Advanced Batteries for Electric Vehicles: An Assessment of Performance, Cost, and Availability

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By

The Year 2000 Battery Technology Advisory Panel

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EXECUTIVE SUMMARY

When the California Air Resources Board began to consider battery-powered EVs as a potentially major strategy to reduce vehicle emissions and improve air quality, it did so with the view that the broadest market would be served by electric vehicles with advanced batteries, and it structured its ZEV credit mechanisms to encourage the development and deployment of EVs with such batteries. Consistent with this view, the Air Resources Board defined the scope of work for the first Battery Technical Advisory Panel study to focus on advanced batteries.

Five years after the modification of the 1991 Zero Emission Vehicle regulation, and after a period of intensive effort to develop, deploy and evaluate advanced electric vehicles, one key remaining question is whether batteries can be available in 2003 that would make electric vehicles acceptable to a large number of owners and operators of automobiles. The answer to this question is an important input to the California Air Resources Board's year 2000 Biennial ZEV regulation review. The authors of this report were asked to assist ARB in developing an answer, working together as a new Battery Technical Advisory Panel (BTAP 2000).

The Panel concentrated its investigation on candidate EV-battery technologies that promise major performance gains over lead-acid batteries, appear to have some prospects for meeting EV-battery cost targets, and are now available from low-volume production lines or, at least, laboratory pilot facilities. In the view of the Panel, other types of advanced batteries not meeting these criteria are highly unlikely to be introduced commercially within the next 5-7 years. While the focus of BTAP 2000 like the first battery panel was to be on advanced batteries because of their basic promise for superior performance and range, ARB asked the Panel to also briefly review the lead-acid battery technologies used in some of the EVs deployed in California. This request recognized that EVs with lead-acid batteries were introduced in the 1990s by several major automobile manufacturers beginning with General Motors' EV1, and that EVs equipped with recently developed lead-acid batteries were performing significantly better than earlier EVs.

The Panel's approach was similar to that of the 1995 BTAP: visits to the leading developers of advanced batteries and to major automobile manufacturers engaged in electric-vehicle development, EV deployment, and in the evaluation of EV batteries; follow-on discussions of the Panel's observations with these organizations; Panel-internal critical review of information and development of conclusions; and preparation of this report. To assist the Panel members with the development of judgment and perspective, they were given business-confidential technical and strategic information by nearly all of the Panel's information sources. This report, however, contains unrestricted material only. The Panel's findings and conclusions are as follows.

The improved lead-acid EV batteries used in some of the EVs operating in California today give these vehicles better performance than previous generations of lead acid batteries. However, even these batteries remain handicapped by the low specific energy that is characteristic of all lead-acid batteries. If EV trucks or representative 4-5 passenger EVs could be equipped with lead-acid batteries of sufficient capacity to provide a practical range of 75-100 miles on a single charge, batteries would represent 50% or more of the total vehicle weight. The specific costs of these batteries produced in volumes of 10,000-25,000 packs per year are projected to be between \$100/kWh and \$150/kWh, about 30-50% of the cost projected for advanced batteries produced in comparable volume. On the other hand, the life of lead-acid batteries remains a serious concern because the high cost of battery replacement might well offset the advantage of lower first costs.

Nickel-metal hydride (NiMH) batteries, employed in more than 1000 vehicles in California, have demonstrated promise to meet the power and endurance requirements for electric-vehicle (EV) propulsion. Bench tests and recent technology improvements in charging efficiency and cycle life at elevated temperature indicate that NiMH batteries have realistic potential to last the life of an EV, or at least ten years and 100,000 vehicle miles. Several battery companies now have limited production capabilities for NiMH EV batteries, and plant commitments in 2000 could result in establishment of manufacturing capacities sufficient to produce the quantities of batteries required under the current ZEV regulation for 2003. Current NiMH EV-battery modules have specific energies of 65 to 70Wh/kg, comparable to the technologies of several years ago—reported in the BTAP 1995 report (1)—and major increases are unlikely. If NiMH battery weight is limited to an acceptable fraction of EV total weight, the range of a typical 4/5-passenger EV in real-world driving appears limited to approximately 75 to 100 miles on a single charge.

Despite extensive cost reduction efforts by the leading NiMH EV-battery developers, NiMH battery cost remains a large obstacle to the commercialization of NiMH-powered EVs in the near term. From the cost projections of manufacturers and some carmakers, battery module specific costs of at least $350/kWh, $300/kWh and $225-250/kWh can be estimated for production volumes of about 10k, 20k and 100k battery packs per year, respectively. To the module costs, at least $1,200 per battery pack (perhaps half of that sum in true mass production) has to be added for the other major components of a complete EV-battery, which include the required electrical and thermal management systems. On that basis, and consistent with the Panel's estimates, NiMH batteries for the EV types now deployed in California would cost EV manufacturers between $9,500 and $13,000 in the approximate quantities (10k-20k packs per year) required to implement the year 2003 ZEV regulation, and approximately $7,000 to $9,000 at production levels exceeding one hundred thousand packs per year.

Lithium-ion EV batteries are showing good performance and, up to now, high reliability and complete safety in a limited number of EVs. However, durability test data obtained in all major lithium-ion EV-battery development programs indicate that battery operating life is typically only 2-4 years at present. Li Ion EV batteries exhibit various degrees of sensitivity when subject to some of the abuse tests intended to simulate battery behavior and safety under high mechanical, thermal or electrical stresses. Resolution of these issues, the production of pilot batteries and their in-vehicle evaluation, and fleet testing of prototype Li Ion batteries meeting all critical requirements for EV application are likely to require at least three to four years. Another two years will be required to establish a production plant, verify the product, and scale up to commercial production. Based on several (albeit not all) of the cost estimates provided by developers and on the Panel's own estimates, these batteries will be significantly more expensive than NiMH batteries at a production volume of around 10,000 packs per year. Even in much larger production volumes, Li Ion EV batteries will cost less than NiMH only if substantially less expensive materials become available, and after manufacturing technologies combining high levels of automation, precision and speed have been developed.

Lithium-metal polymer EV batteries are being developed in two programs aimed at technologies that might cost $200/kWh or less in volume production. However, these technologies have not yet reached key technical targets, including most notably cycle life, and they are in the pre-prototype cell stage of development. It is unlikely that the steps required to achieve commercial availability of Li Polymer batteries meeting the performance and life requirements, as well as the cost goals for EV propulsion, can be completed in less than 7 to 8 years.

Battery developers, USABC, and the six major automobile manufacturers serving the California market have invested extensive financial and talent resources in developing a diversity of EV batteries and evaluating them in electric vehicles. Battery performance and reliability has been excellent in many, and generally adequate in nearly all, of the more than 1400 EVs deployed to date with advanced batteries, most of them of the NiMH-type. However, advanced battery costs will exceed by about $7,000 to $9,000 in the nearer term, and about $5,000 at automotive-mass-production levels, the cost goals derived for EV batteries by postulating comparable life-cycle costs for broadly comparable electric and ICE-powered vehicles.

These cost projections assume reductions arising from incremental technological advances as well as cost reductions resulting from the economies of scale of materials procurement and high-volume manufacturing. In the Panel's assessment, major technology advances or breakthroughs would be required to reduce advanced battery costs substantially below current projections; the Panel considered this unlikely for the next 6-8 years. In addition, the practical range provided by the batteries of current EVs is limited. For applications where increased range is desired, the resulting larger-capacity batteries would aggravate the advanced-battery cost problem in proportion, and they would raise increasingly serious volume and weight issues.

All major carmakers are now actively pursuing other advanced-technology vehicles—such as hybrid and mini EVs—to achieve emission reductions. Like conventional EVs, HEVs and mini-EVs depend on improved batteries for their technical and cost feasibility. However, they require only a fraction of an EV's battery capacity—between 5% and 50%, depending on HEV technology and application. Battery cost is thus substantially reduced, and thereby one of the largest barriers to the commercial viability of these new automotive products. The Panel was made aware of the impressive battery technology progress achieved in this area by several of the EV-battery developers. There is little doubt that the development of NiMH and Li Ion battery technologies for HEV and mini-EV applications has benefited directly and substantially from EV-battery development. Conversely, the successful commercialization of HEVs, and possibly mini-EVs, in the coming years 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.

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Last but not least, the Panel expresses its gratitude to the participating organizations without whose assistance this report would not have been possible. Leading battery developers and manufacturers, automobile manufacturers, and a number of other organizations and individuals associated with electric vehicle battery and battery materials development and evaluation freely provided information on their technologies, plans and perspectives. Most of them also assisted by reviewing the Panel's findings to ensure accuracy of this report.

The final presentation of the Panel's findings and conclusions, however, is the responsibility of the authors.

SECTION I. INTRODUCTION

Background.

When the California Air Resources Board began to consider battery-powered EVs as a potentially major strategy to reduce vehicle emissions and improve air quality, it did so with the view that the broadest market would be served by electric vehicles with advanced batteries, and it structured its ZEV credit mechanisms to encourage the development and deployment of EVs with such batteries. Consistent with this view, the Air Resources Board defined the scope of work for the first Battery Technical Advisory Panel study to focus on advanced batteries.

In December 1995, that panel presented its report on the "Performance and Availability of Batteries for Electric Vehicles" (1). 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 early-year provisions of the 1990 Zero Emission Vehicle (ZEV) regulation. This conclusion was among the factors considered in the 1996 review of the ZEV regulations. The regulations, revised to allow additional time for development and in-vehicle evaluation of advanced batteries, now call for introduction of significant numbers of electric vehicles by the six largest suppliers to the California automobile market beginning in 2003.

Over the past five years, leading EV-battery developers worldwide—several with cost-sharing support from the United States Advanced Battery Consortium (USABC)—have continued to invest large resources (estimated at more than $500 million dollars), and have made important progress in the development of the advanced EV batteries that were examined in the 1995 BTAP report. Additional EV-battery developers have surfaced, and leading automobile manufacturers in Japan and the U.S. have become heavily involved in both the development and deployment of early commercial electric vehicles (primarily in California), and in the evaluation of advanced EV batteries for use in these vehicles.

On the other hand, several important EV-battery programs were discontinued during the last few years, in good part because their sponsors were losing confidence that a market would develop for EV batteries with the currently projected performance and cost characteristics. The experience of the past decade makes it clear that the development of batteries for electric vehicles is facing major technical and cost barriers, and that only those organizations willing to take substantial financial risks and capable of providing extensive resources over a number of years have a realistic chance of overcoming these barriers.

After five years of intensive effort and significant progress in developing and evaluating EV batteries, a key question in the electric vehicle debate is still whether advanced batteries can be available in 2003 that would make electric vehicles acceptable to a large number of owners and operators of automobiles. The answer to this question is an important input to the California Air Resources Board's ZEV regulation review required this year. The authors of this report were asked to assist ARB in developing an answer, working together as a new Battery Technical Advisory Panel (BTAP 2000, termed the Panel in the following). While the focus of BTAP like the first battery panel was to be on advanced batteries because of their basic promise for superior performance and range, ARB asked the BTAP 2000 Panel to also briefly review the lead-acid battery technologies used in some of the EVs deployed in California. This request recognized that EVs with lead-acid batteries were introduced in the 1990s by several major automobile manufacturers beginning with General Motors' EV1, and that EVs equipped with recently developed lead-acid batteries were performing significantly better than earlier EVs.

I.1. PURPOSE AND SCOPE

The purpose of the study summarized in this report was to examine the current state of the leading advanced EV-battery technologies and to assess the prospective costs and commercial availability of these technologies in the year 2003 or soon thereafter.

As in the 1995 BTAP report, the Panel defines "commercial availability" as commercially available for electric vehicle applications, with the performance and reliability of the battery having been demonstrated, the battery having been engineered into a vehicle, and the battery/vehicle combination subjected to validation testing. The word "commercial" implies that the cost of the batteries to EV manufacturers and owners allows the introduction of EVs into economically viable markets.

The main focus of the Panel's study was the investigation of the battery technologies that in 1995 were leading candidates to achieve major performance gains over lead-acid batteries, appear to have some prospects for meeting EV-battery cost targets, and are now available from low volume production lines or, at least, laboratory pilot facilities. In the Panel's view, advanced batteries not meeting these selection criteria are highly unlikely to be available for commercial introduction within the next five years. Although the focus of the BTAP 2000 study thus was on advanced batteries, the Panel briefly reviewed the improved lead-acid EV battery technologies used in EVs operating in California today. As discussed in Appendix F of this report, the Panel found that these batteries are indeed improved but remain handicapped by the low specific energy characteristic of all lead-acid batteries, and that lead-acid battery life remains an important concern.

The scope and time horizon of the investigation reported here thus were different from those of the 1998/99 study by one of the Panel members (2) which emphasized candidate EV-battery systems with future (e.g., ten-year or longer-term) prospects for significantly higher specific energy and lower costs. For the nearer-term EV-battery technologies included in the 1998/99 study as benchmarks, the present investigation adds not only a timely update, but also a strong focus on cost and commercial viability in 2003 or soon thereafter.

I.2. STUDY APPROACH

As in the first BTAP study, the present study employed the following means of obtaining and evaluating information:

- Use of a questionnaire (see *Appendix A.1*) to solicit pertinent information from North American, Japanese and European developers and manufacturers of advanced EV-battery technologies with potential for commercial availability in 2003 or soon thereafter. A similar questionnaire (*Appendix A.2*) was submitted to the six automobile manufacturers (in the U.S. and Japan) currently under obligation to offer EVs for sale beginning in 2003. These manufacturers have active programs to integrate and evaluate advanced batteries in the state-of-the-art electric vehicles developed by them in recent years. The main purpose of these questionnaires was to alert the organizations to the scope of the Panel's interests and the topics to be discussed during the Panel's visits.
- Visits to all these organizations (see *Appendix B*), to discuss EV-battery technology development status and issues, current and prospective costs, and in-vehicle evaluation, as well as strategies, plans and issues for the commercial introduction of EVs and EV batteries. The likely future costs of advanced batteries, and possible strategies and schedules for establishing increasing levels of battery and EV production, were central topics in these visits. In addition, Panel members made many contacts with individuals from organizations engaged in various aspects of electric-vehicle technology and operation, including batteries, battery materials and EV development, battery and EV testing, and the promotion and demonstration of EVs.
- Critical review of the information collected, identification of knowledge gaps, solicitation of additional information from battery and EV developers/manufacturers, and review of report draft material with information sources, to assure accuracy and avoid inadvertent publication of data and other

information given to the Panel in confidence. Panel-internal workshops to review the findings and develop conclusions, and preparation of this report.

Section II below discusses key requirements for EV batteries, with emphasis on costs, and it identifies the advanced-battery systems included in the Panel's investigation. The Section also includes a discussion of the most important factors contributing to battery costs. Section III details the Panel's findings from the discussions with battery developers/manufacturers (Sections III.1, III.2, and III.3) and automobile manufacturers (Section III.4). Finally, Section IV presents the Panel's conclusions from the information collected, discussed with its sources, and subjected to Panel-internal critical discussions.

SECTION II. BATTERIES FOR ELECTRIC VEHICLES

Background. The 1995 BTAP assessment found that several advanced battery types with the potential to meet the mid-term performance and cost targets of the United States Advanced Battery Consortium (USABC) had reached the pre-prototype stage. That Panel also concluded that even the leading candidates among these were unlikely to be commercially available before 2000/2001, and this only in a complete success scenario that required, in particular, firm commitments to battery production plants no later than 1998/99.

In the absence of historic precedent, the 1995 BTAP study had to leave open the question of whether availability of batteries meeting or, at least, coming close to USABC mid-term targets would lead to successful commercialization of electric vehicles (EVs). The study's battery-cost survey indicated [(1), *Table II.4*] that the costs of the batteries being developed were likely to be well above USABC mid-term targets, except possibly in large-scale production, adding to the uncertainty about the prospects of EVs.

Over the past five years, battery developers and automobile manufacturers devoted large efforts to the continued advancement of EV-battery technology and the development of a new generation of electric vehicles. Under the MoA between the six leading automobile manufacturers and the California Air Resources Board, a substantial number of these vehicles has been deployed. Nevertheless, since they are produced in limited volume only, the vehicles—including their batteries—are expensive, and vehicle leases had to be subsidized heavily to attract early users.

As the time approaches for critical decision on actions needed to implement the current ZEV provisions, the question again arises whether batteries with the required performance and cost characteristics could be available in time for commercialization of broadly marketable EVs by 2003. The most important requirements that must be met by EV batteries are re-examined below from today's perspective, and they are used in Section II.2 to identify the candidate EV batteries that were examined more closely by the Panel. The Panel's findings on EV-battery performance, cost, and prospects for availability in the coming years are summarized in Section III.

II.1. BATTERY TARGETS/REQUIREMENTS

Table II.1 summarizes the most important targets established for the battery development program of USABC (1).

Table II.1 Requirements for EV Batteries (Adopted from USABC)

Battery Characteristic	Units	Near-term	Long-term	Commercialization
PERFORMANCE				
Specific Energy	Wh/kg	80-100	150-200	150
Energy Density	Wh/liter	130	300	230
Power Density	W/liter	250	600	460
DURABILITY / LIFE				
Cycle Life (80% DoD)[1]	Cycles	600	1000	1000
Total Miles	000's	40	≥100	≥100
Calendar Life	Years	5	>10	≥10
SAFETY	Abuse tests	Pass	Pass	Pass
CONVENIENCE				
Recharge Time	Hours	<6	3-6	
Quick Charge to 40%	Minutes	15	15	
Operating Temp. Range	°C	-30 to +65	-40 to +85	
COST / ECONOMICS				
Capital Cost[2]	$/kWh	≤150	≤100	≤150 (25,000 packs/year)

[1] *≤ 20% power and capacity degradation*
[2] *Price to OEM, $/kWh for10,000 packs/year*

A technical team drawn primarily from the major U.S. automobile manufacturers derived the long-term battery targets in *Table II.1* nearly a decade ago from the postulate that, to be competitive, an EV intended for the same purpose as an internal combustion engine (ICE)-powered vehicle had to match that vehicle with respect to all key characteristics: performance, durability, safety, convenience and cost. The target ICE vehicle assumed in that derivation was a mass-produced (4/5-passenger) family sedan with characteristics similar to the Chevrolet Lumina, Ford Taurus or Chrysler Concorde.

Recognizing the difficulty of emerging EV-battery technology meeting the very demanding long-term targets, USABC also defined a less severe set of near-term targets (see *Table II.1*) for the batteries of EVs that might find limited applications. Recently, USABC defined a set of battery "Commercialization" targets that, if met, should permit EVs to begin entering the market. As shown in *Table II.1*, the commercialization targets for performance fall generally between the near and long-term values. The commercialization targets for cycle and calendar life are as demanding as the long-term values, while the cost target is relaxed to the near-term value of $150/kWh. The most important requirements for EV batteries are reviewed below from today's perspective and compared to the USABC targets.

II.1.1. Performance

Specific Energy. As shown in *Appendix C*, today's state-of-the-art 4/5-passenger vehicles (*Table C.1*) have practical ranges of about 75-100 miles (*Table C.2, lines 4B and 4C*) with 29-32 kWh batteries. These batteries weigh between 450kg (NiMH) and 360kg (Li Ion), and they represent approximately 30% and 20%, respectively, of vehicle curb weights. The specific energy of the NiMH batteries used varies from about 50 to 64 Wh/kg; it is nearly 90 Wh/kg for the Li Ion battery.

Utility vehicles and vans (see *Table C.1*) attain about 65-85 miles (*Table C.2*) with NiMH batteries having approximately the same capacity, and battery weights represent about 25% of the utility vehicles' 25-35% higher curb weights. Only the lightweight, aerodynamically very efficient 2-seat EV1 has a practical range substantially in excess of 100 miles, approaching 150 miles albeit only with a NiMH battery that represents nearly 40% of the vehicle curb weight.

To attain a 150-mile "real world" range, the capacities of the NiMH batteries for the 4/5-passenger EVs would need to be increased to at least 45kWh and their weight to about 700kg. This is clearly very undesirable since the battery would then represent more than 40% of curb weight, and in all probability is not feasible with current vehicle designs. If the battery weight were kept at around 450kg, battery specific energy would need to be increased to around 95Wh/kg, approximately the USABC near-term target[1].

Thus, unless EVs of much lower specific energy consumption (i.e., much higher efficiency) under realistic driving conditions can be developed, the USABC near-term target of 100Wh/kg appears to be the minimum specific energy requirement, should a 150-mile minimum range prove to be required for widespread acceptance of EVs.

Power Density. The USABC targets for power density (see *Table II.1*) were set to give an EV acceptable acceleration from a battery that meets the minimum specific energy requirements. These targets need to be met by a battery discharged to 20% of its capacity at the lowest design operating temperature, and until the end of battery life when power capability is substantially degraded. (Fully charged, new batteries typically have much higher power capability than needed by EVs.) Since the mass-produced ICE vehicles of today generally have higher acceleration capability than those of 5-10 years ago, the USABC commercialization target for power density probably should also be considered a minimum requirement.

In the longer term, advances in automobile technology—especially substantial reductions of weight and aerodynamic drag—could result in decreased EV-battery power and capacity requirements and/or increases in EV performance, as has been demonstrated by GM's EV1.

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[1] *To attain a 150-mile "real world" range capability for a 4/5-passenger EV with a representative lead acid battery having a specific energy of 35-40Wh/kg would, in all likelihood, require a battery weighing more than 1,200kg which would be more than 50% of the EV's curb weight.*

II.1.2. Durability/Battery Life

The useful service life of a battery is limited by loss of its ability to meet certain minimum requirements for delivery of energy and power. For EV batteries, the minimum requirements are nominally set at 80% of both the new battery's energy storage capacity and the EV's power capability specification. Loss of power capability ("power fading") and energy capacity is caused by cycling batteries. It can also occur while batteries are not being cycled, as a result of chemical processes that over time transform battery active materials irreversibly into inactive forms, and/or reduce the current carrying capability of the battery. If these processes are relatively rapid, battery life can become unacceptably short. Typically, power fading is the limiting factor in EV-battery life.

As will be discussed in more detail below, the likely cost of nickel-metal hydride and other advanced EV batteries is such that, for acceptable life cycle costs, these batteries need to last for at least 100-120 k miles, the nominal service-life of the vehicle. For a battery that can deliver an EV range of 100 miles per charge, the 100k-120k mile life requirement is equivalent to the USABC long-term target of at least 1000 deep cycles over its service life. A 600 deep cycle, 5-year life capability—the near-term USABC target—is almost certainly insufficient in view of the high cost of battery replacement.

II.1.3. Safety

Today's automobile safety requirements are very stringent, and the assurance of a very high level of safety will be a critical requirement for electric vehicles deployed as a broadly available new automotive product. As a high-energy system, the battery is the main safety challenge associated with electric vehicles. However, no statistically valid experience base exists for defining and quantifying adequate safety for the advanced batteries used in EV propulsion. Moreover, the safety issues differ substantially from one type of battery to another, and even within a battery type from one design to another.

Given this difficulty, USABC and the battery and EV developers have resorted to characterizing candidate advanced EV batteries in terms of their tolerance to a series of "abuses", as a provisional indication of the batteries' level of safety. Representative battery abuse tests that EV-battery developers apply routinely to cells and modules are summarized in *Appendix D.* It needs to be emphasized, however, that there are as yet no data correlating test results and failure criteria with safety-related incidents experienced by vehicles equipped with advanced EV batteries. Remarkably, such incidents are extremely rare or altogether absent. Thus, while some of the abuse tests probably represent a realistic failure mode, others may not simulate likely occurrences, and an EV-battery failing to meet one of the standard abuse tests could conceivably be safe under all but the most extraordinary and unlikely conditions. Conversely, it is noted that unsafe situations may not be fully captured by the existing abuse tests but could surface in the future.

II.1.4. Convenience

Several battery characteristics that may offer particular advantages (or, conversely, pose limitations) in EV applications can be grouped under the broad term "convenience": for example, quick charging capability, low self-discharge rate, and wide battery-operating-temperature range. The USABC targets for these characteristics form a reasonable set of requirements, but none of these are as critical to the acceptability of batteries for EV service as are the targets for performance, durability and safety. The numerical values listed in *Table II.1* thus appear to be desirable, rather than required, characteristics although some of them may prove to be important for acceptance of an EV in the market. (Not mentioned among the requirements but also important is the stipulation that EV batteries must be chemically and mechanically maintenance-free to avoid the cost of skilled maintenance labor and/or the inconvenience to the owner/operator. This requirement does not extend to electrical maintenance [such as cell balancing, etc.] that can be provided automatically as part of the battery's electrical-control functions during charging or other phases of operation.)

II.1.5. Cost

Background. By general agreement, the costs of advanced EV batteries having the potential to meet the other critical requirements for EV service are a major barrier to the competitiveness and widespread introduction of EVs. For example, the actual costs of the advanced batteries in the EVs introduced in limited numbers over the past several years range from nearly $30,000 to more than $80,000 per pack, requiring heavy subsidies by the EV manufacturers to attract vehicle lessees. A major focus of the Panel thus was to investigate likely costs of volume-produced advanced batteries and to assess their acceptability against EV-battery target costs.

Most EV and EV-battery developers as well as other stakeholders in the commercialization of EVs have developed EV-battery cost targets/requirements to guide their development strategies and policies. Among these, the USABC cost targets, shown in *Table II.1*, are by far the best known and have been widely used in past assessments. It is the Panel's understanding that the USABC battery long-term cost target was derived from the assumption that the life-cycle (total ownership) costs for EVs need to be comparable to those for the corresponding conventional vehicles. However, no details of that derivation and the underlying assumptions have been published. In addition, the USABC cost targets for EV batteries are nearly a decade old, except for the recently adopted commercialization cost target of $150/kWh. In view of the considerable uncertainty that surrounds this important subject, a current look at what might constitute appropriate cost targets for EV batteries appears justified.

Cost Targets/Requirements. Postulating cost equivalence of EVs with their counterpart ICE vehicles is a rational starting point for establishing battery cost targets. To convert this general postulate into specific cost target(s) requires several assumptions and a cost-estimating methodology. One key assumption is that the total ownership cost of a vehicle over its life (life cycle cost) is the most appropriate measure of cost, another is that the cost of the EV minus battery in mass production will be comparable to the cost of the ICE vehicle. Although there is no universal agreement on the latter assumption, several carmakers mentioned it as a possibility if EVs were eventually produced in numbers comparable to those for popular ICE models.

