BATTERIES FOR ELECTRIC AND HYBRID VEHICLES: RECENT DEVELOPMENT PROGRESS

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DISCLAIMER

EXECUTIVE SUMMARY

This report presents the findings and conclusions of a study to determine the status and prospects of advanced high-energy and high-power batteries. Purpose of the study was to assist the California Air Resources Board staff in the assessment of the growing diversity of batteries being developed for electric and hybrid electric vehicle applications.

The author acquired information from developers of advanced batteries in Europe, Japan and North America. The inquiry addressed two major subjects: (1) high-energy batteries with potential for specific energies sufficient to give electric vehicles a range of 150 miles or more on a single battery charge, and (2) high-power batteries capable of meeting the peak specific power and pulse energy requirements for hybrid electric vehicle applications.

High-Energy Batteries for Electric Vehicles

For advanced EV batteries, a time horizon of about 10 years was adopted to insure that promising battery types were surveyed in the study even if still in a relatively early stage of development. While unlikely to provide a 150-mile range for a practical EV, nickel-metal hydride batteries were included as the benchmark for advanced EV batteries. Consideration of battery prospects for higher specific energy and lower costs than nickel-metal hydride led to the selection of lithium ion, lithium polymer and lithium-active sulfur batteries for survey and assessment. Besides specific energy, peak (pulse) specific power, deep cycle and calendar life, materials costs, the present stage of development and (if applicable) commercialization initiatives or plans were used as evaluation factors.

From the information provided by battery developers and his own analysis, the author concludes that nickel-metal hydride (NiMH) batteries are technically mature and have proven themselves in the electric vehicles offered in limited numbers by major U.S. and Japanese automobile manufacturers. A modest capacity for manufacture of NiMH EV batteries exists, and several manufacturers could establish additional production capacities within two years' leadtime. However, the specific energy of NiMH batteries is below EV application goals, and the technical breakthroughs needed to permit a single-charge EV range of 150 miles with batteries of acceptable weight are unlikely. The high costs of current-generation batteries increase the commercialization barriers for electric vehicles, and automobile manufacturers have not ordered EV-design NiMH batteries in the volumes that would justify investment in battery production plants.

Lithium ion batteries have marginal prospects to attain the desired 150Wh/kg, but further advances in electrode materials and cell design could increase specific energy close to the goal. They have excellent specific power and meet the goal for deep cycle life. Achievement of >5 year calendar life still is a challenge for Li ion and requires restricting the periods during which batteries are at full charge and/or elevated temperatures. Proper cell design and cell-level electric controls are essential for safety and long life of Li-ion batteries. Pre-prototype Li ion EV batteries are now available in low volume and at very high costs from a few developers. Reducing the high materials cost and developing low-cost production methods will be critical for achieving acceptable costs.

Developers of lithium polymer EV batteries project specific energies of ≥150Wh/kg and the capability of meeting the specific power levels needed for EV applications. Deep cycle life still needs improvement but calendar life should be satisfactory because of the good stability of the polymer electrolyte that also serves important safety functions. Materials costs are expected to be lower than for lithium ion batteries. Because of the very thin cells and consequent large cell areas needed to meet specific power goals, lithium polymer batteries must be manufactured with high-speed, automated processes if they are to meet EV battery cost goals. Two major programs (centered in Canada and France, respectively) are now focusing on the development of low-cost manufacturing methods. Several carmakers are evaluating engineering prototype modules of the two technologies but have not made substantial battery purchase commitments.

Pairing lithium with organic polysulfides and/or sulfur ("active sulfur") results in ambient-temperature electrochemical cells that have potential for specific energies up to perhaps 400Wh/kg. Small laboratory lithium-active sulfur cells, developed by two U.S. and one Japanese organization for consumer product applications, are demonstrating basic technical feasibility and permit projection of specific energies in excess of 200Wh/kg. Specific power levels also are promising but cycle life still is well below the goals for EV applications. In principle, costs should be lower than for NiMH, lithium ion and lithium polymer, but little cost information on the prospective costs of EV-design lithium-active sulfur cells is available at this early stage of development.

Beyond the technical challenges to develop lithium-based EV batteries, several issues impede their commercialization. The most important obstacle is the uncertain market for electric vehicles. The consequent lack of quantity orders for EV batteries by automobile manufacturers deters aggressive commitments to battery technology and manufacturing development to reduce costs, and it precludes the major investments required to establish mass production facilities. High battery costs, in turn, heighten the EV market risk perceived by carmakers.

This Catch 22 problem is responsible for Sony and VARTA terminating their leading lithium ion EV battery development programs in 1998. Recently, the 3M Company decided not continue as a major partner but only as a contractor in the next phase of the world's largest lithium polymer battery development program, again because of concerns about the large investments and risks involved in attempting to commercialize batteries for electric vehicles.

Clearly, the remarkable progress in lithium ion and lithium polymer EV battery technology development over the past few years is now bringing to a head the issues surrounding commercialization of these batteries. Creative, collaborative strategies engaging the key electric vehicle and electric vehicle battery stakeholders should be developed and pursued, to prevent loss of investments already made, and to build on the opportunities created through the advances of the last several years. These strategies should also include extensive, cost-shared R&D collaboration between government and industry over the longer term to advance the technology of systems such as lithium-active sulfur, which, if successfully developed, could establish electrical vehicles as a fully competitive transportation mode.

High-Power Batteries for Hybrid Electric Vehicles

The key factors determining the suitability of high-power batteries for hybrid applications included peak and pulse specific power, specific energy at pulse power, shallow cycle and calendar life, prospective cost, and commercial availability within the next five years during which a number of hybrid electric vehicles (HEVs) are likely to be introduced. The PNGV goals are a useful preliminary guide for assessing and developing high-power batteries for HEV applications, but they are too narrow in their focus on power assist/regeneration-type HEVs. The author is suggesting to add battery requirements and goals for HEVs with significant battery-only electric range.

Panasonic EV Energy, jointly owned by Matsushita and Toyota, is the first battery company to commercialize a practical battery for HEVs, the Panasonic EV-6.5Ah nickel-metal hydride technology which is used in Toyota's PRIUS HEV. Several other battery manufacturers have developed engineering prototypes of NiMH high-power cells and modules that promise to meet performance goals. Lithium ion batteries can readily be designed for the high pulse power levels required for PA/R HEVs. Sony's development has reached the engineering prototype module stage, and other battery companies have developed engineering prototype cells that meet PNGV performance and cycle life goals. Testing of lithium ion batteries in HEVs will be essential to validate pulse power performance, calendar and shallow cycling life, and safety, under realistic operating conditions. The Bolder thin-film lead acid technology has exceptionally high peak specific power and sufficient specific energy at pulse power to meet the relevant PNGV performance goals for PA/R hybrids, but it has not yet demonstrated the life required for HEV applications.

While there is only one manufacturer of PA/R hybrid batteries now, others are likely to emerge during the next 2-3 years, first of nickel-metal hydride and then lithium ion batteries, possibly also thin-film lead acid batteries if life and cost goals can be met. Volume production can be expected to reduce the costs of these batteries to acceptable levels if not to current goals.

Electric-Range (ER) hybrid electric vehicles with significant driving range on battery power alone pose different battery requirements that have good prospects of being met by appropriately designed nickel-metal hydride, lithium ion and lithium polymer batteries. If successfully developed to meet cost goals, such batteries could enable the development and commercialization of HEVs with sufficient electric range to capture many of the benefits of electric vehicles, but at a lower cost.

In contrast to the situation with EV batteries, the emerging market for hybrid electric vehicles is stimulating increasing efforts by battery companies to develop a considerable variety of candidate technologies with substantially different characteristics. Most of these efforts focus on cell designs and battery capacities for power assist/regeneration hybrid electric vehicles, the HEV type on which automobile manufacturers appear to be concentrating almost exclusively.

The battery requirements and goals for hybrid electric vehicles should be refined and expanded to reflect the emergence of new HEV types. On that basis, the best battery candidates for the most important HEV types should be determined and evaluated extensively in vehicles. Also, HEV stakeholders should develop a better understanding of the cost-benefit trade-offs between the different types of hybrid electric vehicles. This understanding should then be used to (1) determine whether hybrid electric vehicles with significant urban/suburban electric range, and the batteries for such vehicles, should receive more emphasis in federally and privately supported development programs, (2) set rational goals for such programs, and (3) serve as the basis for regulatory treatment of the different types of hybrid electric vehicles.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

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The author would like to thank the participating organizations, without whose cooperation this report would not have been possible. Managers and experts from technical organizations engaged in the development, evaluation and commercialization of batteries for electric and hybrid electric vehicles freely provided information on their programs, progress, plans and perspectives. Many of these organizations also assisted by updating information in the course of the project and reviewing draft sections to ensure currency and accuracy of the information included in this report.

The findings and conclusions presented in this report are, however, the sole responsibility of the author.

SECTION I. INTRODUCTION

I.1. BACKGROUND

In fall of 1995, a Battery Technical Advisory Committee (BTAP) appointed by the California Air Resources Board conducted an assessment and presented a report (Ref. 1) on the prospective performance and availability of batteries for electric vehicle propulsion. Broadly, the report concluded that, despite encouraging development progress, advanced batteries capable of providing electric vehicles with substantially increased performance and range were unlikely to be available in the quantities and at the costs required to implement the near-term provisions of the 1991 Zero Emission Vehicle (ZEV) regulation. The BTAP conclusions were among the factors considered in the 1996 modifications of the ZEV regulations, which now allow several years for continued development and in-vehicle evaluation of advanced batteries, and which call for introduction of commercial quantities of electric vehicles with advanced batteries beginning in 2003.

Since 1996, substantial progress has been made in the development of several different types of advanced batteries intended for electric vehicle (EV) propulsion, and new battery systems with basic potential for yet higher specific energy and lower costs have entered the R&D stage. On the other hand, several important EV battery programs have been discontinued. Finally, the emergence of hybrid electric vehicles (HEVs) has introduced a new perspective in battery development, raising the question whether advanced batteries will become available to provide the specific power and meet the cycling requirements for hybrid vehicle duty. Clearly, ZEV regulatory strategies for the year 2003 and beyond need to take into account recent changes in the status, requirements and prospects of advanced EV and HEV batteries.

I.2. PURPOSE AND SCOPE

The purpose of the study summarized in this report was to survey recent progress in advanced batteries, in order to assist the staff of the California Air Resources Board in its evaluation of the growing diversity of batteries being developed for electric and hybrid vehicle applications.

While including the battery types assessed in 1995 by BTAP, the scope of the present survey differs from the earlier one. In particular, this study pays special attention to batteries with metallic lithium negatives because of their potential to attain the very high specific energies (e.g. 150Wh/kg and more) desired to give EVs more competitive range. Also, it includes batteries capable of delivering the very high levels of peak specific power (e.g., >600W/kg) required for HEV applications.

A time frame of approximately ten years was adopted for EV batteries, in the belief that availability of several advanced battery types – as well as continued progress in the development of new, yet more capable systems – can be expected over that period and should be considered in the review of regulatory strategy. A shorter time frame was adopted for high power batteries. Here, the ongoing development and near-term introduction of hybrid electric vehicles by several major automobile manufacturer are creating shorter-term needs and opportunities for improved high power storage technologies.

I.3. STUDY APPROACH

Similar to the BTAP survey, the present study employed the following means of obtaining and evaluating information:

Use of questionnaires to solicit pertinent information from organizations engaged in the development of advanced battery/electrochemical energy storage technologies with potential for high specific energy and power, respectively. The two questionnaires are reproduced in Appendix A; the U.S., European and Japanese organizations contacted are listed in Appendix B.

Visits to most of these organizations (see Appendix B) to discuss the status of their technologies, key technical and cost issues remaining to be resolved through continued development, and plans and schedules for commercialization (if applicable).

Critical review of the information collected, identification of knowledge gaps, and solicitation of additional information from developers. In addition, the author reviewed recent papers in the technical literature with respect to research advances that, if successfully translated into technology, could improve the performance and/or reduce the cost of specific battery types.

Review of report draft material with information sources to assure accuracy and avoid inadvertent publication of data and other information given to the author in confidence.

Preparation of this report, which summarizes the author's findings and conclusions.

The findings on electric vehicle battery development are summarized in Section II, which begins with a discussion of EV battery performance requirements. Section III discusses the battery requirements of different hybrid electric vehicle types, and it reviews the technology status of high power batteries; comments on a several promising ultracapacitor developments are appended in Appendix C. Section IV presents the author's conclusions and includes several recommendations for consideration by the Air Resources Board and/or other organizations committed to the success of ZEV regulation and (H)EV commercialization.

SECTION II ADVANCED BATTERIES FOR ELECTRIC VEHICLES

II.1 EV BATTERY REQUIREMENTS

The 1995 BTAP study evaluated candidate EV battery systems by comparing their prospective performance, cycle life and cost with the USABC mid-term goals (see Ref. 1). Focusing on these goals rather than on the more ambitious USABC long-term goals was appropriate because of the near-term focus of the 1995 study on battery prospects for 1998. Also, in 1995 even the mid-term USABC goals represented large performance increases over lead acid and nickel-cadmium, the only EV batteries commercially available at the time of the BTAP survey.

Since then, nickel metal hydride (NiMH) EV batteries have become commercially available and are being used in the electric vehicles manufactured in limited quantities by Honda and Toyota and now also in EVs made by the major U.S. automobile manufacturers. These batteries represent major advances – especially in specific energy – over lead acid and nickel-cadmium, and they have generally performed well in practice. Their costs far exceed the USABC criteria, however. Also, NiMH batteries capable of providing the driving range expected by the majority of automobile users would be very heavy. In combination, these shortcomings are contributing to the sluggish sales of the new generation of otherwise much-improved electric vehicles.

With these considerations in mind, the current study is focusing on battery types with inherent potential for substantially higher specific energy and lower cost than NiMH. However, rather than using the USABC long-term goals as the new yardstick, the author elected to use a set of somewhat less stringent requirements against which to assess candidate advanced battery systems. These requirements and the corresponding mid- and long-term goals of USABC are shown in Table II-1; the underlying considerations and assumptions are discussed below.

Specific Energy. The "kWh-mileage" (in analogy to "fuel mileage" in mpg, the number of miles per kWh used by an electric vehicle) can be expected to increase significantly in the coming decade due to several factors: increased efficiencies of power conversion devices and other electric power train components; improved energy recovery through use of higher power and more efficient batteries (see Section III); and reduced battery, component and vehicle body weights[1].

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[1] *For example, Honda's new "INSIGHT" hybrid vehicle weighs less than 2000 lbs despite the fact that the hybrid drive system is somewhat heavier than a conventional power train of comparable power rating. The weight goal for the hybrid vehicle prototypes being developed by U.S. automobile manufacturers under the PNGV program is 2000 lbs.*

Table II–1. Requirements and Goals for Electric Vehicle Batteries

Battery Characteristics	USABC (mid-term)	USABC (longer-term)	Author's Suggestions
Requirements			
Electric Range (miles)	~ 100	~ 150	~ 150 (200^b)
Weight (kg)	250^a	150^a	150
Capacity (kWh)	20^a	30^a	25
Power (kW)	35 – 40^a	60^a	50
Life (years)	≥ 5	≥10	≥10
Cost ($)	~ 3000^a	~ 3000^a	~ 5000^a
Goals			
Specific Energy (Wh/kg)	≥ 80 – 100	≥ 200	≥ 150
Peak Specific Power (W/kg)	≥ 150	≥ 400	≥ 300
Cycle Life (80% DoD)	≥ 600	≥ 1000	≥ 1000 (≥500, 5-yr.battery)
Specific Cost ($/kWh)			
- for 5 year battery	≤ 150		≤ 150
- for 10 year battery		≤ 100	≤ 200
Battery Life Cycle Cost (approximate) (¢/mile)	~ 6.3^a	~ 4^a	~ 6.3^a (5.2^{b,c})

[a] Inferred from battery life and cost goals, [b] for high-efficiency, lighter-weight EV delivering 6–7 miles per kWh, [c] assuming battery life determined by cycle life.

The author is assuming that, as a result, EV mileage will increase from around 4-5 miles/kWh for a current state-of-the art EV (without air conditioning) in a urban/suburban driving cycle to perhaps 6-7 miles/kWh in the next decade. In that case, a 25 kWh battery can provide an EV range of 150-200 miles per charge. To keep battery weight at a desirable 150±15kg, specific energy needs to be at least 150-180 Wh/kg.

Specific Power. Because of the high torque of most electric motors at low speeds, an EV battery peak power of 50kW is considered adequate, especially if the vehicle weight reductions and efficiency increases sought by all major carmakers for advanced-technology vehicles are attained during the coming decade.

To achieve this power level, a battery weighing 150±15 kg needs to have a peak (pulse) specific power of at least 300-370W/kg. (As is obvious but rarely mentioned, there is a trade-off between specific energy and specific power: for a given kWh capacity, a heavier battery with lower specific energy needs less peak specific power to deliver the same peak power as a lighter battery. This is an important consideration especially for hybrid batteries, see Section III.2, below.)

Life. Five years (USABC mid-term target) is considered a reasonable minimum battery life requirement. Its implications are a) a minimum "stand" (calendar) life of 5 years, and b) the ability to deliver at least 500 deep (for example, 80% of capacity) cycles, calculated as follows: lifetime miles delivered: 12,000 miles/year x 5 years = 60,000 miles; maximum number of miles per cycle: 80% of 150 = 120; resulting minimum cycle life requirement 60,000÷120 = 500 cycles.

A highly desirable ten-year battery life requires a corresponding calendar life and the capability for 1000 deep cycles. Battery cycle life is defined as the number of deep (80% of capacity) cycles over which the EV battery can be operated until it can no longer deliver a) 80% of the original energy storage capacity, and b) the rated peak power after 80% of the available battery capacity has been discharged; for most if not all batteries, b) is the more severe requirement.

Cost. The USABC battery cost goals are based on the postulate that, to be accepted by a large number of owners, electric vehicles need to be cost-competitive with conventional vehicles, with no credits allowed for any special features and benefits of EVs. The 1995 BTAP report, the present survey and most other studies indicate that it will be extremely difficult for EV batteries to meet these goals, especially the $100/kWh long-term cost goal of USABC.

The author's suggestion to relax battery cost requirements (see Table II-1) is based on the following considerations: The USABC near-term specific cost goal of $150/kWh applies to a 5-year battery, and it suggests acceptability of a battery cost of about 6.3 cents/mile[1], calculated with the following assumptions: battery capacity 20 kWh @ $150/kWh; battery cost of 20 x 150 = $3,000 depreciated linearly over 5 years; interest on undepreciated battery cost 10%; vehicle operation 12,000 miles/year. If a 6.3 cents/mile ownership cost is allowed also for a 10-year battery (10-year depreciation), its permissible specific cost becomes a more realistic $200/kWh.

II. 2 CANDIDATE EV BATTERY STSTEMS

Candidate systems for inclusion in the survey are identified below. Consistent with the study's focus, the emphasis is on battery systems with potential for higher specific energy and lower cost than current nickel-metal hydride EV batteries. The prospects of these systems for attaining specific energies of 150-180Wh/kg or more in practical batteries are examined first. This is followed by a brief discussion of battery active (electrode) materials costs, the most fundamental and often the largest component of battery cost.

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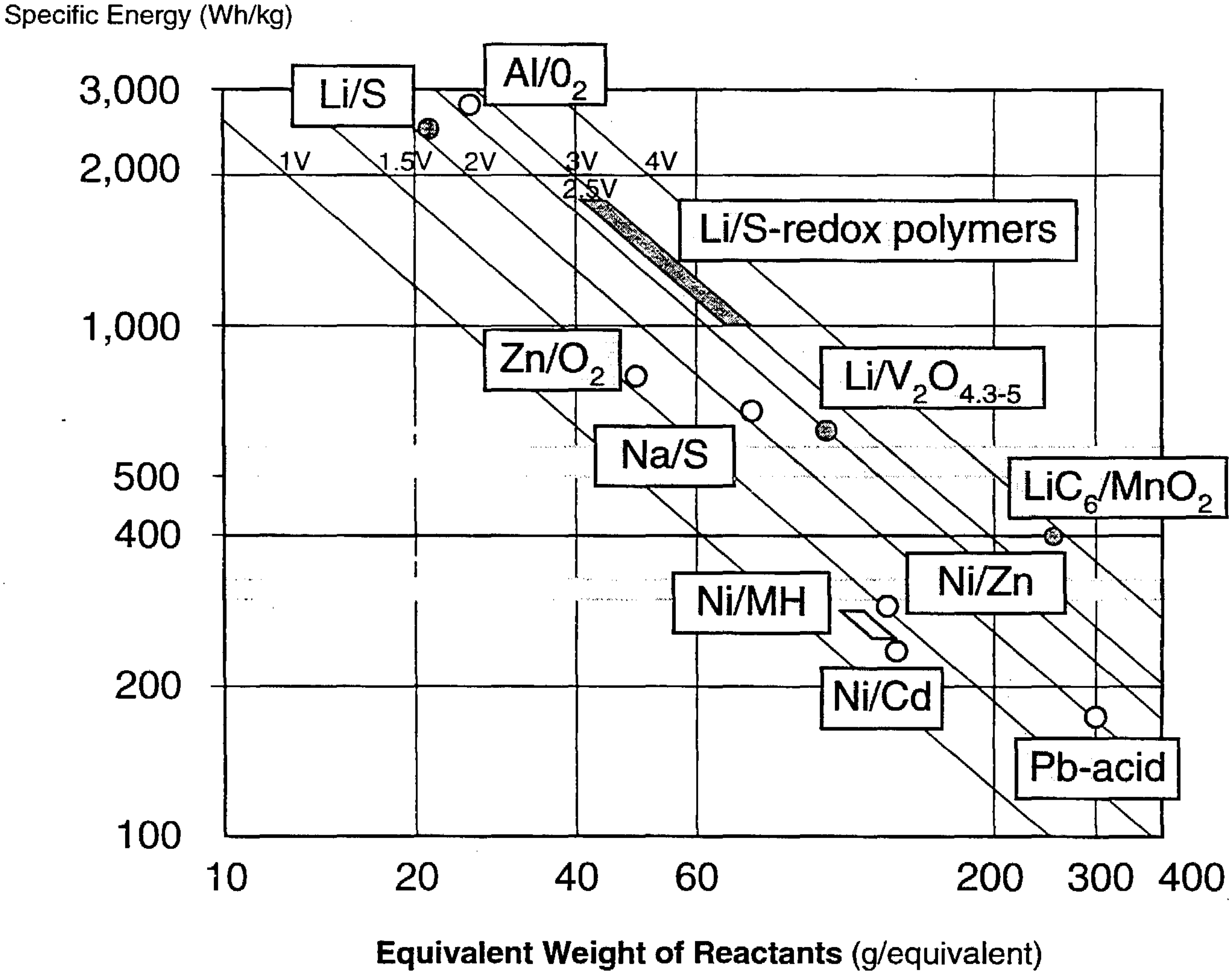
[1] *In practice, some of the per-mile cost contributed by batteries will be offset by the lower energy cost of EVs as well as by environmental and other credits that may become available.*

A Specific Energy

The theoretical maximum specific energy[1] of electrochemical battery systems is plotted in Figure II-1 as a function of the combined equivalent weights of battery positive and negative materials, with the cell voltage as parameter. For example, a hypothetical battery system with a combined positive plus negative equivalent weight of 200 grams and a cell voltage of 4 volts would have a theoretical specific energy of 500 Wh/kg.

Figure II-1.Theoretical Maximum Specific Energies of Electrochemical Battery Systems



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[1] *The theoretical maximum specific energy E_T is the energy content of stoichiometrically matched positive and negative electrode materials of an electrochemical battery system, calculated as follows: $E_T = 26.8$ Ah x $V_T/(W_+ + W_-)$, where V_T is the theoretical cell voltage (in volts), W_+ and W_- the equivalent weights (in grams) of the positive and negative electrode material, respectively.*

Also shown in Figure II-1 are a number of candidate EV battery systems. For all but the lithium-based systems, theoretical maximum specific energies were calculated from combined equivalent weights and theoretical cell voltages. For lithium systems that use chemically ill defined lithium intercalation negative and/or positive electrodes, approximate equivalent weights and the averages of the open circuit cell voltages observed during discharge were used to derive approximate values of their maximum specific energy.

The significance of the shaded bands shown in Figure II-1 at 270-330Wh/kg and 500-600Wh/kg, respectively, is as follows. Battery engineering and manufacturing experience to date indicate that it is extremely difficult to realize more than 30% of the theoretical maximum specific energy in a practical, complete battery designed for long cycle life and with the necessary controls. The implication is that battery systems with potential to meet the USABC near-term specific energy criteria of 80-100Wh/kg must have theoretical maximum specific energies of at least (80-100) $\div$ 0.3 $\approx$ 270-330Wh/kg. Similarly, the specific energy requirement of 150-180Wh/kg for a practical battery implies theoretical maximum specific energies of at least 500-600Wh/kg – the upper band in Figure II-1.

