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Status and Prospects of Battery Technology for Hybrid Electric Vehicles, Including Plug-in Hybrid Electric Vehicles

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Introduction

My name is Menahem Anderman; I have worked in the battery industry for 24 years, with both technology and business management responsibilities. I am the president of Advanced Automotive Batteries, a firm that provides consulting services in the area of energy-storage technology for advanced vehicles. Our activities include—among others—publishing multi-client industry and technology assessment reports, and organizing what is widely regarded as the foremost annual conference in this industry. I was invited by this committee's honorable chairman to brief the committee about the status of battery technology for hybrid electric vehicles, including plug-in hybrid electric vehicles, and am very appreciative of this opportunity.

Hybrid Electric Vehicles

Hybrid Electric Vehicles (HEVs) are propelled by combining mechanical power from an internal-combustion engine with electrical power from a battery. Fifteen hybrid car models offered in several vehicle classes are now available in dealerships across the United States, Europe, and Asia. Sales of no less than 350,000 new hybrid electric cars, representing over 0.7% of the total new car[1] production in the world, were reported in

[1] In this report, the term 'car' is used generically to include all types of 'household' vehicles—cars, light trucks, vans, SUVs, etc.

2006, 60% of which were in the U.S. market, accounting for 1.3% of total car sales. Coverage of the hybrid-vehicle technology by the media has increased substantially, and the average Japanese and North American consumer is now well aware of this new breed of vehicle. The technological and commercial success of the 2004 model year Prius—the third generation of this flagship hybrid—combined with the steep rise in oil prices during 2005/2006, the growing concerns about a diminishing world energy supply, and the increased awareness of the relevance of CO_2 emissions from vehicles to the potential for global warming have all intensified the automotive industry's efforts to develop and introduce hybrid electric cars.

As the realization spreads that fuel-cell vehicles are unlikely to enter mass production within the next twenty years or more, and the pressure to reduce vehicle emissions and fuel consumption continues to rise, hybrid electric vehicles seem to offer a timely solution that is both technically proven and economically viable (or almost viable). However, other technologies with some environmental benefits, including ultra-efficient IC engines, clean turbo-diesel engines, ethanol-fueled IC engines, and advanced hydrocarbon fuel technologies, are also evolving. In most cases, these alternative technologies are less expensive and appear less risky to the automakers, which explains their interest in pursuing them in parallel to, or instead of, the hybrid approach. However, in the competitive race to improve drivability, comfort, and safety, while reducing fuel consumption and emissions, automotive engineers are discovering that many of the prospective solutions to these problems will require increased electrical power, which reinforces the desirability of at least some level of vehicular hybridization.

Hybrid cars today cover a range of technologies, each characterized broadly by the extent to which electrical power is used for propulsion in the vehicle. At one end of the spectrum is the 'micro-hybrid', a car that features a "beefed-up" starter, in which fuel is saved during vehicle idle stop, and mechanical energy is captured during braking. At the other end of the range—which also includes mild, moderate, and strong hybrids—is the 'plug-in hybrid', in which a 40- to 100-kW electric motor is capable of propelling the car on its own for, say, 5 to 50 miles, and supplements the power of the internal combustion engine in most acceleration events. To date the most successful hybrids on the market are the strong (sometimes referred to as ‘full’) hybrids. These vehicles employ a 30 to 70-kW electric motor that is engaged frequently during the drive cycle and is powered by an advanced high-power battery, which is charged on board by the IC Engine and by the kinetic energy captured during deceleration and braking of the vehicle.

The debate over the ‘right’ level of hybridization has recently intensified. While many automakers are searching for a reduced—although measurably beneficial—level of hybridization (to cut the high incremental cost of the hybrid powertrain), governments, many utility companies, and environmental groups, frequently supported by the media, are pointing in exactly the opposite direction, favoring the introduction of plug-in hybrids that will offer significantly reduced fuel consumption, pollutants, and CO_2 emissions, but with a large price tag and other drawbacks.

Hybrid Electric Vehicle Batteries

Central to the discussion regarding the relative merits of the various hybrids is the big box that stores the energy to propel the electric motor—the battery. It is evident that the battery is a key to achieving (or failing to achieve) technical and commercial success with any of the various hybrid architectures. In fact, the battery is responsible for 25 - 75% of the increased weight, volume, and cost associated with the various hybrid configurations. Even more critical are battery life, reliability, and behavior under abuse as they present the largest threat to the commercial success of hybrid technology.

Batteries store electrical energy, which is measured in kWh. Today’s mild, moderate, and strong (‘full’) hybrids on the market utilize batteries with rated capacities of 0.6 to 2 kWh. In general mild hybrids require smaller batteries than do strong hybrids. The rated energy capacity of the battery is dictated by the battery’s level of usage (the duty profile), and includes a significant margin for life, to meet the 10-year minimum life requirement of the automotive market. In today’s hybrid batteries, only about 10% of the rated battery capacity is used frequently, and up to an additional 30% is accessed under extreme driving conditions. The remaining capacity is in place to ensure adequate service life.