Based on these assumptions, the Panel used a simple methodology to develop an independent perspective on target battery costs. In this approach, the battery is amortized over the life of the EV, and the amortization cost is lumped with electricity cost into the EV's cost of "electric energy". Together with the assumption above about basic vehicle costs, the assumption of life-cycle cost-equivalence between an electric and a conventional vehicle then reduces to the equivalence of lifetime costs of the electric energy and the motor fuel consumed by these vehicles, respectively.

In *Appendix E*, target battery costs are calculated with this methodology as the net present value of the EV's energy cost savings over its assumed 10-year life for a range of values of the key parameters. The "Typical Current Parameters" segment of *Table E.1* presents target battery costs calculated for energy efficiencies and costs typical for today's ICE and electric vehicles; the EV efficiencies are taken from Appendix C (see *Table C.2, line 7*)[1].

The calculations indicate target battery costs of approximately \$3,500 to \$4,000 for 5¢/kWh electricity and efficiencies in the 2.2 to 3.2 miles per kWh range that are typical for today's 4/5 passenger EVs with NiMH batteries (*Appendix C, Table C.2*); the corresponding ICE vehicle was assumed to have a 24 mpg fuel efficiency. Note that these costs translate to a specific cost range of about \$120-135/kWh for a typical 30kWh EV-battery, somewhat less then the \$150/kWh USABC commercialization target.

Target battery cost is higher for commercial EVs because of the lower fuel economy of such vehicles; this factor dominates as long as electricity costs are relatively low (see *Table E.1, line 2*). A highly efficient EV delivering 4 miles/kWh (such as the

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[1] *The (overall) EV energy efficiency (in miles/kWh) is calculated as follows: The EVs' test cycle energy usage in Wh/mile (*Table C.2, line 3*) is multiplied by a factor of 1.5 to account for the total amount of electric energy used in charging the battery, and the resulting total energy usage per mile is inverted to the units of miles per kWh. The factor 1.5 is the approximate average ratio of total energy used in charging, and the energy delivered by the battery, (see* Table C.2, line 6*). Evidently, the very efficient Li Ion batteries, as well as air-cooled NiMH batteries, have significantly more favorable (i.e., smaller) factors than NiMH batteries that are cooled with chilled liquids during charge.*

EV1, see *Appendix C, Table C.2*) does not have a higher target battery cost if the anticipated higher motor-fuel efficiency of a broadly corresponding ICE vehicle is taken into account. As expected, motor-fuel cost is the single most important factor. For example, increasing fuel cost by 25% from $1.33/gal to $1.67/gal increases target battery cost for the commercial vehicle by 37 %. On the other hand, the data of *Table E.1* show that target battery costs are substantially reduced at higher electricity costs (e.g. 10¢/kWh).

This general picture does not change greatly with increased annual mileage and for improved electric and ICE vehicle efficiencies, as shown in *Table E.1* under the "Nearer-Term Scenarios Favorable to EVs". The impact of EV efficiency improvements is predictably small[1] at low electricity costs, and even further increases in motor-fuel cost raise target battery costs for 4/5-passenger EVs only moderately to approximately $5000. The effect of yet higher annual vehicle mileage, higher motor-fuel costs, and higher ICE efficiencies, as well as higher EV-efficiencies, is shown in the third segment of *Table E.1*. It is evident that a doubling of today's motor-fuel cost would be required to increase target battery costs very substantially.

One interesting calculation is the last line in *Table E.1*, which displays data consistent with current parameters in Western Europe. Due to the much higher cost of motor-fuel there, the calculated target battery-cost of ~$6700 is almost double that of California.

It appears, therefore, that at current ICE efficiencies and motor-fuel costs, target EV-battery costs range from about $2,000 to $4,000-5,000, depending primarily on the costs of electricity, and secondarily on EV overall (including charging) energy efficiencies. This cost range is broadly consistent with the target battery costs mentioned by major automobile manufacturers. For a battery of 28-33 kWh capacity, battery costs of $4,000-5,000 translate into target battery costs of $120-180 per kWh of capacity, which is compatible with the USABC commercialization target of $150/kWh and other, somewhat higher estimates (2).

[1] *Improved EV efficiency is, however, very important because it extends EV range in direct proportion.*

It is important to note that $5,000 is the upper end of the target battery cost range in the nearer term, valid only if essentially all assumptions—particularly basic vehicle cost equivalence, and battery life—are favorable to EVs. The specific costs target for advanced batteries would be substantially higher only if motor-fuel costs increased drastically above $2/gal, or if the needed EV-battery capacities were to decrease substantially below 28kWh because of much-reduced range requirements and/or greatly increased EV efficiencies. None of these possibilities seems likely in the foreseeable future, at least in the United States, although some of them might materialize over the long term.

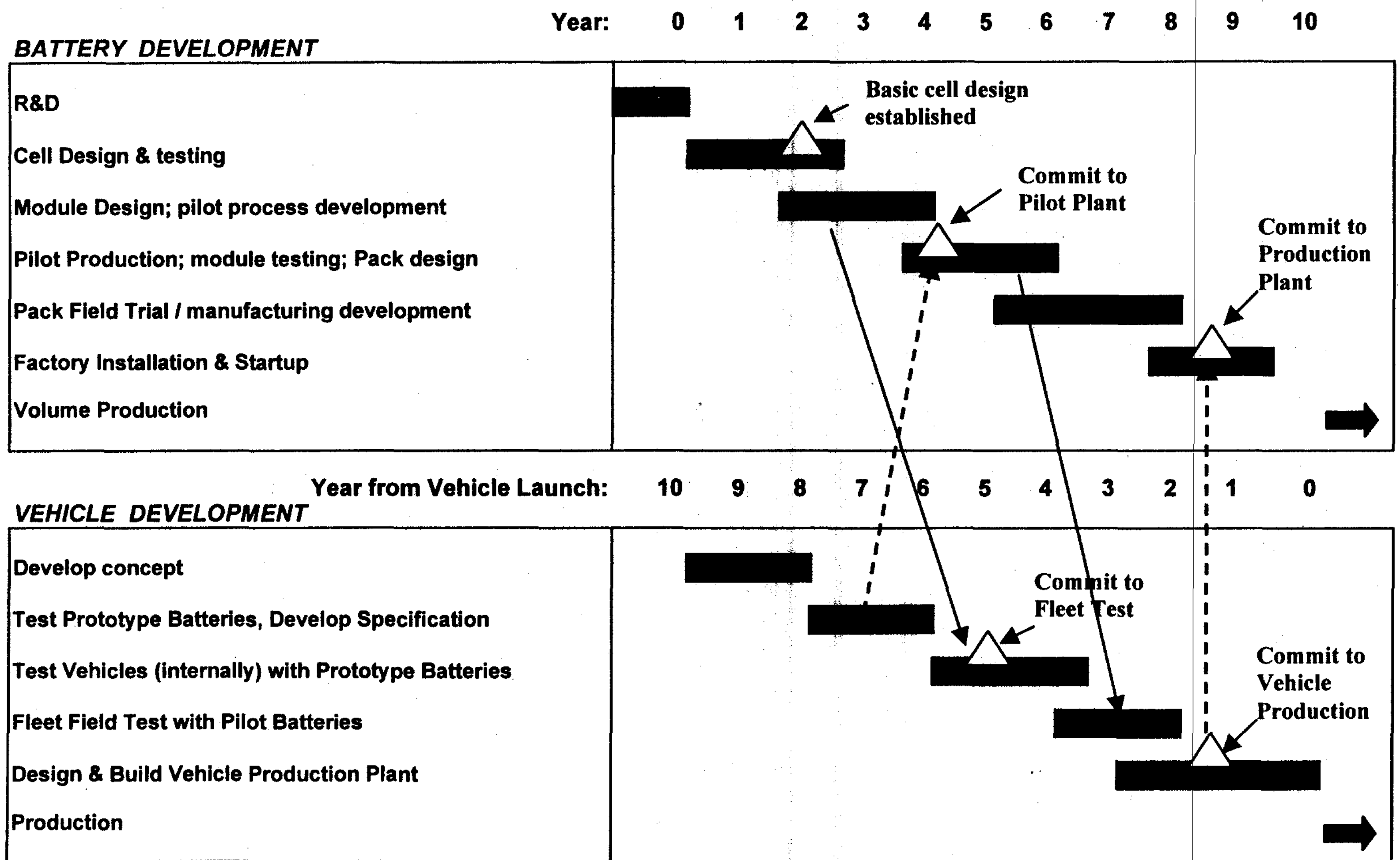
II.2. CANDIDATE BATTERIES

The primary focus of the Panel's investigation was to assess the development status and likely future costs of the advanced batteries that appeared to have reasonable prospects for meeting performance requirements and cost goals for electric vehicle propulsion, and for becoming commercially available by 2003 or soon thereafter.

In the view of the Panel, this assessment could be limited to battery technologies that, at the outset of the study, appeared to meet a number of screening criteria:

- performance that met or at least approached the near-term targets in *Table II.1*, above, with some prospects for improvements beyond these targets;
- prospective mass-production costs that, on the basis of the battery materials and fabrication techniques involved, might fall into the acceptable range discussed above; and
- development status and plans that held out realistic prospects for battery commercial availability within the next 3-5 years, according to the generic timetable illustrated in *Figure II.1.*

Figure II.1. Battery and Electric Vehicle Interactive Development Timeline



Application of these criteria eliminated a number of candidate battery systems from the Panel study. In this regard, lead-acid and nickel-cadmium batteries represent a special case. Neither of these batteries passes the screening test above since they are fundamentally incapable of meeting the key performance targets for specific energy and energy density, see *Table II.1*. On the other hand, both battery types are used in electric vehicles currently on public roads, including EVs deployed under the California's MoA as well as thousands of nickel-cadmium-powered EVs in France. However, with the exception of the lightweight EV1 carrying 44% of its weight in batteries, the lead-acid-powered MoA EVs have ranges of only 40-60 miles (see *Appendix C, Table C.1*) because of the inherently low specific energy of lead-acid batteries. Also, lead-acid batteries are likely to require at least one and perhaps several replacements over the life of an EV, which tends to negate their lower cost advantage. Nickel-cadmium batteries, although capable of long cycle life, are not only rather expensive but (at least in the U.S.) considered undesirable because of the perceived health hazard of cadmium. Despite these reservations, the Panel conducted a limited survey of the lead-acid batteries used in California's MoA EVs. The results are summarized in *Appendix F* that also addresses briefly the status of nickel-cadmium EV batteries.

A number of advanced-battery systems have been proposed, explored and developed for EV propulsion. Systems that promise major performance gains over lead-acid batteries were reviewed briefly in (2). Among the aqueous batteries with potential to meet the near-term specific energy targets in *Table II.1*, only nickel-metal hydride (NiMH) is seen as having good prospects for meeting the power density and cycle life requirements listed in *Table II.1*. NiMH batteries for EV applications have been under development for more than a decade, and are being manufactured on a limited scale by several battery companies. They are used in the majority of the EVs made by five of the six major automobile manufacturers that have signed MoAs. The commercial prospects of NiMH EV batteries depend in large measure on their ultimately achievable cost structure, which became a major focus of the Panel's investigation.

Encouraged by the commercial success of lithium-ion batteries in the consumer electronics market, this battery system has been under development for EV applications for more than five years by a number of companies in Japan and Europe. The system's promise of high specific energy was a major attraction, and its specific power and cycle life also offered reasonable prospects of meeting EV-battery requirements. While Sony and VARTA, two of the technology leaders, terminated Li Ion EV-battery development in recent years, several other experienced developers of conventional and advanced batteries have continued their programs. Equally important, major funding continues to be provided by USABC for key aspects of Li Ion battery development, including achievement of adequate durability and safety, and reduction of battery costs. In view of the promising prospects and ongoing development efforts, and because a number of ALTRA EVs (See *Table C.1*) powered by pre-prototype Li Ion batteries operate successfully in California under Nissan's MoA, lithium-ion batteries were selected by the Panel as the second candidate EV-battery technology to be investigated in some detail.

In addition, the Panel selected lithium-metal polymer batteries for an evaluation of their prospects of becoming commercially available by 2003 or soon thereafter. In part, this selection was made because of the basic potential of the Li polymer system for higher specific energy and lower cost than those of other advanced batteries. The Panel was also aware of the significant technical progress achieved over the last several years in two important programs that appear committed to development of commercially viable Li polymer EV batteries in the relatively near future.

Finally, the Panel examined a specific lithium-ion polymer technology for which claims of high specific energy and energy density are being made; its findings are summarized in *Appendix G.* In the main, however, the Panel's investigation focused on the status and prospects of nickel-metal hydride, lithium-ion, and lithium-metal polymer batteries as the systems with the best prospects of meeting the performance and cost requirements for EV applications. The Panel's findings are summarized in Section III.

II.3. EV-BATTERY COST FACTORS

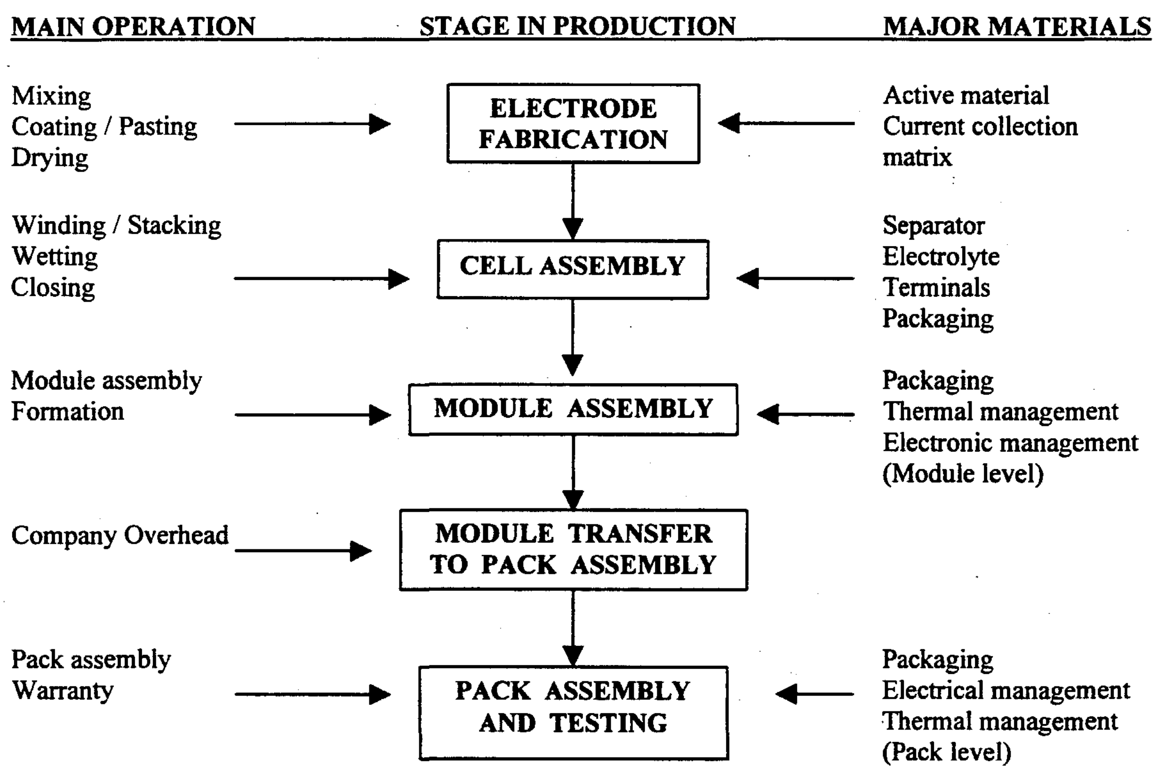
From the outset of this study, it was clear that battery costs were not only important issues with the advanced systems currently used in EVs, but were recognized as a major economic barrier to the widespread market introduction of electric vehicles. Acquisition and analysis of battery-cost information, therefore, became important aspects of the Panel's work.

This section reviews the major factors that contribute to battery cost. It is intended to support the discussion of system-specific costs in subsequent sections and to give the reader of this report (as it did earlier for the Panel) a framework for assessing the battery-cost information acquired in this study.

The basic unit of a battery is the cell, which has a low unit voltage—typically 1-4 volts—determined thermodynamically by the electrochemical processes of the battery system. For use in EVs, cells with capacities in the range of 40-120 Ah are assembled into modules that comprise a number of identical cells connected electrically in series or, in some cases, series/parallel, to form a convenient unit building block with an energy storage capacity typically in the range of 1-3 kWh. The EV-battery pack, in turn, consists of an assembly of modules, also connected in series or series/parallel, to provide the desired system voltage (typically 150-350V) and energy-storage capacity. Additionally, an EV-battery-pack will have a thermal management system for heating, cooling, or both, as well as electrical and electronic controls to regulate charge and discharge, assure safety, and prevent electrical abuse. The level of sophistication and complexity of the needed controls depends on the requirements of specific battery systems.

The major steps in EV-battery-pack production are shown in *Figure II.2.* While production activities up to the level of modules are exclusively the province of the battery manufacturer, pack assembly, electrical-control integration, and reliability testing are operations frequently carried out by the EV-battery customer, the vehicle manufacturer. How these responsibilities are divided affects the selling price of the battery. Thus, while the specific cost (in $/kWh) of the battery pack ready for installation in the vehicle is the most important battery cost characteristic, most of the cost data gathered and reported in this study are for module costs. To arrive at the pack price, we have added a fixed amount to the module cost, using the approximate numbers provided by battery developers and USABC.

Figure II.2. Major Cost Stages in the Production of EV-battery Packs



The costs of cells and their assembly into modules make up the largest portion of an EV-battery pack cost—typically about 70% to 85%, as discussed further below. Materials, in turn, are the largest single cost item in manufacturing cells and modules. For large-size batteries with relatively expensive materials—the situation with advanced EV batteries—materials costs usually exceed 50% of the total manufactured cost in volume production. Finally, cell and module materials costs are dominated by the cost of the functional materials required for cell operation: the electrochemically active electrode-materials, the electrolyte and the electrolyte-filled separator, the materials of the electrode matrix collecting the current, and the packaging of the cell and module. The unit costs of these materials and components decline as the quantities purchased increase. In general, savings will be very substantial for custom-made parts, but much smaller for commodity materials—for example primary metals or common plastics—that have other substantial uses. As in all manufacturing operations, questions arise as to whether to make or buy certain components or partially processed materials. The decision depends on the scale of production, with internal sourcing being favored as production volumes increase.

A second important cost-category is direct labor (including fringe benefits), with labor rates being similar in the countries where the EV batteries investigated by the Panel are under development. Direct labor costs, as a percentage of total costs, decline with increasing capital investment in labor-saving manufacturing equipment that becomes progressively more productive as battery production volume rises. At any given production level, there is a tradeoff between the costs of direct labor and the ownership costs of automated production equipment. The inherently greater efficiency and precision that automation enables in most manufacturing operations make large contributions to the decline in costs as production volume increases.

The third major contributor to costs is manufacturing "overhead", a category that includes the ownership and operating costs of plants and equipment, as well as the costs of manufacturing support services (manufacturing engineering, material handling, quality assurance, etc.). The sum of materials and component costs, labor costs and manufacturing overhead is usually termed the "Cost Of Goods" (COG) for battery production.

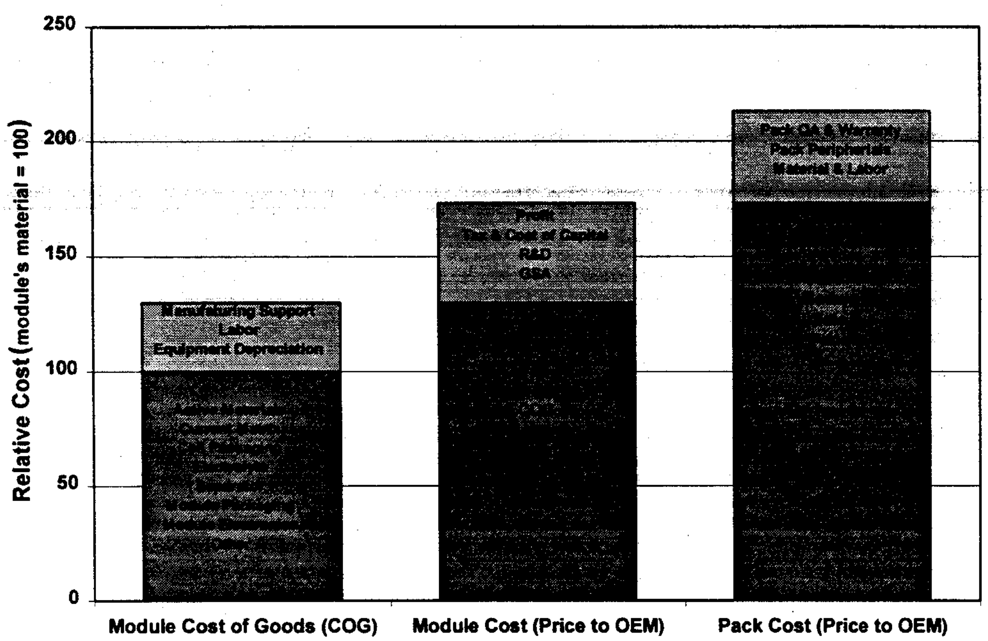
To arrive at a battery-selling price (the cost to the EV manufacturer), estimates must then be added for general, selling and administrative (GSA) expenses, R&D and engineering expenses, cost of financing the required capital investments, profit, and taxes. While the exact contributions of the items above can vary considerably for different types of products and manufacturers, their combination, often termed "gross margin", typically accounts for 20% to 40% of the sale price for a high volume, manufactured product. Somewhat arbitrarily, the Panel has chosen to use a gross margin of 25%, lower than the 1998 U.S. average of 33.8% for industrial companies, and favorable to battery costs. Taking all of these factors into account, the Panel arrives at projected per-kWh battery module cost (selling price to OEMs) by multiplying the estimated unit (per kWh) manufacturing cost (COG) by a factor of 1.33 (4/3).

The fabrication of battery packs from modules involves integration of the modules with other subsystems (structural, electrical and thermal) into a single pack, as well as final testing. These other subsystems as well as the assembly into a single pack contribute additional costs. Finally, EV buyers will expect a substantive warranty for such a critical and expensive component. Whether the warranty is provided by the battery or the vehicle manufacturer, its cost must be included in the price of the battery. The cost increment for the assembly of packs from modules—which is very high at the present, low EV production rates—is difficult to estimate inasmuch as it can be expected to vary substantially with battery and vehicle types. Based on informal information from battery developers, EV manufacturers and the USABC, the Panel assumed a somewhat optimistic figure of $40/kWh ($1,200 for a 30 kWh battery) for production volumes in the order of 10,000-20,000 packs/year. For true mass production rates, this cost item is unknown, but the assumption was made—again probably optimistically—that it will decline by 50% from that of the intermediate production volumes.

Figure II.3 illustrates (on a relative scale, with Materials Cost = 100) how pack costs aggregate from the cost components identified above through the various steps involved in manufacturing batteries on a commercial scale. When using this approach, it must be kept in mind that the current cost of nickel-metal hydride and, even more so, lithium-ion batteries reflect the relatively small-scale operations under which they are produced. The relative numbers in *Figure II.3* do not apply to this scale of production, which is characterized by very high costs of labor, materials and overhead and, consequently, very high battery costs.

In the larger manufacturing facilities that could be operational by 2003 if plant commitments were made in the near future, costs and prices would be considerably lower than present levels. Economies of scale will result from discounts on bulk purchases of materials and components, higher efficiencies in the use of labor and equipment and, especially, use of custom-designed automated manufacturing equipment with high production rates and product yields. Although depreciation charges related to this equipment will contribute significantly to the factory costs of the batteries, they will be more than offset by the savings in labor costs realized.

Figure II.3. Cost Components of EV-battery Packs



Battery production on a true mass production scale by automobile-industry standards can be expected to result in further reduction of specific battery costs. Such reduction would be due to productivity increases from additional automation of manufacturing operations, incremental improvements in battery design, and process technology refinement based on accumulated production experience. However, automation, the key to cost reduction, requires substantial capital investments. Such investments can only be justified if the battery developers are convinced that a sustained market will permit capital recovery over a large product volume, produced over an extended period. Also, the cost-reduction benefits from increasing automation will become relatively less important in true mass production, and further battery cost reductions will be possible only if materials costs also decline significantly.

Of the three battery systems investigated in the Panel's study, nickel-metal hydride developers are already manufacturing at the pilot-plant level and are prepared to implement plans for larger-scale production. Lithium-ion EV batteries are currently produced in relatively small pilot-scale operations, while lithium-metal polymer batteries are assembled on a small scale with the help of laboratory fabrication equipment. Accordingly, these systems will reach the stage where the Panel's battery cost estimating approach can reasonably be applied at different times in the future. Additionally, the uncertainties in the estimates increase with the extent of material and manufacturing development still ahead. Nevertheless, the Panel undertook to apply its approach as a general check on the cost information collected from NiMH and Li Ion battery developers. These considerations are presented in Sections III.1 and III.2 below.

SECTION III. FINDINGS

III.1. NICKEL-METAL HYDRIDE

III.1.1. Introduction

The NiMH battery was first brought into production in the late 1980s, as an environmentally more acceptable replacement for Ni-Cd batteries in consumer applications. Like the Ni-Cd battery, the NiMH battery uses a nickel-oxyhydroxide positive electrode and an alkaline electrolyte, but the active material in the negative electrode is a hydrogen-absorbing metal alloy instead of cadmium. A discussion of the fundamental nature of the technology can be found in the 1995 BTAP report (1) and in other review papers (4).

NiMH batteries have been able to replace Ni-Cd batteries in many portable applications, due to their higher specific energy and energy density, as well as for environmental reasons. Worldwide shipments for 1999 are estimated at over 400 million cells (5). Most of the products for the portable-battery market are spiral-wound cylindrical cells in sizes ranging from AAA (approximately 500 mAh) to D (8-9 Ah), sold singly or in packs of up to 12 cells in series. They typically use nickel-foam current collectors for the positive-electrode structure and nickel-plated steel foils as support for the negative. Small prismatic cells using the same electrode structures, but in parallel-plate configuration, are also produced in significant quantities, although not on the same scale as cylindrical cells. Both types of small portable cells are packed in steel containers and generally operate at above-atmospheric pressure, with hydrogen pressure and cell temperature increasing as the cell approaches end of charge.

Nearly all consumer NiMH cells utilize the AB_5 alloy (4) as the active material for the negative electrode. This alloy, a lanthanum/nickel compound known as "Mischmetal", is very stable during repetitive cycles of hydrogen absorption and desorption, and it has a practical charge storage capacity of about 310 mAh/g. The principal alternative alloy, AB_2, is composed of nickel and a number of transition metals including vanadium, titanium, and zirconium in various proportions. This alloy's charge storage capacity is somewhat greater at 350 mAh/g, and it is claimed to have potential for further improvement. However, the production of AB_2 alloys is more complex, the alloy itself is more susceptible to corrosion, and it very probably operates at higher hydrogen pressure than an AB_5 alloy at the same state of charge (degree of hydrogen saturation) and temperature.

