LG Chem at a glance

Energy Solution
- Lithium-Ion Batteries for
  - Mobile Phone, Laptop, Power Tool
  - Hybrid & Electric Vehicles
  - ESS

Petrochemicals
- ABS/EP
- NCC/Polyolefin
- PVC/Rubber
- Acrylate

IT & Electronics Materials
- LCD Polarizer
- LCD Glass
- OLED Materials
- Color Filter

Revenue
- Energy Solution (10%)
- Petrochemicals
- IT & Electronics Materials

R&D Expense
- Energy Solution
- Petrochemicals
- IT & Electronics Materials

Petrochemicals
- Energy Solution

$22 B (2012)
LG CPI
- Battery Pack Concepts, Design and Prototype Builds
- Battery Management Systems
- Sales and Customer Support

Troy, MI
Sales & Pack R&D

LG CMI
- $300M+ investment with ARRA funding
- Groundbreaking: Summer 2010
- Production begins in 2013

Holland, MI
Cell Manufacturing
Cell Structure: Unique Stack- and-Fold Design

Stacking of Plates & Folding

- Negative terminal
- Lead film (insulation tape)
- Positive terminal
- Stack and Folded cell
- Bi-cell
- SRS™
- Laminated film
Proprietary Safety Reinforcing Separator (SRS™)

SRS™ provides superior abuse-tolerance
- By improved mechanical and thermal stability
- By preventing internal short circuit
- By providing lower shrinkage

- Significantly higher puncture strength than conventional separator

Nano scale Ceramic Particles

Micro porous Polyolefin film
Overview of Current Program

Timeline
- Project Start: April 1, 2011
- Project End: December 31, 2013
- Percent complete: 79%

Budget
- Total project funding: $9.6M
- DOE share: $4.8M
- Contractor share: $4.8M
- Funding for FY12: $2.0M

Barriers
- Specific Energy and Power
- Cycle- and Calendar-life
- Cell Cost goal of <$200/kWh
- Efficient Refrigerant-to-Air cooling system

Partners
- LG Chem, INL, SNL, NREL
- Project lead: LGCPI
Objectives

- Develop a cell suitable for use in the PHEV-40 Mile program using next generation, high capacity Mn-rich cathode materials.

- A key goal of the program is to lower the pack cost to close to the $3400 target.

- Improve upon the Refrigerant-to-Air cooling system we have developed in our previous program with respect to mass, volume, cost and power demand.

- Deliver cells and battery packs to USABC for testing.
## PHEV 40-Mile Battery Pack Goals

<table>
<thead>
<tr>
<th>Characteristics at EOL</th>
<th>Units</th>
<th>Requirements for 40-Mile Program</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Equivalent Electric Range</td>
<td>Miles</td>
<td>40</td>
</tr>
<tr>
<td>Peak Pulse Discharge Power, 2 Sec</td>
<td>kW</td>
<td>46</td>
</tr>
<tr>
<td>Peak Pulse Discharge Power, 10 Sec</td>
<td>kW</td>
<td>38</td>
</tr>
<tr>
<td>Peak Regen Pulse Power, 10 Sec</td>
<td>kW</td>
<td>25</td>
</tr>
<tr>
<td>Available Energy, CD(^4) mode, 10kW rate</td>
<td>kWh</td>
<td>11.6</td>
</tr>
<tr>
<td>Available Energy, CS(^4) mode</td>
<td>kWh</td>
<td>0.3</td>
</tr>
<tr>
<td>Minimum round-trip Energy Efficiency(^5)</td>
<td>%</td>
<td>90</td>
</tr>
<tr>
<td>Cold Cranking Power at -30°C, 2 sec / 3 pulses (2-10-2-10-2)</td>
<td>kW</td>
<td>7</td>
</tr>
<tr>
<td>CD Life / Discharge throughput</td>
<td>Cycles;</td>
<td>5000</td>
</tr>
<tr>
<td></td>
<td>MWh</td>
<td>58</td>
</tr>
<tr>
<td>CS HEV Cycle Life, 50Wh Profile</td>
<td>Cycles</td>
<td>300,000</td>
</tr>
<tr>
<td>Calendar life at 35°C</td>
<td>Years</td>
<td>15</td>
</tr>
<tr>
<td>Maximum System Weight</td>
<td>Kg</td>
<td>120</td>
</tr>
<tr>
<td>Maximum System Volume</td>
<td>Liters</td>
<td>80</td>
</tr>
<tr>
<td>Maximum Operating Voltage</td>
<td>Vdc</td>
<td>400</td>
</tr>
<tr>
<td>Minimum Operating Voltage</td>
<td>Vdc</td>
<td>&gt;0.55V(_\text{max})</td>
</tr>
<tr>
<td>Maximum Self-Discharge</td>
<td>Wh/da</td>
<td>y 50</td>
</tr>
<tr>
<td>System Recharge Rate at 30°C</td>
<td>kW</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(120V/15A)</td>
</tr>
<tr>
<td>Maximum System Production Price @100k units/year</td>
<td>US$</td>
<td>$3,400</td>
</tr>
</tbody>
</table>
Approach/Strategy

- Study high capacity, Mn-rich, layered-layered cathode materials from multiple vendors.
- Characterize and Improve the performance, life and abuse-tolerance of Mn-rich cathode materials.
- Optimize, fabricate and deliver battery packs based on Refrigerant-to-Fin indirect cooling system.
Mn-rich cathode materials from multiple sources have been evaluated.

