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Nickel/metal hydride technology for consumer and electric vehicle batteries — a review and up-date

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Abstract

Nickel/metal hydride batteries today represent the fastest growing market segment for rechargeable batteries due to the high energy density and more environmentally acceptable chemistry offered by this technology. The high energy density of nickel/metal hydride batteries coupled with high power density and long cycle life make this battery chemistry a key enabling technology for practical electric vehicles, including cars, vans, trucks, and other forms of transportation such as scooters, bicycles, and three-wheelers. This paper provides a review of Ovonic technology and up-dates recent developments in materials and cell development for both consumer electronic and EV applications, and highlights areas for future development.

Keywords: Metal hydride anode batteries

1. Introduction

The worldwide market for rechargeable batteries for consumer electronic applications is growing at a record pace due to increased consumer demand for portable devices such as cellular phones, lap-top computers, camcorders, and other personal electronic devices. Nickel/metal hydride batteries today represent the fastest growing segment of this rechargeable battery market for consumer electronics due to their higher energy density and more environmentally acceptable chemistry relative to Ni/Cd. Current estimates indicate that the total portable rechargeable battery market is expected to reach $2 billion in 1996, growing to over $5 billion by 2000 [1].

An exciting new battery market is emerging due to the growing interest and demand for emission-free vehicles, which today can only be achieved through the use of battery power. The limitations of current electric vehicle (EV) battery technologies have been well documented in numerous articles decrying the lack of vehicle range offered by today's EVs. The high energy density, excellent power density, and long cycle life of nickel/metal hydride batteries make this the leading technology of choice for the battery power source for EVs. Several leading automotive companies, including Honda, Toyota, Nissan, General Motors, and Hyundai, have recently announced that they will be offering nickel/metal hydride batteries on EVs to provide long range, high power, and long battery life.

Ovonic Battery Company is the recognized world leader in the development of nickel/metal hydride battery technology, and today over 95% of the worldwide major manufacturers of nickel/metal hydride cells for consumer applications are producing under license to Ovonic. Ovonic continues to develop advanced negative electrode and positive electrode materials for continued product improvements. Additionally, Ovonic is actively involved in the development of cells and batteries for EV applications. Through its joint venture company, GM Ovonic, we are actively entering into the commercialization of this battery technology for EVs. Ovonic is also exploring other applications for nickel/metal hydride technology including transportation applications such as hybrid vehicles, bicycles, scooters, etc., as well as remote and stand-by power applications.

Ovonic nickel/metal hydride batteries today demonstrate specific energies over 80 Wh kg^{-1} and energy densities of over 200 Wh dm^{-3} in commercial cells and up to 95 Wh kg^{-1} in advanced cell designs. Continued advances in electrode materials and cell designs are projected to further improve product performance for a wide range of battery applications.

This paper describes the basic chemistry of the Ovonic nickel/metal hydride technology and reviews cell perform-

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ance characteristics of these batteries, both for portable electronic and EV applications. EV battery performance at the vehicle level is described for some of the many conversion vehicles and 'ground up' EVs that have employed Ovonic nickel/metal hydride batteries. Current R&D efforts are described as well as areas for future development and the projected impact on battery performance.

2. Nickel/metal hydride cell chemistry

The basic cell reaction for nickel/metal hydride can be written as:

$$MH + NiOOH = M + Ni(OH)_2$$

where M represents an intermetallic alloy capable of forming a metal hydride phase. It is interesting to note that the overall cell reaction consists of transfer of a hydrogen ion from one electrode to the other, in much the same manner as a lithium-ion battery functions through two insertion electrodes for the Li^+ ion. Therefore, one could describe nickel/metal hydride batteries as a 'hydrogen ion' battery, or a 'protonic' battery [2,3]. It is the simplicity of the total cell reaction that provides for the fast kinetics and long cycle life demonstrated by nickel/metal hydride batteries.

An important feature of the nickel/metal hydride chemistry is the cell's ability to tolerate both overcharge and overdischarge through gas recombination reactions that result in no net change in battery electrolyte and prevent a build up of pressure inside the sealed and totally maintenance free cell. This ability to tolerate both overcharge and overdischarge is particularly advantageous for EV applications where system voltages over 300 V are common. Under these conditions, with over 200 cells series connected, individual cells will be subjected to varying degrees of overcharge during charging and individual cells can experience overdischarge and cell reversal, particularly during acceleration or at very low states of battery pack charge. The ability of nickel/metal hydride to accept overcharge and overdischarge eliminates the need for single cell voltage monitoring, simplifying battery management in comparison to other high energy systems such as NaS, lithium-ion, or Li-polymer electrolyte.