Small NiMH cells typically deliver 60 to 80 Wh/kg. They have sufficient power for most portable battery applications and can operate at temperatures as low as -10°C. Their nominal cycle life of 500 cycles and operating life of over 3 years are satisfactory for most consumer applications. However, over the last 4 years NiMH batteries have lost market share in consumer applications to the newer Li Ion battery whose main advantages are higher specific energy and superior charge acceptance at moderately elevated (>35°C) temperatures.

The EV application presents significant additional challenges for the NiMH battery designer. In particular, the much higher capacities and voltages of EV batteries put increased demands on thermal management and pressure containment. In fact, before the advent of NiMH EV batteries there was no experience in the battery industry with large, high-voltage sealed battery systems subjected to deep cycling. Beyond these technical challenges, the EV battery market poses demanding requirements for lower cost and longer life.

NiMH batteries for EV applications have been under development for more than five years at three battery companies: GMOvonic (GMO) in Troy, Michigan, Panasonic EV Energy (PEVE) in Kosai City, Japan, and SAFT in Bordeaux, France. All three developers use spherical nickel hydroxide powder pasted into a nickel foam as the positive electrode, and polypropylene separators treated to improve wetting by the KOH-based electrolyte. The composition of the negative electrode varies with the developer:

PEVE and SAFT rely on the AB_5 alloy that is widely used in consumer NiMH batteries, while GMO has developed the AB_2 alloy. The developers also have different module-packaging schemes: GMO contains individual cells in a metal case, PEVE packages individual cells in a thermoplastic case, while SAFT inserts cells in a plastic monoblock.

The NiMH battery system is capable of very long cycle life. The main failure mode is negative-electrode corrosion that causes cells to dry out and gradually lose both capacity and power capability. The corrosion rate increases with temperature, significantly shortening operating life at temperatures above 45°C. AB_5 alloys are more corrosion resistant than AB_2 alloys, but work to improve the corrosion resistance of both alloys is continuing.

A significant difficulty with current NiMH EV batteries is the rather rapid drop in nickel hydroxide electrode charge efficiency when temperatures exceed 35°C. The inefficient portion of the charging current results in the evolution of oxygen that is subsequently reduced to water at the negative electrode. This process generates heat that raises the cell temperature and further reduces the charge-acceptance of the positive electrode and of the cell. Also, the hydrogen equilibrium pressure of the negative electrode increases with cell temperature and state-of-charge, and hydrogen overpressure can result in venting of hydrogen and oxygen, constituting a second mechanism for loss of electrolyte volume and cell dry-out. Thus, managing cell temperature while charging at temperatures much above 25°C is critical to achieving good charging efficiency, high reliability, and long life in NiMH batteries. This presents a major challenge for NiMH EV-battery system designers.

III.1.2. NiMH Battery Companies

GM OVONIC

Company Overview. GMO is a limited liability company that was founded in 1996. It is 60% owned by General Motors Corporation, and 40% by Ovonic Battery Company (OBC). GMO develops, manufactures, and markets NiMH batteries. Its current focus is on advanced electric propulsion applications, and the company works closely with the ATV (Advanced Technology Vehicles) Group in GM that has invested more than $60 million in the GMO—over $20 million in 1999 alone.

The GMO NiMH technology was developed and is still being improved by the Ovonic Battery Company in Troy, Michigan. OBC is a subsidiary of Energy Conversion Devices, a public company with an emphasis on the development of energy-related materials. OBC has a strong patent position in NiMH technology and has licensed a number of NiMH battery manufacturers. Using its unique production capabilities for AB_2 hydride alloys, OBC supplies GMO with processed material for the negative plates. OBC has also developed and installed a pilot-production facility for spherical nickel hydroxide, the active component of the nickel electrode. In addition to supplying GMO with key NiMH battery materials, OBC supports GMO with materials development and in cell and module design. GMO is developing NiMH battery-manufacturing processes, and has pilot facilities for NiMH battery fabrication in Troy, Michigan. A new GMO facility in Kettering, Ohio, is being developed into a battery manufacturing plant.

EV-Battery Design and Performance. GMO's "Generation-1" EV cell, rated at 90 Ah, is a conventional parallel-plate prismatic design with a metal case. Eleven cells connected in series make up a 13.2V, 1.2kWh module with a specific energy of 70 Wh/kg and an energy density of 170 Wh/l. As noted above, the negative-electrode chemistry is based on the AB_2 alloy that has higher specific capacity and, therefore, contains a smaller quantity of expensive metals than the more commonly used AB_5 alloy. The other ingredients of the GMO cell are essentially the same as those of other NiMH technologies: nickel-hydroxide positive electrodes pasted on a nickel-foam current collector, alkaline electrolyte, and polypropylene separators.

Performance data for GMO's Generation-1 EV batteries, which is now installed in many of GM's EVs are included in *Table III.1.* The best module cycle life at 80% DoD (to loss of 20% of initial capacity) is about 800 cycles. Only limited in-vehicle life data are available at this time. GMO estimates that the in-vehicle operating life of the Generation-1 design is between 3 and 6 years. The main fading (i.e., gradual failure) mode during cycling is an increase in cell impedance, as described above. Charge acceptance above 35°C has been problematic and has required active cooling of the batteries. However, like other NiMH developers, OBC is making significant improvements in this area by the use of additives to the nickel hydroxide paste in the positive electrodes.

GMO has been developing a Generation-2 module with a higher energy density target of 215Wh/l, and validation testing has started. The company is also engaged in the preliminary development of a liquid-cooled Generation-3 module packed in a plastic casing. The Generation-3 targets include improved specific energy, a wider range of operating temperatures, improved power, and lower cost. GMO estimates that the Generation-3 design could be ready for production in 2004-2005.

Production Capability, Cost and Business Planning. GMO has produced 700 EV packs since 1997 and shipped most of them to GM. The current manufacturing capability is 750 packs per year, but production for the next few years is expected to be much lower due to lack of new orders. When fully furbished, the Kettering plant will be able to produce approximately 6000 packs per year. GMO plans to produce and ship to its customers fully assembled and tested packs, thereby adding value to the modules. GMO's present operation is still labor-intensive due to the continual integration of technological improvements and design changes. Also, the company has been reluctant to increase capital investment for automation in a business with an uncertain return.

The present pack cost is about $1,000/kWh. GMO's projection for fully burdened costs of the Generation-2 product is $300/kWh at the pack level, for a production volume of 20,000 packs per year. GMO is now evaluating additional markets for the technology, such as hybrid vehicles and scooters, to increase production volume beyond the EV market demand and thus achieve incrementally lower costs. With encouragement from GM's ATV and from USABC, GMO is also exploring the possibility of realizing residual value for NiMH batteries at the end of their useful life in EV service. This effort is focusing on secondary usage of such batteries in less demanding applications such as rural, PV-based electrification in developing countries.

The operating life and elevated-temperature performance of GMO's NiMH technology still need to be fully proven. However, the main obstacle in the development of GMO's EV-battery business—the problem common to all developers of advanced EV batteries—is the high product cost compared to the costs that are considered acceptable if EVs are to be marketable. With few orders and a high rate of operating and capital expenditure, continued support from GM is not assured. A specific barrier mentioned by GMO is battery warranty. GMO surmises that the warranty requirements of vehicle manufacturers might include as much as 3 years with 100% replacement, followed by a prorated warranty for up to 10 years. In GMO's own words, "a business using reasonable risk analysis would not be able to provide such a warranty by the year 2003".

PANASONIC EV ENERGY

Company Overview. Panasonic EV Energy (PEVE), owned 60% by Matsushita and 40% by Toyota, was formed in 1996 to manufacture and market NiMH batteries for EVs. The company is engaged in engineering and manufacturing development and in small-scale production of NiMH batteries. The PEVE plant in Kosai City, Japan, manufactures modules with three different cell capacities for EV and HEV applications, but all use the same basic NiMH materials technology.

EV-Battery Design and Performance. A 95Ah prismatic cell in a thermoplastic case is the basic element of PEVE's NiMH battery for full-size EVs. Ten such cells in series are strapped together in a molded plastic enclosure to make up a 12V and 1.1kWh module (designation: EV-95). The energy ratings of the EV-95 module are 63 Wh/kg and 150 Wh/liter, and specific power is rated 200 W/kg at 80% DoD. The module design and performance characteristics are included in *Table III.1* below.

Features of the cell include the following:

- AB_5 alloy-based negative pasted on nickel-plated steel current collector;
- Spherical nickel hydroxide-based positive with cobalt, zinc, and yttrium-compound additives, spray-impregnated into a nickel-foam current collector;
- Sulfonated-polypropylene separator and KOH-based electrolyte with LiOH additive.

Charge acceptance and cycle life at elevated temperatures of PEVE's NiMH technology, concerns until the recent past, are now adequate for temperatures up to at least 45°C. This improvement, mostly associated with positive-electrode additives, is important not only for improved battery efficiency and life, but because it may make air-cooling acceptable for most EV applications.

PEVE and its car-company customers have demonstrated well over 1,000 cycles at 100% DoD on the test stand, and battery impedance rise at around 25°C is less than 30% over 1,000 cycles. Therefore, it seems quite possible that 1,000 to 2,000 cycles at 100% DoD can eventually be achieved, depending on the battery's initial power versus the car's requirements. The failure mode is, again, increase in cell impedance, which accelerates at temperatures above 35°C. The current warranty for the battery is 3 years, but a longer warranty period may be considered.

In the Kosai plant, PEVE is also producing a 28Ah cell that is used in 12V, 0.34 kWh modules for mini-EVs. While it is based on the same electrode formulations and basic mechanical design as the EV-95, the EV-28 module has higher specific power

(300W/kg) but somewhat lower specific energy (58Wh/kg). In the same plant, PEVE is assembling 6.5Ah, 7.2V modules consisting of 6 cylindrical D-size, ultra-high-rate Panasonic cells. These modules are used in the batteries of the Toyota PRIUS, and the Honda INSIGHT hybrid electric vehicles. Most recently, PEVE has developed a 6.5Ah module comprising 6 prismatic cells with yet higher specific power for the new version of the PRIUS, and a production line for it is currently being completed.

Production Capability, Cost and Business Planning. PEVE's production facility has a capacity of 200 EV-packs per month, each comprising 24 10-cell (95Ah or 28Ah), 12V modules. The manufacturing process is semi-automatic, with considerable hand labor still used in module assembly and in the formation step. PEVE has been the main supplier of NiMH batteries for the EVs produced by Honda, Toyota, and Ford under their California MOAs. Production peaked in 1998 when PEVE supplied over 900 packs to these companies. The production of EV modules has decreased since then, and PEVE does not anticipate substantial new orders in the near future. The production volume of the 28 Ah module, designed for Toyota's "e-com" city EV and Honda's "City Pal", is increasing, but it is still at a very low level. PEVE's production capacity for full-size EV batteries could be scaled up to several thousand packs per year in 12 to 18 months, but there are currently no plans to expand capacity.

PEVE's module cost (sale price to OEMs) is approximately $1,100/kWh at the current production volume of around 60 packs/month. This price is projected to decrease to approximately $500/kWh at a production volume of 500 packs/month. At the latter level, materials account for approximately 65% of total manufacturing cost, direct labor for about 10%, and overhead expenses for about 25%. At a production volume of 2,000 to 5,000 packs/month, the module cost is projected to decrease to approximately $300/kWh. Finally, at production rates exceeding 30,000 packs/month PEVE sees a possibility for further price reductions to approximately $250/kWh.

PEVE's business focus is now clearly on HEVs. The company has two steady customers in Japan: Honda, which uses cylindrical modules in the INSIGHT, and Toyota, which will now be supplied with the new, higher-power prismatic modules for the PRIUS. Currently, HEV packs are being produced at a rate of about 2,000 per month.

PEVE has great confidence in the performance of its NiMH technology for EV and HEV applications. The operating temperature limit for efficient charge and long life has reached at least 45°C, and PEVE believes that air cooling will be adequate for its batteries. The company also considers the low temperature (-20°C) power to be acceptable. Cycle life is excellent, and the feedback from the car companies on battery reliability and life is very positive. However, PEVE does not have immediate plans for further capital investments in the EV version of its MiMH technology. Present costs are very high and not projected to drop below $300/kWh in volumes required for ZEV compliance, nor below $250/kWh in true mass production. As a result, PEVE does not expect a large market to develop for the technology, and the company sees no business justification for increasing investments in EV-95 production.

PEVE's assessment of the market potential of NiMH hybrid-EV batteries is quite different. With two major car companies already in HEV production, and with the expectation of performance improvements and cost reductions for HEV batteries, scenarios for a profitable business do exist. The company, originally founded to commercialize NiMH technology for EV applications, has now become a leading producer of NiMH batteries for HEVs, and it is moving forward to exploit the opportunity.

SAFT

Company Overview. SAFT, a wholly owned division of the French Alcatel group, is a major producer of industrial, military and consumer batteries, with a dominant international position in industrial and aircraft nickel-cadmium batteries. Its manufacturing facilities are located in France, Sweden, and the United States. SAFT is an established manufacturer of EV batteries, producing approximately 1,500 packs/year of 12 kWh vented Ni-Cd batteries for EV conversions of Peugeot and Renault small cars and vans (see *Appendix F*). SAFT's advanced EV-battery capabilities include pilot-level NiMH production as well as early pilot cell and module fabrication facilities for Li Ion batteries. All these activities are carried out at SAFT's Bordeaux facilities.

EV-Battery Design and Performance. SAFT's prismatic-cell 96Ah NiMH EV-battery technology is in pilot production in two different configurations: a 10-cell, 12V module, and a 20-cell, 24V module. In the DaimlerChrysler EPIC van, twenty-eight 12V modules are assembled to form a 33kWh, 336V battery pack.

The cell design includes the following:

- Positive electrode: nickel-foam collector pasted with a slurry of spherical $Ni(OH)_2$ powder containing Co, Zn and other additives;
- Negative electrode: Mischmetal-derived AB_5 powder slurry, pasted with binder on nickel-plated, perforated steel current collector;
- Polypropylene separator treated for improved wetting, with an alkaline KOH-based electrolyte that contains additives.

SAFT's module uses a polypropylene monoblock case with conventional over-the-top cell connections and O-ring terminal seals. The modules are designed to allow fast charge through a combination of features that include a high-charge-efficiency positive electrode formulation, excess negative capacity, and effective thermal management. The monoblock is liquid-cooled (on the narrow side of the cells), keeping temperature variance among cells during normal operation to < 3°C and permitting day-long operation with several fast recharges. The thermal management system also allows pre-warming of the battery to avoid a decline in power capability which becomes significant at temperatures below 0°C.

SAFT's module delivers 66 Wh/kg and 140 Wh/liter; specific power and power density (10-sec pulse at 80% DoD and 25°C) are 200 W/kg and 410 W/liter, respectively. As many as 1250 cycles at 100% DoD have been demonstrated at room temperature, and more than 600 cycles at 40°C; the normal failure mode is impedance increase. Newly developed additives give substantially improved charge-acceptance and efficiency at elevated temperatures—for example, 99% efficiency at 35°C, and 95% at 40°C. The module can be charged from 40 to 80% SoC in 12 minutes (2C rate), and it has passed all SAE-specified abuse tolerance tests (see *Appendix D*).

The key characteristics of SAFT's existing module are included in *Table III.1.* A higher capacity 109Ah cell using the same module case is under development. At the module level, this improved design is expected to increase the specific energy to 73 Wh/kg, energy density to 160 Wh/liter, pulse specific power to 220 W/kg, and power density to 500 W/liter.

Production Capability, Cost and Business Planning. In 1999, the Bordeaux line produced approximately 6000 NiMH modules (~200 packs) for the DaimlerChrysler EPIC van. The current capacity of the NiMH line is 700 battery packs per year. With a relatively small investment, the plant capacity can be increased to about 2,000 packs per year. A plant with a capacity of 10,000 packs per year would require an investment of approximately $60 million.

At the 10,000 packs-per-year production level, the price of the module is expected to be around $350-370/kWh. Of this, approximately $200/kWh is for direct materials and labor, with SAFT buying all key materials from major commercial suppliers. Approximately $60/kWh is for equipment depreciation, while overhead and margin account for the $90-110/kWh balance. SAFT's module-price projection at high volume, excluding depreciation, is $250/kWh. SAFT noted that lower prices might be possible but that they do not have a confident basis for such projections.

III.1.3. Summary

Technical. Representative data for the NiMH EV batteries of the three leading developers are shown in *Table III.1* below. The comparison with the USABC near-term targets (see *Table II.1* above) shows that these batteries appear to meet most of the key EV requirements, with the exception of specific energy and cost.

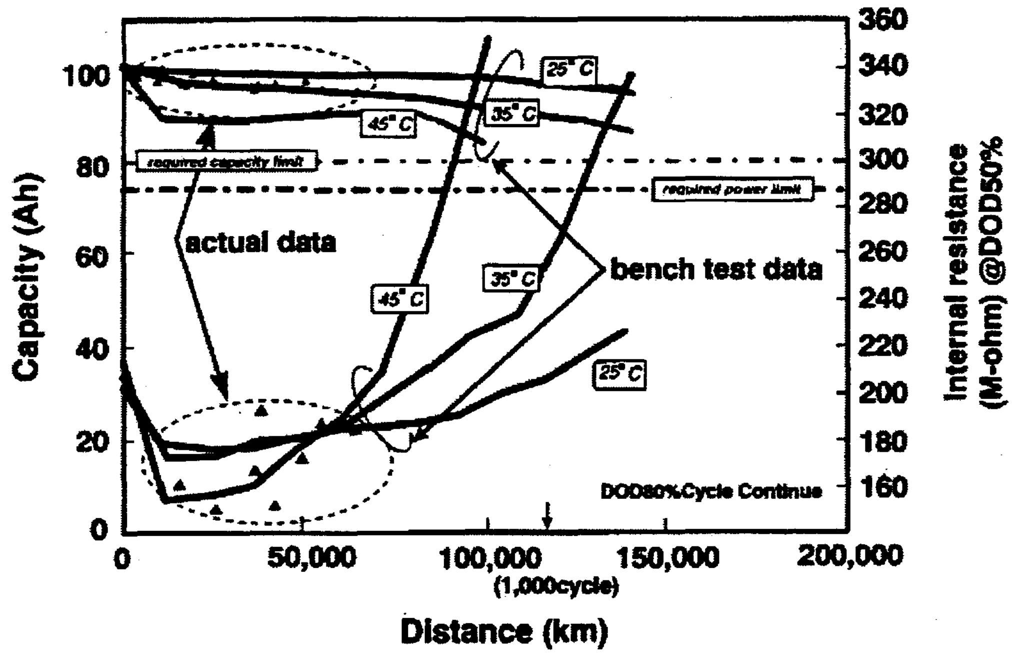
The NiMH module's presently demonstrated specific energy of 63 to 70 Wh/kg, corresponding to approximately 55-60Wh/kg at the pack level, falls well short of the USABC goals (*Table II.1*) and will limit the range of a 4/5-passenger EV to 75 to 100 miles (see *Appendix C*). Carmakers and most battery developers project incremental improvement in specific energy, generally in the range of 10 to 15%. GMO, on the other hand, expects that specific energies higher than 90 Wh/kg at the module level might be achievable if the advanced alloys with higher specific capacity, currently under development at OBC, will prove practical for NiMH batteries. In the Panel's opinion, this expectation—communicated to the 1995 BTAP five years ago—must be considered rather speculative. In particular, the Panel notes that the negative alloy accounts for less than 30% of the weight of the cell. Thus, even a 50% improvement in the specific capacity of the alloy, an extremely ambitious target, will only result in an improvement of ~15% in the specific energy of the cell.

Table III.1. Characteristics of NiMH EV modules

	Unit	GMO	PEVE	SAFT
Design Characteristics				
Nominal Capacity	Ah	90	95	96
Anode Chemistry	-	AB_2	AB_5	AB_5
Nominal Module Voltage	V	13.2	12	12 or 24
Number of cells in module	#	11	10	10 or 20
Nominal Module Energy	KWh	1.2	1.2	1.2 or 2.4
Performance Characteristics				
Specific energy C/3	Wh / kg	70	63	66
Energy density C/3	Wh / liter	170	150	140
Specific power (80% DoD, 25°C, 30 sec.)	W / kg	200	200	150
Power density (80% DoD, 25°C, 30 sec.)	W / liter	485	476	315
Cycle Life (100% DoD to 80% of initial capacity)				
at 20°C to 25°C	Cycles	~800 (80% DoD)	>1200	~ 1250
at 35 to 40°C	Cycles	~600	~ 1100	600

Cycle life and reliability have been satisfactory for NiMH batteries based on AB_5 alloy negatives. Data for the AB_2 alloy designs are less conclusive, particularly at elevated temperatures. *Figure III.1* includes EV-pack laboratory and field-test cycle life data given to the Panel by one of the EV manufacturers. Based on the laboratory data, the manufacturer projects more than 1,200 cycles and 100,000 miles at 25°C, 1,100 cycles and 80,000 miles at 35°C, and around 600 cycles and 80,000 miles at 45°C. The field data collected from vehicles that have reached 50,000 miles closely match the trend line

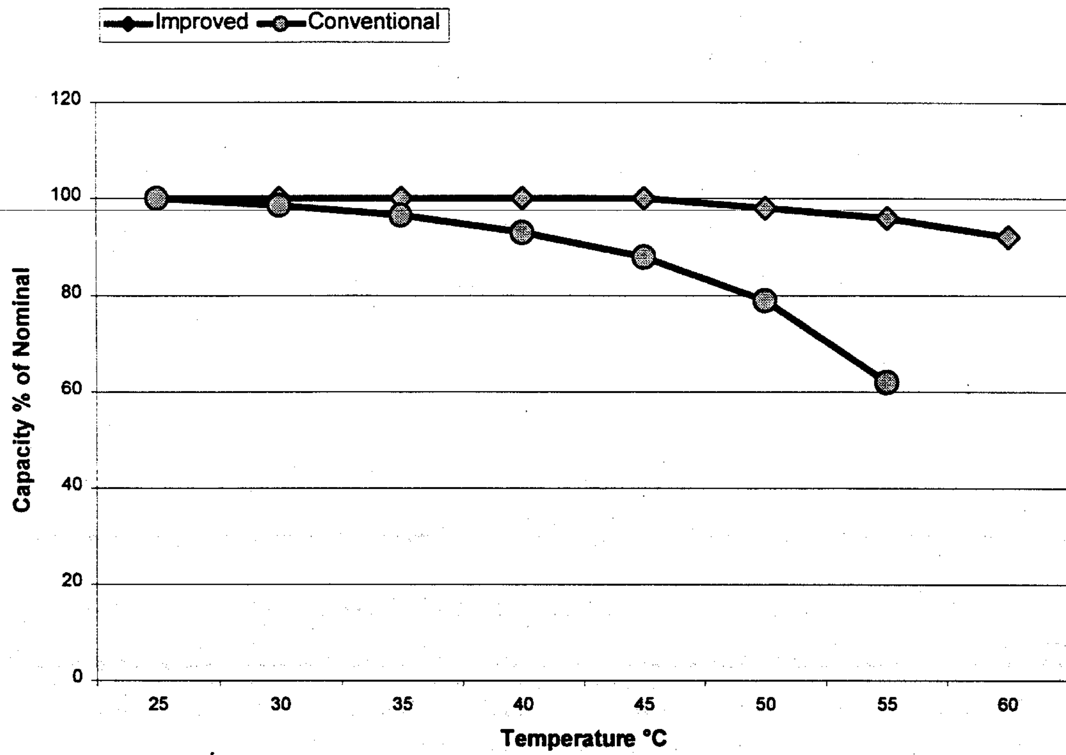
Figure III.1. Life Test Data for NiMH EV Packs
80% DoD Cycle Profile



of the laboratory data. Based on these and similar data, the car companies—and, understandably, the developers of AB_5 alloy-based NiMH batteries—are optimistic that a battery with a life of >100,000 miles can be developed. In almost all cases, the end of life will be caused by a gradual rise in battery impedance until the battery is no longer able to provide the minimum performance specified for the vehicle.

All three battery developers are making good progress in improving the charge acceptance of the positive electrode by use of additives to the Ni(OH)2 paste. Data on improved cells are illustrated in *Figure III.2*. Such cells, not yet incorporated into vehicle packs, show significant improvement, with efficient charging possible at temperatures up to about 45°C and perhaps higher. Two EV manufacturers have confirmed the improved performance in laboratory testing.

Figure III.2. Charge Acceptance vs. Temperature of Improved NiMH Batteries



Several pack designs depend on liquid cooling while others utilize air cooling. The trade-off between battery performance, efficiency, life and cost for the two cooling approaches is a complex optimization problem that will depend on the ambient temperatures in which EVs are operated, and will change with further technical improvements in battery-temperature characteristics. Both battery developers and EV manufacturers need to be involved in the evaluation of the preferred cooling approach.

NiMH EV batteries have adequate specific power at temperatures ranging from –10°C to 50°C. While NiMH batteries exhibit somewhat higher self-discharge rates and lower charge efficiencies than other candidate EV-battery systems, these effects are sufficiently small as to be only minor disadvantages. Finally, car companies and battery developers are confident that the NiMH battery does not create hazards in any of the specified abuse tests and meets the safety requirements of the EV application.

Commercial. The three developers of NiMH EV-battery packs visited by the Panel have reached an advanced pilot-level/early-production stage. All three will require 18 to 24-months prior notice to build the manufacturing plant(s) that would be required to meet the estimated demand generated by the 2003 ZEV mandate. NiMH manufacturing processes are well understood, and scaling up production does not represent a significant technical risk. However, the three developers (and other potential suppliers) will only scale up production if they receive orders from car companies that are large enough to cover the plant investment costs. At present, car companies are delaying such orders due to the uncertain prospects of the EV market.

Projected costs (sale price to OEMs) for nickel-metal hydride EV batteries as a function of production volume have been independently estimated by the major developers and their potential customers. The results are presented in *Figure III.3* and are generally in good agreement, an indication of the technology's relative maturity. The current price of over $1,000/kWh is projected to fall to about $350/kWh at the production volumes necessary to meet the California 2003 ZEV mandate—an implied requirement for 10,000 to 30,000 packs per year. At higher volumes, the lowest projected module price is above $225/kWh, which translates to more than $250/kWh at the pack level.

