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Recent advances in the US Department of Energy's energy storage technology research and development programs for hybrid electric and electric vehicles

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Abstract

This paper provides an overview of recent advances in battery technology resulting from the Department of Energy's (DOE's) energy storage research and development (R&D) programs for hybrid electric vehicles (HEVs) and electrical vehicles (EVs). The DOE's Office of Advanced Automotive Technologies (OAAT) is working with industry, national laboratories, universities, and other government agencies to develop technologies that will lead to a reduction in the petroleum used and the emissions generated by the transportation sector. The programs reviewed in this paper are focused on accelerating the development of energy storage technologies that are critical for the commercialization of HEVs and EV. These include the research conducted at DOE's national laboratories to develop the high-power batteries needed for hybrid electric vehicles (HEVs) and the collaborative research with the US Advanced Battery Consortium (USABC) to develop the high-energy batteries needed for EVs.

Keywords: Advanced batteries; Lithium ion batteries; Lithium metal polymer batteries; Nickel metal hydride batteries

1. Background

According to the Energy Information Administration, the US relied on imports to meet approximately 57% of its total oil demand in 2000. Our nation increasingly relies on imports to quench its thirsty transportation appetite, and this situation is accelerated by the growing change in vehicle mix, with less fuel-efficient sport utility vehicles and pickup trucks accounting for 46% of new light vehicle sales in 2000. This increasing use of petroleum for personal transportation not only threatens our economic stability and energy security but also poses risks to personal health as a consequence of increasing toxic emissions and of climate changes that threaten to alter our environment.

Bringing to market personal vehicles that provide the same benefits as today's conventional vehicles but that will consume far less fuel is one straight-forward method of reducing petroleum demand and the emission of greenhouse gases and toxic pollutants. Hybrid electric vehicles (HEVs) are an attractive alternative to conventional vehicles because they can deliver the extended range and rapid refueling that consumers expect from a vehicle while achieving increased fuel economy and reduced greenhouse gases and criteria pollutants. Zero-emitting battery-powered electric vehicles (EVs) that are fully competitive with conventional vehicles are another attractive route to reducing petroleum use and associated pollutant emissions.

Research and development on advanced batteries has been an integral part of the Department of Energy's (DOE's) work since the late 1970s. Today, the efforts to pioneer battery technologies that will facilitate the commercialization of HEVs and EVs are found in four OAAT programs. These programs, working in concert, represent a comprehensive set of R&D tools that address the broad range of issues inherent in the development of high-performance rechargeable batteries.

- The Electric Vehicle Battery Research and Development Program has as its goal the creation of battery technologies that will enable fully competitive EVs.
- The Vehicle High-Power Energy Storage Program is part of a multifaceted effort to develop the technologies needed to enable the commercial introduction of HEVs.
- The Advanced Technology Development (ATD) Program focuses on finding solutions to barriers that are impeding US battery manufacturers in their efforts to produce and market high-power batteries for use in HEVs.
- The Batteries for Advanced Transportation Technologies Program provides the research base that supports the

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OAAT's efforts to develop advanced rechargeable batteries for HEVs and EVs.

2. Recent advances

The Electric Vehicle Battery Research and Development Program conducts the development of advanced batteries in collaboration with the US Advanced Battery Consortium (USABC). The USABC was formed in 1991 when the big three American automakers, the Electric Power Research Institute (EPRI), and the DOE entered an agreement to pool their technical knowledge and funding to accelerate the development of advanced batteries for EVs). The USABC now has nearly a decade of experience in managing advanced battery development programs with the DOE for both EVs and HEVs. It conducts the world's largest research and development programs for advanced automotive batteries and is generally recognized as one of the leading advanced battery development efforts in the world.

One major objective of the program is to develop a lithium ion battery system that can meet the energy, power, life, cost, and abuse tolerance performance levels required for EVs. The program is continuing to develop the SAFT lithium ion EV cell technology and has made significant progress in the packaging and control of high-energy, compact, batteries. The current performance levels attained at the cell and battery level are shown in Table 1.

To address abuse tolerance, the SAFT design puts individual cell monitoring and control at the module level. The results in an effective hierarchical approach for cell, module, and battery control, with each module able to monitor and control the charge and discharge of the individual cells contained within it as well as to communicate information to the next higher level battery and vehicle control systems.

A second major objective of the EV Battery R&D Program is to develop a lithium metal polymer battery (LMPB) system that attains the power and energy targets specified by the USABC as commercialization goals. The preliminary performances of EV cells, modules and packs tested under the USABC cycling protocols show that the LMPB technology can already meet the essential performance characteristics for a competitive EV, including high-power for acceleration and sustained high speed as well as high capacity for long range. The projected characteristics of the technology now under development are shown in Table 2.

