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Efficient Batteries for Transportation Applications

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ABSTRACT

This paper reviews and analyzes the current and future battery technologies suitable for transportation applications. The success of battery-enabled hybridization of gasoline and diesel power-trains in the past decade has clearly established it as the most credible alternative to the conventional propulsion systems. The current enthusiasm for electric vehicles further accentuates this success.

In this paper, we compare the performance of a number of established and emerging battery technologies against the now well-established performance targets for electric-drive vehicles. Lithium-ion cells' superior performance and life are described, as are requirements for supplantation of NiMH cells in vehicles. Trends are discussed in technology development, which has largely been achieved through insertion of Li technologies in consumer electronics.

Recent developments have given rise to several variants of the Li ion chemistry. We compare these technologies from performance, life, abuse-tolerance and cost perspectives to facilitate selection of appropriate battery technologies for a particular application. Key mechanisms controlling performance degradation as well as life are also discussed. Issues related to high volume manufacturing of large-size batteries are very important and are discussed in the context of likely global demand, and scalabiity of various processes. Finally, resultant cost and calendar-life are discussed, along with cycle-life analysis, recyclability, and business models for efficient, and green reclamation and reuse of materials.

INTRODUCTION

Battery-based hybridization of gasoline and diesel engines will play a major role in our quest for environmentally friendly propulsion systems that also reduce our dependence on fossil fuels for the next 15-20 years and beyond. There are several reasons for this assertion. Hybrid electric vehicles (HEV's) have demonstrated that the technology works in the hands of real customers and have thus successfully completed the first phase of market acceptance (early adopters) for a new automotive technology. In contrast to early concerns of the drivetrain complexity challenges posed by hybridization, these vehicles successfully capture braking energy, with remarkably few maintenance complications or issues. In fact, hybridization is the only "new" technology, as opposed to incremental improvements to gasoline and diesel engines that will continue to be made, that has gone through this phase which typically takes 5-10 years because of automotive design cycle times. The consensus market prediction for hybrid vehicles is ~1M vehicles sold in 2010, with PHEVs and EVs following closely on the heels of successful HEV market penetration

Furthermore, hybridization is very compatible with and complementary to the emerging HCCI (homogeneous charge compression ignition) technology for gasoline engines **[1]**. This is because hybridization can be effectively used to keep the gasoline engine out of the torque-speed regions where HCCI operation may be difficult. This compatibility is very significant since an HCCI-Hybrid would allow the fuel economy (FE) benefits of a diesel hybrid to be realized without having to switch fuels and having to deal with the diesel after-treatment issues associated with achieving SULEV (Super Ultra Low Emission Vehicles) emission levels. In addition, hybridization can synergistically work with valve-disabling technology for truck applications that require a large engine for towing capacity.

Unless distorted by strong legislative actions, a plug-in type HEV (PHEV) or a range-extended EV (REV) such as the Chevy Volt is more likely to be the vehicle of choice than a pure EV because of the PHEV's ability to overcome the range limitations of a pure EV. It should be noted that unlike most of the HEV's on the road today which do not need to be plugged in, widespread use of PHEVs and REVswill require charging infrastructure to be set up similar to that required for pure EVs **[2]**.

For HEVs, PHEVs as well as REVs, the most significant challenge for becoming mainstream is affordability: both for the customer and the vehicle manufacturer. This assumes that the new HEV entries continue to deliver what they promise both in function and reliability and that customer education and expectations are properly managed. For a medium size, full hybrid vehicle, capable of delivering ~100% FE improvement on the Federal

Urban Driving Schedule (FUDS) and discernibly improved acceleration (similar to an engine upgrade), the affordable price premium can be estimated to be ~$3500 for a retail customer and ~$5000 for a fleet customer (FE only), with a 5-year payback period.

At this juncture, the success of the hybrid vehicle has accelerated the move to electrified, rather than mechanically actuated drivetrains. This step, in which motors replace the majority of engine power, offers substantial possible improvement in overall efficiency, given the increase in accessory loads (on board computing, navigation/communication, etc.). It is likely that battery systems' contribution to overall vehicular power, will only grow. Even at present, in "light" hybrids, the battery has significant impact on cost, reliability and life, and to a lesser extent, on package space and weight. For example, as a rule of thumb, the battery system represents ~1/3 of the overall incremental cost of hybridization, which leads to a battery cost target of $1200 - $1500 for high-volume production (>100k packs/year) as indicated in **Table 1**. The Table also lists some of the other important battery attributes used by the US Automotive Battery Consortium (USABC) to drive battery technology development for HEVs and PHEVs.