On that basis, it is clear why **lead acid** and **nickel-cadmium** batteries fall well short of meeting even the relatively modest USABC mid-term specific energy criteria/requirements. **Nickel-metal hydride** batteries based on the currently used AB_2 and AB_5 negative electrode compositions (see Ref. 1, pp. III. 11-18) barely meet these criteria and have no prospects for attaining ≥150-180Wh/kg. The same is true for **nickel-zinc** and **manganese dioxide-zinc** batteries that are handicapped further by the poor cycling performance of zinc negative electrodes.

Very few battery systems not based on lithium have theoretical maximum specific energies above 500-600Wh/kg and also at least some rechargeability. The **zinc-air** battery belongs in this category, but inadequate cycle life and poor specific power have long prevented electric vehicle applications of electrically rechargeable zinc-air batteries. In recent years, batteries recharged "mechanically" by replacing discharged electrodes with fresh zinc negatives have demonstrated specific energies above 150 Wh/kg in EV applications. While such batteries can have simple construction and are potentially inexpensive, they suffer from two handicaps: to minimize battery capital and exchange costs, thick zinc electrodes must be used that limit peak specific power to well below 300W/kg. Also, special zinc electrode regeneration and/or exchange infrastructures are required. Mechanically recharged zinc-air batteries may have merit in battery-battery hybrid power sources for buses and other fleet vehicles. The infrastructure technology and cost implications of such batteries were outside the scope of this report but were recently analyzed (Refs. 2 and 3).

The **aluminum-air** battery has a theoretical specific energy of nearly 3000Wh/kg, highest among potentially practical battery systems, and aluminum is the least expensive battery negative electrode material per equivalent weight (see Table II-2, below). Secondary aluminum-air batteries are not technically feasible, however, because aluminum cannot be recharged from aqueous electrolytes. Mechanical recharging has been explored, but large irreversibilities in battery discharge as well as in aluminum production would make aluminum-air very energy-inefficient as an electric vehicle battery. Low power density for the same reasons as for zinc-air batteries, and aluminum corrosion (self discharge) with associated hydrogen gassing, are additional significant technical issues. No serious efforts to mitigate the underlying fundamental problems appear to be underway. In contrast to lithium, aluminum is difficult to discharge in organic electrolytes. Conditions under which the metal exhibits electrochemical activity in such electrolytes have been described only recently (Ref. 4), and no aluminum-based, rechargeable electrochemical couples appear to have been discovered. Breakthroughs in aluminum nonaqueous electrochemistry might justify future consideration of aluminum as the basis for very high specific energy and low cost batteries.

The **sodium-sulfur** battery was considered promising for EV applications because of its high theoretical specific energy and low materials costs, although its operating temperature of around 300°C is probably somewhat of a handicap for EV applications. After many years of development to the prototype stage, this battery was abandoned by RWE in Germany in 1995 (see also Ref. 1, pp. III 30-35). Three years later, work on the **sodium-nickel chloride** ("ZEBRA") battery – like sodium-sulfur, based on a sodium ion-conducting ceramic electrolyte – was terminated by Daimler Benz. This was unfortunate not only in view of the good performance and long life demonstrated by the ZEBRA battery in experimental EVs, but because the technology had been advanced to the point where a commercial-scale manufacturing facility could have been built. However, in the face of the uncertain prospects for EVs, Daimler Benz apparently judged the large investment in a battery manufacturing plant too risky.

Figure II-1 indicates that electrochemical systems with lithium-based negative electrodes now offer the best hope for secondary batteries with high specific energies. Several of these systems are plotted in Figure II-1; all use organic electrolytes since lithium is not stable in, and cannot be recharged from aqueous solutions.

Lithium ion batteries (represented in Figure II-1 by LiC_6/Mn_2O_4) use solutions of lithium salts in polar organic solvents as electrolytes. Chemical reactions of lithium with the organic solvents are kept to acceptably low levels by allowing lithium to intercalate into carbon/graphite "host" materials during charge. Despite the associated weight penalty, the theoretical specific energy of lithium-ion batteries with manganese-, nickel- or cobalt-oxide-based positives is around 330-440Wh/kg, indicating a practical potential of about 30% x (330-440)≈100-130Wh/kg for a complete battery. Li ion batteries for EV applications are now under development at a number of prospective manufactures. While it is unlikely that 150Wh/kg (nearly 45% of the theoretical maximum) can be achieved with manganese-based positives, nickel- and mixed-oxide positives offer better prospects. Also, possibilities appear to exist for increasing the lithium storage capacity of the carbon/graphite negative host materials and, with it, battery theoretical and practical specific energy. Because Li ion batteries promise to exceed the specific energy of NiMH batteries by 50-100%, the progress of the leading development programs is included in this review.

Armand first proposed (Ref. 5) to utilize in batteries the discovery that polyethylene oxide, a polymer stable in contact with lithium, is capable of dissolving sufficient lithium salt for adequate Li^+ ion conductivity at temperatures above approximately 60°C. This discovery is now enabling the use of metallic lithium in secondary batteries that use transition metal oxides as positives capable of intercalating lithium ions, the discharge product. These **lithium polymer** batteries offer prospects for for significantly higher specific energies than lithium ion systems. For example, the currently preferred combination of lithium negatives with various vanadium oxides as positive host materials for lithium ions has a maximum specific energy of around 560Wh/kg and thus potential for a practical 150Wh/kg battery. Lithium polymer batteries are now being developed in two important programs that are discussed further below.

Figure II-1 includes two other battery systems with metallic lithium negatives, which utilize sulfur-containing positives of low equivalent weight. These **lithium-"active sulfur"** battery systems have very high theoretical specific energies, ranging up to nearly 2500Wh/kg for the lithium-sulfur system. In principle, therefore, lithium-active sulfur batteries should readily exceed 200Wh/kg specific energy. While development of these batteries has only reached the stage of small pre-prototype cells for consumer applications, the longer-term potential of lithium-active sulfur batteries for very high specific energies and low costs motivated their inclusion in this survey.

B. Costs

Many factors contribute to battery cost: the costs of active (positive and negative) materials, conducting electrode support materials and conductivity additives, the electrolyte including solvent and salt, the separator, and other materials needed for cell, module and battery construction; the cost of manufacturing cells and assembling modules and batteries; and the cost of the electric and thermal control systems. Of these factors, only the active materials costs are intrinsically associated with the electrochemical battery system; all others reflect the technical execution (the technology) of the system as a practical secondary battery.

When gauging the prospective costs of battery systems, is useful to consider their active materials costs. This is especially true for multi-kWh systems that use relatively expensive active materials, as is the case for advanced EV batteries. Here, the cost of active materials, electrolytes and separators often exceed 50% of the costs projected for mass-manufactured batteries. Because high specific energy secondary batteries are produced by broadly similar techniques, the differences in active materials cost tend to account for much of the difference in manufactured costs.

Table II-2 summarizes cost information on negative and positive active materials used in the advanced EV batteries identified in the previous section. Materials cost information was obtained from various sources, including battery developers, materials suppliers, published reports, and commodity prices. Where cost data for a material were obtained from more than one source, they were averaged. Generally, the data should be regarded as approximate, and they certainly are subject to both fluctuations and systematic change. Projected future costs for materials purchased in quantity are indicated by arrows in Table II-2.

The table also lists the chemical and electrochemical data needed to calculate the minimum costs of the positive and negative electrode materials per Ah of charge storage capacity. Data for the maximum practical extent of lithium intercalation, expressed as the fractional number of lithium ions or atoms stored per molecule of positive or atom of negative host material, were taken from the literature.

Table II–2. Minimum Cost of Charge Storage in Active Materials

Active Material	Cost ($/kg)	Cost (¢/g)	Atomic or Molecular Wt. (g-eq.)	No.Electrons per Atom or .Molecule	Effective Equivalent Weight (g)	Cost per Equivalent Wt. (¢/g-eq.)	Minimum Cost of Charge Storage (¢/Ah)
Negatives							
Lithium	60[a]- 90[b]	6- 9	7	1	7	42-63	1.6[a] -2.4[b]
Graphite/C[c]	35→14	3.5→1.4	12	1/6	72	250→100	9.3→3.7
AB_2 Alloy	12→9	1.2→0.9	~190[d]	~3.5[d]	~54	65 →49	2.4→1.8
AB_5 Alloy	18→15	1.8→1.5	~432	6	~72	130→108	4.85→4.0
Positives							
Sulfur	<1	<0.1	32	2	16	<1.6	<0.06
NiOOH	12→9	1.2→0.9	76	1	76	91→68	3.4→2.5
$V_2O_{4.3-5}$	~10	~1.0	~175	~1.5	~115	~115	~4.3
$LixNiO_2$[c]	52→33	5.2→3.3	84	0.6	168	728→462	27.2→17.2
$LixCoO_2$[c]	65→42	6.5→4.2	84.5	0.5	169	1100→710	41→26.5
$LiMn_2O_4$[c]	35→14	3.5→1.4	181	1	181	634→253	23.6→12.1

[a] Bulk lithium metal, [b] lithium foil, [c] material used to fabricate cells in discharged state,
[d] data provided by Ovonic Battery Co.

In Table II-3, the cost data from Table II-2 for positive and negative charge storage capacities are combined for the candidate advanced battery systems discussed further below. The systems' active materials costs per kWh of cell capacity are then calculated by dividing charge storage costs by the respective cell voltages and converting from ¢/Wh to $/kWh.

Table II–3. Minimum Specific Cost of Battery Active Materials

Battery System	Min. Cost of Charge Storage		Min. Cost of Charge Storage (Cell) (¢/Ah)	Cell Average Voltage (Volt)	Minimum Cost of Cell Active Materials ($/kWh)
	Negative Electrode (¢/Ah)	Positive Electrode (¢/Ah)			
Nickel-Metal Hydride					
AB_2 Negative	2.4→1.8	3.4→2.5	5.8→4.3	~ 1.2	48→34
AB_5 Negative	4.85→4.0	3.4→2.5	8.25→6.5	~ 1.2	69→54
Lithium Ion					
$Li_xMn_2O_4$ Positive	9.3→3.7	23.2→12.1	32.5→15.8	~3.6	90→44
Li_xNiO_2 Positive	9.3→3.7	27.2→17.2	36.5→20.9	~3.6	101→58
Li_xCoO_2 Positive	9.3→3.7	41→26.5	50.3→30.2	~3.6	140→84
Lithium Polymer	1.6-2.4	~4.3	5.9-6.7	~2.55	23-26
Lithium-Active Sulfur	1.6-2.4	<0.06	1.7-2.5	~2.1	8-12

Several caveats apply to the discussion of the active materials cost data in Table II-3. First, they are minimum values since assuming 100% materials utilization. Second, other materials add to cell costs. For nickel-metal hydride cells, the nickel (foam, sinter or fiber) electrode conductors ("grids") add substantially to cost. For lithium ion cells, separators and electrolyte salt contribute 30% or more to total material costs. Lithium polymer and lithium-active sulfur cells require a polymer electrolyte and electrolyte salt both of which can be significant cost factors. Cells with metallic lithium negatives – especially lithium-active sulfur – tend to need excess lithium for good cycle life, which can add substantially to active materials cost.

Details on these cost factors were not made available to the author. Nevertheless, several broad conclusions can be drawn from the active materials cost estimates in Table II-3. The relatively modest cost reductions projected for NiMH active materials reflect the mature technology status and the already significant current production volumes for AB_5-based technology. AB_2-based cells/batteries have lower active materials costs per kWh of capacity due to both, lower per-kg cost and lower equivalent weight of the storage alloy.

Active material costs currently are substantially higher per kWh of cell/battery capacity for lithium ion compared to NiMH. Li ion materials cost are projected to decline substantially but only for technology using manganese-based positive electrodes. Even after these reductions, positive electrodes are several times more expensive than the nickel oxide/hydroxide positives of NiMH batteries, offsetting the Li ion system's advantage of its three times higher cell voltage. Consequently, manganese-based Li ion batteries will cost less than NiMH only if the costs of materials – especially the positive electrode but also the negative host material as well as separators and electrolyte salt – can be reduced from currently projected levels.

Cobalt-based positives double cell active materials costs and thus are unlikely to be used in batteries for EV applications. Nickel-based positives currently occupy an intermediate cost position. Substantial reductions in the cost and/or increases in the utilization of these positives will be needed to make nickel-based Li ion technology cost-competitive with NiMH batteries. For both, NiMH and Li ion technology, there is a large incentive to reduce the cost of all active materials through advancements in materials (chemical composition and/or electrochemical utilization) as well as through reduction of materials cost in volume production.

The minimum cost of charge storage (in ¢/Ah) in lithium polymer cells and batteries is comparable to, but cell voltage is twice that of NiMH. Compared to Li ion, the much lower cost of the positive active material (vanadium oxide vs. lithium manganese spinell) is the largest factor responsible for the lower active materials cost, more than compensating for the lower voltage of lithium polymer cells. As a result, lithium polymer cells have only about 1/2 to 2/3 of the minimum active materials costs of NiMH or lithium ion cells, and battery costs could ultimately be lower than those of NiMH and Li ion if three conditions are met: polymer electrolyte and electrolyte salt must not increase materials cost substantially, cell and battery manufacturing costs need to be comparable to or less than NiMH and Li ion, and the differences in battery thermal and electric management systems costs must not weigh substantially into total battery cost. At present, it is not clear whether these conditions can be met by a mature lithium polymer battery technology.

Finally, the minimum active materials costs of lithium-active sulfur cells are less than half of lithium polymer and only 1/4 to 1/3 of Li ion and NiMH. At these low materials costs, a high degree of lithium utilization, minimization of the other cell (and battery) materials costs, and low manufacturing costs become increasingly important. If these costs can be kept to levels comparable to those for other advanced batteries, lithium-active sulfur could become the lowest-cost advanced battery technology.

II.3. STATUS OF ADVANCED EV BATTERIES

In the following, the battery systems identified above are reviewed in terms of the technical status achieved by the leading developers and the prospects for meeting key goals for electric vehicle applications. Beginning with the more mature technologies, the potential for significant improvements and the plans of developers to commercialize their batteries are reviewed. For the less developed systems, the emphasis is on their basic characteristics and the main development challenges. The discussion sequence reflects a stepwise increase in theoretical maximum specific energy but also increasing uncertainty as to which fraction of that potential can ultimately be realized.

A. Nickel-Metal Hydride (NiMH)

NiMH is the only advanced EV battery now in production, and its importance in the development and introduction of today's substantially more capable EVs is undisputed. Nevertheless, the battery's use and appeal for EV applications remains limited. The high cost of currently available NiMH batteries appears to be the primary reason. But another factor is that battery specific energy – in the range of 60 to 80kWh/kg – is not sufficient to provide the desired 150-200 mile EV range with a battery of acceptable weight, even if cost were not an issue.

In the 1995 BTAP Report (see Ref. 1, pp. III-18/19), the discussion of NiMH batteries included a reference to ongoing R&D on advanced metal alloys with much higher hydrogen storage capacity than the known AB_2 and AB_5 alloys. If successful, that work could lead to NiMH batteries of substantially higher specific energy. This possibility was one reason for including NiMH among the systems surveyed. The other is to update ARB staff on current activities and plans of organizations that might become suppliers of NiMH batteries in time for the implementation of the current ZEV regulatory provisions in the year 2003. A detailed examination of the prospective costs of such batteries – the critical issue – was beyond the scope of the present survey; it will become the main subject for a new Battery Panel that will be appointed by ARB in the fall of 1999.

The author visited the leading developers/suppliers of NiMH batteries for EV and HEV applications, with the findings below.

Panasonic EV Energy (Sakaijuku, Kosai-shi, Shizuoka Prefecture, Japan), an independent company owned jointly by Matsushita and Toyota, is the only organization worldwide with a commercial plant manufacturing NiMH batteries for EVs. In 1998, about 1000 EV battery packs (95 Ah cells, 29 kWh, 450 kg) were produced. In addition, a limited number of packs with 28 Ah cells intended for Toyota's new "e-com" commuter EV are being produced; this production is growing relative to the 95 Ah EV technology. Because the characteristics of the 28Ah NiMH technology also appear to fit dual mode hybrid electric vehicle applications, the technology is reviewed in Section III.2 below, together with the other key product of Panasonic EV Energy: the 6.5 Ah NiMH cells and modules used in the Toyota PRIUS and other hybrid electric vehicles.

Battery costs remain the most serious concern in the commercialization of NiMH batteries for EVs. Materials costs are substantial (as indicated in Table II-3), but at current production levels manufacturing costs are even larger. One important factor is the cost of 100% cell testing, required for matching capacities within each pack to permit effective capacity utilization and electric management of the batteries. Another substantial cost factor arises from the need for 100% initial cycling to achieve stable cell and pack capacity. Panasonic EV is projecting that per-pack cost might decrease to one third of current cost if volume grows threefold, but even these costs are well above the requirements shown in Table II-1.

Little decline in the energy storage capacity of Panasonic EV Energy NiMH batteries is observed in accelerated tests that simulate 100,000 miles of driving, and only a small increase in impedance (reduction in peak specific power) occurs with extended cycling. As a result, life of EV-type cells/batteries is in excess of 1000 deep cycles, and Panasonic EV's 29kWh batteries in the RAV4EV currently are warranted for three years. This will probably be extended to five years based on the favorable experience to date. In Matsushita's experience, negative electrode alloys other than the AB_5 do not provide the required cycle life. AB_5-based NiMH batteries do have a charge acceptance problem at temperatures >45-50°C, and effective cooling (air or water) is essential in all but cold climates.

In the view of Panasonic EV Energy management, NiMH is likely to remain the best choice for hybrid electric vehicle applications although EVs may eventually require the higher specific energy of batteries with lithium negatives. They believe, however, that no Li-based battery is going to see large-scale applications in EVs (or HEVs) within the next ten years. Table II-4 summarizes the current status of the Panasonic EV Energy NiMH battery technology.

Table II–4. Status of Panasonic EV Energy NiMH Battery Technology

Characteristic	Cell		Module		Battery	
	Current	Projected	Current	Projected	Current	Projected
Capacity - cell (Ah) - module (Wh) - battery (kWh)	95		1200		29	
Specific Energy (Wh/kg)			65		65	
Energy Density (Wh/L)			154			
Peak Specific Power (W/kg)			200			
Life - calendar (years) - cycle (80% DoD)	>5 >1000		>5 >1000		>5 >1000	
Specific Cost ($/kWh)						
Development Status[a]	P		P		P	

[a] E– experimental, LP– laboratory prototype, EP– engineering prototype, PP– production prototype, LVP–low volume production, P– commercial production

Ovonic Battery Co.; GM Ovonic (Troy, Michigan). GM Ovonic (GMO) has been set up by its owners, General Motors and the Ovonic Battery Company, to produce the NiMH battery technology developed by the Ovonic Battery Co. During the past five years, GMO's focus was the development and upscaling of processes for production of battery active materials, electrodes, cells and battery modules. GMO's pilot facilities in Troy are being used to manufacture the NiMH EV batteries used in a number of General Motor's current electric vehicles. Recently, GMO has established a new 80,000 sq. ft. facility in Kettering, OH for production of about 1000 NiMH EV battery packs per year. In this plant, all improvements made to date (including the cost-reducing modifications developed for EV and hybrid electric vehicle batteries) are being integrated into a partially automated and integrated manufacturing process.

The Ovonic NiMH technology (discussed in more detail in the BTAP Report, Ref. 1) uses negative electrodes made from AB2-type hydrogen-absorbing transition metal alloys. Advantages claimed for these alloys include independence from the imported "Mischmetall" that is the basis for production of the AB_5 alloy, and a higher hydrogen storage capacity per unit weight of alloy. The main disadvantage appears to be a somewhat higher hydrogen equilibrium pressure that has to be contained by a cell. Other developers claim that they are unable to achieve adequate cycle life with NiMH cells using AB_2-type negatives. While cycle life of the batteries being produced by GMO seems to be less than the 1000-1500 deep cycles claimed by most developers/manufacturers of AB_5-

based NiMH batteries, at 600-1000 cycles it appears satisfactory. The biggest challenge for the OBC/GMO and other NiMH technologies is to meet the cost targets (see Section II.2.B, above).

Alloys of potentially lower cost and higher hydrogen storage capacity continue to be explored at OBC as negative active materials in NiMH batteries. For example, OBC staff has published data for modified transition metal alloy compositions, which indicate a 20% improvement of specific charge storage capacity (in Ah/kg) over the material used in currently produced cells. With a claimed ~25% improvement of the specific capacity of the positive (nickel oxide/hydroxide) electrode, and coupled with weight savings (such as lighter-weight current collectors) these advances might eventually translate into a 20% gain in specific energy to perhaps 85Wh/kg on a battery module basis.

The current status of the Ovonic/GMO nickel-metal hydrogen battery technology is summarized in Table II-5 which illustrates the specific energy and cost challenges. No large-scale commitments for purchase of EV batteries have been received by GMO, but the company is currently pursuing major automobile manufacturers worldwide – as well as other applications -- for volume orders it is preparing to fill.

Table II-5. Status of Ovonic/GMO NiMH EV Battery Technology

	Cell		Module		Battery	
	Current	Projected	Current	Projected	Current	Projected
Capacity						
- cell (Ah)	90	100				
- module (Wh)			1200	1200		
- battery (kWh)						
Specific Energy (Wh/kg)	75	85	70	80		
Energy Density (Wh/L)			170	200		
Peak Spec. Power (W/kg)			200	230		
Life						
- calendar (year)	>5		>5	>10		
- cycle (80% DoD)			~600	800-1000		
Specific Cost ($/kWh)				200[a]		
Development Status[b]	LVP		LVP	PP		

[a] Assumes successful integration of advanced materials into OBC technology and production volume of ~20,000 battery packs per year, [b] E– experimental, LP– laboratory prototype,
EP– engineering prototype, PP– production prototype, LVP–low volume production, P– commercial production.

SAFT (Bordeaux, France) is a major manufacturer of nickel-based alkaline batteries, including the nickel-cadmium batteries used in the several thousand electric vehicles (conversions of Citroen, Peugeot and Renault small cars) currently on French roads. SAFT also was a major contractor to USABC for the development of NiMH EV battery technology. Based on that technology, SAFT until recently has been producing 32 kWh battery packs for Chrysler (now DaimlerChrysler) at the rate of about one pack per day. At present, the electrode and cell/module production lines are not used since no new orders have been received. Recently, these lines were upgraded to several times higher production capacities. In parallel, the basic cell was redesigned, its capacity enlarged, energy density increased by nearly 20%, and cycle life improved substantially.

The status of SAFT's NiMH EV technology is summarized in Table II-6.

Table II-6 Status of SAFT NiMH EV Battery Technology

	Cell		Module		Battery	
	Current	Projected	Current	Projected	Current	Projected
Capacity						
- cell (Ah)	93	109	93	109		
- module (Wh)			1100	1360		
- battery (kWh)					32	
Specific Energy (Wh/kg)			64	70		
Energy Density (Wh/L)			133	150		
Peak Specific Power (W/kg)			150	165		
Life						
- calendar (year)			>5	>10		
- cycle (80% DoD)			>1100	>1400		
Specific Cost ($/kWh)[a]			>1000	250-300	>1000	300
Development Status [b]	LVP	PP	LVP	PP	LVP	

[a] In mass production, *[b] E– experimental, LP– laboratory prototype, EP– engineering prototype, PP– production prototype, LVP–low volume production, P– in production.*

SAFT has established a road map for commercialization of the technology as follows:

- completion of module development..1st Qtr. 2000
- begin of pre-production..4/2000
- prototype testing to validate performance and life........................5/2000-4/2001
- decision on mass production/plant investment..........................5/2000
- begin of commercial production...4/2002
- mature mass production..8/2002

Crucial to implementation of this road map is the determination whether a market for the technology is likely to materialize in 2002/2003. SAFT believes that NiMH is the only advanced battery technology likely to be commercially available by then and is committed to the battery's commercialization.

Like other NiMH developers/manufacturers, SAFT recognizes the difficulty of meeting the battery cost reduction challenge. According to SAFT senior technical staff, costs (i.e., the price to a car manufacturer) could eventually drop below $250/kWh if SAFT's NiMH EV battery technology is produced on a very large scale, e.g., 100,000 packs per year or more. If automobile manufacturers are not going to place volume orders of NiMH batteries during the next 1-2 years, SAFT expects to shift its development and commercialization thrusts to the company's Li-ion technology that, in any case, is considered the logical successor to NiMH.