Table 1
Performance of lithium ion cells and batteries

Attribute	Value	
	Cell level	Battery level
Specific energy (Wh/kg @ $C/2$)	120	100
Specific power (W/kg @ 80% DOD)	230	200
Energy density (Wh/l)	304	119
Cycle life to 80% DOD	1000	200

Table 2

Attribute	Value	
	Cells	Modules
Specific energy (Wh/kg @ $C/3$)	205	155
Energy density (Wh/l, @ $C/3$)	333	220
Specific power (W/kg @ 80% DOD)	420	315
Power density (W/l @ $C/3$)	700	506

Significant accomplishments include the development of thin film technology for several critical components, including electrodes, electrolytes, and current collectors. A total of 8 kWh packs have been built and tested and a life of over 500 cycles has been validated. The LMPB technology was recently integrated into the Ford Think City electric vehicle (Fig. 1), the first such vehicle to utilize a LMPB. Meeting this objective required a special electrochemical configuration, along with the design of the modules, the pack, and the battery management and thermal management systems.

The Vehicle High-Power Energy Storage Program is focused on overcoming the main technical barriers associated with commercializing high-power lithium ion and nickel metal hydride battery technologies for HEVs. Hybrid vehicles generally need much less electrical energy storage capacity than pure EVs, but require significantly higher levels of electrical power. This means that, at the cell level, hybrid vehicle batteries must have a higher "ratio" of peak power capability to energy storage capability. As a consequence, hybrid vehicle batteries must be optimized for power compared to electric vehicle batteries that are usually optimized for energy.

Specifically, the objectives of the Vehicle High-Power Energy Storage Program are:

- to demonstrate the fabrication and assembly of thin electrodes into compact, lightweight high-power energy storage devices by 2004, and
- to develop, by 2008, low-cost, high-power battery technologies that meet or exceed the energy storage requirements for both power-assist and dual-mode hybrid vehicles.

Fig. 1. Ford Think City electric vehicle.

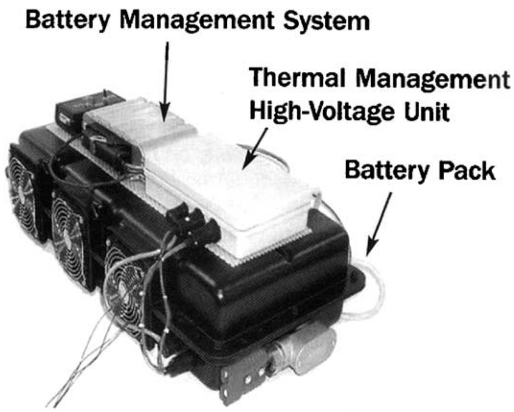

Fig. 2. Components of an integrated high-power battery.

To facilitate the integration of high-power batteries into hybrid vehicles, the Vehicle High-Power Energy Storage Program works with the DOE Vehicles Systems Team to coordinate efforts in modeling, hardware evaluation, and integration activities. Integration between federal agencies is accomplished through the Interagency Advanced Power Group (IAPG).

Recent accomplishments in the Vehicle High-Power Energy Storage Program include the development of a compact, fully-integrated, high-power lithium ion battery system, shown in Fig. 2, that is designed to fit within the engine compartment of a mid-size vehicle. The system achieved a discharge pulse of 25 kW and a peak regenerative pulse of 30 kW and is capable of meeting other stringent performance requirements (e.g. round-trip energy efficiency, cold cranking power, and cycle life) of hybrid vehicles. A similar battery attained over 200,000 cycles, representing about 10 years life, when tested at the Idaho National Engineering and Environmental Laboratory (INEEL).

The Program also transferred advanced battery technologies to automakers, including SAFT Li-ion to DaimlerChrysler; VARTA NiMH to Ford; Texaco-Ovonic NiMH to GM; and AVESTOR Li-polymer to GM. These advanced battery technologies were featured in the automakers' concept HEVs unveiled in early 2000, namely, the DaimlerChrysler ESX3, the Ford Prodigy, and the GM Precept.

The ATD Program focuses on finding solutions to the major barriers—calendar life, abuse tolerance, and cost—that are impeding US battery manufacturers from producing and marketing high-power batteries for HEVs. The ATD Program addresses these technical challenges through five major program areas: baseline (Gen 1) cell development; diagnostic evaluations; electrochemical improvement (Gen 2); advanced materials for Gen 3 cells; and, low-cost packaging. Five national laboratories (ANL, BNL, LBNL, INEEL, and SNL) are working in close coordination to achieve the objectives of this program.

Accomplishments in baseline cell development include characterization of a viable high-power cell chemistry and use of accelerated methods to condition cells to various levels of calendar and cycle age. After completing the accelerated cycle and calendar life aging, the cells were shipped to diagnostics labs for post-test examination and analysis. The preliminary data was analyzed and used in the development of an innovative calendar life modeling methodology. The results from the Gen 1 cell testing will form the baseline against which the performance of Gen 2 and Gen 3 cells will be evaluated.

