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Comparison of NiMH and Li-ion Batteries in Automotive Applications

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Abstract—The pressing need to decrease the greenhouse gases and to improve the efficiency of the existing fleet of vehicles it is imperative that they use some cleaner energy to run the vehicle. Electrical energy can be used in addition with gasoline used by the internal combustion engine of a conventional vehicle to supplement the incremental demand of power above the average power required by the vehicle. This requires for an on-board energy storage system and batteries like NiMH and Li-ion have proven to be efficient storage devices. This paper provides a comprehensive comparison of these batteries used in hybrid electric and plug-in hybrid electric vehicles.

Keywords—Battery Capacity; Battery Specifications; Hybrid Electric Vehicle; Li-Ion Battery; NiMH Battery

I. INTRODUCTION

The increasing demand for the depleting non-renewable energy sources led to the increasing need for research and development for harnessing renewable energy sources efficiently. The worldwide increase in demand for fossil fuels for applications like transportation and the pressing need to reduce the green house gas emissions has fostered the meteoric development in electric and hybrid vehicle (HEV) technology. Using electric energy for transportation purposes will help reduce not only the green house gases but also the dependency on conventional fuels. Using batteries as a source of electric energy along with an internal combustion engine (ICE) supplying the average power required by the vehicle is an efficient way of using the vehicle. Also, less probability for mass production of fuel cell vehicles makes the HEVs a viable near term option to reduce the green house gases and also decrease the dependency on foreign oil resources [1].

Hybrid vehicles that can be charged externally to displace some of their fuel are called plug-in hybrid vehicles. Plug-in hybrid electric vehicles (PHEV) are a special class of hybrid electric vehicles whose on-board electrochemical storage unit (say a battery or an ultra capacitor or a flywheel) which can be recharged with electricity from an off-board source of energy (like the electric power grid itself or from an independent power producer). If the electricity produced is from renewable sources of energy like solar, wind power, bio-gas, then electric vehicles can reduce gasoline requirements and mitigate global warming. Generally, these vehicles are plugged in to the grid during off-peak times for power

demand like during the night time to charge the vehicle. PHEVs can be operated in three modes namely, all electric, all gasoline and in battery-gasoline modes. These vehicles have higher efficiency, are less dependent on foreign oil and are more environmentally friendly than gasoline vehicles.

A hybrid vehicle has the advantages of both gasoline power and electric power. These vehicles have an internal combustion engine (ICE) and an electric motor powered by a battery. Electric motor assists in starting and accelerating the vehicle and hence the user experiences a quieter start of the vehicle. The hybrid electric vehicular technology makes the best use of the energy that would have been otherwise lost during braking to recharge the battery. HEVs are available in about fifteen different models in United States, Europe and Asia. HEVs have these two designs connected in three different configurations – series, parallel and the split. A power electronic interface converts the battery's DC power to AC power for the motor and the generator's AC power to DC power which is used to recharge the battery pack [2]. Owing to the limited life cycle of the batteries, an efficient on-board energy management system is required to monitor the amount of charge in the battery and keep it within acceptable limits so as to help the battery last for the life of the vehicle. A battery system is one of the most important components of a hybrid drive train and is the main cost determining factor for PHEVs as they constitute most part of the price of the vehicle.

The main components of the hybrid electric vehicle are: ICE, electric motor, transmission, battery pack, fuel tank, and an energy management system. It is very important that each of these parts work in perfect coordination. In any HEV, fuel is conserved by using an electric motor that assists ICE during acceleration and harnesses kinetic energy during braking to recharge the battery. This requires for an efficient power management scheme which uses a smaller IC engine and improves the acceleration.

A battery is an electrochemical device which converts electrochemical energy to electrical energy. Many mid-term and long-term battery options were investigated by the United States advanced battery consortium (USABC). A battery weighs about 25 – 75% of the vehicle by weight, volume and cost in HEVs. The desired features for a good EV battery are high specific energy, high specific power, high charge acceptance rate, long cycle life, long calendar life, low self-discharge rate, low cost, and recyclability. Initially, HEVs used lead acid batteries

but with recent advancements in technology NiMH and Li-ion batteries are being used predominantly.

