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MASTER

BATTERY TECHNOLOGY--
AN ASSESSMENT OF THE STATE OF THE ART

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TRW Inc.
Energy Systems Group
Energy Systems Planning Division
McLean, Virginia 22101

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1.0 INTRODUCTION

Interest in battery technology has been motivated by the large increase in federal spending for battery research in the last several years. The annual investment in battery research and development has roughly quadrupled from 1975 to the present. The DOE budget for batteries will approach $17 million for FY 78, with an additional $5 million per year coming from the Electric Power Research Institute (EPRI).

In addition to budget increases, DOE is required by the Electric and Hybrid Vehicle Act of 1977 (PL 94-413) to purchase electric vehicles and the associated battery energy storage systems over the next several years.

As a result of this increased interest in battery technology and its potential to aid in meeting the national energy goals, a state-of-the-art battery technology survey was undertaken. This report summarizes those results. It is intended to provide a data base for understanding and evaluating the various program efforts and the relative merits of battery technology. It summarizes battery technology as it is today as well as estimates the progress likely to be achieved in the next few years.

This survey represents the first step in achieving the ultimate goal of evaluation of the objectives and scope of the DOE Battery Development Program. Other necessary steps include:

- A detailed market analysis of the role of other advanced technologies which compete against battery technology.
- An examination of alternate goals and strategies for the DOE battery development program.

1.1 SCOPE OF REPORT

A state-of-the-art battery survey and data verification process were conducted with battery manufacturers and organizations involved in battery technology research and development. Major battery technologies were identified as shown in Table 1-1.

Table 1-1.
Major Battery Types Identified and Evaluated in this Study

STAGE OF DEVELOPMENT	BATTERY TYPE
Near-Term	Lead Acid Nickel Iron Nickel Zinc
Advanced Development	Advanced Lead Acid Lithium Metal Sulfide Sodium Sulfur (B-Alumina Electrolyte) Zinc Chlorine
Exploratory Development	Hydrogen Halogen Iron Air Zinc Air Lithium Water Air Lithium Organic Redox Sodium Antimony Trichloride Sodium Sulfur (Glass Electrolyte) Zinc Bromine

This report addresses those major battery technologies which were identified as either being developed or explored as potential candidates for major energy storage applications in electric utilities or transportation as well as for future operations with solar or wind energy systems. Near- and far-term battery systems, current data and opinions, and developments in both U.S. and foreign battery technology for utility load leveling and electric vehicles are discussed.

1.2 ORGANIZATION OF REPORT

This report is divided into six sections. Section 1.0 provides background information and the scope of the report.

Basic data for each battery type are summarized in Section 2.0 and Appendix A. A general discussion of other potential battery systems is also included.

A comparative summary of battery cost and performance is presented in Section 3.0. Actual battery capabilities are discussed relative to the general requirements of electric utility load leveling and transportation applications.

The current status of the scarce materials and environmental and safety problems related to battery technology is presented in Section 4.0.

The overall status of the current R&D programs and expected progress toward commercialization is in Section 5.0. The roles of competing technologies in two major markets for battery technology are also discussed.

The general observations, conclusions, and recommendations reached in this study are summarized in Section 6.0.

2.0 OVERVIEW OF BATTERY TECHNOLOGIES

A variety of potential battery technologies can be constructed from the numerous electrochemical "couples" that exhibit energy storage properties. However, only a small number of these couples exhibit sufficiently high energy and power densities and do not use very scarce and/or expensive materials as part of their systems to be considered practical. Specialized types of batteries such as silver-zinc and nickel-cadmium are in the latter category and are not covered by this report.

The basic battery options discussed in this report fall into the two broad categories shown in Figure 2-1. Ambient temperature batteries, which are usually based on aqueous (water) solutions like the electroyte, are in the first category. The second category includes the high temperature batteries that use either molten salts or high conductivity solid electrolytes.

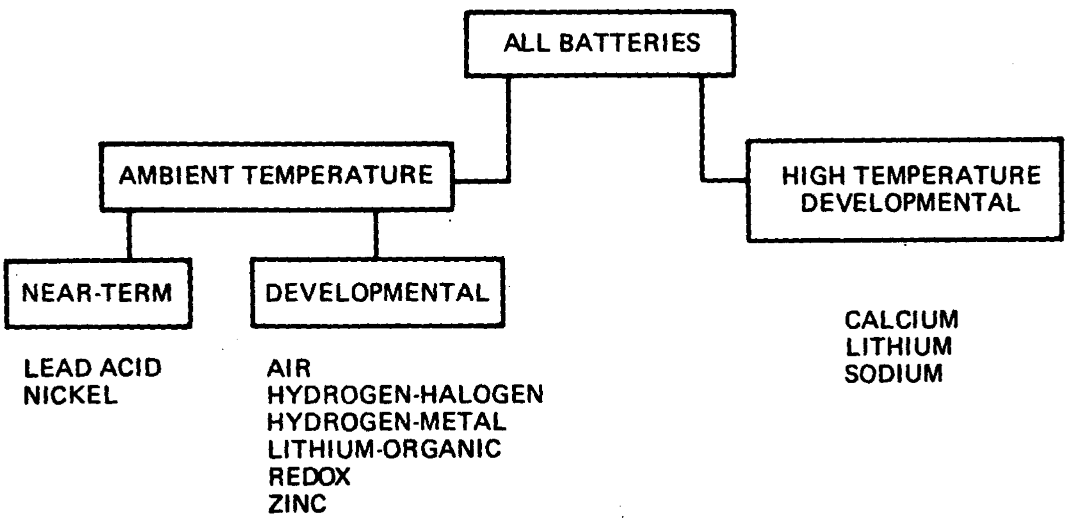


Figure 2-1. Breakdown of Principal Battery Technology Groups

Within the ambient temperature systems, all near-term technical effort has concentrated on the battery system that have been either commercially available or under development for a considerable period, such as the lead acid, nickel iron, and nickel zinc systems.

Developmental ambient temperature systems cover a much wider range of possibilities. (Appendix B has a detailed breakdown of possible battery types.) Only a few of these systems have been examined in sufficient detail to be characterized as shown in Table 1-1.

It also should be noted that some of these battery systems such as air systems are not true secondary batteries with the capability of being directly recharged. Rather, these are primary batteries, and recharging must be accomplished by a separate process (often electrolysis) to regenerate the primary constituents of the battery.

High temperature batteries are a separate class of systems based on the special properties of the materials utilized at elevated temperatures. These systems are subdivided into three broad families, depending on the basic material used in the battery. A more detailed breakdown of the high temperature battery types is given in Appendix B. Again, only a few of the many potential high temperature batteries are sufficiently developed to be characterized in detail, as indicated in Table 1-1.

2.1 KEY ISSUES IN ASSESSING BATTERY TECHNOLOGY

Since battery technologies can be characterized by many technical and economic factors, this study focuses on those factors that would affect the eventual commercialization of these technologies. These include cost and performance, market factors, and certain exogenous factors which are critical to large-scale battery commercialization in specific energy system applications.

2.1.1 Cost and Performance

The cost and performance factors that play the most important role in battery characterization are as follows:

- Energy density
- Power density
- Cycle life

- Efficiency
- Cost/kWh (in pilot and mass production)

Energy and power density are critical factors for vehicular applications of batteries. They relate directly to the range and acceleration characteristics of the vehicle, which are fundamental parameters of the vehicle's usefulness and market acceptability. Cycle life, efficiency, and the capital cost per unit storage capacity are important in determining the economics of the battery storage system for any application. They determine the additional cost involved in storing the energy before it is used. Battery storage systems can be economically competitive only if they do not significantly increase the cost of the basic energy service they supply.

2.1.2 Market Factors

Even if a battery technology appears to satisfy all cost and performance prerequisites for a particular application, its commercialization may be affected by the following:

- Time required to develop and commercialize the technology
- Competition from other battery or energy storage technologies
- Size of the capital investment for mass production
- Normal technology market turnover and lead times

In this report, consistent estimates were obtained only for the development and commercialization time. The other market factors are much more difficult to assess, especially where there is potential for several technologies in the same market area. A detailed assessment of the other factors will require further study where the question of potential competition between battery technologies will be addressed.

2.1.3 Exogenous Factors

Two important exogenous factors play an important role in the eventual commercial introduction of battery technology:

- Materials availability and cost
- Related environmental and safety problems

Batteries often utilize considerable quantities of scarce materials. Consequently, the additional capital investment and lead time required to supply these materials to the battery manufacturing system must be considered. Furthermore, fluctuations in raw material prices can have a significant impact on the battery cost in some cases. Hence, it is important to evaluate the potential for economic recovery and recycling of the scarce materials available from spent batteries.

The safety and environmental problems involved in battery manufacture, utilization,and disposal also pose major obstacles to widespread use of battery technology. Many battery systems utilize toxic or potentially toxic substances. Other batteries use materials that are chemically very reactive and/or operate at high temperatures. Some systems also emit small quantities of toxic and flammable gases in normal operation. These problems must be adequately resolved to the satisfaction of the appropriate regulatory agencies (mainly the Environmental Protection Agency and the Occupational Safety and Health Administration) if batteries are to be commercialized successfully.

2.2 BATTERY TECHNOLOGY OPTIONS

Near-term battery options generally represent battery types that have been in production for many years, though not for the specific applications now envisioned. These systems still offer potential for modest improvements in cost and performance, with the advantage that such improvements can be rapidly included in currently produced batteries by modifying the production process. The improved batteries can be rapidly deployed into many commercial applications through "in place" sales and service organizations.

In addition, the current interest in electric and hybrid vehicles under the Electric and Hybrid Vehicle Act (PL 94-413) requires that a great deal of emphasis be placed on utilizing near-term systems that can meet the electric vehicle market requirements for batteries in the near-term. Any other battery system will require at least seven to ten years to achieve pilot production. Thus, the current availability of near-term batteries is a key to their market penetration. If widespread applications are formed for near-term batteries in certain areas, more advanced battery systems will have to offer significant cost and performance advantages to displace them from those markets.

Advanced development batteries generally represent those systems which have had substantial development and commitment of significant sums of R&D funds. This distinction is highly arbitrary, in terms of this assessment, but reflects the thinking of the DOE, EPRI, and industry battery technology developers.

Basically, all of the advanced development batteries appear to offer significant cost or performance advantages over the near-term systems. These advantages are judged to be sufficient reason to pursue these technologies on at least a pilot plant basis in seven to ten years. Even though the detailed costs for these advanced systems has only been estimated in many cases, these technologies could probably be mass produced at a low cost.

Exploratory development batteries are concepts that are also viable battery technologies in the long run, but which, in general, are being funded at somewhat lower levels than the advanced development systems. In some cases, these exploratory systems represent concepts related to the advanced systems and can benefit from the investment in those systems.