Currently, essentially all hybrids with moderate to significant powertrain hybridization employ a NiMH battery as the main electrical-energy storage device. NiMH batteries are a reliable power source for hybrid cars; their manufacturing base is expanding, and field results suggest long life. However, NiMH batteries are not an ideal energy-storage device for hybrid cars. Their limitations include moderate energy conversion efficiency, which translates to some energy loss and significant heat production in normal usage, reduced life with high depth-of-discharge (DOD) cycling, and unsatisfactory performance at high and low temperatures. NiMH battery packs for HEVs are priced at $900 to $1500 per kWh, which brings the price of today's pack to between $600 and $3,000 per vehicle.

The 2006 NiMH battery market for HEVs is estimated at $600 million. Although NiMH is currently the most economical (and only proven) power source for the application, it has limited potential for cost reduction as production volume further increases, particularly in light of recent substantially higher nickel prices—nickel, in several metallic forms and compounds, being the battery's main component.

Lithium-ion batteries offer higher power and energy per unit weight and volume, and better charge efficiency than NiMH batteries. Thus, if they can maintain performance over life, smaller and lighter batteries can be used in given applications. These attributes allowed them to capture a major part of the portable rechargeable battery market—which requires a battery life of only 2 to 3 years—within a few years of their introduction, and to generate global sales estimated at $5 billion in 2006. Nevertheless, the reliability of lithium-ion technology for automotive applications is not proven—unfriendly failure modes, for example, are a concern—and its current cost is higher than that of NiMH.

Over the last five years, most automakers have started to evaluate the suitability of lithium-ion batteries for HEV applications, and two Japanese automakers even embarked on sizeable in-house lithium-ion battery development projects. In the U.S., significant progress has been made under the auspices of the U.S. Advanced Battery Consortium, a collaborative effort between the U.S. Department of Energy, the auto industry, and battery developers. Sometime in the future, lithium-ion technology is likely to become the battery of choice for most hybrid applications, although the recent reliability problems experienced with lithium-ion batteries in portable devices may delay its acceptance. Nevertheless, following extensive system-verification tests, lithium-ion batteries are still expected to enter the HEV market in 2 to 3 years, and their use to grow thereafter, provided no major negative surprises arise.

Lithium-ion HEV batteries are likely to initially carry a slightly higher price than NiMH batteries but price parity is expected to occur as volume reaches that of the NiMH business. Moreover, they hold better potential for further cost reduction through improvements in technology and economies of scale.

It is useful to note here that world investment in lithium-ion battery technology R&D continues to increase and is estimated at well over $1 billion annually, which is several times the total investment in R&D for all other battery technologies combined. We estimate that there are over a hundred materials, chemicals, and battery companies, several thousand academic researchers, and hundreds of scientists in government-owned laboratories involved in various aspect of lithium-ion battery technology R&D.

Plug-in Hybrids and their Battery Requirements

While the development of plug-in hybrid vehicles by car manufacturers is still at an early stage, industry experience with all-electric vehicles on the one hand, and with conventional hybrid electric vehicles on the other, is sufficient to provide general guidelines for their battery requirements.

In an all-electric vehicle, the battery is the only power source on board and is used in the so-called ‘charge-depletion’ mode, i.e. the battery is fully charged externally (typically at night) and is depleted at a steady rate during driving. In this case, the battery usually provides only one charge-discharge cycle per day, with the depth of discharge depending on the battery capacity and the driving range. In a conventional HEV, the battery is operated in the so called ‘charge-sustaining’ mode, i.e. the battery is charged and discharged on board around an intermediate state of charge, typically about half-way between fully charged and fully discharged. In this application, the battery may be called upon to provide hundreds or more shallow cycles per day, never approaching the fully-charged or fully-discharged state.

In a classical plug-in HEV, the battery is fully charged externally, typically on a daily basis. When the vehicle is driven after charging, the battery operates in the charge-depletion mode, just like an EV battery. Later, as the battery reaches some predetermined low state of charge, the vehicle switches to a charge-sustaining mode, in which the battery will be used like that of a conventional HEV. Because of these dual functions the battery's usage profile in a plug-in HEV is considerably more demanding than that of either a full EV battery or a conventional HEV battery, with obvious negative implications for battery longevity.

For a plug-in hybrid electric vehicle the requirement that dictates its battery capacity is the range of electric drive for which the vehicle is designed (Note: some 'plug-in' architectures do not emphasize electric drive, but to keep this discussion simple, we will consider an architecture that requires it). Depending on its weight, aerodynamic design, and driving pattern, a typical mid-size vehicle with an electric motor will utilize 0.2 to 0.4 kWh of energy per mile driven, which means that 1 kWh of energy will propel a car for between 2.5 and 5 miles. For the sake of simplicity we will assume a 3-4 mile range per kWh of used energy. Thus, for a 20-mile range of electric drive, the car will use 5-7 kWh of energy. However, since the duty cycle of the application is considerably more severe than that of HEV or EV batteries, to even stand a chance of meeting life requirements using today's technology it will be necessary to design a battery with 1.5 to 2 times the energy capacity required for the drive. In other words, a plug-in vehicle with a 20-mile range will require a battery with a rated energy capacity of 8 to 14 kWh. Again for the sake of simplicity we will assume a battery capacity of 10kWh for the rest of the analysis.