VARTA (Kelkheim, Germany) has several commercial NiMH battery products with characteristics suitable for EV and HEV applications, respectively. According to VARTA, the company's 80Ah "high energy" cell technology could be brought into production with less than two years' lead time after receipt of a large order. The characteristics of that technology are summarized in Table II-7; the relatively high (for NiMH) specific energy and good cycle life are noteworthy.

Table II-7. Status of VARTA NiMH High Energy Battery Technology

	Cell		Module		Battery	
	Current	Projected	Current	Projected	Current	Projected
Capacity - cell (Ah) - module (Wh) - battery (kWh)	150					
Specific Energy (Wh/kg)	~80		75			
Energy Density (Wh/L)	220					
Peak Specific Power (W/kg)	~200		190			
Life - calendar (year) - cycle (80% DoD)	>5[a] >1500		>5[a] >1500			
Specific Cost ($/kWh)						
Development Status[b]	EP		EP			

[a] 10 years expected, [b] E– experimental, LP– laboratory prototype, EP– engineering prototype, PP– production prototype, LVP–low volume production, P– commercial production

Japan Storage Battery (JSB) Co., Ltd. (Kyoto, Japan) has a long history of developing EV batteries, including lead acid, alkaline nickel (nickel-cadmium and NiMH), and lithium ion systems. JSB's corporate R&D has completed development of a 100 Ah NiMH cell for EV applications, but the company does not currently have production facilities for this technology. The lead time for a NiMH battery plant is 12-18 months after receipt of a sufficiently large order, and the capital investment for the smallest economic plant (capacity of 1,000 – 2,000 packs per month) is estimated at several billion ¥. Discussions with carmakers are ongoing but no decisions have been made. JSB's NiMH EV technology has the characteristics shown in Table II-8:

Table II-8. Status of JSB NiMH EV Battery Technology

	Cell		Module		Battery	
	Current	Projected	Current	Projected	Current	Projected
Capacity - cell (Ah) - module (Wh) - battery (kWh)	100		1200			
Specific Energy (Wh/kg)			62			
Energy Density (Wh/l)			144			
Peak Specific Power (W/kg)			200			
Life - calendar (year) - cycle (80% DoD)			>5 >1000			
Specific Cost ($/kWh)						
Development Status[a]			PP			

[a] *E– experimental, LP– laboratory prototype, EP– engineering prototype, PP– production prototype, LVP–low volume production, P– commercial production.*

Sanyo (Osaka, Japan) has experience in the development of large NiMH cells for possible application in electric vehicle propulsion. However, as a major manufacturer of NiMH cells and batteries for consumer products, the company is strongly focussed on its consumer cell and battery business, and it does not appear to have fully developed NiMH EV-type battery technology that could be produced in volume after a short lead time. Sanyo is a principal participant in the Japanese LIBES program to develop large lithium-ion cells, see Section B, below.

B. Lithium–Ion Batteries

When the Battery Technical Advisory Panel visited Japan in fall of 1995, it was briefed on Sony's just-announced development of a large Li ion cell intended for EV applications. Encouraged by Sony's initial success and the basic potential of the Li ion system for substantially higher specific energy than NiMH, a number of battery developers have become engaged in developing this promising system into practical EV battery technology. Most of these are battery companies already active in the development and commercial production of Li ion cells for consumer applications.

With the exception of Sony, all Japanese developers of large Li ion cells (for EV and/or stationary energy storage applications) are members of LIBES, the Lithium Battery Energy Storage Technology Research Association. LIBES provides funds (derived from taxes on electric power use) for the developers, and the organization oversees and coordinates the programs it funds. Sony recently decided to terminate work on its Li ion EV battery technology and is now concentrating its efforts on much smaller cells for hybrid electric vehicles, as discussed in Section III.3 below.

The Li ion EV battery development programs at SAFT in France and VARTA in Germany were funded by USABC, but in fall of 1998 VARTA decided to discontinue their program and shift focus to the development of Li ion cells for HEV applications, see Section III.3.

The main goals being addressed in the currently active programs (all of which were visited by the author) are materials cost reduction, especially elimination of expensive cobalt[1], stabilization of positive electrode active materials against structural changes and the associated capacity as well as power loss, capacity increase and cost reduction of the graphite/carbon negative electrode host material, extension of stand (calendar) life, and achievement of safe operation on the cell, module and battery level. A summary of the author's findings follows.

Shin-Kobe Electric Machinery Co. (Saitama-ken, Japan), a subsidiary of Hitachi, is developing large Li ion cells for stationary storage of electricity as a member of LIBES. More relevant to this survey, Shin-Kobe has an independent corporate program for development of Li ion batteries for EVs and HEVs. The EV technology is based on a 90Ah cell that uses manganese in the positive electrode for lower cost. Shin-Kobe staff contends that these cells perform just as well as cobalt-based technology and have comparable cycle life. Abuse tests (extensive overcharge; nail penetration) result in cell venting and failure, but neither cell rupture nor fire are observed.

Cell calendar life, estimated at five years under favorable circumstances, can still be an issue if cells are exposed to high states of charge and/or elevated temperature for extended periods, and the degradation mechanism is not yet fully understood. Cell life is about 1000 cycles at 40% DoD, which Shin-Kobe considers more representative of real-world EV driving then the standard 80% DoD specification for cycle life.

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[1] *Cobalt oxide is the main ingredient of the positive electrode of Li ion consumer cells/batteries. This material also was used in the Li ion EV battery modules that were supplied by Sony to automobile manufacturers for evaluation purposes but are no longer produced.*

Gradual decline of specific power with extended cycling is an aspect that still needs to be improved. Achievement of acceptable cost looms as the largest issue. Shin-Kobe operates a pilot plant to manufacture 90Ah cells for the 30kWh batteries intended for Nissan's ALTRA electric vehicle. Small-scale fabrication and high materials costs (currently around 200¥/Wh, or nearly $2,000/kWh) are responsible for the very high cost of the Li ion batteries Shin-Kobe is selling to automobile manufacturers. The near-term goal is to reduce materials and parts costs by 50%.

The cost of manufacturing facilities for large-scale production of EV cells and batteries is still uncertain. Shin-Kobe does not believe that EV battery costs can be extrapolated from current small-scale fabrication. In large-scale production, per-kWh costs of Li ion batteries should ultimately become less than the costs of NiMH batteries.

Whether a sufficiently large market will develop to support large-scale production is uncertain and part of the current "chicken-and-egg" dilemma facing the commercialization of advanced EV batteries. One opportunity for moving forward may be Nissan's "Hyper Mini" EV that may be powered by a Li ion battery and introduced by the end of 1999, but at present it is not clear how large the market for this type of vehicle could become.

The status of Shin-Kobe's Li ion EV battery technology is summarized in Table II-9.

Table II-9. Status of Shin-Kobe Lithium Ion Battery Technology

	Current	Projected	Current	Projected	Current	Projected
Capacity -cell (Ah) -module (Wh) - battery (kWh)	 90		 2700			
Specific Energy (Wh/kg) (C/3)	104		90			
Energy Density (Wh/L)	238		144			
Peak Specific Power (W/kg)			730[a]			
Life - calendar (year) - cycle (80% DoD)	 ~5 ~1000		 ~5 ~1000			
Specific Cost ($/kWh)			~1600	~800		
Development Status[b]	LVP		LVP			

[a] At 80% DoD; specific power fully charged (0%DoD) is 1220W/kg, [b] E– experimental, LP– laboratory prototype, EP– engineering prototype, PP– production prototype, LVP–low volume production, P– in production

Japan Storage Battery has a very active program in Li ion battery development and testing. As a participant in LIBES, JSB is responsible for developing a 100 Ah, 360Wh cell for EV applications. This development has reached the pre-prototype cell stage, but the technology is still using cobalt-based positive electrodes.

In its corporate program, JSB is pursuing development of a remarkable variation of Li ion cell configurations and sizes for a variety of commercial and military applications. The emphasis is on a spiral wound, elliptic cell of 35 Ah and a prismatic 80 Ah EV cell. Both designs use positive electrode mixtures of manganese, nickel and cobalt oxides or, alternatively, manganese oxide with stabilizing additives, to reduce materials cost and increase the operating temperature limit to about 60°C.

Electrical and thermal controls are key requirements for Li ion batteries. JSB has developed its own cell-level electrical control system that in volume production is estimated to contribute no more than 10% to battery cost. Air cooling is considered adequate for the EV application of Li ion batteries. JSB's very extensive cell and battery testing facilities are used to evaluate performance, life and safety of its various Li ion designs. Safety tests of EV cell designs show tolerance to shorts and no fires in the nail penetration test.

While JSB does not now have sufficient data to compare prospective costs of EV-size Li ion and NiMH cells, Li ion should be less expensive in large-scale production because materials costs per kWh capacity should ultimately be lower. JSB stated that the company could be in commercial-scale production of Li ion batteries within 18 months from an order of sufficient size but that the emergence of large-scale markets for EVs and EV batteries will depend critically on continued ZEV regulation.

The required investment per kWh of production capacity would be about 50% higher for Li ion than for NiMH. In the meantime, JSB is pursuing niche markets for special uses (such as underwater power) with custom-fabricated cells and batteries matched to the intended applications.

Table II-10 summarizes the status of JSB's Li ion EV battery technology.

Table II-10. Status of JSB Lithium-Ion Battery Technolog

	Cell		Module		Battery	
	Current	Projected	Current	Projected	Current	Projected
Capacity - cell (Ah) - module (Wh) - battery (kWh)	85		85 1260			
Specific Energy (Wh/kg) (C/3)			84			
Energy Density (Wh/l)			164			
Peak Specific Power (W/kg)			900[a]			
Life - calendar (year) - cycle (100% DoD)			≥700			
Specific Cost ($/kWh)						
Development Status [b]	PP		PP			

[a] At 80% DoD; specific power at 20% DoD is 950W/kg, [b] E– experimental, LP– laboratory prototype, EP– engineering prototype, PP– production prototype, P– in production.

SAFT regards Li ion as the next EV battery technology, beyond the capabilities of NiMH. In a program cost-shared by USABC, the company has made substantial progress over the past 2-3 years in improving positive electrode technology that is based on nickel oxide but contains other metal oxides for improved cycle life and safety. The capacity of the negative electrode (a mixture of graphite and graphitized carbon) also has been increased. The cells pass standard abuse tests. Achievement of adequate calendar life is recognized as a significant challenge, and the systematic tests necessary to define, diagnose and resolve issues with calendar life are currently underway.

As part of its plan for technology improvement and evaluation in the 2000-2002 period, SAFT is now operating a new pilot line for fabricating 44 Ah "high-energy" Li ion cells for EV applications. It took SAFT less than three months to install and start the line. Currently, cell production capacity is sufficient for 100 EV battery packs per year, to be doubled in the near future by increasing the capacity of the "formation" stage – the initial charge/discharge cycles needed to establish functional cells through a first charge[1] and to measure cell capacities. A decision on the first production plant might be possible as early as next year. Such a decision will be driven by the

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[1] Li ion cells are manufactured in the discharged state, with all lithium contained as ions in the positive active material, for example in form of lithium-manganese spinell, a mixed oxide with the formula $LiMn_2O_4$. There is no need to deal with metallic lithium in Li ion cell manufacturing, an important advantage of the technology.

progress toward cost reduction goals and, importantly, the assessment whether a market for these batteries will exist in 2003 and beyond.

SAFT's cost goal for complete Li ion EV batteries (including all necessary electric and thermal controls) is \$150/kWh in mass production. To achieve this goal, specific energy must be increased and the cost for all key materials -- electrodes, electrolyte salt, and separators -- must be substantially reduced.

The status of SAFT's Li-ion EV battery technology is summarized in Table II-11.

Table II-11. Status of SAFT Lithium Ion Battery Technology

	Cell		Module		Battery	
	Current	Projected	Current	Projected	Current	Projected
Capacity						
- cell (Ah)	44		44 ; 88			
- module (Wh)			950			
- battery (kWh)						
Specific Energy (Wh/kg)	144		126	150		
Energy Density (Wh/l)	308		197			
Peak Specific Power (W/kg)	300		262	300		
Life						
- calendar (year)	>5		>5	>5		
- cycle (80% DoD)	>600		>500	>1000[a]		
Specific Cost (\$/kWh)			>1000	150[a]		
Development Status[a]	LVP		LVP	P		

PP– production prototyp [a] Goal, [b] E-- experimental LP– laboratory prototype, EP– engineering prototype, LVP–low volume production, P-- commercial production.

Sony (Tokyo, Japan), the pioneer, abandoned its Li ion EV cell/module technology in 1998 and changed focus on the development of small, high power cells for HEV applications, see Section III-3, below. Sony's pilot line supplied the EV cells (still with cobalt-based positives) and 8-cell modules for Nissan's ALTRA EV but that line is no longer in use. Sony does not see sufficient commercial potential for Li ion EV batteries to justify completion of the development (including the switch to manganese-based positive electrodes) and the investment in manufacturing facilities.

VARTA, like Sony, made the corporate decision to discontinue its Li ion EV battery development program (co-funded by USABC) in late 1998. The decision appears to be the result of a general de-emphasis of EV battery activities by VARTA-Bosch Autobatterien. This new company, formed by VARTA and Bosch, is to focus on near-term industrial and automotive battery markets. The short (<2 year) calendar life of VARTA's manganese-based cell technology may have contributed to the decision although development of the same basic technology for HEV and auxiliary power applications is continuing (see Section III.3, below).

Matsushita and **Sanyo** are two of the four principal members of LIBES with responsibility to develop large Li ion cells in cost sharing arrangements. Matsushita's development is focused on EV applications and has progressed to the stage of pre-prototype 100Ah cells. In the next phase of the LIBES program, Matsushita (and also JSB, see above) are to develop 8-cell, 3 kWh modules of approximately 30 Volt for evaluation purposes befor a decision is made on subsequent program phase(s). Sanyo's LIBES program responsibilities (like Shin-Kobe's, see above) are to develop a 70Ah cell (Shin-Kobe: 66Ah) and an 8-cell, 2kWh module for stationary energy storage applications. Neither Matsushita nor Sanyo appear to have substantial corporate efforts underway to develop large-cell Li ion technology for EV applications.

Electrofuel Inc. (Toronto, Canada) was formed in 1996 to develop and commercialize a proprietary lithium ion battery technology for laptop computer and other consumer product applications. The Electrofuel technology is reviewed here briefly because of recent publicity about its very high specific energy and energy density that enable greatly increased operating times of laptop computers on a single battery charge.

The status of the Electrofuel cell technology is summarized in Table II-11.

Table II–12. Status of Electrofuel Lithium Ion "Superpolymer" Battery Technology.

Characteristics	Cell		Module [a]		Battery	
	Current	Projected	Current	Projected	Current	Projected
Capacity						
- cell (Ah)	11	15	11	15		
- module (Wh)			160			
- battery (kWh)						
Specific Energy (Wh/kg)	190	230	165	210		
Energy Density (Wh/L)	470	600	400	530		
Peak Specific Power (W/kg)	tbd	tbd	tbd	tbd		
Life						
- calendar (year)	3	7	3	7		
- cycle (80% DoD)	300	600	250	600		
Specific Cost ($/kWh)	1500	600	1500	700		
Development Status [b]	LVP		LVP			

[a] *Module is a 4-cell assembly in a metallic enclosure sold as "Power Pad" computer battery,*

[b] *E– experimental, LP– laboratory prototype, EP– engineering prototype, PP– production prototype, LVP– low volume production, P– commercial production.*

The technical features of the battery include "stacking" of thin, flat cells and (judging from the product designation "Lithium Ion Superpolymer Battery") use of a polymeric electrolyte. However, according to Electrofuel, the battery is not based on the Bellcore lithium ion polymer technology.

The specific energy and energy density values in Table II-12 are much higher than those for other Li ion consumer application cells. These data were provided by Electrofuel, but cell/battery performance data were confirmed independently in the laboratories of the Canadian National Research Council. Also, the greatly extended (≥15 hour) computer run times made possible by the Electrofuel battery were verified in tests conducted by a leading computer magazine.

If Electrofuel's cell materials and designs can be developed to meet the packaging and safety requirements for EV applications without compromising performance unduly, module specific energy could be as high as 125 to 160Wh/kg (75% of the cell-level specific energies of 165-210Wh/kg), and energy density would be 300-400Wh/L. This performance would substantially exceed that of current Li ion EV designs (see Tables II-9 through II-11), and it would meet EV application goals.

Electrofuel notes that their thin-cell design will permit high discharge rates (peak specific power levels), but is not clear to which extent high specific energy (and energy density) can be sustained at the power densities that need to be delivered by EV batteries. Cycle and stand life appear to be comparable to current EV-design cells and modules. Electrofuel points out that these characteristics can be improved if demanded by the application.

The costs in Table II-12 are for current low-volume fabrication using Eletrofuel's small-scale manufacturing facility. In large-scale production, the per-kWh costs of modules/batteries should be comparable or lower than for current Li ion EV designs because higher specific energy translates into a greater utilization of all materials used in cells and batteries. This extrapolation assumes that the Electrofuel battery contains little or no expensive materials, and that the cell's high specific energy can be retained in an EV design.

If the design and manufacturing approaches of Electrofuel are applicable to the fabrication of large cells using manganese-based positive electrodes, exploration of Electrofuel's technology for EV applications certainly appears to be justified. On the other hand, if the positive active material is largely or entirely based on cobalt, it seems unlikely that the costs projected for intermediate-volume production levels (see Table II-12) could come down to the levels needed for EV applications, even in large-scale production

C. Lithium Polymer Batteries

The technical breakthrough of intercalating lithium into carbon-based materials has enabled the use of lithium in high-specific-energy lithium ion cells for consumer applications and, over the last five years, the development of Li ion cell and battery technology with promise for EV applications. The other, historically older breakthrough in making lithium usable in secondary batteries was made twenty years ago (Ref. 5): the discovery that polyethylene oxide (PEO) can be made into a lithium ion conductor through dissolution of lithium salts in this polar polymer.

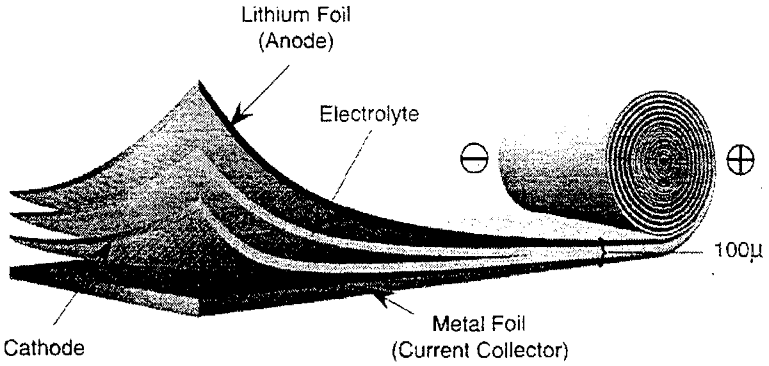
The resulting polymer electrolyte has good stability in direct contact with lithium metal, resists penetration by lithium dendrites, and is stable also in contact with typical positive active materials. One limitation is the much lower Li^+ ion conductivity of PEO-based electrolytes compared to that of the organic electrolytes used in Li-ion batteries. Achievement of practical performance thus requires that the polymer electrolyte is used as a very thin film. In addition, the Li polymer batteries currently under development for EV applications need to be operated at elevated temperature (in the range of 50-90°C) for acceptably low resistance and good specific power.

Two major Li polymer EV battery development programs have emerged publically since the 1995 BTAP report. Both programs were visited by the author in the second quarter of 1999; their technologies and status are discussed in the following.

Hydro Quebec (with its subsidiary **Argo-Tech**) formed a strategic alliance with 3M in 1992 to develop a lithium polymer battery (LPB) for EV applications, on the technical basis of the LPB cell technology developed by Hydro Quebec (HQ) over the past two decades. Since 1994, the program has been cost-shared by USABC which to date has committed nearly $100 million; Argonne National Laboratory also is a program participant.

Within the joint program, 3M is responsible for development and supply of a structure consisting of the positive conductor (aluminum foil) laminated to the positive electrode (vanadium oxide blended with a conductivity additive and some polymer electrolyte) laminated to the polymer electrolyte film. Rolls of this "half-cell" laminate are sent to Argo-Tech in Canada, for lamination with the lithium negative electrode foil/film and winding of this composite into compact electrochemical cells (ECs) as indicated in Figure II-2. To achieve the highest packing density, the ECs are wound into thin prismatic shapes and stacked into compact modules.

Figure II-2. Construction of the 3M-Hydro Quebec Lithium Polymer Cell (Courtesy of 3M)



Larger-capacity "battery cells" are created by connecting a number of (e.g., eight) ECs electrically in parallel, with fuse protecion for individual ECs. This approach provides flexibility in matching battery Ah capacities to different applications with a single EC design. Battery modules of various capacities are assembled from multi-EC battery cells. A key program milestone was the successful fabrication and testing of a 20Volt, 2.4kW module.

For adequate electrolyte conductivity and cell/battery performance, HQ's lithium polymer technology is operated in the 60-80 °C. Batteries are thermally insulated and equipped with electric heaters for start-up and stand-by. During stand-by, a "ready-to-drive" internal battery temperature of 60°C is maintained by drawing electric power from the battery charger or from the battery itself when necessary. While posing special requirements, operation at "warm" temperatures also is an advantage: it facilitates cooling and extends the range of environmental temperatures over which the battery can be used.

Recently, 3M decided that the company will not be a partner in the next program phase (Phase III). However, it will meet its current contractual obligations and continue to supply half cells to Argo-Tech. Development of potentially low-cost cell and battery manufacturing techniques and processes is now the major focus of the HQ program. The program's pilot facilities are being used to fabricate engineering prototype modules for evaluation on test stands for assembly into experimental batteries. Module fabrication capacity is sufficient for 4-5 packs of about 40kWh per month.

Cost projections for the battery are in the $150-300/kWh range for a production rate of about 30,000 packs per year. This translates into $4,000-7,500 for a 25kWh pack, or $6,000-12,000 for 40 kWh. The lower end of the projected battery specific cost range meets the intermediate-term USABC and the author's proposed cost goals (see Table II-2).

While the path to achieving these production volumes and cost projections is not yet clear, Hydro-Quebec/Argo-Tech will continue their program with key contributions from 3M, and HQ/A-T remain fully committed to the development and commercialization of their lithium polymer battery technology. This also implies a commitment to providing and/or seeking the large investments that will be needed to complete battery and manufacturing technology development and establish production facilities.

The status of the HQ technology is summarized in Table II-13:

Table II-13. Status of HQ Lithium Polymer Battery Technology

	Cell		Module		Battery	
	Current	Projected	Current	Projected	Current	Projected
Capacity						
- cell (Ah)			119			
- module (Wh)			2400			
- battery (kWh)						
Specific Energy (Wh/kg)	205		155			
Energy Density (Wh/L)	333		220			
Peak Specific Power (W/kg)	420[a]		315[a]			
Life						
- calendar (years)		>10		>10		
- cycles (80% DoD)	600		600	1000		
Specific Cost ($/kWh)				250-300		
Development Status[b]			EP			

[a] At 80% DoD, [b] E– experimental, LP– laboratory prototype, EP– engineering prototype, PP– production prototype, LVP–low volume production, P– commercial production.

Elctricité de France (EdF) and **Bolloré Technologies (BT)** in France are allied in the other major lithium polymer EV battery development program. EdF (the French national electric utility) decided in 1992 to initiate development of a lithium polymer battery capable of meeting the criteria for EV applications. Achievement of acceptable costs was a key goal that led to the partnership with Bolloré, a manufacturer of low-cost precision thin-film products. Manufacturing cost considerations also motivated the selection of extrusion as the preferred method for producing thin films of the PEO-based polymer electrolyte and of relatively inexpensive V_2O_5-type vanadium oxide.

This approach presented many difficulties in the beginning but films of every cell functional component can now be extruded in high quality and with precisely controlled thickness, so far on the laboratory pilot equipment scale. By the end of 1997, 100-150Wh cells capable of around 1000 deep cycles could be fabricated. This success led to the present commitment to a 3-year program that is expected to result in development by 2001 of a ~2.5 kWh prototype module. The module will include all thermal and cell-level electric controls required for stand-alone operation. The necessary control systems are being developed by Schneider Electric, a major French manufacturer of electronic technologies and now also a partner in the program. Because modules are autonomous, batteries simply will be assemblies of the requisite number of modules. Consequently, the current and projected module performance data also apply to complete batteries.

At this time, battery cost is still considered a major issue. In mass production, EdF and BT expect to ultimately achieve a cost of 200 Euro per kWh (approx. $200/kWh) or even less if materials cost can be reduced sufficiently.