The Panel reviewed Lipman's[1] data on advanced EV-battery costs and compared them to the data presented in *Figure III.3*. Of all the data in Lipman's report, the case that is most relevant to this study is that of the GMO Generation-3 battery at a production volume of 100,000 packs per year (3, page 35). Lipman's material-cost estimates range of $134 to $157/kWh appears optimistic[2]. Using Lipman's material cost estimate nevertheless, and assuming (again somewhat optimistically) that materials represent 77%

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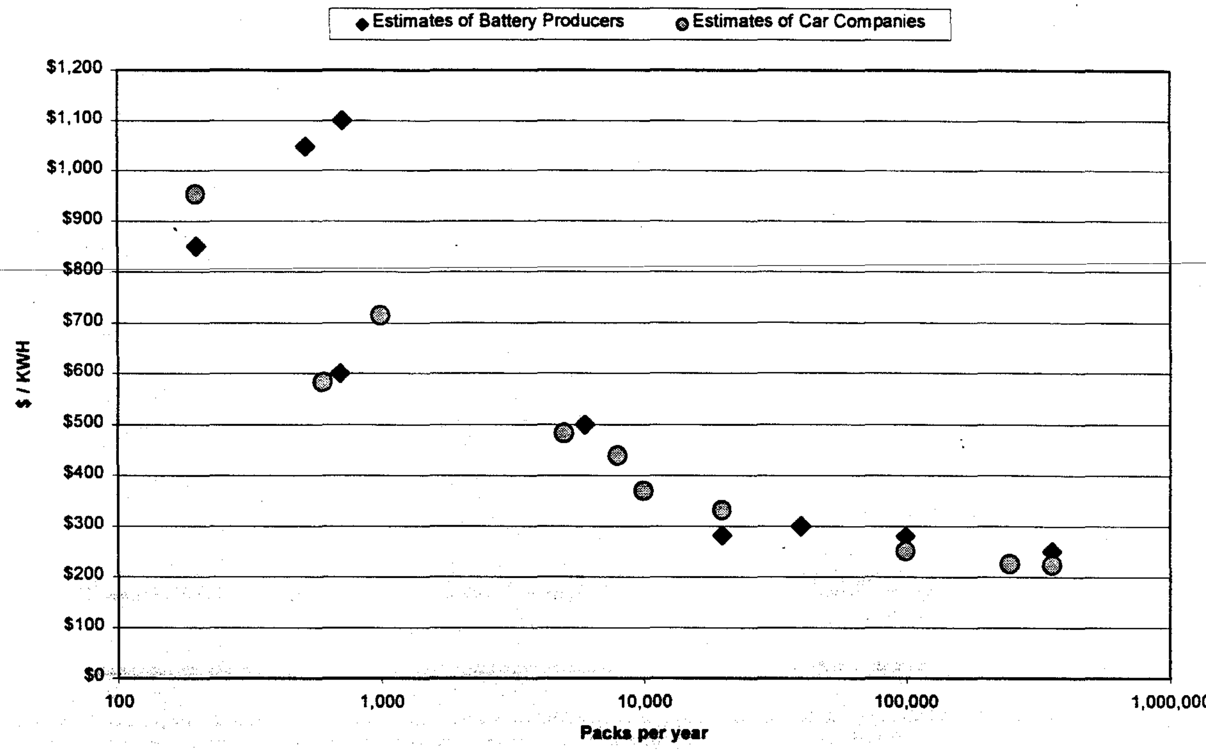
[1] The Lipman study (3) was conducted in early 1999, when the LME (London Metal Exchange) price of nickel—a major factor in the cost of NiMH batteries—was $5 to $6 per kg, lower than it had been in over 10 years. In the first quarter of 2000, the LME price of nickel had risen to between $9.50 and $10 per kg.
[2] In addition to using a lower nickel price, Lipman made no allowance for engineering yield, manufacturing scrap, and product de-rating due to manufacturing variations. Together, these latter factors can add 5 to 20% to material usage per kWh, and thus to the $/kWh estimates of battery cost.

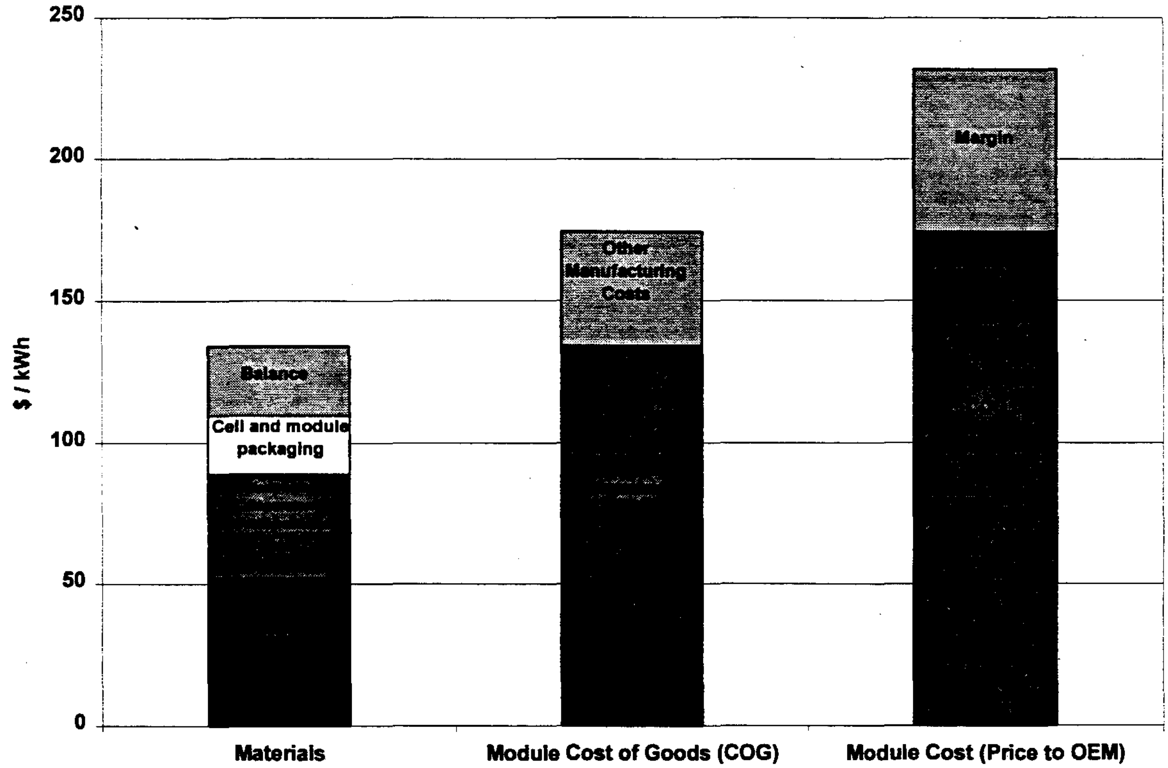
Figure III.3. Cost Estimates for Ni/MH EV Modules



of the Cost of Goods (COG), and that the gross margin is 25%, we obtain a COG in the range of $174 to $204/kWh for the module, and module selling prices to OEMs of $232 to $272/kWh. These figures are in general agreement with the data from the battery developers and car manufacturers (*Figure III.3*). The Panel's low-end estimate, based on Lipman's material cost assumptions, is illustrated in *Figure III.4.*

Adding $23/kWh for the steps required to produce packs from modules and for the cost of the warranty, the low-end OEM price is $265/kWh, or about $8,000 for a 30kWh EV pack at a production volume of 100,000 packs per year. Although claims can be made for some scrap-battery credits, it seems highly unlikely that lower prices can be achieved given the generally optimistic assumptions made above.

Figure III.4. Cost Aggregation for NiMH Modules
(based on Lipman 100,000 packs / year "Generation-3" material pricing)



III.2. LITHIUM-ION

III.2.1. Introduction

Historically difficult issues with cycling and safety of metallic lithium have led to the development of carbon host materials for lithium as negative electrodes in organic-electrolyte batteries. This development was key to the successful commercialization for consumer applications of small Li Ion batteries that use lithiated (i.e., lithium-containing) metal-oxide-positive and lithiated-carbon-negative electrodes.

The host material of Li Ion negative electrodes is made from special grades of graphitic or coke carbons, or from combinations of such carbons. The generic composition of the positive electrode is $LiMO_2$, with cobalt oxide (M=Co) commonly used in small commercial cells. However, due to its high cost, $LiCoO_2$ is precluded from consideration for EV batteries that would need substantial amounts of that material. Developers of large Li Ion cells currently employ a manganese compound, $LiMn_2O_4$, or a partially substituted Ni compound, $LiNi_xM'_yM''_{(1-x-y)}O_2$, where M' is typically Co and M'' can be aluminum or any of several other metals.

The battery electrolyte is a solution of a fluorinated lithium salt (typically $LiPF_6$) in an organic mixed ester (carbonate) solvent. Separators are usually microporous membranes made of polyolefinic materials (polyethylene or polypropylene, either alone or in combination). The cell operating voltage range is approximately 2.75 to 4.2 volts, with most of the capacity delivered between 4.0 and 3.5 volts. At the C/3 discharge rate, the average discharge voltage is about 3.7 volts. Because of the low conductivity of the electrolyte, adequate power can be realized only with electrodes and separators that are much thinner than those used in aqueous-electrolyte batteries. The need for thin electrodes has led to the spirally wound configuration as the preferred design for Li Ion cells.

Li Ion technology was first commercialized by Sony in 1991 (6). Over the last 8 years, small cylindrical and prismatic cells have become the first choice as portable power sources for laptop computers, cellular phones and similar devices. About 380 million small cells with an estimated value of more than $2 billion were sold worldwide in 1999. The top seven producers are all Japanese companies; between them, they account for more than 98% of the 1999 world production (5).

A key attraction of the Li Ion system is its high cell voltage. Not only does this translate to high specific energy, but it also makes it possible to use a smaller number of cells per battery, for reduced cost and increased reliability. Specific energies as high as 150 Wh/kg have been achieved at the cell level. Among the other attractive attributes of the Li Ion battery are high power, high energy efficiency (including essentially 100% coulombic efficiency), low self-discharge, and potential for good cycle life regardless of the depth of discharge (7).

Due to its attractive energy and power characteristics, Li Ion technology has become an important candidate for EV and other applications requiring large cells. The development of EV versions of the battery began at Sony Corporation around 1993. However, Sony and several other major battery companies discontinued Li Ion EV-battery development in recent years, mostly because they perceived future EV-battery markets to be highly uncertain. The three currently leading developers of EV batteries using Li Ion technology are Japan Storage Battery (JSB), Shin-Kobe, a company of Japan's Hitachi group, and SAFT, a division of the French Alcatel group.

The development of Li Ion technology for EV applications presents significant challenges beyond those of consumer batteries. The top three of these are the achievement of acceptable levels of cost, safety and operating life.

Cost. At least four factors make major contributions to the cost of Li Ion batteries:

- Active materials,
- Electrolyte and separator,
- Manufacturing, driven by the high cost of the precision equipment required to achieve high yields of a reliable and safe product, in the face of the very tight process margins for thin-film cell technology,
- Thermal and electrical module and battery management, made necessary by the great sensitivity of the Li Ion chemistry to overcharge and overheating.

Safety / Abuse Resistance. Organic-electrolyte batteries permit the use of high-specific-energy electrochemical couples but generally are more sensitive to abuse. The Li Ion battery employs two very energetic electrodes separated by a thin organic separator soaked in an organic electrolyte. Overcharge can create conditions that are even more energetic, with Li metal deposited on the negative electrode, and with the positive electrode becoming chemically unstable at elevated temperatures (>200°C). Further, the energy released by combustion of the battery materials is substantially higher than the energy stored electrochemically in the battery. Finally, the electrolyte solvents normally used can create hazardous conditions since they have significant vapor pressure at moderately elevated temperatures and are flammable.

Despite these potential safety problems, consumer Li Ion batteries are enjoying rapid growth, with very few, relatively minor safety incidents reported. The industry has been able to provide adequately safe products by combining appropriate cell designs with electronic protection of modules and packs against overcharge, excessive current drain, and overdischarge.

The development of a safe EV Li Ion battery presents greater challenges, due to the much higher energy content of cells, modules, and packs, and because of the difficulty of dissipating heat from a larger mass with a lower surface-to-volume ratio. Standards for the safety qualification of consumer cells have been determined by

Underwriters Laboratory and other groups, and these are accepted as sufficient. However, the abuse-tolerance standards for EV batteries have only been formulated recently (SAE J 2464), and their correlation with battery safety has not yet been validated. While it is beyond the scope of the Panel's study to analyze safety design considerations in detail, it is worth noting that of all the different positive electrode materials, $LiMn_2O_4$ is the most forgiving, due to two factors:

1) it has very little excess Li in the fully charged state. Thus, lithium metal deposition on the negative electrode in overcharge is minimal; and
2) the threshold of thermal decomposition of the charged material is at a considerably higher temperature than that of the alternative $LiNi/CoO_2$-based positive electrodes.

Gel-based organic electrolytes are under development and have recently been introduced into some consumer batteries. These electrolytes have lower vapor pressure than the more conventional liquid organic electrolytes, and should thus offer improved abuse tolerance.

Operating Life. The electrochemical cycling of the Li Ion battery involves transferring ("rocking") Li ions between two host materials. Provided these host materials are stable at the levels of intercalation used, the electrode reactions are reversible and can be repeated many hundred times. Indeed, over 1,000 cycles at 100% DoD have been demonstrated in several types of portable batteries.

However, existing Li Ion systems suffer from significant calendar-life limitations. Several factors are thought to contribute to this problem:

1) The charged negative electrode is thermodynamically unstable with respect to the electrolyte solvent and salt. In fact, the battery can operate only because of the presence on the electrode of a passive film that is formed during initial charge. This film, however, is not totally passive, and slow degradation reactions with the electrolyte take place continuously.
2) Small amounts of metal ions from the positive electrode can dissolve in the electrolyte. Not only does this process degrade the positive electrode capacity and

power capability, but the metal ions are known to interfere with the operation of the negative electrode. This problem is particularly serious for $LiMn_2O_4$-based positive electrodes.

Other degradation processes, including electrolyte oxidation by positive electrodes at high state of charge, are also known to take place (particularly at elevated temperatures) but the reactions involved are not yet fully understood.

Whatever the actual mechanisms of degradation, there is as yet no evidence to support a 10-year life projection for a Li Ion EV-battery.

III.2.2. Li Ion Battery Companies

JAPAN STORAGE BATTERY CO.

Company Overview. Japan Storage Battery Co. (JSB) is a major Japanese manufacturer of automotive starter, industrial and portable batteries, including lead-acid, Nickel-Cadmium, Nickel-metal hydride, silver-zinc, and Lithium-ion. Small prismatic Li Ion cells for the cell phone market are manufactured in volumes of several million cells per month by the GS Melcotech joint venture with Mitsubishi Electric Corporation. JSB's Corporate R&D in Kyoto supports a substantial effort in large Li Ion battery development for prospective markets that include industrial UPS, space, and military applications, as well as electric and hybrid vehicles.

EV-Battery Design and Performance. JSB's Li Ion EV cell is an elliptically wound structure contained in a metal case. Four 88Ah cells are connected electrically in series to form a 15V, 1.3 kWh EV module. JSB is also developing 30 Ah cells for mini-EV and HEV applications, as well as 3Ah and 6.5Ah cells for power assist-type HEVs. The positive electrode material is $LiMn_2O_4$, chosen for improved cost and safety over the alternative Ni/Co-based positive materials. Other major components of the cell—the negative electrode, electrolyte, and separator—are typical for Li Ion technology. For longer life and greater safety, the cell charging voltage is limited to 4.1V.

JSB's design features excess initial power to ensure sufficient power (particularly at low temperatures) as the cell impedance rises over the life of the battery. At room temperature, the module's specific energy at the C rate is 95 Wh/kg, the energy density is 168 Wh/l, and life exceeds 750 cycles in laboratory tests. The company has made significant progress in stabilizing the battery chemistry at elevated temperatures, an area that has been the Achilles' heel of the $LiMn_2O_4$ positive electrode. However, it is premature to predict battery life under field service conditions. Key performance characteristics are given in *Table III.3* below.

JSB's system appears to tolerate temperatures up to 100°C but safety at temperatures higher than 140°C is not proven. The company's development work focuses on three areas: modifying the chemistry to reduce high temperature fading and impedance rise, safety testing and enhancement, and cost reduction. JSB's Li Ion EV-battery is air-cooled with a variable flow system. A sophisticated electronic controller measures and processes several battery parameters to monitor the state of charge, calculate the remaining driving range, and assess safety. A successful 2,000km road test, which included battery fast charge, was conducted last year, in collaboration with Mitsubishi Motors. As installed, the battery used in this test delivered 80 Wh/kg.

Production Capability, Cost and Business Planning. JSB does not have a pilot line for the production of Li Ion EV modules. No significant orders for EV-type batteries are anticipated in the near future, nor does the company appear to have a business plan that would establish an EV-battery production capability by 2003. However, JSB claims that it would be able to install and start up an EV-battery production plant in 12 months in response to an appropriate order. Whether and when a production plan will emerge is likely to depend on the course of the JSB-Mitsubishi collaboration. Given the rapidly growing interest in hybrid electric vehicles, it seems reasonable to expect that Mitsubishi Motors' main business interest will be in hybrid rather than in pure electric vehicles, particularly since Mitsubishi is not one of the six large car companies affected by the 2003 mandate. JSB's cost goal for EV-battery modules in large production volumes is around $270/kWh or less..

JSB is expending significant resources in large Li Ion cell development and is establishing a technology base in the field. As an important industrial battery company and a major participant in the volume production of portable Li Ion batteries, JSB is in a good position to develop a competitive Li Ion EV-battery product. However, due to the large market risk and a series of unresolved technical challenges, the company is developing its Li Ion EV-battery technology very cautiously and without a definite commercialization plan. JSB sees the Li Ion market for large cells as developing first for specialty / military applications, then for HEVs and, possibly, eventually for EVs.

SAFT

Company Overview. An overview of SAFT was presented above (see Section III.1). As noted there, early pilot-cell and module-fabrication facilities for Li Ion batteries are in operation at SAFT's Bordeaux plant. SAFT is also developing Li Ion cells for the space, military, telecom and HEV markets. Especially in the space and military large-cell markets, SAFT already holds a position through the sale of its other battery products.

EV-Battery Design and Performance. SAFT's Li Ion EV cell is cylindrical and spirally wound, with a nominal capacity of 45 Ah. A partially substituted lithiated Ni-oxide of the following general formula:
$LiNi_xM'_yM''_{(1-x-y)}O_2$[1] is used as the positive-electrode active material. The balance of SAFT's EV cell design is conventional: graphite negative electrode, $LiPF_6$ salt electrolyte in a mixed-carbonate solvent, and a multi-layer porous polyolefin separator. For the EV application, SAFT has developed a liquid-cooled 6-cell module within which cells can be arranged in various series/parallel configurations. The preferred module configuration for a 90 Ah EV-battery has 3 sets of 2 parallel cells in series, to yield a 90Ah, 10.5V module.

[1] *Where M' is typically Co, and M'' aluminum or any of several other metals*

The performance characteristics of the 90Ah, 10.5V module are given in *Table III.3* below. They include energy performances of 138 Wh/kg and 210 Wh/liter, and specific power of 379 W/kg for 30 seconds at 80% depth of discharge. The operating temperature range is approximately -5°C to 50°C; below about -5°C, the battery requires external heating. Demonstrated cycle life is currently 550 cycles, but cycling tests are still running. Cycle life is charge-rate dependent, with faster charge resulting in diminished cycle life due to the increased risk that metallic Li is deposited on the graphite negative electrode surface. Therefore, a minimum charge time of 5 hours is specified. Calendar life is under study, with a best current estimate of more than 5 years based on extrapolation of data from ongoing tests. In the current configuration, SAFT's module has not yet passed some of the overcharge and crushing / nail penetration tests.

SAFT is also developing cells with capacities of 25 to 30 Ah and modules composed of these cells for small EVs and HEVs as well as 6Ah cells and modules for power assist-type HEVs. Over the last three years, SAFT has installed 15 Li Ion battery packs in experimental vehicles.

Production Capability, Cost and Business Planning. Earlier this year, SAFT established a pilot-level facility for manufacturing 45Ah Li Ion cells, with all equipment housed in a low-humidity room. The facility's current capacity of 100 packs per year can be expanded to about 400 packs per year with only a small additional investment. SAFT's Li Ion module cost, currently in excess of $2,000/kWh, is projected to decline as a function of production volume as shown in the following table:

Table III.2. SAFT's projected Li Ion module cost

Volume (packs/year)	Year	Module Cost ($/kWh)
100	2000-2001	>2000
400	2002-2004	2000
5,000	2005 based on orders	500
20,000	Beyond 2005	247
100,000	Beyond 2005	175

The estimates for production volumes of 5,000 packs and above appear highly optimistic. In response to the Panel's questioning, SAFT noted that the calculations were based on very high product yields and on the assumption of significant reductions in the cost of several key materials. In the Panel's opinion, these advances will be very difficult to accomplish in a 3-6 year time frame, particularly since SAFT is unlikely to be supported by a high volume Li Ion production base in the consumer battery sector.

SAFT's EV-battery work, partially funded by USABC, uses the same pilot production line to produce prototype Li Ion cells for other potential applications. In SAFT's view, the "best-case" scenario assumes successful resolution of safety issues and demonstration of adequate calendar life by 2003. This could lead to a decision to build a manufacturing plant and begin battery production in 2005.

Clearly, SAFT will not be in a position to manufacture commercial quantities of Li Ion EV-battery packs in 2003. In a complete success scenario, SAFT could begin to produce EV packs by 2005. However, safety and life expectancy are presently unproven, and it is unlikely that module costs could be reduced to less than $250/kWh in the foreseeable future. These issues appear to put major near-term investments in production facilities at high risk. Current uncertainties notwithstanding, SAFT is positioning itself to supply Li Ion packs to the EV market if and when such a market does develop.

SHIN-KOBE ELECTRIC MACHINERY CO., LTD

Company Overview. Shin-Kobe is a Hitachi group company with major business units in batteries, electrical equipment including rectifiers, UPS, golf carts, and plastics. Shin-Kobe's products include lead-acid batteries for automobile SLI, industrial (traction and stationary) and portable applications, as well as portable Ni-Cd batteries.

Shin-Kobe discontinued production of portable Li Ion batteries in 1998 due to pressures from severe price competition in that market. However, a Li Ion cell and module-development program for utility load-leveling and EV/HEV applications is maintained at the company's Saitama facility, and the program has a small pilot plant for producing Li Ion EV cells and modules. These efforts receive technical support form the Hitachi Corporate Research Laboratory.

EV-Battery Design and Performance. Shin-Kobe's Li Ion EV cell is cylindrical and spirally wound, with a nominal capacity of 90Ah. A typical EV module has eight cells in series to yield a 30-volt, 2.7 kWh module. Shin-Kobe's cell chemistry features a hard-carbon (coke) negative electrode, and a $LiMn_2O_4$ positive electrode. The composition of this positive is lithium-rich to enhance stability at high temperatures, while the electrolyte is optimized for adequate power at low temperature. The module is air-cooled.

Shin-Kobe's module design has good specific energy (93 Wh/kg) but only moderate energy density (114 Wh/liter), because of the significant volume required to permit effective air-cooling. However, a new module design is expected to improve energy density by up to 20%. The cell design features excess initial power to ensure sufficient power at low temperature and over an extended operating life. The pack can deliver 48kW at -30°C, presumably sufficient to permit vehicle operation while Joule heating warms up the battery. At the one-hour discharge rate, 84% of room temperature capacity can be realized at temperatures as low as -30°C.

A life of 1,450 cycles (to 80% of initial capacity) has been achieved at room temperature and 40% DoD. At 40°C and 40% DoD, life is 500 cycles. However, at elevated temperatures battery capacity fades relatively rapidly even when the battery is idle, a common weakness of Li Ion technologies using lithium-manganese spinel-based positive electrodes. The Panel suspects that operating life under these conditions is likely to be rather short, possibly only one year. The primary failure mode at room temperature is a rise in cell impedance, mostly caused by growth of the passivating film at the negative electrode-electrolyte interface. At 40°C, fading is accelerated by dissolution of manganese from the positive electrode. The performance characteristics of the Shin-Kobe module are presented in *Table III.3.*

Shin-Kobe and its EV customer, Nissan, have performed a significant number of safety tests on Li Ion batteries, mostly involving modules. According to Shin-Kobe, the company's modules have passed standard electrical abuse tests including overcharge, overdischarge, and external short-circuit. Shin-Kobe also noted that the modules have passed the T-series UN tests, as well as mechanical and environmental abuse tests that included crushing. Shin-Kobe stated that its battery is safe at temperatures up to 100°C. Above 100°C, passing abuse tolerance tests is more difficult, and beyond 140°C the flammable organic solvent can vent, a significant safety concern. However, Shin-Kobe noted that no safety-related incident has been experienced to date in the EVs powered by its Li Ion batteries.

Production Capability, Cost and Business Planning. After the withdrawal of Sony from development and fabrication of Li Ion EV cells and modules, Shin-Kobe became the sole battery supplier for Nissan's ALTRA and HYPER-MINI EVs. Nissan is responsible for battery assembly from the modules and battery integration in the vehicles, including thermal management, and it carries out all in-vehicle battery testing and operation.

Shin-Kobe's current pilot line can produce about 160 modules (13 EV packs) per month; no scale-up is currently planned. At that production level, the cost of Shin-Kobe's ~32kWh Li Ion EV pack is very high. Shin-Kobe's cost projection for 10,000 EV packs per year is $600 to $700 per kWh, or $18,000 to $21,000 per EV pack. At 100,000 packs per year, the projected battery specific cost falls to $250-350/kWh, with materials accounting for as much as 75% of the total. According to Shin Kobe, the cost projections for high production volumes contain a large element of uncertainty, in part because their materials suppliers are not pursuing cost reduction very aggressively due to a general lack of conviction that a substantial EV market will materialize.

Shin-Kobe and Nissan, its main customer for Li Ion EV batteries, see the high cost of these batteries as a major barrier to the commercialization of EVs. Thus, there appears to be no business case for Shin-Kobe to establish an EV-battery production capability. Consequently, Shin-Kobe is now focusing on Li Ion HEV batteries in the belief that a viable market for HEVs and their batteries will develop and that the company can produce a battery capable of meeting the needs of that market. Because Shin-Kobe is not planning to invest in the EV-battery business, the company is not a realistic candidate for the production of EV packs in the 2003-2006 time frame and probably beyond.