It should be noted that depending upon the battery type, some of these attributes become critical for sizing the battery for a vehicle, whereas others may be available for "free" when the design/size of the battery is driven by other requirements. For example, most batteries designed and sized to deliver the power levels shown in **Table 1** will be able to "shuttle" more than the 0.3 kWh of energy identified in **Table 1** within a state-of-charge (SOC) range of 25% - 75%, which is the typical SOC operating window for HEVs. This also implies that $/kWh is not a good metric for comparing HEV battery alternatives, even though it is very useful and widely used in consumer electronics. In addition, there will be tradeoffs involved between certain attributes. For example, for certain Li-ion battery chemistries there may be a tradeoff between calendar life and abuse tolerance. There may also be tradeoffs between battery attributes and characteristics of other vehicle systems.

Table 1

Desired Battery Attributes For HEVs and PHEVs

Battery Attribute	Target (HEV)	Target (PHEV, 10 mile range)
10 S Pulse Power (Discharge/Charge)	25 kW / 20kW Charge	45 kW/30kW Charge
Available Energy	0.3 kWh	0.5 kWh (3.4 kWh in the EV mode)
Minimum in/out Efficiency	90%	90%
-30 ºC Cranking Power	5 kW	7 kW
Cycle Life	300,000	300,000 (5,000 in the EV mode)
Calendar Life#	>10 years	>10 years
Weight	<40 kg	< 60 kg
Volume	<32 L	<40 L
Self Discharge	<50 Wh/day	<50 Wh/day
Cost (>100K units/year)	~$1500	~$2400
Operating Temperature	-30 to 52 º C	-30 to 52 º C

Targets adapted from FreedomCar/USABC.

COMPARISON OF BATTERY TECHNOLOGIES

Table 2 compares Ni-MH and Li-ion technologies using attributes similar to **Table 1**. It should be noted that, for either chemistry, there is a tradeoff between energy and power for a given cell design and therefore currently achievable levels of energy and power density shown in **Table 2** are not for the same cell. It is apparent from **Table 2** that for every attribute, Li-ion is either comparable to or better than Ni-MH. Furthermore Li-ion is already at or above the theoretical limit for Ni-MH energy density. Because of current large volume manufacturing of Li-ion batteries for consumer electronics, which are far more environmentally benign than Pb-Acid or Ni-Cd batteries, the industry is also familiar with their recycling requirements and regulations are already in place to handle spent Li-ion batteries.

Table 2

Ni-MH vs. Li-ion

Attribute	Ni-MH	Li-ion
Energy Density (Wh/Kg)	80	200
Power Density (W/Kg)	1600	>3000
Volumetric Energy Density (Wh/L)	200	550
Cost ($/kWh)	350	300-350
Self Discharge (per month), %	15%	5%
In/Out Efficiency (%)	90	> 95
Temperature Range	-10 - 40	-30 - 50
Cycle Life	900 (EV) 300K (HEV)	1000 (EV) 300K (HEV)
Calendar Life (years)	> 10	>10

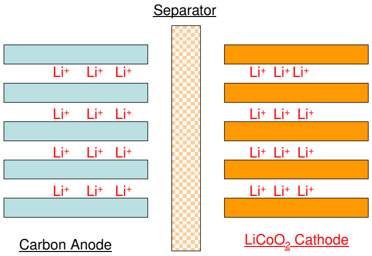
The following factors are further adding to the desirability of Li-ion over Ni-MH for HEV applications. Li-ion technology's advantage in energy efficiency (>95%, **Table 2**) is important not only for the FE improvement resulting from hybridization, but is also directly related to the cost and complexity of the battery cooling system. Improving efficiency from 90 to 95%, for example, effectively halves the required cooling capacity. Li-ion also has an energy/power delivery advantage for low temperature discharge (< -10 ºC) and high temperature charge (>45 ºC).

Calendar-life at high storage temperatures and abuse tolerance were serious concerns for Li-ion technology only a few years ago and were the primary reasons (along with cost) that kept it from being used in the first and second generation HEV's. However, as discussed later, these issues have been satisfactorily addressed, which leads us to conclude that Li-ion is poised to be the battery of choice for the next generation of HEV's and other portable power applications.