EdF believes that it will be difficult for pure battery EVs to compete with ICE vehicles even if battery performance and cost goals can be attained. Nevertheless, in view of the technical success to date, EdF and Bolloré Technologies have decided to continue the program to the production prototype level given continued technology and manufacturing development progress. As with the other leading EV battery development programs, it is as yet unclear how the step from production-ready technology (in 2003?) to the large-scale production of cost-competitive batteries is to be taken. At this time, no French (or other) car manufacturer has indicated willingness to make purchase commitments beyond acquiring modules on a small scale for evaluation purposes.

The EdF/BT technology status is summarized in Table II-14.

Table II-14. Status of EdF-BT Lithium Polymer Battery Technology

	Cell		Module		Battery	
	Current	Projected[a]	Current	Projected	Current	Projected
Capacity						
- cell (Ah)						
- module (Wh)				2500		
- battery (kWh)						
Specific Energy (Wh/kg)	170	200	120	150		
Energy Density (Wh/l)	230	300				
Peak Specific Power (W/kg)	280	360	200	250		
Life						
- calendar (year)						
- cycle (80% DoD)			>500	1000[b]		
Specific Cost ($/kWh)				≤200[b]		
Development Status [c]	LP		LP	EP		

[a] Projections are for 2003, [b] goal, [c] E– experimental, LP– laboratory prototype,
EP– engineering prototype, PP– production prototype, LVP–low volume production
P– commercial production.

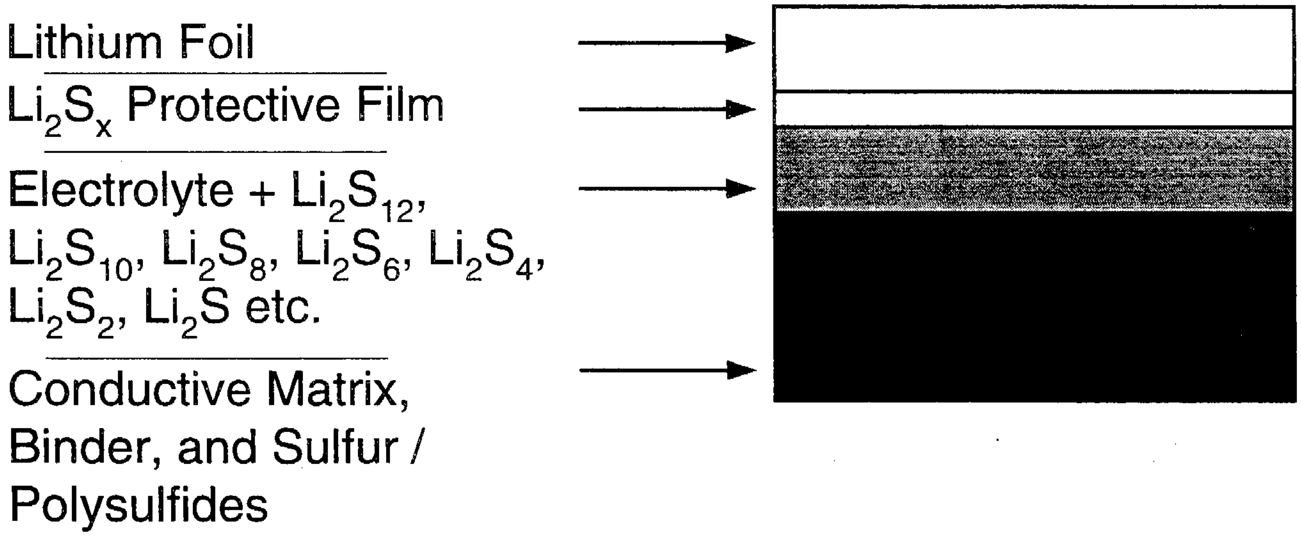
D. Lithium-Active Sulfur Batteries

Looking beyond lithium polymer batteries with metal oxide positives, Figure II-1 indicates that pairing lithium with sulfur or with organic polysulfides of high sulfur content should result in electrochemical cells with very high theoretical specific energies. While sulfur exhibited impractically low electrochemical activity in past research, the sulfide groups in certain organic polysulfides were shown (Ref. 6) to be electrochemically active, making the materials suitable as positives in secondary lithium cells. More recently, conditions were discovered (Ref. 7) under which elemental sulfur is sufficiently active and reversible to be a candidate positive electrode material for batteries.

Cells with metallic lithium negatives and polysulfide and/or sulfur positives are now under development for consumer applications. To gauge the prospects of these potentially important but as yet unexplored opportunities for yet more capable EV batteries, the three leading developers were visited. The status of their programs and technologies is summarized in the following.

PolyPlus Battery Company (Berkeley, CA) has been formed to exploit the discoveries of the company's principals that lithium-polysulfide and lithium-sulfur cells are fundamentally feasible. The second discovery led to the present focus on the lithium-"active sulfur" system and the development of laboratory cells with the structure shown schematically in Figure II-3:

Figure II-3. Structure and Composition of PolyPlus Lithium-Active Sulfur Cell



Several reactions are involved in the discharge and recharge of a lithium-sulfur cell:

(1) $2\,Li + S_8 \rightarrow 2\,Li_2S_8$ (2) $2Li + Li_2S_8 \rightarrow 2\,Li_2S_4$
(3) $2Li + Li_2S_4 \rightarrow 2\,Li_2S_2$ (4) $2Li + Li_2S_2 \rightarrow 2\,Li_2S$

The polysulfides with high sulfur content are soluble in the plastizised PEO electrolyte used by PolyPlus, and they can diffuse across the cell where they react chemically with the lithium negative electrode. In this reaction, they form films of solid lithium sulfide and/or low-sulfur-content polysulfides at the lithium surface which protect the electrode from rapid further attack (i.e., self discharge). However, the film appears to be sufficiently permeable for high-sulfur polysulfides and/or lithium ions to permit safe overcharging of lithium-sulfur cells, an important safety feature not shared by other lithium-based battery systems. Finally, presence of high-sulfur polysulfides also appears to suppress the formation of deleterious metallic lithium dendrites during charging.

The PolyPlus cell technology is still in an early stage of development. Nevertheless, key technology features have been demonstrated, and performance has been advanced from very low active materials utilization and poor cycle life to the levels summarized in Table II-15.

Table II-15. Characteristics and Status of PolyPlus Lithium-Active Sulfur Cells

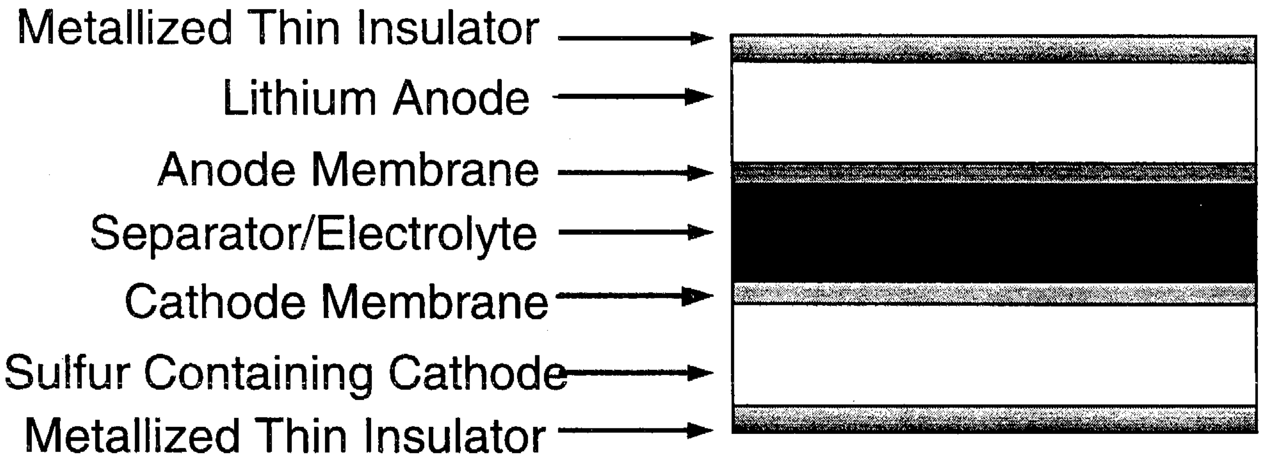
	Cell		Module		Battery	
	Current	Projected	Current	Projected	Current	Projected
Capacity						
- cell (Ah)	1.2					
- module (Wh)						
- battery (Wh)						
Specific Energy (Wh/kg)	~100	>300				
Energy Density (Wh/L)	~120	>350				
Peak Specific Power (W/kg)	~50 (>1000[a])	~200 (>1000[a])				
Life						
- calendar (year)						
- cycle (80% DoD)	>100	≥300				
Specific Cost ($/kWh)		<150 [b]				
Development Status [c]	LP	E				

[a] At 60°C, [b] advanced technology (planned development), [c] E– experimental, LP– laboratory prototype, EP– engineering prototype, PP– production prototype, LVP–low volume production, P– commercial production.

If life above 100 cycles is desired, the depth of discharge of PolyPlus "evaluation" cells needs to be limited, limiting specific energy to approximately 100Wh/kg at present.. At the 300Wh/kg projected for two years from now, specific energy would exceed that of all other secondary battery systems presently under development, with substantial room for further increases. Peak specific power is modest at room temperature but very high at 60°C. Cell cycle life still is well below the levels needed for EV applications (see above), but the technology is not yet optimized, and its ultimate performance and life potential are not known. Active materials costs of the lithium-active sulfur system are the lowest of any lithium battery (see also Table II-3). According to PolyPlus, if current concepts for incorporation and protection of high quality lithium electrode surfaces in their cells prove out, costs could ultimately drop below $150/kWh in fully automated, large-scale production. In the author's view, the promise of very high specific energy and potentially low cost argues for evaluation and possible development of lithium-active sulfur electrochemical systems as EV batteries.

Moltech Corporation (Tucson, AZ) is developing a lithium-organosulfur cell for application in consumer products. The structure of the Moltech cell is shown in Figure II-4.

Figure II-4. Structure and Composition of Moltech Lithium-Organosulfur Cell



Moltech's cell technology has several unique features. Layers of cell functional materials are deposited in a series process steps using vapor deposition and conventional coating techniques. The resulting thin-film cell structure is then wound into flat shapes for good volume utilization. The electrolyte-separator layer is separated from the lithium negative and the organosulfur/active sulfur positive electrodes by proprietary membranes that are permeable for lithium ions. The basic cell structure is very thin (approximately 50 microns) which explains the cell's high specific power and its ability to deliver high specific energy even at high power levels.

Technology development at Moltech has progressed to the point where all fabrication steps have been established on the laboratory pilot scale. Cell sizes of nominally 0.8 and 3Ah are now being fabricated with this equipment. Specific energy is a remarkable 240Wh/kg and projected to increase further. Given the system's theoretical maximum specific energy of 1500-2500Wh/kg depending on the composition of the positive electrode, it is reasonable to expect further increases.

According to Moltech, laboratory prototype cells have demonstrated safety in standard abuse tests and are now being distributed for evaluation purposes to manufacturers of battery-powered consumer products such as mobile telephones, laptop computers and power tools. Assuming favorable reception of these cells and success in upscaling the production process, Moltech expects to begin production of a commercial cell configuration in late 1999 and launch volume production a year later. In September 1999, Moltech signed an agreement with Ralston Purina to acquire Energizer Power Systems, giving the company greatly increased capabilities in battery (including lithium ion) cell production.

Moltech recognizes the fundamental potential of their technology for EV applications but has not yet investigated the technical implications of EV cell/battery development. In the author's view, a preliminary investigation (including estimation of prospective costs) seems justified, considering the technology's progress and potential. The current status of Moltech's lithium-organosulfur/active sulfur cell technology is summarized in Table II-16:

Table II-16. Characteristics and Status of Moltech Lithium-Organo/Active Sulfur Cells

	Cell		Module		Battery	
	Current	Projected	Current	Projected	Current	Projected
Capacity - cell (Ah) - module (Wh) - battery (kWh)	3					
Specific Energy (Wh/kg)	~240	~280				
Energy Density (Wh/l)	~220	~320				
Peak Specific Power (W/kg)	>400					
Life - calendar (year) - cycle (80% DoD)	175	$\geq$300[a]				
Specific Cost ($/kWh)						
Development Status [b]	PP	LVP[c]				

[a] Goal, [b] E– experimental, LP– laboratory prototype, EP– engineering prototype, PP– production prototype, LVP–low volume production, P– commercial production, [c] year 2000.

Matsushita Electric Industrial Co. participated in a recently completed three-year project co-funded by the Japanese Government to explore the practical potential of Matsushita's discovery that addition of polyaniline and copper salts to organo-polydisulfides results in substantially improved capacity and rate capability of lithium-active sulfur cells. Matsushita's cells are constructed much like the PolyPlus cell shown Figure II-4 but have a higher voltage (typically >3Volt), suggesting a somewhat different cell reaction. Although Matsushita acknowledges the fundamental potential of their battery system, concerns about the need for a longer-term R&D engagement and the dominant patent position of PolyPlus appear to be discouraging Matsushita from undertaking a more aggressive corporate program to develop their technology.

II.4. ADVANCED EV BATTERIES: SUMMARY

The main observations on the development status of EV batteries are summarized in this section, organized by battery type. For perspective, the reader is reminded of the focus of this survey: the identification and examination of technologies with basic potential for substantially higher specific energy and lower cost than current nickel metal hydride batteries. Because they are the benchmark for advanced EV batteries and still have potential for significant improvements, NiMH batteries are discussed first.

A. Nickel-Metal Hydride

Two NiMH EV battery technologies are currently produced in limited volume. Panasonic EV Energy and SAFT make cells, modules and battery packs with negative electrodes based on AB_5-type nickel alloys, and GM Ovonic utilizes AB_2-type transition metal alloys in their negatives. Several other battery companies (JSB, VARTA, possibly Sanyo) have fully developed AB_5-based EV cell technologies but no significant production capabilities.

Figure II-5 illustrates that both technologies have achieved maturity in terms of materials, cell and module engineering designs, and fabrication. The specific energies of AB_5-based modules of different developers are close to 65Wh/kg, approximately 30% of the theoretical maximum, and the OBC AB_2-based modules are at about 75Wh/kg, nearly 30% of the ~265Wh/kg theoretical value. Clearly, for the currently used materials, NiMH EV batteries are efficiently engineered.

Figure II-5. Performance Parameters of High-Energy (EV) Batteries

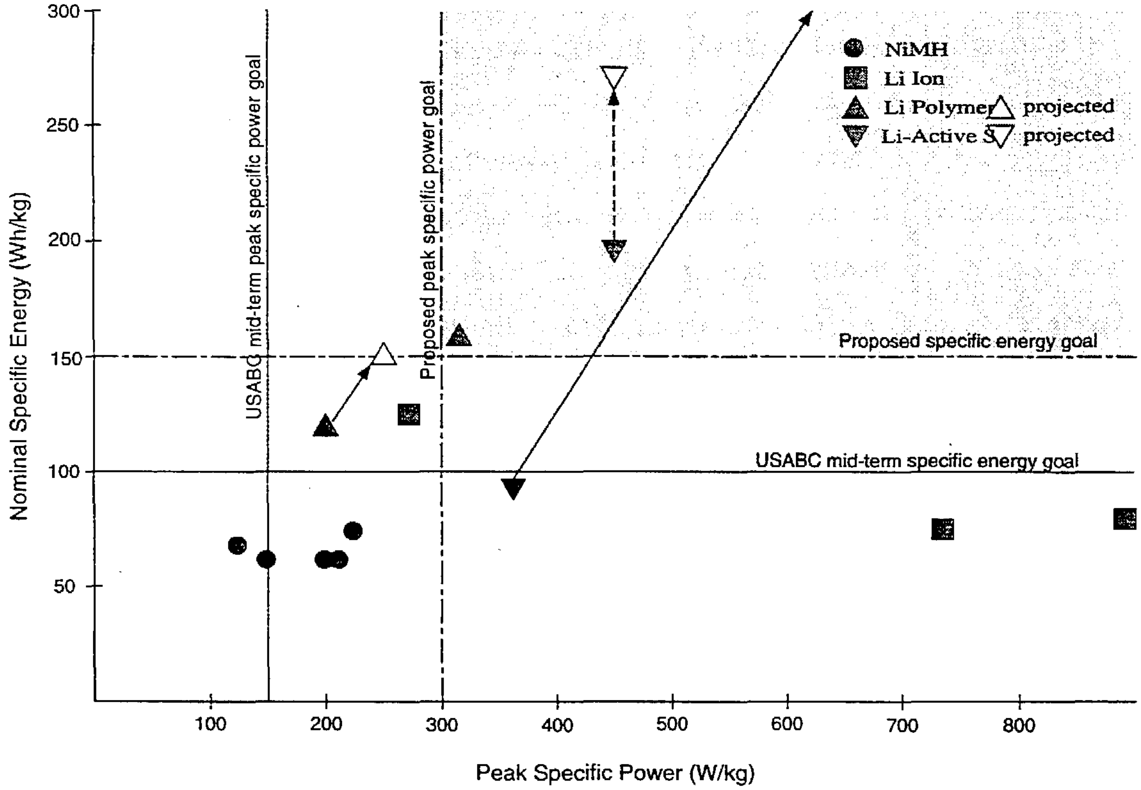


Figure II-5 also indicates that peak specific power capabilities of approximately 200-230W/kg are the state of the art for mature EV-design NiMH batteries of either type. The comparison of these data with the EV battery performance requirements and goals summarized in Table II-1 and included in Figure II-5 shows that specific energy and specific power of NiMH EV-design batteries fall short of meeting the goals that would give EVs fully competitive range and power[1].

Major increases in the specific capacities of the negative and positive electrode materials would be needed to increase the specific energy of EV-design NiMH batteries. Ovonic Battery Company staff has published data that indicate achievement of 20-25% improvements in the

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[1] *An argument can be made that sufficient capacity for a 150-mile range vehicle can be provided by increasing battery weight above the 150 kg goal. However, at 70Wh/kg specific energy, the 30-33kWh battery required for a 150-mile EV with a currently attainable "mileage" of 4.5-5 miles/kWh would weigh about 450 kg, three times the goal. Because of the extra battery and vehicle weight, a 150-mile vehicle would actually require a battery capacity in excess of 33kWh, further increasing battery weight and cost. A vehicle with a "compromise" NiMH battery of 250kg would meet the peak power requirement but be limited to about 85 mile range.*

specific capacities of transition metal alloy negatives and modified nickel oxide positives. If sustainable in production-type battery technology over the needed cycle life, these improvements should result in ~15% increase in specific energy, to perhaps 85Wh/kg , a highly desirable increase but not sufficient to realize a 150-mile EV.

The feasibility of more dramatic improvements of negative electrode capacities through use of magnesium-based alloys has been suggested by Ovonic and in the open literature, but no data have become available on the reversibility and chemical/electrochemical stability of such alloys under conditions prevailing in NiMH cells during long-term cycling. It must be kept in mind that in present-technology cells, the positive electrode has less specific capacity (i.e., weighs more) than the negative. Thus, the effect on battery specific energy even of dramatic percentage increases in negative specific capacity is diluted 2-3 fold unless the specific capacity of the nickel oxide positive is similarly increased. On the basis of the currently known NiOOH electrode electrochemistry, the author considers this highly unlikely.

Available data (see Tables II-4 through II-8) indicate that AB_5-based cells as well as modules and entire batteries should give 5-10 years of calendar life and at least 1000 deep cycles, thus approaching the life of a car. Cycle life appears to be shorter for AB_2 technology but is projected by OBC to reach ≥1000 cycles also.

High cost remains the most critical issue in the commercialization of NiMH electric vehicle batteries. While a thorough analysis of battery cost factors and costs is beyond the scope of this review, the discussions with the leading developers/manufacturers made clear that most of them do not anticipate achieving the $150-200/kWh goal even in mass production. The lowest projection for AB_5-based batteries mentioned to the author was about $270/kWh in very large scale production.The exception is OBC which considers $200/kWh within reach if their next generation of higher-capacity negative AB_2 and positive NiOOH electrode materials can be successfully introduced into mass-produced EV batteries. As will be discussed in Section III, the outlook for NiMH appears to be considerably more promising as a hybrid electric vehicle battery.

B. Lithium Ion

After the discontinuation of Sony's and VARTA's Li ion EV battery programs, only a few organizations are focused on the development and possible commercialization of this technology for EV applications. Shin-Kobe (a Hitachi corporation) has developed and is supplying prototype 30kWh batteries for Nissan's ALTRA EV, assuming this role from Sony. SAFT has installed a pilot production line for fabrication of 44Ah high-energy cells and 4-cell modules designed for EVs, and JSB has developed engineering prototype 85Ah EV cells and 8-cell modules. In addition, under the LIBES program JSB and Matsushita have developed laboratory prototype Li ion cells of approximately 100Ah capacity intended for EV applications.

Performance data for the leading Li ion EV technologies are included in Figure II-5. The Japanese developments are stressing high power capability, at some expense to specific energy; SAFT's technology comes closer to the specific energy potential of Li ion batteries. Lower technical maturity compared to NiMH is suggested by the fact that most of the battery module specific energies are substantially lower than 30% of the approximately 400Wh/kg theoretical maximum. Several developers express confidence that values well beyond 100Wh/kg will be possible with fully engineered, optimized Li-ion EV batteries, but it is doubtful whether 150Wh/kg can be attained for a complete battery. At ≥190Wh/kg (see Table II-13), the specific energy of Electrofuel's Li ion polymer cell for consumer applications is very high, suggest a potential of around 140Wh/kg for a Li ion battery. However, the Electrofuel "Powerpad" technology has a very simple, lightweight enclosure, and the large step to a representative EV battery technology might well involve a larger decrease in specific energy than the 25% that is typical for going from an EV cell to a battery.

There is little doubt that Li ion batteries will be able to meet the peak specific power goal for EV applications (see Tables II-10 and –11and Figure II-5), even at 80% DoD and near the end of life. Data for the cycle life of Li ion EV-design cells and modules are still limited. Developers' and literature data make clear that cycle life is a strong function of several factors, including among others the composition of the positive active material, the number of times positive electrodes are fully charged, and the cell operating temperature. Under optimal conditions, ≥1000 deep cycles appear possible, but control of critical parameters is very important for good cycle life. (For safety reason, Li ion batteries require cell-level controls of current and/or voltage as well as battery thermal controls. It seems likely that algorithms to maximize cycle life and/or optimize life/performance trade-offs could be incorporated into the control logic without significant additional cost.)

Concerns about the limited "stand" (calendar) life of Li ion cells and batteries have developed over the past few years. In particular, cells with positives based on manganese oxide have exhibited substantial capacity degradation in less than two years. Like cycle life, stand life is a function of positive electrode composition, time spent at or near full charge, and temperature. Work to understand and control the factors determining calendar life of Li ion cells and batteries is an important part of current development programs. Several developers claim that their cells have stand life of five years, but they did not specify under which conditions.

Cost is still a major issue with Li ion EV batteries. The pilot-line batteries currently being supplied to carmakers for evaluation purposes exceed the battery cost goal (see Table II-1) by an order of magnitude. The use of specialized materials (positive and negative active materials, electrolyte salts, and separators), low-volume partially manual fabrication, and time-consuming in-cell electrochemical "formation" (first charging) of electrodes all contribute to high costs. In large-scale, fully automated production, these costs can be expected to decrease very substantially. In particular, the costs of lithium manganese spinell positives[1] and of the graphite/carbon negative electrode host material for lithium are projected to decrease with volume (see Table II-3), and manufacturing costs are expected to drop even more than materials costs.

Only a detailed analysis of EV battery materials and manufacturing costs can determine whether and to what extent the specific costs of mass-produced Li ion EV batteries could become lower than those of NiMH. This analysis needs to include the costs of the required control systems, which are likely to be higher for Li ion batteries that need cell level controls for safety. On the other hand, Li ion EV battery cost reduction initiatives are likely to benefit from the cost reduction efforts driven by the increasing competition in the laptop computer and cellular telephone markets for Li ion batteries.