A variety of sophisticated and specialty diagnostic tools were used to determine the mechanisms by which cells degrade as a result of cycling and/or aging. Some key findings of these analyses include the following.

- Significant changes in impedance, surface morphology, and composition of cathodes were detected in aged and cycled Gen 1 (baseline) lithium-ion cells. Polarization and EIS studies indicate that these changes lead to the power fade observed in tested cells.
- All the gases generated during the formation process and after accelerated calendar life and cycle life testing of Gen 1 cells were identified. CO_2 and CO were the only gases detected after aging of Gen 1 cells, formed possibly as a result of decomposition of the passivation film on the negative electrode at the elevated storage temperatures.
- A micro-reference electrode was developed and used to identify the positive electrode as being responsible for the bulk of the impedance rise in Gen 1 cells. In turn, it was found that the charge transfer resistance at the electrode interface was found to be the main cause of impedance rise in the positive electrode and that diffusional impedance for Li^+ inside the cathode lattice is virtually absent.
- Isothermal microcalorimetry was used to demonstrate that the low-temperature, heat generating reactions do not depend on electrical charge/discharge cycling, but are dependent only on temperature, SOC, and time at temperature.

The Batteries for Advanced Transportation Technologies Program addresses fundamental issues of chemistries and materials that face all lithium battery candidates for HEV and EV applications. The Program emphasizes synthesis of components into battery cells and the determination of failure modes, coupled with strong efforts in materials synthesis and evaluation, advanced diagnostics, and improved electrochemical models. The Program is divided into six task areas: (1) cell development; (2) anodes; (3) electrolytes; (4) cathodes; (5) diagnostics; (6) modeling. Task 1 comprises cell fabrication, testing and characterization, tasks 2–4 are aimed at identifying new materials, and tasks 5–6 support all BATT Program work.

DOE's Argonne National Laboratory has identified a new approach to making the negative electrodes for lithium batteries that are being developed for HEVs and EVs. Conventional lithium ion batteries incorporate a graphite negative electrode that, when coupled with a lithium transition metal oxide positive electrode, provides an electrochemical cell

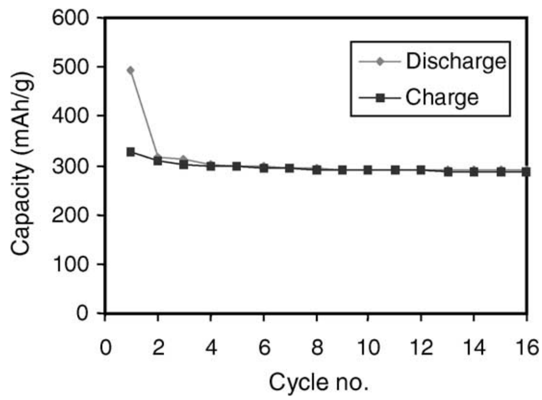

Fig. 3. Early cycling of Cu_2Sb anode.

operating at high voltage, typically 3.5–4.2 V. When lithiated, the graphite electrode operates at a potential close to that of metallic lithium (Li^0), and can react strongly with the organic solvents used in the electrolyte. This limitation introduces serious safety concerns, particularly when the large cells needed for HEV and/or EV applications are overcharged or abused.

Argonne has identified a new class of intermetallic structures that operate by reversible lithium insertion—metal displacement reactions. The voltage of these electrodes is a few hundred millivolts above the potential of Li^0 and, as a result, reduce the safety hazards associated with lithium cells. These intermetallic negative electrodes have the potential to not only significantly improve the safety of lithium batteries but also to reduce costs by avoiding the need for sophisticated electronic control of individual cells during charge.

The discovery of Cu_6Sn_5, InSb, and Cu_2Sb structure types, in which the Sn or Sb array acts as a host for Li, has afforded battery researchers a new approach for designing safe negative electrodes. Electrodes such as Cu_2Sb not only deliver a specific capacity comparable to graphite and a volumetric capacity significantly superior to graphite, but, as seen in Fig. 3, also show the promise of having good cycling behavior. Four patent applications on these new intermetallic electrodes have been filed by ANL.

3. Summary

The DOE's research and development programs to develop energy storage technologies for hybrid electric and EVs have made possible significant progress in lithium battery technology. The research has led to a better understanding of why cell performance declines as cells age and/or are cycled; to the development of new materials that offer the promise of enhanced performance and safety; and to the introduction of the advanced batteries into both electric and HEVs. Future R&D in these areas offers the prospect of further reducing the barriers to even more widespread commercialization of HEVs and to the development of EVs with range and performance competitive with gasoline-powered vehicles.