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**ENERGY & ENVIRONMENT
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**Status and Evaluation of Hybrid Electric Vehicle
Batteries for Short Term Applications**

A. Himy

July 1995

**ENERGY
AND ENVIRONMENT
DIVISION**

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**STATUS AND EVALUATION OF
HYBRID ELECTRIC VEHICLE BATTERIES FOR
SHORT TERM APPLICATIONS**

Final Report

July 1995

by

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This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Transportation Technologies, Electric and Hybrid Propulsion Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098, with the Lawrence Berkeley National Laboratory.

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1.0 INTRODUCTION

The objective of this task is to compile information regarding batteries which could be used for electric cars or hybrid vehicles in the short term. More specifically, this study applies to lead-acid batteries and nickel-cadmium battery technologies which are more developed than the advanced batteries which are presently being investigated under USABC contracts and therefore more accessible in production efficiency and economies of scale. Moreover, the development of these batteries has advanced the state-of-the-art not only in terms of performance and energy density but also in cost reduction.

The survey of lead-acid battery development took the biggest part of the effort, since they are considered more apt to be used in the short-term.

Companies pursuing the advancement of lead-acid batteries were not necessarily the major automobile battery manufacturers. Innovation is found more in small or new companies. Other battery systems for short-term are discussed in the last part of this report.

We will review the various technologies investigated, their status and prognosis for success in the short term.

To put in perspective the parameters of the new technologies, we should use as reference the desirable goals for the requirements of the Electric Vehicle and the Hybrid Vehicle Energy Storage System.

(Source: INEL Report EEG-EP-10949, September 1993).

ITEMS	PRIMARY ENERGY STORAGE	PULSE POWER
Gravimetric Density	40 -65 Wh/kg	5 to 10 kW/kg
Volumetric Density	90 - 130 Wh/l	10 - 20 Wh/l
Peak Specific Power	600 - 900 W/kg	100 - 1700 W/kg
Cycle Life	1500 deep cycles	100K shallow cycles
Cost	\$200/kWh	\$1000/kWh

Appendix A is a more comprehensive paper on the general energy storage requirements for hybrid systems.

2.0 SURVEY OF BATTERY COMPANIES

The known lead-acid battery companies (most of them visited) are:

Bipolar Technologies Inc., Provo, UT

Bolder Technologies Corporation, Denver, CO

Arias Research Associates, Whittier, CA

Trojan Battery Company, Santa Fe Springs, CA

Electrosource (ELSI), Austin, TX

GNB Battery Inc., IL

2.1 Bipolar Technologies Inc.

This company started work in bipolar lead-acid battery a few years ago under SBIR contracts with the Department of the Navy, essentially for the SDI project, requiring high power pulses for very short times (milliseconds).

The concept is being presently applied to high power pulses for hybrid electric vehicles, with a capability in the range of 1 to 10 Kw/kg for a discharge lasting a few seconds.

The principal reason that the bipolar design has not been considered in the past is the difficulty in sealing the individual bipolar cells. The availability of new materials which can be used for cell seals now makes the bipolar design a viable approach.

Specific energy levels of over 50 Wh/kg are projected by some of the researchers. However specific energies actually achieved and reported are only a fraction of these high values. The principal reason is related to electrolyte considerations. During discharge, sulfate ions are consumed at both electrodes. The electrolyte stored in the electrode pores becomes quickly depleted. There is not sufficient electrolyte which can be stored in the pores of the electrodes to react with the solid reactants. At typical acid concentrations, the porosity required to store sufficient acid is about 90% for both the lead and lead dioxide electrodes. This high projected value is not achievable with the present pasted electrode, which is about 50% porous. Some higher porosity pastes have been developed but they only achieve

55-60% porosity and may lack the mechanical strength in finished electrodes to provide long cycle life.

In order to continue cell discharge and thus achieve higher specific energy, acid must therefore be transported from somewhere else. Acid can be stored in the separator, but a thick separator can substantially increase the cell impedance and lead to low power output. Thus the key to achieving high specific energy and high specific power simultaneously is the development of high porosity electrode structures.

At Bipolar Technologies, work is under way to develop bipolar batteries which employ the Plantè-formed electrode structures with stable porosity values of 70% and higher. Bipolar electrodes are created by first electrodepositing a layer of lead onto both sides of the bipolar foil. The electrode is then passed through rollers which contain large numbers of thin, parallel teeth which cut parallel grooves in the lead, creating a corrugated lead structure. The channels which are thus created are several mils wide and deep and the ridges between the channels are several mils wide. The Plantè corrosion process is then applied to create a porous active material region over all of the lead surface. The active material region has a naturally-stable 50% porosity. When the volume of the channels is also considered, the total porosity of the electrode is 70% or higher. The performance of bipolar cells which use this electrode type is quite high. At a sustained discharge rate, the current density can be as high as 700 mA/cm² versus 8mA/cm² for a VRLA battery.

A lightweight composite material (carbonfluoroelastomer) is used as the bipolar electrode substrate. The material consists of a thin, carbon fiber mat, impregnated with a carbon powder/fluoroelastomer mixture. The material surface is treated to discourage oxygen evolution at the positive electrode side. The individual cells are sealed using the same fluoroelastomer material that is used to make the bipolar substrate (without the addition of the carbon powder). The polymer is applied to the edges of the bipolar electrodes, around the electrode active material, dried and cured so that the seal between the seal material and the electrode edges is a strong chemical bond. This seal is thus impervious to liquid or gas penetration.

Table 1 compares the performance (either actual or projected) of various bipolar lead-acid batteries with those of Bipolar Technologies Inc. It is clear that other bipolar batteries are achieving improvement in specific power primarily through the weight savings inherent in the bipolar design and not through the use of low impedance, due to their need to store large amounts of acid in the intercell gaps. High cell impedance will lead to low overall efficiency during typical use conditions. This is especially evidenced by examining the ratio of power to energy storage for the different systems, which is a measure of the electrode active material.