Exploratory concepts are typically technologies which offer unique feature for certain applications. However, until their advantages over other battery systems are seen more clearly, the level of funds committed to R&D activities in these areas is likely to remain modest. At best, exploratory battery systems will not be available for seven to ten years and, in some cases, can only be considered as long-term options.

Appendixes A and B contain listings of other battery technologies that are not covered in this study. We were unable to find any active consideration at this time of these technologies for the major applications being discussed. However, they may be considered for specialized applications, such as nickel-hydrogen systems for spacecraft batteries. Further, basic research could result in a new battery type evolving in the future. However, insufficient data is available to evaluate these potential batteries at this time.

3.0 BATTERY PERFORMANCE AND COST COMPARISONS

Some of the battery system requirements for the two major markets, transportation systems and utility load leveling, are already known. Therefore, the performance and cost characteristics of various battery technologies can be reviewed relative to requirements and comparatively among battery systems.

3.1 ENERGY AND POWER DENSITY

Energy and power density are the two most important factors in batteries for vehicle applications since they relate directly to the performance capabilities of the vehicle. Many of the advanced battery technologies were originally pursued because of their promise of high energy and power density for vehicle applications.

Energy density translates directly into a vehicle's range capability. Usually, electric vehicles must have a sufficient daily range to meet most driving needs with a single overnight charge. Techniques for rapidly replacing the battery or recharging during the day could mitigate these requirements. Similarly, power density determines the vehicle's ability to accelerate and climb hills and in some cases determines its maximum speed. Again, the power density requirements can be minimized by using hybrid systems such as a flywheel or a second high-power density battery to supply power bursts.

An exact translation or ratio of vehicle performance to battery performance involves assumptions about the fraction of the vehicle weight (or volume) that can be devoted to batteries, with a typical upper weight limit of about 30 to 40 percent. It also involves assumptions about characteristics of the vehicle and the electric propulsion system technology.

Basic approximate transportation system requirements for batteries are summarized in Figure 3-1. As shown, private automobiles tend to place very stringent requirements on the battery system. On the other hand, specialized vehicles, especially the small utility car, place much lower requirements on the battery.

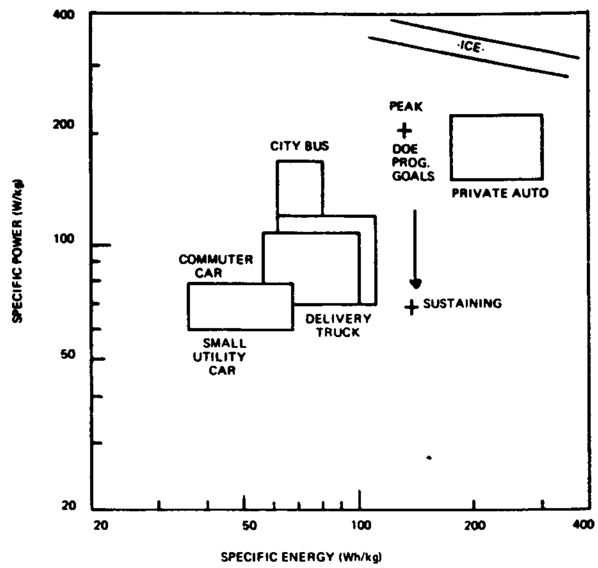


Figure 3-1. Transportation System Requirements for Battery Performance

Limited use electric vehicles have been built for many years with lead-acid batteries, despite the fact that they do not meet the minimal requirements shown.

The actual capabilities of the vehicular batteries are summarized in Figures 3-2 through 3-4. The near-term systems (Figure 3-2) approach or meet the requirements for specialized vehicles. Improvements in the batteries as projected do not allow competition with private vehicles having heat engines.

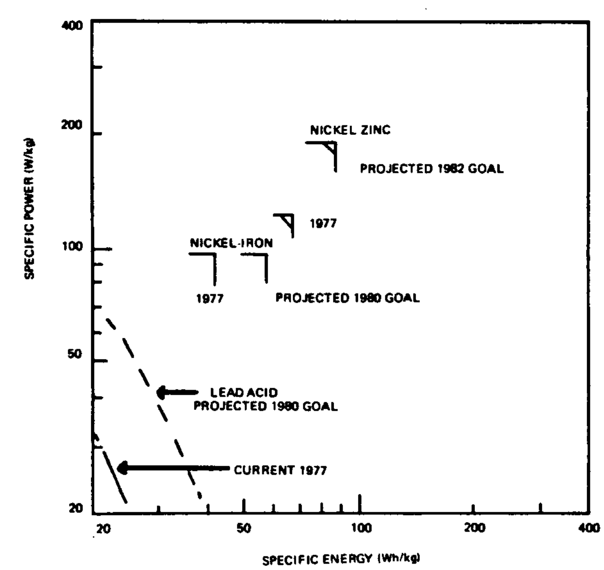


Figure 3-2. Summary of Near-Term Battery Performance

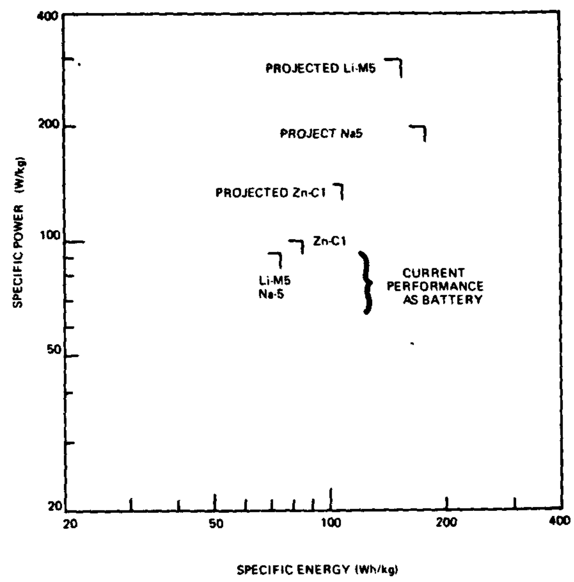


Figure 3-3. Summary of Advanced Development Battery Performance

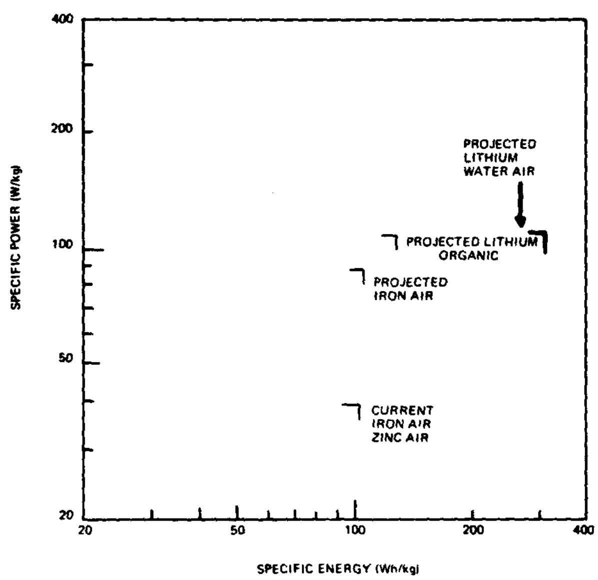


Figure 3-4. Summary of Exploratory Development Battery Performance

Advanced development batteries currently meet specialized vehicle requirements. In the long term, the two high temperature systems are projected to approach the requirements of the private automobile, if the technology development is successful in meeting its goals. This implies that electric vehicles, broadly competitive with heat engine vehicles, will not be produced for some time if at all.

Several exploratory development batteries also have potential use in vehicle applications. Iron air and zinc air batteries have good energy density for specialized applications but poor power density. This can be overcome by using a hybrid power system such as a flywheel or second battery system. The lithium organic battery also could meet the needs of the specialized vehicles. The only exploratory system that appears truly competitive in the private vehicle sector is the lithium water air battery. However, other drawbacks such as very low system efficiency may limit the applicability of this battery.

3.2 EFFICIENCY

Table 3-1 summarizes the efficiency of the major battery systems. It can be seen that most battery systems demonstrate sufficiently high efficiency, so that losses will not be a serious technical or economic problem. The air batteries and the lithium water air system have low efficiencies, which may be acceptable if the cost of the input energy is sufficiently low. This potential could be achieved by minimizing the amount of <u>electrical</u> energy used in the recharging process. However, in a detailed economic evaluation, such systems are likely to be at a serious disadvantage because of higher energy costs.

Table 3-1. Summary of Battery Efficiency Data

STAGE OF DEVELOPMENT	CURRENT EFFICIENCY (Percent)	PROJECTED EFFICIENCY (Percent)
Near-Term		
Lead Acid	65-70	>60
Nickel Iron	55-70	60-70
Nickel Zinc	60-65	60-65
Advanced Development		
Lithium Metal Sulfide[1]	70	75
Sodium Sulfur[1]	70-80	70-80
Zinc Chlorine	55	65
Exploratory Development		
Hydrogen Halogen	--	70
Iron Air/Zinc Air	40	40-50
Lithium Water Air	--	26
Zinc Bromine	--	75-80

[1]Does not include idling losses to surroundings.

3.3 CYCLE LIFE

Table 3-2 summarizes the data on battery and test cell cycle life. It should be noted that it is generally assumed that cycle life requirements are 1000 cycles for transportation systems and 2500 cycles for utility load leveling systems. This assures that battery replacement costs are not excessive, since longer battery cycle life lowers the total cost of a battery storage system.

Table 3-2. Summary of Battery Cycle Life Data

Stage of Development	Current (Cycles)	Capacity Level
Near-Term		
Lead Acid	300-700	Full Battery
Nickel Iron	1500	Full Battery
Nickel Zinc	200-300	Full Battery
Advanced Development		
Advanced Lead Acid	2000	Projected for Full Battery
Lithium Metal Sulfide	500-1000	100-300 Wh Cell
Sodium Sulfur (B-Alumina)	>250	200 Wh Cell
Zinc Chlorine	200-300	1.4 kWh Cell
Exploratory Development		
Iron Air Zinc Air	150	No Data
Lithium Organic	250	20 Wh Cell
Sodium Ant. Trichloride	500-900	20 Wh Cell
Sodium Sulfur (Glass)	250	10 Wh Cells

The survey results indicate that achieving cycle life goals in larger cells and batteries remains a major problem for developmental battery technology. Even the near-term batteries are marginal performers on cycle life in the electric vehicle application.

Cycle life problems are usually related to details of cell design, including purity of materials and manufacturing technique. Although considerable progress has been made in some areas, the key technical problem for all battery systems concerns cell life.

