VEHICLE HIGH-POWER ENERGY STORAGE

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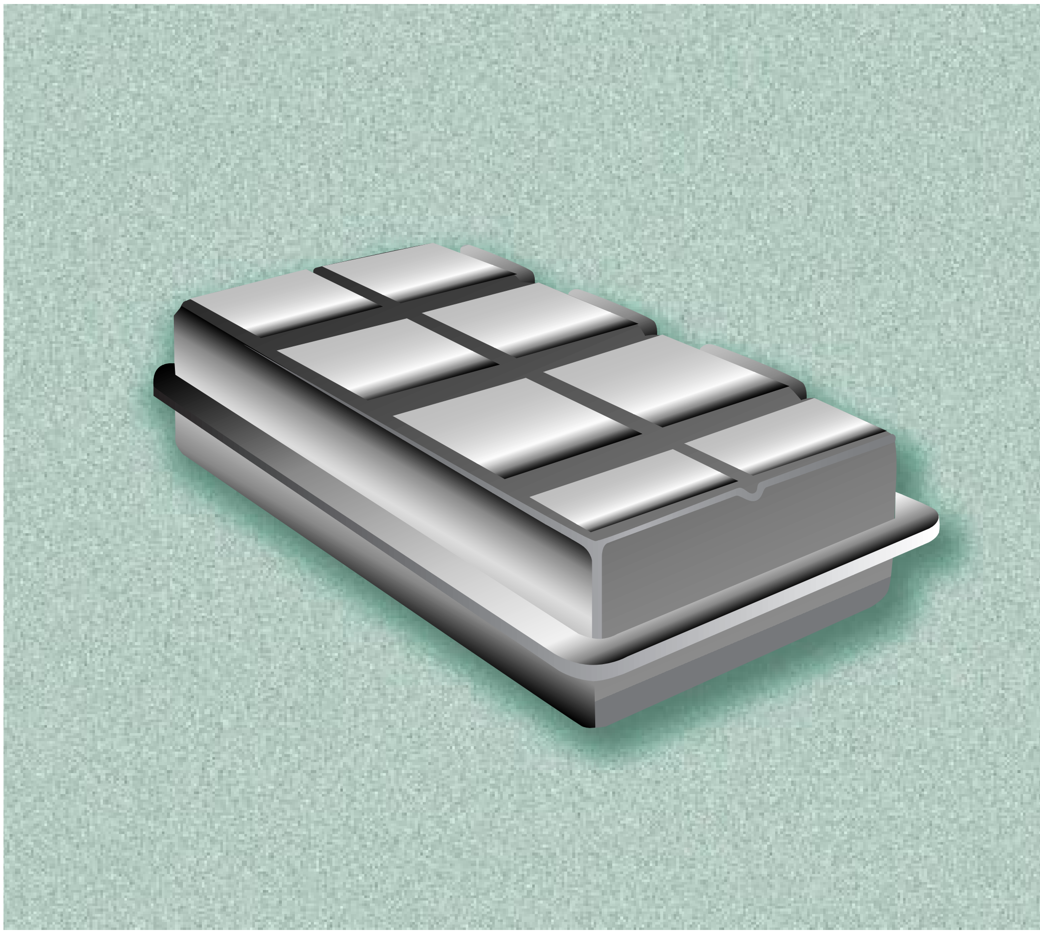

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Energy Efficiency and Renewable Energy

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A C K N O W L E D G E M E N T

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FY 2001

Highlights Report for the Vehicle High-Power Energy Storage Program

Energy Efficiency and Renewable Energy
Office of Transportation Technologies
Office of Advanced Automotive Technologies
Energy Management Team

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1. Introduction

Vehicle High-Power Energy Storage Program

The number of vehicles on American roads and the number of miles driven by those vehicles continue to grow, resulting in increased air pollution, increased petroleum consumption, and, indirectly, increased reliance on foreign sources of that petroleum. To counter these trends, new vehicles will need to be introduced that can achieve better fuel economy while producing fewer harmful emissions.