LI-ION BATTERIES: DEVELOPMENT AND PRINCIPLE OF OPERATION

The introduction by Sony of Li-ion batteries in 1991 was a landmark event in the field of rechargeable batteries in general and Li battery research in particular **[3].** Instead of using metallic Li anode, as had been the case prior to this, Sony introduced a graphitic carbon as the anode and a metal oxide as the cathode ($LiCoO_2$). Both electrodes work on the principle of intercalation and de-intercalation of Li ions into and out of their layered structures, thus eliminating Li plating and the associated Li dendrites, which have hitherto plagued the development of long cycle-life and abuse-tolerant rechargeable Li batteries. In Li-ion batteries, Li ions leave the metal oxide cathode during charge and intercalate into the graphitic carbon anode. The reverse happens on discharge. The nominal voltage of Li-ion cells is 3.7V, three times that of Ni-MH cells, and the cycling is typically carried out between 3.0 and 4.2V.

Schematic of Li-ion Battery Operation:



$$LiCoO_2 + C_6 = Li_{1-x}CoO_2 + C_6Li_x \quad \text{(Full Reaction)}$$

As shown in Table 2, Li-ion cells are characterized by,

- i. High gravimetric- and volumetric energy densities (>200 Wh/kg and >700 Wh/l)
- ii. Long cycle-life (1000+ full depth-of-discharge cycles for EV-type cells and >300K cycles for HEV-type usage)
- iii. Low self-discharge rate (~5% per month)
- iv. High power (>3000 W/kg)
- v. Good low-temperature performance down to -30°C.

The most common Li-ion cells are the so-called 18650-sized cells, which has a diameter of 18 mm and a height of 65 mm. When introduced in 1991, these cells had about 1200 mAh of capacity. After 15 years, the cell capacity has now been increased to about 2900 mAh, reflecting the significant innovations made both with respect to material properties and manufacturing know-how. The cell price, on the other hand, has dropped by almost a factor of 5, a net 12X gain in $/kWh. Indeed, against many industrial predictions, the cost of commodity Li-ion cells dropped below that of NiMH cells in around 2002. The presumed cost reduction by R&D in commodity cells will likely be repeated in high-performance automotive cells.

PERFORMANCE OF LI-ION CELLS

Fig. 1 shows the typical discharge plots of 18650-sized Li-ion cells, while **Fig. 2** shows the typical cycling behavior of these cells. The data below clearly show that the cells cycle even at the high temperatures of 45 and 65°C.

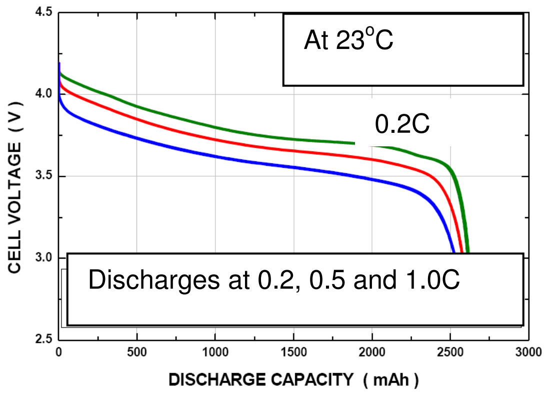


Fig. 1. Typical discharge plots for 2600 mAh 18650 cells.

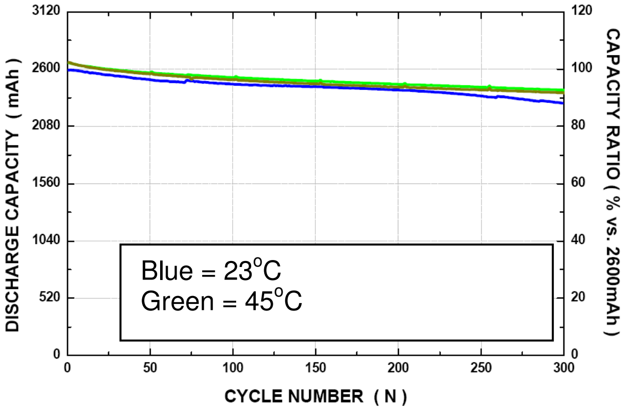


Fig. 2. Typical cycling data for 18650 cells.

