Recently lithium-ion batteries have started to be used in a number of automotive passenger car applications. This paper will review these applications and compare the requirements of the applications with the capabilities of the lithium-ion chemistries that are actually being used. The gaps between these requirements and capabilities will be highlighted and future developments that may be able to fill these gaps will be discussed. It is concluded that while improvements to the lithium-ion cell chemistry will help reduce the weight of battery packs for electric vehicle applications the largest weight gains will come from the pack design.

1. Introduction

Lithium-ion cells (Figure 1) (1), in their most common form, consist of a graphite anode, a lithium metal oxide cathode and an electrolyte of a lithium salt and an organic solvent. Lithium is a good choice for an electrochemical cell due to its large standard electrode potential (–3.04 V) resulting in a high operating voltage (which helps both power and energy) and the fact that it is the metal with the lowest density (which reduces weight).

The construction of a typical cylindrical cell is shown in Figure 2, while Figure 3 shows a typical pouch cell. Such cells provide a relatively light and small source of energy and are now manufactured in very large quantities (>1 billion cells per year) (2). In an automotive application a lithium-ion battery consists of tens to thousands of individual cells packaged together to provide the required voltage, power and energy.
Individual cells are normally mounted into a number of modules, which are then assembled into the complete battery pack as shown in Figure 4.

Many countries have now put in place binding carbon dioxide emissions targets for cars, for example in Europe the requirements are for fleet average CO$_2$ emissions of 130 g km$^{-1}$ by 2015 and 95 g km$^{-1}$ by 2021 (3). It will be shown in Section 2 of this paper that by using a (lithium-ion) battery it is possible to significantly reduce a car’s CO$_2$ emissions. More lithium-ion batteries are now being used in automotive applications for this reason.

The structure of this paper is as follows. In Section 2 a number of automotive passenger car applications for lithium-ion batteries are presented and their key requirements listed. Section 3 will give a brief overview of the capabilities of a number of lithium-ion chemistries currently in use for automotive applications and Section 4 will compare the requirements (from Section 2) with the capabilities listed in Section 3. Section 5 will look at future developments, while Section 6 will offer some conclusions.
2. Automotive Applications for Lithium-ion Batteries

There are a range of applications for batteries in passenger cars (4). The ones that will be considered here were selected either because they already use lithium-ion batteries or because they could potentially do so in the future. Note that there are a number of standard automotive requirements that all lithium-ion batteries used in cars need to meet: these include life (8–15 years are typical requirements), temperature range (−40°C to at least +60°C, ideally 80°C) and vibration resistance (at least 4.5 root-mean-square-acceleration (grms)) (5). Each application will now be briefly described.

2.1 Starting Lighting Ignition

Starting lighting ignition (SLI) is the ‘car battery’ that has been in almost every car for the last 100 years. Commonly this is called a ‘12 V battery’, but its normal voltage (while in use in the car and being charged by the alternator) is nearer 14 V. In almost all current production cars this is a lead-acid battery, but there are a few cars now that use a lithium-ion battery either as standard (for example, the McLaren P1) or as an option (for example, some Porsche models). In the Porsche Boxster Spyder the lithium-ion battery is a US$1700 option and has the same form factor and mounting points as the standard lead-acid battery, but weighs only 6 kg which is 10 kg lighter than the lead-acid option. It should be noted that Porsche supply a conventional lead-acid battery as well as the lithium-ion one for use in cold temperatures where the lithium-ion pack may not be able to provide enough power to crank the engine (see Section 3).

2.2 Idle Stop

This is a system that is now fitted to the majority of European vehicles which switches the combustion engine off whenever the vehicle is stationary, restarting it when you go to drive off (4). It offers around a 5% saving in fuel economy at an estimated system cost of around US$350 (4), which makes it an attractive solution for original equipment manufacturers (OEMs) looking to meet the European 2015 CO₂ limits. The requirements for a battery for this application are very similar to those of an SLI battery, but the more frequent starting and stopping of the engine requires a longer cycle life. The vast majority of batteries for this application are still lead-acid, but a number of other options are used including ultracapacitors and lithium-ion which was first used in 2002 on the Toyota Vitz CVT, which to the author’s knowledge was the first production car to use a lithium-ion battery pack.