3.4 CAPITAL COSTS

Capital cost requirements for batteries in different applications arise from the needs of the battery systems to compete economically against other energy storage systems that serve the same application. The cost data shown are derived from several sources and are used to provide a basis for understanding the economic goals that a successful battery technology must eventually meet.

3.4.1 Transportation System Requirements

Transportation systems can utilize batteries in a wide range of possible applications from specialized vehicles such as postal vans, mining vehicles,and electric trucks to eventual potential use in private automobiles.

Preliminary analyses indicate that there are limited markets for battery-powered vehicles, even at high battery costs of $200-300/kWh. The battery vehicle offers specialized features that make it unique for stop and go service, indoor or underground applications, but there is little or no economic competition from other technologies. This limited market is summarized in Figure 3-5. Larger markets for urban buses, delivery trucks, and limited performance automobiles would create a substantial potential market for batteries at $50-70/kWh, assuming the batteries have reasonably long cycle life (1000 cycles).

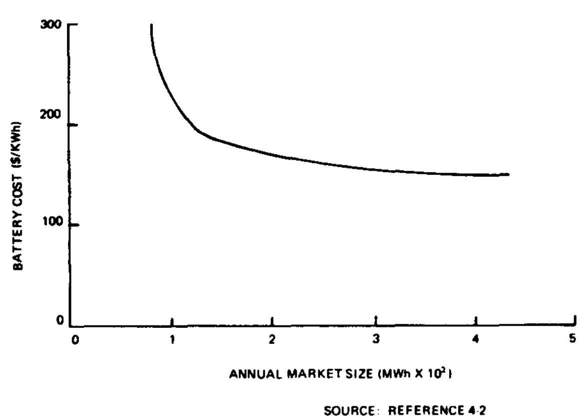
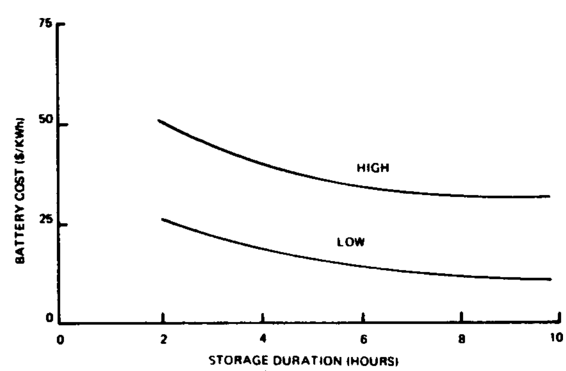


Figure 3-5. Specialized Transportation Market Requirements for Battery Costs

3.4.2 Utility System Requirements

Batteries for utility load leveling applications must be competitive with other utility storage systems such as pumped hydro and direct generation of electricity by intermediate and peaking power plants. These alternative systems place severe constraints on battery costs as shown in Figure 3-6. Since most of the interest and potential capacity requirements are for battery systems with five to ten hours of storage capacity, battery costs of \$30/kWh or lower are needed. The curves assume that the batteries have a sufficiently long life (2500 cycles) and are replaced every ten years. The variation between the high and low curves is a result of differences between utility systems across the country.



Source: Reference 3-2

Figure 3-6. Electric Utility Storage Market Requirements for Battery Costs

3.4.3 Battery Cost Summary

Table 3-3 summarizes the current status of battery costs. It can be seen that near-term batteries can begin immediately to meet the needs of the transportation market. Advanced lead acid batteries are at the cost threshold for the electric utility application. The remaining battery types are in too early a stage of development to have a meaningful price associated with them, though they are projected to be competitive in the long run.

Table 3-3. Summary of Battery Costs

STAGE OF DEVELOPMENT	CURRENT ($/kWh)	PROJECTED PILOT PROD. ($/kWh)	PROJECTED MASS PROD. ($/kWh)
Near-Term			
Lead Acid	45-80	80-100	40
Nickel-Iron	120-400	100-200	50-60
Nickel-Zinc	150	100-120	50-60 [1]
Advanced Development			
Advanced Lead Acid [2]	70-80	--	40-50
Lithium Metal Sulfide	>2000	100	40 [2]
Sodium Sulfur	>2000	100	40 [2]
Zinc Chlorine	>2000	--	50
Exploratory Development			
Hydrogen Halogen			40-60
Iron Air/Zinc Air	>2000		30-60
Lithium Organic			42
Redox			27-38
Sodium Ant. Trichloride			40
Zinc Bromine			21-42

[1] Long-term.
[2] Includes balance of plant.

3.4.4 Open Issues--Battery Costs

The estimates of advanced or exploratory battery costs, as shown in Table 3-3, usually indicate that the particular technology will have acceptable costs in eventual mass production. In reality, actual costs of capital equipment and associated costs for processing the battery materials (energy, material, and labor inputs) cannot be accurately estimated without a complete production engineering study for each particular battery. This is especially true for the advanced batteries requiring unusual materials processing and handling. Considerable production engineering effort will be required to assure that the batteries will eventually be economically viable.

In the interim, battery market development is likely to start in the transportation area where the economic constraints are less severe and the near-term batteries can begin to meet the market requirements. However, once the near-term batteries become entrenched, newer battery technologies will have to offer significant advantages in cost and performance to justify changing the production facility required by an advanced battery.

4.0 EXOGENOUS FACTORS AFFECTING BATTERY TECHNOLOGY COMMERCIALIZATION

The two principal exogenous factors which affect battery technologies are materials requirements and safety and environmental problems associated with each technology. This section contains a preliminary discussion of these problems; detailed results were unavailable at this time.

4.1 SCARCE MATERIALS

The use of scarce materials in some battery technologies creates several problems for the potential deployment of a given battery technology. First, it introduces uncertainty in the future price of batteries if the price of the material is subject to market pressure. Secondly, it may require the investment of additional capital to create new supplies of the needed material. Finally, many of the materials would potentially have to be imported as shown in Table 4-1. Antimony, cobalt, and nickel could become critical supplies for batteries in the near-term.

Table 4-1. Battery Materials Analysis Summary of Imported Materials

MATERIAL	PERCENTAGE IMPORTED
Cobalt	98
Chromium	91
Aluminum	85
Tin	75
Nickel	71
Zinc	64
Antimony	56
Potassium	49

4.1.1 Materials Requirements

The materials requirements for several key battery types are shown in Table 4-2, along with the current annual production of that material in the United States. In the right-hand column, the battery capacity produced from one percent of that production is shown. Supplies of some materials can put severe limits on battery manufacturing capacity. Alternatively, considerable additional capital investment would have to be made for new raw materials, mining, and processing to supply the increased requirements of the battery industry.

Table 4-2.
Battery Materials Analysis
Preliminary Supply Constraint Summary

BATTERY TYPE	MATERIAL	BAT. REQ. (kg/kWh)	USE LEVEL 1973 (TONNES X 10^3)	CAPACITY AT 1% OF USE LEVEL (GW)
Lead Acid	Lead	22	1400	0.63
	Antimony	1.6	40.3	0.025
Nickel Zinc	Nickel	3.29	211	0.64
	Zinc	1.28	1500	11.7
	Cobalt	.055	8.5	1.54
Lithium Metal Sulfide	Lithium	0.2-0.3	3.4	0.1
	Aluminum	1.0	6175	61.7
Zinc Chlorine	Zinc	0.74	1500	13.5
	Titanium	0.39	585	15
	Chlorine	0.80	7640	95.5

4.1.2 Materials Recycling

The lead acid battery, the most widely used battery technology today, has an associated technology for recovery of lead from spent batteries. However, if other battery types using nickel, zinc, lithium, etc., were deployed, no associated materials recovery technology would exist. A need exists to develop such recovery technologies to help stabilize and minimize the long-term requirements for these special materials.

Materials recycling for batteries drastically reduces the material needs for any given battery system because of the short lifetime of the battery. Current battery systems typically have lives of three to ten years, the latter figure being typical of heavy-duty industrial batteries. Because of this relatively short lifetime, a large amount of scrap material is generated. If the scrap material can be effectively recovered and recycled, the material requirements for new batteries could be substantially reduced.

4.2 SAFETY AND ENVIRONMENTAL PROBLEMS

Each battery technology has potential hazards associated with its manufacture, operation, and disposal. This section summarizes the key problems that will be associated with battery technology in general.

The specific problem areas associated with each battery are indicated in Table 4-3. No attempt has been made to evaluate the safety and environmental problems associated with each battery type or to estimate the cost of internalizing those hazards to acceptable levels for each battery technology. A definite need exists for such quantitative evaluations.

Table 4-3. Battery Technology
Safety and Environmental Summary

BATTERY TYPE	TOXIC MAT.	TOXIC COMP.	HIGH TEMP.	REACT. MAT.	VENT-ING	COMMENTS
Near-Term						
Lead Acid	X			?	X	Considerable operating experience
Nickel Iron		X		?	X	Considerable operating experience
Nickel Zinc		X		?	X	
Advanced Development						
Lithium Metal Sulfide		X	X			
Sodium Sulfur		X	X	X		
Zinc Chloride	X				X	
Exploratory Development						
Hydrogen Halogen	X			X	?	
Iron Air				?		
Zinc Air		X		?		
Lithium Organic	?	?				
Lithium Water Air		?		X	X	
Redox	?	?				
Sodium Ant. Trichloride	X		X			
Zinc Bromine	X				?	

4.2.1 Hazardous Materials

Several of the battery types involve the use of hazardous materials such as antimony, bromine, chlorine, and strong acids or bases. In some cases, the basic battery material itself is benign, but the compounds used in manufacturing, formed in normal operation, or formed in contact with the environment are toxic. This includes the formation of compounds with antimony, bromine, lead, lithium, nickel, sulfur, and zinc. It implies a need for special attention in the manufacturing, operation, and disposal of the batteries to assure that these materials are not dispersed in the environment.

4.2.2 Battery Emissions

Most of the aqueous batteries evolve hydrogen and some times other gaseous materials depending on the battery's chemical makeup. This normally occurs during the charging process, when there is a tendency to electrolyze part of the water if the recharging voltage is above a certain threshold.

One approach to this problem has been to provide venting systems, allowing the hydrogen and other gases to escape to the atmosphere. Another approach has been to use sealed cells and provide an internal catalyst to recycle the hydrogen back into the aqueous electrolyte. However, an acceptable approach has not been found for each battery system.

4.2.3 High Temperature Batteries

High temperature batteries pose unique problems in that a considerable mass of material has to be safely maintained at temperatures of 200°C-450°C. This presents some unique problems for the transportation applications. No detailed experimental studies of how well high temperature batteries can withstand accident impacts have been performed.