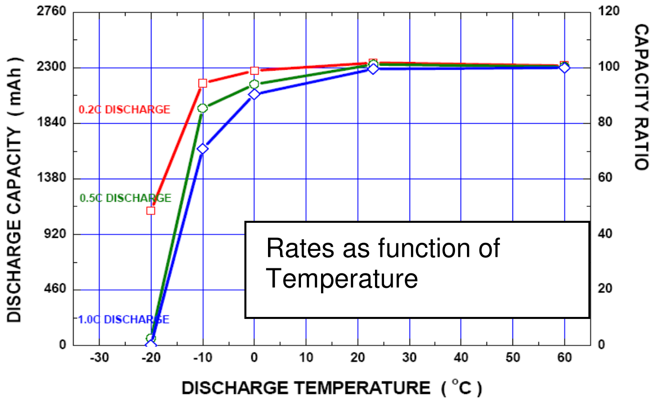


Fig. 3. Dependence of discharge capacity on temperature.

Fig. 3 shows the performance of 18650-cells at different temperatures. We note here that there is in general a reduction of capacity at low temperatures; however, cells for HEVs or PHEVs are designed to deliver cold-cranking power at -30 ºC, as discussed below.

If the more optimistic predictions are realized, and because of the large power demand of vehicles, automotive batteries will quickly become a substantial proportion of the overall battery market, despite the ubiquity of consumer electronics. To wit: with an estimated HEV market of 2M vehicles by 2015, the Li ion battery market share could exceed 35%, comprising 2.3b batteries. Thus, consideration of both performance and availability (cost) of materials are critical in considering the next contenders in battery materials.

Cathode Materials

The capacity (energy) of Li-ion batteries is currently limited by that of the cathode. Therefore, substantial effort has been dedicated to discovery/synthesis of new cathode materials. Cobalt, a strategic metal, is expensive ($30 to $40/kg) and subject to price volatility. Thus, $LiCoO_2$ used as a cathode in commodity cells, such as laptop batteries, is not a contender for automotive applications. In addition, $LiCoO_2$ has inferior abuse tolerance, especially on overcharge and internal shorting. There has, therefore, been continuous attempt to replace this cathode by a less expensive, more energetic one possessing better abuse-tolerance. Efforts in this regard have resulted in several alternative cathode materials. **Table 3** shows key attributes of these cathode materials.

Table 3

Li-ion Battery Cathode Chemistry Comparison

	$LiCoO_2$	$LiMn_2O_4$	$LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$	$LiFePO_4$
Energy	High	Low	High	High
Power	Moderate	High	Moderate	Low
Abuse-Tolerance	Poor	Good	Poor	Very Good
Cost	High	Low	High	High
Low-Temperature Performance	Moderate	High	Moderate	Low
Life	Long	short	Long	Long

To reduce cost, manufacturers of cells for use in cellular phones and laptops are already mixing $LiCoO_2$ with either $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ or $LiMn_2O_4$, or moving to $LiNi_{1/3}Co_{1/3}\ Mn_{1/3}O_2$ to increase energy.

The so-called layered cathodes such as $LiNi_{1-x-y}Co_xAl_yO_2$ or $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$, which have better thermal stability than their $LiCoO_2$ counterpart, are receiving a great deal of attention. The former has good calendar-life and high capacity but is utilized only within a limited high voltage window of up to 4.0V. Beyond that, this cathode displays undesirable characteristics such as gassing and lower abuse-tolerance. Of course, the cost of these materials is an important drawback. Daimler is planning to use the $LiNi_{1-x-y}Co_xAl_yO_2$ cathode chemistry in their S-class SUVs to be introduced later this year. Toyota is reportedly going to use the same cathode in their 1st generation Li ion vehicle batteries.

$LiFePO_4$ appears attractive as a cathode material due to its high thermal stability. A lower operating voltage of ~3.2V, and lower material density has precluded its penetration of the cellphone and laptop markets, in which specific energies (both gravimetric and volumetric) are important. The power capability of this chemistry has been significantly improved by A123 Systems, using nano-architectured materials, and these batteries are being successfully used in power tools and implemented now in HEVs and PHEVs. Cost and long-term calendar life are under study.

$LiMn_2O_4$ has the highest power among all the Li-ion cathode materials, and also carries the advantages of high stability, resisting the tendencies to thermal runaways typically associated with layered compounds. Manganese is abundant, and low cost. Limited calendar-life, which originates from the dissolution of $LiMn_2O_4$ at high temperatures has recently been surmounted via modification of its chemistry as well as the use of different additives by LG Chem/CPI. Data indicate that this modified spinel cathode chemistry can comfortably deliver >15 years of calendar life; Hyundai Motors is planning to use these batteries in their HEVs to be launched in 2009.

