Brief Assessment of Improvements in EV Battery Technology since the BTAP June 2000 Report

Dr. Menahem Anderman
President
Advanced Automotive Batteries

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Contracting Officer:
Tom Evashenk
California Air Resources Board

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SUMMARY

Direct efforts to develop EV batteries have generally declined over the last 3 years. At the same time, battery development for HEV applications continues to gain momentum as HEV market development picks up speed. NiMH is now a mature technology, showing small incremental improvements in performance and life and in cost reduction. Li Ion technology is developing at a more rapid rate, and potentially offers EVs a longer drive range than NiMH batteries. However, Li Ion batteries are still unproven in the EV application due to their shorter life and, for some designs, to their questionable abuse tolerance. While their current low-volume cost quotations are higher, they have the longer-term potential to match, or even fall slightly below, the cost of NiMH in $/kWh.

We find that the two key conclusions (shortened here) of the BTAP 2000 report still hold true today.

1. *NiMH batteries show good characteristics and reliability in EV applications with a life expectancy exceeding 6 years. With a specific energy approaching 70 Wh/kg, the real-life range of practical midsize cars is limited to 70-100 miles. Prices for a typical 30-kWh pack are projected to drop from about $15,000 at production volumes of thousands per year to about $9,000 at volumes of hundreds of thousands per year.*

   Comment: NiMH batteries continue to show good performance but improvements in specific energy are only incremental. For lower pricing than the above estimate at high volumes, a significant reduction in nickel metal pricing (which is independent of the battery market) and relocation of production to China or equivalent low labor/cost area would be required.

2. *Current Li Ion EV batteries do not have adequate durability, and their safety under severe abuse is not yet fully proven. Moreover, the early cost of these batteries is expected to be considerably higher than that of NiMH EV batteries. Even in true mass production, the cost of Li Ion batteries is unlikely to drop below those of NiMH without major advances in materials and manufacturing technology.*

   ***Comment**:* Improvements in life are occurring but are too early to quantify. Although cost is dropping, we are not aware of any major breakthrough in material selection or processing that can support significantly lower prices than those of NiMH.

BACKGROUND

This report is a brief evaluation of changes in EV battery technology since the June 2000 submittal of the Battery Technical Advisory Panel (BTAP 2000) report. While this report is authored by a member of the BTAP, its conclusions are those of the author and do not represent additional BTAP work.

Due to scope, time, and budget constraints for this present report, the author has mostly drawn from information collected over the past two years during the preparation of his Multiclient Study entitled "*The 2002 Advanced Automotive Battery Industry Report - A critical New Assessment of Automotive Battery Trends*", published by Advanced Automotive Batteries in August 2002. During the preparation of the above study, the author conducted over fifty site visits to the major technical centers of leading car companies and advanced automotive battery development firms, and participated in half a dozen international conferences on the subject. To complement the information gathered for the above study, the author also sent a short survey, aimed at gathering specific information and projections, to major battery developers. The surveys are attached in appendices 1a, 1b, and 1c, six of the major EV battery developers have answer the survey. As did the 2000 BTAP report, this report mostly covers NiMH and Li Ion technologies, with a shorter section on VRLA batteries. All three technologies are now available from low-volume production lines or, at least, laboratory pilot facilities.

DETAILS

NiMH

Specific Energy: Improvement—between 5 and 15%—is mostly related to material utilization and packaging efficiency. As did the BTAP panel, we foresee that this technology can achieve about 75 Wh/kg at the pack level, unless an unforeseen breakthrough occurs.

Life: A cycle life of 1,500 to 2,000 cycles at 70% DOD is probably achievable if the battery is kept below 40ºC for the majority of its life. This should translate into a calendar life of 6 to 12 years in typical EV applications.

Field Experience: There are over 1,000 NiMH-powered EVs on the roads, the majority of which were fielded between 1997 and 2000. While no statistical life data are available, some of these vehicles are reported to maintain close to original capacity, even after 5 years, and 60,000 miles or more in the field. However, there are numerous reports of loss of capacity greater than 10 to 20% within the first two to four years of operation with a driving history of less than 50,000 miles.

Charge Efficiency: In the late 1990s some improvements were realized through the use of additives to the positive electrode and these have now been incorporated in production technologies. However, efficient charge at temperatures above 45ºC has not yet been attained. The improvement in charge efficiency should have a positive effect on the battery's operating life, as the average operating temperature of the battery will be lower.