4.2.4 Manufacturing Impacts

Manufacturing advanced battery systems, using potentially hazardous materials, will require care in two critical areas. First, workers in areas where these materials are present will have to be suitably protected from receiving high exposures to these materials through various industrial safety measures. Secondly, the gaseous, liquid, and solid wastes produced by the plant must be carefully controlled so that these substances are not distributed into the environment. For most advanced battery technologies, sufficiently detailed designs of battery plants have not been produced to estimate the cost of meeting the associated occupational safety and environmental protection standards. Such studies would be an important factor in production engineering of any new battery technology,since they could contribute significantly to the battery's total cost.

4.2.5 User Impacts

The potential widespread use of batteries in the electric utilities and transportation sector poses very different problems. For a utility application at a fixed site, more control technology can potentially be used to make the battery system "acceptable," although the costs of such controls would pose a problem in this cost-sensitive application.

In those transportation applications where the potential users are more numerous but less sophisticated, a regulatory approach to achieve a safe technology will be needed. Unfortunately,little attention has been paid to this problem by the appropriate regulatory agencies, i.e., Department of Transportation and National Highway Transportation Safety Administration. Therefore, the necessary technical work and cost penalties to battery costs cannot be discussed in detail. Suitable vehicle safety guidelines for the development of batteries for transportation applications are needed.

5.0 R&D PROGRAM STATUS AND TECHNOLOGY COMMERCIALIZATION

5.1 REVIEW OF DEVELOPMENT STATUS

The development status of the various battery technologies is largely a function of the effort that has been invested in each option. Near-term batteries are essentially existing battery types with a considerable history of development. Most of the current efforts involve testing a series of small refinements, each of which slightly improves the battery. Since the batteries are already in production, the changes can be rapidly engineered into the production procedures if they are considered worthwhile.

The advanced development batteries are those for which the basic concept has emerged, but considerable work is still required to get a suitable prototype battery ready for performance testing. Testing is still largely limited to cells, because the batteries themselves are not suitable for application. The lead acid battery for the utility load leveling market is an exception. In this case, the technology exists, but the projected cost of the battery is too high for the application.

Since the eventual costs projected for the other advanced development batteries do not have a detailed basis from a production engineering standpoint, the ability of these batteries to meet the economic requirements of the utility market or even the transportation market is to some degree uncertain.

For the exploratory development batteries, even the technical characteristics of the individual batteries are highly uncertain, and little effort has been devoted to understanding their economic characteristics. Most of the exploratory development program is aimed at getting these systems to the point where they can be characterized as viable alternatives to near-term and advanced development systems.

Funding levels for each of these areas is summarized in Figures 5-1 and 5-2. It can be seen that considerable effort is being placed on the advanced development systems to accelerate cell and battery testing and development. By contrast, most of the exploratory efforts are still small. The advanced battery system will need a continued high

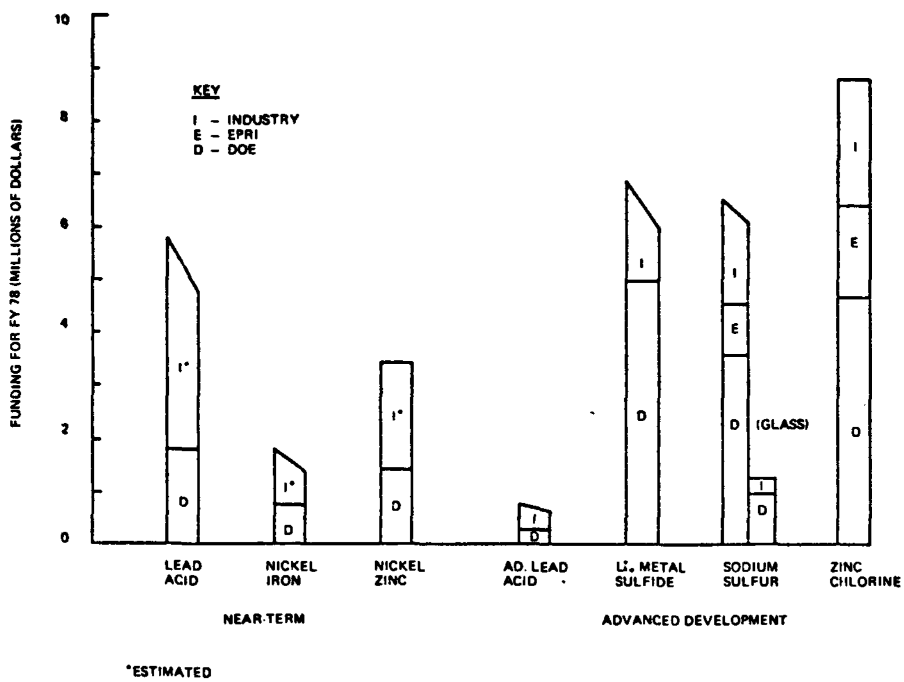


Figure 5-1. Current Funding Levels for Near-Term and Advanced Development Battery Programs

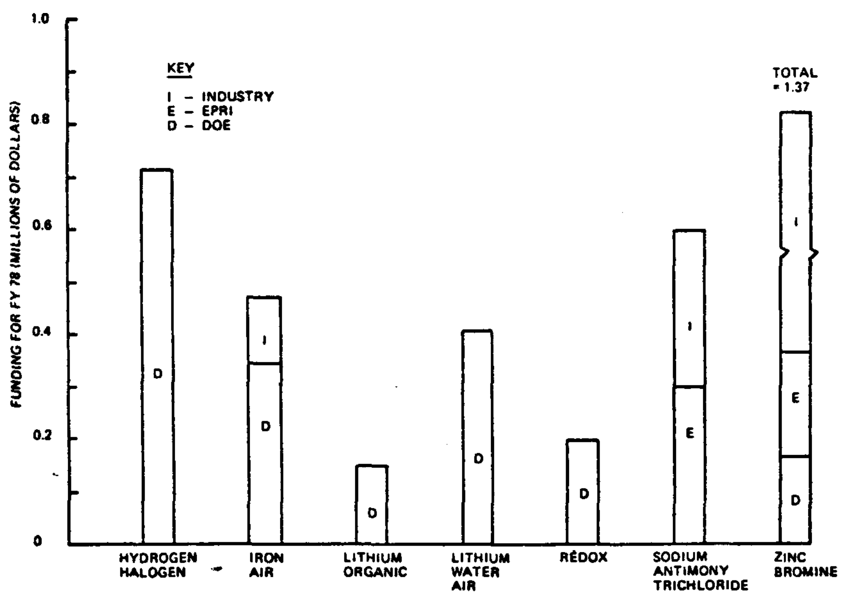


Figure 5-2. Current Funding Levels for Exploratory Battery Programs

level of support if the prospects for their commercialization are to remain viable. The potential, or lack thereof, in the exploratory technologies should be resolved in a few years. Thus, the exploratory funding could be diverted to other areas if the current candidate technologies are not viable.

A significant percentage of R&D funding from industry has been dedicated to near-term batteries. However, without funding from DOE and EPRI, advanced and exploratory development efforts would be drastically reduced with the exception of perhaps a few battery types for military applications.

Most of the activity in battery technology development tends to be concentrated on the near-term and advanced development technologies, as shown in Table 5-1. Work on exploratory development batteries is performed by very few organizations.

Table 5-1. Government/Industry Battery Development Program Summary

BATTERY TYPE	DOE-STOR	EPRI	ANL	BNL	LLL	NASA-LEWIS	NRL	ATOMIC INT.	DOW CHEM.	EAGLE-PICHER	EDA	EIC CORP.	ELECTRO. CHEM.	ELTRA	ENERGY RES. CO.	ESB	FORD MTR.	GENERAL ELEC.	GLOBE U.	GOULD	LOCKHEED	WESTINGHOUSE	YARDNEY	EUROPEAN ORG.	JAPANESE ORG.	EXXON	GENERAL MOTORS
Near-Term																											
Lead Acid	X		X				X							X		X			X	X				X	X		
Nickel Iron	X		X							X												X		X			
Nickel Zinc	X		X												X					X			X				X
Advanced Dev.																											
Advanced Lead Acid	X		X													X			X	X		X					
LithiumMetal Sulf.	X		X					X		X						X				X							X
Sodium Sulfur	X	X							X								X	X						X	X		
Zinc Chlorine	X	X									X																
Exploratory Dev.																											
Hydrogen Halogen	X			X																							
Iron Air	X																					X			X		
Zinc Air																								X			
Lithium Water Air	X				X																X						
Lithium Org.	X											X	X													X	
Redox	X					X																					
Sodium Antimony Trichloride		X														X											
Zinc Bromine	X	X																		X						X	

It appears therefore that battery technology is viewed by industry as a high risk area. Because of high uncertainties about future markets and technical difficulties in obtaining prototypes of advanced batteries, few private organizations are attempting to develop new battery technology independently.

A notable exception is the undertaking of two exploratory technologies by Exxon Enterprises. General Motors also has internally funded programs, but they are in the near-term and advanced development areas. It appears that only the largest corporations can afford the high risks involved in such development programs.

5.2 COMMERCIALIZATION STATUS

The commercialization timetable envisioned for the various battery technologies is summarized in Figure 5-3. Except for the existing near-term systems, a major new battery technology is at least seven to ten years away. Although some of the advanced development batteries are scheduled for tests in vehicle or utility test bed facilities during the interim period, these will be hand-built prototypes rather than production systems. Major development efforts, as reflected by the current funding levels and additional funding nominally committed for the next five to seven years by EPRI and DOE, are required to assure that these systems can remain on this timetable. Some of the more exotic exploratory development systems can only be considered as candidates for very long-term development based on current knowledge and funding commitments.

Figure 5-3.
Battery Technology Commercialization Timetable

BATTERY TYPE	1978	1980	1985	1990
Lead Acid	SOA →	ADVANCED →	ADV. UTILITY	
Nickel Iron	SOA →	ADVANCED →	→	→
Nickel Zinc	SOA →	→ ADVANCED →	→	→
Advanced Development				
Lithium Metal Sulfide	T	U	COMMERCIAL →	
Sodium Sulfur	T	U	COMMERCIAL →	
Zinc Chlorine	TU	→	COMMERCIAL →	
Exploratory Development				
Hydrogen Halogen				LONG-TERM
Iron Air	T		COMMERCIAL →	
Zinc Air		(No active programs)		
Lithium Organic			COMMERCIAL →	
Lithium Water Air				LONG-TERM
Redox				LONG-TERM
Sodium Ant. Trichl.			COMMERCIAL →	
Zinc Bromine			COMMERCIAL →	

T - Test in transportation system

U - Test in utility system

The expected market for each technology is summarized in Table 5-2. Several options are being developed for each area because of the uncertainty in the eventual technical and economic performance of any given system. This seems to be a justifiable near-term strategy.