Under the leadership of the Department of Energy's (DOE) Office of Advanced Automotive Technologies (OAAT), the Vehicle High-Power Energy Storage Program is part of a multifaceted effort to develop the technologies needed to enable the introduction of commercially viable, cleaner, program supports the recently announced FreedomCAR Program and has contributed to the success of the Partnership for a New Generation of Vehicles (PNGV). Although falling short of cost and total miles per gallon targets, this government-industry partnership has made considerable progress towards developing a mid-sized passenger vehicle capable of surpassing current emissions and vehicle mileage standards while maintaining performance, safety, and comfort.

Hybrid vehicles, which consist of an engine that consumes fuel and a battery capable of load leveling and absorbing energy otherwise lost on breaking, demonstrate significant fuel economy and emissions advantages over ICEs, and have also enjoyed some commercial acceptance (e.g., see the successful Toyota Prius and Honda Insight). Lightweight, affordable, high-power batteries are one of the key enabling technologies and improvements in this technology are essential for the continuing development of hybrids.

Why Focus on Hybrid Vehicles?

In general terms, a hybrid vehicle combines an engine, e.g. internal combustion engine (ICE) or other engine such as a fuel cell system, with an energy storage device, e.g. battery, flywheel, ultracapacitor, to achieve lower fuel consumption and emissions. In conventional vehicles, the engine is sized according to customer performance and acceleration requirements to meet the most demanding aspects of a drive cycle. This makes the engine substantially oversized for most driving, with the extra weight and power leading to low fuel efficiency. Conventional engines also waste fuel when idling.

The advantage of a vehicle with a hybrid-electric powertrain is that it can have a smaller ICE that satisfies the demands of normal driving (operating in its highest efficiency range) and an energy storage device that supplements the engine's power when needed for rapid acceleration. In many cases the ICE in a hybrid vehicle can be shut down when it is not required for propulsion, such as when the vehicle is stopped at a signal or going downhill, and instantly restarted again when needed, which leads to additional fuel savings. Hybrid vehicles also offer the opportunity to capture additional energy through a regenerative braking system, where the propulsion motor is used as a generator to slow the vehicle while generating electricity to recharge the batteries. Altogether, hybrid vehicles may be up to two or three times as fuel efficient as conventional vehicles, and by burning less fuel they also produce lower emissions, particularly greenhouse gases linked to global warming.

Based on a carefully crafted down select period, the battery was selected as the system of choice for energy storage. Based on this selection, there still persists a continuum of hybrid vehicle types, ranging from those with conventional or nearly conventional sized engines and small electrical propulsion systems (that boost acceleration and recapture braking energy) referred to as "power assist" vehicles, to "range-extender" or "plug-in" hybrids that are essentially electric vehicles with a small engine that extends their driving range by partially recharging the batteries between full recharges. The power assist battery targets are provided in Table 1 and have essentially no capability to operate on battery power alone. The "dual mode" targets, also in Table 1, represent a mid-point on the continuum of hybrid vehicle types, having a limited electric only driving range (a few tens of miles). Battery-dominant "range-extender" hybrid vehicles have similar electrical performance requirements to pure electric vehicles, so batteries for these vehicles are being developed under the Electric Vehicle Battery Program.

While hybrids are not zero emission vehicles, they can be significantly cleaner than conventional vehicles and are more likely to meet increasingly stricter emissions standards. Hybrid vehicles have a greater driving range than today's electric vehicles and operate in a manner that is indiscernible from today's ICE vehicles, thus they are likely to find greater acceptance in the commercial marketplace in the short-term.

Addressing Technical Barriers to Hybrid Vehicles

Hybrid vehicles generally need much less electrical energy storage capacity than pure electric vehicles because hybrids have a small ICE that supplies most of the vehicle's energy needs; however, they still require significant power levels. This means that at the cell level, hybrid vehicle batteries must have a high ratio of peak power capability to energy storage capability. Thus, hybrid vehicle batteries are, to the extent they can be, engineered for high power-to-energy ratios on the order of 80:1, whereas electric vehicle batteries are optimized for lower power-to-energy ratios on the order of 2:1.

Batteries designed for a high power to energy ratio are typically composed of electrodes with high internal surface area. This may play a detrimental role in abuse situations. A short circuit of a power cell, either internally or externally, will rapidly release energy. This can in turn lead to a rapid thermal response if not adequately managed.