Specific Power: Driven by the requirements of the HEV market, specific power has been raised to 1,200 W/kg at the module level. However, this additional power comes at the expense of specific energy. Because of the increased cost in $/kWh, this development is not beneficial for the EV application but is significant for gasoline/battery or FC/battery hybrids.

Cost: Since a significant market for EV batteries has not materialized, no new cost projections have been made for EV packs. However, several new developments have occurred in the technology generally:

a) Production volume for consumer cells picked up in 1999 but has been dropping since.
b) There is a significant new supply base for both materials and consumer cells in China. The new facilities include Chinese-owned plants as well as joint ventures with foreign, particularly Japanese, manufacturers.
c) The new Chinese supply, in conjunction with the reduction in the total demand on the consumer market, has altered the supply/demand balance. There is now excess capacity for cells as well as for several key raw materials—all of which puts downward pressure on market prices.

d) Most notably, the high-volume price of spherical nickel hydroxide (a key material) has dropped below $6/kg, a fall of about 30% in 3 years, while the ultra-high-volume bare cell pricing of Chinese-made products has dropped below $200/kWh.
e) The price of ultra-high-power HEV packs is currently about $750/kWh for volumes on the order of 20,000 to 50,000 packs.

While the 2000 Panel did not project the specific developments noted above, the author of this report does not see them as significant enough to change the cost projections for future NiMH EV-battery pricing. We believe that, unless a major worldwide change occurs in nickel prices, the lowest price for packs at ultra-high production volume (100,000s packs per year) is still between $250 and $300/kWh, which translates to a minimum of $7,500 for a typical 30-kWh EV-battery pack—required for a fully functional midsize EV.

Li Ion

This 12-year-old technology is still progressing at a rapid rate, helped along by a significant pull from the consumer market. In the 2000 BTAP report, the issue of selecting the cathode material was discussed in detail. We will here review progress in the two leading cathode technologies.

$LiNiCoO_2$ Cathode

Specific Energy: Further improvements in this area can support a specific energy of 150 Wh/kg at the module level.

Life: Data on laboratory prototypes (mostly for the HEV application) indicate a potential operating life of 1,500 cycles and a calendar life of 5 to 10 years. However, the data were obtained from controlled laboratory-built prototypes and it is not clear whether or not the design can i) be adopted for high-volume economical manufacturing and ii) support a minimum 10-year life in the field.

Cost: The cost of materials is coming down in line with the BTAP 2000 projections. However, since no breakthrough has occurred (i.e. none of the cost-driving materials have been substituted), we believe that these projections are still valid.

Abuse Tolerance: Because the basic chemistry of the battery is rather volatile, there is understandable reluctance to install the battery in cars that will be in the hands of customers. However, there is some encouraging work with flame-retardant electrolytes and improved separators that seem to improve abuse tolerance. Other development work is aimed at protecting the battery against abuse by mechanical and thermal means.

$LiMn_2O_4$ Cathode

Specific Energy: Incremental progress has achieved battery specific energies of about 95 Wh/kg, well within the BTAP projections.

Life: Efforts to improve life, driven by the HEV market, have yielded some progress. Most of this work involves additives and/or partial substitution of Mn with nickel and other metals. However, battery developers have focused on improving life at intermediate states of charge, as required by the HEV application. They have made no new projections for the life of an EV battery, and the estimate of a two to three-year life published in the 2000 BTAP report is probably still reasonable. The battery's operating temperature is a key issue, as it cannot withstand temperatures above 40ºC without a major decrease in life.

Life Experience: An unofficial report from Nissan on its Altra Li Ion battery experience with several hundred cars during 2-4 years of service in California reveals a capacity loss of 10-30% over this moderate field life.

Cost: Developers are optimistic in their belief that the cost curves can come down and match those of NiMH at moderately high volumes ($500/kWh for 100,000 packs per year). However, at the level of a million packs per year, the projections made in the BTAP report suggesting ultimate prices similar to those of NiMH—i.e. about $250 to $300 / kWh for a 30-kWh pack—still hold.

Abuse Tolerance: Additional data have been developed that raise confidence that the technology can be made safe in the EV application.

