

Advanced batteries for electric vehicles—a look at the future

Improvements in lead-acid systems and successful developments in other chemical systems, including Ni/Fe, Ni/Zn, Li/FeS, Zn/Cl₂, and Na/S, may help reduce our dependence on liquid fuels.

William J. Walsh



One of the most serious energy problems faced by our nation during the remainder of this century will be shortages of liquid fuels for transportation. It may be possible to reduce the magnitude of this problem by developing smaller, more efficient vehicles, by reducing non-essential travel, by producing synthetic fuels from coal or biomass, or by exploiting oil shales or tar sands. Each of these is only a partial solution, however, and serious liquid-fuel shortages are possible even with dramatic successes in each of them.

Another partial solution to this problem would be the widespread use of electric vehicles. Because electric-power generating plants can use a wide variety of energy sources, many of them abundant for the foreseeable future, replacing conventional vehicles with electric ones reduces the demand for high-grade liquid fuels. Intensive efforts by government and industry to develop acceptable electric vehicles will probably produce great improvements in performance and range within ten years. These advanced electric vehicles will incorporate light-weight components, efficient motor-control systems, more efficient transmissions, and reductions in aerodynamic drag and rolling resistance. The major obstacle to the successful development and commercialization of the electric vehicles is the lack of a battery of suitable performance, ruggedness, and cost.

Battery candidates

The very real possibility of an immense transportation market has created a technological race to develop a suitable battery for electric vehicles. Dozens of laboratories in Western Europe, Japan and the US have entered this competition, whose result appears to be a world-wide renaissance in battery technology. The timeliness of these advances is underscored by recent announcements by General Motors and Ford that they intend to market electric vehicles during the 1980's.

More than thirty electrochemical systems are potential candidates for electric-vehicle batteries. Several of them can be ruled out from the start because they require large quantities of rare or expensive materials. The remaining 15 to 20 batteries each possess a group of loyal advocates who insist that their system is clearly the best, and that successful development and commercialization is nearly certain. In reality, each of these battery development efforts is a high-risk enterprise with major barriers to commercialization associated with their electrical

performance, cycle life (number of charge-discharge cycles they can survive) or cost. In fact, only a few of the battery candidates have promise for being technologically successful and for penetrating large transportation markets by the year 2000.¹

For the near term the most promising electric-vehicle battery systems are

- lead-acid
- nickel-zinc
- nickel-iron

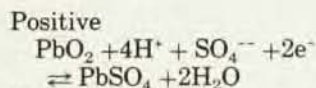
These systems are already in use or are close to commercialization. Battery systems that show some promise but require considerably more work include

- lithium-metal sulfide
- zinc-chlorine
- sodium-sulfur (ceramic electrolyte)

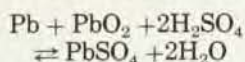
Because they may have some advantages over the near-term systems, such batteries may prove to be useful intermediate-term candidates. We will not consider long-term possibilities here.

Lead-acid batteries

The lead-acid battery is the most widely used electrochemical system. Lead-acid cells consist of positive and negative electrodes that are immersed in an electrolyte solution of sulfuric acid. When the cell is fully charged, the active material of the positive electrode is lead dioxide (PbO_2), and the active material of the negative is lead (Pb). As the cell is discharged, the lead dioxide of the positive electrodes and the lead of the negative electrodes are converted to lead sulfate by the following reactions:



The overall cell reaction is to convert lead dioxide and sulfuric acid to lead sulfate and water:



During the process, the electrodes remain solid because lead, lead dioxide, and lead sulfate are all relatively insoluble in sulfuric acid. The reactions are reversible, and the cell may be recharged to its initial state.

There are two types of electrode structures in lead-acid batteries used for motive-power applications: flat plate (pasted) and tubular. The flat-plate electrode has a center skeleton (grid) made of a lead alloy that has been coated with a paste-like mixture of the active materials. In the tubular electrode, powdered active material is in a tubular envelope, usually of woven glass or polyester fibers. Tubular-electrode batteries have somewhat higher volumetric energy density but are more costly and somewhat more difficult to

fabricate. The majority of current US lead-acid batteries for vehicles are of the flat-plate type.

Work on lead-acid batteries is being carried out on two fronts: to improve the current state of the art, and to develop "advanced" systems with about 50% better performance. These efforts represent very different technologies.

Improvements in state-of-art batteries should lead, within a year and a half or so, to batteries that can store 40–50 Wh/kg and have lifetimes of 500–800 cycles. Even with these improvements the lead-acid batteries are not well suited for use in electric cars. Because they have low specific energy (less than 50 Wh/kg), cars incorporating a reasonable weight of lead-acid batteries have a short range until they need recharging and have poor driving performance.