Many idle stop systems also intelligently control the vehicle’s alternator, for example using it to generate maximum power when the vehicle is slowing down (giving a limited degree of regenerative braking capability) and these systems are frequently called micro hybrids.

2.3 Mild Hybrid

In a mild hybrid the electrical energy is used to supplement the energy from the combustion engine. By use of a suitable control system to decide how to mix these two energy sources significant savings in fuel (typically 10%–15%, but up to 30% has been shown in some demonstrator vehicles) can be obtained for a moderate increase in system cost (4). Batteries for this application only require a small amount of power and energy. Most batteries for this application at present are nickel metal hydride (NiMH), with lithium-ion first used in 2010 for the Mercedes S400 hybrid. As this paper is focused on lithium-ion batteries, NiMH batteries (which is an older technology that offers lower energy density than lithium-ion) will not be covered in further detail here.

Note that the number of mild hybrids produced is soon expected to significantly increase due to the use of 48 V systems within a vehicle. This shift is driven by the European 2020 fleet CO₂ requirements (3). The use of 48 V was originally proposed in 2011 by Audi, BMW, Daimler, Porsche and Volkswagen (6) and resulted in the LV 148 standard (7). Audi recently stated that they expect such systems to be in production within the next two years (8) and it is expected that all 48 V systems will be based on lithium-ion batteries.

It should also be noted that most fuel cell vehicles will also be hybrids (4). For example, Toyota has recently announced that it will start sales of a fuel cell sedan in early 2015 and this is a mild hybrid using a small battery to supplement the fuel cell and increase the vehicle’s overall efficiency (9).

2.4 Full Hybrid

In a full hybrid, the approach is similar to that of the mild hybrid, but the electrical power and stored energy are now high enough to power the car purely from electrical energy. The battery energy available normally limits the range in this mode to a few kilometres. An example of
this sort of vehicle is the Toyota Prius (although this currently uses a NiMH battery pack), which is by far the most successful hybrid vehicle sold so far. It has around a 1 mile range in electric vehicle (EV) mode. Fuel consumption savings in a full hybrid are typically 30%–40%, for example on the 2014 Toyota Yaris the 1.33 gasoline (98 bhp / 73 kW) produces 114 g km\(^{-1}\) of CO\(_2\) emissions, while the hybrid (also 98 bhp / 73 kW) achieves 75 g km\(^{-1}\), a 34% reduction.

Batteries for this application must provide more power (to act as the sole source of power in the vehicle) and more energy than for a mild hybrid application. Most applications (by volume) are still NiMH, but a significant number of vehicles are now lithium-ion based, including the BMW Active Hybrid 3 which can drive for 2.5 miles at up to 37 mph on electric power alone. Hybrid electric vehicle (HEV) is a phrase that has been used to describe mild hybrid and a full hybrid vehicles and has even been applied to some vehicles with little more than idle-stop systems (micro hybrids).

2.5 Plug in Hybrid Electric Vehicle

The plug in hybrid electric vehicle (PHEV) could be considered to be a full hybrid with the ability to charge the battery from the grid. The vehicle is designed to initially preferentially use the electrical energy from its last charge until this is depleted, at which time it behaves like a full hybrid vehicle. Thus the energy obtained by charging from the grid replaces some energy that would have been required from the liquid fuel (gasoline or diesel), further lowering fuel consumption (and hence tailpipe CO\(_2\) emissions). The VW XL1 is a PHEV that offers 313 mpg and 24 g km\(^{-1}\) of CO\(_2\), but the Vauxhall Ampera (GM Volt) and Toyota Prius PHEV (note the Toyota Prius PHEV is a different vehicle to the ‘standard’ Toyota Prius which is a full hybrid vehicle) are more affordable options. All use lithium-ion batteries. The power required from the battery is similar to that required in a full hybrid, but more energy needs to be stored to make the effort to recharge from the grid worthwhile.