3. Metal hydride alloy development

Early development work on hydride alloys for rechargeable batteries focused on traditional hydride materials of well-defined composition and crystal structure. The most widely studied of these materials were alloys of the $CaCu_5$ family, most notably $LaNi_5$ [4]. While early prototype batteries using these hydride materials in negative electrodes displayed high specific energy when coupled with conventional nickel electrodes, these cells suffered in other performance areas such as cycle life, internal cell pressure, and corrosion of the hydride alloy. These performance limitations were largely due to the simple single phase nature of these early hydrides.

Ovshinsky and his team of material scientists at Energy Conversion Devices employed a fundamentally different approach to developing hydride materials specific to a rechargeable battery application [5]. The material requirements for an electrochemical application were defined and engineered alloys specifically developed to meet these demanding and diverse materials requirements. Among the required properties for a negative electrode hydride material are:

(a) high hydrogen storage capacity
(b) proper metal to hydrogen bond strength
(c) oxidation and corrosion resistance
(d) fast gas recombination kinetics
(e) manufacturable at low cost

The engineering of multicomponent, multiphase materials allows for alloys that satisfy these required properties by introducing compositional and structural disorder [6]. By controlling the alloy composition one can control the metal-to-hydrogen bond strength to the desired value. Control of alloy microstructure provides for increased hydrogen storage sites as well as improved kinetics and corrosion resistance. Ovonic and Ovonic licensees have successfully employed this concept of compositionally complex, multiphase materials to develop alloys that in today's commercial nickel/metal hydride batteries provide high energy, high power, and long cycle life. All commercial batteries today incorporate alloys based on the concepts developed at Energy Conversion Devices (our parent company) and Ovonic of multielement composition and controlled microstructure. Today for example, those alloys derived from the $LaNi_5$ family are in actuality complex materials containing generally 6 to 8 elements with complex phase structures. Similarly, the V–Ti–Zr–Ni alloys commonly employed at Ovonic are equally complex and contain local disorder and multiple phases [7].

Ovonic has continued to focus predominately on alloys of the V–Ti–Zr–Ni type due to their intrinsic ability to store very high amounts of hydrogen. While typical rare earth based materials store $< 300\ mAh\ g^{-1}$ specific capacity, commercial Ovonic alloys today store up to 400 $mAh\ g^{-1}$. Moreover, unlike simple crystalline materials, there is no readily definable theoretical limit for hydrogen storage in these complex materials and Ovonic is actively developing materials that store 550 to 700 $mAh\ g^{-1}$ hydrogen [2,8]. The specific role of each component in these intermetallic compounds is well understood and has been described in previous publications [6,9].

Ovonic currently operates a production facility capable of producing hydride alloys and negative electrode 'belt' material for both consumer battery and electric vehicle battery applications. Rolls of compacted electrode strip suitable for cutting or profiling into electrodes are produced in a low-cost, continuous, roll-to-roll process. Upon completion of our most recent capital expansion, Ovonic will have the capability of producing over 800 000 linear feet of electrode material per month to meet the ever-growing demand for hydride battery electrodes.