III.2.3. Summary

Technical. The design and performance characteristics of the EV modules of the three leading Li Ion EV-battery developers are summarized in *Table III.3*. The JSB and Shin-Kobe technologies utilize $LiMn_2O_4$ positive electrodes that lead to specific energies of currently around 90 Wh/kg, with an incremental improvement of less than 20% projected. Energy densities, between 110 and 150 Wh/liter, are relatively modest. Module designs feature air-cooling, and specific power is adequate for EV applications. The main challenge for this technology is to achieve an acceptable operating life, in particular at 40°C and above. Both companies, as well as other R&D organizations worldwide, are spending significant resources to study and mitigate the relatively rapid fading of the $LiMn_2O_4$-based Li Ion battery at elevated temperatures. However, the time required to resolve this issue is difficult to predict because it involves substantial R&D. Even after improvements are developed and implemented, it will take several years to confirm their validity through extended-duration life tests.

The SAFT technology differs from those of other developers in that it uses a nickel-based positive-electrode material with higher charge-storage capacity. Energy parameters at the module level are an impressive 140 Wh/kg and 210 Wh/liter, with up to 20% further improvement projected. Also, in contrast to the Japanese designs, SAFT has developed a higher-energy but lower-power technology that is liquid-cooled and has provisions for heating the battery to improve power capabilities in low temperature environments. The main technical challenge for the SAFT technology is abuse tolerance, a consequence of its choice of positive-electrode material. SAFT expects to focus on this issue over the next several years. Abuse tolerance aside, the operating life of SAFT's Li Ion technology is also still unknown. The company projects a life of more than 5 years for its current cell design. However, only 550 cycles have been demonstrated to date for modules at room temperature, and cycle-life as well as operating life at higher temperatures appear to be open questions.

Table III.3. Characteristics of Li Ion Batteries

	Unit	JSB	Shin-Kobe	SAFT
Design Characteristics				
Nominal Cell Capacity	Ah	88	90	90
Cell Design	-	Prismatic	Cylindrical	Cylindrical
Positive Electrode Chemistry	-	$LiMn_2O_4$	$LiMn_2O_4$	LiNiM'M"O_2 (*)
Nominal Module Voltage	V	15	30	10.5
Number of Cells in Module	#	4	8	6
Nominal Module Energy	KWh	1.32	2.7	1
Performance Characteristics				
Specific Energy C/3	Wh / kg	97	93	138
Energy Density C/3	Wh / liter	168	114 (136)**	210
Specific Power (cell level)		50% DoD, 20 sec.	50% DoD, 10 sec	80% DoD, 30 sec.
at 20°C or 25°C	W / kg	810	750 (25°C)	430
at low temperature	W / kg	125 (-20°C)	328 (-15°C)	296 (0°C)
Cycle Life (100% DoD to 80% of initial Capacity)				
at 20°C or 25°C	Cycles	750 (25°C)	600	≥550
at 40°C	Cycles	230 (45°C)	<500	510
Irreversible Capacity Loss on storage				
100% SoC				
at 20°C or 25°C	% / 90 days	3	8	0
at 40°C	% / 90 days	9 (45°C)	15	2
50% SoC				
at 20°C or 25°C	% / 90 days	0	7 (65% SoC)	0
at 40°C	% / 90 days	5 (45°C)	12 (65% SoC)	0
Self-discharge at 100% SoC				
at 20°C or 25°C	% / 90 days	10		10
at 40°C	% / 90 days	22		10

(*) M' is typically Cobalt, and M'' one of several possible third metals

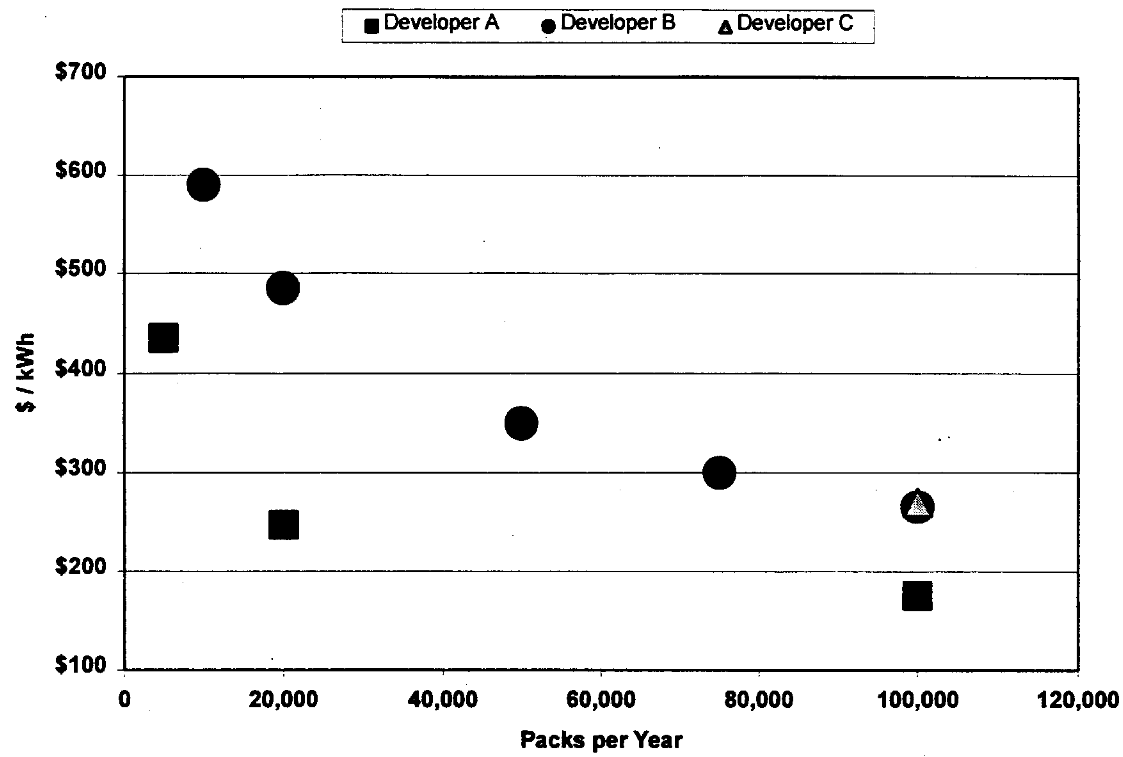
(**) Excluding terminals

Commercial. Li Ion EV-battery technology development is presently in the early pilot stage (see also *Figure II.1*). Shin-Kobe, which has produced more modules than the other two developers, has shifted its focus to HEVs and has no plans to scale up the production of EV batteries. SAFT and JSB are continuing to work on product and process development but at present do not have definite plans for volume production.

The basic chemistry and design of Li Ion EV cells are quite similar to those of small consumer cells, suggesting that the basic manufacturing processes for EV batteries should be well understood. However, the Panel notes that the manufacture of Li Ion cells requires a higher level of process control and precision than most other types of battery manufacturing and, as a result, scrap rates tend to be higher. Most, if not all producers of small Li Ion batteries have experienced product recalls and/or production shut down due to reliability issues and/or safety incidents. Projecting this experience to the much larger EV cell, it seems likely that scaling up the production of EV cells from the current early pilot level will be slow and costly.

Present costs for small-lot production (100-200 packs/year) are very high—in the order of $2,000/kWh—since they do not capture the economies of large-scale production. Battery costs are projected to decrease as production volume increases, as shown in *Figure III.5* that presents a composite projection of estimated future costs (selling prices to EV manufacturers) as a function of production volume. The data in the Figure were derived by the Panel from projections provided by the developers. In contrast to NiMH, the spread of projected costs at high production volumes is relatively large. The two Japanese companies are projecting costs around $275/kWh at production volumes of ~100,000 EV-battery packs/year, while SAFT's projections are as low as $175/kWh. The large spread is most likely related to the difficulty of making accurate projections for all key cost factors at this rather early stage of EV-battery materials and manufacturing development. In this context it should be noted that the two companies with more extensive commercial production experience in Li Ion batteries (and which are using the less expensive $LiMn_2O_4$ cathodes) offer the less optimistic cost projections.

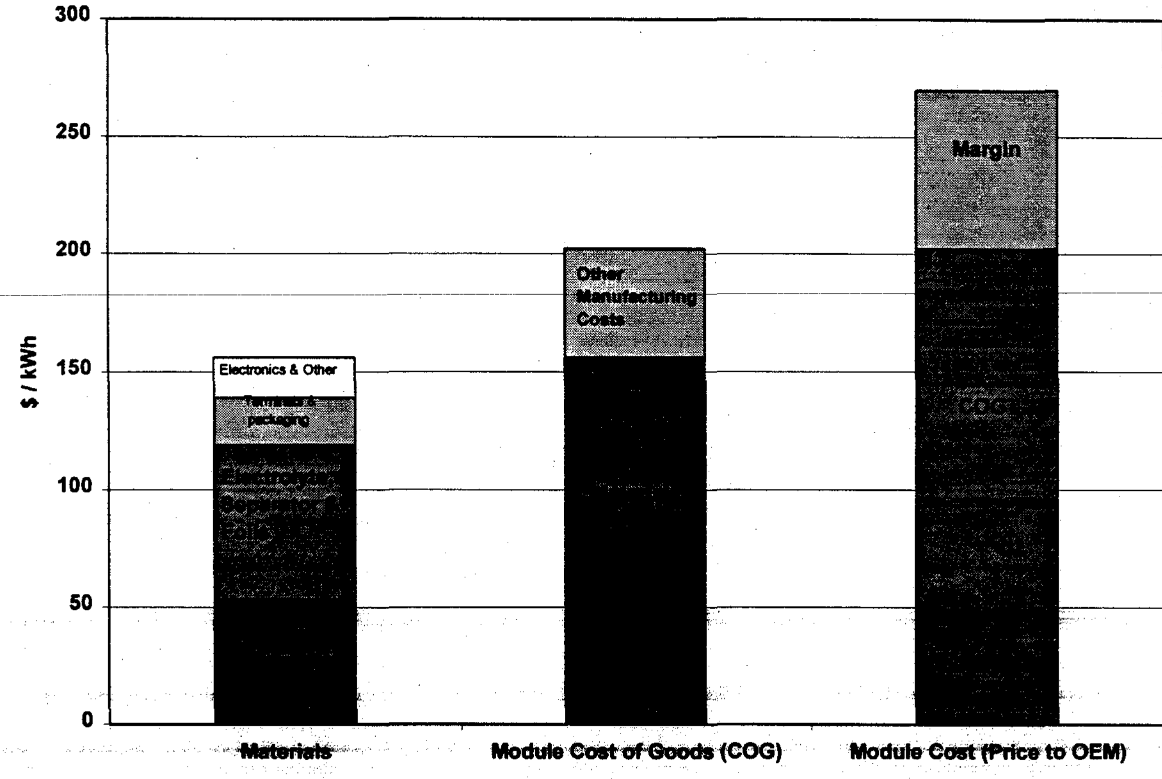
Figure III.5. Cost Estimates for Li Ion EV Modules



In an attempt to shed light on these discrepancies, the Panel developed a simplified material cost estimate for the future production of 100,000 EV-battery packs per year, based on the first-hand experience of Li Ion technology by one of its members. The Panel's estimates are illustrated in *Figure III.6.* The low-end module material costs were estimated at $156/kWh[1]. Assuming (as in the Panel's analysis of NiMH-module costs) that materials represent 77% of the Cost of Goods (a high percentage that translates into the lowest realistic cost), and with a low gross margin of 25%, a module cost of $270/kWh was calculated, in good (if perhaps somewhat fortuitous) agreement with the estimates of Shin-Kobe and JSB.

[1] The Panel obtained cost projections from established suppliers for the 5 largest cost drivers of the Li Ion cell at a future (assumed to be 2006) production volume equivalent to 100,000 30-kWh EV packs per year. The Panel then assumed a 30% reduction in the cost of the positive and negative active materials to anticipate 1) further cost lowering in LiNiM'M"O_2 presently made in relatively small quantities, and 2) the use of lower-cost natural-graphite negatives. Other assumptions included $20/kWh for cell and module casing and terminals, $10/kWh for module electronics, and $7/kWh for miscellaneous materials.

Figure III.6. Cost Aggregation for Li Ion Modules
(low-end estimates; 100,000 packs / year)



The Panel notes that the EV business will not be large enough to drive Li Ion material costs, even at production volumes of 100,000 packs/year[1]. While R&D in this area remains very active, due to the rapid expansion of the technology in the consumer products sector and its growth potential in other markets, major innovations that could lead to materials costs significantly below those estimated by the Panel appear unlikely in the near term. Thus, the Panel tends to agree with the Japanese developers that Li Ion EV module prices much below $300/kWh cannot be expected in the foreseeable future.

If Li Ion EV batteries are to become commercially viable, operating life and abuse tolerance issues will need to be resolved first, and then the cost of the technology will

[1] *Based on an estimated 1999 production of 2 million kWh of small Li Ion batteries (400 million cells at an average of 5 Wh) and a projected annual growth rate of at least 20% (5), the production of small batteries in 2006 should exceed the equivalent of 7 million kWh. Production of 100,000 30-kWh EV packs in that year, equivalent to 3 million kWh, would be less than 50% of consumer usage.*

have to be reduced, at least to the levels projected for NiMH batteries. When considering the prospects for achieving these objectives, it must be kept in mind that any less expensive, new materials—especially active materials and electrolytes—that might be introduced, will have to comply with the life and abuse tolerance requirements of the EV-battery.

III.3. LITHIUM-METAL POLYMER

III.3.1. Introduction

Forty years of research to develop rechargeable batteries with lithium-metal negative electrodes has established that achieving a practical cycle life for lithium electrodes in liquid electrolytes is extremely difficult. With continued cycling, the lithium deposited during charging becomes finely divided and, therefore, highly reactive as well as increasingly unavailable to the cell reaction. This process creates substantial safety hazards and severely limits cycle life. About 20 years ago, the discovery that polar polymers of the polyethylene-oxide (PEO) family can dissolve lithium salts prompted systematic investigation of the use of such polymers as film electrolytes in rechargeable lithium batteries (8). It was found that lithium electrodes cycled while in contact with PEO-based solid electrolytes appears to maintain a smoother surface, making longer cycle life possible. Also, polymer electrolytes are more stable in contact with lithium than are organic solvents, and they have very low vapor pressures. All these characteristics contribute to the chemical stability and safety of the Li polymer systems compared to lithium-metal-based cells and batteries with organic-liquid electrolytes.

Due to the very low lithium salts solubility and ion mobility in PEO-based solid electrolytes, lithium-metal polymer batteries must operate above room temperature, typically between 60°C and 90°C. This constraint tends to limit these batteries to applications for which thermal insulation and management can be provided within the applications' physical and cost constraints. This excludes the portable battery market but is not considered a major issue for EV batteries that, in any case, require thermal management for reasons of battery life and safety. Accordingly, for more than two decades, several organizations have been attempting to develop Li polymer batteries for electric vehicles. Two programs are still active today: those of Argo-Tech/Hydro-Québec near Montreal, Canada, and Bolloré/EDF in Quimper, France. The Panel visited both organizations to discuss their development status and plans.

Argo-Tech's and Bolloré's Li polymer batteries use thin lithium-foil negative electrodes, and positive electrodes that contain vanadium oxide ($V_2O_{(5-x)}$, with x<1) as the active material. The electrolyte (which also serves as the separator) is a PEO polymer with other polymeric additives into which a fluorinated lithium salt (typically lithium-trifluoromethanesulfonimide) is dissolved. When in contact with a source of lithium ions, the V_20_5 compound can reversibly intercalate and release up to 0.9 Li ions per vanadium atom. The specific capacity (for 1.8 Li ion per V_20_5) is 246 mAh/g at a discharge voltage ranging between 3.2 and 2.0V, and averaging 2.6V per cell.

The main construction features of the Argo-Tech lithium-metal polymer battery are as follows: the electrolyte film is laminated to the positive electrode that is coated on an aluminum foil. A thin (for example, less-than-50-micron thick) lithium foil is then calendered onto the laminate film structure, and the whole "stack" is spirally wound on a rectangular mandrel. In the language of the Li polymer battery developers, the resulting multi-layer structure is called an element, with a voltage of about 2.6V and a typical capacity of 2 to 20 Ah. Several elements connected electrically in parallel make up a "cell", with a capacity of 50 to 120 Ah for EV applications. Finally, several such cells are configured in a series or a parallel-series combination to form a module. The elements and cells are packed in an aluminum-laminated plastic pouch, with sputtered electrical contacts and terminals placed on opposite sides of the cell. The module design includes mechanical compression of the cell stack to enhance dimensional stability of the electrodes. This promotes cycling ability, facilitates thermal insulation and management, and permits electrical monitoring of individual cells, for protection against overcharge and overdischarge conditions.

The Li polymer system's theoretical specific energy of 640 Wh/kg is markedly higher than that of Li Ion systems (between 380 and 450 Wh/kg depending on the choice of positive active material) and more than double that of the nickel-metal hydride systems. It is not clear, however, whether the Li polymer technology can achieve significantly higher practical specific energy and/or energy density than the best lithium-ion systems in a fully packaged battery. Four factors must be taken into account: 1) the amount of excess lithium needed to achieve adequate cycle life; 2) the practical extent to which the positive electrode material can be utilized; 3) the weight and volume needed for thermal insulation, and the energy required to keep the battery hot during stand-time; and 4) the somewhat less volume-efficient stack design of the thin film technology.

An attractive feature of the Li polymer system is its potential for lower cost than Li Ion or NiMH systems because of its lower active materials cost per kWh. However, it is again unclear whether this fundamental advantage can lead to the production of a less expensive battery. The high cost of the electrolyte salt, the complex and as yet unproven manufacturing processes for the large areas of very thin structures required per kWh of battery capacity, and a relatively complicated electrical and thermal management system are all factors that appear likely to inflate the total cost of the Li-polymer battery system.

III.3.2. Li Polymer Companies

ARGO-TECH

Company Overview. The Institut de Recherche d'Hydro-Québec (IREQ), the research organization of the large Canadian electric utility, has been engaged in Li Polymer Battery research since 1979. In 1994, Argo-Tech Productions Inc. was set up as a sister company of IREQ to further develop and commercialize IREQ's Li Polymer Battery (LPB) technology. Argo-Tech has a dedicated facility located in Boucherville, Canada, near IREQ with over 100 employees engaged in bench-level LPB fabrication and process development. Both IREQ and Hydro-Québec's LTEE Laboratory support this development with advanced material and analytical R&D. Argo-Tech's main sources of outside revenue are its development contracts, the largest by far being with USABC. In addition to EV batteries, Argo-Tech is developing low-power batteries for the "outdoor-cabinet" telecommunication market as well as a high power battery for HEV applications.

EV-Battery Design and Performance. The basic construction of the Li Polymer battery is discussed above. In Argo-Tech's technology, the thickness of the EV-battery stack is about 100 microns. The cathode and the electrolyte films are made by slurry-coating the functional materials using an organic solvent, and the films are laminated together into a single thin sheet. A thin lithium foil of <40 microns is extruded and calendered in a dry room to achieve optimum surface control. Li film thickness is determined by the amount of lithium needed to provide current collection with a "reserve" of the metal for improved cycle life. The EV pack is designed to operate at temperatures between 60°C and 85°C, with the thermal management function divided between the module and the pack.

Argo-Tech's design goal is a 119Ah cell for the EV applications. Eight such cells will be assembled in series to create a 21V, 2.5kWh module, and 15 modules in series will form a 38kWh, 315V battery pack. Argo-Tech's LPB design is still evolving, and performance data are consequently incomplete. Most of the available cycle life data were obtained from cells with lower capacity than those being developed for the 119Ah cell.

Without the benefit of complete data, the Panel's best estimates of the current performance of Argo-Tech's battery module are as follows:

Specific energy:	110 to 130 Wh/kg
Energy density:	130 to 150 Wh/liter
Cycle life, 80% DoD, DST:	250 to 600 cycles
Specific power:	~300 W/kg (80% DoD, 30 seconds)
Calendar life:	Unknown, but probably more than 3 years

Development and Commercial Status, Business Planning and Prospects. Argo-Tech's EV element, cell, and module production processes are in the pre-pilot stage. A full-size EV pack has been assembled, and Argo-Tech plans to install it in a vehicle later this year. As the design and the manufacturing processes are still evolving, the organization's capability for pilot production is difficult to assess.

The cost of Argo-Tech's EV-battery development is being shared by USABC. The USABC contract for the now completed Phase 2 program had been awarded to a joint venture between 3M (Minnesota Mining and Manufacturing Co.) and Argo-Tech, in which 3M was responsible for the development and fabrication of the positive electrode-electrolyte "laminate" structure. While the joint venture was discontinued in 1999, 3M is still continuing to manufacture and supply the half-cell laminate. However, Argo-Tech is now seeking alternative supplier(s) with a longer-term commercial commitment.

Argo-Tech's current module production cost is estimated to be several thousand dollars per kWh. The company projects a reduction to $300/kWh at a production volume of about 30,000 EV packs per year. To bring the cost down to less than $240/kWh, significant changes in materials, design, and processes are necessary.

Since the Argo-Tech LPB fabrication processes are unique in the battery industry, scaling up is a major challenge. In the Panel's view, it is still an open question whether the manufacturing processes can be scaled up to operate at an economical speed while at the same time providing high product yield and meeting the stringent design and quality specifications required to guarantee reliable performance. Despite the progress achieved in the last several years, the potential of Argo-Tech's technology to meet the requirements of the EV application is still largely unproven. Improvements in cycle life and energy density are needed, and adequate calendar life and safety have not yet been demonstrated. Design changes are still being made to improve energy density, cycle life and manufacturability, and efforts to reduce the prospective cost of the product are underway. Pilot production of EV packs is not planned until 2004. Thus, it is difficult to envisage that investment in an EV production plant could occur before 2006 or 2007. Consequently, the Panel concludes that Argo-Tech is unlikely to be in a position to manufacture EV batteries in commercial quantities and at competitive costs until late in this decade.

As mentioned above, Argo-Tech has also developed a LPB module (90 Ah, 48V) for telecommunication applications. To Argo-Tech, this market appears to offer lower risk, less stringent technical requirements, and prospects for a higher market price, which should add up to a better near-term opportunity. In all likelihood, successful commercialization of a telecommunications version of the LPB battery should advance the technology's long-term prospects as an EV-battery.

BOLLORÉ, ELECTRICITÉ DE FRANCE (EDF), SCHNEIDER ELECTRIC

Company Backgrounds. EDF is the largest electric utility company in the world and the dominant utility company in France, with large corporate R&D facilities and substantial expertise in the field of battery management and testing. EDF has had an interest in EV technology for over 20 years, and it owns and operates several thousand electric vehicles. Its commitment to EVs led EDF to start the lithium-polymer battery project in the early 1990s.

Bolloré is a French industrial conglomerate with sales exceeding $3.5 billion in several industrial fields. Bolloré's battery development is carried out by the company's plastic films and specialty papers group in Quimper, France. The group has extensive experience and expertise in the precise extrusion and metalization of plastic films for capacitors and holds about 40% of the world market for such products.

Schneider Electric, a major French manufacturer of electrical and electronic equipment and owner of Square D in the U.S.A., is the third partner in this development project.

All three partners have made long-term commitments to Lithium-metal polymer Battery (LPB) development, and the goal of the current project phase is to establish a pilot plant at Bolloré that will be capable of producing pre-prototype 2kWh battery modules by 2002.

EV-Battery Design and Performance. The LPB's electrochemistry and the functional components of the cell are described above. Bolloré's fabrication method has several distinctive features in that the positive-electrode and electrolyte films are extruded in a solvent-free process, followed by calendering and lamination steps. These techniques, although presenting difficult development challenges, were adopted at the outset of the program because of their potential for high-speed, low-cost manufacturing. Commercial lithium foil, the V_2O_5 compound, and the electrolyte salt, are purchased from outside vendors. The electrolyte includes PEO as well as a second polymer that is added to facilitate film processing and improve mechanical properties.

According to Bolloré, at the current stage their LPB system is achieving a specific energy of 145 Wh/kg at the element level, corresponding to approximately 110 Wh/kg, and an energy density of 125 Wh/liter at the module level. Cycle life at the element level is presently about 350 cycles to 80% of initial capacity, with the main failure mode being low-current dendritic lithium shorts. Cycle life has been found to decrease at higher charge rates. Bolloré's module performance goals for 2001 are a specific energy of 150 Wh/kg and a life of 1,000 cycles at 50% DoD to 80% of initial capacity.

Commercialization Timeline and Plans. Bolloré and its partners' current focus is on module development for EV batteries_although they plan to initiate a program for HEV batteries in 2001. The timeline for the program is as follows:

1992 to 1997: Research: basic cell design
1997 to 2000: Development: prototype cell and process development
2001 to 2004: Industrialization: pilot production and field-testing
After 2004: Commercial production

Construction of a pilot-production line is scheduled to start in the first half of 2000. Successful pilot development and field-testing could lead to a decision to build an EV-battery production plant as early as 2004. The program's battery cost goal (price to vehicle manufacturers) is less than $200/kWh, but no "ground-up" cost model was presented to the Panel to support this figure.

The cycle-life currently achieved by Bolloré's LPB elements is not yet sufficient for the needs of the EV-battery market. Also, the technology's energy density is only moderate, and adequate calendar life and safety performance have not yet been demonstrated at the module level. However, the partners estimate that, because of its large chemical stability temperature margin, the lithium-metal polymer system holds a larger potential for safety than other lithium systems. While Bolloré expressed confidence in its ability to scale up the manufacturing process, the Panel considers it unlikely that, given the current state of development and the issues remaining to be resolved, the present effort can result in a technically proven, high-performance and cost-competitive lithium-metal polymer battery for the EV market, that will justify investment in a volume production plant in less than 5 to 6 years.

III.3.3. Summary

The LPB technology has the highest theoretical specific energy of the three systems reviewed in this report. However, the actual specific energy and energy density demonstrated to date at the module level are not better than those of the best Li Ion EV batteries.