For the purposes of this paper a range extended electric vehicle (REEV) will be considered a type of PHEV.

2.6 Electric Vehicle

An EV has the battery as its only source of energy. An example of this type of vehicle is the Nissan Leaf. An EV has zero tailpipe emissions, although the Leaf is estimated to emit 66.83 g km\(^{-1}\) CO\(_2\) in the UK based on the CO\(_2\) produced by the mains electricity used to refuel it. The power required from an EV battery is the same as for a PHEV (both need to be able to power the car), but in an EV as much energy as practical is fitted to give a reasonable range (typically ~100 miles). This large energy requirement explains the ‘low cost’ requirement (in $/kWh terms) for EVs in Table I, as the battery cost needs to be compared with a conventional fuel tank (~€100 or ~US$130).

All of the applications listed above are summarised in Table I. The typical properties and requirements of the battery technology for each application are shown. The power and energy data in Table I can also be viewed as a chart, as shown in Figure 5.

3. Lithium-ion Chemistries

Lithium-ion cells, in their most common form, consist of a graphite anode and a lithium metal oxide cathode and an electrolyte of a lithium salt and an organic solvent.

| Table I Typical Passenger Car Applications for Lithium-ion Batteries |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Application     | Typical voltage(s), V | Typical Power levels, kW | Typical energy, kWh | Commonest battery type today | Special requirements |
| SLI             | 14              | 3               | 0.7             | Lead-acid      | Cranking at cold |
| Idle stop       | 14              | 3               | 0.7             | Lead-acid      | Cranking at cold |
| Mild hybrid     | 48–200          | 10–30           | 0.3             | NiMH           | Long cycle life |
| Full Hybrid     | 300–600         | 60              | 1–2.5           | NiMH           | Long cycle life |
| PHEV            | 300–600         | 60              | 4–10            | Li-ion         | Long cycle life |
| EV              | 300–600         | 60              | 15+             | Li-ion         | Low cost        |
Table II Summary of the Main Lithium-ion Variants

<table>
<thead>
<tr>
<th>Variant</th>
<th>Cell level energy density, Wh kg⁻¹</th>
<th>Cell level energy density, Wh l⁻¹</th>
<th>Durability cycle life, 100% DoD</th>
<th>Price estimate, US$ Wh⁻¹</th>
<th>Power C-rate</th>
<th>Safety thermal runaway onset, °C</th>
<th>Potential, V</th>
<th>Temperature range in ambient conditions, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiCoO₂</td>
<td>170–185</td>
<td>450–490</td>
<td>500</td>
<td>0.31–0.46</td>
<td>1 C</td>
<td>170</td>
<td>3.6</td>
<td>–20 to 60</td>
</tr>
<tr>
<td>LiFePO₄ (EV/PHEV)</td>
<td>90–125</td>
<td>130–300</td>
<td>2000</td>
<td>0.3–0.6</td>
<td>5 C cont. 10 C pulse</td>
<td>270</td>
<td>3.2</td>
<td>–20 to 60</td>
</tr>
<tr>
<td>LiFePO₄ (HEV)</td>
<td>80–108</td>
<td>200–240</td>
<td>2000</td>
<td>0.4–1.0</td>
<td>30 C cont. 50 C pulse</td>
<td>270</td>
<td>3.2</td>
<td>–20 to 60</td>
</tr>
<tr>
<td>NCM (HEV)</td>
<td>150</td>
<td>270–290</td>
<td>1500</td>
<td>0.5–0.9</td>
<td>20 C cont. 40 C pulse</td>
<td>215</td>
<td>3.7</td>
<td>–20 to 60</td>
</tr>
<tr>
<td>NCM (EV/PHEV)</td>
<td>155–190</td>
<td>330–365</td>
<td>1500</td>
<td>0.5–0.9</td>
<td>1 C cont. 5 C pulse</td>
<td>215</td>
<td>3.7</td>
<td>–20 to 60</td>
</tr>
<tr>
<td>Titanate vs. NCM/LMO</td>
<td>65–100</td>
<td>118–200</td>
<td>12,000</td>
<td>1–1.7</td>
<td>10 C cont. 20 C pulse</td>
<td>Not susceptible</td>
<td>2.5</td>
<td>–50 to 75</td>
</tr>
<tr>
<td>Manganese spinel (EV/ PHEV)</td>
<td>90–110</td>
<td>280</td>
<td>&gt;1000</td>
<td>0.45–0.55</td>
<td>3–5 C cont.</td>
<td>255</td>
<td>3.8</td>
<td>–20 to 50</td>
</tr>
</tbody>
</table>