Though calendar life and cost are the most important requirements of batteries used in HEVs, they can be compared based on cost, size and weight, power requirements, number of cells in a battery pack and the available peak power, cell chemistry and geometry, specific energy and power density, charging and discharging cycles, cycle life and calendar of the battery, VI characteristics, state of charge, resistance to overcharging, efficiency, environmental impacts and recycling methods, temperature dependent performance, and safety certifications based on impact, heating, crush, nail penetration, and overcharge tests. In this paper a comparison of NiMH batteries and Li-ion batteries used in automotive applications is presented. Some of the important long term goals set by the USABC for advanced battery system are mentioned in Table I.

TABLE I.
DESIRED CHARACTERISTICS OF ANY HEV BATTERY PACK

Desired characteristics	Units	Value
Power density	W/L	460
Specific power	Discharge 80% DOD/30secW/Kg	300
Energy density	Wh/L	230
Specific energy	Wh/Kg	150
Total pack size	kWh	40
Life	Years	10
Normal recharge time	Hours	6

TABLE II.
COMPARISON OF NiMH AND LI-ION BATTERY [4]

Parameter	NiMH battery	Li-ion battery
Gravimetric energy density	60-120	110-160
Fast charge time	2-4h	2-4h
Resistance to overcharging	Low	Very low
Cell voltage	1.25V	3.6V
Maintenance Cycle	2 to 3 months	Not required
Cost (for a 7.2V, in US \$)	60	100
Commercially available since	1990	1991

This paper compares the advantages and disadvantages of using NiMH batteries or Li-ion batteries in hybrid electric vehicles. Section II presents the comparison of these batteries based on their chemistry, cost, power requirements, number of cells and the peak power available, cell chemistry and geometry, specific energy and specific power, charging and discharging cycles, cycle life of the battery, V-I characteristics, state of charge, resistance to overcharging, efficiency, environmental impacts and recycling methods, and temperature dependent performance.

II. COMPARISON OF TWO BATTERIES

NiMH and Li-ion batteries have their own advantages and disadvantages with respect to charge acceptance,

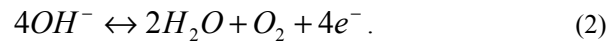
calendar life, energy density, efficiency, cost and environmentally friendliness. Though excellent high rate charge acceptance, high power density, high specific power, long calendar life and efficiency are the desired characteristics of batteries used in automotive applications, cost and safety determine their practical applicability [3]. Also, these batteries add an extra 200 to 300 lbs to the vehicle which directly affects the performance and efficiency of the vehicle. Honda Civic is one of the HEVs which use Li-ion batteries and Toyota Prius uses the NiMH battery technology for its energy storage system. This section provides a comprehensive comparison of the two types of batteries with respect to their automotive applications. Table II shows the comparison of these battery technologies in with respect to gravimetric energy, fast charge time, resistance to overcharging, cell voltage, maintenance requirements and cost.

A. Chemistry

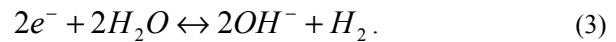
NiMH battery: The anode is made up of rare-earth or nickel alloys, and the cathode is made up of potassium hydroxides. NiMH batteries have great importance in the industrial and consumer applications due to their design flexibility, environmental acceptability, high power and energy densities, and most importantly cost competitiveness [2]. In hybrid electric vehicles NiMH battery technology is the dominant battery technology as they meet the wide ranging requirements set by automotive companies. The following features have established NiMH batteries in the hybrid vehicles industry: flexible sizes ranging from 30 mAh to 250 Ah, safe operation at high voltage, flexible vehicle packaging, safety in charge and discharge, requires no maintenance, has excellent thermal properties, capability to use regenerative braking energy, simple and inexpensive charging and electronic control circuits, and environmentally acceptable and recyclable materials [5]. This battery technology uses non-toxic and recyclable materials. The overall chemical reaction is