Clever designs can let one stuff more batteries into the vehicle; however, as the battery pack in the car becomes heavier, energy conservation suffers because more and more energy is required to propel the battery pack itself. The large battery packs also tend to become excessively expensive.

The peak power of the improved batteries is still quite marginal, especially late in the discharge and at low temperatures. This limits acceleration and other performance characteristics, particularly in the case of intermediate and compact automobiles. In addition, these batteries are quite bulky (storing less than 100 Wh/liter) and thus are difficult to pack into an electric vehicle.

On the positive side, improved lead-acid batteries can be produced using existing production facilities, and will be the only car battery available at less than \$100/kWh by 1982. Eventual costs of about \$45/kWh are projected, assuming the present cost of lead remains stable. Environmental and safety problems associated with lead mining and battery manufacture are becoming of increasing concern; resolution of these problems could raise the cost of batteries made with lead.

At present, the lead-acid battery is the only battery system available for any kind of electric vehicle. In general it appears to be most attractive for applications in which a limited range (less than 100 miles) is acceptable. One can therefore expect that the principal markets for lead-acid vehicles will be local commercial fleets, especially vans, trucks and buses.

The development of "advanced" lead-acid batteries will require one or more major technological break-

The "Electrovette," an all-electric passenger car with a zinc-nickel-oxide battery pack. (Photo courtesy of General Motors.)

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throughs. The goal is to produce batteries that carry 60 Wh/kg and can survive 1000 deep cycles (that is, nearly complete discharges and recharges). Attaining these goals will be difficult, and research in this field is quite exploratory and challenging, similar to work on high-temperature batteries. Much of this advanced work is being done in Europe and Japan. Several promising approaches are under investigation, including bipolar systems, layered negative plates, circulating electrolytes and improvements in lead utilization. A dramatic technical improvement in one of these areas, such as the development of a practical bipolar cell, will be needed for lead-acid batteries to approach the performance levels required for widespread use in electric vehicles.

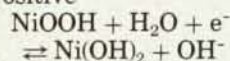
The development of a low-cost lead-acid battery capable of 60 Wh/kg and 1000 cycles would have a major impact on the emerging electric-vehicle market. Unfortunately, the probability that this will occur by 1990 appears to be less than 10%.

Nickel-zinc batteries

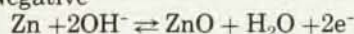
Prospects for commercialization of nickel-zinc batteries have improved greatly during the past few years, and the battery has emerged as a leading candidate for near-term transportation applications. However, the batteries must survive a considerably greater number of charge-discharge cycles before they can significantly penetrate a major market. This appears to be the only remaining barrier to successful development.

In a nickel-zinc battery the electrode reactions are:

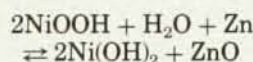
Positive



Negative



The complete cell reaction is:



One of the inherent problems with this system is that ZnO is partly soluble in the electrolyte (30–45% KOH solution) leading to shape changes, dendrite formation, and densification of the electrode during cycling, so that the battery life is shortened. A wide variety of potential solutions to this lifetime problem are under investigation, including

- ▶ electroporous and other advanced separators
- ▶ additives to the electrolytes and zinc electrodes
- ▶ techniques to homogenize ion currents and reaction rates within the cells
- ▶ the use of advanced designs.

Successful resolution of the lifetime problem is far from certain, although



A four-passenger electric car being loaded with advanced lead-acid batteries. It is designed for urban driving, and has a range of about 45 miles. (Photo courtesy of General Electric.)