Batteries designed with high internal surface areas also expose more electrolyte to side reactions, which in most cases leads to shorter life spans. Side reactions are responsible for the build-up of resistive layers in the cell that reduce power. Batteries for automotive applications are generally perceived as reaching end-of-life when the power available over a prescribed energy range falls by 24%.

The cost per kW for batteries possessing the high energy densities and space requirements for in-vehicle applications is too high for widespread consumer acceptance. However, the cost problem is less severe, on a per vehicle basis, for hybrids than it is for pure electrics, where larger overall systems are required. The costs for hybrid batteries arise from a combination of raw materials and the processes required to distribute the materials over a large surface area.

The VHPBP is focused on overcoming the main technical barriers associated with improved commercialization of hybrid vehicles by concentrating on the following defined major areas for improved high-power battery performance and acceptance:

Abuse Tolerance. High power batteries are not intrinsically tolerant of abuse such as short circuits, overcharge, over-discharge, mechanical shock, vibration, crush, or fire exposure. Chemical additives that circumvent smoke and/or fire generation are being designed and evaluated to operate in conjunction with mechanical safeguards. In addition, challenging thermal management requirements faced during stressful periods in a driving cycle need to be addressed.

Cost. The current cost of nickel-metal hydride and lithium-based batteries (the most promising high-power battery chemistries) is prohibitively high on a kW or kWh basis. Multiple strings of cells pose a problem for lithium-based technologies, because they require overcharge and over-discharge protection at the cell level. The main cost drivers being addressed are:

- High cost of raw materials and materials processing,
- Cell and module packaging cost, and
- Low-cost, failsafe electric and mechanical safety devices.

Calendar Life. At present, a 15-year calendar life is required to meet the California emissions standards. Calendar life of lithium-based batteries is estimated to be approximately 6-10 years (although there are encouraging estimates approaching 12 years). Nickel-metal hydride batteries have a calendar life of 6+ years. Mechanisms resulting in poor calendar life are further exasperated as the temperature of the system increases. This requires additional effort in advanced thermal management and the development of more robust chemistries.

Manufacturing Processes. These high power / high surface areas cells require thin laminates. Proven fabrication and assembly techniques for manufacturing relatively thin electrode assemblies at high throughput rates and assembly into compact, lightweight packages do not exist.

Battery Performance. The advanced battery systems considered for hybrid vehicles can be designed to meet most of the performance targets as set by the Electrochemical Energy Storage Tech Team. However, some barriers still remain, in particular the discharge pulse power required to start a vehicle at low temperature, –30^{o}C, and the loss of available power over time due to use and aging.

The second section of this report covers the objectives, accomplishments, and future directions of the Vehicle High-Power Energy Storage Program. We are pleased with the progress made in addressing the technical barriers outlined above. In FY 2002, we look forward to working with our industrial, government, and scientific partners to overcome the challenges that remain to delivering advanced high-power batteries for hybrid vehicle applications.

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2. Program Overview

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The Vehicle High-Power Energy Storage Program (VHPESP) was created to develop solutions to the technical challenges outlined in this paper's introduction by developing low-cost, high-power batteries that meet or exceed the energy storage requirements shown in Table 1 (set by the Electrochemical Energy Storage Tech Team) by 2010. The specific objectives of the VHPBP include:

By 2006, demonstrate fabrication and assembly of thin electrode components at high throughput rates, along with high-speed assembly of electrodes and components, into compact, lightweight, high-power batteries, and

By 2010, develop low-cost, high-power battery technology that meets or exceeds the energy storage requirements for the power-assist and dual-mode hybrid vehicle applications.

Table 1: ENERGY STORAGE REQUIREMENTS

FreedomCAR Goals		**Power Assist**	**Dual Mode**
Characteristics	**Units**	**Minimum**	**Minimum**
Pulse discharge power	kW	25 for 18-sec	45 for 12-sec
Max regen pulse (10s)	kW	30 (50Wh pulse)	35 (97Wh pulse)
Total available energy	kWh	0.3 (at C/1)	1.5 (at 6kW rate)
Round trip efficiency	%	>90, 25Wh PA cycle	>88, 100Wh DM Eff cycle
Cycle life for specified SOC increments	Cycles	300k for 25Wh PA cycles	3750 DM cycles
Cold cranking power at –30°C [1]	kW	5	5
Calendar life	Yrs	15	15
Max weight	kg	40	100
Max volume	Liters	32	75
Production cost @ 100k units/year	$	500	900
Maximum operating voltage	Vdc	<= 440	<= 440
Minimum operating voltage	Vdc	>= 0.55 Vmax	>= 0.50 Vmax

[1] Three 2 sec pulses, 10 sec rests between.