Since the average capacity of today's strong hybrid batteries is 1.7 kWh, the above calculation shows that the 20-mile plug-in battery will need an energy capacity 6 times higher than that of today's average HEV battery. This brings out several significant issues:

1) The plug-in battery will be about 3 to 5 times the size of today's conventional HEV batteries, essentially filling the cargo space of an average sedan.

2) The weight of this battery will add 200 to 300 lb. to that of the car, which will adversely affect vehicle performance and efficiency.

3) If the plug-in battery vehicle contains a lithium-ion battery, which is to be given a full charge every night in a residential garage, there is a much more serious concern about hazardous failure than with the smaller batteries of conventional HEVs, which are always kept at an intermediate state of charge.

4) The cost of this plug-in battery (at pack level) to carmakers, using present technology, will be 3 to 5 times the average cost of today's HEV batteries, i.e. around $5,000 to $7,000 per pack.

5) The life of either battery technology, NiMH or lithium ion, in the plug-in application is not known. There is a significant risk that its life will be shorter than that of conventional hybrid-car batteries.

Unfortunately, items 4) and 5) above compound each other, making the cost of replacing the battery prohibitive (should the battery need to be replaced during the life of the car).

It is our opinion that wide-spread commercialization of plug-in hybrids with a range of 20 miles or more is only possible if there is notable improvement in battery performance, proven battery longevity and reliability in well-designed lab and field tests—which, in combination, are likely to require 3 to 5 years—along with a significant reduction in battery cost.

Government Initiatives

U.S. government initiatives to promote the growth of the HEV market through subsidies, incentives, taxation, or tighter fuel-efficiency regulations will all encourage further industry investment in fuel-efficient transportation. Because batteries are critical to the potential success of the hybrid-vehicle business, direct investment in battery technology is also likely to advance the technology and in turn the viability of HEVs. Lithium-ion battery chemistry is clearly the most promising in terms of supporting future conventional HEVs as well as in approaching the target requirements of plug-in HEVs. While lithium-ion technology will continue to evolve as a consequence of the large worldwide investment in this technology, U.S. Government regulations that support the growth of the HEV market and/or its funding of lithium-ion battery development would certainly accelerate progress. In our opinion, such enhanced progress could allow lithium-ion battery technology to enter the conventional U.S. HEV market earlier than without it, thereby increasing the attractiveness of these vehicles and stimulating their market growth. In the longer term—perhaps in about 10 years—accelerated progress may gradually close the gap between the targeted battery requirements for plug-in HEV and the state and cost of battery technology, thus facilitating the introduction of plug-in hybrid vehicles as well.

It also is our opinion that as far as electric drive and electric-assist drive technology is concerned, conventional HEV technology is the only one mature enough for its market growth to have an impact on the nation’s energy usage in the next 10 years. Pending significant improvements in battery technology, plug-in hybrids could possibly start making an impact in about 10 years, while vehicles powered by fuel cells are unlikely to enter high-volume production in less than 20 years.

Other Considerations

Leadership in the development of advanced rechargeable batteries migrated to Japan in the eighties and has remained there since. Today’s Japanese suppliers provide over 60% of the world’s lithium-ion battery demand, and Korean and Chinese suppliers share the vast majority of the remaining 40%.

Regarding batteries used in today’s high-volume hybrids, two Japanese battery producers, Panasonic EV Energy, a joint venture between Toyota Motor Company and Panasonic

Batteries, and Sanyo, share over 95% of today's $600 million HEV battery market (currently nearly all NiMH). A single U.S. supplier, Cobasys, supplies NiMH batteries for the 2007 mild-hybrid Saturn Greenliner. Both Japanese battery giants are also developing lithium-ion battery products for the HEV market, where over a dozen additional battery makers from Japan, Korea, and the U.S. intend to compete.

While North America and Europe maintain strong competence in basic battery research, including in materials and electrochemistry, major producers in Japan, and more recently Korea, have opened a significant gap between them and other parts of the world in advanced-battery manufacturing expertise. The manufacturing of high-volume, low-cost, and high-reliability lithium-ion batteries for the portable market is challenging, and established producers have paid dearly to move up the learning curve (and down the cost curve). The manufacturing of low-cost, high-power lithium-ion batteries for HEV is considerably more demanding, when one considers the higher voltage and the larger size of the battery on the one hand, and the long life expectancy and harsh operating environment on the other.

To the degree that the U.S. Government is interested in supporting the establishment of a domestic supply of HEV batteries, thought should be given to addressing this significant gap in high-volume lithium-ion manufacturing expertise between U.S. developers and their Japanese and Korean counterparts, in addition to supporting the development of battery materials and improved cell design.

Thank you for the opportunity to brief the committee. I hope that this presentation will help direct attention to the apparently most promising and affordable technologies for reducing fuel consumption and the impact of vehicles on the environment, yet without sacrificing vehicle functionality and affordability, or threatening human safety.