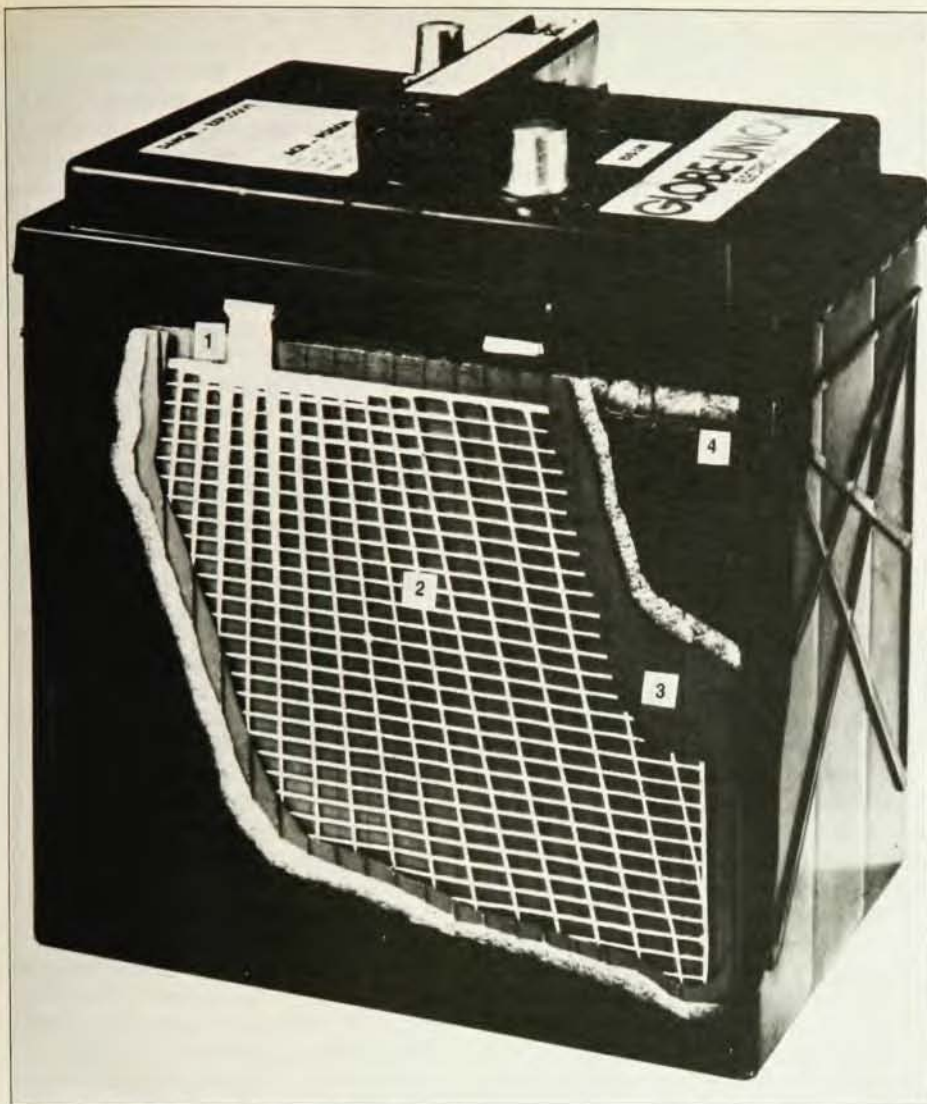
the 200–300 deep cycles possible with current batteries may be extended to 300–500 cycles within a few years. Moreover, most vehicle batteries would require a mix of deep and shallow discharges, which should extend their practical lives. For example, private cars in the US are typically driven hundreds of short trips and only a few dozen long trips per year. In this case, a ten-year, 100 000-mile electric car may require thousands of shallow cycles, but only a few hundred deep cycles. The lifetime of nickel-zinc batteries for this type of service is very poorly known, but it will definitely be superior to that achievable with repeated deep cycling.

The specific energy attainable in Ni/Zn batteries with today's technology is about 65 Wh/kg, with an additional 25% improvement expected by the year 2000. Their peak power and sustained power are excellent, with about 175 W/kg attainable throughout the discharge. Volumetric energy density is also excellent (about 120 Wh/liter) and steadily improving with

time. The nickel-zinc battery is well suited for the transportation application and easily adaptable into a wide variety of vehicle designs. General Motors has announced its intention to develop a Ni/Zn electric car for sale to the public in the mid 1980's. However, General Motors has assumed an early resolution of the battery lifetime problem, which is far from certain.

The cost of nickel-zinc batteries will be in excess of \$100/kWh until the market for them is sufficiently large to make automated mass production worthwhile. Eventually, the mass-produced batteries should cost about \$50–60/kWh, assuming nickel would contribute about \$7/kWh to this cost.

Production and reserves of nickel in the US are insignificant when compared with the world production of nickel, which is dominated by Canada. It is clear that efficient battery recycling (better than 90% nickel recovery) will be mandatory if the future US vehicle fleet is to include a large fraction of nickel-zinc vehicles. However, unlike gasoline, which is totally con-



Advanced lead-acid battery, as used in the car shown on the opposite page. The electrodes (1) have radial grids (2). The separators (3) and active materials (4) are specially designed.

sumed in automobiles, nickel imports will represent a resource that can be reused many times. The nickel required for one million passenger automobiles (with 25 kWh batteries) corresponds to about 10% of the 1975 world production of nickel.

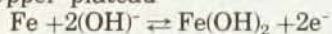
Nickel-iron batteries

The nickel-iron battery was developed by Thomas Edison in 1901 and was the most prominent secondary (that is, rechargeable) battery in industrial use until the 1920's. Although nickel-iron battery is still widely used in Russia, the lead-acid battery has displaced it almost entirely from the market in this country. Recent advances in Russia, the US, Japan, Sweden and Bulgaria, especially improvements in sintered-iron technology, have revived interest in this battery system.