Other Cathodes: There is considerable interest in a new cathode material based on $LiFeO_4$. Batteries using this material would have lower specific energy, but this disadvantage could be offset by lower cost, potentially longer life, and superior abuse tolerance. Currently available data are not sufficient to assess whether or not the overall cost/performance ratio could surpass those of batteries using the more mature cathodes.

VRLA

There is no significant change in specific energy, cost, or life for this technology. The use of the battery in the EV application is held back by the battery's low specific energy of 32 to 38 Wh/kg, which would restrict the vehicle's practical range to less than 60 miles. Although life is slightly improved, it is still limited to about 600 to 800 cycles at 70% DOD which, depending on the usage profile, is equivalent to a service life of 2 to 5 years at best. The main attraction of VRLA is its low cost, and there is no fundamental change in the projections published in the 2000 BTAP report—i.e. $150 to $200 / kWh at moderate production volumes.

Other battery technologies

The Na/NiCl$_2$ High-Temperature 'Zebra' Battery: This battery, developed earlier in Germany by the Daimler Benz AEG group, has been purchased by a Swiss group and is attracting some new interest. However, it is beyond the scope of this report to closely evaluate this technology. We note here that it is used in a limited number of HEV plug-in buses and city cars. Earlier data, which are probably still representative, indicate a battery with a specific energy of 70 to 90 Wh/kg. The use of a ceramic electrolyte necessitates an operating temperature of over 250ºC. The Zebra battery is bulky, has modest power density, and although the cell material cost is moderate, the price of the pack includes significant additional costs associated with the requirements for thermal management.

The Lithium Metal Polymer Battery: This technology's leading developer, the Canadian company Avestor, has lost its USABC Phase-3 EV-battery development contract, presumably due to slow progress in the area of cycle life, and to the technology's poor prospects for lower cost. However, Avestor has recently built a factory to produce smaller low-rate batteries for stationary applications.

Implications of the Development of the HEV Battery Market for EV Batteries

The author was also asked to comment on the potential impact of the development of the high-volume HEV battery market on the future of EV batteries.

We will start with a quote from the Executive Summary of the BTAP 2000 report:

> *"There is little doubt that the development of NiMH and Li Ion battery technologies for HEV applications has benefited directly and substantially from EV battery development. Conversely, the successful commercialization of HEVs can be expected to result in continued improvements of advanced battery technologies. Over the longer term, these advances—together with likely advances in electric drive technologies and reductions in vehicle weight—might well increase performance and range, and reduce costs, to the point where electric vehicles could become a widely accepted product."*

We find the above statement continues to hold true. We note that the top three contending technologies for EV batteries: NiMH, Li Ion, and VRLA, are the same three technologies that are competing on the HEV market. It is also instructive to examine the key areas of development for the two newer battery technologies: NiMH and Li Ion. **Table 1** details the key development areas for NiMH EV and HEV batteries.

The most important area of development in both cases is cost. The top six material cost drivers are the same for both applications. The second most important development area is life enhancement. Here again the two main failure mechanisms, namely negative electrode corrosion and cell venting, are identical. In both cases, improved charge efficiency at high temperatures is a top priority, and it receives considerable attention. The batteries differ only in that specific energy is most important for the EV battery, while for the HEV battery, specific power, particularly at low temperatures, is a key area of development.

Table 1. EV versus HEV NiMH Battery Development

Area	EV Battery	HEV Battery
1) Material cost drivers		
1	Nickel foam	Nickel foam
2	Metal hydride	Metal hydride
3	Nickel hydroxide	Nickel hydroxide
4	Cobalt compounds	Cobalt compounds
5	Packaging	Packaging
6	Thermal management	Thermal management
2) Life driver		
1	Metal hydride corrosion	Metal hydride corrosion
2	Venting	Venting
3) Performance drivers		
1	Improved charge efficiency at high temperatures	Improved power at low temperatures
2	Improved specific energy	Improved charge efficiency at high temperatures

A similar comparison is detailed in **Table 2** for Li Ion batteries. Here again cell construction and design, material cost drivers, life, performance, and abuse tolerance issues are quite similar.