Table 1. Comparison of Lead Acid Batteries

	Bipolar Tech. Present Design	Bipolar Tech. Proposed Design	Trojan* Bipolar Battery	Arias Bipolar Battery	GM (Delco) "Impulse" Battery	Traditional Parallel Plate
Active Material Thickness (Positive Electrode; mil)	7.5	(15)				
Active Material Thickness (Negative Electrode; mil)	7.5	(15)				
Porosity (Positive; %)	30	(73)				
Porosity (Negative; %)	30	(73)				
Bipolar Plate Thickness (mil)	2	4	30		-	-
Bipolar Plate Density (g/cm ³)	11.4	1.8	10.7		-	-
Separator Thickness (mil)	4	4				40
Cell Thickness (mil)	21	(38)			-	-
Cell Density (g/cm ³)	6.77	(3.23)	(1.64)	(2.08 ^{**})	1.90 ^{**}	2.06 [*]
Specific Power (kW/kg) +	3.5 ^{***}	(4.0) ^{***}	(0.225)	(0.216 ^{**})	0.253 ^{**}	0.160 [*]
Power Density (kW/l) +	24.0 ^{***}	(13.1) ^{***}	(0.370)	(0.450 ^{**})	0.480 ^{**}	0.330 [*]
Specific Energy (W•hr/kg) ++	14.0 ^{***}	(44.0) ^{***}	(55.0)	(55.0 ^{**})	38.0 ^{**}	35.0 [*]
Energy Density (W•hr/liter) ++	94.0 ^{***}	(141.0) ^{***}	(90.0)	(114.0 ^{**})	72.0 ^{**}	72.0 [*]
Power/Energy (hr ⁻¹)	250	(90.9)	(4.09)	(3.93)	6.66	4.57

Values in Parentheses are Projected Values

* Information taken from Trojan trade literature

** Information taken from a private conversation with representatives of General Motors

*** @ 1.8 V/cell. These values are for the battery core, with seals and packaging neglected. The actual values for the entire battery will be lower by approximately 15% when these factors are included. The specific energy and energy density will be higher at higher cell potential, which is where the projections for Arias and Trojan are likely to have been calculated.

+ $\frac{C}{3}$ rate, 20 seconds

++ $\frac{C}{3}$ rate, 100% state of charge

BIPOLAR TECHNOLOGIES

Bipolar Technologies Inc. has presently a contract on bipolar lead-acid battery with the Department of the Navy.

2.2 Bolder Technologies Corporation

This technology is based on the concept of very-thin metal film which leads to a design allowing higher rate capability and fast recharge.

The company was founded in 1991, and presently has 15,000 sq. ft. with a production of 50 cells (cylindrical C size) per day, mostly manually manufactured.

The technology claims:

- advanced thin film lead-acid technology
- low cost
- unconventional configuration
- special wound plates
- opposite current collectors
- full plate length terminal connections
- ultra low impedance
- ultra high power

Table No. 2 shows the capability of this technology.

The conceptual design of the cylindrical C-size cell consists of wound thin foil electrodes, thus forming a large surface area and allowing a high discharge rate. The surface area is 23 cm²/gram, whereas other lead-acid batteries (such as the SLI) allow only 3 cm²/gram. The maximum path length through the active material is only 0.025 inches, whereas it is 0.2 inches in SLI batteries. The current density between the two foil electrodes is uniform due to equal resistance paths. The capacity outputs are 1.42 Ah at the 1-A rate, 1.22 Ah at the 10-A rate and 1.08 Ah at the 30-A rate. At the 30-A rate, the Bolder C-size cell discharge gives 130 minutes to a cut-off voltage of 1.6 V, whereas the nickel-cadmium cell gives only 90 minutes to a cut-off voltage of 0.9 V. A Bolder battery of 12 V can deliver 42 pulses to a cut-off of 9 V, whereas a 12-V nickel-cadmium battery delivers 32 pulses to the cut-off voltage. When normalized to cell capacity, the outputs at various discharge rates (1 C, 5 C, and 20 C), the Bolder battery gives 100%, 90% and 75%, respectively, whereas the conventional lead-acid cell gives 72%, 55%, and 40%, respectively. In terms of peak power, the Bolder battery gives 800 W/kg at 20% depth of discharge (DOD) and 700 W/kg at 80% DOD, whereas the VRLA battery gives 75 and 160 W/kg, respectively. The Bolder battery has been shown to be capable of 5000 10-second pulses at 50 A on 22% DOD.

Table 2. 1.5 Ah Cell Performance

voltage		2.1
Wh/kg		40
Wh/l		150
Cycle life	100% DOD	>300
	20% DOD	>5000
Internal impedance	Ω	$\leq .002$
Inst. Peak Power	(W/kg)	5,000
Shelf life		1-2 years

Bolder Technologies

Bolder Technologies Corporation presently has a contract with ARPA to scale up its battery technology from the cell size of 1.5 Ah (C size) to a cell size of 30 Ah. This kind of battery could make an important, cost-effective contribution for several military and commercial applications, including the development of electric and hybrid vehicles.

2.3 Trojan Battery Co.

The concept of the Trojan battery is based on the lamination of a very thin lead foil over a structural conductive substrate, which could be aluminum or copper. Other companies have used polymer composites utilizing metal, metal oxides or carbon, both in particulate or fiber form. However, the use of these composites is not so simple.

On the negative side, thin pure lead foil of 3 or 4 mils will interface successfully with the negative active material because that too is pure lead.

On the positive side, imperfections in the dense surface corrosion phases cause cracks. These set up differences in local pH and establish areas of different potential within the surface film. One solution is to increase the thickness of the lead alloy foil on the positive, but this will mitigate the weight saving. Trojan's solution is to use a sacrificial layer in contact with the active material. Under this sacrificial layer are several layers of different corrosion-resistant alloy foils. Using compression-welded composite three-layer foils of only one mil, a corrosion life in excess of 2000 deep cycles has been demonstrated.

Trojan Battery Co is now supported by a large battery manufacturer (JCI) to continue this line of work.

2.4 Arias Research Associates

The Arias "Sealed Bipolar Lead-Acid" (SBLA) has been under development for electric vehicles for the past 5 years.

Most of the latest test results were obtained on a 12 V-2 Ah battery, although batteries as large as 12 V-35 Ah have been constructed, but not extensively tested.

The data obtained as of October 1993 are as follows:

- Energy Density at the C/2 rate
on single cell testing: 51 Wh/kg

- Specific Power on a 12 V battery:

100% state of charge	950 W/kg for 20 seconds
20% state of charge	345 W/kg for 20 seconds

- Cycle Life (at C/3 rate and 50% Depth of Discharge)

	> 2800 cycles
--	---------------

These data are based upon the performance obtained from test batteries of 12 V - 2 Ah size and scaled up to a full battery of 90 V - 27 Ah size.

Details on the design and assembly are considered proprietary by Arias Research Associates and have not been revealed to date.

2.5 Electrosorce (ELSI)

ELSI has completed the merger with Horizon Battery Technology, Inc. (HBTI), a company 50% owned by ELSI and 50% by BDM Technologies, Inc., of McLean, VA. ELSI has been funded by EPRI for the R&D work and 12 V-95 Ah batteries have been supplied to Argonne National Laboratory (ANL) for test and evaluation. Approximately 5000 batteries are being evaluated in the field, many installed in electric and hybrid vehicles. ELSI also has a contract with Chrysler for \$75 million over three years for 12 V-85 Ah batteries (the same design as the 12 V-95 Ah, except the height has been reduced by 0.5 inch).