Built cells with control of various cell fabrication parameters/processes such as electrode formulations, formation protocol etc. to identify conditions optimum for performance and life.

Studied the effect of operational voltage ranges on energy, power and life.

Studied the effect of electrolyte additive on life.

Surface coatings on cathode particles considerably improve the durability of Mn-rich cells.
1\textsuperscript{st} Gen cells (24Ah) were built and sent to National Labs for evaluation. Results showed the need for significant improvement in life.

Battery packs using refrigerant-to-fin indirect cooling system have been designed and optimized with respect to Volume, Weight, Robustness, and Power demand.

Testing of prototype packs under various heat-loads using different driving profiles have been carried out. Data show good efficacy of this cooling system.

Prototype packs have been built and delivered to National Labs for evaluating their cooling efficiency.
Baseline studies with Mn-rich cathodes show capacities as high as ~ 250 mAh/g at RT.

Strong dependence on rate.
- Rapid increase in DC resistance at low SOCs.
- This can limit the usable SOC range for PHEV applications.
Charging to voltages such as 4.5V to access higher capacity leads to significant gas evolution. This causes swelling and premature cell failure.

This gas generation necessitates considerable adjustment to cell processing conditions, such as formation.
High voltage operation results in severe Mn dissolution in regular electrolyte.
Max charge voltage has a strong influence on cycle-life.
Discharge cut-off voltage has significant effect on cycle-life.
Electrolyte additives appear to enhance cycle-life.

45°C 4.5V~2.0V 1C/2C cycle
Improved separator helps to enhance cycle-life.
Surface coating enhances cycle-life.

Results—continued……

Normalized Capacity vs. Cycle for ALD Mn-rich (mono cell) and Bare Mn-rich (mono cell) at 25°C, 4.35V-2.5V, 0.5C/1C cycle.
Surface coating reduces resistance rise during cycling.
Results - *Effect of Surface coating...*

- Amount of $\text{Al}_2\text{O}_3$ secondary ion ($\text{AlO}^-$, $\text{AlO}_2^-$) after cycling was decreased, while that of $\text{AlF}_3$ secondary ion ($\text{AlF}_2^-$, $\text{AlF}_4^-$) was increased.
  - $\text{Al}_2\text{O}_3$ was changed to $\text{AlF}_3$ by the reaction of $\text{Al}_2\text{O}_3$ with HF.
- $\text{AlF}_3$ is known to show lower resistance to Li ion diffusion than $\text{Al}_2\text{O}_3$. 
Results: *Refrigerant Cooling System*

- Requires refrigerant loop; but:
  - Avoids coolant fill and maintenance, obviates need for complex coolant manifolds and risks of leaking.

- Phase I- Two thermal zones:
  - Refrigerated compartment (cells, evaporator, fan)
  - Ambient compartment (controls, compressor, condenser, fan)
Results: Phase II Cooling System- integrated design

- A refrigerant loop is used to cool the cold-plate at the bottom of the battery pack which, in turn, is attached to solid fins located between the cells.

![Picture of a Pack delivered to USABC](image-url)
Results: Thermal and Electrical Compartments

- Condenser
- TXV
- Fans
- Filter
- Compressor Control Boards
- Compressors
- BDU Assembly
- HV Vehicle Interface
- MSD
- LV Vehicle Interface
- Charger Connector
Results: Cooling System - Module Level Testing

US06 Drive Profile
SOC range = 90-20% 25°C, Cold-plate at 15°C
Max ΔT among cells: ~2°C

Efficient cooling - satisfies target
Results: *Cooling System- Pack Level Testing*

UDDS Drive Profile
SOC range = 90-20% 25°C, Cold-plate at 15°C
Max $\Delta T$ among cells : $\sim 0.5^\circ C$
Results: Cooling System - Pack Level Testing

UDDS Drive Profile
SOC range = 90-20% 25°C, Cold-plate at 15°C
Max ΔT among cells: ~0.5°C
Future Work

- Studies to develop Gen 2 of cells having improved life and performance are currently underway. These include:
  - Use surface-modified cathodes
  - Use of new electrolyte compositions/additives.
- Delivery of Gen 2 cells to National Labs for evaluation with improved power and life.
- Delivery of final packs to National Labs.
Use of LGC’s Cells in Production Vehicles

<table>
<thead>
<tr>
<th>OEM</th>
<th>Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM</td>
<td>Chevy Volt</td>
</tr>
<tr>
<td>Ford</td>
<td>Focus BEV</td>
</tr>
<tr>
<td>Hyundai</td>
<td>Sonata Hybrid</td>
</tr>
<tr>
<td>Volvo</td>
<td>XC 60</td>
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<tr>
<td>Renault</td>
<td>Zoe</td>
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</tbody>
</table>

- These cells benefitted directly from the development programs LGCPI had with USABC.
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