C. Lithium Polymer

The programs of Hydro Quebec and EdF-Bolloré Technologies appear to be the only integrated efforts worldwide to develop lithium polymer battery technologies for EV applications as well as the techniques required for large-scale, low-cost production of such batteries. The active materials and the polyethylene oxide-based polymer electrolyte used in these technologies are

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[1] *Lithium manganese spinell ($LiMn_2O_4$), a basically (although not currently) inexpensive material, is used in the majority of the EV (and HEV) battery development programs. Specific capacity of this positive electrode material is somewhat lower than lithium cobaltate ($LiCoO_2$). More importantly, the chemical stability of the pure material appears to be inadequate for long stand and cycle life of cells. These problems apparently can be overcome with mixed oxides that contain nickel and/or cobalt in economically acceptable amounts. SAFT is using lithium nickelate ($LiNiO_2$) positives with additives to stabilize the lithium-depleted nickel oxide structure formed during charging.*

broadly similar although not identical (except for the lithium negative). The main differences are in the processes used for fabrication of the thin-film cell structures: coating and lamination (HQ) versus extrusion (EdF-BT) of the active material. Both processes lend themselves to inexpensive mass production of continuous-film cell structures, with extrusion probably more difficult but potentially very low in cost.

The current and projected performance of 3M-HQ and EdF-BT modules are included in Figure II-5, indicating that module specific energy is attaining or projected to attain the goal for EV batteries, and peak specific power also is at or close to the goal. Deep cycle life has been improved greatly in recent years but the 1000-cycle goal is not yet reached. Minimizing deleterious structural changes of metallic lithium negatives as a result of cycling clearly is a greater challenge than maintaining the lithium capacity of carbon/graphite host materials in Li ion cells. On the other hand, the greater stability of the polymer electrolyte against lithium attack should make achievement of long stand life less difficult. From the tests conducted to date, the polymer electrolyte barrier between lithium and the vanadium oxide positive is a significant safety factor of Li polymer cells and batteries.

Lithium polymer batteries, too, face a cost issue. While the cost of the positive and negative electrodes are substantially less per unit of charge storage than for Li ion, the 30% lower cell voltage of lithium polymer cells with vanadium oxide positives reduces the basic cost advantage. Also, manufacturing costs of Li polymer cells are likely to be higher because of two factors: the need to handle metallic lithium, and the larger cell area per unit battery capacity required for thin-film cells. 3M indicated that a cost of $250-300/kWh should be achievable in mass production while EdF-BT are aiming for approximately $200/kWh, which would meet the cost goal for a 150-mile battery (see Table II-1). A confident assessment of prospective battery costs will be possible only after the manufacturing development efforts at HQ and EdF-BT are further along.

D. Lithium-Active Sulfur

Although still in the laboratory prototype stage, lithium-active sulfur cells are demonstrating promising performance, as discussed above (see Tables II-15 and –16) and shown in Figure II-5. Even after reducing cell-level data by 15% to approximate module performance, the specific energy and power values of small lithium-active sulfur evaluation cells already are comparable (PolyPlus) or superior (Moltech) to those for Li ion modules. The projections for somewhat larger, engineered cells (still not yet optimized for highest possible specific energy) are well above the highest values for other ambient-temperature secondary batteries, substantially exceeding even the 200Wh/kg USABC long-term goal. Specific power values also exceed goals (see Figure II-5), despite the fact that the cells are not engineered for high power. The Ragone diagram for current-technology PolyPlus cells operated at 60°C is approaching that of the advanced Li ion high-power cells (see Figure III-2, below).

On the other hand, cycle life currently is only about 100 deep cycles, far below requirements, and even the projected improvement to 300 cycles is well below EV battery goals. The formation during discharge of electrolyte-soluble species with intermediate sulfur content opens the possibility of safely overcharging cells, a potentially important advantage. However, it is likely to also result in a continuing reaction of these species with lithium negatives, with the attendant loss of specific power and, ultimately, cell capacity. Given the limited knowledge of lithium-active sulfur electrochemistry and chemistry, it is too early to judge whether the cycle life needed for EV applications will be attainable.

The ultimately achievable cost of lithium-active sulfur cells and batteries also is an open question. The costs of the active materials per kWh of cell/battery capacity are very substantially lower than for other lithium batteries, especially if sulfur and/or polysulfides can be made to perform well with inexpensive conductivity additives such as carbon. On the other hand, if elaborate conductor and/or cell structures are required to achieve high sulfur utilization at practical levels of power, some of that advantage may be lost. Finally, at this time, little is known about the costs of the techniques suitable for large-scale production of Li-active sulfur cells. Multi-step vapor deposition as used by Moltech is a potentially inexpensive manufacturing method, but thin-film cells require large areas for each kWh of capacity. PolyPlus apparently has not yet decided on a specific manufacturing process.

It is accordingly difficult to assess the overall potential of the lithium-active sulfur battery system. However, its already demonstrated capability for high specific energy and potential for low cost call for exploration of feasibility as an EV battery, with focus on the most critical issues: cycle life, and the feasibility of low-cost manufacturing. If these issues can be resolved and the special advantages of its electrochemistry retained in practical batteries, the lithium-active sulfur system could become the ultimate battery for fully competitive electric vehicles.

SECTION II. ADVANCED BATTERIES FOR HYBRID ELECTRIC VEHICLES

The successful introduction of Toyota's PRIUS hybrid vehicle in Japan and the announcements by Honda and Toyota of plans to introduce their hybrid vehicles in the U.S. market later this year (Honda) or next year (Toyota) have dramatically increased interest in this new automotive product. Automobile manufacturers, regulators and environmentalists see HEVs as a potentially major avenue to increasing vehicle energy efficiency and reducing the emissions of air pollutants. Energy and environmental policy leaders view HEVs – especially those that derive some of the driving energy from electricity-- as a strategy to replace imported oil with domestic energy resources and to reduce the emissions of carbon dioxide. Finally, electric utilities consider grid-connected hybrid electric vehicles a possible business opportunity.

Batteries are an essential component of the hybrid electric vehicle types currently under development. In this section, the different types of hybrid electric vehicles that are being introduced or proposed are defined for the purpose of this study, and the requirements they pose for HEV batteries are discussed. Following that discussion is a summary of the author's findings on the development status of advanced batteries that have potential to meet these requirements.

III.1 HYBRID ELECTRIC VEHICLE TYPES

In the functionally simplest HEV concept, a battery or other energy storage device is employed to store vehicle kinetic energy captured in regenerative braking and to utilize the stored energy for starting the vehicle's combustion engine and assisting the engine during acceleration. Toyota's PRIUS and Honda's recently announced INSIGHT are examples of this "Power Assist/Regeneration" (PA/R) hybrid electric vehicle. The hybrid vehicles currently under development at the three major U.S. carmakers also fall in this category. This type of HEV requires only a rather small battery that, however, must have very high specific power capability, as discussed below.

Hybrid batteries and their control systems can be designed to supplement not only the power but also the energy delivered by the hybrid vehicle's combustion engine. In that case, the battery is charged by an off-board power source, and it gives the vehicle a limited range over which it can be driven with battery power only, with the associated advantages of zero local emissions and yet lower consumption of oil-derived fuels. Designations such as "grid-connected", "charge-depletion" and "dual-mode" hybrid electric vehicles point to the various energy source and management aspects of this HEV type. In the following, the terms "electric-range" (ER) hybrid electric vehicle and ER HEV battery will be used to indicate the main distinguishing feature: significant vehicle driving range on the battery alone.

A number of experimental and prototypical ER hybrid electric vehicles have been built. The Audi DUO probably is the best known example, with more than 100 prototype DUOs built and driven on public roads. However, Audi is not planning to produce the DUO commercially. Electric-range hybrid electric vehicles not only require larger batteries than PA/R hybrids, but ER HEV batteries must meet different requirements, as discussed in the next section.

Yet another type of hybrid electric vehicle is created if a (very small) combustion engine is added to an electric vehicle to provide emergency driving range when the battery is fully discharged. From a battery standpoint, there is little if any difference between the type of battery required for this "range extender" HEV and the EV batteries discussed in Section II.1, above.

III.2 HEV BATTERY REQUIREMENTS AND GOALS

A. PA/R Hybrids

Power assist/regeneration-type hybrid electric vehicles of competitive performance impose a number of requirements on the PA/R battery. Several years ago, these requirements were analyzed in the PNGV program to establish targets for the program's hybrid battery development efforts (see, for example, Ref. 8). These requirements are summarized in Table III-1; they are based on the following assumptions:

- Vehicle weight approximately 1000kg
- HEV internal combustion engine power 40kW
- Combined engine and battery power for vehicle acceleration from zero to 100km/h in 10 sec
- Sufficient battery energy for acceleration of vehicle to 85mph
- Regeneration power decreasing linearly with time from 30kW to zero in 10 sec
- Battery life of 100,000 miles in a representative driving cycle (FUDS/HWFET)

Pulse Energy and Battery Capacity. The PNGV requirements do not include a nominal battery kWh capacity (for example, at the 1- or 3-hour rate) but only a minimum "available energy" of 0.3kWh (300Wh). As shown in Figure III-1, available energy is defined as the sum of the battery charge and discharge capacities at 25kW pulse discharge and 30kW regeneration power, respectively, centered at approximately 50% DoD.

Table III-1. Requirements and Technology Goals for Different HEV Battery Types

Battery Characteristics	Power Assist/ Regen. (PNGV)	Electric Range (Short)	Electric Range (Medium)
Requirements			
HEV Electric Range (miles)	0	20 (30[a])	40 (60[a])
Weight (kg)	≤ 40	≤ 100	≤ 100
Pulse (Peak) Power for 18 sec (kW)	25 (30 for regen.pulse)	50	50
Capacity (kWh)	1 - 3	4 – 5	8 – 10
Life (years)	≥ 10	≥ 10	≥ 10
Technology Targets			
Specific Power (W/kg)	625 (18 sec pulse)	≥ 500	≥ 500
Specific Energy (Wh/kg) - at 1C rate (battery capacity) - available at pulse.power	 75 (1kWh); 25 (3kWh) ≥ 7.5[b]	 ≥ 40 – 50 ≥ 6[c]	 ≥ 80 – 100 ≥ 6[c]
Cycle Life - for specified amounts of pulse energy per cycle - kWh delivered per kWh of capacity over battery life	 200 K for 25Wh 50 K for 100Wk ≥ 5000[f] (≥ 1670[f])	 ~167 K for 25Wh[d] ~33 K for 100Wh[d] ≥ 660[g]	 ~67 K for 25Wh[e] ~17 K for 100Wh[e] ≥ 170[h]
- no. of cycles @ 80% DoD	not applicable	~ 2000[i]	~ 2000[k]

[a] *Electric range for high-efficiency, lighter-weight HEVs,*

[b] *Basis: 300Wh of energy capacity available from 40kg battery at pulse power*

[c] *Basis: 2x300Wh of energy capacity available from 100kg battery at pulse power*

[d] *Assumes 4,000 miles/year in battery-only driving mode*

[e] *Assumes 8,000 miles/year in battery-only driving mode*

[f] *5,000kWh in shallow cycles delivered over life of 1kWh (3kWh) battery*

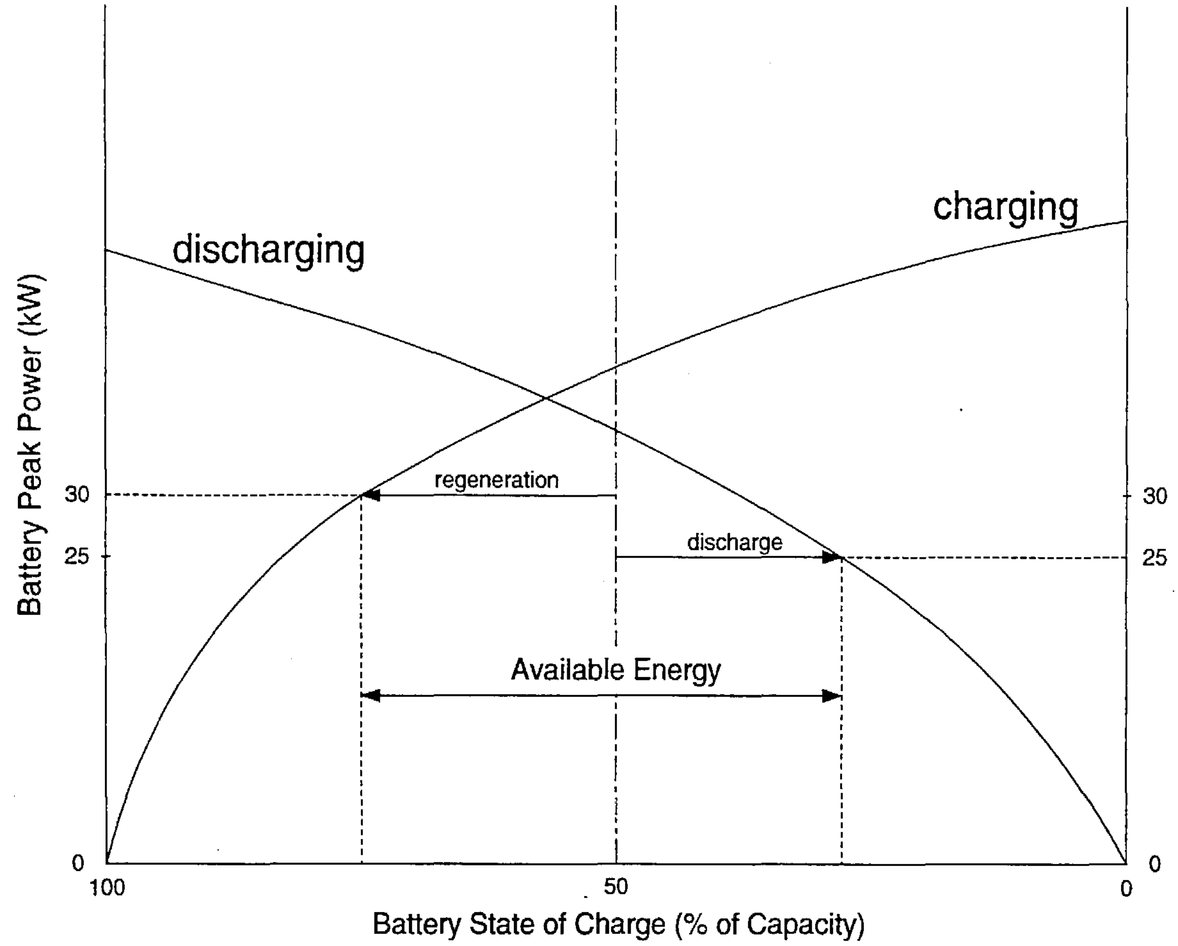
[g] *3,300kWh in shallow cycles delivered over life of 5 kWh battery*

[h] *1,700kWh in shallow cycles delivered over life of 10kWh battery*

[i] *8,000-10,000kWh in deep cycles delivered over life of 5kWh battery*

[k] *16,000-20,000kWh in deep cycles delivered over life of 10kWh battery*

Figure III-1. Battery Peak Power Versus State of Charge



The battery capacity needed to provide 300Wh of available energy (see Table III-1) depends on the shapes of the discharging and charging peak power vs. state-of-charge characteristics (see Fig. III-1); these differ substantially for different battery designs and electrochemistries. As noted in Table III-1, in practice approximately 1-3kWh of high-power battery capacity is needed to provide 300Wh of available energy at 25/30kW pulse power. For a 40kg battery, this capacity range translates into a minimum specific energy range of 25Wh/kg (3kWh battery) to 75Wh/kg (1kWh battery).

Power. The battery's minimum peak specific power of 625W/kg is calculated from the specified battery peak discharge power (25kW) and the allowable battery weight (40kg). In the (currently unlikely) case that a PA/R hybrid battery weighs less than this allowance because of its high specific energy, the battery's peak specific power must increase in inverse proportion to battery weight and specific energy. In that case, the peak power requirement rather than the minimum storage capacity needed may determine the minimum battery weight and capacity.

Cycle Life. A PA/R hybrid battery receives charging energy only from on-board generator(s) coupled to the wheels and the engine, and it must be kept at an intermediate state of charge to be ready for accepting or delivering energy, see also Fig. III-1. Over the desired 10-year life, the battery must tolerate a large number of high-power, shallow cycles. As indicated in Table III-1, this requirement translates into 5000 kWh of pulse energy to be delivered by the battery over its useful life. For a 1kWh battery, 5000kWh are equivalent to more than 6000 deep cycles (80% of 6250kWh = 5000kWh), and the 25kWh (resp. 100Wh discharge) pulses represent 2.5% (resp.10%) of the nominal capacity. For a 3kWh battery, on the other hand, 5000kWh are the charge-discharge equivalent of 2000 deep cycles in form of shallow cycles that use less than 1% (resp. 3.5%) of nominal capacity – much less severe requirements.

Cost. There is as yet little well-supported information from automobile manufacturers regarding allowable costs for HEV batteries. PNGV has indicated a PA/R battery total cost goal of $300, which translates into specific battery costs of between $300/kWh and $100/kWh for battery capacities between 1kWh and 3kWh. The PNGV goal of $500 for the 3kWh battery matched to a "slow-response" engine (see Ref. 10, Table 2-2) translates into ~$170/kWh. Finally, a cost goal of $267/kWh was indicated by DOE personnel (see Ref. 10, p.8).

The lowest possible PA/R battery costs consistent with acceptable performance and life are, of course, very desirable. However, the $300 and $500 PNGV cost goals appear arbitrary compared, for example, to the USABC goals for EV battery costs which are dictated by the large cost fraction EV batteries contribute to EV costs. In view of this, and because no known high-power battery appears capable of meeting the $100/kWh or even the 170/kWh goal, the $267/kWh goal ($800for a 3kWh battery) is used in this study. Even this goal is far below the PA/R HEV battery costs projected by Japanese car and battery companies for mass-produced PRIUS batteries, see below.

With the assumptions made in Section II.1 (linear depreciation of battery capital cost over a 10-year life, 10% interest on the undepreciated balance, 12,000 vehicle miles per year), the life cycle (ownership) cost of a 3kWh, $267//kWh PA/R battery is approximately 0.9 ¢ per vehicle-mile.

B. ER Hybrids

Electric-range hybrid vehicle batteries must meet a different set of requirements that are dictated by the desired vehicle range on battery power alone.

Capacity and Specific Energy. As noted in Section II,1., 4-5kWh and 8-10kWh are required to provide a 20-mile and 40-mile driving range, respectively, for a state-of-art electric vehicle with an overall efficiency of 4-5 miles per kWh. Assuming somewhat arbitrarily but realistically that a battery weight of 100 kg is acceptable for an ER hybrid electric vehicle, the specific energy goals become >40-50Wh/kg and >80-100Wh/kg for ER HEV batteries that can provide short and medium electric range, respectively.

Power. If an ER hybrid electric vehicle driven in the battery-only mode is to match the acceleration capability of a PA/R hybrid, its battery needs to deliver approximately twice the power of the 25kW PA/R battery, to make up for the combustion engine power. However, because of its 100kg weight, the ER HEV battery needs somewhat less peak specific power than a 40kg PA/R hybrid battery. Also, the ER hybrid total power (battery plus engine) will exceed that of the PA/R hybrid by as much as 50%, giving the ER hybrid vehicle better acceleration and, because of the larger battery capacity, superior hill climbing performance.

Cycle Life. Over their life, ER HEV batteries need to deliver substantially more energy than a PA/R battery. The shallow and deep cycle life targets in Table III-1 (2nd and 3rd data columns) were estimated by requiring a 10-year battery life and assuming that a 20-mile (~5kWh) and 40-mile (~10kWh) ER HEVs are operated in the battery-only mode for 1/3 and 2/3, respectively, of their 12,000 annual mileage. With a "kWh mileage" of 5 miles/kWh, these assumptions translate into about 8,000 and 16,000 kWh to be delivered by 5kWh and 10kWh batteries, respectively, or about 2000 cycles @ 80% DoD for both battery capacities. Achievement of this target will be a difficult challenge. More efficient vehicles and a less severe battery-only duty cycle will reduce this challenge in direct proportion.

In addition, ER HEV batteries need to provide shallow charge-discharge cycles while operated in conjunction with the combustion engine. In first approximation, the corresponding cycle life targets for 5kWh and 10kWh batteries can be assumed to be 2/3 and 1/3, respectively, of the PA/R cycle life targets. As shown in Table III-1, on a per-kWh basis these targets are far less demanding than those for the smaller PA/R batteries.

Cost. ER hybrid vehicle batteries will cost more than PA/R hybrid batteries although not in proportion to their larger capacities because the costs of packaging and of the required electric and thermal control systems do not increase proportionately with battery capacity. Also, ER hybrid electric vehicle batteries can have somewhat lower specific power, which reduces their cost per kWh compared to batteries for PA/R-type HEVs. On the other hand, the requirement to tolerate up to approximately 2000 deep cycles will translate into design features that may add to ER battery cost. In first approximation, these factors are likely to offset and result in similar per-kWh costs of PA/R and ER hybrid electric vehicle batteries.

Accordingly, a reasonable starting point for setting ER HEV battery cost goals is to permit an ownership cost of 1¢ per vehicle-mile, similar to that for a 3kWh, $270/kWh PA/R battery (see above). When estimating ER battery cost goals from a 1¢/mile allowance, a 1.5¢/mile energy credits[1] can be taken for each mile driven with battery power only because of the cost difference between motor fuel and electricity. Accordingly, a 20-mile ER hybrid vehicle operated for 1/3 of its annual mileage of 12,000 miles on battery energy can claim a credit of 0.5¢ for each of the 120,000 vehicle miles; for the 40-mile ER HEV driven 2/3 electrically, this credit increases to 1¢/mile. With this assumption, and using the simplified life cycle cost calculation noted above (see pages 6 and 49), the specific cost goals for the 20- and 40-mile ER HEV batteries become $240/kWh and $160/kWh, respectively. For a still modest battery cost allowance of 2.5¢/mile, the battery specific cost goals increase to a more realistic $480/kWh and $280/kWh, respectively.

The evolution of hybrid electric vehicle concepts and designs is continuing. Accordingly, the battery requirements and targets listed in Table III-1, and the cost considerations in this section, should be taken as general guides rather than firm criteria when assessing the prospects for application of specific battery types in hybrid electric vehicles.

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[1] *Assumptions: PA/R hybrid fuel mileage 50mpg, gasoline cost $1.25/gal, ER hybrid vehicle electricity mileage 5 miles/kWh, electricity cost 5¢/kWh.*

III.3 STATUS OF ADVANCED HEV BATTERIES

The most important feature of HEV batteries – high specific power – is a design rather than a fundamental electrochemical characteristic. As a consequence, there is no direct parallel to the use of specific energy (see Section II.2 on candidate EV batteries) when identifying candidate HEV batteries. Nevertheless, consideration of specific energy requirements is useful if done properly. This consideration is simple for ER (electric-range) hybrid electric vehicle batteries. Here, the specific energy goal is determined by the battery weight and the battery-only range specified for the vehicle. As indicated in Table III-1, ER hybrid batteries need to have ≥40-50Wh/kg and at least 80-100Wh/kg for short and medium electric range HEVs, respectively.

On that basis, all of the EV batteries discussed in Section II are candidates also for the ER hybrid application, at least in principle. The key questions are whether these batteries can be designed for adequate specific power (e.g., 500W/kg), whether the high-power designs can meet the demanding cycle life goal of up to 2000 cycles, and whether battery costs can become competitive.. These questions are discussed below for the likely candidate battery systems.

Identification of candidate PA/R hybrid batteries presents a more complex question, as suggested in Table III.1. At first glance, the specific energy goals calculated from the 1-3kWh capacity and the maximum battery weight of 40kg seems to limit candidates systems to those with more than 25Wh/kg and preferably >75Wh/kg. However, the more important goal is the availability of ≥7.5Wh/kg (300Wh from a 40kg battery) at the specified pulse discharge power. Accordingly, the list of candidates for the PA/R hybrid application needs to be extended to systems that may have only modest nominal specific energy but can deliver most of that energy at very high power levels.

Batteries with potential to meet this requirement and the other goals listed in Table III-1 are discussed below, beginning with those that have already been used in hybrid electric vehicle power trains. The discussion then turns to systems for which high-power modules or cells have been fabricated and successfully tested at least in the laboratory, with the expectation that commercial technology could become available within the next 3-5 years pending development of a market for HEV batteries.

A. Nickel-Metal Hydride (NiMH)

Panasonic EV Electric Energy is the only organization engaged in the commercial production of NiMH HEV cells, modules and batteries. About 23,000 1.9 kWh battery packs were produced in 1998, largely for the Toyota PRIUS HEV. Table III-2 gives the technical data for this battery which uses the Panasonic EV 6.5Ah high power cell.