The equation describing the chemical reaction for overcharge is



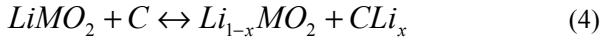
The equation for over discharge is



Li-ion battery: Li-ion rechargeable batteries have proven excellent performance in portable electronic devices and several other medical devices [6]. These batteries have high specific energy and power densities and hence they are being considered by automobile industry for use in their hybrid and electric vehicles to meet their specific battery requirements. Research and development is mainly focused on to improve the energy capacity, density, cycle life and performance of these batteries with enhanced safety [6]. The advantages of using lithium ion batteries are: light weight, high volume capacity, high specific energy, good high-temperature performance, low maintenance, and low self discharge. The certain disadvantages of these batteries are they have a moderate discharge current, require protection circuit,

subject to aging and transportation regulations, and are expensive.

The chemical reaction describing its operation is in 4. This battery technology also uses non-toxic and recyclable materials which have low heat generation and minimum memory-effect. There is a possibility for over-discharge which can be dangerous and may lead to an explosion. In comparison with NiMH batteries, these are more risky in terms of safety, low self discharge and high costs [3].



B. Specific energy and specific power

Most passenger vehicles have 75-100 mile ranges which use about 29-32 kWh batteries. Specific energy of the NiMH batteries used is about 50 Wh/Kg to 64 Wh/Kg while it is around 90 Wh/Kg for the Li-ion batteries. The near-term target of USABC is to attain a specific energy of about 95 Wh/Kg with a total weight of about 450 Kg. For example, a 20-mile range HEV operates as an EV for the first 20-mile drive range calls for a battery capacity of 8 to 14 kWh. Fig.1 shows the specific power comparison of the NiMH and Li-ion batteries. It is observed that the specific power of the Li-ion battery is twice that of the NiMH battery at the high power to total energy ratio.

Figs. 2 and 3 show the specific energy comparisons of NiMH and Li-ion batteries produced by various manufacturers. Also, medium power batteries have high specific energy and high power batteries have low specific energy. There are many products available in the market while there is no proper method to evaluate the effectiveness of these products.

Figs. 4 and 5 show the specific power comparisons of NiMH and Li-ion batteries produced by various manufacturers. Also, medium power batteries have low specific power and high power batteries have high specific power. It is difficult to prove the claim of the battery manufacturers and it demands for a yardstick to clearly identify the performance of these batteries.

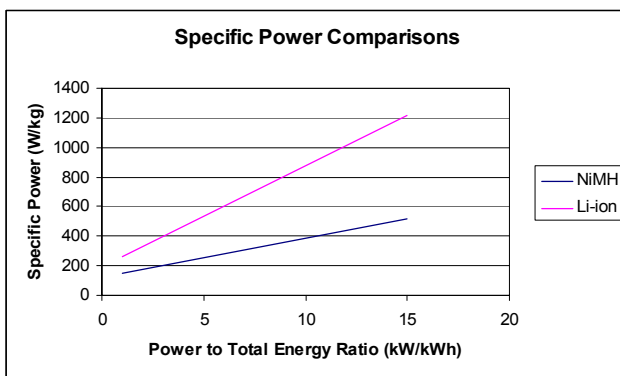


Fig. 1. Specific Power comparisons

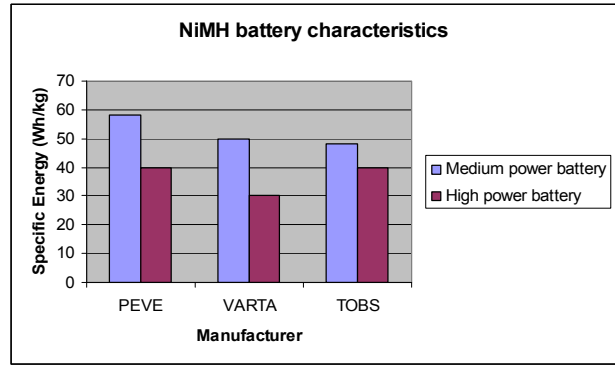


Fig. 2. Specific energy comparison of high and medium power NiMH batteries by various manufacturers