The concept developed by Electrosorce is based on the fabrication of a composite fiber-glass reinforced lead wire used as grid material in a woven mesh structure. Sheathed with a high density lead-tin alloy, this coaxial wire reduces the weight of the positive plate grid. The fiberglass core of this composite prevents growth of the positive grid and provides a dimensionally stable foundation for the positive plate, thus extending the battery life.

Pairs of grids are interconnected to form a bipolar unit. One grid is pasted as a positive grid, the other as a negative. Combining grid pairs, positive of one facing negative of another, in a horizontal array permits the assembly of submodules. The separator is a glass mat. Plates are disposed horizontally to avoid electrolyte stratification. The positive plate design is proprietary.

After seven years of development, the standard unit tested is a submodule of 4 V - 35 Ah size. It surpassed the best comparable battery of conventional design, the Sonneshin 6 V - 160 battery (see Table 3).

Table 3. Comparison with the Sonneshein 6 V - 160 Battery

ITEMS	ELSI	SONNESHEIN
Specific Energy*	40 Wh/kg	31.5 Wh/kg
Specific Power**	440 W/kg	127 W/kg
Cycle Life (cycles)***	929	370

*C/3 rate

**100% state of charge, 20 seconds

***C/3 rate

Table 4 gives the information supplied by Electrosource (ELSI). Table 5 supplied by EPRI shows the data obtained to date by Argonne National Laboratory. The data are not advanced enough to allow a full evaluation of the battery capability.

2.6 GNB Battery, Inc.

GNB has started a major development program of a battery for electric and hybrid vehicles.

The present status of the proposed GNB battery is in a conventional sealed recombinant battery, using a modified 12 V - 100 Ah, 75 Ah and 45 Ah batteries.

GNB expects to get at the 3-hour rate:

170 W/kg
430 W/l
750 Cycles at 80% depth of discharge

To date, GNB has obtained:

39 Wh/kg (DELCO: 35 Wh/kg)
101 Wh/l
300 W/kg at 100% state of charge for 20 seconds
170 W/kg at 20% state of charge for 20 seconds
100 cycles at 80% depth of discharge at C/3 rate (still continuing)

Batteries are also being tested on the DST regime.

GNB has a contract with Ford Motor Company on these batteries and on a bipolar design, started a year ago. No information is yet available on this design.

SUMMARY:

Table 6 gives a summary comparison of the aforementioned batteries from various companies.

Electrosource, Inc.

Table 4. Performance Data

Performance	Initial design (1991)	Current Baseline	Baseline (1994)	Production Goals (>94)
Specific Energy (Wh/kg)*				
C/3 (90 F)	42	45	52	>55
SFUDS (77 F)	38	41	45	>50
DST (77 F)	37	40	44	>50
Energy Density (Wh/l)*				
C/3	88	93	107	
SFUDS	80	85	93	>100
DST	78	82	91	
Specific Power (80% DOD, W/kg)				
J227aD/IETV-1	300	TIP	>300	>300
@ 0.400 Amps/cm ²	200	TIP	>300	
Cycle Life				
C/2 (80% DOD)	>600	TIP	>500	
C/2 (TO 64% CAP @ 1.75 VPC)	>900	>900	>800	
C/3 (100% DOD)	>550	TIP	>400	
SFUDS	300 (100% DOD)	350 (100% DOD)	600 (80% DOD)	600 (80% DOD)
DST	N/A	TIP		

*TE-Van Module

Notes:

SFUDS and C/3 Specific energy are approximately the same at the same discharge temperature

DST is the USABC designated acronym for Dynamic Stress Test.

TIP = Test in Progress

N/A = Not Available

Table 5. EPRI/ANL Lead-Acid Battery Technology Comparison

		GNB EValyte 12-EVB-1180					ELSI H53				
		3-h Rate		D-Cycle	SFUDS	DST	3-h Rate		D-Cycle	SFUDS	DST
		Initial	Last				Initial	Last			
Cycle Number		1	13	6	14	9	11	21	7	8	9
Capacity	Ah	9.2	70.4	79.7	63	61.3	94.6	90	87.7	89.7	82.5
Specific Energy	Wh/kg	37.7	29.0	30.9	24.8	23.3	41.6	39.7	37.7	38.7	35.2
Energy Density	Wh/l	93	71.5	76.2	61.2	57.6	95.2	90.8	80.3	88.6	80.5
Specific Power	W/kg			132					227		
Power Density	W/l			326					519		
Weight	kg	28.9		(Pwr. 0			27.2		(Pwr. 0		
Volume	l	11.7		64 Ah)			11.9		80% of Rated Ah)		

Table 6. Comparison of Batteries from Various Companies

	Bipolar Technologies	Bolder Technologies	Arias Research Associates	Trojan Battery	Electrosorce (ELSI)	GNB Battery
Wh/kg†	14	40	50	—*	42	39
Wh/l‡	94	150	—*	—*	95	101
W/kg	3500	5000	950	—*	440	300
W/l	24000	13100	—*	—*	—*	430
Power/ Energy ratio (by mass)	250	125	19	—*	94	8
Cell Size Tested	1 Ah	1.5 Ah	2 Ah	2 Ah	95 Ah	100 Ah
Cycle Life	2000	300	2800	2000	1000	100

*Data not available.

†At C/3 rate

‡At 100% state of charge for 20 seconds

3.0 RISK ASSESSMENT AND PROJECTIONS

In order to make an assessment and prognosis of success for the short term, the aforementioned technologies have been rated and listed in an order of probability from most likely to least likely success.

GNB, Inc. This company has been well established for a long time, and has a production infrastructure capable of rapid deployment of a low cost battery. Although not the highest in energy density, the battery will certainly satisfy several requirements of the hybrid vehicle and some requirements of the small electric vehicles. It has over 2000 batteries in the field for testing and evaluation in EVs and hybrid vehicles on various regimes.

Electrosources, Inc. (ELSI). This company has established a recognized and significant production line. If the batteries produced on this line show their promising capability after the ANL and the field testing, it will be a good contender for electric and hybrid vehicles.

Bolder Technologies. This company is considered too small to make a dent in the low cost requirement and has not shown yet how a battery meeting the requirements for electric or hybrid vehicles can perform, let alone be produced within a short term. Assuming that scale up to 30 Ah is successful, it will require more funding to establish that a large battery can be produced at low cost.

Trojan. This company has a very good concept, but requires a large infusion of funding to demonstrate, even on a small scale, that such a battery is feasible, can perform as expected and meet the requirements of electric and hybrid vehicles. Its association with a large battery manufacturer may be the key to success, however funding may be required to bring the concept to some measure of success.

Arias Research. This company, although connected with Exide, has demonstrated very little in terms of scale up beyond the 2 Ah size. Not enough is known about Arias Research's concept of bipolar construction to make a real assessment.

Bipolar Technologies Inc. This company has just started to demonstrate that its concept of bipolar assembly is viable. It may be successful in showing the capability of the concept, without producing a large size to be tested in an independent laboratory. It is not likely that such a model or prototype can be produced in the short term.

