

**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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BTAP 2000 FINAL REPORT

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EXECUTIVE SUMMARY

Five years after the modification of the 1990 Zero Emission Vehicle regulation, and after a period of intensive effort to develop, demonstrate and evaluate advanced electric vehicles, one key question in the electric vehicle debate [still] 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 a key 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).

The Panel focused 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 commercially introduced within the next 5-6 years.

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 most important findings and conclusions of the Panel follow.

Nickel-metal hydride (NiMH) batteries capable of meeting the power requirements for EV propulsion have been demonstrated in more than 1000 vehicles in California. 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 battery quantities 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, and major increases are unlikely. If NiMH battery weight is limited to an acceptable fraction of EV total weight, the range of a typical family EV in real world driving is limited to approximately 70 to 100 miles on a single charge.

Despite extensive cost reduction efforts of the leading NiMH EV battery developers, NiMH battery cost remains the largest obstacle to EV commercialization in the near term. Battery manufacturers and some carmakers projected future NiMH EV battery costs for increasing levels of production. From these projections, 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 100,000 battery packs per year, respectively. To the module costs, at least \$1,200 per battery pack (perhaps half of that amount in true mass production) has to be added for the other major components of a complete EV battery, including 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 EV 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 the 100,000 packs per year level. These projections exceed the automobile manufacturers' cost goals by about \$7,000 to \$9,000 in the nearer term and by approximately \$5,000 at automotive mass production levels.

The reliability of the Li Ion EV batteries in the ALTRA EV has been excellent up to now, but the battery durability test data obtained in all major lithium ion EV battery development programs indicate that battery operating life is typically only 2-3 years at present. Current Li Ion EV battery technology also does not pass some of the tests used to gauge battery safety under simulated abuse conditions. 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 cost estimates provided by developers and the Panel's own estimates, these batteries will cost substantially more 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 technology combining high levels of automation, precision and speed is developed.

Lithium metal polymer EV batteries are being developed in two programs aimed at technologies that would cost \$200/kWh or less in volume production. However, these technologies have not yet reached key technical targets including cycle life and 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.

The six major automobile manufacturers serving the California market have invested extensive financial and talent resources in developing and deploying a diversity of electric vehicles and in the evaluation of advanced EV batteries. The performance and reliability of the more than 1400 EVs deployed with advanced batteries (most of them of the NiMH-type) has been excellent for some and generally adequate for nearly all of them. Automobile manufacturers stress, however, that NiMH and other advanced batteries will be too expensive for acceptable EVs costs. Also, the practical range provided by the batteries of current EVs is considered less than desirable by most drivers. Larger batteries that could increase range would aggravate the battery cost problem as well as raise increasingly serious volume and weight issues. In general agreement with the Panel's assessment, the automobile manufacturers' projections indicate that both, major technology advances and true mass production would be required to reduce advanced battery costs substantially below current projections. This is considered unlikely for the next 6-8 years.

All major carmakers are now actively pursuing alternatives to the currently deployed EV types – advanced-technology vehicles such as hybrid and mini EVs – to achieve emissions 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 EVs battery capacity – depending on vehicle technology and application, between approximately 5% and 50%. Battery cost thus is substantially reduced, and with it 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 now and, possibly, mini-EVs in the future 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 the costs, of electric vehicles to the point where they appeal to broad markets.