Table 5-2. Battery Technology Market Survey

BATTERY TYPE	UTILITY LOAD LEVELING	TRANSPORTATION
Near-Term		
Lead Acid		X
Nickel Iron		X
Nickel Zinc		X
Advanced Development		
Advanced Lead Acid	X	
Lithium Metal Sulfide	X	X
Sodium Sulfur	X	X
Zinc Chloride	X	X
Exploratory Development		
Hydrogen Halogen	X	
Iron Air		X
Zinc Air		X
Lithium Organic	?	X
Lithium Water Air		X
Redox	?	
Sodium Ant. Trichloride	X	
Zinc Bromine	X	

In reality, however, each new battery technology is in competition with other battery technologies as well as with other technologies to provide the same energy service. (See Table 5-3) Since the scope of this study does not include a detailed market analysis, it will be sufficient to note that there are many existing technologies which currently dominate their respective markets and against which the new battery technologies will have to compete.

Table 5-3. Competing Technologies for Potential Battery Market

POTENTIAL MARKET	TECHNOLOGY
Transportation Market	Improved internal combustion vehicles (including diesel) Advanced heat engines (Stirling, gas turbine) Alternative energy storage systems (flywheels)
Utility Load Leveling Market	Alternative utility side storage systems (pumped hydro, underground compressed air storage, flywheels, thermal energy storage) Customer side storage systems (thermal energy storage) Advanced gas turbine peaking systems Improved load management techniques

6.0 SUMMARY AND CONCLUSIONS

6.1 GENERAL CONCLUSIONS

Over the past ten years, battery research and development efforts have resulted in a considerable advancement in the state-of-the-art and a sharpened understanding of the problems to be overcome in meeting battery performance and cost goals. Despite this progress, no single battery technology has emerged with clear-cut overall advantages for either the transportation or electric utility load leveling applications.

A substantial reduction of technical and economic uncertainties is required, particularly for the advanced and exploratory development batteries, before commercialization prospects can be confidently assessed. Actual commercialization success will be critically dependent on whether cost goals can be achieved in pilot or mass production.

Near-term batteries can satisfy the initial needs of the transportation market for limited performance and/or specialized vehicle applications. While the size of this market is uncertain, it includes at least Federal Government purchases of electric vehicles under the Electric Vehicle Demonstration Act (PL-94-413) in addition to existing electric vehicles.

The initial application of batteries in load leveling is less certain. This application not only requires an inherently low-cost technology, but also fairly large production runs to realize economies of scale. Except for a few special cases (e.g., Consolidated Edison in New York City), load leveling applications may have to await commercial introduction of one of the advanced battery types.

6.2 SPECIFIC CONCLUSIONS

The major battery technology problem is cycle life which, for most batteries, is marginal or inadequate for any application. Although cycle life can frequently be improved at the expense of increased battery cost, the net result is that storage system costs remain too high for most applications.

While many of the battery technologies could meet transportation requirements for limited performance and specialized vehicles, considerable improvements in battery energy and power density would be necessary to compete against heat engines for private automobiles. This seems unlikely at present. Furthermore, it must be assumed that heat engine technology will also continue to improve in terms of efficiency and ability to utilize synthetic fuels from shale or coal. This would result in a continued limited market for battery-powered vehicles.

In the utility load leveling market, the major battery problem is achieving low cost in mass production. The considerable production engineering effort necessary to mass produce at low cost while retaining the technical characteristics achieved in handmade prototype batteries is still in the earliest stages. Most experience in this area is drawn from work on lead acid batteries and will require considerable rethinking when the production of high temperature batteries is considered.

Costs of scarce materials often have a significant impact on battery costs. Recovery and recycling of materials from spent batteries, together with possible expansion of the scarce materials supply system, is an area deserving more detailed attention.

Nearly every battery technology has potential safety and environmental problems associated with battery manufacture, operation, or disposal. Many systems that are potentially suitable for specialized application may not be suitable for widespread use by the general consumer. An assessment of this problem, including required levels of safety and environmental protection and the costs of their internalization, needs to be conducted so that potential barriers to commercialization can be better understood.

Foreign efforts in battery technology development have been substantial, with the emphasis on near-term and advanced development batteries for electric vehicles. In some cases, such as lead acid, nickel zinc, and sodium sulfur, foreign developments are greater in depth and more advanced than in the United States. However, foreign technologies do not appear to hold any commanding technical leads.

Most of the advanced and exploratory development effort in batteries exists because of the DOE/EPRI programs and other government activities aimed at developing military battery technology. The private funds supporting battery research are mainly devoted to near-term technologies, which are considered product improvements rather than new product development. It could be concluded that battery technology development is viewed by industry as a high risk area with a low expected return on any given venture. Exceptions to this trend include Exxon Enterprises and General Motors efforts in funding battery development work without government support.

At the present pace of battery development, a major new battery technology is at least seven to ten years away. A substantial commitment, on the order of 50 million dollars per program, is needed to bring the three major advanced development battery types to the point in the early 1980's where the prototype batteries can be considered to have reached the program goals. Substantially more money will be required to set up pilot production lines for the successful technologies. Primary concerns for the future include the transition from the prototypes test battery to pilot production and who will pay for the commercialization program.

6.2 RECOMMENDATIONS

It is difficult to make firm recommendations at this point in the study, since the assessment of battery technology markets and in particular the role of competing technologies has not been analyzed.

It is clear, however, that the research and development programs in the past have focused mainly on the achievement of technical performance goals for various alternate battery technologies. As the technical characteristics of these batteries become more clearly defined, the development programs should concentrate on achieving cost goals and accommodating exogenous factors in the battery commercialization process. In the long run, these latter factors may determine which technologies have the greatest potential and permit resources to be concentrated on fewer development programs.

Finally, stronger market pressure on industry to pursue development with its own resources is necessary for more rapid evaluation of battery technology. Separate studies on how to encourage more aggressive private technology development in this area should be conducted.

APPENDIX A

BATTERY TECHNOLOGY SUMMARIES

A.1 NEAR-TERM BATTERIES

Lead Acid Batteries

Lead acid battery technology has been in existence for over 60 years and has proven itself in many applications, such as starting, lighting and ignition for automobiles and as a secondary power source for many other applications. It is also used today in a limited electric vehicle market application. Basically, it represents a well-developed technology, but still has some potential for improvement.

The current characteristics of the lead acid system as used in electric vehicle applications are shown in Table A-1. The variation in

Table A-1. Lead Acid Battery Characterization
(for Transportation Application)

CHARACTERISTIC	CURRENT[1]	PROJECTED-1980
Energy Density	25-30 Wh/kg	50 Wh/kg
Volumetric	60 Wh/L	90 Wh/l
Peak Power Density	50-80 W/kg	150 W/kg
Sustaining Power Density	15 W/kg	25 W/kg
Efficiency	65-70%	>60%
Cycle Life	300-700 Cycles	1000 Cycles
Operating Temperature	Ambient	Ambient
Low Temp. Capacity	Poor	-
Pilot Costs	$100/kWh	$80-100/kWh
Mass Production Costs	$45-80/kWh	$40/kWh

[1]Golf Cart-Traction   Sources: References 3 and 4

energy and power density occurs basically as a result of varying the plate thickness. Higher energy and power densities may be achieved with thinner plates at the expense of cycle life. Longer lived batteries require thicker plates. The current versions of "golf cart" batteries are produced in sufficient quantity to achieve the lower bound of the cost range indicated in Table A-1. Heavy-duty traction batteries (i.e., for industrial use) are still in limited production, so costs are higher. In very high volume production, the battery costs begin to approach those of the basic materials since the production process can be highly automated.

Most improvement in lead acid batteries for traction applications is aimed at achieving higher energy and power density, without compromising cycle life. The key technical problem in reaching these goals is to achieve better utilization of the active battery materials. It means cutting the battery weight wherever possible by use of light weight grids, separators and casings. Attempts also must be made to prevent the active material from degrading and reducing storage capacity as the battery is being cycled, or from corrosion processes taking place in the battery itself.

Predicting the actual improvements that could be made in lead acid technology over the next two or three years is difficult. In general, the battery manufacturers are fairly conservative in their prediction as to possible progress; government research officials seem more optimistic.

The data shown in Table A-1 represent an upper bound of what may be possible with this technology in the near-term. More likely, future lead acid systems will perform only slightly better than those available today, although cost can be reduced by larger scale production.

Extensive near-term development efforts on lead acid batteries are being carried out in Europe, Japan, and the U.S.S.R. Of particular interest are the Japanese systems using a flowing electrolyte concept which has not been pursued in this country. Japanese attempts to achieve high energy density systems have not been successful to date, since these systems are found to exhibit very poor cycle life.

Lead acid batteries use two critical materials, i.e., lead and antimony. Since the lead is recovered at a very high rate from scrap batteries, the lead supply is not a problem unless the rate of battery utilization increases very rapidly. Antimony supplies, about 56 percent imported, could be more critical if battery designs continue to use high antimony levels (1.6 kg/kWh). Alternative designs involving little or no antimony use have been developed for some applications which could mitigate this problem.

Lead acid batteries have safety and environmental problems which arise from the use of lead and antimony, both of which are toxic materials. Most of the problems are associated with the battery manufacturing process, where these materials must be handled in large quantitites.

Several major battery manufacturers are involved in the DOE program to improve the lead acid battery. In addition, industry is spending a considerable amount of its own resources on the near-term technology. The major developers of the DOE/ANL program are ESB, ELTRA, Globe U, and Gould. This would indicate that the lead acid battery will play an important role as an electric energy storage source for transportation for the next several years. Development costs in millions of dollars are estimated to be:

	DOE PROGRAM	INDUSTRY
FY 78	1.85	3-4 (estimated)
Total Estimated Cost (TEC)	12.5	

Nickel Iron Battery

The nickel iron battery is a second battery with a history of more than 50 years of commercial use with continuous development. It has been used in transportation applications in the past, but its fairly high costs have restricted its use more recently to heavy-duty industrial applications where cost is a lesser problem, but long battery lifetime is important. Basically, this is also a well developed technology with some potential for improvement.

The current characteristics of the nickel iron systems are shown in Table A-2. The battery has very good cycle life, but a rather high cost, partially because these batteries are only produced in very limited quantities (pilot scale production) today.

Table A-2. Nickel Iron Battery Characterization

CHARACTERISTIC	CURRENT	PROJECTED-1980
Energy Density	44 Wh/kg	60 Wh/kg
Volumetric	85 Wh/L	110 Wh/L
Peak Power Density	130 W/kg	200 W/kg
Sustaining Power Density	20 W/kg	50 W/kg
Efficiency	55-70%	60-70%
Cycle Life	1500 Cycles	2000 Cycles
Operating Temperature	Ambient	Ambient
Low Temp. Capacity	Poor	-
Pilot Costs	$120-400/kWh	$100-200/kWh
Mass Production Costs	-	$50-60/kWh

Sources: References 2-1, 2-2

The key technical problem with the nickel iron battery is to achieve more effective utilization of the nickel in the nickel electrode to reduce battery costs. This is because the nickel electrode material costs contribute significantly to the costs of the system. Techniques for effectively recovering the nickel from spent cells would also help reduce costs.