PROJECTIONS:

The following projections can be made for the next few years:

1998: GNB, Inc. and Electrosorce, Inc. will have acceptable batteries of the required size for large field testing in electric vehicles and hybrid vehicles on various regimes.

2004: GNB, Inc., Electrosorce, Inc., and Bolder Technology will have production facilities for a relatively large quantity of acceptable batteries to be used in actual commercial vehicles.

In relation to the hybrid vehicle requirements as proposed in Appendix A (Tables 2 and 3) on the basis of the NIST and INEL studies, the data as presently obtained or projected for the near future for various lead-acid battery technologies are shown in Table 7 on the basis of the same specifications.

Table 7. Comparison with Hybrid Vehicle Requirements

Items	NIST/ INEL	Bipolar	Bolder	Arias	Electrosorce	GNB
W/kg	750	3500	5000	950	440	300
Wh/kg	50	14	40	50	42	39
Wh/l	130	24000	13100	unknown	unknown	430
Life (cycles)	2000	2000	300	2800	1000	100

Although the energy densities do not meet the proposed guidelines, most technologies meet some of the others. However, those that don't meet the cycle life are the most mature.

4.0 OTHER BATTERY SYSTEMS

Three other systems have been briefly considered: nickel-cadmium, nickel-metal hydride and nickel-zinc

Nickel-cadmium. The only new technology being investigated is done by SAFT. SAFT produced some batteries using a pasted Cadmium electrode, which supposedly could yield up to 53 Wh/kg with a long cycle life.

As a next step, SAFT is exploring a pasted Nickel electrode which could eventually bring the energy density to over 60 Wh/kg, competitive with the Nickel-Metal Hydride battery, but with longer cycle life.

Nickel-metal hydride. Besides the conventional cylindrical and prismatic Ni/MH cell, another technology is being pursued by Electro-Energy Inc. who has a contract with the US Air Force on a bipolar configuration. This technology can yield an energy density up to 70 Wh/kg. Presently, the specific power is 120 W/kg with projection to be higher in the short-term. Cycle life is over 2000 cycles (at 67% depth of discharge) in a vented configuration. Tests on a sealed 5-cell stack have reached 800 cycles with a pressure not exceeding 10 psi.

Nickel-zinc. The conventional designed Ni/Zn battery has been rejected on the basis of short cycle life. However two sources have shown progress in this area:

Lawrence Berkeley Laboratory: 1.5 Ah size cells have reached 600 cycles, with a special electrolyte and conventional centered nickel plaques.

Energy Research Corporation: 5 Ah size cells have reached 600 cycles with rolled-bonded (pasted) electrodes using a calcium-zinc complex in the negative electrode and a special electrolyte.

5.0 CONCLUSION

From this study, only certain types of the lead-acid battery technologies meet the hybrid vehicle requirements of the near future; however, their energy densities are slightly those required. The technologies meeting these requirements are those of GNB, Inc. and Electrosorce (ELSI). Meeting the cost requirement may take a longer time, depending on the success of the battery in the market and the volume of production. However, it is felt that the cost per kWh may never be below the value required. These two types of technologies are presently being tested extensively in laboratories and in the field in actual electric vehicles, although not hybrid. Information on the results of these tests will be obtained shortly and may focus the actual requirements on more realistic numbers, if these technologies are the only ones available for a long time before the advanced batteries under development (only cells are on test in laboratories) are considered reliable enough to be field tested as the present are.

APPENDIX A

ENERGY STORAGE REQUIREMENTS FOR HYBRID SYSTEM

ENERGY STORAGE REQUIREMENTS FOR HYBRID SYSTEMS

ABSTRACT

Energy storage requirements for hybrid electric vehicles (HEV) are proposed for dual-mode and power-assist mode energy storage devices. Presently, there are no energy storage devices that meet all of the specifications for the hybrid application. High-power batteries, flywheels, and ultracapacitors are discussed with regard to meeting the demands of the proposed hybrid energy storage requirements.

INTRODUCTION

The development and subsequent commercialization of hybrid electric vehicles (HEV) are critically dependent upon the advancement of low-cost, high power, energy storage devices. Two primary HEV options are being considered for development by the OEMs: a dual-mode and a power-assist mode HEV. Depending on the mode that is selected, the energy storage requirements are very different. This paper examines the energy storage systems requirements in general terms as they relate to vehicle requirements, proposes a set of energy storage requirements for the dual-mode and power-assist, and then discusses those requirements in light of proposed energy storage alternatives: batteries, capacitors, and flywheels.

ENERGY STORAGE REQUIREMENTS

The basic concepts for relating the vehicle requirements to the requirements for the energy storage subsystem are shown in Table 1.

Table 1. DEVELOPMENT OF HYBRID ENERGY STORAGE SYSTEMS REQUIREMENTS FROM VEHICLE REQUIREMENTS

Vehicle Requirements	Energy Storage Parameter	Storage Requirements Dual Mode	Power Assist
Maximum Acceleration	Peak Power	Power/kg	Power/kg
Hill Climb Headwinds, etc.	Energy & Power	Power/kg Energy/kg	Power/kg Limited Energy/kg
Zero Emissions Vehicle Range	Total Stored Energy	Energy/kg	

The basic requirements for the energy storage system relate to the vehicle requirements in a very direct manner. For the dual-mode, the basic requirements for power are determined by the vehicle's acceleration requirements while the requirement for the total amount of stored energy is determined by the need for a zero emission vehicle (ZEV) range, if any. For power-assist, power requirements are determined again by the vehicle's acceleration requirement. Since there is no ZEV range, there is no energy requirement. For hill climbing, operating against headwinds, towing trailers, or carrying additional loads varying power and energy will be required for the dual-mode. For the power assist-mode, there is a need for power and a limited amount of energy storage depending on the requirement of the vehicle. This set of requirements is harder to estimate, because these loads will

vary with time and individual use patterns.

Table 2 compares the energy storage requirements for the mid- and long-term goals of the USABC, the dual-mode and power-assist specifications obtained from the National Institute of Standards and Technology Workshop Proceedings on Advanced Components for Electric and Hybrid Vehicles⁽¹⁾, and a recent INEL study⁽²⁾ which was aimed at defining the energy storage requirements for HEVs.

Table 2. ENERGY STORAGE SPECIFICATIONS FOR HYBRID VEHICLES

	USABC		NIST		INEL	
	Mid Term	Long Term	Dual Mode	Power Assist	Unassisted	Pulsed Power
Power (kW)	80	80	100	50-70	60-90	50-75
Energy Storage (kWh)	40	40	6-8	0.5-2	3.5-7	0.5-0.75
Weight (Kg)	n/s	n/s	136	23	100	50-150
Specific Power (W/kg)	150-200	400	733	2,200-3,100	600-900	900-1,200
Specific Energy (Wh/kg)	80-100	200	44-59	22-88	35-70	10-12
Power/Energy Ratio	2	2	13-17	25-140	13-17	100
Energy Density (Wh/l)	135	300	n.a.	n.a.	90-130	10-20
Life (Cycles)	600	1,000	2,000	100,000	1,500	100,000
Cost (\$/kWh)	150	100	<133	250-600	200	1,000

n/s = not specified; n.a. = not available.