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 members have agreed on the following conclusions:

- 1. Nickel-metal hydride (NiMH) batteries promising to meet the power and endurance requirements for electric vehicle (EV) propulsion have been demonstrated in vehicles and could be available by 2003 from several manufacturers. The specific energy of these batteries is adequate to give representative EV-battery combinations a practical range of around 70-100 miles.**

Field experience shows that the power of the 26-33 kWh NiMH batteries installed in the different EV types 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 65-70/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 family EV to around 70-100 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 achievable 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 the EV types currently deployed in California a practical range of 70-100 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 the same battery capacities, exceeding automobile manufacturers' 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-20k and 100k packs per year, respectively. To these module costs, about \$1200 and \$600, respectively, have to be added for the remaining components of a complete EV battery, including 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), \$9,500-\$11,000 (20k packs/year) and \$7,000-\$9,000 (100k packs/year), compared to the \$2000-\$4,500 range of EV battery cost goals of automobile manufacturers. This range can be derived from the assumption that, for comparable vehicle life cycle costs, the cost of the EV battery plus charging electricity should be no more than the fuel cost of a comparable conventional vehicle. The calculation is favorable to electric vehicles inasmuch as it assumes that an EV minus battery in mass production will cost no more than a complete ICE vehicle, and that the battery will last the life of the EV.

- 3. Lithium Ion EV batteries have demonstrated good performance and, up to now, high reliability in Nissan's ALTRA EVs. However, current Li Ion EV batteries do not have adequate durability, and their safety is not fully proven. Li Ion batteries meeting all key requirements for EV propulsion are not likely to be available in commercial quantities before 2006. Moreover, the early costs of these batteries are expected to be considerably higher than those of NiMH EV batteries. Even in true mass production, Li Ion battery costs are unlikely to drop below those of NiMH without major advances in materials and manufacturing technology.**

The ALTRA's Li Ion battery has performed well and shown high reliability to date. However, the test data of all major Li Ion EV battery development programs indicate that the operating life of current technology is likely limited to 2-3 years. Current Li Ion EV batteries also do not pass some of the tests used to gauge battery safety under simulated abuse conditions. 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 cost substantially more 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 is 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 7-8 years.**

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 7-8 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 successful development of low-cost cell designs and manufacturing processes in the years ahead.

- 5. The EVs deployed by the six major automobile suppliers in California generally appear to be performing well. However, according to their manufacturers' customer surveys, even if equipped with advanced batteries these vehicles do not meet most driver's perceived need for EV range. All major automobile manufacturers appear to have come to the conclusion that EVs with the battery costs and limitations anticipated for the foreseeable future will find only very limited markets, well below the numbers of vehicles called for by the ZEV regulatory provisions beginning in 2003.**

The six major manufacturers serving the California automobile market have invested very substantial resources in the development of competent electric vehicles, evaluation of advanced EV batteries, launch and cost-subsidization of a diversity of EVs under their Memoranda of Agreement with the California Air Resources Board, and continued improvements of EV technology. The performance and reliability of the more

than 1400 EVs with advanced batteries (of the NiMH-type except for about 80 Nissan ALTRAs with Li Ion batteries) deployed in California over the last 21/2 years has been excellent for some vehicles and generally adequate for nearly all of them. However, automobile manufacturers stress that NiMH and other advanced batteries will be too expensive for acceptable EVs costs. Also, at around 70-100 miles per charge (about 2/3 to 3/4 of the test cycle ranges), the practical range of the vehicles is considered less than desirable by most drivers. Larger batteries that could increase range would aggravate the battery cost problem as well as pose increasingly serious volume and weight issues. In general agreement with the Panel's assessment, the automobile manufacturers' projections indicate that major technology advances as well as true mass production would be required to materially reduce advanced battery cost. This is considered unlikely for the next 6-8 years.

All major carmakers are now actively pursuing alternatives to the currently deployed EVs – advanced-technology vehicles such as hybrid and mini EVs – to achieve emissions 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 EVs battery capacity – depending on vehicle technology and application, between approximately 5% and 50%. Battery cost thus is substantially reduced, and with it one of the largest barriers to 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 successful development of HEV and mini-EV battery technologies – both, NiMH and Li Ion – have benefited directly and substantially from the advances in EV battery development. Conversely, the successful commercialization of HEVs now and, possibly, mini-EVs in the future will likely 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 the performance and reduce the costs of electric vehicles to the point where they appeal to broad markets.

