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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 our roads and the number of miles driven by those vehicles are increasing each year, resulting in increased national petroleum consumption and air pollution. To balance these trends, new vehicles will need to be introduced that can achieve better fuel economy while producing fewer harmful emissions.

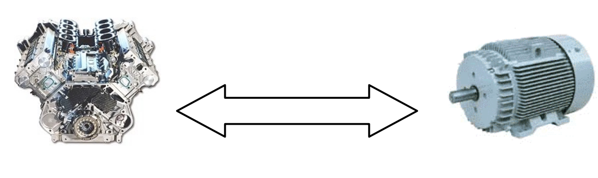
Under the leadership of the Department of Energy's Office of Advanced Automotive Technologies (OAAT), the Vehicle High-Power Energy Storage Program is part of a multifaceted effort to develop the technologies needed to enable the commercial introduction of cleaner, more fuel efficient hybrid-electric (or simply, “hybrid”) vehicles. The Vehicle High-Power Energy Storage Program supports the Partnership for a New Generation of Vehicles (PNGV), a government-industry partnership striving to develop by 2004 a mid-sized passenger vehicle capable of achieving up to 80 miles per gallon while adhering to future emissions standards and maintaining such attributes as affordability, performance, safety, and comfort. Hybrid vehicles have demonstrated promise in achieving PNGV goals of high fuel economy and low emissions, and lightweight, affordable, high-power energy storage devices are one of the critical component technologies needed for viable hybrid propulsion systems.

Why Focus on Hybrid Vehicles?

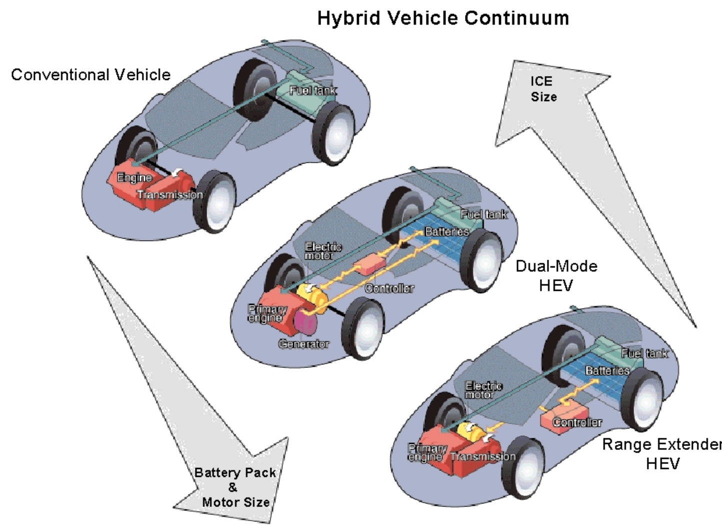
In general terms, a hybrid vehicle combines an internal combustion engine with an electric motor to achieve lower fuel consumption and emissions. In conventional vehicles, the engine is sized according to customer performance and acceleration requirements. This makes them substantially oversized for most driving, where their predominately light-load driving demands and extra weight lead to low fuel efficiency. Conventional engines also waste fuel when idling. Since most driving is done under light-load conditions, the heavy, oversized engine does not operate in its optimal range, which leads to poor fuel economy and increased emissions.

ADVANTAGES OF A HYBRID VEHICLE OVER A CONVENTIONAL VEHICLE

- Ability to use smaller engine due to the addition of an electric motor.
- Engine can operate more efficiently with an electric motor assisting at low speeds and/or high end speeds.
- Ability to capture otherwise wasted braking energy and recharge batteries with it.
- Idle-off feature can save fuel normally wasted at standstill, and can restart engine immediately.



