Proceedings of the Symposium and Workshop on Advanced Battery Research and Design, Argonne National Lab., Report ANL-76-8, Mar. 1976, p. A-81.

110. General Electric, Review of the Advanced Battery Development Program for Electric Utility Application, May 1979.

111. D. W. Bridges, R. W. Minck and D. G. Paquette, Reproducibility and Performance of Large Prototype Na/S Cells, Proc. of the 14th IECEC, ACS, Washington, D.C., 1979, p. 703.

112. I. W. Jones, Recent Advances in the Development of Sodium-Sulfur Batteries for Load Leveling and Motive Power Applications, Electrochem. Acta, 11, 681 (1977).

113. R. M. Dell, J. L. Sudworth and I. W. Jones, Sodium/Sulfur Battery Development in the United Kingdom, Proc. of the 11th IECEC, AIChE, NY, 1976, p. 503.

114. J. M. Bird, A. R. Tilley and J. L. Sudworth, Sodium/Sulfur Cell Designed for Quantity Production, Proc. of the 13th IECEC, SAE, Warrendale, PA, 1978, p. 685.

115. M. Mikkor, R. W. Minck and L. E. Unnewehr, Pulse Characteristics of Sodium/Sulfur Cells for Electric Vehicle Propulsion, Proc. of the 13th IECEC, SAE, Warrendale, PA, 1978, p. 662.

116. W. Fischer, H. B. Gels, F. Gross, K. Liemort and H. Meinhold, Sodium/Sulfur Batteries for Peak Power Generation, Proc. of the 14th IECEC, ACS, Washington, D.C., 1979, p. 710.

117. H. Y.-P. Hong, New Lithium Solid Electrolyte, Electrochem. Soc. Extended Abstracts, 77-1, 1977.

118. Los Almos Scientific Lab., Proceedings of the Fuel Cell in Transportation Applications Workshop, Report No. LA-7270-C, July, 1978.

119. W. H. Johnson, Phosphoric Acid Fuel Cell Technology Improvement Program, Abstracts of the National Fuel Cell Seminar, Courtesy Associates, Washington, D.C., June 1979.

120. A. Kaufman, Phosphoric Acid Fuel Cell Stock Development, Abstracts of the National Fuel Cell Seminar, Courtesy Associates, Washington, D.C., June 1979.

121. H. C. Marv, L. G. Christner, S. G. Abens and B. S. Baker, Phosphoric Acid Fuel Cell Stock and Technology Programs, Abstracts of the National Fuel Cell Seminar, Courtesy Associates, Washington, D.C., June 1979.

122. P. R. Prokopius, M. Warshay, S. M. Simons and R. B. King, Commercial Phosphoric Acid Fuel Cell System Technology Development, Proc. of the 14th IECEC, ACS, Washington, D.C., 1979, p. 538.

123. L. B. Welsh, R. W. Leyerle and D. S. Scarlata, Stability of Kocite Electrocatalysts in Phosphoric Acid Cathodes, Abstracts of the National Fuel Cell Seminar, Courtesy Associates, Washington, D.C., June 1979.

124. H. Shimotake, Lead-Acid Batteries, ANL Office for Electrochemical Project Management (OEPM), Presented at the DOE/TEC Electric/Hybrid Vehicle Program Contractors' Coordination Meeting, Reston, VA, Dec. 1977.

125. R. C. Elliott, Nickel/Iron Batteries, ANL Office for Electrochemical Project Management (OEPM), Presented at the DOE/TEC Electric/Hybrid Vehicle Program Contractors' Coordination Meeting, Reston, VA, Dec. 1977.

126. W. J. Walsh, Nickel/Zinc Batteries, ANL Office for Electrochemical Project Management (OEPM), Presented at the DOE/TEC Electric/Hybrid Vehicle Program Contractors' Coordination Meeting, Reston, VA, Dec. 1977.

127. Electric Vehicle Systems, FY1978, Environmental Development Plan, EDP/C-01(77), Energy Research & Development Administration, Aug. 1977.

128. L. H. Gaines, Private Communication, Exxon Research and Engineering, Jan. 1978.

129. E. J. Cairns and J. S. Dunning, High-Temperature Batteries, General Motors Research Laboratories, Warren, Mich., GMR Publication 2065, Jan. 1976.

130. J. F. Norberg, Private Communication, Automotive Division of ESB, Inc. May 1974.

131. Zinc/Nickel Oxide Brochure and Data Sheets, Energy Research Corporation, Third International Electric Vehicle Symposium and Exposition, Washington, D.C., Feb. 1974.

132. Nickel-Zinc Secondary Batteries, Eagle-Picher Industries, Inc., Joplin, Mo., Jan. 1975.

133. J. R. Kettler, Batteries for the Hybrid Heat Engine/Electric Vehicle, Proceedings of the Symposium on Batteries for Traction and Propulsion, Columbus Section of the Electrochemical Society, Mar. 1972, p. 213.