While all these cell chemistries have been used in passenger vehicles and hence can be made adequately safe, the temperature at which thermal runaway starts is used here to illustrate the differences between the chemistries – the higher this temperature the safer the chemistry is considered to be. Life is given in Table II in terms of cycle life, while the ranking in Table III can be considered to also include calendar life.

Note that the chemistry that provides the best power (lithium iron phosphate (LiFePO₄)) is the
worst for energy. Both power and energy need to be considered when selecting candidate chemistries for applications and this idea will be explored further in Section 4.

The last parameter for consideration is low temperature performance and this is best shown by a graph (Figure 6 which is based on data from (11) with lithium-ion added by the present author based on measurements of an automotive LiFePO₄ lithium-ion cell).

This graph shows that valve-regulated lead-acid (VRLA) battery technology offers significantly higher power at cold temperatures and so is better suited for cold cranking applications (which require the ability to crank the engine at –40°C).

### 4. Lithium-ion for Various Applications

One way to view the suitability of lithium-ion for various applications is to compare the power:energy ratio for the cells vs. the applications as shown in Figure 7. Here the yellow lines show the power:energy ratios for the various chemistries (from Table II), while the dots show the requirements for each of the applications (Figure 5). The lines closest to the dots are likely to be the best fit to the application from a power and energy viewpoint, as chemistries with lines a long way away will have a significant excess of power or energy beyond the requirements. This is likely to make them a more expensive solution (in terms of cost, weight and volume) than solutions with lines close to the dot.

It can be seen that there are good matches for the mild and full hybrid and PHEV, but not a particularly good match for the EV requirements.

This means that companies offering a range of different types of hybrid vehicle will normally need to select multiple chemistries (which also normally means multiple suppliers). For example BMW uses A123 LiFePO₄ cells in its hybrids, while it uses Samsung SDI (nickel-manganese-cobalt (NMC)) for its EV and PHEV vehicles (12), both of which can be seen to be sensible choices based on Figure 3. However there is no industry consensus, for example while BMW selected NMC for its EVs, Honda uses a titanate chemistry in its Fit EV and Renault uses spinel lithium manganese oxide (LMO) in the ZOE EV (13).

It should be noted that while lithium-ion batteries are in use in production cars, low temperature operation (see...
Section 3), life (especially calendar life), temperature range, safety and cost are all areas that ideally need to be improved and these challenges still remain after many years of research and development (10). Some progress has been made, for example battery packs have improved from 80 Wh kg\(^{-1}\) in the Mitsubishi iMiEV (launched in 2009) and Nissan Leaf (launched in 2010) to 97 Wh kg\(^{-1}\) in the new Kia Soul EV (launched in May 2014) (14) which is a 4% per year average (compound) improvement. This is partly due to the automotive industry’s long timescales (five or more years from part selection to volume production is common), but also due to the need for improvements without adversely impacting other parameters.

5. Future Developments

Much research is ongoing into lithium-ion batteries. The review of lithium batteries (2) dates from 2009 but it is still a useful overview and many of the research topics it discusses have yet to make it into volume automotive applications. A theoretical model created at Rice University and Lawrence Livermore National laboratory which predicts how carbon components will perform as electrodes (15) also has the potential to significantly benefit future lithium-ion cell developments.