The advantage of a vehicle with a hybrid-electric powertrain is that it can have a smaller engine that satisfies the demands of normal driving and an electric motor that supplements the engine’s power when needed for rapid acceleration. In many cases the engine in a hybrid vehicle can also be stopped when it is not required for propulsion, such as when the vehicle is waiting at a light or going downhill, and instantly restarted when needed again, which saves fuel. Hybrid vehicles also offer the opportunity to capture regenerative braking by using the propulsion motor 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.



There is a continuum of hybrid vehicle types, ranging from vehicles with conventional or nearly-conventional sized engines and small electrical propulsion systems that boost acceleration and recapture braking energy, to vehicles that are essentially electric vehicles with a small engine-powered generator that extends their driving range between recharges. The "power assist" battery targets in Table 1 pertain to vehicles with small electrical propulsion systems relative to their engines; power-assist hybrid vehicles rely on their engines for the majority of their propulsion needs and have essentially no capability to operate only on battery power. The "dual-mode" targets represent a mid-point on the continuum of hybrid vehicle types; a dual-mode vehicle would have a limited driving range (up to a few tens of miles) using only its batteries. Battery-dominant "range-extender" hybrid vehicles have similar electrical performance requirements to pure electric vehicles, so batteries for these vehicles are being developed under a separate 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 the increasingly strict emissions standards. Hybrid vehicles have a greater driving range than electric vehicles; thus they are likely to find greater acceptance in the commercial marketplace.

Addressing Technical Barriers to Hybrid Vehicles

Hybrid vehicles generally need much less electrical energy storage capacity than pure electric vehicles, but they still require significant electrical power levels. This means that at the cell level, hybrid vehicle batteries must have a higher "ratio" of peak power capability to energy storage capability. Therefore, the design of hybrid vehicle batteries must be optimized for power, whereas electric vehicle batteries are generally optimized for energy.

Costs of hybrid vehicle batteries are presently too high for widespread acceptance by most automotive consumers. This problem is less severe for hybrids than it is for pure electric vehicles that require a greater number of larger batteries.

The Vehicle High-Power Energy Storage Program is focused on overcoming the main technical barriers associated with the commercialization of high-power battery technology by concentrating on five (5) major areas, namely:

- **Abuse tolerance.** High-power batteries are not intrinsically tolerant of externally imposed abuse conditions – short circuits, overcharge, over-discharge, mechanical shock and vibration, crush, and fire exposure. Multiple strings of cells pose a problem for lithium-based technologies, because they require overcharge or over-discharge protection at the cell level. Low-cost, fail-safe electric and mechanical safety devices need to be developed. In addition, challenging thermal management requirements need to be addressed.

- **Cost.** The current cost of nickel-metal hydride and lithium-based batteries is prohibitively high on a kWh or kW basis. The main cost drivers being addressed are:

    - High cost of raw materials and materials processing; and,
    - Cell and module packaging cost.

- **Calendar life.** Calendar life based on power for lithium-based batteries is estimated to be approximately 2-3 years. Nickel-metal hydride has a calendar life of 6+ years. A 10-year calendar life is required to reduce overall system costs. Issues that are driving the poor calendar life include:

    - Material degradation at extreme temperatures; and,
    - Lack of reliable methods for predicting battery life and warranty costs.

- **Manufacturing processes.** Proven fabrication and assembly techniques for manufacturing relatively thin electrode assemblies at high throughput rates and assembly into compact, lightweight packages (cells, modules, and batteries) do not exist.

- **Battery Performance.** The main barriers related to battery performance are the reduced discharge pulse power that is available at low temperatures, 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 progress made to date in addressing the technical barriers outlined above. In FY 2001, we look forward to working with our industrial and scientific partners to overcome many of the technical challenges that stand in the way of delivering advanced high-power batteries for automotive applications.

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2. PROGRAM OVERVIEW

Objectives, Partners, Accomplishments, and Future Directions of the Vehicle High-Power Energy Storage Program

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The Vehicle High-Power Energy Storage Program was created to develop solutions to the technical challenges outlined in the introduction by developing low-cost, high-power energy storage devices that meet or exceed the energy storage requirements shown in the Table 1, by 2008.