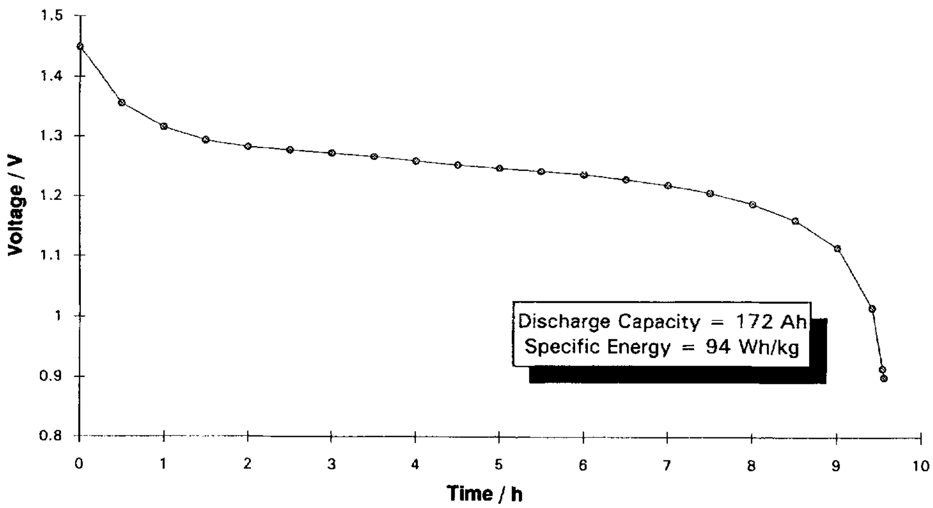

Fig. 1. Discharge curve for advanced prototype EV cell demonstrating a specific energy of approximately 95 Wh kg^{-1}.

4. Positive electrode development

During the early stages of product development, Ovonic developed a high capacity sintered, chemically impregnated ('CI') $Ni(OH)_2$ electrode that surpassed the Ni battery industry standard at that time. Through careful control of sintering parameters and development of optimized impregnation conditions, Ovonic was able to produce CI electrodes with specific energies of 150 mAh g^{-1} total electrode weight (> 550 mAh cm^{-3}).

However, even with these high energies, we recognized that the high specific energies required for today's portable products and, in particular, for EV applications, could not be achieved with the decades old CI electrode technology. To solve this problem, Ovonic undertook development of newer, mechanically impregnated ('MI') electrodes using the new high porosity, low weight Ni foam and felt structures. These MI electrodes have the benefit of higher specific energy and energy density while maintaining high power capability and long cycle life. MI electrodes also utilize a simpler manufacturing process requiring less capital investment than sintered, CI electrodes, providing for opportunities in cost reduction of Ni electrodes, particularly for the high volume manufacturing required for EV batteries.

By proper selection of active material composition together with proper types and levels of active material additives, one can achieve high utilizations of $Ni(OH)_2$ together with high electrode loadings. For good loading and utilization, a high density, spherical $Ni(OH)_2$ active material is used which also incorporates other transition metal ions as co-precipitates. Other electrode additives such as cobalt compounds are typically added to improve active material utilization and cycle life [10]. In addition to optimizing the electrode slurry composition. Ovonic has developed a mechanical impregnation manufacturing process that provides for high electrode loading. This process, together with active material utilizations of 90%, yields positive electrodes with specific capacities of up to 200 mAh g^{-1} based on finished electrode weight.

While this level of energy represents a significant advance over the CI electrode used in previous cell technology, Ovonic is continuing to pursue further advances in positive electrode cost and energy. In particular, while the Ni electrode charge/discharge reaction is commonly written as a simple one-electron transfer reaction, it is well known that this reaction is much more complex [11]. In fact, up to 1.6 electron transfers are theoretically possible for this reaction. Energy Conversion Devices and Ovonic researchers have been working on advanced $Ni(OH)_2$ materials incorporating the same principles of compositional and structural disorder as those demonstrated so successfully in hydride materials. These proprietary materials have demonstrated up to 1.5 electron transfers in thin-film electrodes and up to 1.3 electrons per Ni atom in battery electrodes containing bulk spherical powders produced through a proprietary process [12,13]. Scale-up of these materials and their incorporation into full cell designs will result in energy densities of 95 Wh kg^{-1} and greater in commercial consumer and EV batteries, as has already been demonstrated in prototype EV cells employing these advanced positive active materials (Fig. 1).

5. Cell development — portable batteries

Ovonic has provided regular up-dates on the progress of nickel/metal hydride technology for wound cells developed for portable consumer electronic applications [2,14–16]. The history of these cell development activities has clearly been one of continuous improvement. Ovonic nickel/metal hydride batteries today meet the strictest performance requirements for the '3C' applications of communication, computing and camcorder. Recent advances in cell performance include higher capacity designs, longer cycle life, improved operating temperature range and lower self-discharge rates [16].