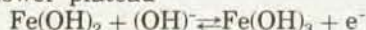
The active materials in a Ni/Fe battery consist of finely divided hydrated nickel peroxide for the positive plate and finely divided iron for the negative plate. Nickel-electrode technology, which has generally been developed for

other systems such as Ni/H₂, Ni/Cd, and Ni/Zn, is directly applicable to the Ni/Fe system. The iron electrode operates on two voltage plateaus because the negative electrode reaction takes place in two steps: $\text{Fe} \rightarrow \text{Fe}^{2+}$ followed by $\text{Fe}^{2+} \rightarrow \text{Fe}^{3+}$. The reactions at the negative electrode are:

Upper plateau



Lower plateau



In recent years, there has been less emphasis on the use of the lower plateau reaction; most Ni/Fe developers have designed their battery to utilize the upper plateau reaction only. The reaction at the positive electrode is the same as in the Ni/Zn system.

An inherent problem with the Ni/Fe battery is that during charging hydrogen gas is evolved, because the voltages for H₂ evolution and for iron reduction from $\text{Fe}(\text{OH})_2$ are similar. This gas generation is, of course, not desirable. A number of additives and design techniques have been proposed to reduce

the gassing. In general, trace quantities of a sulfur-bearing anion appear to decrease the gas evolution to a more manageable rate; however, this as well as other "advances" are untested in large-scale batteries. The principal ill effects of the gassing reaction are reduced energy efficiency, the need for gas and electrolyte maintenance systems, and safety problems related to hydrogen management.

At present, the nickel-iron battery system appears to be greatly underrated in the US. It is, in fact, in a relatively mature state of development and is the only system among the major contenders that has demonstrated ruggedness and long life. Currently Ni/Fe batteries can store 50 to 55 Wh/kg, and there appears to be no major technical barrier to increasing the specific energy to 60 Wh/kg.

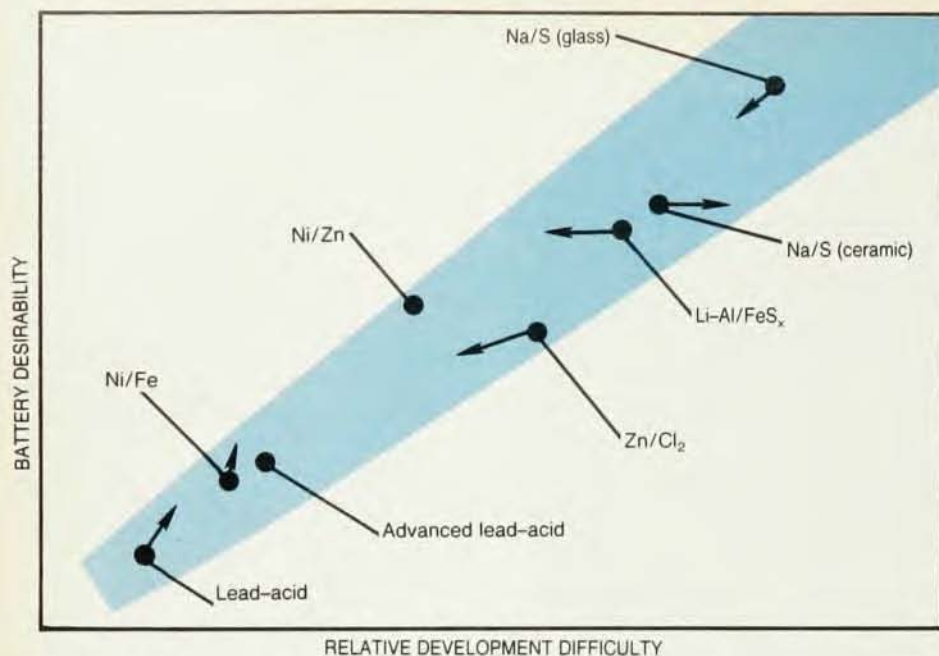
The major problem associated with nickel-iron batteries is their high initial cost. Their lifetime costs, however, may well be competitive, because of their excellent cycle life. They are also quite bulky, making them less attractive for use in private cars; for commercial fleets (buses, light trucks, and so on) their bulk should not be a problem.

Two other problems may further restrict the use of nickel-iron batteries. First, their performance is sharply reduced as the temperature drops below 10° C and they become nearly inoperable below 0° C. As a result, these batteries may not be suitable for use in cold climates unless one can provide them with a low-cost, reliable heater. Second, their cell voltage is relatively low, so that they may ultimately require about 20–40% more nickel per kilowatt-hour of capacity than nickel-zinc batteries. As a result, nickel-iron batteries are particularly sensitive to nickel prices, and the nickel availability problem is somewhat more serious than in the case of Ni/Zn batteries.