Improvements are also possible in the iron electrode, with new designs and fabrication techniques. Methods of obtaining sealed cell operation or handling the venting of hydrogen gas involved during charging are also needed.

A revival of interest in the nickel iron system has taken place in Europe (Germany), probably because of the system's long cycle life.

Nickel iron cells require considerable amounts of nickel which is primarily imported (91 percent). However, since the nickel supply is primarily from nations "friendly" to the U.S., i.e., Canada, the scarcity of nickel is not a "strategic" problem.

Nickel iron batteries appear environmentally benign though some nickel compounds are possibly toxic. Suitable systems for controlling hydrogen evolution during battery charging are required.

Two major battery manufacturers are involved in further development of the nickel iron system with DOE support. About equal amounts of federal and private funds are committed to this technology. In millions of dollars there are:

	DOE PROGRAM	INDUSTRY
FY 78	0.76	0.6-1.0 (estimated)
TEC	7.3	

The major developers of the DOE/ANL nickel iron battery program are Westinghouse, Eagle Picher, and the Swedish National Development Company. A modest improvement is expected in the battery's energy density and cycle life. Improved electrode designs could raise the battery's sustaining power density. Larger scale production would lower system costs, though the high cost of nickel for this system limits the extent to which reductions are possible.

Nickel Zinc Battery

The nickel zinc battery is similar to the nickel iron battery, except that a zinc electrode is used in place of the iron electrode. The result is a battery with considerably higher energy and power density, but cycle life is low because of dendrite formation associated with the zinc electrode.

The current characteristics of the nickel zinc battery manufactured by Yardney are summarized in Table A-3. In addition to the favorable energy and power density, this battery exhibits favorable low temperature characteristics. Its main drawbacks are the short life and high costs for the currently available batteries.

Table A-3. Nickel Zinc Battery Characterization

CHARACTERISTIC	CURRENT	PROJECTED-1982
Energy Density	75 Wh/kg	90 Wh/kg
Volumetric	120 Wh/L	150 Wh/L
Peak Power Density	130-200 W/kg	200 W/kg
Sustaining Power Density	20-50 W/kg	50 W/kg
Efficiency	60-65%	60-65%
Cycle Life	200-300 Cycles	1000 Cycles
Operating Temperature	Ambient	Ambient
Low Temp. Capacity	Good	-
Pilot Costs	$150/kWh	$100-120/kWh
Mass Production Costs	-	$50-60/kWh[1]

[1]By 1985-90. Sources: References 2-1, 2-2, 2-3

Current development efforts are focused on obtaining improved cycle life from this system. The primary cause for poor cycle life is dendrite growth and plate shape changes of the zinc electrode. This can potentially be overcome by better cell separators and other system design changes.

Development efforts will eventually also have to focus on cost reduction, mainly through effective utilization and recycling of the nickel part of the battery.

Foreign technology has produced one variant of the basic nickel zinc battery, the AGA-Tudor vibrating electrode cell (Reference 2-4). This technique apparently overcomes the cycle life problems associated with the cell, but at the expense of lower energy density and higher cost. The commercially available batteries in this country do not use that approach.

Both nickel and zinc utilized in the nickel zinc battery are scarce materials, though zinc is more plentiful. Relatively large amounts of cobalt are also required as an alloying material, so this particular technology is very dependent on scarce materials. Suitable recovery techniques will be required to recover these materials from spent batteries for reuse.

The nickel zinc system appears environmentally benign, although some nickel and zinc compounds are toxic. Means must be provided for controlling hydrogen evolved during battery charging.

Because of its potentially attractive characteristics (as shown in Table A-3) for a more advanced nickel zinc cell, considerable development effort is being conducted in the DOE program and by the battery industry. In addition, a major in-house program exists at General Motors. There is also interest in this battery technology for military applications. The major developers of the DOE/ANL program are Eagle Picher, Energy Research Corporation, Gould, and Yardney. There are no detailed data about DOD programs. Funding in millions of dollars is estimated to be:

	DOE PROGRAM	INDUSTRY
FY 78	1.46	2.0 (estimated)
TEC	10.2	

A.2 ADVANCED DEVELOPMENT BATTERIES

Advanced Lead Acid Battery

The advanced lead acid is a special battery type being evolved from large lead acid storage battery technology, such as that formerly used in submarine propulsion systems. Such batteries could serve for utility load leveling because of their relatively high efficiency and good cycle life.

Table A-4 summarizes the key characteristics of these batteries as currently estimated by battery manufactuers. The key barrier to their utilization by the utility industry is the total system cost. This must be reduced considerably, if this type of battery storage is going to be acceptable to the utility industry.

Table A-4. Advanced Lead Acid Battery Characterization
(for Utility Load Leveling Application)

Source: Reference 2-5

CHARACTERISTIC	CURRENT	PROJECTED
Efficiency	70%	70%
Cycle Life	2000 Cycles	2000-5000 Cycles[1]
Mass Production Costs	\$70-80/kWh[2]	\$40-50/kWh

[1]Westinghouse estimate.

[2]Includes \$25-30/kWh for balance of plant

Currently, in a program directed by Argonne National Laboratory, DOE and industry are spending about equal amounts of money to develop this system. If the development program is successful, such batteries could be made available to the utilities in the mid-1980's. A summary of development costs for the advanced lead and battery program is shown below. Costs are in millions of dollars.

	DOE PROGRAM	INDUSTRY
FY 78	0.3	0.3-0.5 (estimated)
TEC	5.0	

Lithium Metal Sulfide Battery

The lithium metal sulfide battery technology has evolved from work with the high energy density lithium-sulfur couple, begun at Argonne National Laboratory in 1968. Development proceeded in the direction of using metallic alloys of lithium and sulfur for the electrodes, with the current technology, that is the lithium aluminum iron sulfide battery, which emerged only three years ago. Individual cell testing of this system is currently being extended to the development of prototype batteries consisting of perhaps 20-30 cells. The characteristics of the cells currently being tested are given in Table A-5.

Table A-5. Lithium Metal Sulfide Battery Characterization

Source: References 1-1, 2-1, 2-2

CHARACTERISTIC	CURRENT	PROJECTED-1981-85
Energy Density[1]	80-100 Wh/kg	150 Wh/kg
Volumetric	200 Wh/L	250 Wh/L
Peak Power Density	100-120 W/kg	300 W/kg
Sustaining Power Density	No Data	No Data
Efficiency	70%	75%
Cycle Life	500-1000 Cycles[2]	>1000 Cycles
Operating Temperature	450°C	450°C
Pilot Costs	$2000/kWh	$100/kWh
Mass Production Costs	-	$40/kWh[3]

[1]Based on cell data; battery densities likely to be lower by 20-25 percent.

[2]100-130 Wh cells.

[3]1990 cost.

The key problems facing this technology are largely related to the choice of materials and fabrication techniques to produce the cells and eventually batteries. A durable low cost material is still needed for the cell separators. Boron nitride paper is one option being evaluated.

Corrosion of the internal cell structure and case by the high temperature sulfur compounds and the molten salt electrolyte is also a major problem affecting battery life. Successful means of fabricating multiple electrode lightweight cells are needed to meet energy and power density goals. The fabrication techniques are also critical if the battery is to meet reasonable cost goals.

There has been some recent interest in this technology in European research laboratories, but most of the work to date has been done in the U.S.

A key problem with the use of lithium battery technology is that lithium is not a widely used material. Present supplies of lithium are limited and would have to be expanded many fold if the technology was deployed (Reference 2-6) for a significant number of electric vehicles or significant load leveling capacity.

Lithium and its compounds are toxic, and the high temperature lithium and sulfur compounds in the battery are quite reactive. This and other high temperature batteries have special environmental and safety problems that still have to be reviewed in detail.

Development of the lithium metal sulfide battery is a major DOE program headed by Argonne National Laboratory (ANL). Costs in millions of dollars are shown below.

	DOE PROGRAM	INDUSTRY
FY 78	5.0	1-2 (estimated)
TEC	50.0	

(Subcontractors to ANL are Carborundum, Catalyst Research, Eagle Picher, and Gould.) EPRI coordinates its interest in this technology through DOE. Several major battery manufacturers receive support through this program. In addition, General Motors is reported to have a large internal program in this area. Atomics International is also a major industrial developer.

If all development plans were successful, pilot production of the batteries could start in the mid-1980's. By then, the technology should reflect the characteristics shown in Table A-5. By 1990, mass production of this battery would allow the long-term cost objectives to be achieved.

Sodium Sulfur Battery

The sodium sulfur battery was developed from research in solid electrolytes in the late 1960's. It is based on the high energy sodium-sulfur couple and uses a solid electrolyte consisting of either B-alumina or a conducting glass. Most of the development effort on this technology has been with the B-alumina electrolyte, the glass electrolyte being an associated exploratory development project.

The current characteristics of a sodium sulfur battery are given in Table A-6. As can be seen, work with B-alumina systems is considerably more advanced, both in terms of the size of cell being tested, and the cycle life achieved.

Table A-6. Sodium Sulfur Battery Characterization
Source: References 1-1, 2-1, 2-2

CHARACTERISTIC	CURRENT	PROJECTED-1981-85
Energy Density	90 Wh/kg[1]	170 Wh/kg[1]
Volumetric	150 Wh/L	200 Wh/L
Peak Power Density	100 W/kg	200 W/kg
Sustaining Power Density	No Data	No Data
Efficiency	70-80%	70-80%[2]
Cycle Life	500 Cycles[3]	1000 Cycles
Operating Temperature	300-350°C	-
Pilot Costs	$2000/kWh	$100/kWh
Mass Production Costs	-	$40/kWh[4]

[1]For cells, battery is up to 25% lower.

[2]Thermal losses in idle mode not counted.

[3]200 Wh cell (B-alumina); 200 cycles for 10 Wh cell (glass).

The current focus of the research in the more advanced B-alumina program is beginning to scale up from the work on individual cells into batteries. This process will require continued improvements to assure adequate cycle life of multiple cell batteries, which are still affected by failures in the electrolyte (cracking), cell leaks (poor seals), and corrosion of the cell casing by the sulfur compounds. In addition, current fabrication costs for the B-alumina cell "tubes" are very high. Suitable materials and fabrication techniques are also needed for the cell electrodes and casings. Assuming these problems can be overcome in the next few years, sodium sulfur batteries could be put into pilot production by the mid- to late-1980's.