Early Ovonic batteries exhibited specific energies in the 55 to 60 Wh kg^{-1} range, corresponding to an energy density

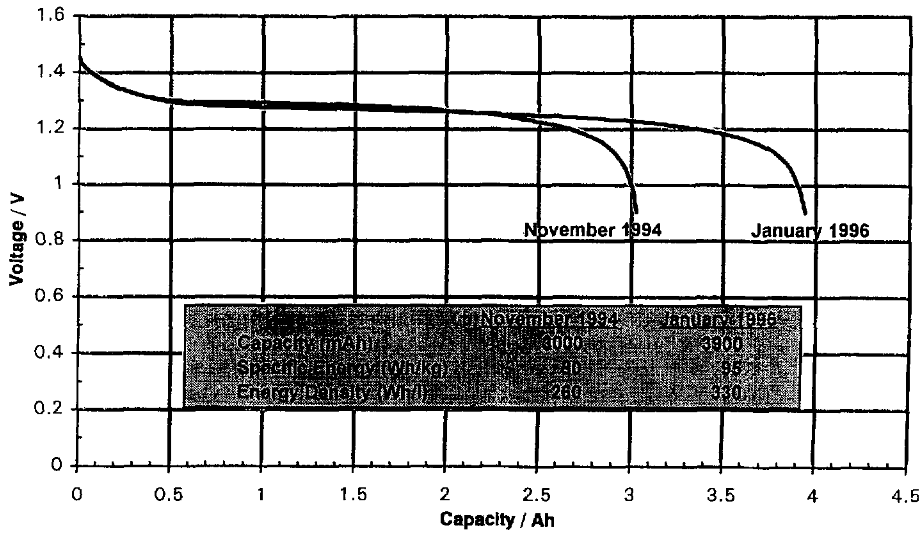

Fig. 2. Discharge curves for commercial and advanced nickel/metal hydride cells, 17.5 mm diameter × 67.5 mm long (type 7/5 Af, as produced by Gold Peak).

of 180 Wh dm^{-3}. While this represented a significant improvement over other rechargeable batteries, continued product development and advances in battery materials have allowed for continuous increases in cell capacity. One Ovonic licensee, Gold Peak, first announced achievement of 80 Wh kg^{-1} in 1994 [15]. Since then GP has continued to improve product design and manufacturing, together with advanced Ovonic materials, resulting in achievement of 95 Wh kg^{-1} in prototype 7/5 Af cells (17.5 mm diameter × 67.5 mm long; weight 46 g) having a rated capacity of 3900 mAh (Fig. 2) [16,17]. Perhaps more importantly for portable devices is battery size rather than weight. Energy density for these prototype 7/5 Af cells is an impressive 330 Wh dm^{-3}, greater than existing lithium-ion batteries [18].

In addition to the traditional OEM products requiring rechargeables, improvements in cell capacity and charger technology make nickel/metal hydride batteries an attractive option to consumers to replace primary alkaline batteries. Traditionally consumers have shied away from rechargeables due to unacceptable device run times and long charging cycles. The recent market introduction of 're-usable' alkaline manganese batteries indicates that the consumer is willing to consider rechargeables if he can maintain the same or nearly identical device performance. However, these batteries exhibit poor cycle life, offering a limited incentive to the consumer. High capacity Ovonic nickel/metal hydride batteries now offer the same, or greater, run-time than a primary battery, can be recharged in 1–3 h, and provide many hundreds of cycles. Due to the bobbin construction of alkaline cells, rate capability for these primary batteries is quite poor. This is true even for the re-useable alkaline manganese technology. The wound construction and low impedance of nickel/metal hydride batteries provides high capacity over a wide range of currents, exceeding primary battery capacity even at relatively moderate drain rates (Fig. 3). The replacement of literally hundreds of primary batteries with a single nickel/metal hydride cell offers a strong economic incentive to the properly educated consumer. Additionally, the environmental impact of disposing of billions of primary batteries annually is significant and can be alleviated by the use of nickel/metal hydride rechargeables.

6. Cell and battery development — electric vehicles

It has long been acknowledged that the key enabling technology for practical EVs has been the development of advanced batteries that would provide the requisite range and performance. While considerable sums of money were spent in the 1970s and 1980s to develop such technologies, EV developers continued to have little choice of battery beyond those technologies that had been employed in the earliest EVs. While advances have certainly been achieved in lead–acid and Ni/Cd batteries, these technologies continue to fall short of providing the desired performance level for a market-driven electric vehicle.

In recognition of this fundamental limitation in battery technology, the Big Three automotive companies, together with the US Department of Energy, with cooperation from the Energy Power Research Institute (EPRI) established the United States Advanced Battery Consortium (USABC) for the express goal of accelerating development of batteries for EVs for the late 1990s time frame and beyond. USABC established a set of performance criteria for mid-term and long-term battery technologies and solicited proposals for the development of technologies capable of achieving these goals.