Altogether, the nickel-iron battery is one of the leading contenders for use in electric buses and trucks; it is not well suited for cars.

Lithium-iron-sulfide batteries

Research on lithium-iron-sulfide batteries grew out of earlier work on lithium-sulfur cells. That earlier work has largely been abandoned because of problems associated with irreversible sulfur-transfer mechanisms and with the containment of liquid lithium. In 1973 it was found that one could avoid both problems by using iron sulfides and alloys of lithium and aluminum instead of the molten elements. Both FeS_2 and FeS have been studied as positive-electrode materials; either sulfide may be satisfactory. The electrolyte is a molten salt consisting of a LiCl/KCl eutectic mixture, with a melting point of 352° C. The electrode



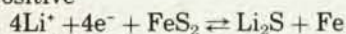
Relationship between the technical barriers to developing new battery systems and their desirability. Difficulty and desirability were measured with a Bayesian interrogation method.

and cell reactions for the Li-Al/FeS₂ systems are:

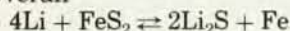
Negative



Positive



Overall



Because the battery will not work near the freezing point of the electrolyte, one must keep it above 400° C for operation. Although Li-Al/FeS_x batteries appear to be capable of surviving many temperature cycles through the melting point, most applications will require battery temperatures to be continuously maintained above 400° C by a well-engineered insulating jacket. The energy losses associated with this high-temperature operation may be very small in batteries that are used several times per week, because the normal energy dissipation (which occurs in all batteries) may equal or exceed the energy lost through the insulation.

This battery technology has made impressive progress during the past few years, but many difficult problems must be overcome before the Li-Al/FeS_x battery is a practical reality. Although lifetimes of over two years have been achieved in low-performance cells (50 to 75 Wh/kg), and although high-performance cells can initially store more than 100 Wh/kg, such a high specific energy has never been achieved after 200 cycles of operation. An intensive effort is underway to determine the causes of this problem.

The boron-nitride fabric that is currently used to separate the electrode reactions appears to have excellent compatibility with the cell environ-

ment. It is, however, expensive. For a reasonably priced battery, the separator cost must be reduced by an order of magnitude. One possible solution may be the use of thin boron-nitride felts to reduce the amount of boron nitride required and to produce better filtering action for electrode particles; however, the forces that tend to expand the electrodes are large, and these thin separators may not be durable enough.

Gould Laboratories, Eagle-Picher Industries and other manufacturers have been engaged in a large commercial development program for over three years. They have made rapid progress since the conception of Li-Al/FeS_x batteries in 1973 and have produced hundreds of 100- to 400-Wh cells.

However, practical units will not be possible until the separator and lifetime problems are resolved. Prospects for overcoming the technical barriers appear to be fairly good, but successful development of the system is not expected until the mid-1980's.

Lithium demand and production are quite low at present; world production of lithium will have to be increased by a

factor of 10 to allow a meaningful number of Li-Al/FeS_x vehicles. For example, the 1975 world production of lithium corresponds to only 300 000 Li-Al/FeS_x vehicles with 25-kW batteries. On the positive side, lithium producers are optimistic about being able to expand lithium production rapidly to meet this possible need. The US Geological Survey has pointed out that although sufficient lithium resources no doubt exist for use in electric vehicles, proven reserves are grossly inadequate, and extensive geological exploration efforts will be required to meet future needs.

The Li-Al/FeS_x battery is very well suited for use in electric vehicles. This battery will probably be the most compact battery by 1990, with volumetric energy densities expected to exceed 200 Wh/liter. The specific energy is expected to be about 20 to 40% higher than that of Ni/Zn systems, and peak power should be satisfactory.

Safety appears to be a strong point of these batteries. The Budd Company has performed safety tests in which engineering-scale cells were crushed. The results were encouraging in that no reaction or combustion of cell materials was observed, and the cells were able to absorb the energy of a barrier crash at 30 miles per hour.

There have as yet been only inadequate tests of multi-cell Li-Al/FeS_x batteries. The first full-scale Li-Al/FeS_x battery was built in 1979 and scheduled for a road test. However, this battery developed a short circuit, overheated and failed. One to two years of engineering work may be required before such a test is attempted again.

The future cost of these batteries is very difficult to project. Mass-production costs of about \$60/kWh may be possible, provided that a low-cost separator is developed and that the price of lithium does not escalate. Although successful development of this battery system is far from certain, the Li-Al/FeS_x battery has emerged as the most promising "advanced-stage" (or intermediate-term) battery for electric vehicles.