A recent overview which focuses on energy and cost (and is so most relevant to EV applications) (16) suggests that lithium-ion chemistries will improve by probably no more than 30% in terms of energy per unit weight and proposes a range of potential replacement chemistries. However, it should be remembered that an automotive battery pack is much more than just the chemistry, as the cells themselves have to be packaged using a pouch or can and then hundreds or possibly thousands of these cells need to be packaged in the car together with thermal management and electronic control equipment. A typical automotive battery pack today achieves 82 Wh kg\(^{-1}\) (for example, the Nissan Leaf) which is considerably lower than that achievable from the cells alone.

Recently prototype battery packs have been developed with significantly higher energy density. For example the SmartBatt programme (17) has recently demonstrated an EV battery pack with 148 Wh kg\(^{-1}\) while meeting all other automotive requirements, this pack was shown as CAD in Figure 4 and the assembled pack is shown in Figure 8. This was achieved by combining 1408 relatively high energy lithium-ion cells (each of 181 Wh kg\(^{-1}\)) with innovative materials (including an aluminium hybrid foam sandwich material) and state of the art engineering (including a large number of crash test simulations to optimise the design).

Table IV gives the weight breakdown of the SmartBatt pack. The 85% gain in energy per unit weight obtained by the SmartBatt pack far exceeds the long term projections of a 30% improvement in energy per unit weight from lithium-ion chemistry improvements and together they suggest that a 100% gain in energy per unit weight (to around 160 Wh kg\(^{-1}\)) may be possible at the pack level for EV packs.

6. Conclusions

This paper has shown the range of applications for automotive batteries and summarised the different requirements for each. This has shown that while lithium-ion based battery packs could be used in all the major passenger car battery applications, they are best suited to use in PHEV and EV applications.
and are least suited to SLI applications. Even for the applications where lithium-ion is being used, it has been shown that different vehicle OEMs have selected different chemistries for the same application based on different interpretations of the trade-offs between the chemistries’ performance and the requirements of the specific application.

It has been stated that new lithium-ion chemistries offer limited potential for improvement (~30% in terms of Wh kg\(^{-1}\)) which has resulted in significant research in non lithium-ion based chemistries which offer the promise of significantly higher gains (16). However it is shown here that, especially for EV battery packs, major weight gains can come from the overall design of the battery pack and these together with better chemistries suggest that a doubling of the energy per unit weight for EV battery packs is possible in the relatively near future.

Acknowledgments

The author wishes to thank the anonymous referees and the editor for their constructive comments as well as Johnson Matthey for permission to publish this paper.

References

6. C. Hammerschmidt, ‘German Carmakers Agree on 48V On-board Supply, Charging Plug’, *Automotive EE Times Europe*, 16th June, 2011, 222901632
12. P. Buckley, ‘Samsung SDI Batteries to Drive Future BMW EVs’, EE Times Europe, 15th July, 2014

The Author

In December 2013 Dr Peter Miller took up the role of Chief Electronics Technologist at Johnson Matthey Battery Systems. Prior to this he was the Director, Electrical/Electronic Engineering at Ricardo and until 2001 he was the European Director of Technology at Motorola Automotive/Industrial Electronics Group. His primary interests relate to the design, control and use of lithium-ion batteries. Dr Miller is the author of a large number papers and patents. He holds a BSc and PhD from Hull University, UK, is a Chartered Engineer, a fellow of the Institute of Engineering and Technology (IET) and a member of the Institute of Electrical and Electronics Engineers (IEEE) and the Association of Computing Machinery (ACM).
Johnson Matthey Battery Systems is a leading independent provider of battery design, development and supply for demanding automotive applications, such as performance hybrids and PHEVs. We also manufacture high volumes of batteries for e-bikes, power tools and mobile technologies.

What we do - Battery Design, Development and Supply for Demanding Applications

Visit our website or contact us to get a free guide to electric vehicle battery technology

www.jmbatterysystems.com