USABC awarded its first battery development contract in May of 1992 to Ovonic Battery Company for a three phase programme to scale up nickel/metal hydride technology for EV applications and to continue development of the technology to meet USABC 'mid-term' criteria. Within weeks of

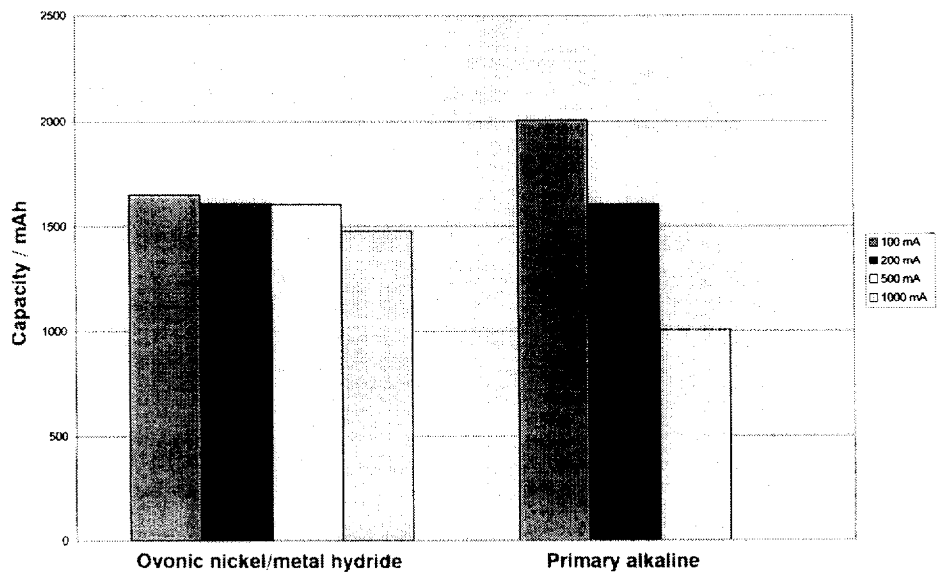

Fig. 3. Comparison of discharge capacity vs. rate for primary alkaline and Ovonic nickel/metal hydride 'AA'-size cells.

receiving this contract, Ovonic delivered its first prismatic cells to USABC, demonstrating successful scale-up from small wound cells to EV design cells with no loss in energy density or performance. Continued development led to increases in energy density, specific energy, power, life, and charge retention [19,20].

Based on the early success of this program, USABC placed an order for prototype batteries in April 1993, almost two years ahead of the original program plan. The first vehicle demonstration of a nickel/metal hydride battery was achieved in August 1993 when a Chrysler TEVan soundlessly rolled down the streets of Troy, MI. Even this early prototype battery provided 28 kW h energy with over 60 Wh kg^{-1} demonstrated at the vehicle pack level.

Since this early vehicle demonstration, Ovonic has continued to improve its technology and battery design expertise, achieving improvements in vehicle range and power [21,22]. Some of the more notable achievements include:

- March 1994 — Ovonic-powered Solectria Force wins APS 500 electric stock car race, with an average speed of greater than 65 m.p.h. (104 k.p.h.) over the 125 mile (200 km) event;
- May 1994 — Ovonic-powered Solectria wins Tour de Sol road rally with a record 214 mile range on a single charge;
- May 1995 — Ovonic-powered Solectria Sunrise wins Tour de Sol road rally with a record 238 mile range on a single charge;
- May 1996 — Ovonic-powered Solectria Sunrise wins Tour de Sol road rally with an impressive 373 mile range on a single charge with a 33 kW h battery pack employing the latest Ovonic technology.

Today Ovonic, together with its EV battery business partner GM Ovonic, has successfully completed dozens of vehicle conversions of all types, including conversion sedans, ground-up EVs, vans, and light trucks.

Hyundai Motor Company, a licensee of Ovonic technology, has established a prototype battery manufacturing facility and has designed and built nickel/metal hydride batteries for a number of conversion vehicles, including the Hyundai Sonata, Grace van, Elantra, and Accent vehicles [22]. Performance of these vehicles has far exceeded that obtained with lead–acid or Ni/Cd batteries. A converted Accent vehicle equipped with nickel/metal hydride batteries, for example, is capable of travelling 390 km (242 miles) on a single battery charge.