The NIST data was provided by Larry Oswald on the energy storage requirements GM is seeking to achieve for the dual-mode and power-assist HEV. In the INEL study, the drivelines for the vehicles included both an unassisted (dual-mode) and/or pulse power (power-assist) energy storage devices. The unassisted device was sized to provide a range up to 60 km (38 mi). The vehicles investigated had a 0 to 96 km/h (0 to 60 mph) with acceleration times of 10 to 12 seconds. In comparing the NIST and INEL requirements to the USABC requirements, there are similarities and substantial differences. For the NIST and INEL hybrid energy storage requirements, the energy storage requirements are lower, 0.5 to 8 kWh, than the USABC requirement of 40 kWh, the specific power is higher for the dual mode, 600 to 900 W/kg, and substantially higher for the power assist, 900 to 3,100 W/kg, the specific energy is lower, 10 to 88 Wh/kg, the power to energy ratio is high for the dual-mode, 13 to 17 and substantially higher for the power-assist, 25 to 140, and the cycle life is higher for the dual-mode, 1,500 to 2,000 and substantially higher for the power-assist, 100,000. Finally, all energy storage specifications require that the devices can be produced economically at little or no cost increase to the vehicle if it is to be competitive with the internal combustion engine.

Based on the NIST and INEL specifications and discussion with industry representatives, Table 3 shows a proposed set of energy storage specifications for the hybrid vehicle.

Table 3. SBH* ENERGY STORAGE SPECIFICATIONS FOR HYBRID ELECTRIC VEHICLES

	DUAL-MODE	POWER-ASSIST
Power (kW)	75	60
Energy Storage (kWh)	10	3
Weight (Kg)	<100	60
Specific Power (W/kg)	750	1,000
Specific Energy (Wh/kg)	100	50
Power/Energy Ratio	7.5	20
Energy Density (Wh/l)	130	>20
Life (Cycles)	>2,000	>100,000
Cost (\$/kWh)	<133	<500

SBH* = Sutula, Burke, Heitner

The SBH energy storage specifications show that 1/3 less energy has to be stored for the power-assist than for the dual-mode; the specific power for the power-assist, 1,000 W/kg, is higher than for the dual-mode, 750 W/kg; the power to energy ratio for the power-assist is 2 and 2/3 times the dual-mode power to energy ratio; and >100,000 cycles are required for the power-assist vice >2,000 cycles for the dual-mode.

Figure 1 shows where the SBH energy storage specification for specific power (W/kg) and specific energy (Wh/kg) falls when compared to capacitors, projected flywheel capability, and advanced batteries being developed by the USABC.

Figure 1. PERFORMANCE LEVELS FOR ENERGY STORAGE TECHNOLOGIES

As noted previously, the HEV requires a high-power storage device since it must accommodate all power and regeneration pulses. Since weight is a premium for HEVs, the power per unit weight for the energy storage device is driven toward the high side. In addition, the energy storage system has to store enough energy to handle the load swings found in the urban

driving cycle. Current vehicle use patterns are associated with higher rates of acceleration and deceleration than the Federal Urban Driving Schedule⁽³⁾ which will have a further impact on the energy storage requirement.

TECHNOLOGY ASSESSMENT

As shown in Figure 1, the three technology areas that look potentially attractive for fulfilling the HEV energy storage specifications are flywheels, batteries and capacitors.

Flywheels: Recent reports from Abacus Technologies⁽⁴⁾ and Lawrence Livermore National Laboratory⁽⁵⁾ (LLNL) find that flywheels can meet the requirements for load leveling in an electric or hybrid vehicle. The LLNL study concludes that with current technology, flywheel systems could provide specific energies in the range from 28 to 37 Wh/kg, and peak specific power of 250 to 800 W/kg. These projections of flywheel capability show a close match with the specific power requirements shown in Table 3 for the power-assist and dual-mode. Although the specific energy is on the low side, an improvement in this area could make flywheels very attractive for HEVs provided other issues such as safety are resolved.

Construction of prototype flywheel systems for space and other applications is being pursued by several organizations. The Department of Energy (DOE) continues to follow the development of this technology. DOE under the Hybrid Vehicle Program is investigating the potential use of flywheels and expects to fabricate, test, and evaluate flywheels as a vehicle load leveling device.

Batteries: Very little data exists on using batteries to satisfy the repeated high power demands of a HEV. Two battery technologies considered most often for HEV application are lead/acid and nickel/cadmium. A number of efforts are underway at major battery companies such as Delco, GNB, Johnson Controls, Inc., and Trojan, and smaller R&D organizations such as Arias Research and Pinnacle Research Institute to develop bipolar or quasi bipolar lead/acid batteries with high power capability. Other high power developments such as the spirally wound lead/acid (Boulder Battery Company) are also being pursued.

Although these lead/acid systems may achieve the power requirements for dual-mode or power-assist, it is problematic whether they can achieve long cycle life and higher specific energy than the current 25-35 Wh/kg with 50 Wh/kg projected. Tests by the fuel cell bus program with several types of lead/acid battery using a simulated bus cycle showed severe degradation with cycling. A nickel/cadmium battery was finally selected to avoid this problem⁽⁶⁾.

Nickel/cadmium batteries have good power characteristics and a longer cycle life than lead/acid batteries and can be recharged quickly. The best results shown to date are tests of the Saft STM5-200 on SFUDS which completed over 1,000 cycles⁽⁷⁾. Like the lead/acid system the specific energy for nickel cadmium is on the low side, 40-45 Wh/kg with 55 Wh/kg projected. Several companies, Eagle Picher, Hoppecke, and Saft produce nickel/cadmium batteries for aircraft, aerospace, and the consumer market. Further

development may produce a battery that could meet the specification for power-assist mode but would have difficulty meeting the dual-mode specification because of the low specific energy. Extensive testing will be required to establish the suitability of this technology for HEVs. As a note, the most recent hybrid design made public uses a nickel/cadmium battery in the Volvo Environmental Concept Car.

Other batteries such as nickel/metal hydride, lithium/ion, and lithium/polymer may also have acceptable performance to meet the specifications proposed above. However, no work has been done to design and test these batteries for HEVs under realistic conditions. DOE expects to evaluate these batteries and others as part of its current efforts in HEV propulsion development.

