Electric Vehicle Battery Thermal Issues and Thermal Management Techniques

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NREL/PR-5400-52818

Presented at the SAE 2011 Alternative Refrigerant and System Efficiency Symposium
September 27-29, 2011 • Xona Resort Suites Scottsdale, Arizona USA
Outline

• Introduction
• Importance of battery temperature
• Review of electric drive vehicle (EDV) battery thermal management options
• Techniques to improve battery life
  - Standby thermal management
  - Preconditioning
• Tradeoff with thermal comfort
• Summary
Battery is The Critical Technology for EDVs

✓ Enables hybridization and electrification
✓ Provides power to motor for acceleration
✓ Provides energy for electric range and other auxiliaries
✓ Helps downsizing or eliminating the engine
✓ Enables regenerative braking
✗ Adds cost, weight, and volume
✗ Could decrease reliability and durability
✗ Decreased performance with aging
✗ Raises safety concerns

Lithium-ion battery cells, module, and battery pack for the Mitsubishi iMiEV (Courtesy of Mitsubishi)
As The Size of The Engine Is Reduced, The Battery Size Increases

- Conventional internal combustion engine (ICE) vehicles
- Micro hybrids (start/stop)
- Mild hybrids (start/stop + kinetic energy recovery)
- Medium hybrids (mild hybrid + engine assist)
- Full hybrids (medium hybrid capabilities + electric launch)
- Plug-in hybrids (full hybrid capabilities + electric range)
- Electric vehicles (EVs) (battery or fuel cell)

Axes not to scale
# Battery Requirements for Different EDVs

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Power (kW)</th>
<th>Energy (kW/h)</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro and Mild Hybrid Electric Vehicles (HEVs)</td>
<td>Very high power</td>
<td>Low energy</td>
<td>Many (400K) shallow charge/discharge cycles (±5% change)</td>
</tr>
<tr>
<td>Medium and Full HEVs</td>
<td>High power</td>
<td>Moderate energy</td>
<td>Many (300K) shallow charge/discharge cycles (±10% change)</td>
</tr>
<tr>
<td>Plug-in HEVs (PHEVs)</td>
<td>High power</td>
<td>High energy</td>
<td>Many (200K) shallow charge/discharge cycles (±5% change) Many (3-5K) deep discharge cycles (50% change)</td>
</tr>
<tr>
<td>Battery EVs</td>
<td>Moderate power</td>
<td>Very high energy</td>
<td>Many (3-5K) deep discharges (70% change)</td>
</tr>
</tbody>
</table>

Calendar life of 10+ years

Safety: the same as ICE vehicles
Lithium ion technology comes close to meeting most of the required technical and cost targets in the next 10 years.
Battery Cycle Life Depends on State-of-Charge Swing

- PHEV battery likely to deep-cycle each day driven: 15 yrs equates to 4,000–5,000 deep cycles
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Impact of Geography and Temperature on Battery Life

Li-ion technology must be sized with significant excess power to last 15 years in hot climates.
Li-Ion Battery Resistance Increases with Decreasing Temperature

- Power decreases with decrease in temperature
- Impacts power capability of motor and vehicle acceleration
Li-Ion Battery Capacity Decreases with Decreasing Temperature

- Useful energy from the battery decreases with decrease in temperature
- Impacts driving range and performance of vehicle
Battery Temperature is Important

Temperature affects battery:
- Operation of the electrochemical system
- Round trip efficiency
- Charge acceptance
- Power and energy availability
- Safety and reliability
- Life and life-cycle cost

Battery temperature affects vehicle performance, reliability, safety, and life-cycle cost

http://autogreenmag.com/tag/chevroletvolt/page/2/
Temperature Impacts Battery Sizing & Life and Thus Cost

Power Limits

15°C  35°C

Desired Operating Temperature

Sluggish Electrochemistry

Rated Power

Degradation

Power limited to minimize T increase and degradation

Dictates power capability

Power and energy fade rates determine the original battery size

Also limits the electric driving range

Kandler Smith, NREL Milestone Report, 2008
Battery High-Temperature Summary

• Primary considerations
  - Life
  - Safety
  - Non-uniform aging due to thermal gradients