The specific objectives of the Vehicle High-Power Energy Storage Program include:

- By 2004, 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 energy storage devices, and

- By 2008, develop low-cost, high-power battery technology that meets or exceeds the energy storage requirements for the power-assist and dual-mode hybrid vehicles.

TABLE 1: ENERGY STORAGE REQUIREMENTS

PNGV Goals		Power Assist	Dual Mode
Characteristics	**Units**	**Minimum**	**Minimum**
Pulse Discharge Power (18s)	**kW**	25	**45 for 12-sec**
Max Regen Pulse (10s)	**kW**	30 (50Wh pulse)	**35 (97Wh pulse)**
Total Available Energy	**kWh**	0.3	**1.5 (at 6kW rate)**
Round Trip Efficiency	**%**	**>90 - 25Wh PA Cycle**	**>88 - 100Wh DM Eff. Cycle**
Cycle Life for specified SOC Increments	**Cyc.**	**200k for 25Wh PA Cycles**	**2500 DM Cycles**
Cold-cranking Power at -30°C (Three 2-sec pulses, 10-sec rests between)	**kW**	**5**	**5**
Calendar Life	**Yrs**	10	10
Max Weight	**kg**	40	**100**
Max Volume	**Liters**	32	**75**
Production Cost @ 100k units/yr	**$**	300	500
Maximum Operating Voltage	**Vdc**	**</= 440 Max**	**</= 440 max**
Minimum Operating Voltage	**Vdc**	**>/= 0.55xVmax**	**>/= 0.5 x Vmax**
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 Vehicle High-Power Energy Storage Program participates in and complements 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 for the Partnership for a New Generation of Vehicles (PNGV). 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 energy storage 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 completed 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 6-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 PNGV technical targets. Based on the results, PolyStor was awarded an 18-month contract beginning in June 1998 to develop and demonstrate a 50-volt, 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 (approximately 9-12 months duration) in 2000. The contracts were awarded to Delphi (lithium-polymer), AVESTOR (formerly Hydro-Quebec) (lithium-polymer), Texaco-Ovonic (formerly GM-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 PNGV systems analysis team.

Unique Program Features

As with the Electric Vehicle Battery Program, the most unique feature of the Vehicle High-Power Energy Storage Program 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 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 government-sponsored Interagency Advanced Power Group (IAPG).

Current Program Participants

The main participants involved in the Vehicle High-Power Energy Storage Program, and their primary responsibilities, are shown in the table below.

PARTICIPANT	RESPONSIBILITY
SAFT America, Inc.	Develop and demonstrate SAFT high-power battery technologies based on nominal 6 and 12-Ah lithium-ion cells at the nominal 50-V module level with electronic and thermal management. See Exhibit 1.
VARTA	Develop and demonstrate VARTA high-power battery technologies using nominal 10-Ah Ni-MH cells at the nominal 50-V module level with electronic and thermal management.
PolyStor	Develop and demonstrate a 50-volt, full-capacity lithium-ion module using a 9-Ah PolyStor cell design.
Delphi	Benchmark and demonstrate that Delphi lithium- metal polymer technology can meet the technical targets.
AVESTOR	Benchmark and demonstrate that AVESTOR lithium-metal-polymer technology can meet the technical targets.
Texaco-Ovonic	Benchmark and demonstrate that Texaco-Ovonic, Inc., NiMH technology can meet the technical targets.
Electro Energy, Inc	Benchmark and demonstrate that Electro Energy, Inc., bipolar NiMH technology can meet the technical targets.

FY 2000 Accomplishments

The major accomplishments in the Vehicle High-Power Energy Storage Program in FY 2000 were:

- Completed initial evaluation of alternative technologies, reporting: NiMH shows promise for lower cost and stable life, and; Lithium polymer systems are still under evaluation.

- Continued efforts to improve Li-ion life, abuse tolerance and cost. Calendar life was improved by ~50%.