Capacitors: The Department of Energy's Ultracapacitor Program Plan defines mid- and long-term goals for capacitors that could be used to load level an energy source for electric and/or hybrid electric vehicles, and thus, provide pulse power for acceleration and limited hill climbing. The long-term goal is aimed at developing a device that has 1,600 W/kg and 15 Wh/kg. Currently, a single cell device has demonstrated more than 500 W/kg and >5 Wh/kg with cycle life in excess of 100,000 for similar type devices. Current efforts involve developing advanced materials technologies capable of meeting the long-term goals. Furthermore, a small effort has been initiated on interface electronics which will be needed to manage electric energy flow to and from the ultracapacitor. This interface is required because ultracapacitors operate over a wider voltage range compared to the electric drivetrain.

SUMMARY

A set of specifications for the dual-mode and power-assist mode for HEV has been proposed. Conceptually, the energy storage specifications for a HEV could be met by three different technologies: flywheels, batteries, and/or capacitors. Flywheel systems have the potential for meeting the specifications. However, considerable effort is still needed to develop and rigorously test prototype systems. The capabilities of current systems fall short of the energy storage required for HEVs.

The ability of batteries to meet these specifications is questionable because of the high required pulses and subsequent effect on cycle life. Extensive testing of advanced systems will be required to establish the capabilities of batteries for this demanding application.

The ultracapacitor is potentially useful as a secondary energy storage device providing pulsed power for acceleration and limited hill climbing capability in HEV. The technology needs to be further matured through advanced materials development, scale-up, and efficient packaging. In addition, appropriate interface technology has to be economically developed.

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⁶ Christ, A. R., and Kaujman, A., "Phosphoric Acid Fuel Cell Bus Development," Annual Technology Development Contractors' Coordination Meeting, October, 1993.

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APPENDIX B

FOREIGN BIPOLAR LEAD-ACID BATTERY

FOREIGN BIPOLAR LEAD-ACID BATTERY:

Another type of bipolar configuration has been announced by Edison's Research and Development Center located in Trafarelo near Turin (Italy). They claim to have, in an advanced stage, a proprietary bipolar lead-acid battery which is expected to represent an important step forward in EV-technology. They have already manufactured and tested fully operational 12 V-20 Ah bipolar battery prototypes. The major advantage is increase of 30 percent energy density, while cost remains competitive. Due to the high modularity of the bipolar configuration, it was also possible to build larger 72 V battery packs which were able to move a Marbella city-car under real-world conditions. Further improvements are obtained by replacing lead with lightweight conductive material for the electrodes. This would bring the performance closer to the level of the nickel-cadmium battery.

APPENDIX C

PAPERS PRESENTED AT NESEA/EV CONFERENCES

PROVIDENCE, RHODE ISLAND

Within the context of this project, two papers were prepared on the subject of hybrid electric vehicles at the request of the Department of Energy for presentation at the NESEA/EV conference in Providence, RI. The first paper was prepared in conjunction with Ray Sutula who presented the paper in October 1993. The second paper was presented in October 1994 by Albert Himy (Westinghouse Electric Corporation, Machinery Technology Division).

Copies of the papers can be found in Attachment 1 and Attachment 2, respectively.

Attachment 1:

Title: Near-Term Batteries for Electric Vehicles

Authors: Ray A. Sutula (DOE) and Albert Himy (Westinghouse-MTD)

Date: 21-23 October 1993

Attachment 2:

Title: Overview of Various Types of Batteries for Electric and Solar Applications

Author: Albert Himy (Westinghouse-MTD)

Date: 4 October 1994

Title: Near-Term Batteries for Electric Vehicles

**Author: R. A. Sutula, U. S. Department of Energy
and Albert Himy, Westinghouse Electric Corporation**

Date: October 21-23, 1993

S/EV 93 SYMPOSIUM; BOSTON, MA
21-23 OCTOBER 1993

NEAR-TERM BATTERIES FOR ELECTRIC VEHICLES

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ABSTRACT

Battery technologies being developed for electric vehicles (EVs) can be divided into three categories: near-term, mid-term, and long-term. Near-term batteries are lead-acid and nickel-cadmium, while examples of mid-term technologies include sodium-sulfur and nickel-metal hydride. Long-term technologies are being addressed by room temperature and high temperature lithium systems. All technologies require tradeoff considerations involving energy density, power, cycle life, and calendar life versus the cost of the EV battery. Characteristic properties are presented for the near-term lead-acid and nickel-cadmium technologies. Near-term technologies are compared to the mid- and long-term technologies being considered for EV batteries. The United States Advanced Battery Consortium (USABC) criteria for mid-term and long-term EV batteries along with general battery goals are discussed. For near-term application, a two battery system is suggested in which one battery provides the range and the other the power. In future systems, ultracapacitors, which are currently under development, could be used to supply the power.

NESEA
S/EV 93 SYMPOSIUM
BOSTON 21-23 OCTOBER 1993

**NEAR-TERM BATTERIES
FOR ELECTRIC VEHICLES**

A. HIMY (WESTINGHOUSE ELECTRIC CORPORATION)
R. SUTULA (DEPARTMENT OF ENERGY)

EV BATTERY CHOICES

AVAILABLE TODAY

- o **LEAD-ACID**
- o **NICKEL-CADMIUM**

EV BATTERY CONSIDERATIONS

o BATTERY PACK SIZE

- VEHICLE REQUIREMENTS**
- ENERGY AND POWER REQUIREMENTS**
- CYCLE AND CALENDAR LIVES**
- SPACE AND WEIGHT CONSIDERATIONS**

o BATTERY MANUFACTURER

- DISCUSS REQUIREMENTS WITH BATTERY MANUFACTURER**
- DISCUSS AVAILABILITY**
- DISCUSS BATTERY CHARACTERISTICS**
- DISCUSS BATTERY CAPACITY vs DISCHARGE RATES**
- DISCUSS BATTERY CHARGING REQUIREMENTS**
- DISCUSS COST**
- DISCUSS INSTALLATION**

o TESTING

- TEST BATTERY, TEST BATTERY, AND TEST BATTERY**

o SAFETY

- ELECTRICAL: WIRING, DISCONNECT SWITCHES**
- LABELS: HIGH VOLTAGE, SWITCHES, ETC.**
- BATTERY COMPARTMENT: ELECTRICALLY ISOLATED
VENTILATED**

LEAD-ACID

CHARACTERISTICS AND PERFORMANCE

OPEN CIRCUIT VOLTAGE (CHARGED)	2.15 V
CLOSED CIRCUIT VOLTAGE (5 HR-RATE)	1.98 V
CALENDAR LIFE	5 YEARS
ENERGY DENSITY	25 - 40 Wh/kg
POWER DENSITY (FULLY CHARGED)	200 W/kg
(HALF CHARGED)	130 W/kg