An Ovonic nickel/metal hydride battery pack was first tested in the state-of-the-art GM Impact vehicle in January 1994. With this first battery pack design, a range of over 200 miles was demonstrated, with acceleration from 0 to 60 m.p.h. in under 8 s [23]. GM has since announced that it will be producing for sale in 1996 the EV1, a commercial vehicle based on the Impact concept car. GM has announced that this vehicle, while initially equipped with VRLA lead–acid batteries, will be introduced with nickel/metal hydride batteries within two years [24].

These impressive vehicle demonstrations are possible because of the high level of performance that has been achieved with the Ovonic battery. The current status of battery performance relative to the USABC mid-term criteria is shown in Fig. 4. The specifications for the initial GM Ovonic production design nickel/metal hydride EV battery module are given in Table 1.

Advanced battery designs presently being provided to customers for evaluation exceed the current specifications for energy and power, demonstrating 80 Wh kg^{-1} and over 220 W kg^{-1} at 80% depth of discharge. Ovonic batteries have been tested over a wide range of ambient temperatures, from −20°C to over 50°C, including testing under actual vehicle conditions. By proper thermal management of the battery pack using forced air cooling, battery performance is maintained over this temperature range (Fig. 5).

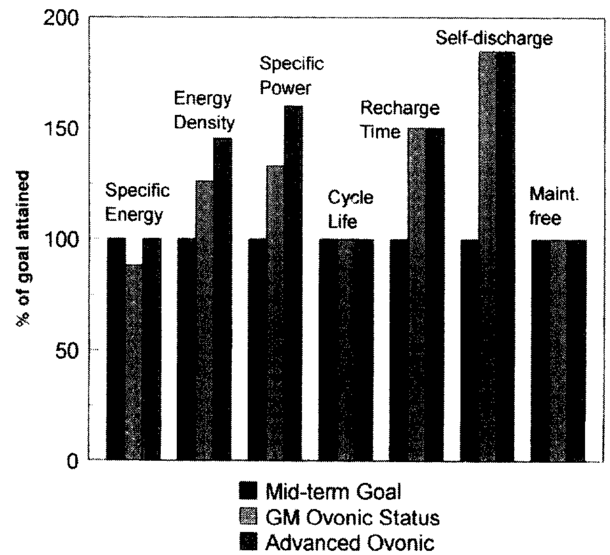

Fig. 4. Ovonic EV battery performance vs. USABC mid-term technical goals.

Table 1
Product specification for nickel/metal hydride EV battery module

Product code	Gen 1 design, model 13-EV-90
No. of cells	eleven
Nominal voltage	13.4
Capacity	90 Ah (at $C/3$ rate)
Energy	1.2 kWh
Specific energy	70 Wh/kg
Energy density	170 Wh/dm^3
Specific power	200 Wh/kg (30 s at 80% DOD)
Power density	485 Wh/dm^3
Charge retention	93% at 26°C (80°F) after 48 h 85% at 38°C (100°F) after 48 h
Operating temperature	<43°C (110°F) for maximum life <65°C (150°F) to avoid damage
Cycle life	600 D.S.T. cycles to 80% DOD
Other attributes	maintenance free no spillable liquids recyclable

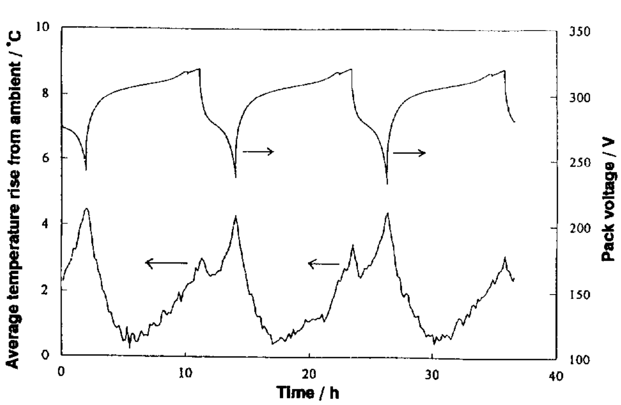

Fig. 5. Thermal performance of air-cooled Ovonic nickel/metal hydride EV battery pack vs. pack voltage.

We have previously described the recombination chemistry that allows for overcharge and overdischarge of individual cells. Additionally, these batteries are resistant to physical abuse. Batteries have been subjected to a wide range of 'abuse' tests including short-circuit, prolonged high-rate overcharge and overdischarge, puncture, crush, drop, etc. In all instances, no safety issues were encountered with the battery module or cell beyond those normally encountered in traditional sealed cells such as Ni/Cd or VRLA.