Table III-2. Characteristics and Status of Panasonic EV Energy NiMH HEV Batteries

Characteristics	Power Assist / Regen.HEV			Small EV or HEV(ER)		
	Cell	Module	Battery	Cell	Module	Battery
Capacity						
- cell (Ah)		6.5			28	28
- module (Wh)		50			350	
- battery (kWh)			~1.9			8.4
Peak Spec. Power (W/kg) (%DoD)		500 (50)	500 (50)		320 (80)	320 (80)
Peak Power Density (W/L)						
Specific Energy (Wh/kg)						
- @ nominal rate		44	44		56	56
- @ pulse power						
Life						
- calendar (years)		>5	>5		>5	>5
- deep cycles (80% DoD)					>1000	>1000
- shallow cycles (%DoD)						
Development Status [a]		P	P		PP→P	PP→P

[a] *E– experimental, LP– laboratory prototype, EP– engineering prototype, PP– production prototype, LVP–low volume production, P in commercial production.*

A comparison with Table III-1 shows that the EV-6.5 technology comes close to meeting several important requirements and performance goals for a PA/R HEV battery. However, because data for the battery's energy (and specific energy) available at peak power were not provided, the question is still open whether the energy available from this battery at peak (pulse) power would be sufficient for adequate acceleration of a hybrid electric vehicle that is larger (and, presumably, heavier) than Toyota's PRIUS. The new Honda INSIGHT HEV uses only half of a PRIUS battery which attests not only to the lighter weight of that vehicle but points to possibilities for assigning batteries reduced roles in operating hybrid electric vehicles.

Included in Table III-2 are data for the Panasonic EV-28 cell, module and battery technology designed for the Toyota e-com (commuter) all-battery EV. The production of EV-28 batteries will be increasing, possibly substantially if the e-com commuter EV becomes a commercial success. A comparison with Table III-1 indicates that a 4-5 kWh version of the EV-28 battery would meet most of the short-range ER HEV battery requirements and performance goals. Total and peak specific power would fall short by about 35%, but the goals could probably be reached with appropriate cell design changes.

Cost remains an issue with the EV-6.5 and EV-28 batteries. It is likely that their specific cost will be higher (perhaps significantly) than the cost of a mass-manufactured NiMH EV battery. Since the latter cost is unlikely to drop below $300/kWh in Panasonic's view, the EV-6.5 and –28 batteries are likely to cost substantially more than $300/kWh even in volume production.

Ovonic Battery Co. (OBC) has developed high-power NiMH batteries for the power assist/regen, electric-range, and range extender hybrid electric vehicle applications. The characteristics of OBC's 10-HEV-12 plastic monoblock module are shown in Figure III-4. This technology falls somewhat short of meeting the PNGV specific power goal for the PA/R HEV but is likely to meet the requirements of a "milder" hybrid. Table III-4 also presents data for the OBC 7-HEV-28 battery module. A 100 kg battery of 23 such modules would have a capacity of 5kWh and peak power of 55kW, thus meeting the technical requirements and goals for the short-range ER HEV (see Table III-1).

Table III-3. Characteristics and Status of Ovonic Battery Co. NiMH HEV Batteries

Characteristics	Power Assist / Regen.HEV			Electric-Range HEV		
	Cell	Module	Battery	Cell	Module	Battery
Capacity						
- cell (Ah)		12			28	
- module (Wh)		150			210	
- battery (kWh)						
Peak Specific Power (W/kg)		550			550	
Peak Power Density (W/L)		800			1200	
Specific Energy (Wh/kg)						
- @ nominal rate (1C)		48			50	
- @ pulse power (500W/kg)		18			7.5(est.)	
Life						
- calendar (years)		>5			>5	
- deep cycles (80% DoD)						
- 25 – 100 Wh cycles (kWh/kWh)						
Development Status [a]		PP			PP	

[a] *E– experimental, LP– laboratory prototype, EP– engineering prototype, PP– production prototype, LVP–low volume production, P– in commercial production.*

VARTA has developed a "ultra-high power" (UHP) NiMeH 10Ah cell technology; this development was co-funded by PNGV. As indicated in Table III-4, these cells meet the peak specific power requirement for the PA/R hybrid application. VARTA's preliminary data for a 46-cell module of these cells can be used to estimate that a battery of 45kg (12% above the goal) would be able to deliver a more than adequate 700Wh at 25kW, the battery's peak pulse power. Since designed for high power, this technology has only half the specific energy that would be required for the ER (short-range) HEV application. To date, VARTA has delivered several thousand of their UHP NiMH cells to Daimler Benz, Volvo and other carmakers for evaluation in hybrid vehicle drive systems.

Table III-4. Characteristics and Status of VARTA NiMH HEV Batteries

Characteristic	Power Assist/Regen HEV			Electric-Range HEV		
	Cell	Module	Battery	Cell	Module	Battery
Capacity						
- cell (Ah)	10					
- module (Wh)		250				
- battery (kWh)						
Peak Specific Power (W/kg)	750	630		≥240	>220	>200
Peak Power Density (W/L)	2300	1150		≥560	≥520	≥460
Specific Energy (Wh/kg)						
- @ nominal rate	33	30		55	50	45
- @ pulse power	≥17	≥10				
Life						
- calendar (years)	>5[a]	>5[a]		>5[a]		>5[a]
- deep cycles (80% DoD)	>2000	>2000		>2000		>2000
- 25-100-Wh cycles (kWh/kWh)	>2500	>2500		>2000		>2000
Development Status[b]	PP	PP		PP		PP

[a] ≥10 years expected, [b] E– experimental, LP– laboratory prototype, EP– engineering prototype, PP– production prototype, LVP–low volume production, P–commercial production.

Table III-4 also presents data for VARTA's 45Ah, 9kWh NiMH HEV battery prototypes that are currently being tested. This technology meets the power and energy requirements for the medium-range ER HEV but only at a weight of 150kg, 50% above the goal. VARTA did not reveal cost data for their 10Ah and 45Ah NiMH technologies, nor did they discuss plans for commercial production. It seems reasonable to assume that the company could establish production relatively quickly (e.g., within two years) if a sufficiently large market for NiMH HEV batteries develops.

JSB has completed the development of a 7Ah high-power NiMH cell with a specific energy of about 50Wh/kg and a peak specific power of 500 W/kg, intended for PA/R HEVs like the Toyota PRIUS. At present, JSB does not have a production facility for that technology. Whether it will be established depends on JSB receiving sufficiently large orders from one or more car manufacturers. The lead time for a NiMH HEV battery plant is about 1 to 1½ years, and the investment required is several billion ¥ (i.e. several tens of millions of dollars).

Regarding battery costs, according to JSB the ~1.9kWh PRIUS battery is about 400,000 ¥, or approximately $1600 per kWh; this cost might be reduced by about 50% in mass production. A specific cost of $800/kWh would still be well above the goals for PA/R HEV batteries noted in Table III-1, even if a battery life cycle cost of 2¢/mile were acceptable. HEV battery markets and competitive costs rather than technology readiness will determine the availability of NiMH HEV batteries from JSB.

SAFT is a manufacturer of NiMH cells for consumer applications. The combination of technology capabilities in NiMH EV batteries and in very-high-power Li-ion cells (see below) puts SAFT in a good position also for the development and manufacture of high power NiMH technology for HEV applications. Currently, SAFT is developing an 8Ah cell which is intended primarily for the automotive auxiliary power supply (42 Volt system) market, but this cell very likely will also be applicable to PA/R-type HEVs.

Sanyo is strongly focussed on the consumer market for NiMH (and Li-ion) cells, but its extensive technology capabilities and resources no doubt would enable Sanyo to become a producer of NiMH cells for PA/R HEV batteries in response to an emerging market.

B. Lead Acid Batteries

The primary requirement for a PA/R HEV battery is that it can deliver sufficient energy for acceleration (and absorb the energy available from regenerative breaking) at a pulse power of about 25kW. As indicated in Table III-1, for a 40kg battery this requirement translates into a specific energy goal of $\geq$7.5kWh/kg at a pulse specific power of at least 625W/kg. Until recently, this level of performance was not available from the lead acid (or nickel-cadmium) batteries used in experimental and prototypical HEVs. As discussed below, this limitation is being overcome.

For short-range ER applications, a HEV battery has to provide both, ≥50Wh/kg specific energy and ≥500W/kg pulse specific power (see Table III-1). The author is unaware of lead acid or nickel-cadmium batteries capable of such performance. Given that specific energies of 40-45Wh/kg rate appear to be the upper limits at the 2-3 hour discharge rate, cell designs capable of retaining 50Wh/kg at the 6-minute rate (5kWh ÷ 50kW = 0.1hour = 6 min.) are not within reach for these systems.

Bolder Technologies Corporation (Golden, CO) has developed a very high power 1Ah lead acid cell. Trade-marked TMF™, Bolder's cells use very thin lead foils coated with active material on both sides. The coated lead foils are spiral-wound (together with a highly porous glass microfiber separator) into bobbins, filled with sulfuric acid electrolyte and sealed into cylindrical plastic cans. Electric losses and cell heating of 1Ah cells are small even at the 200C (1/200 hour or 18 second) discharge rate; the cells can also be charged at very high rates (up to 100C). Recently, Bolder developed a 5 Ah TMF™ cell with the characteristics shown in Table III-5.

Table III-5. Characteristics and Status of Bolder TMF™ High Power Lead Acid Cells

Characteristics	Power Assist / Regen.HEV			Electric-Range HEV		
	Cell	Module	Battery	Cell	Module	Battery
Capacity						
- cell (Ah)	5					
- module (Wh)						
- battery (kWh)						
Peak Specific Power (W/kg)	~6500					
Peak Power Density (W/L)	~20,000					
Specific Energy (Wh/kg)						
- @ nominal rate	~21					
- @ pulse power (625W/kg)	~15[a]					
Life						
- calendar (years)						
- deep cycles (80% DoD)	≥1300[b]					
- shallow cycles (%DoD)	>25000[b]					
Development Status [c]	EP					

[a] *Estimated from Ragone plot for 1Ah cells,* [b] *projected from 1Ah cell data,* [c] *E– experimental, LP– laboratory prototype, EP– engineering prototype, PP– production prototype, LVP– low volume production, P– commercial production.*

More than half of the cell's stored energy is still available when discharged at a specific power of almost 2kW/kg. Allowing for a 15% specific energy and power decrease when going from cells to modules, a 40kg battery would be able to deliver about 300Wh at a pulse power of nearly 75kW, more than meeting the PA/R HEV battery requirements (see Table III-1). Bolder's discharge test data indicate capabilities for pulse specific power and power density higher than any other rechargeable electrochemical energy storage device (except metal-based ultracapacitors) under development for high power applications.

Bolder's 1Ah cells have tolerated more than 1300 complete charge-discharge cycles at the 10 C rate. More than 500 deep cycles and between 20,000 and 45,000 shallow cycles are projected for the 5 Ah cell technology, but the shallow cycling performance is not quite sufficient for the PA/R HEV application. The other key question surrounding the Bolder TMF™ technology is its cost. Bolder indicated that specific cost might eventually be decreased to less than that of NiMH high power cells, but only in mass production. Thus, Bolder will face similar cost and market questions and risks as other developers of HEV (and, more so, EV) batteries.

In the meantime, Bolder has established the first full-scale production line for 1Ah cells at its 100,000sq.ft. facility in Golden. As markets develop in engine (jump) starting and power tools, additional lines can be installed. Plans for production of 5 Ah cells will depend on the emerging hybrid electric vehicle battery market and on the success of Bolder's 1Ah cell technology in the consumer product market. Commercial production of 5Ah cells is at least two years away.

C. Lithium-Ion

Sony has been very active in the development and evaluation of a 3Ah cell technology for HEV applications; this development has resulted in Sony's LIPY01 48-cell module. The high-power cell design is evident from the modest specific energy and retention of nearly 50% of the nominal 1C value at very high power levels. The author estimates that a 2-module battery could deliver about 250Wh at 25kW, nearly meeting the PA/R HEV battery goals. Sony's HEV cells have manganese-based positives for lower materials cost.

The characteristics of Sony's LIPY01 Li ion HEV module are shown in Table III-6.

Table III-6. Characteristics and Status of Sony's Li-Ion HEV Battery

Characteristic	Power Assist / Regen.HEV			Electric-Range HEV		
	Cell	Module	Battery	Cell	Module	Battery
Capacity						
- cell (Ah)		3				
- module (Wh)		525				
- battery (kWh)			1.05			
Peak Specific Power (W/kg)		~700				
Peak Power Density (W/L)		~650				
Specific Energy (Wh/kg)						
- @ nominal rate (1C)		25.6				
- @ pulse power (~610W/kg)		~11[a]				
Life						
- calendar (years)						
- deep cycles (100% DoD)		≥1000				
- shallow cycles (%DoD)						
Development Status [b]		EP				

[a] *Estimated from module power characteristics,* [b] *E– experimental, LP– laboratory prototype, EP– engineering prototype, PP– production prototype, LVP–low volume production, P– in commercial production.*

Deep cycle life is similar to that of Li ion cells with cobalt-based positives up to ~40°C, but the manganese-based cells suffer more rapid capacity decline at higher temperatures (e.g., 60°C). In shallow cycling, Sony's cells and modules deliver at least as much energy per unit capacity as in deep cycling, but this is not yet sufficient to meet the PNGV cycle life goal (see Table III-1).

Sony projects a cost of about 200,000 ¥ for a 2-module, 1.05kWh battery. The cost projection of approximately $1,750/kWh (including the controller) is based on a production of 20,000 modules per month; it greatly exceeds the cost goals noted in Table III-1.

Sony's pilot plant can produce some 100s of modules per month. About 2 years would be needed to build a production plant and another 6 months to achieve full capacity. The capital investment for such a plant is likely to be similar to a consumer cell manufacturing plant of comparable production capacity. Investments of such magnitude will be made only after Sony receives an order from a carmaker or, at least, fully understands the market for HEV batteries.

SAFT's focus in developing high-power versions of their Li-ion technology is at SAFT America (Cockeysville, MD). Co-funded by PNGV, the SAFT America program now can fabricate prototype cells in 8 Ah and 16 Ah sizes, with the characteristics shown in Table III-7. Pulse specific power (2 sec pulse) of the 8Ah high power cell is an impressive 1500W/kg. More important for HEV applications, half the cell capacity is available at a specific power of 750W/kg. Allowing for a 25% weight penalty from single cell data, a 40kg battery would have about 80 cells, 2.75kWh storage capacity, and a pulse power of approximately 25kW down to 80% DoD.

From SAFT's cell discharge characteristics, one can estimate that about 480Wh of energy is available at 25kW from a 50% charged battery; the corresponding specific energy is about 12.5Wh/kg. Accordingly, such a battery would meet PNGV performance goals for a PA/R HEV battery.

At present, abuse tolerance tests (including mechanical penetration of cells [nail test], electrical shorting, and exposure to above-design temperature), result in smoke but no fire and no explosion. Calendar life (as determined by accelerated tests at elevated temperature) is projected to be about four years for current technology, shorter than the 10-year requirement established by PNGV. Up to 85% overcharge does not present a safety issue although the cell is damaged irreversibly in the process; over-discharging destroys the cell but does not create safety problems. Cell-level battery electric management is essential to avoid off-design cell conditions and possible safety issues. Cost is a key issue that has led SAFT and SAFT America to concentrate on nickel-based positive electrodes. Both programs are engaged in efforts to reduce the cost of every cell component and to automate manufacturing process steps.

Table III-8 also includes data for the SAFT America 30 Ah Li ion high-power cell, with specific power and energy ratings intermediate between the SAFT's high-energy and high-power cell versions. A 100kg battery of 30Ah cells would meet or exceed the performance requirements for the intermediate-range dual mode HEV applications, but the cost of this technology probably is too high since engineered for high-power military applications.

SAFT (Bordeaux) is considering development of a ~25Ah cell for HEV applications that may meet ER hybrid electric vehicle battery requirements. SAFT America staff noted that the ER HEV is of significant interest in Europe but apparently not in the United States.

Table III-7. Characteristics and Status of SAFT's's Li-Ion High-Power Batteries

Characteristics	Power Assist / Regen.HEV			Military Technology		
	Cell	Module	Battery	Cell	Module	Battery
Capacity						
- cell (Ah)	8			30		
- module (kWh)						
- battery (kWh)						
Peak Specific Power (W/kg)	1500			950		
Peak Power Density (W/L)	3100			2100		
Specific Energy (Wh/kg)						
- @ nominal rate (C/3)	74			100		
- @ pulse power (620W/kg)	~12[a]			~75[b]		
Life						
- calendar (years)	~4			~4		
- deep cycles (80% DoD)	>1000			>1000		
- 25 – 100 Wh cycles	>100000			>100000		
Development Status[c]	PP			EP		

[a] *Estimated from cell power characteristic,* [b] *at a specific power of 500W/kg,*

[c] *E– experimental, LP– laboratory prototype, EP– engineering prototype, PP– production prototype, P– in production.*

VARTA has shifted emphasis to the development of high power versions of their manganese-based lithium-ion cell/battery technology. The specific power and energy characteristics of Li ion cells, plus their ability to operate at fairly low temperature, are of interest not only for hybrid applications but for the emerging "booster" batteries: higher-voltage (e.g., 36-42 Volt) batteries capable of meeting the increased auxiliary electric power requirements of future ICE cars. There appears to be considerable synergism between VARTA's efforts to develop a hybrid battery under the PNGV program and its booster battery development for VARTA-Bosch Autobatterien.

The characteristics of VARTA's high-power Li-ion cells are summarized in Table III-9. A comparison with Table III-2 indicates that VARTA's 6.5 Ah cell technology meets the PA/R HEV battery performance goals on the cell level, with good prospects also for the module level if the associated weight increase can be kept to ≤15%. The very long cycle life at 100% DoD suggests that shallow cycle life (expressed as kWh of energy delivered per kWh of cell over its life) will meet the HEV application goal. The information provided by VARTA was insufficient to judge whether the technology is likely to meet the PA/R HEV battery calendar life goals of 5-10 years.

Table III-8. Characteristics and Status of VARTA Li-Ion HEV Batteries

Characteristics	Power Assist / Regen.HEV			Electric-Range HEV		
	Cell	Module	Battery	Cell	Module	Battery
Capacity - cell (Ah) - module (kWh) - battery (kWh)	6					
Peak Specific Power (W/kg)	>850					
Peak Power Density (W/L)						
Specific Energy (Wh/kg) - @ nominal rate (1C) - @ pulse power (625W/kg)	60 ~45[a]					
Life - calendar (years) - deep cycles (80% DoD) - 25 – 100 Wh cycles (kWh/kWh)	~1000 >4000					
Development Status[b]	LP					

[a] *Estimated from cell discharge characteristics* [b] *E– experimental, LP– laboratory prototype, EP– engineering prototype, PP– production prototype, P– commercial production*

Polystor (Dublin, CA), a small company owned by private investors and the British BTR group (which includes the Hawker Energy battery company) is engaged in a program cost-shared by DOE since mid-1998 to develop a 9 Ah Li-ion cell and 48-cell module for HEV applications.

To date, engineering prototype cells with the performance summarized in Table III-9 have been developed. Peak specific power and specific energy (both at pulse power and at the 1C discharge rate) meet PA/R HEV battery goals, as does shallow cycle life. Calendar life is not yet established. PolyStor stated that optimization of the design for high specific energy would increase cell capacity from 9Ah to 15Ah and cell-level specific energy to 140-155Wh/kg. This possibility would seem to be of interest for the development of EV and Electric-Range HEV cells and batteries.

The DOE-funded 9Ah cell/module program is parallel to and synergistic with the PolyStor efforts to establish a manufacturing facility for 1.25Ah cells for consumer applications. At present, cells are fabricated by a combination of pilot-level machinery (for cell winding, etc.) and hand assembly. The key step to high-volume, automated production of 1.25Ah consumer cells will be taken in a new 70,000sq.ft. plant that is currently being furnished with turn-key cell manufacturing equipment from a Japanese supplier.

Table III-9. Characteristics and Status of PolyStor Li-Ion HEV Batteries

Characteristics	Power Assist / Regen.HEV			Electric-Range HEV		
	Cell	Module	Battery	Cell	Module	Battery
Capacity						
- cell (Ah)	9					
- module (Wh)		~400				
- battery (kWh)			~3			
Peak Specific Power (W/kg) [a]	1650	~1350	~1300			
Peak Power Density (W/L) [a]	~2900	~1500	~1400			
Specific Energy (Wh/kg)						
- @ nominal rate (1C)	~90					
- @ pulse power (690W/kg)	~25					
Life						
- calendar (years)	10 [b]		10 [b]			
- 25 – 100 Wh cycles (kWh/kWh)			1700 [b]			
Development Status[c]	EP	LP				

[a] For 18 sec discharge pulse applied at fully charge, [b] goal, [c] E– experimental, LP– laboratory prototype, EP– engineering prototype, PP– production prototype, LVP—low volume production, P– commercial production.

PolyStor considers the PNGV cost goal very challenging since almost every material used in their cells contributes substantially to cost. Materials are expected to contribute more than half of the cell cost once volume production has been achieved. Compositional and manufacturing cost projections on which to base reliable battery cost estimates are not yet available. However, assuming further advances in materials utilization and manufacturing development, PolyStor believes that a specific cost of about $300/kWh should be achievable in large-scale production. This would come close to meeting the goal of $270/kWh.

JSB's corporate R&D is developing a 7Ah Li-ion cell for HEV applications around the materials technology used in JSB's EV cells. Laboratory prototype cells with peak specific power of 1500W/kg @ 50% DoD (700W/kg @ 80% DoD) and a specific energy of about 55Wh/kg are currently being tested. Available data are insufficient to estimate the technology's specific energy performance at pulse power, the critical characteristic. Cell cycle and calendar life data are now being acquired by JSB.

Shin-Kobe has been developing HEV-size Li ion cells, originally 6 Ah but now focussing on 4 Ah. Test data demonstrate high specific power as well as good retention of performance over tens of 1000s of shallow cycles. Peak specific power near the end of discharge still needs improvement, however. Shin-Kobe has built 48-cell modules of 4Ah cells and is interested in becoming a supplier of Li ion HEV batteries to carmakers. The company believes that compared to EVs, the HEV application has lower technical and market risks for commercialization of Li ion batteries, and the investment needed for manufacturing facilities will be less. In Shin-Kobe's view, cost is the most serious hurdle in the commercialization of Li ion batteries for HEVs and, even more so, for EVs.

D. Lithium Polymer

The HQ lithium polymer battery technology is fabricated by thin-film techniques that offer substantial flexibility in cell design and module configuration. As a result – and despite the lower Li^+ ion conductivity of the polymer electrolyte compared to that of the liquid organic electrolytes used in Li ion cells – the HQ LPB technology can be a candidate for HEV applications. 3M recently released performance data for a 50V, 15Ah (750Wh) module using HQ ultrathin cells. Prorating module performance data for a hypothetical 40kg battery indicates that such a battery could deliver 25kW for 18 seconds, for an available energy of 125Wh and pulse specific energy of about 3Wh/kg.

This performance falls somewhat short of the PNGV goals for the PA/R-type hybrid battery but may be sufficient for a "milder" HEV. Upscaling the battery to 100kg (e.g., 7 modules) would increase available energy to an adequate 300Wh, usable peak power to >60kW, and battery capacity to 5.2kWh. These characteristics would meet the performance goals for the short-range ER HEV, see Table III-1.

Cycle life also is promising, with more than 140,000 shallow charge-discharge cycles demonstrated to date in the laboratory. If HQ are able to eventually achieve their EV battery cost goal of <$300/kWh also for their high-power lithium polymer battery technology, it would be one of the most promising candidates for the short-range electric range HEV applications. Because of the similarity of the HQ HEV and EV technologies, an earlier introduction of the HEV version could help underwrite the cost learning curve for HQ's EV battery.

EdF-BT, the other developer of lithium polymer EV batteries, also is designing a hybrid (higher power) version of its technology. Since this aspect of the EdF-BT program is relatively new, data on achieved performance characteristics are not yet available. It seems likely, however, that hybrid versions of the EdF-BT lithium polymer battery technology will be better suited for electric-range than power assist/regen HEV applications.

III.4. ADVANCED HEV BATTERIES: SUMMARY

In 1998, Panasonic EV Energy commercialized the 6.5Ah, 1.9kWh NiMH battery used in Toyota's PRIUS HEV. Spurred by the apparent success of the PRIUS hybrid electric vehicle in Japan and plans for its international introduction, high power battery technologies with potential for yet higher performance and potentially lower cost are now being pursued by a number of battery developers in Japan, the United States and Europe.

The battery performance characteristics achieved in these efforts are summarized in this section and compared to the goals discussed in Section III.2.

A. Nickel-Metal Hydride (NiMH).

A PNGV-specified HEV battery of 40kg needs to have a pulse specific power of ≥625W/kg and an available specific energy (at this power level) of ≥7.5Wh/kg. These requirements define the shaded area in Figure III-2.