The sodium sulfur battery technology has received a great deal of attention in European and Japanese advanced battery research, with a strong emphasis on transportation applications. Large-scale engineering efforts in the United Kingdom are considerably ahead of the U.S., with 1000 cycle lives achieved on individual cells. Demonstration efforts including fabrication and testing of multicell batteries are currently in progress.

The sodium sulfur battery nominally uses no scarce materials, since sodium sulfur and the mild steel casing are both widely available. Furthermore, these materials are rather inexpensive to obtain, so the eventual materials' related costs for the battery in mass production should be very low.

The main safety and environmental problem associated with the sodium sulfur battery is the high chemical reactivity of the sodium-sulfur constituents. The special safety problems of this battery system still remain to be addressed in detail.

Table A-7 summarizes the major development program in sodium sulfur battery technology jointly supported by DOE and EPRI. Several major corporations are involved in the development program. Eventually, the characteristics of this system would reflect the projected values given in Table A-6. Such a battery system would have high energy density, long cycle life, and the low manufacturing cost desired of the "ideal" battery system.

Table A-7. Summary of Sodium Sulfur Battery Development Program

	DEVELOPMENT COSTS (MILLIONS OF DOLLARS)				
	DOE PROGRAM		EPRI	INDUSTRY (MATCHING)	
	(B-Alumina)[1]	(Glass)[2]	(B-Alumina)[3]	(B-Alumina)	(Glass)
FY 78	3.6	1.0	0.94	1.5-2.0	0.27
TEC	36 (Both)		15[4]	2.5[5]	No Data

[1]Major developer is Ford.

[2]Major developer is Dow Chemical

[3]Major developer is General Electric.

[4]Current total commitment to high temperature batteries which also includes sodium antimony trichloride.

[5]Currently committed funds.

Zinc Chlorine Battery

The zinc chlorine battery is a high energy aqueous battery system using a flowing electrolyte containing the chlorine reactant. The chlorine reacts on an inert electrode and is stored externally from the reaction cell as a frozen hydrate.

The basic characteristics of the zinc chlorine battery are summarized in Table A-8. Current test cells are of the kWh size, but the cycle life of these cells must be improved. The system efficiency must also be higher, especially for utility storage applications. Current systems are still bulky, and eventually control of the flowing electrolyte and the hydrate storage subsystem must be automated.

Table A-8. Zinc Chlorine Battery Characterization

CHARACTERISTIC	CURRENT	PROJECTED-1982
Energy Density	66-95 Wh/kg	80-100 Wh/kg
Volumetric	90 Wh/L	115 Wh/L
Peak Power Density	100 W/kg	150 W/kg
Sustaining Power Density	70 W/kg	-
Efficiency	55%	65%
Cycle Life	200-300 Cycles[1]	1000 Cycles
Operating Temperature	Ambient to 50°C	Ambient to 50°C
Pilot Costs	$2000/kWh	-
Mass Production Costs	-	$50/kWh

[1] 1.4 kWh cell Source: References 1-1, 2-1, 2-2, 2-7

The key technical problems that have to be overcome to make this system practical are as follows:

- The system's cycle life must be improved.
- Series battery systems must be developed to obtain high battery voltages.
- Low cost plastic containers must be developed for the aqueous electrolyte.
- Current ruthenium-titanium electrodes must be replaced by low cost substitutes.
- The systems must be designed for mass production and automated operation.

Current designs of the battery utilize considerable amounts of zinc (60 percent imported) as well as ruthenium and titanium. Use of ruthenium and titanium could pose a materials constraint on the deployment of this technology because of their high cost and limited availability.

The use of zinc and chlorine compounds poses some environmental and safety problems because of the potential toxicity of chlorine and some zinc compounds. Provision must be made for controlling production of free hydrogen and chlorine gas in the battery operation, since they are either flammable or toxic substances.

The work on the zinc chlorine battery is being performed by Energy Development Associates (EDA) with support from DOE and EPRI. This ambient temperature system is the major program alternative to the high temperature battery programs previously discussed. Development costs in millions of dollars are shown below.

	DOE PROGRAM	EPRI PROGRAM	INDUSTRY (MATCHING)
FY 78	0.7 + 4.0 (EES[1])	1.69	2.39
TEC	15	15[2]	3.8 (Current Commitments

The commercialization of this battery system is being examined by EDA and could occur in the mid-1980's.

A.3 EXPLORATORY DEVELOPMENT BATTERIES

Hydrogen Halogen Storage Battery

The hydrogen halogen battery is actually a family of batteries, since different halogens can be used to form a couple with hydrogen. Usually chlorine and bromine are the halogens considered. In this system, the hydrogen and halogen are stored separately from the battery and reacted in a fuel cell to produce electricity. The operational characteristics of the fuel cell part of the system are still being explored, as well as

[1] EES - Funds from Electric Energy Systems.

[2] Total commitment to aqueous batteries, including zinc bromine.

suitable materials to work with the corrosive hydrogen and halogens. Cell recharge is accomplished via electrolysis of the hydrogen halogen reaction products.

Working with the hydrogen and halogen requires some care, since the materials are either flammable or toxic.

Exploratory research into this system is sponsored by DOE at the Brookhaven National Laboratories. Funding in millions of dollars is shown below.

	DOE PROGRAM (Batteries)	DOE PROGRAM (Chemical Storage)	INDUSTRY
FY 77	0.315	0.5	No data
FY 78	0.325	0.5	No data

This program will require considerable development. Projected characteristics of the hydrogen halogen system are shown in Table A-9. Such a system would primarily be envisioned as a storage system for utility load leveling or in conjunction with wind or solar energy systems.

Table A-9. Hydrogen Halogen Storage
Battery Characterization

CHARACTERISTIC	PROJECTION
Efficiency	70%
Operating Temperature	Ambient to 100^{o}C
Cost	\$40-60/kWh for 5-10 hour storage

Source: Reference 2-8

Iron Air/Zinc Air Batteries

Iron air and zinc air batteries have been under exploratory development in many industrial laboratories in the U.S. and overseas because of the potentially high energy density of the iron air and zinc air couples. The data in Table A-10 show that both systems can yield good energy density, but have rather low power density and cycle life. Overall system efficiency is also poor, and it is generally accepted that this cannot be greatly improved.

Table A-10. Iron Air/Zinc Air Battery Characterization
Exploratory Development

CHARACTERISTIC	CURRENT	PROJECTED
Energy Density	80-120 Wh/kg	110 Wh/kg
Peak Power Density	40 W/kg	90 W/kg
Sustaining Power Density	No Data	No Data
Efficiency	40%	40-50%
Cycle Life	150 Cycles	1000 Cycles
Operating Temperature	Ambient	Ambient
Pilot Costs	>$2000/kWh	-
Mass Production Costs	-	$30-60/kWh

Sources: References 2-9, 2-10

To be practical competitors, the power density and cycle life of the systems for electric vehicle applications have to be improved. The systems also have to be automated, since they utilize a flowing electrolyte and external storage. They also have to be designed for much lower costs when produced in quantity.

Extensive work with both systems is being carried out in Japan, with a program of battery and vehicle testing. Hybrid battery systems are used to overcome the low power density of the system, i.e., a lead acid battery is used for short bursts of power.

The zinc air system shares the same scarce materials problems as many other zinc batteries. The iron air system requires no scarce materials. Both systems appear environmentally benign though some zinc compounds are toxic.

Development of the iron air version of this battery is being pursued by Westinghouse with DOE support. Current work involved developing a 40 kWh vehicle battery. If successful, such systems could be in vehicle use by the mid-1980's. Development costs in millions of dollars are shown below.

	DOE PROGRAM	INDUSTRY
FY 77	0.35	No Data
FY 78	0.35	0.125

Lithium Organic[1] Battery

The lithium organic battery is a family of batteries based on utilizing the high energy lithium electrode in an ambient temperature system. Exploratory research has involved testing cells using various metal sulfide cathodes and organic solvents with the lithium anode. Titanium, niobium, and vanadium sulfides are typical of the cathode materials investigated.

From the limited data available, the most complete set of projected characteristics for the battery is given in Table A-11 for the lithium titanium disulfide system. Current tests on cells are yielding a cycle life of about 250 cycles.

Table A-11. Lithium Organic Battery Characterization (Projected on Basis of Li/TiS_2 Cells)

CHARACTERISTIC	PROJECTION
Energy Density	135 Wh/kg
Volumetric	324 Wh/L
Peak Power Density	110 WL/kg
Sustaining Power Density	22 W/kg
Operating Temperature	Ambient
Mass Production Cost	$42/kWh

Source: Reference 2-11

[1]Also known as the lithium sulfide ambient temperature battery.

The use of lithium and titanium in a battery system poses a potential scarce materials problem, since both of these materials are not widely used. Lithium and some sulfide compounds are toxic and thus also pose potential environmental and safety problems.

A modest program of exploratory research is being carried out by DOE as shown below. (EIC Corporation and Electrochemica are the major developers.) However, most of the significant results in this area are drawn from the work done internally by Exxon and used as the basis which characterizes this system.

DEVELOPMENT COSTS IN MILLIONS OF DOLLARS

	DOE PROGRAM	INDUSTRY
FY 77	0.15	No Data
FY 78	0.15	--

Since this battery is in the early stages of development, commercialization is only practical in the long-term.

Lithium Water Air Battery

The lithium water air battery is a third family of batteries to utilize the high energy properties of lithium. It is an outgrowth of the lithium-water primary cell development, which has demonstrated fairly high energy densities. (See Table A-12.)

Table A-12. Lithium Water Air Battery Characterization

CHARACTERISTIC	CURRENT LI-WATER	PROJECTION
Energy Density	160 Wh/kg	300-400 Wh/kg
Peak Power Density	18 W/kg	100 W/kg
Efficiency (System)	Primary Cell	25 %
Operating Temperature	Ambient	Ambient

Sources: References 2-12, 2-13

Concepts for achieving these high energy densities vary, but the system most often proposed utilizes lithium, oxygen and carbon dioxide to form lithium carbonate. This is essentially a primary battery reaction, but the proposal is to reprocess the carbonate to recover the lithium for reuse. The key barrier to achieving a working system has been the lack of hard data with which to design test cells.

Applied research to date has concentrated on studies of the lithium anode, on suitable lithium alloys, and a survey of similar cell types. Baseline cells are being developed to understand cell design parameters. Many technical options have to be explored, including consideration of other more commonly available anode materials, i.e., calcium or sodium in lieu of lithium. Continuing work is also needed to develop better prototype batteries.

The main defect of this battery is its low overall efficiency as a system because of the high energy requirements to recycle the battery materials. Thus, the cycle might be practical only if low cost sources of primary energy are available to the recycle system, or the recycling system has considerably lower energy losses than the electric utility.

