What Next for Lead Battery Technology

The Work of ALABC – Past, Present and Future

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Advanced Lead Acid Battery Consortium
The Advanced Lead Acid Battery Consortium (ALABC)

An international research and development consortium dedicated to enhancing the capabilities of lead-acid batteries

Created in 1992, based in Durham, North Carolina

Over 70 member companies, mainly lead producers and lead-acid battery manufacturers

Has invested over $60m in lead-acid battery research and development

Current annual budget ~$1.8m
The main driver for ALABC’s creation was California’s zero emissions policy for vehicles.

Electric vehicles (EVs) powered by lead-acid batteries already existed (e.g., forklift trucks, milk floats) but these used flooded (free acid) cells.

Sealed batteries were needed for passenger cars and the deep cycling required for EV use resulted in short lifetimes for the batteries.

ALABC’s objective was to make lead-acid batteries competitive in EVs.
During the 1990s, ALABC focused mainly on solving a series of technical constraints which prevented the lead-acid battery performing to maximum efficiency:

- Premature capacity loss (PCL)
  - PCL 1 “interface effect”
  - PCL 2 “active material effect”

- Improving the speed of charging

- Avoiding gassing in stand-by applications
The valve-regulated lead-acid (VRLA) batteries needed for EV use had short lives on deep cycling due to the formation of a corrosion layer on the grid which inhibited the electric current and prevented full recharge.

New alloys were investigated to overcome this.

The solution was found in alloys containing tin at around 1%, together with smaller amounts of elements such as calcium and silver.
On deep discharge, the volume of the active material increases considerably as lead sulphate has a higher molecular volume than lead and lead oxide. This results in poorer electrical contact and eventually shedding of paste.

The solution was found in applying high degrees of compression to the plate stack. By using AGM separators, alloys with greater creep resistance (PbSnCa) and stronger boxes, the active material expansion problem was overcome.

VRLA batteries could now be made capable of being cycled many hundreds of times, thus making them suitable for EV use.
A disadvantage of EVs is their limited range on a single charge. This disadvantage can be offset if the battery can be recharged rapidly.

Research established that suitable charging algorithms (timed pulses, etc) enable fast charging to be achieved up to about 80% State of Charge (SoC) in a matter of minutes.

This enabled “opportunity charging” to be practised, eg when the operator of a fork lift truck is on a break.

Fast charging extended the life of EV batteries to as much as 1000 cycles.
Avoiding Gassing in Stand-by Applications

In addition to their use in electric vehicles, lead-acid batteries are widely used in applications requiring a full state-of-charge for long periods (eg telecommunications and uninterruptible power supplies).

These batteries require a continuous tiny float current to avoid self-discharge, and this can cause dissociation of water with resulting generation of hydrogen and oxygen.

Research established which impurity elements were responsible and the maximum concentration which could be tolerated eg Te 0.5ppm, Se 1ppm.

It was also found that certain elements are not harmful and may even be beneficial eg Bi, Zn.
Summary of the First 10 Years

After 10 years of sponsored research, ALABC had helped optimise the lead-acid battery for EV use and stand-by applications by:

- Solving premature capacity loss problems on the positive plate
- Improving the speed of charging
- Optimising alloys for corrosion and gassing resistance

However, interest in pure electric vehicles was declining, while excitement was growing about the potential for hybrid electric vehicles (HEVs).
A Change of Focus

The growing interest in HEVs presented lead batteries with both an opportunity and a threat.

At first the only suitable battery chemistry was nickel-metal hydride (NiMH), with lithium (Li-ion) also chasing the emerging market.

HEV batteries require power (high power for short periods) rather than energy (lower power for long periods) which is lead’s strength. This requires operation under high rate partial state of charge conditions (HRPSoC) and the ability to recharge rapidly from the energy dissipated in braking.
A New PCL Mechanism

Operation at partial state of charge avoids the positive plate problems (PCL1 and PCL2) for lead batteries because they are never fully charged.

However a new failure mechanism (PCL3) soon emerged, caused by a build-up of lead sulphate on the negative plate, with resulting rapid failure.

Research to address this problem resulted in simple but highly efficient solutions based principally on design of grids and additions of specific forms of carbon to improve current flow.
Conventional grids with a single lug have a current distribution which declines rapidly the greater the distance from the lug, reducing the efficiency of recharging and allowing sulphate to build up and hydrogen to be evolved.

Potential distribution of a conventional plate with a single lug.
Grid Design

Alternative designs give better current distribution by means such as changing the grid shape or adding a second lug.
Carbon Additions to Active Material

Conductive forms of carbon incorporated into the paste on the negative plates increase the volume exposed to electrolyte and sustain higher currents.

The carbon also impedes the growth of lead sulphate crystals, making recharging more efficient.