LEAD-ACID

APPLICATION TO ELECTRIC VEHICLE (EV) TODAY

ASSUMING A 40 kWh BATTERY AND BEST ADVANCED DESIGN

WEIGHT WOULD BE

1000 kg

RANGE BETWEEN RECHARGES

70 to 100 km

COST (PROJECTED)

\$4000 TO \$6000

NICKEL - CADMIUM
CHARACTERISTICS AND PERFORMANCE

OPEN CIRCUIT VOLTAGE (CHARGED)	1.35 V
CLOSED CIRCUIT VOLTAGE (5 HR-RATE)	1.20 V
CALENDAR LIFE	UP TO 10 YEARS
ENERGY DENSITY	40 TO 55 Wh/kg
POWER DENSITY (CHARGED)	190 W/kg

NICKEL - CADMIUM

APPLICATION TO ELECTRIC VEHICLE TODAY

ASSUMING A 40 kWh BATTERY AND BEST ADVANCED BATTERY

WEIGHT WOULD BE

800 TO 900 kg

RANGE BETWEEN RECHARGES

170 km

COST (PROJECTED)

\$18000 TO \$30000

EXAMPLE OF EV NICKEL - CADMIUM BATTERY

PRESENTLY UNDER CURRENT CONTRACT

CHRYSLER/SAFT

- o 36 kWh BATTERY**
- o 52 Wh/kg**
- o 180 V**
- o \$30000**

COMPARATIVE COSTS

WITH TODAY TECHNOLOGIES

	LEAD-ACID	NICKEL-CADMIUM		
ITEMS		WEIGHT EQUAL TO LEAD-ACID	VOLUME EQUAL TO LEAD-ACID	RANGE EQUAL TO LEAD-ACID
Battery				
Weight (kg)	882	882	368	465
Volume (liters)	368	496	368	257
Range (miles)	40	80	60	40
Payload (kg)	698	698	924	1115
Cost:				
\$per battery	5500	18000	14200	11300
cents/mile	9.8	5.3	5.7	6.5
cents/ton-mile	14.1	7.6	4.1	5.8

COMPARISON WITH FUTURE BATTERIES

	NEAR-TERM		MID-TERM		LONG-TERM
	Best-Advanced Pb/A	Ni-Cd	Ni/MH	Na/S	Li
Range (km)	90	170	240	250	450
Acceleration (sec) (0 to 100 kph)	47	18	14	19	14
Total Life (in km)	27,000	68,000	120,000	38,000	158,000
Available by (best guess)	1994	1995	1996	1996	> 2000

Note: Even the most advanced batteries under investigation store less than 1/5 of the energy per unit weight of gasoline.

USABC CRITERIA FOR EV BATTERIES

ITEMS	MID-TERM	LONG-TERM
Wh/kg	80	200
W/kg	135	300
W/liter	150	400
LIFE (Years)	5	10
CYCLES (80% DEPTH)	600	1000
RECHARGE TIME	< 6 Hrs	3 to 6 Hrs
COST \$/kWh	< 150	< 100

USABC CATEGORIZES THE VARIOUS BATTERIES SURVEYED AS FOLLOWS

- o NEAR-TERM: MATURE**
- o MID-TERM: DEVELOPMENTAL**
- o LONG-TERM: EXPERIMENTAL**

DEFINITIONS OF USABC

- o MID-TERM TECHNOLOGY is one which will result in mass production of EV batteries in this decade"**
- o LONG-TERM TECHNOLOGY is one "with performance competitive with today's internal combustion engine and capable of commercial production early in the next decade."**

GENERAL GOALS

- o MAXIMIZE SPECIFIC ENERGY (Wh/kg) FOR RANGE BETWEEN RECHARGES**
- o MAXIMIZE SPECIFIC POWER (W/kg) FOR ACCELERATION**
- o MAXIMIZE LIFE (cycles and years) FOR MAXIMUM TOTAL MILEAGE**
- o MINIMIZE COST**

REMARKS

- o SPECIFIC ENERGY DENSITY AND SPECIFIC POWER CANNOT BE SIMULTANEOUSLY MAXIMIZED.**
- o IF AN ELECTRIC CAR CLAIMS A LONG LIFE, THE BATTERY HAS TO HAVE A LARGE NUMBER OF CYCLES AND A LONG CALENDAR LIFE. OTHERWISE THE COST OF REPLACEMENT WOULD BE PROHIBITIVE.**
- o COST IS VERY CRITICAL, SINCE THE BATTERY MAY HAVE TO BE REPLACED 2 OR 3 TIMES DURING THE LIFE OF THE CAR**

MEANTIME ALTERNATIVES

- **TWO-BATTERY APPROACH:**

SINCE IT IS IMPOSSIBLE TO SIMULTANEOUSLY MAXIMIZE SPECIFIC ENERGY DENSITY AND POWER DENSITY, USE TWO BATTERIES: ONE WITH MAXIMUM ENERGY DENSITY FOR STORAGE (LONG CRUISING RANGE) AND ONE SMALLER WITH MAXIMUM POWER DENSITY FOR ACCELERATION AND HILL CLIMBING

- **BATTERY-CAPACITOR APPROACH:**

BATTERY PROVIDES ENERGY DENSITY FOR STORAGE AND ULTRACAPACITOR PROVIDES POWER FOR ACCELERATION AND HILL CLIMBING

EVEN WITH AN ALL-ELECTRIC CAR

IN A SURVEY CONDUCTED BY GM, IT WAS FOUND THAT ABOUT 70% OF DRIVERS USE THEIR CARS TO DRIVE LESS THAN 80 km A DAY. THE IMPACT-4 CAR HAS A RANGE OF 110 km (WITH LEAD-ACID BATTERIES) TO 80% DOD.

SURVEY COVERED DRIVERS IN 3 METROPOLITAN AREAS: BOSTON, HOUSTON, LOS ANGELES. 80% OF THOSE SURVEYED PARK THEIR CARS IN THEIR OWN GARAGES OR DRIVEWAYS, MAKING THEM GOOD CANDIDATES FOR HOME RECHARGING.

SUMMARY AND CONCLUSIONS

FOR NEAR-TERM, SOME APPROACHES CAN BE IMPLEMENTED ALMOST IMMEDIATELY IF COST IS ACCEPTABLE

- **TWO-BATTERY APPROACH**
- **BATTERY-CAPACITOR APPROACH**
- **LIMITED RANGE, ACCEPTABLE TO THE MAJORITY OF USERS**

**Title: Overview of Various Types of Batteries for Electric
and Solar Applications**

Author: Albert Himy (Westinghouse-MTD)

Date: 4 October 1994

Paper for NESEA S/EV94
Presented at the RI Convention Center, Providence RI
4 October 1994

Overview of Various Types of Batteries for Electric Vehicle and Solar Applications.