Figure III-2. Performance Characteristics of High-Power (PA/R) Battery Modules

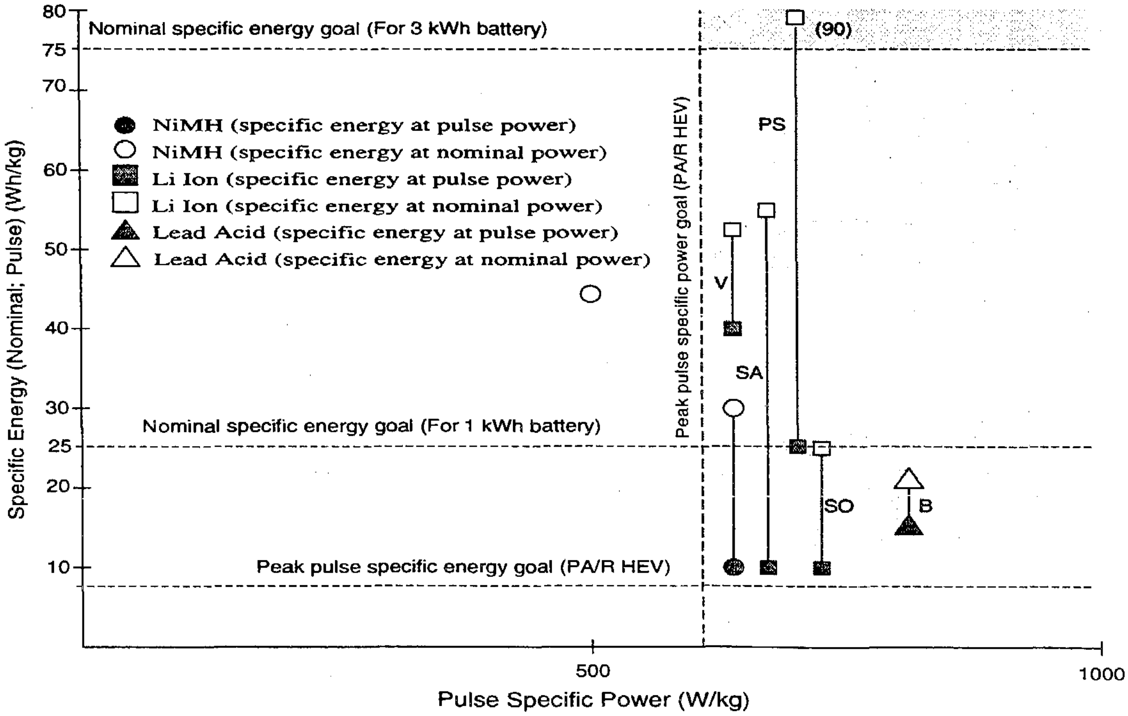
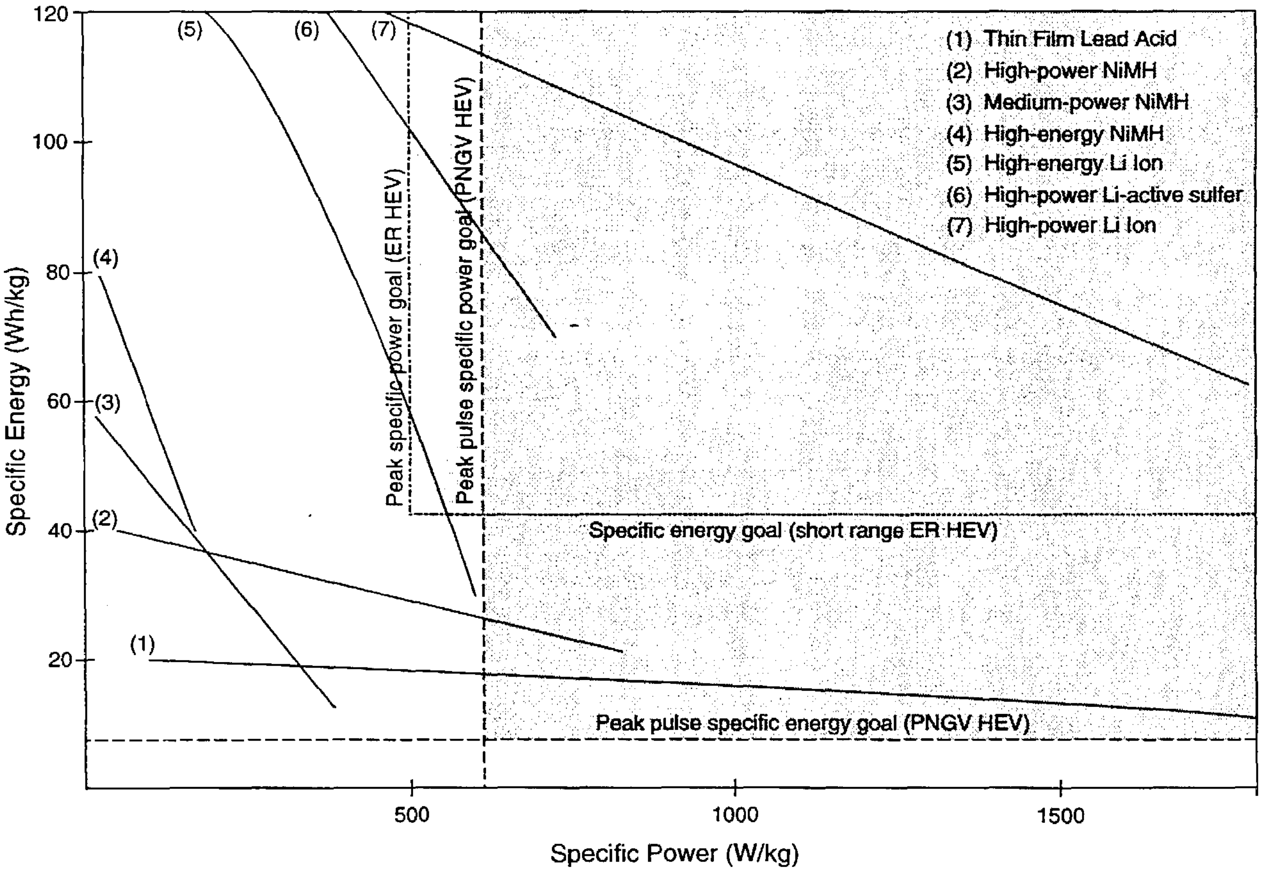


Figure III-2 includes the performance for the Panasonic EV Energy 7-cell (50Wh) modules of 6.5Ah cells (peak specific power 500W/kg; nominal specific energy 44Wh/kg). These cells and modules are designed to deliver the pulse power specified for the PRIUS; they do not meet the PNGV pulse specific power goal for a PA/R HEV battery. The data provided by Panasonic do not permit an estimate of their module's specific energy at pulse power. VARTA's 10Ah engineering prototype module meets the pulse specific power and energy goals of PNGV, as shown in Figure III-2. The differences between the Panasonic EV Energy and VARTA NiMH technologies most likely reflect differences in cell design rather than in fundamental materials capabilities.

The Ragone plots in Figure III-3 illustrate the differences in the characteristics of three different NiMH cell designs from the same manufacturer (VARTA), identified as curves (2)-(4).

Figure III-3. Ragone Diagrams For NiMH and Li-Ion Cell Designs



The highest-power design [see line (2)] has a specific energy of only about 40Wh/kg at the C/3 discharge rate, but its specific energy at 625W/kg is well above 7.5Wh/kg. (The available specific energy is always less than the discharge specific energy plotted in Ragone diagrams; their exact relationship depends on the shape of the charging and discharging power curves, see Fig. III-1)

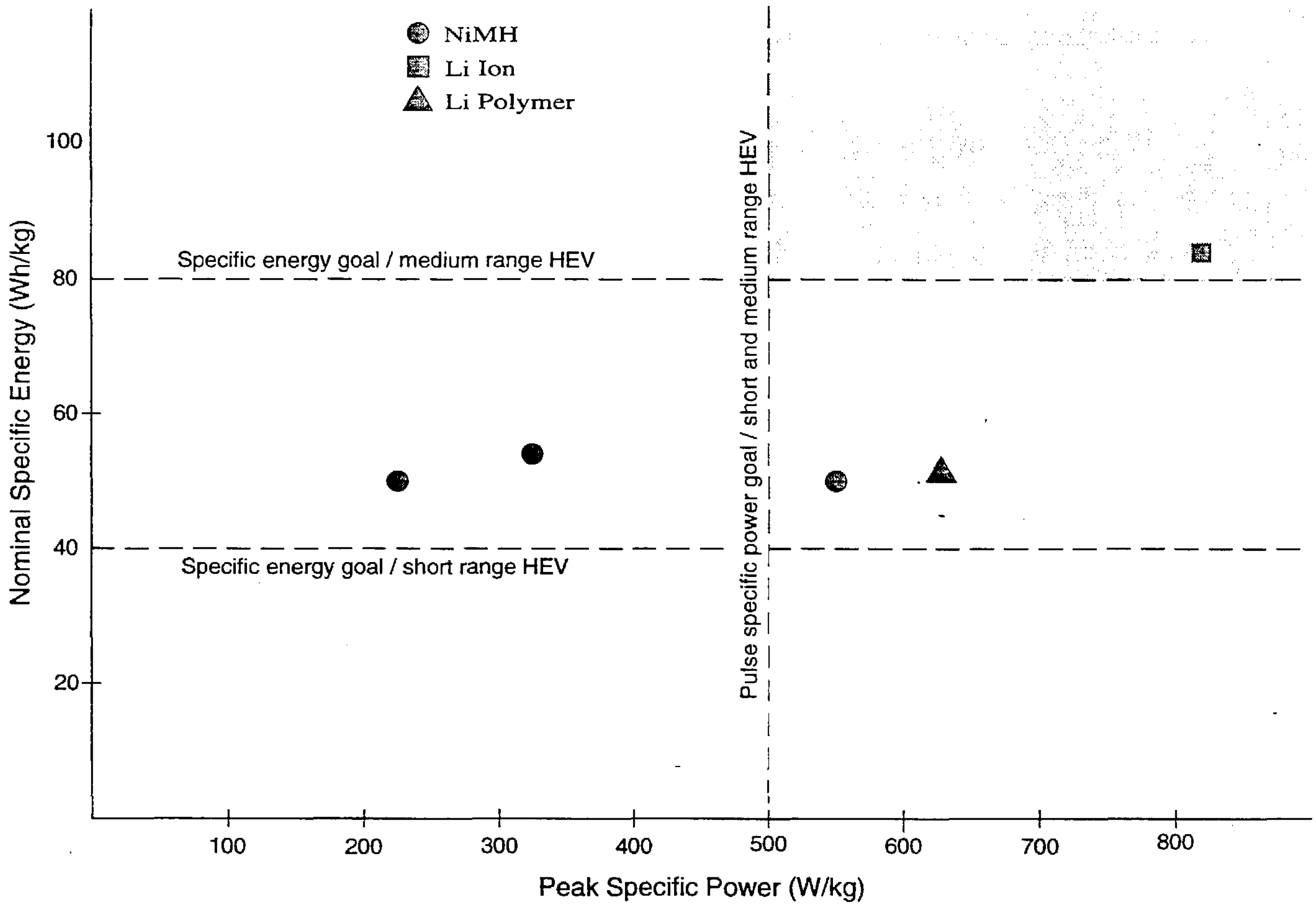
At present, there is only one commercial supplier. Panasonic EV Energy has an estimated production capacity of more than 5 million 6.5Ah cells; approximately 23,000 PRIUS batteries of 240 cells each were produced in 1998. JSB in Japan has a fully developed 7Ah cell technology with characteristics similar to Panasonic's cell, and SAFT in France is developing an 8Ah cell. In addition to a 12Ah-10cell module, Ovonic Battery Co. has developed a very high performance 3.5Ah cell that is said to exceed the PNGV performance goals.

Most of these developers probably could establish similar or larger capacities with relatively short lead time (e.g., less than two years) if they were to receive sufficiently large orders. This scenario should develop if the introduction of HEVs produced by Honda, Toyota (and, eventually, by U.S. automobile manufacturers) turns into a market success. In addition or alternatively, the development of a market for higher voltage (up to 42 V) automotive "booster" batteries could result in orders for high-power NiMH batteries that also might meet the requirements also for PA/R HEV applications.

Figure III-4 shows the performance of medium-power NiMH battery modules from several developers. At present, only the OBC 28Ah cell/module technology appears to meet the battery specific energy and peak specific power goals for short-range ER HEVs as defined in Table III-1.

NiMH battery cost is a key issue also for HEV applications although the goals are not quite as stringent as for EVs. On the other hand, higher-power cell and module designs will cost more per kWh of capacity because they require more material, as expressed, for example, by their lower specific energy. Not surprisingly, in view of the developing market competition, little cost information on NiMH HEV batteries was provided by the developers. The only cost data mentioned for current PA/R HEV battery technology – $1600/kW, reducing to perhaps $800/kW in volume production – exceed the goal by factors 3-6. Emerging markets and developing price competition for automotive "booster" batteries could help reduce PA/R battery costs. No credible information is as yet available for electric-range NiMH HEV batteries, but a reasonable assumption is that cost per kWh will be significantly lower than PA/R hybrid battery versions.

Figure III-4 . Performance Characteristics of Electric-Range HEV Battery Modules



B. Lead Acid

The Bolder thin metal film lead acid cell is the only lead acid technology that meets the pulse specific power and energy goals, as shown in Figure III-2 [line (1)]. Its remarkably flat Ragone diagram (see Figure III-2) reflects the extremely low internal resistance of the cells. The key issue with this technology is whether it can meet the requirement for >100,000 shallow cycles and, also, the stand life requirement of 5-10 years. Achievement of the cost goal also will be a challenge, but probably a less difficult one than for NiMH HEV batteries. However, Bolder does not appear to have immediate plans for commercialization of their 5Ah technology, the cell size that would match the requirements of a PA/R HEV battery.

C. Lithium Ion

Their high specific power makes Li ion cells a logical target for development of PA/R HEV batteries. Figure III-2 includes performance characteristics for modules from four different developers (Sony, SAFT, VARTA and PolyStor). All these technologies meet the pulse specific power goals for the PNGV PA/R HEV, probably also the available energy goal. Figures III-2 points to systematic differences in cell design: generally speaking, the higher the specific energy is at the nominal discharge rate, the lower is it at pulse (high) power, and vice versa.

The Ragone diagrams in Figure III-3 illustrate the differences between a high-power and a high-energy Li ion cell design; they also point to the excellent high-power capability even of high-energy Li ion batteries. It is, therefore, not surprising that an intermediate-power design (SAFT's 30Ah cell for military applications) meets the specific energy and peak specific power goals not only for the short- but for the medium-range ER HEV battery, as shown in Figure III-4.

The key challenges in the development of commercially viable PA/R and ER Li ion HEV batteries are similar to those for the EV-design versions: achievement of adequate stand and cycle life, a high degree of cell and battery safety, and acceptable cost. The data in Tables III-6 through III-10 indicate that all developers are achieving ≥1000 deep cycles, and most of them report very good shallow cycle life as well. Achievement of >5 year stand life appears possible but depends on positive electrode composition and control of time spent at full charge and/or elevated temperature. The limited safety-related information available indicates that cells/modules can safely pass the standard abuse tests. As with Li ion EV batteries, cell-level electric and battery thermal controls are key safety requirements.

Most developers consider high cost the largest barrier for commercialization of Li ion batteries for HEV applications. Sony's estimates a cost of about $1750/kWh for current technology, mass-produced at the rate of 10,000 1.05kWh batteries (total of about 1 million cells) per month. Because high-power Li ion cells retain much of their nominal specific energy at pulse power, a ~1kWh battery might be sufficient to provide the needed pulse energy for a PNGV-specification PA/R-type HEV. However, even a 1kWh battery would exceed the cost goal ($267/kWh) by a factor of 5. It seems doubtful whether a reduction of Sony's battery specific cost by 80% can eventually be achieved. PolyStor, on the other hand, estimated that in mass production the cost of their high-power Li ion cell technology might come down to $300/kW, close to the goal.

D. Lithium Polymer

The feasibility of increasing peak and pulse specific power of the lithium polymer battery by reducing cell thickness has been demonstrated in the HQ program and stated by EdF-BT for their technology. At HQ, this technical thrust has resulted in an engineering prototype module that meets the pulse specific power and energy goals for the short-range ER HEV battery. The other key battery characteristics – deep and shallow cycle life, stand life, and safety characteristics – also promise to meet ER battery goals. If the HQ HEV battery technology can approach the EV battery cost goal, this technology will be a good candidate for electric-range HEV applications. Whether the technology can eventually achieve the pulse specific power-specific energy combination needed for PA/R HEV batteries is still an open question.

SECTION III.   CONCLUSIONS

On the bases of the information provided by battery developers and his own analysis, the author arrives at the following conclusions on the development status of advanced batteries and their prospects to meet reasonable performance goals for applications in electric and hybrid electric vehicles, respectively:

1. Electric Vehicle Batteries

Nickel-metal hydride batteries are technically mature and have proven themselves in the electric vehicles offered in limited numbers by major U.S. and Japanese automobile manufacturers. However, the specific energy of these batteries is insufficient to permit single-charge EV ranges of 150 miles or more with batteries of acceptable weight, and their high cost adds substantially to the commercialization barriers for electric vehicles. Modest increases of specific energy through improvement of electrode materials and cell designs can be expected, but the breakthroughs in negative and positive materials required to approach 150Wh/kg are unlikely. A modest capacity for manufacture of current-generation NiMH EV batteries exists, and additional production capacities could be established with less than two years' lead time by several battery manufacturers. However, automobile manufacturers have not placed the large-volume orders that would justify investment in NiMH battery plants.

Fundamental considerations show that only a few battery types have reasonable prospects to attain the specific energies required to realize a practical 150-mile EV: systems with lithium, sodium or aluminum negative electrodes and high-capacity positive electrodes, and zinc-air batteries. Of these, the sodium-sulfur and sodium-nickel chloride (ZEBRA) high-temperature batteries have been abandoned, and no efficiently and inexpensively rechargeable versions of aluminum-air and zinc-air batteries have emerged despite considerable R&D. (The author was not able to confirm rumors of a new high-specific-energy battery using an aluminum negative electrode.) From the present perspective, systems using lithium in the negative electrode offer the best prospects for EV batteries capable of 150Wh/kg or more, the specific energy needed to enable an EV range of ≥150 miles with a battery of acceptable weight.

Three different, lithium-based rechargeable battery types show potential to meet the performance goals for EVs of extended (e.g., 150 mile) range:

a. **Lithium ion** batteries have only marginal prospects to attain 150Wh/kg, but further advances in electrode materials and cell design might increase specific energy close to that goal. Li ion batteries have excellent specific power and meet the goal for deep cycle life. Achievement of >5 year calendar life still is a challenge and requires restricting the periods during which Li ion batteries are at full charge and/or elevated temperatures. Proper cell design and cell-level electric controls are essential for safety and long life of Li-ion batteries. Pre-prototype Li ion EV batteries are now available in low volume and at very high costs from a few developers. Reducing the high cost of the materials used in Li-ion batteries – positive and negative electrodes, electrolyte salt and separator – and developing low-cost production methods will be critical for achieving the acceptable costs projected by at least one developer for Li ion batteries if produced in large volume (100,000 packs per year).

b. Two developer alliances have advanced **lithium polymer** batteries to the engineering prototype module stage. For adequate power capability, these batteries must be operated at 60-80°C. Specific energies of ≥150Wh/kg are projected by the developers for both of these, and the thin-film cells can be engineered for the specific power levels needed for EV applications. Deep cycle life still needs some improvement but calendar life should be satisfactory because of the good stability of the polymer electrolyte that also serves important safety functions. Materials costs are expected to be lower than for Li-ion batteries. Because of the very thin cells and consequent large cell areas needed to meet specific power goals, lithium polymer batteries must be manufactured with high-speed, automated processes if they are to meet EV cost goals as projected. Development of such methods is the focus of ongoing programs.

c. R&D over the past 5-10 years has shown that lithium can be paired with organo-polysulfides and/or sulfur in **lithium-active sulfur** ambient-temperature electrochemical cells that have potential for specific energies up to perhaps 400Wh/kg. Development has progressed to small laboratory cells intended for consumer product applications. These cells demonstrate basic technical feasibility and permit projection of specific energies well over 200Wh/kg. Specific power levels also are promising but cycle life still is well below the goals for EV applications. In principle, costs should be lower than Li-ion and lithium polymer but little concrete cost information is available at this early stage of development. Exploration and development of lithium-active sulfur batteries for possible future EV applications seem well justified, given their potential for very high specific energy and relatively low cost.

Beyond the technical challenges mentioned above, several important, closely interrelated issues impede the commercialization of lithium-based batteries for electric vehicle propulsion. From the battery developers' perspective, the most important of these is the uncertain market for electric vehicles. The consequent lack of quantity orders of EV batteries by automobile manufacturers deters aggressive investments in battery technology and manufacturing development to reduce costs, and it precludes the – for typical battery companies, major – investments required to establish production facilities. For automobile manufacturers, the high current and uncertain future battery costs add to the large market risk they perceive because of the uncertain acceptance of electric vehicles by prospective users and the inadequate infrastructure to support this new automotive product.

The Catch 22 problem described above is the major reason why a number of important EV battery development programs were terminated in recent years. Sony, the pioneer in the development of Li ion batteries for EVs, discontinued efforts to commercialize its EV (albeit not its HEV) battery technology. VARTA, another leading developer of Li ion batteries, made a similar decision. Very recently, the large lithium polymer program of 3M-Hydro Quebec was restructured, with 3M dropping its corporate resource commitments and leadership role in the program – again because of concerns about the large investments and risks involved in attempting to commercialize batteries for electric vehicles. **The impressive progress in lithium ion and lithium polymer EV battery technology development over the past few years is now bringing to a head the issues surrounding commercialization of these technologies.**

Recommendations

Creative, collaborative strategies engaging the key electric vehicle and electric vehicle battery stakeholders should be developed and pursued, to prevent loss of investments already made, and to build on the opportunities created through the remarkable progress of the last several years. These strategies should include regulation that encourages and fosters alliances between battery developers and automobile manufacturers to jointly set goals, develop EV battery technologies and manufacturing methods, and share the costs and risks in establishing increasing levels of production.

Because of the as yet unexplored potential of very-high-specific-energy batteries, a comprehensive electric vehicle battery strategy also should include extensive, cost-shared R&D collaboration between government and industry over the longer term. The goal of this collaboration should be to explore the potential and advance the technology of systems such as lithium-active sulfur that, if successfully developed, could establish electrical vehicles as a fully competitive transportation mode. A regulatory strategy fostering zero emission vehicles over the longer term would encourage this R&D investment and the continued involvement of automobile manufacturers in ZEV and ZEV battery development.

2. Hybrid Electric Vehicle Batteries

Panasonic EV Energy, jointly owned by Matsushita and Toyota, is the first battery company to commercialize an advanced HEV battery. The Panasonic EV-6.5Ah nickel-metal hydride high-power cell meets the performance requirements of the Toyota PRIUS and Honda INSIGHT hybrid electric vehicles. The apparent success of the PRIUS in Japan has catalyzed interest in HEVs and spurred development of HEV batteries with yet higher performance in Japan, Europe and this country. These efforts benefit from the growing interest in, and possible synergism with, the development of higher-power "booster" batteries to meet the increasing power demand of conventional automobiles.

The current Panasonic EV Energy high-power NiMH battery technology falls somewhat short of meeting the peak (pulse) specific power performance goals established by PNGV for hybrid electric vehicles that use batteries only for starting HEV engines, assisting the engine in vehicle acceleration, and recovering energy during breaking (PA/R hybrid). Several other battery manufacturers have developed engineering prototypes of NiMH high-power cells and modules that appear to meet performance goals. These technologies also appear to meet the calendar and shallow cycle life requirements for PA/R HEV batteries, and they probably could be in production in less than two years from receipt of a quantity order from an automobile manufacturer. High HEV battery costs remain a concern of automobile manufacturers and battery developers. Specific cost goals are less stringent for HEV than EV batteries but, on the other hand, HEV batteries cost more per kWh. Nevertheless, if produced on a large scale, 10-year NiMH batteries for PA/R hybrid electric vehicles might cost HEV owners no more than 1- 2¢ per vehicle-mile.

Lithium ion batteries can readily be designed for the high pulse power levels that must be delivered by HEV batteries. Sony now has reached the engineering prototype module stage, and other battery companies have developed engineering prototype cells that meet PNGV goals for pulse specific power, specific energy at pulse power, and shallow cycle life. Calendar life is being improved and projected to exceed five years. At this stage, it is difficult to estimate the costs of lithium ion batteries for PA/R hybrid vehicles, in part because it is not yet clear whether such batteries – because of their higher pulse power capabilities – can have lower capacities than NiMH batteries for the same application. **Testing of lithium ion batteries in hybrid electric vehicles will be essential to validate pulse power performance, calendar life, shallow cycling capability, and safety under realistic operating conditions.**

The Bolder thin-film lead acid technology has exceptionally high peak (pulse) specific power and sufficient specific energy at pulse power to meet the relevant performance goals for PA/R hybrids. Small cells show promising cycle life but have not yet demonstrated the number of cycles and calendar life required for HEV applications. However, because its potential cost is lower than that of other candidate PA/R batteries, the Bolder technology is of sufficient interest to warrant investigation of its characteristics under representative hybrid vehicle operating conditions.