The conductivity of carbon varies considerably with form and particle size, and there is still scope to make improvements.
Another Carbon Development

Conventional lead-acid batteries have lead alloy electrodes (plates) and lead oxide/lead sulphate active material (paste)

Supercapacitors (which can hold a very high charge but discharge very rapidly) employ carbon electrodes

CSIRO (Australia) came up with the idea of combining lead and carbon electrodes in parallel and invented the UltraBattery which has very long life and excellent charge acceptance, making them ideal for partial state of charge applications (both in vehicles and in industrial batteries)
The UltraBattery
Vehicle Demonstration Projects

As the performance of lead-acid batteries has improved, ALABC has pursued a series of demonstration projects aimed at showing that lead-acid batteries can compete with established (NiMH) and emerging (Li-ion) batteries in mild-hybrid vehicles:

- Rholab Project, Honda Insight, 2000
- Isolab Project (2003) and Isotest, Ford Focus, 2006
- Insight UltraBattery 100,000 mile test 2007
- Honda Project, Honda Civic, UK, 2008
- Dept of Energy Project, Honda Civic, USA, 2010
- Isolab 3 Project, Honda Insight (Model 2), Austria, 2010
- Hyboost Project, Ford Focus, UK, 2009
- LC Super Hybrid Project, VW Passat, 2011
RHOLAB (Reliable Highly Optimised Lead-Acid Battery) began in September 2000 and replaced the Nickel-Metal Hydride (NiMH) battery in a Honda Insight with a lead-acid battery.

The 144V (4x36V modules) battery pack employed Enersys 2V twin tab spiral wound cells.

The car successfully completed a 50,000 mile (80,000 km) on-road test cycle in August 2007.

The battery required periodic conditioning and was seen as a “first generation” battery, so testing was terminated, but the work had helped lay the foundations for a series of new projects.
ISOLAB (Installation and Safety Optimised Lead-Acid Battery) began in June 2003, was aimed at producing a lead-acid battery solution for what appeared to be a new market for a 36V battery. Two modular approaches were looked at - one based on Exide 6V Orbital batteries and another on a 2V cell design being worked on by FIAMM.

While interest in the 36V battery did not materialise, it was felt the 2V cell could be of interest as building block to a low cost hybrid pack and a re-design was undertaken by Banner. This first attempt was beset by sealing problems (Isolab 2) and a third generation design is being produced to retrofit into a new generation Insight later this year.

The 112V 5.5 Ah battery pack is split into (1 x 48V, 1 x 64V) to match the Honda electronics.
Another Honda Insight was given a 144V (12x12V modules) UltraBattery pack manufactured by Furukawa.

The car successfully completed 100,000 miles (160,000 km) of on-road test cycle driving in January 2008 - well in excess of the normal warranty distance for the NiMH battery.

Remarkably, the battery required no equalisation or conditioning throughout the tests.

Overall fuel consumption was 4.73l/100km (just under 60 mpg).
In conjunction with Honda (UK) a straight comparison between a production model Honda Civic with a 158V NiMH battery and one containing a 176V (4x44V modules) Effpower bipolar lead-acid battery was undertaken at Millbrook.

The lead-acid powered vehicle successfully completed 37,500 miles (60,000 km) in on-road tests. It was then taken to Sweden for more on road testing by Effpower.

Fuel consumption was comparable in the two vehicles.

(Unfortunately Effpower have ceased their bipolar battery work.)
A Honda Civic retrofitted with a 178V (14 x 12V modules) UltraBattery pack manufactured by East Penn

The car is undergoing extensive road trials in challenging conditions (high temperatures and mountainous terrain) as a courier vehicle in Phoenix, Arizona

It has recently completed 100,000 miles of courier duty with no significant loss of battery capacity. It’s performance will continue to be monitored
HYBOOST Project

HYBOOST (Hybridised Boosted Optimised System with Turbocompound) is an alternative approach to fuel efficiency and carbon reduction employing a smaller engine with electric- and turbo-charging to restore performance.

A 2.0l Ford Focus has been fitted with a 1.0l prototype Ford Fox engine, stop-start function, regenerative braking, the Valeo StARS+X system (combining a lead-acid battery with a supercapacitor pack), plus electric- and turbo-chargers.

The aim was to match the performance (acceleration, etc) of the 2.0l Ford Focus (169gCO₂/km) but with emissions of only 99gCO₂/km. In fact 95gCO₂/km was achieved.
Evolving from the Hyboost concept, the LC Super Hybrid is a programme aimed at achieving mild hybrid performance (to meet projected future CO₂ targets) using existing technologies and at a fraction of the cost.

It will employ an advanced 12V lead-acid (or more accurately lead-carbon (LC)) VRLA battery with high Ah capacity and will bridge the gap between micro-hybrids (stop-start only) and mild hybrids.