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

- Completed two Phase II programs for 50V module demonstrations. Two programs delivered 50V modules.

- Transferred advanced battery technology to OEMs, including: Saft Li-ion to Daimler Chrysler (DCX); VARTA NiMH to Ford; Texaco-Ovonic NiMH to GM, and; AVESTOR Li-P to GM. These advanced battery technologies were featured in the PNGV concept cars unveiled in early 2000, namely, the DaimlerChrysler ESX3, Ford Prodigy, and GM Precept .

- Additional work was conducted to revise the test manual to include a cold cranking test; adjust the hybrid pulse power cycle to reflect dual mode requirements; improve efficiency profiles; refine the dual mode cycle life procedure, and; assess thermal management energy consumption.

FY 2000 Progress by Battery Developers

DEVELOPER	PROGRESS
SAFT America Li-Ion Module Demonstration	- Delivered full-scale hybrid battery system - Improved life capability to 7 years.
VARTA NiMH Module Demonstration	- Developed low-cost modular design.
PolyStor Li-Ion Module Demonstration	- Delivered 50-V modules. - Improved life capability to 7 years.
Delphi	- Adopted ATD materials.
AVESTOR	- Demonstrated high power capability.
Texaco-Ovonic	- Demonstrated 600W/kg electrode stacks.
Electro Energy, Inc	- Demonstrated bi-polar NiMH in high power configuration.

The National Laboratories' accomplishments in high-power batteries are detailed in a companion report on the Advanced Technology Development Program.

Future Directions

Looking ahead, the Vehicle High-Power Energy Storage Program is being restructured to further enhance its effectiveness, better leverage available technical and financial resources, and promote information exchange among the various elements of the program. The core program R&D by the industrial battery developers for high-power lithium-ion and nickel-metal hydride batteries will continue. In addition, the DOE Vehicle High-Power Energy Storage Program will continue to reassess long-term technologies that promise performance, life, and cost benefits over the nickel-metal hydride and lithium-ion technologies as candidates for future development and use in hybrid propulsion systems.

References/Publications

1. *Recent Accomplishments of the Electric and Hybrid Vehicle Energy Storage R&D Program at the U.S. Department of Energy: A Status Report*, Dr. Raymond Sutula, Dr. Kenneth Heitner, Ms. Susan Rogers, Mr. Tien Duong, and Dr. Robert Kirk, Office of Advanced Automotive Technologies, U.S. Department of Energy; Dr. Vincent Battaglia and Mr. Gary Henriksen, Argonne National Laboratory; Dr. Frank McLarnon, Lawrence Berkeley National Laboratory; Dr. B.J. Kumar and Ms. Connie Schonefeld, Energetics, Incorporated. Paper presented at the 17TH International Electric Vehicle Symposium, October 2000.

2. *Advanced Automotive Technologies Energy Storage R&D Programs at the U.S. Department of Energy - Recent Achievements and Current Status*, Dr. Raymond Sutula, Dr. Kenneth Heitner, Ms. Susan Rogers, Mr. Tien Duong, and Dr. Robert Kirk, Office of Advanced Automotive Technologies, U.S. Department of Energy; Dr. B.J. Kumar and Ms. Connie Schonefeld, Energetics, Incorporated. Paper presented at the 2000 Future Car Congress, April 2000.

3. *Electric and Hybrid Vehicle Energy Storage R&D Programs of the U.S. Department of Energy*, Dr. Raymond Sutula, Dr. Kenneth Heitner, Ms. Susan Rogers, and Mr. Tien Duong, Office of Advanced Automotive Technologies, U.S. Department of Energy; Dr. Vincent Battaglia and Mr. Gary Henriksen, Argonne National Laboratory; Dr. B.J. Kumar and Ms. Connie Schonefeld, Energetics, Incorporated. Paper presented at the 16TH International Electric Vehicle Symposium, October 1999.