Electric-Range (ER) hybrid electric vehicles with significant driving range on battery power alone impose different battery requirements. For comparable battery voltages, battery and cell capacities need to be intermediate between those of PA/R hybrid and EV batteries, typically 5-10kWh and 20-30Ah, respectively. Compared to PA/R hybrid batteries, peak (pulse) specific power is less critical but specific energy needs to be higher; the shallow cycling goal is less demanding but the need for very long deep cycle life is an challenging additional requirement.

Several of the advanced battery systems currently being developed have potential to meet the requirements and goals for ER hybrid electric vehicles.

a. Among current **NiMH** designs, only the Ovonic 20/28Ah cell and module technology has sufficient specific energy for the short-range ER HEV application. This technology has reached the engineering prototype stage and could be produced in volume within 2-3 years given a corresponding order. Design optimization would likely enable other NiMH battery developers to offer similar performance if a market developed. The specific cost goal – and the difficulty in meeting it – are intermediate between those for PA/R hybrid and EV batteries. NiMH batteries are unlikely to meet the specific energy goal for intermediate-range ER hybrids.

b. **Lithium ion** cell/battery specific energy and power capabilities appear well matched even to the demanding requirements and goals for intermediate-range ER hybrid batteries. In particular, the SAFT America military prototype 30Ah cell has characteristics that, extrapolated to the module level, would be suitable for both applications. In France, SAFT is considering engineering development of a cell of similar capacity that could be produced on SAFT's new pilot line, for evaluation in vehicles in the near future. Calendar life, the combination of shallow and deep cycle life, and safety need to be demonstrated in practical operation.

c. The recently announced hybrid version of the Hydro Quebec **lithium polymer** battery appears to be a good candidate for the short-range ER hybrid application, promising more than adequate peak power and sufficient specific energy. The required combination of shallow and deep cycle life still needs to be demonstrated. While the HQ cost projection for its EV battery technology falls short of the EV battery cost goal proposed in this study, it would meet the goal for the short-range ER HEV application. At this stage, it is not clear whether further development could increase the performance of lithium polymer batteries to the point where re-optimized designs could meet the requirements of PA/R and intermediate-range ER hybrid electric vehicles, respectively.

In contrast to the situation with EV batteries, the emerging market for hybrid electric vehicles is stimulating increasing efforts by battery companies to develop a considerable variety of candidate technologies with substantially different characteristics. Most of these efforts are focused on cell designs and battery capacities for power assist/regeneration hybrid electric vehicles – the HEV type on which automobile manufacturers appear to be concentrating almost exclusively. While there is only one manufacturer of PA/R hybrid batteries now, others are likely to emerge during the next 2-3 years, first of NiMH and then Li ion batteries, possibly also thin-film lead acid batteries if life and cost goals can be met. Volume production should reduce the costs of these batteries to acceptable levels, if not to current goals.

Promising technology opportunities exist for development of advanced batteries that could enable the development and commercialization of hybrid electric vehicles with sufficient electric range to capture many benefits of electric vehicles, but at a lower cost. Nickel-metal hydride, lithium-ion and lithium polymer batteries all are reasonable candidates for this application.

The cost of ER HEV batteries will be significantly higher than that of batteries for PA/R hybrids but probably not in proportion to the larger capacity, and some of that cost will be offset by the lower per-mile cost of HEV operation in the battery-only mode.

Recommendations

The battery requirements and goals for hybrid electric vehicles should be refined and expanded to reflect the emergence of new HEV types. On that basis, the best battery candidates for the most important HEV types should be identified and evaluated extensively in vehicles.

HEV stakeholders should develop a better understanding of the cost-benefit trade-offs between the different types of hybrid electric vehicles. This understanding should then be used to (1) determine whether hybrid electric vehicles with significant urban/suburban electric range, and the batteries for such vehicles, should receive more emphasis in federally and privately supported development programs, (2) set rational goals for such programs, and (3) serve as the basis for regulatory treatment of the different types of hybrid electric vehicles.

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ATTACHMENT A. 1

Advanced High-Specific-Energy Battery Technology Information Questionnaire

Please provide the best available data and information on your organization's high-energy battery technology:

I. Basic Characteristics of the Electrochemical System

1. Reactions at the positive and negative electrodes
2. Reactions in the electrolyte (if part of the overall cell reaction)
3. Overall cell reaction
4. Open circuit cell voltage (theoretical; practically observed)
5. Theoretical specific energy (Wh/kg) for the overall cell reaction
6. Overcharge and over-discharge reactions
7. Self discharge reaction[s] (if any)
8. Composition of the electrolyte
9. Operating temperature (range)

II. Key Features of the Individual Battery Cell

1. Materials providing electronic conductivity for positive and negative electrodes
2. Thickness of positive and negative electrodes (representative value or range)
3. Electrolyte conductivity (representative value or range)
4. Thickness of electrolyte (representative value or range)
5. Composition and thickness of the separator used (if any)

III. Cell Performance Characteristics

1. Discharge characteristic (cell voltage @ representative current densities)
2. Charge characteristic (cell voltage @ representative current densities)
   (provide charge and discharge characteristics at different states of charge [SOC], e.g., characteristics at 80%, 50% and 20% SOC)
3. Cycling ability of individual battery cells
   (provide charge and discharge characteristics after cells have been deep cycled, e.g., characteristics after 10, 50, 250 and 1000 cycles @ 50-80% depth)

IV. Battery Technology Features

1. Maximum cell size (in ampere-hours [Ah]) achieved to date
2. Maximum cell size (in Ah) targeted for development
3. Maximum number of cells used in a battery to date
   (describe how cells are assembled into batteries)
4. Maximum number of cells in batteries targeted for intended application[s]

V. Battery Performance and Life Characteristics

1. Battery specific energy (Wh/kg) and energy density (Wh/l) at different rates of discharge, e.g., at the C/3, C and 2 C rates
   (provide this information for different stages of battery life, e.g., after 10, 50, 200 and 1000 cycles)
2. Battery specific power (W/kg) and power density (W/l) at different states of charge, e.g., at 100%, 50% and 20% SOC
   (provide this information for different stages of battery life, for example after 10, 50, 200 and 1000 deep cycles)
3. Battery cycle life (number of deep cycles before capacity declines to ≤80%)
4. Battery stand/calendar life (years; indicate main cause of stand life limitation)

VI. Battery Operating and Safety Characteristics

1. Approach adopted for cell and/or battery electric management (at present; in future)
2. Approach adopted for battery thermal management (at present; in future)
3. Failure modes observed or anticipated, and control or failure effects mitigation strategies that might be used in electric vehicle service of the batteries

VII. Battery Cost Considerations

1. Prospective specific cost (in $/kWh of capacity)
2. Cost prospects compared to battery types with known specific costs
3. Battery cost targets adopted for the intended applications
4. Main development directions/strategies to achieve cost targets

VIII. Major Issues Needing Resolution for Possible EV Application[s] of the Technology

1. Performance-related issues
2. Life-related issues
3. Safety-related issues
4. Cost issues

IX. Plans for Development and Commercialization of the Technology

1. Plans and prospective schedule for non-EV applications (portable power, etc.)
2. Plans and prospective schedule for EV applications
3. If no plans for EV applications exist to date, which factors could lead to the decision to pursue EV battery development?

X. General Considerations/Comments on High-Specific-Energy Batteries for EV Duty
(please comment on your organization's position on EV battery development)

ATTACHMENT A.2

High-Specific-Power Battery Technology

Information Questionnaire

Please provide the best available data and information on your organization's high-power battery technology:

I. Basic Characteristics of the Electrochemical System

If your high-power battery is not based on one of the following systems:
lead-acid, nickel-cadmium, nickel-metal hydride, or lithium-ion,
please provide information in response to I. 1. - 9., immediately below:

1. Reactions at the positive and negative electrodes
2. Reactions in the electrolyte (if part of the overall cell reaction)
3. Overall cell reaction
4. Open circuit cell voltage (theoretical; practically observed)
5. Theoretical specific energy (Wh/kg) for the overall cell reaction
6. Overcharge and over-discharge reactions
7. Self discharge reaction[s] (if any)
8. Composition of the electrolyte
9. Operating temperature (range)

II. Key Features of the Individual Battery Cell

1. Materials providing electronic conductivity for positive and negative electrodes
2. Thickness of positive and negative electrodes (representative value or range)
3. Electrolyte conductivity (representative value or range)
4. Thickness of electrolyte (representative value or range)
5. Composition and thickness of the separator used (if any)

III. Cell Performance Characteristics

1. Discharge characteristic (cell voltage @ representative high current densities (corresponding to the 10 C to 100 C rate)
2. Charge characteristic (cell voltage @ 10 C to 100 C rate))
   (provide charge and discharge characteristics at different states of charge [SOC], e.g., characteristics at 80%, 50% and 20% SOC)
3. Cycling ability of individual battery cells
   (provide charge and discharge characteristics after cells have been cycled at high power levels, e.g., characteristics after 5,000, 25,000 and 100,000 shallow cycles at the 10 C to 100 C rate)

IV. Battery Technology Features

1. Maximum cell size (in ampere-hours [Ah]) used to date
2. Maximum cell size (in Ah) targeted for development
3. Maximum number of cells used in a high power (hybrid) battery to date

(describe how cells are assembled into batteries)
4. Maximum number of cells in batteries targeted for intended application[s]

V. Battery Performance and Life Characteristics

1. Battery specific power (W/kg) and power density (W/l) at different states of charge, e.g., at 100%, 50% and 20% SOC (provide this information for different stages of battery life, for example after 5,000, 25,000 and 100,000 shallow cycles)
2. Battery specific energy (Wh/kg) and energy density (Wh/l) at high-power discharge, e.g., at the 10 C, 30C and 100 C rate (provide this information for different stages of battery life, for example after 5,000, 25,000 and 100,000 shallow cycles)
3. Battery cycle life (number of shallow cycles before capacity has dropped substantially, e.g. to =50%)
4. Battery stand/calendar life (years; indicate main cause of stand life limitation)

VI. Battery Operating and Safety Characteristics

1. Approach adopted for cell and/or battery electric management (at present; in future)
2. Approach adopted for battery thermal management (at present; in future)
3. Failure modes observed or anticipated, and control or failure effects mitigation strategies that might be used in hybrid vehicle service of the batteries

VII. Battery Cost Considerations

1. Prospective specific cost (in $/kW of peak power and in $/kWh of capacity)
2. Cost prospects compared to established high power battery types
3. Battery specific power cost targets adopted for the intended application[s]
4. Main development directions/strategies to achieve cost targets

VIII. Major Issues Needing Resolution for Possible Hybrid Vehicle Application[s] of the Battery Technology

1. Performance-related issues
2. Life-related issues
3. Safety-related issues
4. Cost issues

IX. Plans for Development, Demonstration and Commercialization of the Technology

1. Plans and prospective schedule for hybrid automobile applications
2. Plans and prospective schedule for hybrid bus/heavy duty vehicle applications
3. If no such plans exist to date, which factors could lead to the decision to pursue hybrid vehicle applications?

X. General Considerations/Comments on High-Specific-Power Batteries for Hybrid Vehicle Applications

(Please comment on your organization's position on high power/hybrid battery development)

Attachment B

Organizations Contacted

Legend

Q – Received Questionnaire(s)
QR – Responded to Questionnaire(s)
V – Visited by Author
AI – Provided Additional Information

Bolder Technologies Corporation Table Mountain Drive Golden, CO 80403 Fax. 303-215-2500	(Lead Acid)	Q,V4403
chemTEK GmbH Attenbergerstr. 23 D-75038 Oberderdingen Germany Fax. 49-7258-91 44-11	(Zinc-Air)	Q, QR, V, AI
Electricité de France (EdF) Direction des Études et Recherches Service Matériel Électrique 1, Avenue du Général de Gaulle 92141 Clamart Cedex France Fax. 33-1-47-65-42-74	(Li Polymer)	Q, V, AI
Electric Fuel Limited Har Hotzvim Science Park P.O.Box 23073 Jerusalem 91230 Israel Fax. 972-2-322-252	(Zinc-Air)	AI
Electrofuel, Inc. 21 Hanna Avenue Toronto, Ontario M6K1W9 Canada Fax. 416-535-2361	(Li Ion Polymer)	Q, QR, AI
Honda Engineering Co., Ltd 1-10-1, Shinsayama Sayama-shi, Saitama Japan Fax. 81-42-953-3375	(Applications)	Q, V

Accumulatorenwerke Hoppecke Grundlagenforschung D-59914 Brilon Germany Fax. 49-2963-61-493-260	(NiMH)	Q, V, AI
Japan Storage Battery Co. Ltd. EV Systems Development Center Corporate Research & Development Center Nishinosho, Kisshoin, Mimami-ku Kyoto 601-8520 Japan Fax. 81-75-312-1261	(NiMH; Li Ion)	Q, QR, V, AI
Lithium Battery Energy Storage (LIBES) Technology Research Association Technology Division 3-9-10, Higashi Ikebukuro Toshima-ku, Tokyo 170-0013 Japan Fax. 81-3-5951-1025	(Li Ion)	V, AI
Matsushita Battery Industrial Co., Ltd Corporate Engineering Division EV Battery Development Center 1-1, Matsushita-cho, Moriguchi Osaka 570-8511 Japan Fax. 81-6-6994-4807	(NiMH; Li Ion; Li-Organosulfur; Ultracapacitor)	Q, V, AI
Maxwell Energy Products, Inc. 4949 Greencrag Lane San Diego, CA 92123 Fax. 619-576-7672	(Ultracapacitor)	Q, V, AI
Moltech Corporation 90662 South Santa Rita Road Tucson, AZ 85747-9108 Fax. 520-799-7501	(Li-Organosulfur)	Q, V, AI
Nissan Motor Co., Ltd. Product Planning Department Powertrain Engineering Division Technical Center 560-2, Okatsukoku, Atsugi-city Kanagawa 234-0192 Japan Fax. 81-462-70-1820	(Applications)	V

Optima Batteries Inc. 17500 East 22nd Ave. Aurora, CO 80011 Fax. 303-340-7474	(Lead Acid)	V
Osaka National Research Institute 1-8-31, Midorigaoka, Ikeda Osaka 480-1192 Japan Fax. 81-727-51-9629	(Battery Materials R&D)	V
Ovonic Battery Company 1707 Northwood Troy, MI 48084 Fax. 248-362-9921	(NiMH)	Q, V, AI
Pinnacle Research Institute 141 Albright Way Los Gatos, CA 95032 Fax. 408-379-1974	(Ultracapacitors)	Q, V
PolyPlus Battery Company, Inc. 2431 5th Street Berkeley, CA 94710 Fax. 510-841-4313	(Li-Active Sulfur)	Q, V, AI
PolyStor Corporation 6918 Sierra Court Dublin, CA 94568-2641 Fax. 510-829-6251	(Li Ion)	Q, QR, V, AI
SAFT 111-113, Boulevard Alfred Daney 33074 Bordeaux Cedex France Fax. 33-5-57-10-64-86	(NiMH; Li Ion)	Q, V, AI
SAFT America Advanced Technology Division Research & Development Center 107 Beaver Court Cockeysville, MD 21030 Fax. 410-771-0234	(Li Ion)	Q, V, AI
Sanyo Electric Co. New Materials Research Center 1-18-13 Hashiridani, Hirakata-shi Osaka 573-8534 Japan Fax. 81-720-41-0302	(Li Ion; NiMH)	Q, V

Shin-Kobe Electric Machinery Co., Ltd. Saitama Research Laboratory 2200 Oka Okabemachi, Ohsato-gun Saitama-ken 369-0297 Japan Fax. 81-485-46-1137	(Li Ion)	Q, V
Sony Co. RME Co. Energy Division 6-7-35, Kitashinagawa, Shinagawa-ku Tokyo 141-000 Japan Fax. 81-3-5435-3456	(Li Ion)	Q, V
Toyota Motor Corporation Engineering Administration Division 1,Toyota-cho, Toyota, Aichi 471-8572 Japan Fax. 81-565-23-5746	(Applications)	Q, V, AI
VARTA Batterie AG Forschungszentrum Gundelhardtstr. 72 D-65779 Kelkheim/Taunus Germany Fax. 49-6195-802-332	(NiMH; Li Ion)	Q, V, AI

Attachment C
Ultracapacitors

Ultracapacitors have been attracting interest as energy storage devices for hybrid electric vehicles. Historically, this interest was driven by the high power with which properly designed ultracapacitors can be discharged and charged, and by the very large number of cycles that can be delivered by ultracapacitors over their life.

Both of these characteristics derive from the physical principle that underlies the ultracapacitor concept: storage of electric charges and energy in the ionic double layer that forms at the surface of electrodes in contact with an ionically conducting material, typically but not necessarily an aqueous or non-aqueous liquid. Storage is achieved by applying a voltage between two chemically stable and electrochemically inactive electrodes. The voltage is limited to values that permit double layer charging but preclude electrochemical processes at either electrode.

The energy stored in a double layer-based ultracapacitor is given by $E = ½ F \times V^2$ where E is the energy in Watt-seconds (Wsec), F the capacitance in Farads (F), and V the applied voltage (V). The capacitance of an electrode with an effective surface area S (cm^2) and a per-cm^2 capacitance f is $F = f \times S$. In aqueous electrolytes, a typical value of f is 50-100 $\mu F/cm^2$ = 0.5-1 F/m^2. To store 300Wh (approximately 1 million Wsec) of energy (see Table III-1) in an aqueous-electrolyte ultracapacitor (V_{max} = 1V) would require two electrodes, each with a surface area of approximately 2-4 million m^2, or about one square mile. With the presently used organic electrolytes, about 2.5 V can be used as the charging voltage limit for a ultracapacitor cell. The higher cell voltage reduces the surface area requirement approximately 6-fold, to around 0.35-0.7 million m^2 for the same 300Wh of stored energy.

To accomodate these large electrode surface areas in devices of practical size requires use of porous materials with highly developed surfaces, for example specially treated metals in aqueous electrolytes, or activated carbon in organic electrolytes. To be effective, ultracapacitor electrode surfaces must be accessible to current from the electrode contacts and ions from the solution. In practice, this means that surface development cannot exceed approximately 100m^2 per gram (100,000m^2 per kilogram) of electrode material. Accordingly, in aqueous electrolytes about 20-40kg of high-surface material would be needed for each of the two 2-4 million m^2 electrode surfaces needed to store 300 Wh, and approximately 3.5-7 kg in an ultracapacitor using organic electrolytes.

Because the effective electrode materials must be distributed as thin layers on conducting supports, their weight has to be multiplied by factors of 3-10 to arrive at the weight of a complete ultracapacitor device including electrodes, electrolyte, separator, contacts, and an enclosure.

As a result, current practical UC devices have specific energies in the range of 1-3Wh/kg, about one order of magnitude less than HEV batteries at high levels of power. On the other hand, the peak power available from at least one type of UC device is higher than that of today's high-power batteries (see Figure III-2), and ultracapacitor cycle life is likely to be substantially higher as well. The characteristics of representative UC devices are shown in Table C-1:

Table C-1. Characteristics of Developmental Ultracapacitor Devices

Characteristics	Matsushita		Maxwell		PRI	
	Achieved	Projected	Achieved	Projected	Achieved	Projected
Capacity						
- cell (F)	10	6000	2500		2 [a]	1 [b]
- cell (Wh @ voltage [V])	~8	5@2.5	1.8@2.3		0.11@20 [a]	
- module (Wh @ [V])				~30@56		1.4@100 [b]
Peak Specific Power (W/kg)	~200	200-800	1400	670	16,000	16,000
Peak Power Density (kW/L)			1700	650	50,000	50,000
Specific Energy (Wh/kg)	2-3	5-8	1.65	~1	2.2	2.2
Life (millions of cycles)			>0.1		0.25	> 1
Development Status [a]	EP/ LVP		EP		LP	

[a] 20-cell bipolar device, [b] 100-cell bipolar device, [c] E– experimental, LP– laboratory prototype, EP– engineering prototype, PP– production prototype, LVP–low volume production, P– commercial production

Matsushita Electric Industrial Co./Panasonic (Osaka-Moriguchi, Japan) has pioneered the development of supercapacitors and ultracapacitors (UCs)[1] since more than ten years during which a variety of devices were developed, initially for low-energy/low-power applications several of which are now commercial.

Since about five years, high-power devices are being developed and evaluated in several types of hybrid electric vehicles. This technology uses high surface area, activated carbon electrodes wound (together with a separator and aluminum conductor films) into "jellyroll" structures that are filled with the organic electrolyte and sealed into cylindrical cans. Single-cell devices with 2.5 V and up to 6000F are under development. Higher voltages are achieved through series-combination of single cells ("monopolar" arrangement). The largest Panasonic UC multi-cell modules evaluated in HEVs have about 110 Wh and weigh approximately 45kg.

As expected, the Panasonic UC technology has significantly lower specific energy compared to batteries. It also has relatively modest peak specific power, less than high-power batteries. As a result, the average power of a current-technology 45kg (multi-cell) device is likely to in the 10-20kW range. Both energy and power fall somewhat short of the PNGV goal for a PA/R hybrid electric vehicle energy storage system. However, UC energy and power is likely to be sufficient for a "milder" and/or lighter HEV, see the discussion in Section III.2.A, above. Whether Panasonic's UC devices are able to meet cost goals for HEV applications is as yet an open question.

Maxwell Technologies (San Diego, CA) has been developing UC devices similar to those of Panasonic. However, the higher specific power and lower specific energy (see Table C-1) of Maxwell's "Powercache" UC devices point to differences in cell materials and/or design. At present, Maxwell is seeking electronic (e.g., power outage ride-through) applications for small (5-10 F) UC devices. Larger cells and multi-cell devices for power quality management, automobile starting and hybrid electric vehicle application are expected to follow once device costs have been reduced through continued materials (especially carbon and electrolyte) cost reduction and cell manufacturing development.

PRI (Pinnacle Research Institute, Los Gatos, CA) has developed a very-high-power, bipolar UC technology based on a high surface ruthenium oxide layer deposited on thin tantalum metal sheets; sulfuric acid is used as the electrolyte. Because of the high electrode material costs, this technology is too expensive for HEV applications.

More recently, PRI turned its development efforts to UC devices that use a high-surface-area titanium oxynitride layer created on the surface of thin titanium sheets through appropriate chemical processing. To avoid corrosion of the electrodes, a neutral aqueous electrolyte is used, and cells are stacked in a bipolar arrangement to build up device voltage. While the neutral electrolyte is less conductive than sulfuric acid, PRI's cells nevertheless have much lower impedance than activated carbon-based UC devices that use organic electrolytes.

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[1] *The terms supercapacitor and ultracapacitor tend to be used interchangeably. To avoid confusion, it has been proposed to limit the "ultracapacitor" designation to devices that have very high specific power, e.g., 1-2kW/kg or more.*

The characteristics of PRI's advanced UC technology are included in Table C-1, above, showing a much higher peak specific power capability than carbon-based technology. Specific energy is somewhat lower, as expected because of the lower cell voltage. The very long cycle life of PRI's UC devices attests to the chemical stability and electrochemical inertness of the titanium oxynitride electrodes. These electrodes also are more stable at elevated temperatures than carbon-based UC electrode materials which tend to degrade at temperatures above 25-30°C.

The main advantage of PRI UC devices is the lower impedance that permits the stored energy to be discharged in less than one second, compared to 10-100 seconds for carbon-based devices with organic electrolytes. This results (see Table C-1) in much higher peak specific power and far superior power density. For example, a 3.2 kg, 1.2 liter PRI device can start an automobile diesel engine in a fraction of a second. Consistent with this characteristic, PRI is exploring applications for which extremely rapid delivery of short high-power pulses is of special value.

For hybrid electric vehicle applications, the high specific power advantage is less important inasmuch as the time period over which pulse power is demanded by an HEV is in the order of 10 to 20 seconds. Even at these lower discharge rates, the PRI UC technology will have substantially higher power density and efficiency, both important advantages. At present, it is not clear whether the inherent advantages of PRI's advanced UC technology match well with the requirements of hybrid electric vehicles, and whether the per-kWh and per-kW costs of the technology will be compatible with the goals for HEV energy storage devices.