Low-Temperature Performance

Currently available data indicate that requirements such as cold-cranking for automotive applications can be satisfied at temperatures as low as -30°C. Despite superior power compared to Ni-MH batteries, there are concerns that current Li-ion batteries might have some issues of regen power at low-temperatures for use in HEVs and PHEVs. A sub-ambient temperatures there is a risk of Li plating at the carbon anode due to slow intercalation kinetics especially at very high rates. To address this issue, several strategies are being simultaneously studied, including the use of alternative anodes such as Li titanate. This anode allows fast charging and impressive cyclability at low-temperatures. This is attributed to the lack of strain in the titanate anode on cycling. Reduced specific energy, due to lower cell voltage, however, remains a challenge especially for PHEV and REV applications.

Mechanisms controlling life:

Both calendar and cycle life must be considered in design of batteries for automotive applications. Failure is manifested either as loss of capacity (energy) or of power. Loss of capacity is the result of a loss of available Li ions, which in turn is the result of the following main factors:

a. Degradation of cathode structure. We note here that the cathode is the initial and sole source of cyclable Li in the cell.
b. Generation of passivation film on the electrodes, which impedes the access to electroactive sites. We note that these occur on both cathode and anode, and their growth, composition, and direct linkage to performance are presently poorly understood.
c. Electrical isolation of active sites in the electrode due to mechanical degradation of electrode structure in course of cycling. It should be pointed out here that though localized particle failure has been linked to reduced performance, causation and failure progression have not yet been established.
d. Lithium plating on the anode

Loss of power is correlated with increases in cell resistance. Such losses originate at interfaces between anodes/cathodes and electrolyte, active materials and current collectors, and breakdowns in primary electrode structures which lead to poorly connected materials. Interfacial alterations, in turn, have their origins in reactions with electrolyte (cathode), and continuous accumulation of reaction products (anode). As a result, the stability of the anode and the cathode interfaces in contact with the electrolyte governs the key processes leading to power losses. It is important to note that mechanics, kinetics and transport properties are tightly linked: high rates of operation increases local (particle-scale) stresses in electrodes, resulting in mechanical damage, which in turn leads unavoidably to electronic transport losses. Thus, the load profile the battery experiences strongly affects its ultimate failure mechanism.

Nonetheless, the electrochemistries described here are sufficiently mature to be suitable for vehicles at present, though costs are still too high to allow full penetration of PHEVs and REVs without additional development work. While mainly proprietary, data from various battery developers indicate that all the chemistries mentioned above are capable of demonstrating calendar-life > 10 years. This is a significant milestone for the development of Li ion batteries for automotive applications, since adequate calendar-life was a key prior concern. Since the procedures to determine calendar-life rely on accelerated testing methodologies (that is testing 15 year life in 1-2 years at elevated temperatures and using Arrhenius-type equations), estimation of life still remains a challenging task.

Abuse-tolerance:

Li-ion batteries possess very high energy densities and they may contain cathodes which are vulnerable to decomposition at high temperatures. In addition, they use electrolytes containing solvents with low flash-points. Consequently, there are natural concerns with respect to the abuse-tolerance of these batteries. Conditions under which Li-ion batteries have shown potentially hazardous behavior are internal-shorts, thermal excursions and overcharge. Under these conditions, the separator melts, leading to hard shorts between the anode and cathode. The released energy then heats up the cell components triggering a set of highly exothermic reactions which can lead to thermal runaways.

The abuse-tolerance of Li-ion batteries is critically dependent on the choice of the cathode. While cathodes such as $LiCoO_2$ and $LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$ are vulnerable to thermal runaways during overcharge and internal shorts due to the release of oxygen, $LiMn_2O_4$ and $LiFePO_4$ are much more robust, releasing little or no oxygen. This attribute of the latter two cathodes is highly attractive for large-format batteries such as those for HEVs and PHEVs.