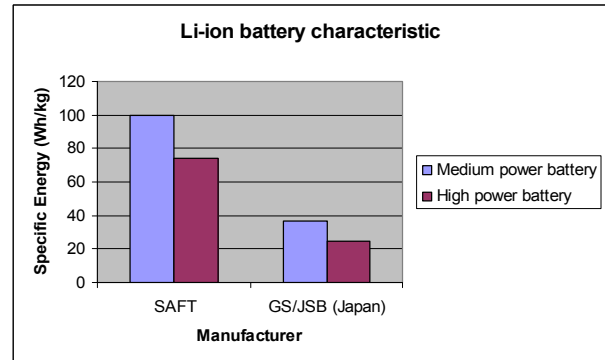


Fig. 3. Specific energy comparison of high and medium power Li-ion batteries by various manufacturers

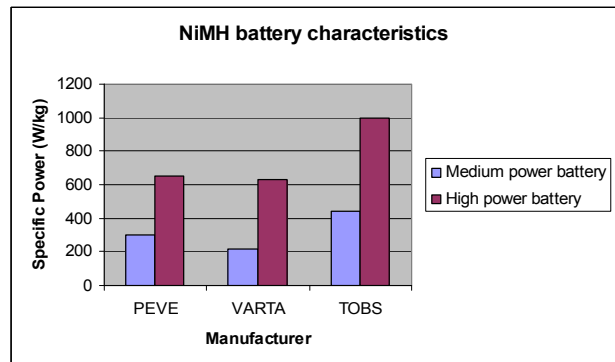


Fig. 4. Specific power comparison of high and medium power NiMH batteries by various manufacturers

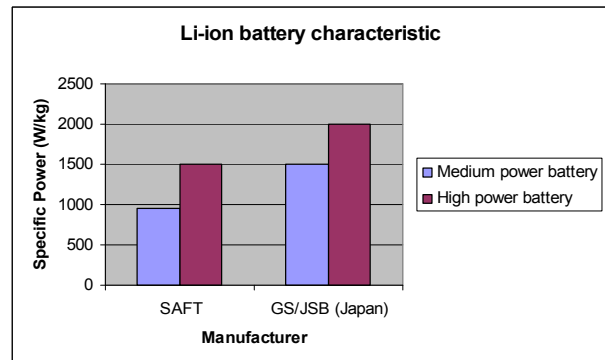


Fig. 5. Specific power comparison of high and medium power Li-ion batteries by various manufacturers

B. Charging and discharging cycles

NiMH batteries have limited service life of about 200-300 cycles if repeatedly discharged at high load currents. The best operation of these batteries is achieved with load currents of 0.2C to 0.5C (one-fifth to one-half of the rated capacity). NiMH battery has high self discharge which can be improved by the addition of new chemical additives which results in low energy density [7]. Fig. 6 shows the self discharge of NiMH battery stored at 100% SOC versus time in hours. It is observed that for a particular make of battery, it loses about 32% of charge if stored for about 80 hours. This calls for more research and development in this area. Fig. 7 shows the discharge characteristics of a Li-ion battery. The cell voltage drops to approximately 2.4 V after about 1000 charge and discharge cycles.