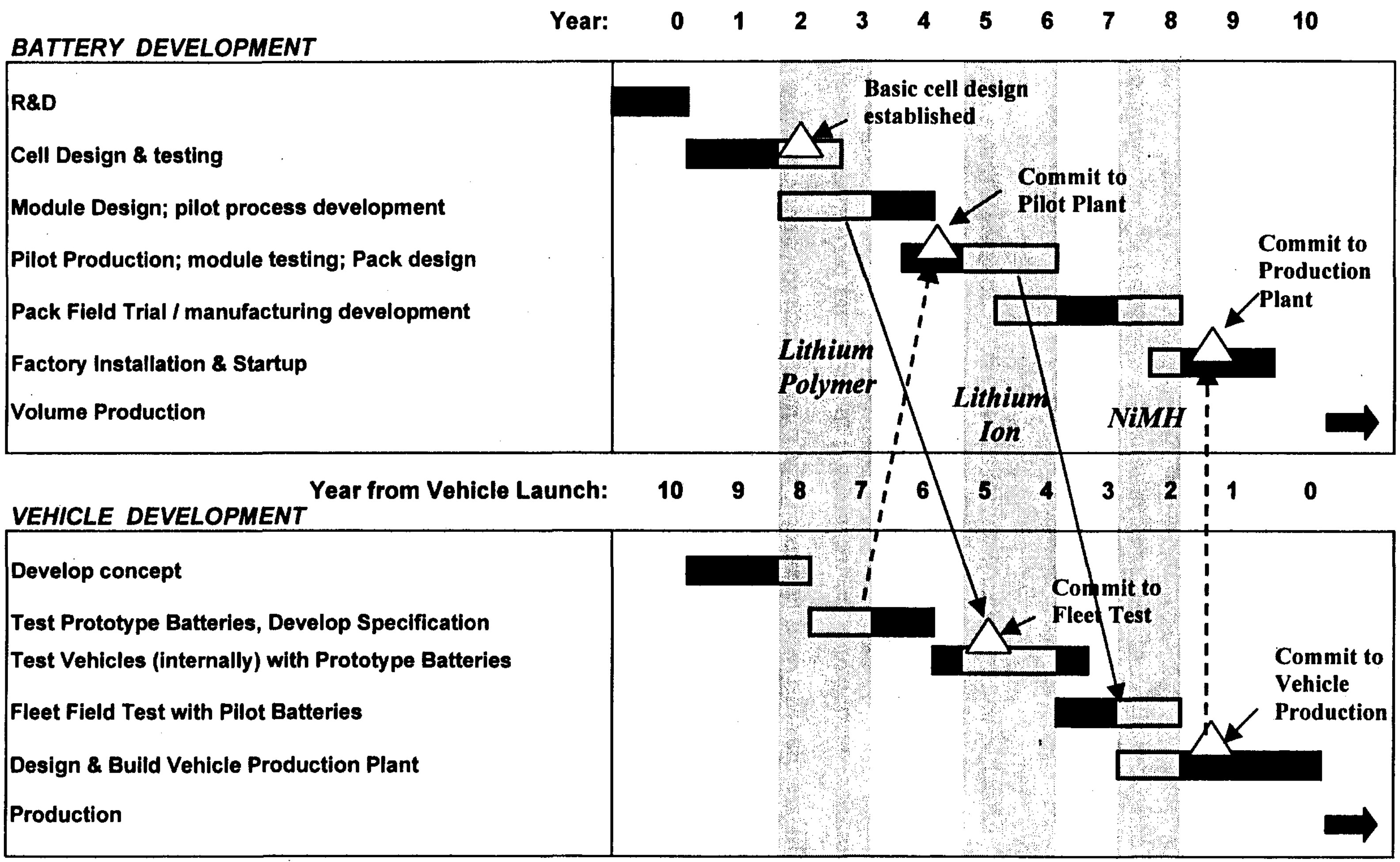
If LPB battery-level specific energy and energy density can achieve parity with those of Li Ion batteries, the technology's advantages over the Li Ion technology are expected to be greater safety and lower cost. Regarding safety, the absence of high-vapor-pressure organic solvents should give the LPB battery greater tolerance to abuse. While this is a reasonable expectation, it is too early to be quantified, as is the potentially hazardous presence of metallic lithium in the LPB system.

The LPB technology offers the lowest potential cost of unprocessed active materials among the advanced batteries presently under development for EV applications. However, this advantage might well be offset by the cost impact of the stringent manufacturing requirements and the difficulties inherent in assembling a large thin-layer battery. When considering the steps still ahead, LPB development does not have the benefit of the knowledge and experience acquired in the mass manufacturing of small Li Ion and NiMH cells. Material specifications, cell and module design, and process parameters are still evolving for the LPB technology, and until a more mature design and proven manufacturing processes emerge, cost estimates for high volume production of LPB EV batteries remain uncertain.

A limited ability to cycle has always been a weakness of rechargeable lithium-metal batteries. While both LPB developers are showing significant improvements in this area compared to their status of only 1-2 years ago, the best cycle-life performance demonstrated so far at the module level is about 450 cycles. Because the cycle life of the LPB technologies is very sensitive to manufacturing process variations (such as those caused by lack of surface uniformity or adequate compression at the cell level), reproducing module and battery pack performance consistently will be a major challenge. Thus, a reasonably confident prediction of the operating life of complete LPB packs in electric vehicles is not yet possible.

LPB EV-battery technology is still several years away from a credible field trial in EVs. This schedule implies that commercial production of EV batteries is very unlikely prior to 2007 (see *Figure III.7*). Not surprisingly, given the present status and uncertainties surrounding the technology, the cost and performance levels projected for the LPB are the least well defined of the three advanced battery systems investigated by the Panel.

Figure III.7. Battery and Electric Vehicle Interactive Development Timeline and the Status of the Advanced Batteries of this Study



III.4. AUTOMOBILE MANUFACTURERS

Background. The 1995 BTAP assessment focused on the battery developers that were engaged in key phases of EV-battery engineering and prototype development and thus held the key to the possible availability of advanced EV batteries in time for use in 1998 ZEVs. In its report, BTAP stressed the need for electric-vehicle developers/manufacturers to be intimately involved in the specification, testing and in-vehicle evaluation of EV batteries, as shown schematically in *Figure II.1*. This involvement is essential for the earliest possible availability of advanced EV batteries in electric vehicles with characteristics acceptable to manufacturers and potential owners/users.

Recognizing this need, several of the major automobile manufacturers have been collaborating with developers of EV batteries since the early 1990s. In the United States, this collaboration involved all three major carmakers, both individually and through their active participation in the USABC program. Under their 1996 agreements with ARB, the six largest suppliers of the California car market substantially increased their EV involvement, focusing their efforts on the development and introduction of a significant number of state-of-the-art EVs and, also, on the advancement and evaluation of EV-battery technology. The automobile manufacturers' positions on current and prospective performance, cost, and other key characteristics of EV batteries (such as durability and safety) clearly are impacting the technical programs and business decisions of battery developers, and thus have a direct effect on the commercial availability of EV batteries in 2003 and beyond. The Panel, therefore, decided to visit all six manufacturers for discussions of their battery-related activities and views. The findings from these visits and from follow-on discussions are summarized below.

III.4.1. DaimlerChrysler

More than a decade ago, Chrysler selected the minivan as the corporation's primary electric vehicle platform. The 56 electric TE Vans sold by Chrysler in 1993-1995 were equipped with nickel-iron or nickel-cadmium batteries, both of which proved unsuitable. The EPIC electric van was introduced in 1997 with an advanced-design lead-acid battery. The EPIC van remained the main EV platform of the newly formed DaimlerChrysler corporation, but the limitations of lead-acid batteries led the corporation to evaluate NiMH EV batteries. On the basis of its evaluations, DaimlerChrysler turned to SAFT's 95Ah NiMH battery technology (developed with co-funding from USABC) for the majority of the EPIC electric vans produced and deployed under the corporation's MoA with the California ARB. Key characteristics of these vans are summarized in *Table C.1*; details on the SAFT NiMH battery technology were presented in Section III.1 above.

Field experience with the more than 90 EPIC vans equipped with NiMH batteries indicates that the EPIC electric van can provide satisfactory function and utility for selected fleet operators. For example, the EPIC proved very suitable in handling the payload and relatively mild duty cycle (20-40 miles/day) of a Los Angeles area post office. With its fast charging capability, the EPIC also was able to handle the 200-300 mile/day duty cycle of a Los Angeles airport shuttle. This experience proved NiMH batteries to be more reliable and predictable than the previously used lead-acid batteries. The electronically controlled, thermally managed NiMH battery packs performed best when used every day. The experience also indicated that self-discharge, shelf-life, and battery pack balance remain significant issues, and make it difficult to optimize battery management systems for different duty cycles and operator behavior.

On the basis of that experience and SAFT's efforts to improve battery performance (especially energy density and specific energy), DaimlerChrysler has stayed with the selection of the SAFT NiMH technology as the EV-battery most likely to meet minimum performance requirements and be commercially available by 2003. If needed to address ZEV requirements, DaimlerChrysler would contract with SAFT to produce battery packs in sufficient numbers to meet DaimlerChrysler's needs at a fixed battery price that is consistent with the module cost levels in *Figure III.3* above.

SAFT's NiMH EV-battery technology will have the performance improvement and cost reduction features that are currently being implemented at the module level. Key manufacturing processes will be verified in SAFT's Bordeaux NiMH battery plant, which is being modified to produce the improved modules and handle an increased production rate. DaimlerChrysler is working with SAFT to define an approach to NiMH battery production that, if needed, would establish an EV-battery manufacturing capability for DaimlerChrysler. This approach utilizes the advanced technology and manufacturing expertise of a leading battery manufacturer, limits the financial burden and risk for the much smaller battery company, and permits the automobile manufacturer to increase its financial and people resources exposure in a series of well-defined steps.

While DaimlerChrysler thus is taking concrete steps and financial risks in preparing to meet ZEV requirements if needed, the company has serious doubts about the market prospects of electric vehicles. Even with the most optimistic cost for NiMH EV-modules produced in very large volume, DaimlerChrysler projects large price increments for electric vehicles compared to the ICE-powered counterparts. The corporation believes that prospective owners or lessees are very unlikely to pay such a large premium for vehicles that also have utility limitations, especially with respect to range.

DaimlerChrysler staff expressed the opinion that the ZEV regulation in its early years had value as a "driver" of technology, including but not limited to batteries. However, they further stated that now that the most viable of these technologies have become accepted, the regulation is seen as diverting development resources from potential mainstream automotive products (such as fuel cell and battery hybrid electric vehicles) that have better prospects than EVs to contribute to the reduction of automotive emissions.

III.4.2. Ford

Ford has been engaged in EV development for several decades, with a historically strong focus on advanced electric power train technology development. Under its MoA with the California ARB, Ford developed and deployed a battery-powered version of its Ranger truck with the characteristics included in *Table C.1*.

Approximately 500 Ranger EVs were supplied originally with Delphi lead-acid EV batteries, a product that had significant reliability and durability problems. A number failed in less than two years, and replacement after only 10,000 miles of service was required for many of them because of substantially degraded performance. Delphi has since discontinued promotion and the Ranger is now supplied with a battery from East Penn Manufacturing Co., whose characteristics are shown in *Appendix F*.

A major issue common to lead-acid technology is weight: to provide a 40-60 mile range for the Ranger EV in "real life" driving (see *Table C.1*), a battery weighing nearly 900 kg (40% of the vehicle curb weight) is needed. Other problems with the battery include decreased performance at lower states of charge (SoC), poor performance at temperatures below 0ºC, and reduced battery life at temperatures of 50ºC and above. Finally, the life-cycle cost of lead-acid batteries probably will be quite high inasmuch as the batteries' initial cost appears to be upwards of 175/kWh, and two or more replacements are likely to be required for every 100,000 miles of vehicle operation.

Ford also offered the Ranger EV with NiMH batteries but with a higher monthly lease. The characteristics of the Ranger EV and its NiMH batteries are included in *Tables C.1 and III.1*, respectively. Ford has evaluated NiMH batteries with active liquid cooling from two manufacturers. The active refrigeration cooling used in both systems brings with it cost and energy penalties[1]. The limited experience to date with NiMH battery-equipped Ranger EVs indicates that these batteries are quite rugged and durable over a limited range of ambient temperatures.

In Ford's view, the primary issue with NiMH batteries is their high cost. One leading manufacturer quoted prices of nearly $500/kWh and about $330/kWh, for guaranteed production volumes of 5,000 and 20,000 packs/year, respectively. Even true mass production (e.g. 100,000 packs/year) would lower this number only to $225-250/kWh. The energy density of about 150Wh/liter is another serious concern because it limits the Ranger EV-battery capacity to less than 30kWh and the vehicle range to about 82 miles (under the SAE J 1634 test cycle), less than 75 miles at freeway speeds, and 50-75 miles in real-world driving (see *Appendix C, Table C.2*).

Ford technical staff believes that lithium-ion EV batteries are several years behind NiMH and that they are unlikely to offer significant energy density increases or cost reductions compared to NiMH, even if current technical issues with calendar life and abuse tolerance are resolved. These problems are considered fundamental and, accordingly, thought to require major advances or breakthroughs, primarily in the active-materials area. As a consequence, Ford is not currently working on the integration and evaluation of Li ion batteries in its EVs. The company is satisfied with its participation in the USABC program that is supporting Li ion EV-battery technology development and advanced materials R&D.

Similarly, Ford is not directly involved in lithium-metal polymer EV-battery technology but relies on its participation in the USABC program. USABC has been supporting Hydro Quebec/Argo-Tech who are engaged in the world's largest program to develop lithium-metal polymer EV batteries (see also Argo-Tech and USABC subsections under Sections III.3 and III.4, respectively).

Like the other major automobile manufacturers, Ford seriously doubts that EVs with the high costs and limited range projected for 2003 can be marketed in the numbers called for by the current ZEV regulation. City cars and similar vehicles in Ford's

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[1] *The improvements in higher-temperature performance of NiMH technology reported in Section III.1 above might eliminate the need for active cooling of NiMH batteries in all but extreme temperature environments.*

"THINK!" family of small EVs—perhaps equipped with different (including lead-acid) battery choices that would allow users to trade off EV performance and cost—might find appreciable uses. However, Ford believes that despite inclusion of these new small EVs, the aggregate demand for EVs in California will fall short of meeting ARB's ZEV requirements. Consequently, even small EVs would need subsidies to attract sufficient buyers or lessees. This would result in market distortions that could hurt the longer-term prospects of such vehicles. In Ford's view, a free-market approach is needed for the introduction of ZEV and partial-ZEV vehicles.

III.4.3. General Motors

GM has remained a world leader in electric vehicle technology over the last several decades, and the development and introduction of the EV1 was originally conceived as a demonstration of that leadership. Together with the S-10 electric truck, the EV1 is now serving as GM's EV offering under its MoA with the California ARB. GM published a complete set of performance, efficiency and mileage cost data for the EV1 and S-10 operated with two types of lead-acid and a nickel-metal hydride battery; some of these data are included in *Tables C.1 and C.2.*

In keeping with GM's strategy to develop and introduce EV and other advanced-vehicle technologies in a series of steps to limit cost and risk, the second-generation EV1 is now being introduced. It has a number of technology improvements including more compact power electronic controls that represent a 75% cost reduction from first-generation control technology. The EV1 and S-10 EVs were originally delivered with Delphi lead-acid EV batteries. The experience with these batteries was disappointing inasmuch as they did not deliver their rated capacity in typical driving. As a result, EV1 range was limited to 75-80 miles in various city and highway test cycles, 50-75 miles in "real world" driving. The corresponding ranges for the S-10 electric truck were lower than for the EV1 by a factor that exceeded the 1.67 ratio of the two vehicles' gross vehicle weights. The substitution of the Panasonic EV-1260 lead-acid battery in late 1999 increased the range of both vehicles by 30-40% for a 10% increase in battery weight.

EV1 range with the Panasonic lead-acid battery exceeds 100 miles in test cycles, although real-world range is typically less at about 65-95 miles (see *Table C.1*), depending on driver behavior.

Since fall 1999, both vehicles are also available with a GMO 77Ah, 343V NiMH battery having the characteristics outlined in *Table III.1*. For a 12% lower weight, the NiMH battery permits an average range increase of 40% over the best lead-acid battery—approximately the advanced battery's increment in capacity. It is noteworthy that the NiMH-powered EV1 delivers a range of almost 150 miles, although it must be noted that the battery accounts for nearly 40% of the vehicle's curb weight. According to GM, in real-world driving, ranges of 75-140 miles are expected, depending primarily on driver and terrain, and on the electricity consumption of auxiliary equipment, especially the air conditioner.

Recently, GM recalled the Generation-1 EV1 vehicles because of an overheating problem with a capacitor in the charging circuit. The problem shows that, despite extensive efforts to ensure reliability, failures are likely to occur during market introduction of new products such as EVs and EV batteries. These can be damaging to market prospects. Considering the technical and financial resources required to introduce a trouble-free new technology to the automobile market place—including product testing before launch, and follow-up on potential early field failures—only large organizations are in a position to meet the challenge.

GM's major concern is the current high cost of NiMH batteries, with no real prospects that the technology will eventually meet GM's cost target of $4,500 for a 30kWh battery (specific cost target of $150/kWh). GM ATV management noted that no developer of advanced batteries has shown a credible path to achieving this goal. Yet, an advanced battery is needed to achieve the >100 mile real-life range that, according to GM's market research in conjunction with the EV1, is important to users. Even increments of range in the >100 mile domain are considered valuable by operators of the EV1. The market importance of factors beyond cost is attested to by GM's finding that dropping the EV1 lease rate substantially did not generate many more leases.

GM concludes that, in addition to seeking continued battery-cost reductions, alternative strategies are needed to achieve cost feasibility of battery-powered EVs. Possible strategies include obtaining revenue from sale of used NiMH EV batteries, and introduction of city cars. GM believes that mandating the introduction of EVs is not a constructive step towards their commercialization and that "conventional" EVs are not a solution to the Los Angeles air-quality problem. The city car could become part of the solution, but only with a system-level change of transportation in the Los Angeles air basin.

III.4.4. USABC

The United States Advanced Battery Consortium was formed in 1991 as a collaborative program of the U.S. Federal Government (represented by DOE), the three major U.S. automobile manufacturers (represented by USCAR), and the country's electric utilities (represented by EPRI). The mission of USABC is to support and guide R&D programs to develop electric vehicle batteries with the performance, operating and cost characteristics required for commercially viable electric vehicles. The USABC programs are carried out and cost-shared by industrial organizations capable of commercializing successfully developed EV-battery technologies.

Since the program's initiation, USABC has funded the development of nickel-metal hydride, lithium-ion and lithium-metal polymer EV batteries with about $220 million, supplemented by $80 million worth of in-kind contributions from the battery developers. USABC continues to be a major factor in advanced EV-battery development because the organization represents the financial commitments of major U.S. stakeholders in EVs and EV batteries, and it benefits from the views and guidance of the stakeholders' battery experts.

The Panel met with USABC management for a discussion of the program's current focus and of the management's future perspective on advanced EV batteries. USABC program support played a major role in the evolution of two of the three NiMH technologies used in the EVs introduced under the California MoAs. USABC recently concluded its sponsorship of NiMH EV-battery cost-reduction programs with indications that NiMH materials costs could be reduced to levels close to $140/kWh. In SAFT's analysis, this materials cost translates to approximately $240/kWh for a mass-produced complete battery, compared to the USABC commercialization goal of $150/kWh and long-term target of $100/kWh (see *Table II.1*).

USABC program emphasis and support has shifted to the development of the lithium-ion and lithium-metal polymer battery technologies at SAFT and Argo-Tech, respectively. The current performance status, cost projections and outlook for commercial availability of these systems are reviewed in Sections III.2 and III.3 above. For Li Ion, the key remaining issues are calendar and cycle-life, abuse tolerance/safety, and cost (especially materials cost). For Li polymer, they are cycle-life and cost, especially manufacturing cost. These issues need to be resolved without compromising the achievement of performance targets.

Although funding from DOE has been eroding, the collaborative industry/federal government program of the USABC remains committed to pursuing the development of Li Ion and Li polymer batteries with the performance and costs required to make EVs attractive to customers. If successful over the coming 3-4 years, one or both of these programs should result in pilot-plant quantities of pre-prototype batteries that more closely approach the USABC performance and life targets. If achievement of cost goals can be projected with confidence at that time, *Figure II.1* suggests that commercial battery production could start within another four years, assuming that all technical and cost issues are resolved well before then. USABC management cautions, however, that to date no credible case has been made for battery specific costs below $175/kWh.

III.4.5. Honda

With the EV PLUS, Honda introduced the world's first modern, purpose-designed four-passenger electric vehicle with an advanced battery. The characteristics of the EV PLUS are included in *Table C.1*; approximately 280 of these vehicles are currently in service in California. Honda maintains that the EV PLUS has a highly efficient power train, with motor-controller efficiency averaging above 90% in city driving. However, as with other state-of-the-art EVs, the vehicle's range is substantially less in real-life driving than in typical test cycles due to several factors, the most important being driving conditions on public roads versus dynamometer tests, driver behavior, and the extent of air conditioning and/or heating used (see *Appendix C, Table C.2*).

All EV PLUS vehicles have the Panasonic EV Energy EV-95 NiMH battery, with the characteristics presented in *Table III.1*. The latter all fall within the envelope of the battery performance curves specified by Honda for the vehicle. In the Honda EV PLUS, the battery is liquid-cooled, and the coolant loop is integrated with motor cooling. Control of coolant flow is managed to allow for different thermal conditions, including the relative temperatures of components and coolant. The battery has a number of important safety features including charge termination triggered by a hydrogen-detection system, waterproof electric wiring, and automatic high-voltage cut-off in case of a collision. Battery box, water-cooling and other pack components add more than 10% to battery weight when modules are assembled into the battery installed in the vehicle.

Battery quality control and reliability have been encouraging for such a radically new automotive component, with a defect rate of about 1% for a production run of approximately 300 EV-PLUS batteries. Battery capacity remained above 80% for customers' vehicles used up to 32 months, but a first replacement was required for one very-high-mileage vehicle after less than two years of operation. A small number of battery packs required a special reconditioning procedure to restore capacity. Battery charge management has since been modified to incorporate a reconditioning cycle under operating conditions that can cause a temporary loss of battery capacity. Honda's evaluation of liquid-cooled 95Ah NiMH batteries is continuing. It is also carrying out testing of improved 95Ah PEVE NiMH technology, and evaluating an air-cooled 50Ah, 15kWh NiMH battery having both significantly improved charging efficiency at elevated temperatures and a higher operating temperature limit.

Honda has a long history of monitoring candidate EV-battery systems that included lead-acid, nickel-cadmium, sodium-sulfur, nickel-metal hydride, lithium-ion and sodium-nickel chloride (ZEBRA). Of the latter four systems with potential to deliver good specific energy, the ZEBRA and sodium-sulfur high-temperature (300-350°C) batteries have been eliminated, since in Honda's view they do not offer significant advantages over the other advanced technologies.

Honda has worked with several Li Ion battery developers for almost a decade and evaluated three different positive electrode chemistries. On that basis, Honda does not have an optimistic evaluation of Li Ion batteries and believes that major improvements are needed to make the technology a serious candidate for EV propulsion. In particular, Honda is concerned about capacity degradation with cycling and over time, and it sees issues with safety, including leakage of flammable electrolyte during overcharge. In addition, Honda's in-house analysis suggests that the costs of Li Ion batteries would be substantially higher than NiMH costs for comparable production volumes. Lithium-metal polymer batteries might be evaluated in the future, although Honda has questions regarding the adequacy of Li polymer battery power density.

From its experience with the EV PLUS introduction and the interaction with owners and users of the vehicles, Honda has concluded that cost, range and battery recharge time are the most important battery-related factors in the acceptance of EVs in the market place. The difficulty of the cost challenge is illustrated below, where Honda's estimates of future NiMH battery module costs (derived from detailed projections of materials costs by key materials suppliers, and from manufacturing-cost estimates provided by battery developers) are compared with Honda's battery cost-goals:

2003 projection:	\$20k / 28kWh, or \$720 / kWh	@ 1,000 packs / year
2003 projection:	\$10k / 28kWh, or \$360 / kWh	@ 10,000 packs / year
Cost goal:	\$2k / 28kWh, or ~ \$70 / kWh	

Honda's market research indicates that, despite a number of attractive characteristics, EVs with the current high-cost and performance limitations appeal only to a very limited number of customers. To overcome this market limitation, major advances or breakthroughs are required in EV costs (primarily battery but also vehicle costs), EV range (higher battery specific energy and energy density), and charging time (higher battery charge rate and charger power). Achievement of these advances over the next several years is considered highly unlikely, and the prospects for EV commercialization in 2003 accordingly very limited.

III.4.6. Nissan

Nissan's engagement in advanced technology vehicle development, driven by the company's sustained environmental commitment, goes back to the 1970s but was accelerated in response to the 1991 ZEV regulation. Test marketing of EVs began about five years ago, following a production run of 30 PRAIRIE JOY vehicles (all deployed in Japan), the world's first lithium-ion battery-powered EV. The battery was developed by Sony in a collaborative program with Nissan; it gave the PRAIRIE JOY a projected range of about 200km. Problems included a somewhat more rapid than expected loss of Li ion battery capacity over time, and some controller failures in humid climates. The controller problem has been corrected, and the capacity loss issue is being addressed in collaboration with Shin-Kobe, the current supplier of Li Ion batteries for Nissan's EVs.

The ALTRA EV—designed as a multi-purpose vehicle with reasonable performance—was Nissan's next step, taken in 1998. It is a pre-mass production vehicle to test EV (including battery) technology and gage customer acceptance. Key vehicle characteristics are shown in *Table C.1.* Similar to operators' experience with the EVs of other automobile manufacturers, drivers of ALTRAs report a real-life range that is substantially less than vehicle range in a representative test cycle (see *Table C.2*). According to Nissan, this is primarily a consequence of drivers maintaining some battery reserve capacity. If an ALTRA is driven until the battery is fully discharged, range is typically more than 100 miles.

To date, more than 220,000 cumulative miles have been driven by 30 vehicles in 53,000 (mainly short) trips followed by charging; no significant problems have been encountered. An extensive database is now being established for the ALTRA vehicles operated in Japan and California. The characteristics of the ALTRA's Li Ion battery are summarized in *Table III.3*. Reliability of the battery has been excellent to date, with no failures observed among the thousands of 90Ah cells used in Nissan's ALTRA and Hyper-Mini EVs. Nissan believes that the key challenges in the introduction of lithium-ion battery-powered EVs are cost reduction, extension of driving range, and demonstration of satisfactory durability, especially of the battery.

In the nearer term and at low production volumes (e.g. a few thousand units/year), ALTRA costs will exceed those of comparable ICE vehicles severalfold, with the battery contributing materially to the high cost. This can be inferred from *Figure III.5* (see Section III.2 above) which summarizes Li Ion battery cost projections from several developers. As can be seen from *Figure III.5*, at a module cost of around $900 per kWh for a production volume of around 3,000 packs/year, and allowing $1,200 for the cost of the electrical and thermal management systems, a 32kWh-battery would cost about $30,000—clearly far too much for cost feasibility. In mass production, Nissan believes that the costs of EVs (excluding batteries) could eventually approach the cost of higher-end ICE vehicles. Taking a $270/kWh battery module cost for a production volume of 100,000 pack/year from *Figure III.5* and a per-pack cost of roughly $600 for battery management systems in mass production, a 32kWh Li Ion battery would cost about $9,300. This approaches NiMH battery mass production costs but remains significantly above the highest cost targets discussed in Section II.2.5 above.