FreedomCAR Goals		**Power Assist**	**Dual Mode**
Characteristics	**Units**	**Minimum**	**Minimum**
Maximum dc link current	A	<= 217	<= 217
Maximum self discharge	Wh/d	50	50
Operating temperature	°C	-40 to +52	-40 to +52
Survival temperature	°C	-46 to +66	-46 to +66

Partnering for Success

The VHPBP participates in and compliments numerous public-private partnerships that are working towards developing advanced technologies for the next generation of vehicles. Through a cooperative agreement between the United States Advanced Battery Consortium (USABC) and the Department of Energy, the USABC is focusing on the development of high-power batteries. Two candidate battery chemistries have been identified as the most likely to succeed in meeting performance and cost targets: nickel-metal hydride (Ni-MH) and lithium-based technology. Ni-MH batteries offer relatively good power capability as a result of the good ionic conductivity of the potassium hydroxide electrolyte. Lithium-based batteries offer excellent energy density that can be traded for higher power. Both chemistries are being investigated under the USABC program – first to establish the basic performance and life capabilities in small laboratory and full-size cells and then to demonstrate the best of these technologies in full-size modules. Ultimately, full-capacity battery subsystems will be engineered for delivery and operation in technology-validation test-bed vehicles.

Four USABC subcontracts to establish baseline cell chemistries and electrode designs were awarded at the program's inception in 1997. During 1997, two of the four subcontractors – SAFT America and VARTA – were awarded follow-on subcontracts to develop and demonstrate their high-power battery technologies at the nominal 50-V module level with electronic and thermal management. The SAFT technology is based on 6 and 12-Ah lithium-ion cells; the VARTA technology uses 10-Ah Ni-MH cells.

In addition, in 1997 the USABC awarded two six-month subcontracts to PolyStor and VARTA to further explore alternative lithium-ion technologies for high-power batteries. In 1998 PolyStor successfully demonstrated in small laboratory cells the potential of its lithium-ion technology to meet the technical targets shown in Table 1. Based on the results, PolyStor was awarded an 18-month contract beginning in June 1998 to develop and demonstrate a 50-V, full capacity module using a 9-Ah cell design.

As a result of new developments in lithium-polymer technology and the potential for lower cost Ni-MH, the USABC awarded two lithium-polymer and two Ni-MH development subcontracts in 2000. The contracts were awarded to Delphi (lithium-polymer), AVESTOR (lithium-polymer), Texaco-Ovonic (Ni-MH), and Electro Energy, Inc. (bipolar Ni-MH) to benchmark and demonstrate that their respective technologies can meet the technical requirements for this application.

Under the Advanced Technology Development (ATD) Program, DOE national laboratories are focusing on finding solutions to the barriers that are impeding U.S. battery manufacturers in their efforts to produce and market high-power lithium-based batteries for use in hybrid vehicles. Also, selected national laboratories are conducting performance and cycle life testing of cells under a Cooperative Research and Development Agreement with the USABC. Test data from the national laboratories and subcontractors is being used to develop and refine a generic battery model for use by the FreedomCAR systems analysis team.

Unique Program Features

As with the *electric* vehicle high-*energy* battery program, the most unique feature of the VHPESP is its reliance on an extremely broad spectrum of contributors. Developing high-power batteries requires the involvement and coordination of battery developers and suppliers, government agencies, national laboratories, automotive manufacturers, and university organizations. Coordination activities include high-level programmatic inputs, major program reviews, workshops, meetings, and symposia with experts on special topics related to high-power batteries.

To facilitate the integration of high-power batteries into hybrid vehicles, the high-power battery 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 government-sponsored Interagency Advanced Power Group (IAPG).