C. Cycle life and calendar of the battery

The battery is more stressed in HEVs than in conventional EVs. In a HEV, the battery is fully charged initially and the vehicle is operated in a charge depleting mode until the charge reaches a predetermined low state-of-charge, after which it will be operated in charge-sustaining mode. With this additional stress on the battery, the calendar life is more negatively influenced [1]. The actual calendar life of these batteries either for NiMH or Li-ion technology is not known accurately and there is always a risk for reduced calendar life in comparison to those when used in conventional batteries. Also, the performance of the battery slowly deteriorates with the degradation of its electrochemical constituents. Extreme temperatures, overcharging, discharging, rate of charge/discharge, and the DOD of battery cycles are the most important factors that lead to degradation of the life of the battery [8].

The calendar life of NiMH batteries can be improved by regular maintenance with full discharge to prevent crystalline formation [7]. While Li-ion batteries do not need any regular maintenance and has no periodic discharge is needed and has no memory.

Li-ion batteries are subject to aging, even if not in use. The best way to store these batteries is to store it in a cool place at a 40% SOC helps reduce the aging effect [9]. Early and unexpected battery failures should be eliminated and also its average service life can be extended by avoiding abusive conditions [10].

Reactions of active materials with electrolyte at electrodes interfaces, self degradation of active materials structure on cycling, aging of non active components, are the main reasons for aging in Li-ion cells. These phenomena lead to power and/or energy losses [12].

D. V-I characteristics

Li-ion battery requires protection circuit as protection circuit is required to limit voltage and current [9]. A battery with a storage system voltage of < 42V is either a micro- or a mild- hybrid. A voltage level of >42V like in a Honda IMA makes it a medium hybrid with additional capabilities like medium power assist and full regenerative braking. A voltage of >200V like in a Escape hybrid has additional features like full power assist and an electric drive [10].

E. State of charge (SOC)

Memory effects in NiMH battery systems can significantly reduce the usable power in HEV applications as it reduces the usable SOC window of operation to a significantly smaller than the 100% charge/discharge SOC window capability of the battery [10]. Fig. 8 shows charge and discharge characteristics of a NiMH battery. It is observed that there exists a constant voltage profile for this battery from 80% - 30% SOC and hence this can be considered as the operating window for this battery. Fig. 9 shows the discharge characteristics of a Li-ion battery.

The battery used in PHEVs need to be fully charged every night before it is ready for the next drive the following day and there is a potential risk hazard for larger batteries say, Li-ion, when charged in a residential area [1].