Nissan considers that the market for EVs with limited performance and projected high costs is nowhere near the 4% share mandated by the current regulation for 2003. With a number of performance and cost breakthroughs, it believes that ZEV technology based on more advanced batteries or on fuel-cell engines might be market-ready in the 2020-2030 time-frame. Nissan also expressed the view that it and the other major carmakers are working diligently to make their ICE vehicles cleaner. Nissan is of the opinion that regulators should regulate air quality and emission levels, not the technologies to attain them. Regulating technology runs the danger that the realities of the market place and of customer behavior are ignored, and the objectives of the regulation are thereby not achieved.

III.4.7. Toyota

Like other leading automobile manufacturers worldwide, Toyota has maintained active electric vehicle development programs for decades. In the 1990s, Toyota substantially increased its efforts to develop the RAV4EV electric and PRIUS hybrid electric vehicles and, more recently, the e-com battery-powered commuter/city car. In Toyota's view, the lack of suitable batteries has been historically the single largest barrier to the commercialization of competitive EVs. In particular, Toyota considers the specific energy, specific power and cycle life of lead-acid EV batteries to be inadequate. Even if further development improved specific power and cycle-life to the point where they ceased to be significant drawbacks, the range limitation imposed by their inherently low specific energy argues against lead-acid batteries for general EV use.

Nearly ten years ago, Toyota selected nickel-metal hydride as the battery with the most promising combination of performance, reliability/durability and safety for electric-vehicle propulsion in the then-foreseeable future. Toyota's solicitation of battery manufacturer interest in EV-battery development led to a close collaboration between Toyota and Matsushita/Panasonic, and to the formation of Panasonic EV Energy (PEVE) as a jointly owned, independent company chartered with manufacturing EV and HEV batteries. The timeliness and effectiveness of this collaboration is attested to by the fact that PEVE is now the world's leading manufacturer of batteries for state-of-the-art EVs and HEVs.

Under Toyota's MoA with ARB, nearly 500 RAV4 EVs with PEVE NiMH batteries had been delivered by the end of 1999. Key features of the RAV4 EV are included in *Table C.1*, and the characteristics of its 95Ah, 29kWh battery are shown in

Table III.1. Experience with all RAV4 EV vehicles and their batteries has been excellent. The PEVE 95Ah battery technology is fully developed and has confirmed the positive test experience with reliability and cycle-life, although in-vehicle operating data are not yet sufficient to prove that it is a life-of-car (that is, 10-12 year and >100,000 miles) battery. The main performance issues have been insufficient power at -10°C and below, and poor charge acceptance of the nickel oxide positive at elevated temperatures. However, an additive to the positive is now permitting satisfactory charge acceptance of improved NiMH batteries tested in the laboratory at temperatures as high as 55-60°C.

Because of the limited number of RAV4 EV vehicles in the field and the excellent durability of their batteries, good battery failure statistics are not yet available. The bench test data in *Figure III.1* show that EV-95 batteries retain >80% of their capacity and power beyond a simulated 100,000km (60,000 miles) range. The main battery-failure mode is a gradual rise in cell/battery internal impedance that reduces peak-power capability.

For Toyota, the biggest EV issue is now battery cost. At current production levels, a specific cost of $900/kWh can be estimated for the RAV4 EV-battery from the PEVE battery-cost learning curve (see *Figure III.3*), far in excess of the USABC targets in *Table II.1*. According to PEVE projections, module cost could decrease to perhaps $350/kWh if they were produced in substantially higher volume (e.g. 10,000 packs /year), but this is still well above any of the targets or the target costs discussed in Section II.2.5 above.

Toyota is well aware of the potential of lithium-ion batteries for higher specific energy and power than NiMH. Consequently, Toyota continues to evaluate Li Ion technology from several developers/manufacturers and is conducting advanced battery materials R&D in-house, with emphasis on non-cobalt type materials for positives. At present, durability (calendar and cycle life) and safety of Li Ion EV batteries are considered less than adequate. In Toyota's view, their cost will become lower than those of NiMH only if there is a breakthrough in the cost of key materials and components, including the cell-level electric control system necessary for Li ion batteries. At present, Li ion batteries are considered at least 5 years, and perhaps as much as 10 years, behind NiMH for EV applications.

With the limitations imposed on EVs by the current and near-term projected cost and performance of EV batteries, implementation of the 2003 ZEV regulation is not considered feasible by Toyota. EVs (and HEVs with partial ZEV credits) should be produced and offered based on market demand. Toyota will continue to explore and investigate and, if feasible, offer new types of EVs for alternative markets, such as city car/commuter vehicle applications. However, this will be a slow process since the lead times for advanced-technology vehicles and their markets are longer than those for conventional vehicles.

III.4.8. Summary

The Panel's discussions with the six major automobile manufacturers supplying the California market revealed significant differences in their approaches to the development and introduction of electric vehicles, both historically and with respect to their current EV technologies and strategies.

The most striking differences are in the manufacturers' choices of the vehicles themselves, involving seven vehicle types. These comprised a van (DaimlerChrysler EPIC), trucks (Ford Ranger and GM S-10), a sports-car-type two-seater (GM EV1), a sedan (Honda EV PLUS), a station wagon (Nissan ALTRA), and a small sports-utility vehicle (Toyota RAV 4). These vehicles also represent a wide range of EV-design philosophies and approaches, ranging from relatively straightforward conversions of trucks (Ranger and S-10) and extensive conversions of utility vehicles (EPIC and RAV4) to ground-up designs of substantially different, purpose-built cars (EV1, EV PLUS and ALTRA).

These rather large differences result in substantially different vehicle characteristics such as weight, energy efficiency and range as shown in *Table C.1*, and the differences in vehicle purpose translate to significantly different use patterns and duty cycles. As a consequence, cross-comparisons of these EV types in terms of performance and utility are not particularly useful. On the other hand, comparisons of owner/operator experience and responses should be rather revealing with respect to the vehicles' market acceptance and prospects. While such comparisons were outside the Panel's study scope, the Panel noted that for every vehicle the "real-life" range was reported to be significantly less than the range achieved in simulated test cycles (see also *Appendix C, Table C.2*). This fact has the important consequence that the battery capacity required for a desired EV range capability—and thus battery weight as well as cost—tend to be significantly higher than would be calculated from vehicle and battery test data.

The differences between the seven vehicle types above were much smaller with respect to their batteries. The trucks and the EV1 originally used Delphi lead-acid batteries of about 15kWh which limited the practical range of the trucks to 30-40 miles, and the EV1 to about 50-75 miles. Performance and durability of these batteries were considered inadequate, but an improved lead-acid battery (Panasonic EV-1260) is now providing better performance and increased range—exceeding 100 miles per charge for the EV1 under certain conditions.

Except for the Nissan ALTRA, all vehicles are available (the EPIC, EV Plus and RAV4EV exclusively) with nickel-metal hydride batteries, which have proved generally satisfactory with respect to performance. These batteries are made by three different manufacturers but have broadly similar characteristics, as shown in *Table III.1*. However, if reasonably limited to 25-30% of the vehicle weight, NiMH batteries (with a specific energy exceeding that of lead-acid by 60-75%) can provide no more than 95-115 miles highway range in test cycles, and typically at most 75-100 miles in real-world driving—well short of the 150 miles or more that, according to the suppliers of these vehicles, appear to be desired by EV owners/operators.

The most significant technical issue with currently installed NiMH EV batteries is their reduced charge efficiency at elevated temperatures. This, in turn, can cause excessive battery heating and temporary reduction of available capacity unless counteracted by active cooling of batteries during charging. Operation at significantly above room temperature shortens NiMH battery life, although field experience appears insufficient to quantify this problem. As discussed in Section III.1, recent improvements have the potential to increase the temperature tolerance of NiMH batteries to as much as 55-60°C, a substantial and practically very important advance that may permit elimination of active cooling, improve overall energy efficiency, and increase cycle life.

The Nissan ALTRA is the only EV on California roads with lithium-ion batteries. Compared to a typical NiMH battery, the Li Ion battery's higher specific energy permits a 100-kg-lighter battery despite a 10% larger battery capacity, and the ALTRA matches the range capability of NiMH battery-powered EVs, except for the EV1 (a two-seater which has an unusually large ratio of battery-to-vehicle weight of nearly 40%, as well as superior aerodynamics). The reliability of the ALTRA's battery to date is noteworthy considering its current state of development and the limited previous experience with Li Ion EV batteries. However, battery durability is not yet established, and its confirmation appears some time away (see Section III.2 above).

The other five automobile manufacturers subject to the ZEV mandate have been assessing lithium-based EV-battery technologies (primarily, Li Ion batteries) for some time, with the general conclusion that substantial advances in durability and reductions in cost are required before the performance potential of these batteries can be realized. Several of these manufacturers also consider that battery safety under abuse conditions still remains to be established. The U.S. automobile manufacturers rely largely on the USABC programs to achieve the major advances considered necessary before Li Ion and Li Polymer battery technologies are ready for deployment in EVs. In Japan, Toyota and Honda are continuing to monitor Li Ion batteries on several levels that include supporting laboratory efforts to seek improvements in battery active materials. However, none of these five automobile manufacturers appears to have a timetable for estimating the prospective commercial availability of lithium-based, advanced EV batteries.

All automobile manufacturers stress that NiMH and other advanced batteries are too expensive to permit introduction of EVs with costs acceptable to broad markets. At the current, limited-production volumes, the costs of NiMH batteries are on the order of $1000/kWh, or nearly $30,000 for a battery of representative capacity. Li Ion batteries cost substantially more, since they are produced in yet smaller numbers and with less developed fabrication processes.

In the projections of automobile manufacturers working with battery developers, the specific costs of NiMH battery modules produced in ZEV regulation-prescribed quantities are above $300-350/kWh (>$10,000-12,000 for a complete 30kWh including the required electric and thermal management systems, see Section III.1). Projected Li Ion battery costs are substantially higher in production volumes of 10,000-20,000 packs per year. Even in true mass production by automobile industry standards (e.g., annual production of >100,000 units), the specific costs of modules of either battery type are unlikely to drop below about $225-250/kWh, or approximately $8,000-9,000 for a complete 30kWh battery. These costs greatly exceed the $2,000-4,500 range mentioned by carmakers to the Panel as the target for EV batteries.

Based on the high prospective battery costs and the experience gathered with the MoA EVs and their owners/operators, all major automobile manufacturers appear to have come to the same conclusion: that EVs with the battery costs and limitations anticipated for the readily foreseeable future—at least the next 3-5 years—will find only very limited markets, well below the numbers of vehicles called for by the ZEV regulatory provisions beginning in 2003. As a consequence, these manufacturers consider that their various ZEV-regulation compliance strategies—some of them discussed with the Panel on a confidential basis—are highly undesirable since they misapply limited resources, do not result in marketable EV products and are, therefore, counterproductive to air-quality improvement objectives.

An interesting trend in EV development that appears to be gathering momentum among the major automobile manufacturers is the emergence of small city/commuter electric vehicles. Most or all of the leading developers of "conventional" EVs are working on such vehicles that typically seat two persons, weigh about 50% less than a conventional EV, and have batteries that provide ranges of up to 60 miles. Several of these (for example, Toyota's e-Com) are being evaluated in small fleets, with the number of authorized users exceeding the number of vehicles more than 10-fold. Lead-acid, NiMH, and even Li Ion batteries (Nissan Hyper-Mini) are used in capacities around 8-15 kWh to power the city/commuter mini-EVs currently being evaluated. While not specifically excluded from counting against a manufacturer's ZEV obligations, none of these vehicles meets the federal Motor Vehicle Safety Standards. Moreover, in the view of several automobile manufacturers engaged in this area, broad market acceptance of such vehicles in the U.S. is very questionable for a number of reasons, including not only their relatively high current and prospective cost, but also their inherent characteristics (small size and limited performance), and the structure of the transportation systems in U.S. cities.

SECTION IV. CONCLUSIONS

From the Panel's discussions with battery developers and major automobile manufacturers engaged in the development and evaluation of electric vehicle batteries, and based on the Panel's own analysis of the information collected in these discussions, the BTAP 2000 members have agreed on the following conclusions:

1. **Nickel-metal hydride (NiMH) batteries have demonstrated promise to meet the power and endurance requirements for electric vehicle (EV) propulsion and could be available by 2003 from several manufacturers. The specific energy of these batteries is adequate to give a practical range of around 75-100 miles for typical current EVs.**

Field experience shows that the power capability of the 26-33 kWh NiMH batteries installed in the various types of EVs deployed in California by major automobile manufacturers is generally sufficient for acceptable acceleration and speed. Bench tests, and recent technology improvements in charging efficiency and cycle life at elevated temperature, indicate that NiMH batteries have realistic potential to last for 100,000 vehicle miles. Several battery companies now have limited production capabilities for NiMH EV batteries, and plant commitments in 2000 could result in establishment of plant capacities sufficient for production of the battery quantities required under the present ZEV regulation for 2003.

Current NiMH EV-battery modules have specific energies of about 65-70Wh/kg (about 55-62Wh/kg at the pack level). These numbers represent small increases at best over the technology of several years ago, and fundamental considerations indicate that future increases of more than 10-15 % are unlikely with proven materials. If battery weight is limited to an acceptable fraction of EV total weight, the specific energy of NiMH batteries limits the range of a typical 4/5-passenger EV to around 75-100 miles on a single charge in "real-world" driving that includes use of air conditioning, heating and other electric-powered auxiliaries. This definition of driving also allows for variations in traffic conditions and driver behavior which reduce practically achievable range well below the ranges that can be attained in standardized, simulated driving cycles.

2. **Under the most favorable of the presently foreseen circumstances, and if batteries were produced in quantities of 10k-20k packs per year, the cost of NiMH batteries with sufficient capacity to give typical EV's currently deployed in California a practical range of 75-100 miles would be $9,500-$13,000. Even in true mass production by automotive industry standards, costs would not decrease below $7,000-$9,000 for NiMH batteries of this size, exceeding battery cost goals by about $5,000.**

Extensive efforts have been undertaken by the leading NiMH EV-battery developers to reduce battery cost, but high materials cost and limited production (in part still manual) have kept current specific costs at around $1000 per kWh of battery capacity. Materials cost projections, manufacturing process conceptualization, and engineering cost estimation have been used by battery developers and some carmakers to project future NiMH EV-battery production costs for increasing levels of production. From these projections, approximate module specific costs of >$300-350/kWh and >$225-250/kWh can be estimated for battery production volumes of 10k-25k and 100k packs per year, respectively. To these module costs, about $1200 and $600, respectively, must be added to account for the remaining components of a complete EV-battery which include the integrated electrical and thermal management systems, the battery tray if needed, and other hardware.

The resulting costs for complete 28-33kWh batteries would be $11,000-13,000 (10k packs/year production), $9,500-$11,000 (20k packs/year) and $7,000-$9,000 (over 100k packs/year), compared to the $2,000-$5,000 range of EV-battery cost goals. This cost range can be derived from the postulate that the target cost for the battery is the difference between the cost of motor fuel for a broadly comparable ICE vehicle and the cost of AC electrical energy used in charging the EV battery, discounted back to the present. The calculation assumes that the cost of EV minus battery in mass production will be no more than that of a complete ICE vehicle. It also assumes that the battery will last the life of the EV, a possibility supported by NiMH battery extended-test data, but not yet proven in the field.

3. **Lithium-ion EV batteries have shown good performance and, up to now, high reliability and complete safety in a limited number of EVs. However, current Li Ion EV batteries do not have adequate durability, and their tolerance of severe abuse is not yet fully proven. Li Ion batteries meeting all key requirements for EV propulsion are not likely to be available in commercial quantities before 2005. Moreover, the early costs of these batteries are expected to be considerably higher than those of NiMH EV batteries. Even in mass production volumes on the order of 100,000 packs per year, Li Ion battery costs are unlikely to drop below those of NiMH without major advances in materials and manufacturing technology.**

The Li Ion batteries in the limited number of EVs deployed so far have performed well and shown excellent reliability and complete safety. However, the test data of all major Li Ion EV-battery development programs indicate that the operating life of current technology is limited, in most cases, to 2-4 years. Current Li Ion EV batteries exhibit various degrees of sensitivity when subject to some of the abuse tests intended to simulate battery behavior and safety under high mechanical, thermal or electrical stresses. Resolving these issues, producing pilot batteries and evaluating them in vehicles, and fleet-testing prototype Li Ion batteries that meet all critical requirements for EV applications is likely to take at least 3-4 years. Another 2 years will be required to establish a production plant, verify the product, and scale up to commercial production.

Based on cost estimates provided by developers and the Panel's own estimates, Li Ion batteries will be significantly more expensive than NiMH batteries in production volumes of about 10,000 packs per year. Even at much larger volumes, Li Ion EV batteries will cost less than NiMH only if substantially less expensive materials become available and after manufacturing technology combining high levels of automation, precision and speed has been developed.

4. **Lithium-metal polymer batteries are being developed in two programs having as their objectives technologies that would meet all requirements for EV propulsion and cost $200/kWh or less in volume production. However, these technologies have not yet reached key technical targets, and it is unlikely that the steps required to actualize commercial availability of batteries meeting the requirements for EV propulsion can be completed in less than 6-8 years of successful programs.**

Argo-Tech in Canada (co-funded by USABC) and Bolloré in France are developing rechargeable battery systems that, because of the batteries' unique polymer electrolyte, can use metallic lithium as the negative electrode and thus might attain higher specific energy and, possibly, lower cost than Li Ion EV batteries. The two programs are carried out by organizations not originally connected to the battery industry, and both are developing their own unconventional, thin-film cell/battery manufacturing techniques. Both programs have made important progress toward practical battery configurations and performance (including improved cycle life) and have adopted manufacturing techniques that appear to offer potential for low-cost manufacturing.

However, cycle life is still a difficult issue, and the development of the high-precision, high-speed manufacturing processes needed for low-cost mass production of reliable thin-film batteries presents many challenges. Achievement of adequate cycle life, and completion of the steps from the current pre-pilot cell fabrication stage to a fully tested EV-battery produced in commercial quantities, are likely to take at least 6-8 years even if the programs realize rapid advances. While Li Polymer EV batteries potentially could cost less than NiMH and Li Ion EV systems, achievement of lower costs will depend critically on the successful development of low-cost cell designs and manufacturing processes in the years ahead.

APPENDIX A

ELECTRIC VEHICLE BATTERY INFORMATION QUESTIONNAIRE

1. QUESTIONS FOR BATTERY DEVELOPERS AND SUPPLIERS

Please provide the best available data and information on the following aspects of the BTAP 2000 survey. Please provide data on full EV size batteries and for individual modules (including kWh rating as well as capacity and voltage of full battery and individual modules) to which the data below apply.

I. Battery System Characteristics

1. **Cell Electrochemistry**
   a) Cell composition (cathode [positive electrode], anode [negative electrode], electrolyte, separator)
   b) Electrochemical reactions (charge and discharge; overcharge)
   c) Cell voltage (min, max, and average during C/3 discharge)
   d) Theoretical energy density based on all active materials

2. **Cell and Battery Configuration**
   a) Cell configuration (shape and winding/stacking arrangement; dimensions)
   b) Module configuration (smallest unit; i.e. single cell, 4-cell block etc.)
   c) Module voltage, capacity, volume, weight
   d) Cooling approach
   e) Battery management approach (mechanical; thermal; electrical)

3. **Energy and Power Characteristics**
   a) Specific energy and energy density at C/3 discharge rate
   b) Specific energy and energy density at C/ discharge rate
   c) Maximum pulse power for 3 and 20 seconds for new battery (please provide data for 20°C, 0°C and -20°C)
   d) Maximum pulse power for 3 and 20 seconds after deep cycling, for example after 100 and 500 80% DoD cycles (please provide data for 20°C, 0°C and -20°C)

4. **Additional Performance Characteristics**
   a) Recommended charge rate
   b) Minimum charge time to 80%SoC at 40°C, 20°C, 0°C, and -20°C
   c) Roundtrip energy efficiency at the recommended charge rate for C/1 and C/3 rate discharges
   d) Self discharge rate at 100% SoC at 40°C and 20°C

e) Self discharge rate at 80% SoC at 40°C and 20°C
f) Irreversible capacity loss during 1 year storage of fully charged battery (please provide data for different storage temperatures, e.g. 40°C and 20°C)
g) Irreversible capacity loss during 1 year storage at 80% SoC and 0% SoC (please provide data for different storage temperatures, e.g. 40°C and 20°C)

Please comment and provide data if available on the change in any of the above characteristics after 100 and 500 80% DoD cycles.

5. Cycle Life and Reliability

a) Average cycle life achieved at the recommended charge rate for a C/3 discharge rate to 80% of initial capacity, at 20°C and 40°C.
b) Cycle life statistical data on modules with similar designs.
c) Best cycle life achieved for a module discharged to 80% of initial capacity (please state under which conditions this was accomplished)
d) Average battery cycle life projected for calendar years 2000 and 2002
e) (please provide supporting data for these projections)
f) Please comment on the relative importance for your battery technology
g) of each of the following potential failure modes:
    - Capacity fading of positive electrodes
    - Capacity fading of negative electrodes
    - Internal short circuit
    - Open cell
    - Cell dryout
    - Cell imbalance within a battery
    - Rise in impedance
    - Drop in charge acceptance
    - Thermal management failure
    - Electrical control failure
    - Other failure modes (if important)

II. Experience with In-Vehicle Testing of Batteries

1. Specific energy and energy density of battery as installed in vehicle
2. Charging rate and methodology
3. Maximum power achieved for battery as installed
4. Average calendar time and mileage to failure for batteries used in vehicles.
5. Most common failure modes observed for batteries used in vehicles.
6. Experience with battery management:
   a) Thermal
   b) Electrical
   c) Mechanical

III. Battery Cost

On a strictly confidential basis, please provide data and/or best current estimates for:

1. Cost of producing complete EV batteries in present (1999) volume
2. Present production rate in modules and/or packs per year
3. Prospective year 2003 price to OEM for 1000 and 10,000 packs per year
4. Prospective year 2006 price to OEM for 10,000 and 100000 packs per year (please explain basis for these projections)
5. Largest 4-5 materials cost contributions to battery cost for III.1., 3. and 4.
6. Cost of thermal and electrical management systems for III.1., 3. and 4.

IV. Business Considerations and Issues

On a strictly confidential basis, please provide your perspective on the following questions and issues:

1. What technical and cost barrier(s), if any, need to be overcome to enable battery production and commercialization? How much time and money will be required to overcome these barriers?
2. What is your current plan for commercialization of EV batteries, and which timetable for the major commercialization milestones and decisions do you foresee and/or advocate?
3. What business arrangements with car companies are contemplated and/or desired to move EV-battery commercialization forward?
4. What is the battery cost level considered necessary for good commercialization prospects?
5. What is the minimum sales/production volume needed to achieve the necessary cost level?
6. What is the investment required for the minimum production volume?
7. What do you consider the most important impact(s) of the California ZEV mandate on the prospects for EV-battery commercialization?
8. Do you foresee and/or advocate any other government intervention in the US or elsewhere that could help establish a viable market for EV batteries?
9. Are you now pursuing, or considering to pursue, markets for batteries similar in size and design to your EV batteries? Do you see a realistic possibility of battery production volume and cost synergism between this market and the EV-battery market?
10. Do you foresee realistic market opportunities for used EV batteries if these batteries meet the requirements for applications less demanding than EV service? Which application could be considered?

2. QUESTIONS FOR AUTOMOBILE MANUFACTURERS

Please provide the best available data and information on the following aspects of the BTAP 2000 survey:

I. EXPERIENCE WITH BATTERIES PRESENTLY IN PUBLIC AND/OR RESTRICTED USE IN ELECTRIC VEHICLES MANUFACTURED BY YOUR COMPANY

Electric Vehicle Characteristics

a) Weights (without payload; with representative payload)
b) Performance (acceleration, top speed, hill climbing capability)
c) Efficiency (kWh consumption for representative driving cycles, with and without space conditioning equipment operating)
d) Special characteristics (if any) affecting battery specifications

Battery Specifications

a) Battery type and weight
b) kWh capacity, module capacity, cell size
c) Performance (specific energy and energy density at different rates; specific power as function of depth of discharge)
d) Charging characteristics (typical kWh consumption for full charge; normal charging rate and efficiency; maximum charging rate; efficiency at maximum rate)
e) Thermal characteristics (battery temperature limits for charging and for discharge; cooling and heating requirements and implications for battery weight, volume and cost)
f) Control and safety systems
g) Reliability and abuse tolerance
h) Calendar and cycle life

Batteries Characteristics (during and after use in electric vehicles)

a) Usable battery capacity
b) Performance (specific energy and energy density at different rates; specific power as function of depth of discharge)
(when new; after extended operation, e.g., >100 cycles and >½ year)
c) Charging characteristics (efficiency at normal charging rate; maximum charging rate; efficiency at maximum rate)
d)Thermal characteristics (practical temperature limits for charging and for discharge; experience with cooling and heating requirements and implications for battery weight, volume and cost)
e) Control and safety systems experience

f) Reliability and abuse tolerance (key factors and experience)
g) Calendar and cycle life experience

II. BATTERIES UNDER EVALUATION OR CONSIDERATION FOR EV APPLICATION

- Battery types currently under evaluation in vehicles and/or on test stands
- Ratings and performance [questions I.3. a)-b), above]
- Charging and thermal characteristics [questions I.3. c)-d), above]
- Control and safety systems
- Reliability and abuse tolerance
- Calendar and cycle life
- Plans for demonstration of these batteries
- Batteries under consideration for future evaluation

III. COST OF BATTERIES

- Cost goal(s) (as functions of battery capacity and life; for different purchase volumes)
- Cost of batteries used in recently and currently produced EVs:
  a) for actual numbers purchased
  b) if purchased in 1000s per year
- Costs projections for purchases of batteries under consideration for 2003 model year EVs:
  a) in 1000s per year
  b) in 10,000s per year
- Costs projections for large-scale purchases of batteries after 2003:
  a) in 10,000s per year
  b) in 100,000s per year

IV. TECHNICAL AND COST ISSUES NEEDING RESOLUTION FOR EV BATTERIES

- Performance (prospects for achieving goals)
- Reliability (prospects for achieving goals)
- Abuse Tolerance (prospects for achieving goals)
- Controls and Safety (prospects for achieving goals)
- Testing and Demonstration (resources and time required)
- Manufacturing Development (resources and time required)
- Manufacturing (schedules, decision points, needed investments)
- Costs (prospects for achieving goals; cost learning curves; etc.)