Zinc-chlorine batteries

Until recently, the zinc-chlorine couple, long recognized as offering high energy and low cost, was not exploited because chlorine is hard to manage. Storing chlorine as chlorine hydrate, however, makes the system into a viable secondary battery that is approaching the engineering stage of development. The only significant developer of Zn/Cl₂ batteries appears to be Energy Development Associates.

The Zn/Cl₂ battery developed by EDA represents a unique and very complex system involving a circulating

Barriers to development

Battery system	Number of technical barriers	Average difficulty of barriers
Ni/Fe	1	Medium
Lead-acid	2	Medium
Ni/Zn	2	Difficult
Zn/Cl ₂	5	Difficult
Li-Al/FeS _x	7	Difficult
Na/S (ceramic)	8	Difficult
Na/S (glass)	10	Difficult

(pumped) electrolyte and a refrigeration system for storage of frozen chlorine hydrate. The electrolyte is an aqueous solution of zinc chloride, and the operating temperature is about 40–50° C. When the battery is charged, zinc plates out of the solution onto graphite substrates in the individual cells that make up the battery stack, while chlorine gas is liberated into a common gas space between the stack and the chlorine store. The liberated chlorine is contacted with a small element of cooled electrolyte to form the chlorine hydrate, which is filtered out and retained in the hydrate store. When the battery is in the discharged state, zinc chloride must be stored, dissolved in the electrolyte at high concentrations (initially 40% by weight Zn/Cl₂) to minimize volume. The charge is generally terminated when the Zn/Cl₂ concentration drops to about 10 wt%. For discharge, warm electrolyte from the electrode stack circulates through the hydrate store, causing decomposition of chlorine hydrate and liberating the chlorine into the gas space. Chlorine is then dissolved in the electrolyte via the chlorine adsorber and circulated through the battery stack for reaction of the cells. Hydrogen liberated during the charge/discharge cycle is reacted with chlorine to form hydrochloric acid and then returned to the pump.

The present specific energy of Zn/Cl₂ batteries is about 75–85 Wh/kg. EDA recently lowered its specific energy goal from 130 Wh/kg to about 80–100 Wh/kg, not including the refrigeration system. Energy efficiency may be an inherent problem because of losses associated with the refrigeration and pumping systems, together with coulombic efficiencies that are well below 100%. However, the developers are optimistic about their ability to attain 65% energy efficiency in vehicle batteries.

The Zn/Cl₂ battery will be attractive as an off-peak energy-storage device for electric utility systems. A strong point in its favor is that the raw materials for manufacturing it are readily available and inexpensive. It will probably be the first advanced battery developed for electric-energy storage by utilities. There is little doubt that Zn/Cl₂ batteries with specific energies about 100 Wh/kg and service lifetimes possibly greater than five years will be developed. Unfortunately, this battery is not well-suited for electric vehicles. It is intrinsically bulky and presents serious packaging and safety problems for use in electric vehicles. In addition, it does not "scale down" well because of the multiple auxiliary systems; its use, therefore, would probably be restricted to the larger buses and trucks, and it is highly unlikely that Zn/Cl₂ batteries will ever be successfully developed for

Relative desirability of battery systems							
	Lead-acid	Ni/Zn	Ni/Fe	Zn/Cl ₂	Li-Al/ FeS _x	Na/S (ceramic)	Na/S (glass)
Specific energy	3	5	4	6	8	8	8
Volumetric energy density	3	6	4	4	8	5	5
Peak power ^a	2	8	4	4	5	5	9
Sustained power	3	7	5	8	5	5	9
Cost	7	(5)	3	(5)	(5)	(5)	(8)
Cycle life	(5)	(5)	10	(5)	(5)	(5)	(5)
Safety	7	7	7	2	8	2	3
Resource availability	4	3	3	9	(4)	9	9
Overall desirability rating ^c	3.5	7.5	4.5	6.0	8.0	6.0	8.5

^aAt 80% state-of-discharge.

^bParentheses denote relatively uncertain assessment.

^cThe values have no meaning except to illustrate the "overall relative desirability" for the automobile application on a linear scale (obtained using Bayesian interrogation).

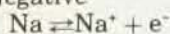
electric passenger automobiles.

Energy Development Associates make a very persuasive case that serious chlorine releases can be made highly improbable through clever engineering and design. The most serious questions center around the consequences of the rare incident that could result in the sudden release of over 50 kg of chlorine. Years of testing and some very favorable safety test results will be required before the Zn/Cl₂ battery can be considered seriously for use in electric vehicles. It appears that the probability of overcoming the electrical performance, lifetime, and safety barriers by 1990 is less than 20%. However, the Zn/Cl₂ battery will be the first advanced system to progress into the vehicle-testing stage, with the first road tests scheduled for 1980.