Additionally, systems utilizing lithium share the problem of an adequate lithium supply. The lithium systems also potentially have environmental or safety problems arising from the toxic nature of lithium.

The exploratory development work in this battery is carried out by DOE as summarized below. It should be noted that there is considerable military interest in this system because of its high energy density. Again, because the development process is in the early stages, commercialization of such systems seems reasonable only in the long-term. (Lawrence Livermore Laboratory, Lockheed Palo Alto Research Laboratories are the major developers.)

DEVELOPMENT FUNDS IN MILLIONS OF DOLLARS

	DOE PROGRAM	INDUSTRY
FY 77	0.36	No Data
FY 78	0.41	No Data

Redox Batteries

The redox battery is the term used to cover a variety of possible battery systems utilizing separate aqueous solutions as electrolytes carrying the anode and cathode cell materials. The actual electrodes on which the oxidation and reduction reactions take place are inert, and ion exchange between the half cells takes place through a dividing membrane. Various couples can be used, but the most common proposals are for titanium or chromium chloride and iron chloride.

Current laboratory cell development is exploiting previous knowledge and exploring areas such as membrane development, basic electrochemistry, cell hydrodynamics and battery systems analysis. Potentially, the systems should offer very long cycle life because there are no active electrodes to degrade. In reality, reaction kinetics are very slow so the systems have very low power densities. Suitable membrane technologies are needed if the concepts are to be successful.

The material requirements and environmental and safety problems associated with the redox system depend on the actual choice of couple. Exploratory development is proceeding with limited DOE support through NASA Lewis. Development costs in millions of dollars are shown below.

	DOE PROGRAM	INDUSTRY
FY 77	0.38	No Data
FY 78	0.20	No Data

Ionics, Inc., Southern Research, Inc., and Diamond-Shamrock are assisting in the development of the redox battery. This is at best a prospect for long-term commercialization. Projected characteristics of the redox battery are summarized in Table A-13.

Table A-13. Redox Battery Characterization

CHARACTERISTIC	PROJECTION
Energy Density	55 Wh/kg
Operating Temperature	Ambient
Costs	$27-38/kWh

Sodium Antimony Trichloride Battery

The sodium antimony trichloride battery is similar to the basic sodium sulfur battery, but utilizes antimony trichloride in lieu of sulfur. The electrolyte is solid B-alumina. This system operates at about 200°C, which is considerably cooler than other higher temperature batteries.

Prototype work with disc and tubular cells has aimed at improving electrolyte quality and cell life. Twenty watt-hour cells have operated from 500 to 900 cycles, and larger cells are being designed and tested.

The critical material for this battery is antimony, half of which is imported. Also antimony trichloride is very toxic, and this battery will share some of the environmental and safety problems of the high temperature systems.

This system is being sponsored by EPRI and ESB. Development funds in millions of dollars are shown below.

	DOE PROGRAM	EPRI PROGRAM	INDUSTRY
FY 78	0	0.3	0.3 (Matching Funds)

The projected characteristics of the developed system are shown in Table A-14. In general, the lower operating temperature makes this system technically easier to develop than the sodium sulfur battery; however, its lower energy and power density cause it to be an economic disadvantage, especially if fabrication of the B-alumina electrolyte is a major cost of these battery systems.

Table A-14. Sodium Antimony Trichloride Battery Characterization

CHARACTERISTIC	PROJECTION
Energy Density	100 Wh/kg
Power Density	100 W/kg
Operating Temperature	200°C
Costs	$40/kWh

Source: Reference 2-15

Zinc Bromine Battery

The zinc bromine battery is an alternative ambient temperature aqueous battery related to the zinc chlorine battery. The battery is divided into two half cells by a semi-permeable membrane, and uses inert carbon electrodes. The cell solutions are zinc bromide and dissolved bromine gas, respectively.

Experimental cell studies are being carried out to improve the systems power density and cell life. Methods to assure containment of the bromine are needed. Bromine and its compounds are toxic, posing potential environmental or safety problems. Bromine is also not widely used, so battery commercialization would require significantly increased bromine production.

Exploratory development of the zinc-bromine battery is being performed by several organizations with DOE and EPRI support. The development funds in millions of dollars are shown below.

	DOE PROGRAM	EPRI PROGRAM	INDUSTRY
FY 77	0.17	0.20	1.0 (Estimated)
FY 78	0.20	0.20	No Data

General Electric was previously the major DOE program developer; the new contractor is to be determined. Gould is the major EPRI program developer. Activity is reported by Exxon and Diamond Shamrock. The projected characteristics of the developed zinc bromine system are given in Table A-15. If the development process is successful, such batteries could be available by the late 1980's.

Table A-15. Zinc Bromine Battery Characterization

CHARACTERISTIC	PROJECTION
Energy Density	60 Wh/kg
Power Density	20-25 W/kg
Efficiency	75-80 Percent
Mass Prod. Cost	$21-42/kWh
Operating Temperature	Ambient

Source: Reference 2-16

Other Battery Technologies

Because many battery technologies are possible, no assessment of battery technologies can be considered complete unless every possibility is explored. Even within the limits of this study, awareness of several potential battery systems that could potentially be of future interest was generated. These are discussed in the following paragraphs.

High Temperature Calcium-Metal Sulfide Battery

Preliminary experimental work has been carried out at Argonne National Laboratory in fabricating and testing the calcium analog to the lithium-metal sulfide system. Such systems would allow abundant calcium, aluminum, iron and sulfur to be the primary materials for an advanced battery technology.

Reactive Metal Water Air Systems

In this concept, calcium, potassium, or sodium could substitute for lithium in various water air systems. No experimental work has been performed on these concepts.

Hydrogen Systems

If the system requirements for safety (and cost) do not preclude storage and handling of hydrogen, then systems such as nickel hydrogen become attractive. Such systems are currently under development for satellite applications. Their volumetric energy density tends to be low for vehicle applications.

APPENDIX B

DETAILED BREAKDOWN OF BATTERY TECHNOLOGIES

The following listings of major groups of battery technologies include the major types studied in this report and their close variants. Systems utilizing scarce materials such as cadmium, selenium, silver and tellurium are not shown. Some systems utilizing aluminum and flourine are also possible, but are not listed since they seemed only to be mentioned in the literature with no detailed description.

1.0 Near-Term
- 1.1 Lead Acid
- 1.2 Nickel Systems
  - Nickel Iron
  - Nickel Zinc

2.0 Development Systems--Ambient Temperature
- 2.1 Air Systems
  - Iron Air
  - Lithium Water Air (also Lithium Carbon Dioxide Air)
  - Other Reactive Metals Water Air (Aluminum, Calcium, Sodium)
  - Zinc Air
- 2.2 Hydrogen Halogen Systems
  - Hydrogen Bromine
  - Hydrogen Chlorine
- 2.3 Hydrogen Metal Systems
  - Hydrogen Lead
  - Hydrogen Nickel
- 2.4 Lithium Organic Systems
  - Lithium { Niobium Sulfides / Titanium Sulfides / Vanadium Sulfides }
- 2.5 Redox Systems
  - Anodes: Copper, Titanium, Chromium, Tin
  - Cathodes: Bromine, Iron, Antimony

2.6 Zinc Systems

Zinc Chlorine

Zinc Bromine

3.0 Developmental Systems--High Temperature

3.1 Calcium Systems

$Ca\ Al_{2-4}$ / $Ca\ Cl_2$ - Na Cl / Fe S

$Ca_2\ Si$ / $Ca\ Cl_2$ - Li Cl - KCl /

3.2 Lithium Systems

Li / Li Cl - KC 1 / $Fe\ S_2$

Li Al / Fe S

$Li_4\ Si$ /

Lithium Chlorine

Li Al/Li Cl - KCl/C - $Te\ Cl_4$

3.3 Sodium Systems

Sodium Sulfur (B-Alumina Electrolyte)

Sodium Sulfur (Glass Electrolyte)

Sodium / Antimony Trichloride (B-Alumina Electrolyte)

Nickel Trichloride

Iron Trichloride

Copper Trichloride

APPENDIX C

EXTERNAL STUDY REVIEWS AND DATA COLLECTION

In addition to literature sources, meetings to review the results of this study were held with knowledgeable battery researchers and manufacturers. These were supplemented by extensive telephone conversations as noted. More meetings would have been held if time permitted.

Meetings were held with the following organizations or companies and their representatives:

- Argonne National Laboratory--Energy Storage Program
  - Paul A. Nelson, Director
  - N. P. Yao, Associate Director
  - A. A. Chilenskas
  - F. Hornstra
  - W. Walsh
  - R. K. Steunenburg
- Electric Power Research Institute--Advanced Battery Systems
  - J. R. Birk, Project Manager
- Gould, Inc.--Gould Laboratories
  - D. L. Douglas, V. P., Contract Research
  - H. R. Espig, Director, Energy Research
  - B. Burrows
  - R. J. Rubischko
- Lockheed--Palo Alto Research Laboratory
  - E. L. Littauer, Manager, Chemistry Research
- TRW Systems and Energy
  - G. H. Gelb
  - R. R. Sayano

The following telephone contacts were made:

- ESB, Inc.
  - J. Werth
- Exxon Enterprises, Inc.
  - E. Read
- Ford Motor Company, Inc.
  - R. W. Minck

APPENDIX D

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2-7. "Evaluation of a 1 kWh Zinc Chloride Battery System, Energy Development Associates, Madison Heights, Michigan, Sept. 1976.

2-8. "Hydrogen Halogen Energy Storage System - Preliminary Feasibility and Economic Assessment," First ERDA Battery Contractors Coordination Meeting, Jan. 27, 1977.

2-9. "Iron Air Battery Development Program," E. X. Buzzelli, Westinghouse Corp., Presentation to First ERDA Battery Contractors Coordination Meeting, Jan. 27, 1977.

2-10. "Current Status of Zinc-Air and Na-S Batteries in France," A. J. Appleby (see Reference 3-2).

2-11. "Ambient Temperature Electric Vehicle Batteries Based on Lithium and Titanium Di-Sulfide," L. H. Gaines et al, Exxon Research and Engineering Co., Linden, J.J., Twelth IECEC, p. 418, No. 769071.

2-12. "Lithium-Water-Air Battery for Automotive Propulsion," E. J. Littauer, First ERDA Battery Contractors Coordination Meeting, Jan. 27, 1977.

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2-14. "NASA Review of CY76 Redox Program," L. Thaller, First ERDA Battery Contractors Coordination Meeting, Jan. 27, 1977

2-15. "Sodium Chloride Battery Development Program for Load Leveling," ESB, Inc., Yardney, Pa., June 1975.

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3-2. Personnal communication from Samuel H. Nelson, Argonne National Labs, Energy and Environmental Systems, June 1977.

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