V. BARRIERS AND STRATEGIES FOR EV-BATTERY COMMERCIALIZATION

- EV market size as function of performance and cost
- Possible strategies for overcoming commercialization barriers
- Role of, and prospects for formation of alliances between automobile manufacturers and developers/suppliers of EV batteries
- Prospects for availability of marketable EV batteries and EVs for implementation of ZEV regulations in the 2003 model year
- Prospects for EV-battery and EV commercialization beyond 2003

APPENDIX B

ORGANIZATIONS VISITED BY BTAP 2000

1. North America

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APPENDIX C

CHARACTERISTICS OF MOA ELECTRIC VEHICLES

Table C.1. Specifications of EVs Deployed in California

	EPIC	RANGER EV*	EV-1*	S-10 EV*	EV PLUS	ALTRA	RAV4E V
Manufacturer	Daimler Chrysler	Ford	GM	GM	Honda	Nissan	Toyota
Vehicle type	van	small truck	sports car	small truck	family hatchback	family hatchback	small SUV
Curb mass (kg)	2270	(2150); 1960	(1400); 1350	(2340); 2340	1620	1700	1560
Wheelbase (cm)	287	283	250	274	252	280	240
Battery type	NiMH	(PbA); NiMH	(PbA); NiMH	(PbA); NiMH	NiMH	Li Ion	NiMH
Battery cooling	Air	Water	Air	Air	Water	Air	Water
Capacity (kWh)	33	(18.7); 28.5	(19.7); 26.4	(19.7); 27.4	28.8	32	28.8
Battery mass (kg)* **	600	(870); 485	(594); 520	(622); 578	449****	360	449****
Range (miles)**	70-85	(40-60); 60-80	(65-95); 75-140	(40-55); 65-80	60-80	80+	70-90

* Numbers in parentheses are for lead-acid versions which are technically not MoA Vehicles
**Expected "real-world" range according to EV manufacturers
***Battery weights provided by EV manufacturers include the weights of modules and module thermal & electrical control/management systems.
****Does not include hardware required for installation of battery in the vehicle

Table C.2. Energy Use and Range Estimates for California MoA EVs with Advanced Batteries

		EPIC EV		Ranger EV		EV1		S-10		EV PLUS		ALTRA		RAV4 EV	
	Manufacturer:	DaimlerChrysler		Ford		GM		GM		Honda		Nissan		Toyota	
		City	Hwy	City	Hwy	City	Hwy	City	Hwy	City	Hwy	City	Hwy	City	Hwy
1	**Nominal battery capacity (kWh)**	33		28.5		26.4		27.4		28.8		32		28.8	
2	**ARB test cycle range (miles)***	92	97	94	86	143	152	92	99	125	105	120	107	142	116
3	**ARB (except for Nissan) test cycle energy usage (Wh/mile)**	359	340	303	331	185	174	298	277	230	274	238	263	203	248
4	**Practical "real-world" range:**														
a	Assuming 80% of test cycle**	74	78	75	69	114	122	74	79	100	84	96	86	114	93
b	Assuming 70% of test cycle***	64	68	66	60	100	106	64	69	88	74	84	75	99	81
c	Carmaker data	70-80		50-75		75-140		65-80		60-80		80+		70-90	
5	**AC usage (Wh/mile):**														
a	Calculated assuming AC = 1.5 x DC Energy	539	510	455	497	278	261	447	416	345	411	n/a		305	372
b	Carmaker data	n/a		485		330		560		n/a		297	319	333	
c	Southern California Edison data	526		434		n/a		n/a		384		400		400	
6	**Calculated actual AC to DC ratio********	1.47	1.55	1.60	1.47	1.78	1.90	1.88	2.02	1.67	1.40	1.25	1.21	1.64	1.34
7	**EV efficiency (miles/kWh)**	1.85	1.95	2.2	2.0	3.6	3.8	2.2	2.4	2.9	2.45	2.5	2.25	3.3	2.7

* Source: ARB Preliminary Draft Staff Report, May 31 workshop, ZEV 2000 Biennial Review, p.14
** Assumes 10% range reduction for auxiliary power consumption, 10% reduction for driver/traffic factors
*** Assumes additional 10% range reduction to provide reserve
**** Calculated by dividing lines 5b or 5c by line 3

APPENDIX D

REPRESENTATIVE BATTERY ABUSE TESTS

Table D.1 below summarizes the abuse tolerance tests that are typically applied to EV cells, modules and packs. For many of these tests, more specific parameters are still evolving, as are pass/failure criteria. In the ideal scenario, the battery will remain intact, will not emit any effluent (gas or liquid), and will not catch fire. However, under many mechanical tests, mechanical deformation (but no "flying pieces") is allowed, and smoke, liquid, and gas emission (but no fire) are acceptable under several other abuse conditions.

Table D.1. Typical Abuse Tests for EV cells and modules

TEST	*CONDITIONS*
A. MECHANICAL	
Drop	10-meter onto cross-wise 150-mm cylinder
Roll over	90° increments with 1-hour hold
Static crush	To 85% and 50% of original dimension
Shock half-sine	25 to 35 g for 30 to 60 msec
Steel rod penetration	3-mm into cell or 20-mm into module
Sea water immersion	Complete immersion for 2 hours
B. THERMAL	
Radiant heating	10-minute to 890°C
Thermal control failure	Overheat after disabled thermal control
Thermal heating	Slow heat to 200°C
Thermal storage	Two months in up to 80°C
Thermal shock	-40°C to 80°C five cycle
Low temperature (electrolyte freeze)	Operate down to -40°C
C. ELECTRICAL	
External Short-circuit	With or without passive protection
Internal Short-circuit	By nail or crush (multiple cells)
Overcharge	100% of nominal capacity, protection disabled
Overdischarge	To reversal, with voltage control disabled

APPENDIX E

EV-BATTERY COST TARGET ALLOWANCE

In the table below, target battery costs are calculated as the Net Present Value (NPV) of the EV's energy cost savings (cost of fuel minus cost of electricity) over its assumed 10-year life, for a range of values of the key parameters. The basic assumptions are that the cost of the EV excluding the battery is equal to the cost of an ICE vehicle, and that the battery and the EV last for 10 years, and have no residual value at the end of their 10 year life[1].

Table E.1. Net Present Value (NPV) of EV Energy Cost Savings

	Annual miles	Gasoline Energy		Electric Energy		Energy Saving NPV
	Thousand miles	Cost \$/gal	Efficiency miles/gal	Cost \$/kWh	Efficiency miles/kWh	\$
Typical Current Parameters	10	1.33	15	0.05	1.8	4,569
	10	1.67	15	0.05	1.8	6,270
	10	1.67	24	0.05	2.2	3,511
	10	1.67	24	0.05	2.7	3,834
	10	1.67	24	0.05	3.2	4,051
	10	1.67	24	0.10	2.2	1,800
	10	1.67	24	0.10	2.7	2,445
	10	1.67	24	0.10	3.2	2,881
'EV-1'	10	1.67	30	0.05	4	3,239
	10	1.67	30	0.10	4	2,301
Nearer-Term Scenarios Favorable to EVs	12	1.67	27	0.05	2.7	3,904
	12	1.67	27	0.05	3.5	4,284
	12	2	27	0.05	2.7	5,005
	12	2	27	0.05	3.5	5,384
Longer-Term Scenarios Favorable to EVs	15	2	30	0.05	5	6,379
	15	2	35	0.05	5	5,307
	15	3.34	35	0.05	4	9,335
	15	3.34	35	0.05	5	9,617
Europe 2000	10	4	30	0.15	3.5	6,787

Assumptions: A. Battery life = 10 years; B. Inflation rate = 3%; C. Interest rate = 8%

[1] *The Panel was informed about ongoing studies trying to assess the possible residual values of EV batteries beyond covering the cost of collection and disposal. The general idea is to use these batteries in secondary, less demanding applications after they no longer meet EV power requirements. A major uncertainty in any such assessment is whether failed EV batteries can have adequate residual life to be of tangible value for secondary applications such as uninterruptible power, solar photovoltaic distributed power, and the like. Other questions surrounding this idea concern the collection, reconditioning, distribution and warranty costs of used EV batteries; the degree to which used-battery market(s) can match the number of discarded batteries; and at what point in the future markets with predictable price(s) might develop. The Panel was not presented data that would allow these questions to be answered and residual values of failed EV batteries to be estimated. We note, however, that any value that is realized needs to be discounted over the 10-year primary life assumed for the EV battery. On that basis alone, it is unlikely that a residual value substantial enough to affect the overall battery cost targets can be realized.*

APPENDIX F

LEAD-ACID AND NICKEL-CADMIUM EV BATTERIES

1. LEAD-ACID BATTERIES

The majority of electric vehicles currently in service are powered by lead-acid batteries which are used almost exclusively in industrial motive-power applications. Forklift trucks, mining locomotives, airport ground equipment, and other off-road applications use "industrial-grade" lead-acid batteries. These batteries have relatively low specific energies (about 25 Wh/kg), as a consequence of their thick flat or tubular positive-plate, flooded-electrolyte designs that enable them to provide up to 1500 deep-discharge cycles over a 5-10 year lifetime at an initial cost of $150-200/kWh. Less robust lead-acid battery designs, having thinner plates, more in common with automotive starter battery construction, are used to power the large number of electric golf carts, personnel carriers and similar vehicles that are in service in the United States. This type of battery, also with flooded electrolytes, typically delivers 200-300 deep-discharge cycles over a 3-year period at specific energies of about 30 Wh/kg and costs of $75-100/kWh.

The renewed interest over the last decade in on-the-road electric vehicles (EVs), has stimulated efforts to make the lead-acid battery—a well-established albeit in several respects limited EV-battery technology—a more attractive candidate for this application. Probably the most important recent innovation in lead-acid battery technology has been the development of the so-called valve-regulated lead-acid battery (VRLA) that uses low-gassing lead grid alloys and starved electrolyte designs that permit internal gas recombination, thus eliminating the need for periodic water addition. The sulfuric-acid electrolyte in VRLAs is immobilized, either in an absorptive-glass-microfiber (AGM) separator or, less commonly, as a gel. Another important innovation is the continuous production of lead-grids, which facilitates the manufacture of thin uniform plates that permit higher battery power. Because of the good specific power of VRLA battery designs and the large weight of the batteries used for EV propulsion, total battery power and the acceleration capability of EVs with such batteries is not normally an issue except near the end of discharge and at low temperatures.

To encourage lead-acid battery manufacturers to utilize these developments and to provide continuing financial support for generic technology-advancement research, the Advanced Lead-Acid Battery Consortium (ALABC) was founded in 1992 by an international group of battery companies and suppliers to the lead-acid battery industry. Partly as a result of ALABC efforts, several manufacturers now offer and sell small quantities of VRLA batteries specifically designed for the EV application. The best of these have specific energies of about 35 Wh/kg and on-the-road service lives of 300-400 cycles (up-to-1000 cycles under laboratory conditions) over 2-3 years. Their costs are generally (and sometimes significantly) above $175/kwh. These costs reflect low volume and heavy emphasis on quality control and are projected to be reducible to the $100-150/kwh range for production levels above 10,000 EV-battery packs/year. Importantly, ALABC-sponsored research established that VRLA batteries for EV applications can be partially recharged very rapidly, for example to the extent of 50% in 5 minutes, and 80% in 15 minutes.

Prominent manufacturers of VRLA EV batteries presently include East Penn Manufacturing and UK-based Hawker in the United States, and Matsushita (Panasonic) in Japan. Also of interest since they are used in a limited number of EVs produced by small manufacturers are the VRLA batteries of Optima, a relatively small Swedish-owned U.S. company. In contrast to the conventional flat-plate designs of other VRLA EV batteries, Optima batteries are composed of cylindrical, spiral-wound cells. While apparently demonstrating somewhat lower cycle lives under actual service conditions, Optima batteries are reported to be available for less than $100/kWh. Finally, several European battery companies including VARTA, Exide, and FIAMM, offer VRLA batteries for EVs, some based on the gelled-electrolyte design that has a good record in deep-cycle applications.

Table F.1 shows the most important characteristics of three VRLA EV-battery modules used in EVs in the United States.

Table F.1. Characteristics of VRLA EV-Battery Modules

Manufacturer	East Penn	Matsushita	Optima
Model	UX 168	EV 1260	D 750S
Voltage (V)	8	12	12
Capacity (Ah)	85	60	57
Weight (kg)	19	21	19
Volume (l)	7.9	7.9	8.9
Specific Energy (Wh/kg)	36	34	36
Energy Density (Wh/l)	86	91	80
Specific Power (W/kg) At 50% DoD	180*	315**	280**
Specific Power (W/kg) At 80% DoD	43*	215**	220**
Source	Major Auto Co.	Manufacturer	Manufacturer

* 30-second pulse

** 10-second pulse

Three of the EVs deployed in California under the MoAs with the Air Resources Board are or were available with VRLA batteries as one option. As noted in *Appendix C, Table C.1*, the GM EV1 two-seater and S-10 small truck were originally equipped with a Delphi VRLA battery but performance and life of this battery proved disappointing. In late 1999, GM switched to the Panasonic EV-1260 battery (see *Table F.1* above), which is now providing much improved EV performance, especially in range. On the basis of laboratory data that show a 1,000 DST cycle capability, the batteries are expected to have improved cycle life although life data are still lacking at this early date. Operating temperature range is -20°C to +50°C, but, as with all lead-acid batteries, power (including regenerative power) is seriously reduced at the lower temperatures.

The Panel visited Panasonic for a discussion of the technology and inspection of the company's limited-scale VRLA EV-battery manufacturing facility. The EV-1260 module is the main product but shorter modules of 28 and 38Ah using the same plates are also produced; these are intended for smaller EVs. Manufacturing is based on standard VRLA technology, but facility and operation are designed for high-quality manufacturing and uniformity of product. For example, considerable effort is put into sorting electrodes by weight to get uniform stacks.

Panasonic sold approximately 18,000 modules in 1999 and expects similar sales in 2000. At this production level, module cost (i.e. price to EV manufacturers) is about $350/kWh. For 2003, the company projects production of 50,000 to 85,000 modules (approximately 2000-3000 EV-battery packs) at an approximate cost of $275/kWh. Cost would decline further with increasing production rate, to perhaps $200/kWh and $120/kWh at 5,000 and 15,000 packs/year respectively.

Ford uses a VRLA battery manufactured by East Penn Manufacturing in the Ranger EV. Performance characteristics of this battery are generally similar to that of the Panasonic EV-1260, but life of the battery can be as short as 10,000 miles when Rangers are driven only short distances in some climates, despite the fact that batteries can deliver about 600 cycles on the test stand. The cost of the East Penn battery is currently about $175/kWh, with the prospect of declining to $135/kWh at production levels above approximately 1,500 packs/year.

Small specialist EV manufacturers such as Solectria and AC Propulsion, and numerous electric-vehicle conversion enthusiasts also rely on one or the other of these VRLA batteries in the EVs manufactured by them.

A radically different approach to increasing specific energy and power of the VRLA lead-acid batteries has been taken by the small U.S. company Electrosource in its development of the "Horizon" battery. The key new feature of this battery is the use of grids woven from glass fibers covered with a thin extruded lead coating; a second unusual feature is the technique of making electrical connections between plates with continuous strands of the grid fibers. This design permit specific energies of about 40 Wh/kg at the substantial discharge rates typical for the EV application. Costs, although currently high because of low-volume production, may have potential to be lower than for most other lead-acid batteries because of the battery's reduced requirement for lead. The Horizon battery was once a candidate for use in DaimlerChrysler's EPIC electric van, but its development is now directed toward hybrid EVs and a new class of "street-legal, low-speed" electric mini-cars aimed at applications in restricted traffic zones.

Outlook. While the new VRLA EV batteries can provide acceptable performance in on-the-road electric vehicles, they are still handicapped by their low specific energy that limits the range per charge in any vehicle having a not unreasonable proportion (25-30%) of its weight allocated to batteries. If the capacity of the battery were increased substantially, the increased weight and volume would force vehicle redesign including mechanical reinforcement of the EV. As a consequence, range does not increase proportionally with capacity because of the additional weight contributed by the battery. The fast partial-recharge feature of VRLAs does, of course, partly offset the problem of limited vehicle range, but does not dispel the "running-on-empty" syndrome that affects EV operators faced with an unexpected trip away from charging facilities.

Another disadvantage of VRLA and other lead-acid batteries is that they appear to offer no possibility of providing a "lifetime" vehicle battery (nominally 10 years or more) for EVs. Since one or two replacements are likely to be required during the EV's service life, the lead-acid battery's initial cost advantage over other advanced batteries will be greatly diminished—not to mention the associated inconvenience and high labor cost. It seems clear also that the price of the replacement battery to the EV owner will be substantially higher than the original battery cost to an OEM. Other concerns include the adequacy of performance at low temperatures, the possibility of hydrogen explosions under abusive charging conditions, and of battery failure through plate "sulfation" if left in a discharged condition. In combination, these factors have limited the major auto companies' interest in lead-acid EV batteries and motivated the creation of USABC to foster the development of advanced batteries with much higher specific energies.

2. NICKEL-CADMIUM BATTERIES

Although rarely encountered in countries outside continental Western Europe, on-the-road EVs powered by nickel-cadmium batteries are prominent in France. Over the last five years, the major automakers, PSA (Peugeot/Citroën) and Renault, and some smaller companies have converted several thousand conventional IC-powered small cars to electric drive with Ni/Cd batteries. These EV batteries are manufactured by SAFT in a small (2,000 packs/year capacity) dedicated factory that was partly financed by PSA, Renault, and the French government.

The SAFT Ni/Cd EV-battery has a 5-cell monoblock construction, giving a 6-volt module with an energy storage capacity of about 600 Wh. Its specific energy in an EV-battery pack—at 45-50 Wh/kg—is significantly greater than that of VRLAs, even after inclusion of a single-point watering system for infrequently required maintenance. However, at approximately $600/kwh its costs are much higher. Due to the inherently high discharge-rate capabilities of nickel-cadmium batteries, the acceleration of EVs powered by a typical 12kWh pack is good. The ranges achieved per charge are generally comparable to those of EVs powered by somewhat larger VRLA batteries.

Outlook. Nickel-cadmium batteries have excellent cycle life and in normal operation can be expected to last the life of the EV. However, higher initial costs and a lower energy density than those projected for advanced batteries are significant disadvantages. Widespread use of Ni/Cd batteries in EVs is unlikely also because of perceived limitations in the supply of cadmium. Finally, a major concern is the effect on the environment and health that might result from such a large increase in the use of a metal that is generally considered as toxic. In view of these concerns, SAFT is no longer investing in efforts to improve the technology but is focusing on the development of nickel-metal hydride and lithium-ion EV batteries, as is described in Section III of this report.

APPENDIX G

ELECTROFUEL MANUFACTURING COMPANY

Electrofuel Manufacturing is a Canadian company founded in 1983, with business interests in ceramic materials and production equipment, and batteries. A subsidiary, Electrofuel Inc., was founded in 1996 to commercialize the Li Ion battery technology of Electrofuel Manufacturing.

The Panel visited Electrofuel after the company had attracted attention with the claim of very high specific energy for its "Lithium-ion SuperPolymer Battery". The Electrofuel technology utilizes conventional $LiCoO_2$ positive electrodes and graphite negative electrodes, but with a claimed unique polymer (probably gel-type) electrolyte. Electrofuel stated that it is producing a 14.8V, 11Ah flat pack, notebook-computer battery prototype with a claimed specific energy of 160 Wh/kg, higher than any other commercial Li Ion battery.

However, the Panel was not shown the company's facilities for R&D or manufacturing, nor was it given any performance, cycle life or safety data beyond the limited information that had already been published in the company's brochures and press releases. Consequently, the Panel was unable to assess the Electrofuel technology's prospects for EV-battery development. In late 1999, Electrofuel was awarded a first-phase USABC contract intended to establish whether the Electrofuel technology provides a technically feasible basis for development of an EV-battery.

APPENDIX H

VARTA AG

Company Background and Organization. Because of VARTA's prominence in the battery industry and its earlier participation in USABC-sponsored programs to develop NiMH and Li Ion batteries for EVs, the Panel visited VARTA at its Hanover, Germany headquarters to ascertain the company's views on the prospects of advanced battery technologies for EV applications.

Traditionally one of the world's most diversified and technically advanced battery companies, VARTA has recently narrowed its product lines to concentrate on automotive batteries (in a joint venture owned 20% by Bosch) and in a separate, wholly owned company, on portable batteries. As part of this reorganization, VARTA's highly reputed R&D center was closed, and a new organization, NBT-VARTA, was established at Hanover to develop advanced batteries for future automotive applications. NBT-VARTA was the host for the Panel's visit.

Activities at NBT-VARTA. NBT-VARTA is developing NiMH and Li Ion battery systems for three vehicle categories: high-energy batteries for pure EVs, high-power designs for HEVs with significant electrical range, and ultra-high-power designs for power-assist HEVs. NBT-VARTA has completed NiMH battery designs for all three applications, and Li Ion designs for the high-energy and ultra-high-power applications. Nevertheless, at present the company has discontinued the high-energy battery development because of the lack of interest in EV batteries by potential automotive industry customers. However, NBT-VARTA would consider producing NiMH batteries for pure EVs in response to an order by a car company.

In NBT-VARTA's view, the outlook for the high-power and ultra-high-power batteries is more promising, and active development of such batteries for both HEV applications and the future 42-volt electrical systems of conventional powered vehicles is continuing.

NBT-VARTA's Assessment of Battery Technologies, Performance and Cost. NBT-VARTA has a generally favorable opinion of NiMH batteries, citing their good cycle- and calendar-life, abuse tolerance, power capability and (relative to lead-acid) specific energy. Potentially a "lifetime" battery for a car, the NiMH systems' major and seemingly insurmountable drawback is seen to be its high cost.

The Li Ion system promises somewhat higher specific energy than NiMH, but is less developed, with operating life and abuse tolerance not sufficiently proven to date. Designs based on $LiMnO_2$ positives have been found to have a calendar life of less than three years. The $LiNiCoO_2$ variant has shown somewhat better (but still unquantified) life capability, but presents significant safety issues, at least in designs suitable for pure EVs. NBT-VARTA also has concerns about the fast-charge capability of the Li Ion system. Finally, in NBT-VARTA's view, the costs of Li Ion will not be lower than those of NiMH, even in volume production.

In summary, NBT-VARTA is skeptical about the prospects of EVs but believes that markets will develop for advanced batteries in HEVs and in 42-volt electrical systems for ICE-powered vehicles. At present, NiMH appears to be the advanced battery with the best prospects for these new applications.

REFERENCES

(1) F. R. Kalhammer et al., *Performance and Availability of Batteries for Electric Vehicles: A Report of the Battery Technical Advisory Committee*, California Air Resource Board, (1995).

(2) F. R. Kalhammer, *Batteries for Electric and Hybrid Vehicles: Recent Development Progress*, California Air Resource Board (1999).

(3) T. E. Lipman, *The cost of Manufacturing Electric Vehicle Batteries*, U.C. Davis -ITS-RR-99-5, (1999).

(4) D. Linden, *Sealed Nickel-Metal Hydride Batteries*, Chapter 33 in *Handbook of Batteries,* D. Linden, editor, 2nd edition (1994).

(5) H. Takeshita, *Global Battery Market Trend'*, in *Proceeding of the 17th International Seminar on Primary and Secondary batteries*, Florida (2000).

(6) T. Nagura, in *Proceeding of the 3rd International Battery Seminar*, Florida (1990).

(7) K. Ozawa, *Solid State Ionics*, 69, page 212 (1994).

(8) M. B. Armand, *Solid State Ionics*, 745, page 9810 (1979).

(9) T. E. Lipman, private communication with a Panel member.

AUTHORS' BIOGRAPHIES

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Dr. Anderman received his B.Sc. in Chemistry from the Hebrew University in Jerusalem, Israel, and his Ph.D. in Physical Chemistry from the University of California in Santa Barbara. He joined W.R. Grace and Company in 1983 where he was responsible for the development of rechargeable Lithium batteries. He moved to Acme Electric Corporation in 1988 to take the position of Technical Director, where he lead the development and introduction to the aerospace market, of Acme's high power sealed nickel-cadmium battery systems. He later served as Director of new business development and as Vice President and General Manager of Acme's Aerospace Division. His last corporate position between 1997 and 1999 was as Vice President of Technology of PolyStor Corporation, a US manufacture of Li Ion Batteries. In 1996, Dr. Anderman founded Total Battery Consulting Inc., a firm which provides consulting services in development assessment and application of battery technologies.

Fritz R. Kalhammer

Dr. Kalhammer received B.Sc. and M.Sc. degrees in physics and a Ph.D. degree in physical chemistry from the University of Munich. In 1958, he joined Philco Corporation in Pennsylvania as a project manager in solid-state physics R&D. He became a staff member of Stanford Research Institute in 1961, serving first as a senior physical chemist and later as manager of the Physical and Electrochemistry Laboratories, conducting and directing R&D on fuel cells, batteries, and electrochemical synthesis. In 1973, he joined the Electric Power Research Institute, initially with responsibilities for the Institute's programs in fuel cell, battery and electric vehicle development.. From 1979 to 1988, he directed EPRI's Energy Management and Utilization Division. His last full-time position at EPRI was as Vice President of Strategic R&D with responsibility for organization and direction of EPRI's longer-term core R&D programs. Since 1995, Dr. Kalhammer has carried out a number of studies for industry and government to assess status and prospects of batteries and fuel cells for electric and hybrid vehicles.

Donald MacArthur

Dr. MacArthur earned a B.Sc. in Chemistry and Physics from the University of Western Ontario in 1960, a Ph.D. degree in Chemistry from McMaster University, Hamilton, Ontario in 1965 and a MBA degree from Oakland University, Rochester, Michigan in 1979. He was a Member of the Technical Staff, Bell Laboratories, Murray Hill from 1965-74 with responsibilities in research and development for advanced batteries and semiconductor devices. From 1974-76 he was involved in development and early production of the innovative recombination lead-acid battery technology developed at Gates Energy Products. He was a member of the Technical Staff at General Motors Research Laboratories from 1974 to 1991 with responsibilities in batteries for automotive use. After retiring in 1991, he formed CHEMAC which provides reports and consulting services to the battery industry.