A second feature of the program that is fairly unique and distinguishes it from other OAAT programs is its relatively small size, fast turnaround, and interest in emerging, high-risk technologies and research objectives. The OAAT, as mentioned above, supports the ATD program but is also committed to supporting research into advanced materials by commercial battery suppliers. Therefore, this program has shown, and continues to show, a great degree of flexibility in order to respond to new opportunities and promise in technology.

Current Program Status

Due to a number of technical challenges, including several related to calendar life and/or cycle life of cells, several of the activities listed under Partnering for Success in the VHPESP were suspended by April of 2001. Nevertheless, significant progress was made and insights into cell chemistries were gained (see program accomplishments below). The ATD program continues to play an integral role in the development of scientific understanding and innovative solutions to short life and high cost of Li-ion chemistries. Throughout the year, deliverables are required of each of the programs. Those deliverables are benchmarked by the national laboratories with the results shared with the respective developers and members of the Electrochemical Energy Storage Technical Team.

Current Program Participants

The main battery developers currently involved in the VHPESP, and their primary responsibilities, are shown in the table below. As mentioned above, some of the companies who were supporting this program at the start of FY 2001 are not currently engaged in research, their effort being suspended pending additional understanding of the cause of poor calendar life. SAFT, PolyStor, Texaco Ovonic, and Electro Energy Inc. continue to support the program and have made fairly significant progress in FY 2001.

PARTICIPANT	RESPONSIBILITY
SAFT America, Inc.	Develop and demonstrate high-power technologies based on nominal 6 and 12-Ah lithium-ion cells at the 50-V module level with electronic and thermal management. See Exhibit 1.
Texaco-Ovonic (TOBS)	Benchmark and demonstrate that the Texaco-Ovonic, Inc.'s NiMH technology can meet all technical targets.
Electro Energy, Inc. (EEI)	Benchmark and demonstrate that Electro Energy, Inc.'s, bipolar Ni-MH technology can meet the technical targets at the cell level.
PolyStor	Continue working to demonstrate sufficient cycle and calendar life in its newly developed gel based lithium polymer system.

FY 2001 Accomplishments

The major accomplishments in the VHPESP in FY 2001 were:

- EEI developed a new bladder system for uniformly applying pressure on NiMH pseudo-bipolar cells.
- TOBS discovered a potential plastic for module construction that demonstrates good mold ability and weld ability, chemical resilience, toughness, and non-flammability. The material is also recyclable, commercially available, and low cost.

Exhibit 1. SAFT Li-ion high-power battery.

- TOBS was successful in the construction of lower cost system assemblies for NiMH batteries, with a total cost based on 1,200,000 models projected to be $800 or less. Part of the cost reduction is a result of reducing the parts count from over 100 down to 23 parts/module.
- SAFT identified and demonstrated a new, low-cost anode material capable of high-rate performance that alleviates lithium plating even during cold cranking.

- SAFT has demonstrated the use of a new low temperature electrolyte that exhibits reduced power fade, and a new crimp cell design that further reduces cost. They also implemented a new binder from a class of homo-polymers that shows improved abuse tolerance. SAFT claims their cells meet all of the technical targets except cost; their G4 chemistry is projected to achieve a 15-year calendar life, and they are in the process of incorporating a new flame retardant electrolyte developed at the Army Research Laboratory.
- SAFT submitted two battery packs for independent testing at INEEL.
- PolyStor demonstrated an innovative cell sealing approach for their low-cost flexible packaging design.
- PolyStor has improved the cycle life of its gel based lithium polymer system from 50,000 to 200,000, and has estimated calendar life to be up to 10-years.

The National Laboratories' accomplishments in high-power batteries (focused on lithium technology) are detailed in a comparison report on the ATD Program.

Future Directions

Looking ahead, the VHPESP is continuously evolving to further enhance effectiveness, better leverage available technical and financial resources, and promote information exchange among the various participants in the program. It is anticipated that, in addition to the programs presently being supported, the VHPBP may take on additional applications including 42 V systems and ultracapcitors. The program may also take a more aggressive role in reducing cost by soliciting suppliers who specialize in the manufacturing of high cost items such as separators.

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