While challenging studies are currently underway to replace the present low flashpoint organic solvents in the electrolyte preferably with nonflammable solvents, without sacrificing performance and life, excellent progress has been made with respect to developing a separator which is mechanically superior to the conventional separators and resistant toward internal shorts. These separators reinforced by nanoparticles have much higher puncture strength (> 5 times than baseline) and do not allow the propagation of localized hotspots stemming from the presence of metal debris left during manufacturing processes such as welding [4] or due to separator weak spots. The concept of shutdown separator has not proven to be useful in high power automotive batteries.

Use of electrolyte additives, though elegant in concept, has not yet proven to be useful in improving abuse-tolerance without affecting cell performance. Oftentimes use of such additives comes at a significant cost to either power or life.

To make Li ion batteries abuse-resistant, various other concepts of protection mechanisms, both at the cell and system level, are also being implemented. For example, the PTC (positive-temperature coefficient) and CID (current-interrupt device) are two safety mechanisms which have long been a part of small Li on batteries. The former changes resistance at a set temperature or current and prevents any thermal runaway. The CID interrupts the current flow between the cathode tab and the positive terminal when the internal pressure inside the cell reaches a certain value. An additional device, the vent, is also built inside the cell. This releases when the cell pressure exceeds some set value. Other approaches include the use of electronic controls.

We believe that these devices might not be enough to protect large, high power cells during abuse situations when large amounts of heat is rapidly released, melting the separator, causing runaways.

Manufacturing of Li ion batteries

The manufacturing of Li ion batteries generally involves the following complex and carefully controlled steps.

a. Selection of the appropriate electrode materials and design of electrodes and cell parameters with due considerations given to the desired energy and power targets as well as abuse-tolerance and cost.
b. Manufacturing of positive and negative electrodes. This is the key step in determining the performance of the cell. Electrodes are then calendared and sized to the desired dimensions.
c. Fabrication of electrode stacks using separators and placing them in respective cases, filling them with electrolytes followed by sealing.
d. Subject the cells to the so-called “formation” step. This involves the initial charging step.
e. Cycle, store, sort and ship.

Each of the above steps is associated with a number of proprietary and R&D intensive steps for a company to decide on a particular material or process. Each company has its own sets of cell components and processes, either developed internally or outsourced, based on target application, performance, price and process considerations. Many of the key processes such as manufacturing of electrodes and formation are company know-hows developed over a long period of time oftentimes through trial and error and are guarded closely.

The manufacturing of small-size Li ion cells is driven by the demands and requirements of the portable electronics market such as laptop and cellphones. The worldwide market for cellphones (which typically use a single cell) increased to about 1.02 billions in 2006 (up about 23% from 2005) while that of laptops (using 6 to 8 cells) was over 70 million in 2006, resulting in shipment of over 2 billion units of small-size Li ion cells. Indeed, worldwide, around 10 billion electronic devices can be approximated as consuming 80TWh/year. As the cellphone and laptop markets are enjoying double-digit annual growth in volumes, it is expected that similar growth will also be recorded for the production of small-size Li ion cells. With a US automotive fleet of 220 million vehicles, the total power consumption can be approximated to be 4,700 TWh/year against the worldwide automotive fleet of 790 million vehicles (2005), which is expected to draw around 16,000 TWh/year. Presently, automobiles consume greater than two orders of magnitude more energy than engineered devices powered by batteries worldwide. Thus, incursions of HEVs, PHEVs, REVs and EVs into the automotive markets will quickly make automotive needs the most important force driving the battery markets.

The batteries that power future vehicles will doubtless be large-format cells (≥5Ah), as safety concerns are allayed by the strategies described earlier. These larger format cells offer substantial benefits in gravimetric properties, since there is a reduction of parasitic mass in casing materials.

The general steps described above are common to the manufacturing of large-sized cells. However, there are few aspects of large cell design which require careful considerations. Large cells require electrodes several meters long, winding/handling of which is not trivial. In addition, current collection from a long electrode using multiple tabs is tedious and a manufacturing challenge. One way to circumvent these two issues is to employ plate-type electrodes using a prismatic case. Selection of proper cell parameters which optimizes electrical and, more importantly, thermal and abuse-tolerance characteristics is especially very important for the manufacturing of large-format batteries.