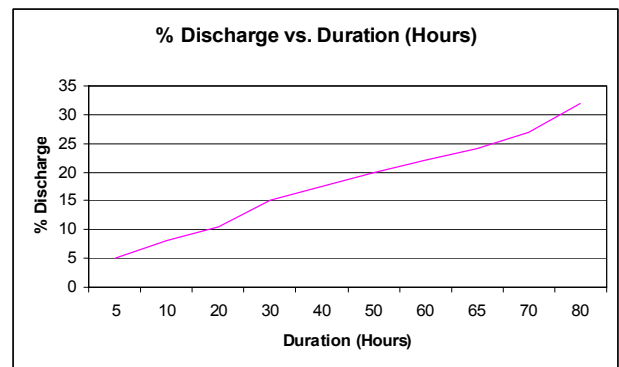


Fig. 6. Self-discharge of NiMH battery stored at 100% SOC

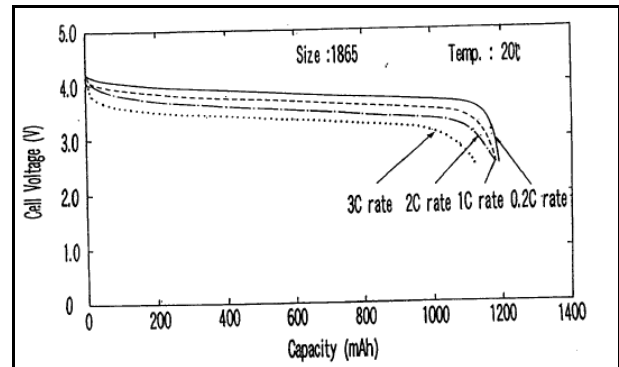


Fig. 7. Discharge characteristics of a Li-ion battery

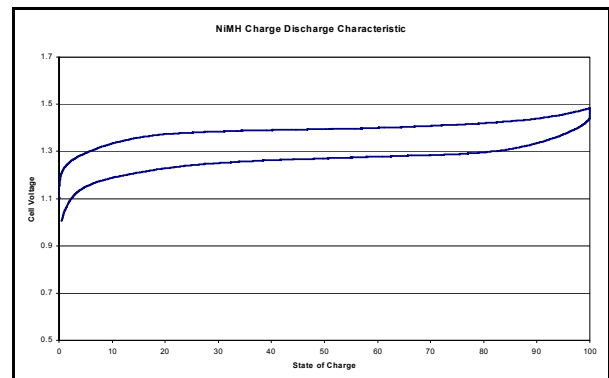


Fig.8. NiMH charge/discharge characteristics

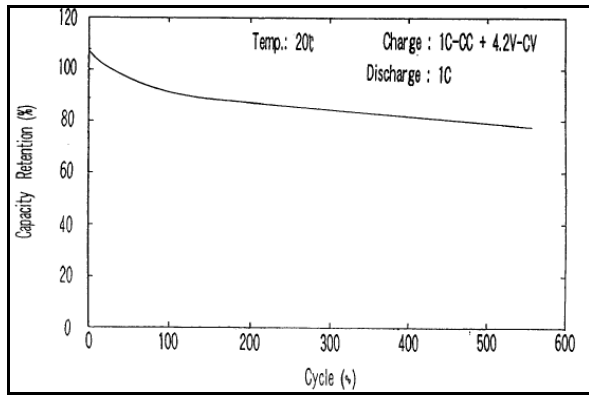


Fig. 9. Cycle characteristics of a Li-ion battery

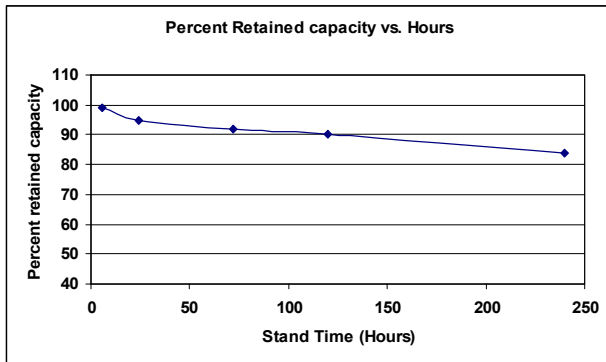


Fig. 10. Capacity retention of an EV NiMH battery at different temperatures

F. Environmental impacts and recycling methods

NiMH batteries do not have regulatory control, contains only mild toxins, is environmentally friendly and is profitable for recycling. Shipment of high capacity Li-ion batteries is subjected to regulatory control [9].

G. Temperature dependent performance

Temperature has a double effect on the performance of the battery. As the temperature increases, the efficiency of the battery is increased while the battery life is reduced. With the increase in temperature, the effective internal resistance decreases which improves the efficiency. Also, increased temperature might cause faster chemical reactions, and in might increase the rate of unwanted chemical reactions that which cause permanent damage to the battery [8]. Though NiMH batteries are capable of long life cycles, the main failure is negative electrode corrosion which is proportional to the temperatures, that causes cells to dry out and lose their power capability and capacity. Thus, a proper temperature management system is required to achieve good charging efficiency, long life and high reliability of these batteries [12]. Fig. 10 is a graph between charge acceptance (as a percentage of nominal capacity) and temperature (in °C) [12]. NiMH batteries show unsatisfactory performance at high or low temperatures [1].