Table 2. EV versus HEV Li Ion batteries

Area	EV battery	HEV battery
1) Cell design		
Cathode	$LiMn_2O_4$ or $LiNiCoO_2$	$LiMn_2O_4$ or $LiNiCoO_2$
Anode	Carbon / Graphite	Carbon / Graphite
Separator	UHMW PE/PP	UHMW PE/PP
Electrolyte	$LiPF_6$ in mixed carbonates	$LiPF_6$ in mixed carbonates
Configuration	Spirally wound	Spirally wound
1) Cell material cost drivers		
1	Positive active mass	Separator
2	Separator	Positive active mass
3	Electrolyte	Electrolyte
4	Negative active mass	Negative active mass
5	Copper foil	Copper foil
2) Life driver		
1	Positive electrode decomposition	Loss of ionic lithium
2	Negative electrode passivation	Positive electrode decomposition
3	Loss of ionic lithium	Negative electrode passivation
3) Performance drivers		
1	Safety	Safety
2	Specific energy	Specific power

It is clear that the continued research and development work on HEV batteries by automakers, battery producers, material developers and research organizations around the world, along with the increasing HEV application experience, will improve the key characteristics of these batteries, which in turn will improve their future viability for EV applications.

Appendices

1a. Questions for NiMH battery developers:

1) EV batteries:

1) Has there been any significant development in NiMH EV batteries that could support any of the following assertion:
    a. Improvement in specific energy to beyond 75 Wh/kg at the module level
    b. Improvement in charge efficiency above 50º C
    c. Data that can positively support 2000 or more 70% DOD cycles over a 12-year period
    d. A significant reduction in cost that can support a module cost below $500/kWh at the production level of 100,000 30-kWh packs per year, or below $300/kWh at a production volume of one million packs per year.

2) Have there been improvements in HEV NiMH battery technology to support any of the following:
    a. Power at – 20ºC exceeding 300 W/kg (10 sec 50% DOD)
    b. Improvement in charge efficiency above 50ºC
    c. Life longer than 10 years at an average operating temperature of 35ºC, assuming 2000, 5% DOD cycles per year at an average rate of 12 to 15 C or about 400 to 600 W/kg.
    d. Cost of ultra-high-power packs (1000W/kg or more) dropping below $600/kWh

1b. Questions for Li Ion battery developers:

1) EV batteries:

3) Has there been any significant development in Li Ion EV batteries that could support any of the following assertion:
    a. Improvement in specific energy to beyond 150 Wh/kg (Ni based cathode) or 120 Wh/kg (Mn-based cathode) at the module level
    b. Resolution of abuse tolerance issues
    c. Data that can positively support 1500 or more 70% DOD cycles over an 8-year period.
    d. A significant reduction in cost that can support a module cost below $500/kWh at the production level of 100,000 30-kWh packs per year, or below $300/kWh at a production volume of one million packs per year.

4) Have there been improvements in HEV Li Ion battery technology to support any of the following:
    a. Power at – 20ºC exceeding 400 W/kg (10 sec 50% DOD)
    b. Life longer than 10 years at an average operating temperature of 35ºC, assuming 2000, 5% DOD cycles per year at an average rate of 15 to 20 C or about 600 to 800 W/kg.

c. Cost of ultra-high-power packs, 1400W/kg or more, dropping below $700/kWh, anytime soon.

1c. Questions for VRLA battery developers:

5) Has there been any significant development in VRLA EV batteries that could support any of the following:
    a. Improvement in specific energy to beyond 40 Wh/kg at the module level
    b. Data that can positively support 1500 or more 70% DOD cycles over a 6-year period
    c. A reduction in cost that can support a module cost below $150/kWh at the production level of 100,000 20-kWh packs per year, or below $100/kWh at a production volume of one million packs per year

6) Have there been improvements in HEV VRLA battery technology to support any of the following:
    a. Life longer than 3 years at an average operating temperature of 35ºC, assuming 2000, 5% DOD cycles per year at an average rate of 12 to 15 C or about 300 to 500 W/kg
    b. Cost of ultra-high-power packs, 500W/kg or more (10-second pulse, at 50% SOC) dropping below $120/kWh anytime soon

2. The following major EV battery developers have answered the survey:

a) Japan Storage Battery - (Kyoto, Japan)
b) Johnson Controls - (Milwaukee, WI, USA)
c) Matsushita Battery Industry (Panasonic) - (Kosai City, Japan)
d) Panasonic EV Energy (Kosai City, Japan)
e) Saft (Bordeaux, France, and Cockeysville, Maryland, USA)
f) Shin-Kobe Electric Machinery (Saitama, Japan)