Although it is conventional to use metal cans (both cylindrical and prismatic) for fabricating large cells, preference was given by companies such as LG Chem, NEC Lamilion and Enerdel, among others, to adopt laminated packaging for this purpose **(Fig. 4)**. Metallic cans involve a multitude of processes for fabrication, terminal connections, gas vents, insulation etc. As a result, even though a can could be inexpensive, various process costs lead to a high cost for cells using large metal cans. The laminated packaging is especially suitable for plate-type electrodes and involves far fewer case parts than its metal counterpart, so that it has advantages both with respect to manufacturing and cost. Some of the Li-ion chemistries are ideally suited to take advantage of this low-cost package because, unlike Ni-MH, these Li-ion cells are not prone to gassing and do not require a rigid can for containment.

Only the cathode in a Li ion cell is potentially environmentally hazardous. While manufacturing of consumer cells entail environmentally hazardous materials such as $LiCoO_2$, manufacturers of large-format batteries are striving to either minimize the use of such materials or eliminate them entirely. The remaining materials are environmentally benign. Processes have been or are being developed (such as coating e.g.,) which will be more efficient from material use and environmental impact points of view.

Fig. 4. Picture of an HEV Cell using Al-polymer laminate packaging.

Battery Maintenance

Electrical:

Since life and abuse-tolerance are critically dependent on it, Li ion cells require careful monitoring of its charging voltage. Beyond a certain maximum charging voltage (overcharge), which is dependent on cell chemistry, the cells will likely lead to deterioration of performance and, in worst case, to abuse-tolerance issues. Cells are much more tolerant to overdischarge but again there is an adverse effect on cell performance when cell voltage drops below a cutoff voltage. Consequently, a microprocessor-based battery management system is a requirement for the consistent, reliable and safe operation of Li-ion batteries over the life of the battery/vehicle.

Even with the best manufacturing and quality control disciplines in place, there will be differences in cell capacity and impedance as well as exposure of individual cells to unequal thermal environment in a multi-cell battery pack. It is, therefore, imperative that cell-balancing algorithms are an integral part of the battery management system to ensure consistent performance and long-life. Current strategy to achieve this objective involves keeping the cell voltages within a specified range using resistive equalization. When cells reach a certain voltage, the current to the cell is bypassed through a resistor.

Current protocols to gauge the state-of-charge call for monitoring of voltages of each cell. Sophisticated estimation techniques such as Kalman filtering [5] can be used to estimate the SOC under dynamic conditions. This technique uses current measurements for short-term SOC dynamics and voltage measurements for longer-term dynamics, while using Coulomb counting to improve accuracy. Simulation results arrive at ±3% accuracy within 100s at temperatures greater than -20°C, even when the data are deliberately started with significant initial error.

***Thermal*:**

Performance, life and abuse-tolerance of Li ion cells and packs are also critically dependent on the ambient temperatures. While high temperatures have significant impact on life as well as abuse-tolerance, low temperatures usually affect performance. Thermal management, thus, tries to achieve two objectives: i) prevent overheating and ii) maintain a uniform temperature across the cells in the pack to assure consistent performance and long-life.

Li ion cells have significantly higher energy efficiency (>97%) than their Ni-MH counterparts (<90%). This is desirable from the view point of designing an efficient thermal management system. In this regard, a prismatic cell is more attractive than a cylindrical cell. This is shown by the data below for a prismatic cell in laminated packaging **(Fig. 5)**. Even at an exceptionally high rate of 30C continuous discharge, the cell body temperature rose only a modest 10°C. More importantly, the temperature within the electrochemically active area of the cell varied within 3°C, indicating not only lower but also uniform heat output during discharge. This is also confirmed by the data when the cell is subjected to the more real-life but stringent driving profile of US06. A temperature rise <3°C was recorded when the test was carried out at 30°C.

While passenger compartment air is used for convective cooling of HEV batteries, liquid cooling will be necessary to thermally manage large PHEV or EV batteries. This is because of the necessity to dissipate much larger quantities of heat generated when these batteries are operated over a significantly wider SOC window than a HEV battery.