Albert Himy
Westinghouse Electric Corporation

A battery is an electrochemical system equivalent to an engine: it needs a fuel and oxygen which is supplied by air. Ideally the fuel is hydrogen. In the case of an engine, it is supplied in the form of hydrocarbon (gasoline) or alcohol. In the case of an electrochemical system, the system is called a fuel cell. In the case of a battery, the fuel is supplied by a metal located at an electrode, and the oxygen is under the form of an oxide in the opposite electrode. When the battery is discharged, its "fuel" is depleted, i.e. the metal of one electrode is oxidized, while the oxide of the other electrode is reduced. Upon recharge, the electrodes return to their original state.

The battery systems currently existing or under investigation are: lead-acid, silver systems, nickel systems, air systems, lithium systems, and others (working at high temperature).

The criteria established for a viable electric vehicle are:

- the energy density (Wh/kg) which determines the driving range
- the power density (W/kg) which determines the needed acceleration
- the cycle life which determines the total mileage during the battery life
- the calendar life, which determines how long the battery will last, whether used or not
- the recharge time which should be as short as possible
- the cost which should be as low as possible

Let us consider the characteristics of all battery types.

Lead-Acid:

Energy Density: 25-40 Wh/kg
Power Density : 130-200 W/kg
Cycle Life : 500-800
Calendar Life : 4-5 years
Recharge : up to 8 hours
Cost : 150 to 250 \$/kWh

Silver Systems:

They are Silver-Zinc, Silver-Cadmium and Silver-Iron. Due to their high cost and relatively short life, they are not considered for electric vehicle applications.

Nickel Systems:

They are Nickel-Iron, Nickel-Cadmium, Nickel-Hydrogen, Nickel-Metal Hydride, Nickel-Zinc. Because of its very high cost (\$50000/kWh), the Ni/H battery is excluded. The Ni/Fe has shown long life, but is excluded because its high gassing requires frequent addition of water. This leaves only the following systems:

	Ni/Cd	Ni/MH	Ni/Zn
Energy Density (Wh/kg)	50	60	70
Power Density (W/kg)	190	120	300
Cycles	2000	500+	300
Life (years)	10	5+	3
Recharge (hours)	3	3	8
Cost (\$/kWh)	2000	3000	unknown

Air Systems:

Of all air systems, only the Zinc-Air has retained attention for electric vehicle applications. Its disadvantage is the mechanical recharge: once depleted, the zinc electrodes have to be replaced. It offers an energy density of 200 Wh/kg and a power density of 100 W/kg, but to date it has shown a capability of only 200 cycles and

2 years life.

Lithium Systems:

Several rechargeable types are still experimental and in the research stage. They have an energy density in the range of 110 Wh/kg, a power density less than 100 W/kg, and to date a capability of approximately 200 cycles and 3 years life. Their cost is still unknown and a major issue is their safety because of the presence of explosive lithium and toxic elements used in some batteries. The lithium ion battery may be the best candidate.

Others:

Other batteries are the ones operating at high temperature (over 350 degrees Celsius): Sodium-Sulfur, Sodium - Nickel Chloride, and Lithium alloy - Iron Disulfide. The first two are considered for electric vehicles and the last one for solar application. Another operating at room temperature and with a circulating electrolyte is the Zinc-Bromine, considered for solar application.

Their characteristics are as follows:

	Sodium	Lithium	Zn/Br
Energy Density (Wh/kg)	80	80	70
Power Density (W/kg)	150	250	60
Cycles	600	1000	300
Calendar Life (years)	1	1	unknown
Recharge (hours)	8	8	8
Cost (\$/kWh)	2000	2000	unknown

=====
Presently the USABC categorizes the various batteries and defines the technologies as follows:

Near-term : mature

Mid-term : developmental.

Mid-term technology is one "which will result in mass production of EV batteries in this decade".

Long-term : experimental.

Long-term technology is one "with performance competitive with today's internal combustion engine and capable of commercial production early in the next decade".

The criteria set by USABC for electric vehicle batteries are:

	Mid-Term	Long-Term
Energy Density (Wh/kg)	80	200
Power density (W/kg)	135	300
Cycles (80% Depth)	600	1000
Life (years)	5	10
Recharge Time	< 6 hours	3 to 6 hours
Cost (\$/kWh)	< 150	< 100

The general goals are: maximize the energy density for range between recharges, maximize the power density for maximum acceleration, maximize life (cycles and years) for maximum total mileage and minimize cost. The energy density and the power density cannot be simultaneously maximized, always one at the expense of the other. A compromise has to be attained. The battery has to have a long life, otherwise the cost of replacement would be prohibitive. The cost is very critical since the battery may have to be replaced 2 or 3 times during the life of the car.

Assuming a 40 kWh battery, the batteries applicable to an EV in the short term are only lead-acid and nickel-cadmium. An advanced lead-acid battery would weigh 1000 kg, would provide a range of 70 to 100 km and would have a projected cost of approximately \$4000 to \$6000. An advanced nickel-cadmium battery would weigh 800 to 900 kg, would provide a range of 170 km, and would have a projected cost of \$18000 to \$30000.

A comparison between near-term and long-term batteries is in order. Between the two, only the Ni/MH may be usable if its cost is low enough.

	Near-Term		Long-Term		
	Pb/A	Ni/Cd	Ni/MH	Na/S	Li
Range (km)	90	170	240	250	450
Acceleration (sec) (0 to 100 km)	47	18	14	19	14
Total Life (in km)	27000	68000	120000	38000	158000
Available by (best guess)	1994	1995	1996	1996	>2000

Note: Even the most advanced batteries under investigation store less than 1/5 of the energy per unit weight of gasoline.

In the meantime, there are two alternatives:

- o A two-battery approach: since it is impossible to simultaneously maximize energy and power densities, use one battery optimized for maximum energy density for long cruising range and one optimized for maximum power density for acceleration and hill climbing.
- o A hybrid approach: use of electric motor in conjunction with a small IC engine, which will reduce the emission by 70 % now instead of 95% decades from now.

Even with an all-electric car, in a survey conducted by GM, it was found that about 70% of drivers use their cars to drive less than 80 km a day. The Impact-4 car had a range of 110 km (with lead-acid batteries to 80% depth of discharge). The survey covered drivers in 3 metropolitan areas (Boston, Houston, Los Angeles). 80% of those surveyed park their cars in their own garages or driveways, making them good candidates for home recharging.

Solar stationary applications presently evaluated are:

Lead-acid: One unit of 170 kWh (from Delco-Remy)
One unit of 2 MWh (from GNB)

Zinc-Bromine: One unit of 15 kWh (from JCI)

Sodium-Sulfur: One unit of 15 kWh (from Silent Power)

SUMMARY:

Several types of batteries are under considerable investigation for EV applications. Some are more mature than others, but will have a shorter driving range between recharges. Besides the issues of performance, availability, environment and safety, the most important one is the reduction in cost to make an electric vehicle viable and market-accepted.