H. Cost

The ever fluctuating gas prices averaging to about \$3.00 it has become very important for the automotive

industry to handle this situation and find effective and efficient low cost alternatives. The total cost of a battery is mostly comprised of raw-material costs and manufacturing costs. There are five stages in production and different costs are associated with each stage of battery production. Electrode fabrication followed by cell, module, and pack assemblies and finally testing are the different stages and the corresponding costs associated with the same are considered to be the part of the manufacturing costs [12].

Nickel which is the basic raw-material for NiMH battery is either melted from sulphide ores or is obtained from a hydrometallurgical process. For the case of Li-ion batteries, lithium need be produced in its metallic form but is required in lithium carbonate form for it to be used in HEVs. 96% of the total cost of a Li-ion battery is the raw-material costs for a high-energy cell and about 83% is the total share of the cost of a high power Li-ion battery. The average annual price of Nickel has been rising slowly for the last 40 years from \$8/lb in 1958 to \$19/lb in 1998 based on 1992 dollars. Lithium in metallic form is more expensive than in the carbide form. The average annual price of Lithium carbonate has been widely varying from about \$3.2/lb in 1958 to about \$2/lb in 1998 based on 1992 dollars. Recycling costs of the battery also influences the quantity of batteries produced and thus indirectly affects the price of the battery [5].

NiMH batteries are priced at \$250 to \$1,500 per kWh in 2007 US dollars, hence the total price of the battery pack for a hybrid varies anywhere from \$600 to \$3,000 per vehicle. Also, this technology has limited cost reduction potential as the prices of Nickel, the main component of these batteries are increasing [1]. The cost of Li-ion battery pack required for automotive applications is higher than for NiMH batteries of the same capacity. With more advanced and proven Li-ion technology for automotive applications, cost will probably not be a road-block as they would decrease with mass production. In all, the cost of the PHEV batteries will be around \$5,000 to \$7,000 per pack which is about 3 to 5 times the average cost of today's HEV batteries. In particular, developing a low-cost, high power Li-ion battery for HEV with higher voltage, larger capacity and smaller size along with a long calendar life is very challenging [1].

The battery cost is comprised of two parts, costs associated with the manufacturing and material costs. Manufacturing cost depends on production volumes and manufacturing technology. Battery material costs are mainly due to electrodes, separator, cell hardware and others [13]. The proportion of the battery costs by these components is as shown in Fig. 11. The MH electrode weighs about 45% of the total battery and its cost share is also similar to this proportion and research is on to reduce both the weight and cost of these electrodes.

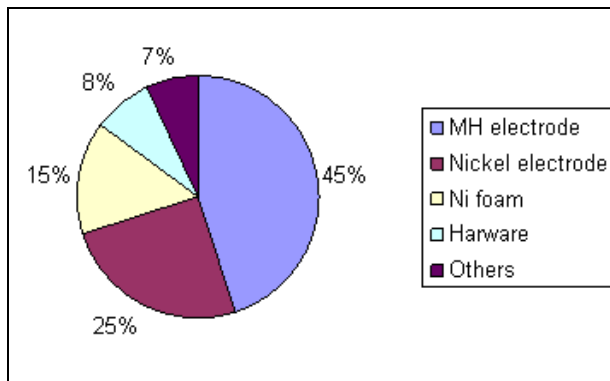


Fig. 11. Cost distribution of NiMH battery components

III. CONCLUSIONS

Plug-in hybrid electric vehicles have the potential of entering the United States power grid but the extent of their penetration will depend on economics and to some extent the performance of these vehicles [14]. The key remaining concerns for the growth of this part of automotive industry is battery size, cost and performance. NiMH and Li-ion batteries are the dominating and potential battery technology for higher efficiency HEVs. Li-ion is currently in the research and development stage has many promises for improved performance and cost [10]. Li-ion batteries are expected to provide a 40-50% battery weight reduction, a 20-30% battery volume reduction and a slight increase in efficiency. Additionally, Li-ion batteries might become available at a relatively lower cost than Ni-MH batteries for automotive applications.

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