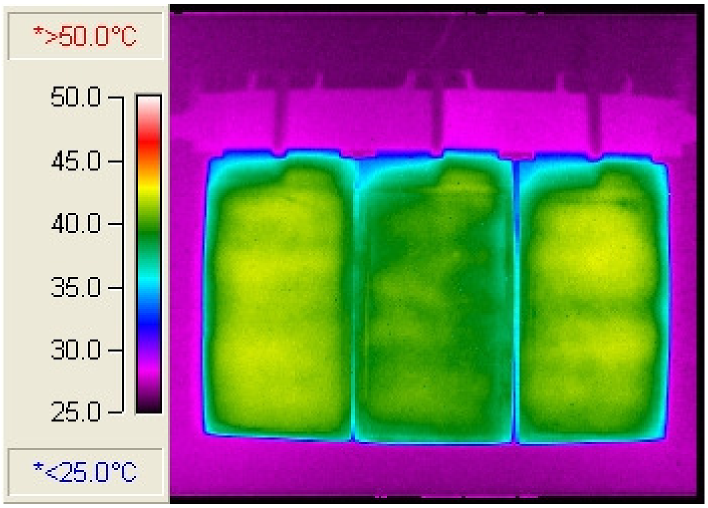


Fig.5. Example of high thermal efficiency for the prismatic cell in a laminated packaging. The center cell is the test item. Discharge was carried out at the rate of 30C.

BATTERY OWNERSHIP ISSUES

The USABC/FreedomCar has set a long-term goal of \$20/kW for an HEV battery system. This appears currently an ambitious goal considering the fact that even after producing over 1 million of Ni-MH battery packs for Prius, their price is still in the range of \$2000, or about 10% of the vehicle cost. It is generally expected that the HEV Li ion batteries will cost less than the Ni-MH packs. We note here that the HEV battery pack is included as a part of the overall vehicle purchase.

For a 10-mile range PHEV, the USABC target cost is \$500/kWh and \$293/kWh for a 40-mile range PHEV. In our opinion these targets are very aggressive. Our reasoning is based on the high volume price of limited-life Li ion cells and batteries used in consumer applications such as laptops and cellphones. The current cost for such batteries, having very little to no de-rating due to pack components, is >\$300/kWh. However, this price is based on Begin-of-Life energy content for the full range of SOC for applications which do not last for more than 2 to 3 years compared to 10 to 15-yrs in vehicular applications. Further, in PHEV or REV applications, one would use only a certain portion of the available energy in a pack which also has to consider de-rating due to pack components. When adjusted for these factors a pack cost ~\$1000/kWh can be envisaged.

It is quite possible that a new battery ownership scenario has to be developed to protect customers from a sticker shock. There are already ideas currently being implemented which have the carmakers owning the batteries to make these vehicles affordable to the customers. Plans are that the batteries will be leased, details of which are being worked out. It remains to be seen how these ideas play out in this rapidly evolving market place.

A number of concepts and proposals are presently being developed and evaluated to address the issue of recyclability of these large-size batteries. One idea is to use these automotive batteries after they have reached their End-of-Life in utilities as stationary power sources. Li ion batteries, after useful automotive life, will still have energy and life significantly higher than those of Pb-acid batteries currently used for leveling or energy storage for solar cells at a cost competitive manner.

Currently consumer Li ion batteries are recycled solely for the purpose of recovering the costly Co metal from the cathode and to a lesser extent Cu current collector metal from the cell. Recovery of the other components is yet to be economically viable. Similarly, automotive Li ion batteries containing expensive components such as Co and Ni will also be recycled. Studies are also being carried out at present to evaluate processes to recover Li compounds.

CONCLUSIONS

The foregoing analysis and discussion lead us to the following somewhat straightforward conclusions.

- For the next 15-20 years, hybridization of gasoline/diesel engines represents the most credible technology to reduce our dependence on fossil fuels.
- Batteries represent perhaps the most critical enabling technology for HEVs, PHEVs and EVs to become main stream.
- Li-ion represents the most promising technology for HEV, PHEV and other moderate- to high-power portable power applications and is poised to dominate these applications.
- Not all Li ion battery systems are equal. Choice of chemistry, separator and packaging can provide significantly advantages to one system compared to another.

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Table 4

Li-ion Current Status vs. Table I Attribute Targets for HEVs

Battery Attribute	Target	Current Status
10 S Pulse Power	25 kW Discharge/ 20kW Charge	Meets or Exceeds
Available Energy	0.3 kWh	Meets or exceeds
Min. in/out Efficiency	90%	> 95%
-30 ºC Cranking Power	5 kW	Meets or exceeds
Cycle Life	300000	Meets or exceeds
Calendar Life	>10 years	10 to 15 years
Weight	<40 kg	Meets or exceeds
Volume	<32 L	Meets or exceeds
Self Discharge	<50 Wh/day	Meets or exceeds
Cost (>100K units/year)	$1200 - $1500	TBD
Abuse Tolerance	Electrical / Mechanical	Meets

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