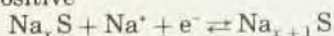
Sodium-sulfur batteries

Large programs have been under way for more than 10 years in the US, the United Kingdom, France and Japan to develop a sodium-sulfur battery system. The essential feature of this system is the ceramic electrolyte "beta alumina" (Na₂O · 11 Al₂O₃). This material is ionically conductive at 300–350° C, with sodium ions as the charge carrier. The active materials, sodium and sulfur, are both liquid at the operating temperature, and the solid electrolyte serves as the separator. The electrode and cell reactions are

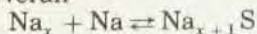
Negative



Positive



Overall



Typically, sodium-sulfur cells involve a central tube of beta alumina containing liquid sodium; this tube is surrounded by a layer of graphite felt loaded with liquid sulfur and polysulfide. This cell assembly is encased in a metal housing that also acts as the

positive current collector. Corrosion of the positive current collector is a serious problem, especially for batteries to be used in vehicles. British researchers have developed an "inside-out" design, in which the sulfur is contained within the beta-alumina tube and the sodium contacts the exterior surface of the tube; this approach appears to result in reduced electrical performance, but it may have advantages for the cost and lifetime. Researchers at Ford feel that the "inside-out" design is not promising for high-performance batteries for vehicles because of heat-transfer problems in the positive electrode.

The reaction mechanism of the sulfur electrode is quite complex. Because elemental sulfur is an electronic insulator, one adds a conductive material, such as graphite felt, to assist current collection. The sodium polysulfide formed during discharge is not soluble in sulfur. Thus, the sulfur electrode contains two liquid phases throughout about 60% of the discharge. Beyond this point, essentially no elemental sulfur remains, and, because all the polysulfides are miscible, only one phase remains. To keep this phase liquid throughout its compositional range (Na₂S₅ to Na₂S₃), it is necessary to operate above 270° C, with typical operating temperatures falling in the range of 300–375° C. For transportation applications involving a high peak-to-average-power ratio, sodium-sulfur batteries must operate in the single-phase region (Na₂S₃ to Na₂S₅), which limits energy density significantly. The present goals for Na/S electric vehicle batteries (more than 110 Wh/liter and 130 Wh/kg) may therefore be very difficult to achieve.

The prospects for successful commercialization of Na/S batteries (ceramic electrolyte) for electric vehicles appear to be declining; they are far better suited for bulk energy storage on electric-utility networks. The major technical problems are the following:



Sodium-sulfur battery pack (experimental model). The batteries operate at 300–375° C. (Photo courtesy of Ford Motor Co.)

- marginal durability of the ceramic electrolyte tubes
- corrosion of current collectors in the positive electrode
- design inflexibility and packaging problems
- safety

The probability of solving these problems by 1990 appears to be less than 10%. Raw materials, on the other hand, pose no problems; none of the resources required is likely to become expensive in the near future.

Even if the electrical performance and ruggedness problems were overcome, extensive safety testing would be required before Na/S batteries could be introduced for public use. A crash-worthy battery casing may be necessary to minimize the likelihood of sodium fires, sodium-water explosions, and runaway sodium-sulfur reactions. The cost and weight of these safety systems may represent a significant performance and economic penalty. Because of these problems, world-wide interest in this battery system seems to be declining.

Other battery systems

Other battery systems are judged far less likely to be successfully commercialized by the year 2000. Of course, a major breakthrough or technical advance could radically change these prospects. The most promising exploratory battery systems include Na/S (glass electrolyte), Zn/Br₂, Fe/Air, Al/Air, Li/TiS₂, and various special-

purpose batteries for hybrid vehicles.

A group at the Dow Chemical Company has made impressive advances during the past 12 months on a sodium-sulfur battery that has a glass electrolyte and is hermetically sealed in a metal case. The Dow researchers have built several 40 Ah versions of this cell, which they believe is large enough for electric cars. These cells are expected to attain about 145 Wh/kg and 175 Wh/liter within about 12 months. Dow plans to build a pilot plant in 1980 to produce the 40 Ah cells. The group has developed a flow regulator to prevent excessive contact of sodium with sulfur, which had produced a "roman candle" effect in some of their earlier test cells. Newly developed helium-tight tube-sheet seals and rigid reservoir cups have greatly improved the lifetimes of the cells. The cells have demonstrated good overcharge capability. Major problems that remain unsolved include failure from repeated freezing and thawing, a relatively short lifetime in full-scale cells, and the need for an improved tube-sheet composition and fabrication method.