Using a combination of engine downsizing, longer gear ratios, electric supercharger, turbocharger, stop-start and regeneration in a 1.4l VW Passat, the car is expected to have the performance of the 2.0l variant but with a 15-25% reduction in CO₂ emissions - and all for an estimated add-on cost of only €750 - €1500.
LC Super Hybrid

Fun to Drive

Base

Target

Electric Super-charger

Regeneration

Stop-Start

Engine Downsizing + Downspeeding

Exhaust Gas Turbo-charger

Fuel Economy/CO₂ Improvement

The Advanced Lead-Acid Battery Consortium
# Performance Comparison

<table>
<thead>
<tr>
<th></th>
<th>Passat 1.4 TSI</th>
<th>Passat 1.8 TSI</th>
<th>LC Super Hybrid 1.4 l</th>
<th>Volvo S40 2.0 l</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power PS</strong></td>
<td>122*</td>
<td>160&quot;</td>
<td>146**</td>
<td>145*</td>
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<tr>
<td><strong>Torque (Nm)</strong></td>
<td>200*</td>
<td>250*</td>
<td>275**</td>
<td>185*</td>
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<tr>
<td><strong>Acceleration (0-100 kph) (Secs)</strong></td>
<td>11.1**</td>
<td>8.5*</td>
<td>8.7**</td>
<td>9.5*</td>
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<tr>
<td>60-100 kph 4th gear 80-120 kph 6th gear</td>
<td>7.9**</td>
<td>16.1**</td>
<td>7.2**</td>
<td>12.5**</td>
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<tr>
<td><strong>Fuel: mpg/l per 100 km (Combined)</strong></td>
<td>45.6/6.2**</td>
<td>40.9/6.9*</td>
<td>50.5/5.6**</td>
<td>40.9/6.9*</td>
</tr>
<tr>
<td><strong>Emissions CO2/km</strong></td>
<td>140**</td>
<td>160*</td>
<td>130**</td>
<td>176*</td>
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## CO₂ Costs and Benefits

<table>
<thead>
<tr>
<th>System Metric</th>
<th>Micro Hybrid</th>
<th>LC Super Hybrid concept</th>
<th>Mild Hybrid</th>
<th>Full Hybrid</th>
<th>Plug-in Hybrid</th>
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<tbody>
<tr>
<td>Voltage</td>
<td>12V</td>
<td>12-48V</td>
<td>24-130V</td>
<td>200-270V</td>
<td>300-400V</td>
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<tr>
<td>e-Motor Power</td>
<td>2-3kW</td>
<td>3-6kW</td>
<td>10-15kW</td>
<td>20-50kW</td>
<td>60-70kW</td>
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<td>Regen. Power</td>
<td>0.5-3.0 kW</td>
<td>3-8 kW</td>
<td>~10 kW</td>
<td>~20 kW</td>
<td>20 kW +</td>
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<tr>
<td>Launch Assist</td>
<td>0</td>
<td>20 – 35kW</td>
<td>&lt;15kW</td>
<td>&gt;15kW</td>
<td>&gt;60kW</td>
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<tr>
<td>e-Drive Range</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>~2 km</td>
<td>~30 km</td>
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<td>OEM on-cost</td>
<td>€150 - €700*</td>
<td>€750 - €1500</td>
<td>€1600 - €3000*</td>
<td>€3000 - €5000*</td>
<td>€6000 - €10000*</td>
</tr>
<tr>
<td>CO₂ Benefit %</td>
<td>4 - 7 %</td>
<td>15-30%</td>
<td>8-12%</td>
<td>15-20%</td>
<td>20%+</td>
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<tr>
<td>OEM Cost/ Benefit</td>
<td>€35 - 100 /1%</td>
<td>€50 - 60 /1%</td>
<td>€200 - 250 /1%</td>
<td>€200 - 250 /1%</td>
<td>€300 - 500 /1%</td>
</tr>
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Three new projects are already planned

- A 48V version of the LC Super Hybrid. German premium car makers are moving towards 48V architecture for greater energy efficiency and it is vital to demonstrate that lead-carbon batteries can provide this function

- A 48V Hyundai diesel mild hybrid. For the first time a major global automobile manufacturer (Hyundai) has approached ALABC to help with their development of a new mild hybrid vehicle, which they would like to be based on lead batteries

- Discussions are ongoing with Ricardo and Ford for a follow-up HyBoost project with additional 48V electrification of other systems over and above the stop/start, boosting and regenerative braking systems
The LC Super Hybrids
ALABC’s work is organised in 3-year programmes, the latest of which (2013-2015) has just begun.

In addition to the development of batteries for vehicle applications, ALABC is keen to pursue larger scale energy storage applications:

- A project is being sponsored for the use of lead batteries to recover wasted energy in cranes and lifts (projected energy saving of 40-50%)
- Another potential project is being considered for storage batteries to support an electric vehicle recharging station
- Further energy storage project proposals are being invited, particularly in the area of renewable energy generation
Summary

In its 20 years of existence, ALABC has invested over $60m in lead-acid battery research and development.

The Consortium has over 70 member companies and is growing steadily.

The performance of lead-acid batteries has improved dramatically due to ALABC research which has resolved a series of performance-limiting problems.

Demonstration projects are showing that lead-acid batteries will have a major role to play in future generations of fuel-efficient vehicles with lower carbon emissions.

A greater future focus on energy storage applications offers promise of significant improvements in performance and markets in these areas too.