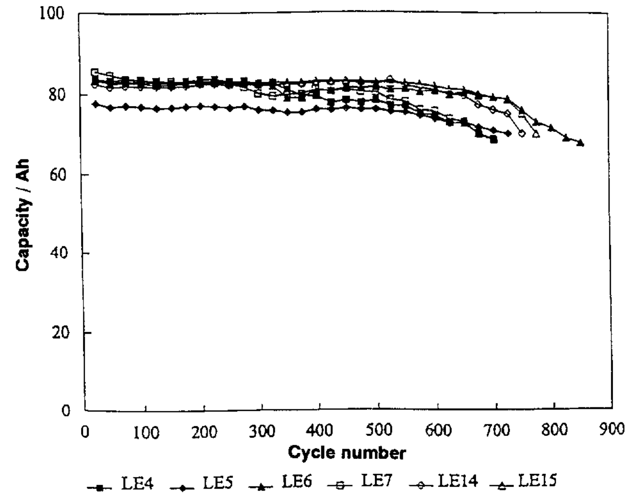

Fig. 6. Cycle life performance of Ovonic nickel/metal hydride EV cells, discharged at $C/3$ rate to 80% depth-of-discharge.

A key advantage of Ovonic nickel/metal hydride batteries is long cycle life (Fig. 6). EV cells and modules cycled to 80% DOD under the demanding 'DST' (Dynamic Stress Test) simulated driving profile have achieved over 600 cycles. For an average vehicle range of 200 miles, this would correspond to 96 000 miles of driving. Battery cycle life improves at lower states of charge, so that under actual driving conditions the driver could expect even longer battery life.

Other battery performance goals include the ability for rapid recharge and charge retention. Ovonic modules have been subjected to rapid recharging and meet the USABC goals of recharge from a 40% SOC to 80% SOC in 15 min, with a charge acceptance > 99%. Charge retention for current modules of > 90% for 48 h exceeds the USABC goal of 85% charge retention.

Perhaps equally important as battery performance is that these batteries are manufacturable using already established manufacturing processes. Energy Conversion Devices and General Motors have joined together in a joint venture, GM Ovonic, to commercialize and manufacture these batteries for EV customers [25]. Prototype batteries are currently being constructed at our Troy, MI, sample build facility for customer vehicle applications. GM Ovonic is validating the manufacturing processes and implementing the quality systems needed for high reliability at this facility. Particular focus today is on reducing the material, labor, and processing costs for this battery. Advanced cell designs optimized for manufacturability, together with advances in battery active materials, are projected to lead to significant cost savings as production volumes increase. GM Ovonic is projecting that, in commercial scale production, batteries can be manufactured for \$200 to \$250 per kW h. Further advances in battery technology are currently under evaluation at Ovonic that will result in higher specific energy and reduced costs to meet the aggressive cost targets required for a market driven EV.

7. Summary and future work

Today, Ovonic nickel/metal hydride batteries for consumer electronic applications are in high volume commercial production around the world by our growing network of licensees. Ovonic batteries for EVs are being demonstrated in a wide variety of vehicle types in the US, Europe, and Asia. GM Ovonic has established prototype manufacturing and will be scaling-up battery production to meet market demand while actively pursuing development programs to reduce battery cost.

Ovonic batteries today offer high specific energy and power with long cycle life, low self-discharge, wide operating temperature range, and quick recharge. Next generation products will offer even higher performance, outperforming other advanced batteries such as lithium-ion at lower cost without the need for complex protective circuits required for safe operation of lithium-ion batteries.

Researchers at Ovonic, and our parent company Energy Conversion Devices, continue to develop advanced materials for negative and positive electrodes that will provide for higher specific energy and lower cost batteries. The goal of 95 Wh kg^{-1} has already been achieved and it is believed that specific energies approaching 120 Wh kg^{-1} will be reached in the near future.

Ovonic is continuing to look at new markets and applications for this battery technology. We have already demonstrated the application of this technology for such forms of personal transportation as scooters and bicycles and several licensees are developing commercial products for these applications. Stored energy for off-grid power or emergency power is another exciting application for the nickel/metal hydride battery. As technology advances and costs are reduced, other applications and markets are certain to open up.

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