Work on an aluminum-air battery has made good progress during the past 12 months; the cell chemistry has been demonstrated and cell stacks have been developed. The recent improvement of their power capability could make Al/air batteries suitable for use in compact automobiles. The principal problems relate to the "chemical engineering" of the system (rather than the

cell stack itself) and a very poor energy efficiency—less than 40%. However, its high specific energy and the fact that it can be recharged mechanically make the Al/air battery the only electrochemical system with realistic prospects for achieving performance equivalent to gasoline-fueled vehicles. This battery system is especially difficult to evaluate because of uncertain costs, and lack of experience with fully-integrated battery systems.

The Exxon Corporation's development of Li-Al/TiS₂ batteries has been stalled by the lack of a suitable electrolyte for carrying the high currents required in vehicles. This battery is a close relative of the lithium-iron sulfide batteries we discussed earlier. As is the case for the other lithium-metal sulfide batteries, a lithium-aluminum alloy appears to be preferable to liquid lithium as a negative electrode. If a suitable electrolyte can be developed, this may well become an excellent vehicle battery.

Work on the Ca/FeS₂ battery system at Argonne has progressed to exploratory work with cells that store up to 300 Ah. The battery system represents an attempt to make metal-sulfide cells without lithium, because lithium is relatively expensive and produced in limited quantities. The Argonne group has found that high-solubility sulfur species are not formed in the electrochemical reactions at the positive electrode. These cells may therefore have much longer lifetimes than the lithium batteries. Present efforts, which are still very exploratory, center on developing a reliable, long-lived cell. For this battery to become suitable for use in cars its specific power will have to be greatly improved.

Risk/reward relationships

I have developed a Bayesian decision-analysis technique for evaluating electric vehicle batteries.² The principal features of this system are

- sub-division of batteries into groups of comparable technical maturity
- assessment of technical risk, including methods for coping with poor quality or distorted inputs from "experts"
- a Bayesian interrogation technique for quantifying subjective judgments
- direct comparison of development risk and the benefits of successful development.

The assessment of technical risk is the most important and most difficult task in the comparative evaluation of batteries. The Bayesian decision-analysis method is a two-step procedure. First one identifies the "key" technical

barriers (those which could potentially disqualify the battery), and then one estimates the probability of overcoming each key barrier. The table on page 38 summarizes the findings for the most promising battery systems. There is clearly a wide variation in the number and relative difficulty of technical barriers.

To evaluate the consequences of successful development, I selected eight "battery desirability factors" that were judged to be the most important characteristics in defining the suitability of a battery for electric vehicles. The table on page 39 gives, for each battery candidate, its rating with respect to each factor and an overall "battery desirability" rating.

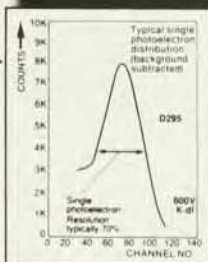
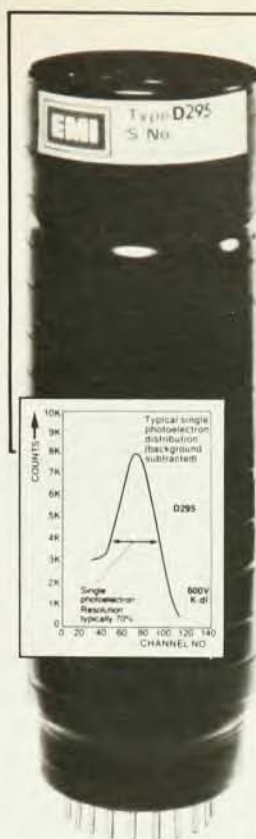
We can now compare risks and rewards; in general one finds a rough proportionality between the difficulty of development and the desirability of the resulting battery. This relationship is shown graphically on page 38 for the case of batteries for urban electric vehicles. We can see that all of the batteries lie within an approximately linear envelope in the graph; apparently, the ratio of relative reward to risk is not greatly different for these battery systems. Recent trends in the various battery technologies are indicated by the arrows in the graph. Not shown in the figure are the points for 23 relatively unpromising battery systems: each of them falls well below the linear envelope in the graph.

As one can see from the tables and from the graph, we can project no clearcut "winners" in the battery competition at this time. Each individual battery system has a less than 50% probability of successful development and commercialization; however, we expect that the cumulative probability that at least one of the batteries would be successfully developed is greater than 75%.

It is clear that vastly improved electric vehicles will be developed by 1985. However, the gasoline-powered vehicle will probably continue to predominate until gasoline becomes scarce or much more expensive. By 2000 AD we are likely to see a large number of electric vehicles on the road, possibly millions. The actual number will depend on the severity of future shortages of liquid fuels as well as on the progress of research on advanced batteries.

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2. W. J. Walsh, "A Bayesian Approach to Forecasting Technical Success," University of Chicago Conference on the Economics of Research and Development Policy (April 1979). □



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