• Cooling typically required
  - In hot environments (could be 24 hr)
  - During moderate to large current demands during drive
  - During fast charging

Photo Credit: John Rugh, NREL
Battery Low-Temperature Summary

• Primary considerations
  - Performance
  - Damage due to charging too fast

• Heating typically required
  - In cold environments during charging and discharging
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Battery Pack Thermal Management Is Needed

- Regulate pack to operate in the desired temperature range for optimum performance/life
  - 15°C – 35°C
- Reduce uneven temperature distribution
  - Less than 3°C – 4°C
- Eliminate potential hazards related to uncontrolled temperatures – thermal runaway
Battery Thermal Management System Requirements

- Compact
- Lightweight
- Easily packaged
- Reliable
- Serviceable
- Low-cost
- Low parasitic power
- Optimum temperature range
- Small temperature variation

http://www.toyota.com/esq/articles/2010/Lithium_Ion_Battery.html
Thermal Control Using Air

**Outside Air Ventilation**

Outside Air → Battery Pack → Exhaust

**Cabin Air Ventilation**

Outside Air → Cabin Air → Battery Pack → Exhaust
Vehicle heater and evaporator cores → Return → Fan

**Heating/cooling of Air to Battery – Outside or Cabin Air**

Outside Air → Battery Pack → Exhaust
Auxiliary or vehicle heater and evaporator cores → Return → Fan

i-MiEV (fast charge)
# Battery Heating and Cooling Using Air

<table>
<thead>
<tr>
<th>Pro</th>
<th>Con</th>
</tr>
</thead>
<tbody>
<tr>
<td>All waste heat eventually has to go to air</td>
<td>Low heat transport capacity</td>
</tr>
<tr>
<td>Separate cooling loop not required</td>
<td>More temperature variation in pack</td>
</tr>
<tr>
<td>Low mass of air and distribution system</td>
<td>Connected to cabin temperature control</td>
</tr>
<tr>
<td>No leakage concern</td>
<td>Potential of venting battery gas into cabin</td>
</tr>
<tr>
<td>No electrical short due to fluid concern</td>
<td>High blower power</td>
</tr>
<tr>
<td>Simple design</td>
<td>Blower noise</td>
</tr>
<tr>
<td>Lower cost</td>
<td></td>
</tr>
<tr>
<td>Easier maintenance</td>
<td></td>
</tr>
</tbody>
</table>
Thermal Control Using Liquid

Ambient cooling

Outside air → Liquid/air heat exchanger → Fan → Exhaust

Battery Pack → Liquid direct-contact or jacketed

Liquid

Active dedicated cooling/heating

Vehicle engine coolant → Liquid/liquid heat exchanger or electric heater → Pump → Return

Battery Pack → Liquid direct-contact or jacketed

Liquid

Volt, Tesla

A/C heat exchanger → Refrigerant
## Battery Heating and Cooling Using Liquid

<table>
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<tr>
<th>Pro</th>
<th>Con</th>
</tr>
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<tr>
<td>Pack temperature is more uniform - thermally stable</td>
<td>Additional components</td>
</tr>
<tr>
<td>Good heat transport capacity</td>
<td>Weight</td>
</tr>
<tr>
<td>Better thermal control</td>
<td>Liquid conductivity – electrical isolation</td>
</tr>
<tr>
<td>Lower pumping power</td>
<td>Leakage potential</td>
</tr>
<tr>
<td>Lower volume, compact design</td>
<td>Higher maintenance</td>
</tr>
<tr>
<td></td>
<td>Higher viscosity at cold temperatures</td>
</tr>
<tr>
<td></td>
<td>Higher cost</td>
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Standby Thermal Cooling in Hot Climates

- Battery life can greatly benefit from cooling the battery during standby, i.e., while vehicle is plugged in to the grid
- Slower battery degradation rate enables smaller, lower cost battery
- NREL study investigated
  - Insulation
  - Insulation and air cooling
  - Insulation and small vapor compression system (VC)
  - Insulation, small VC system, and phase change material (PCM)
Battery Life for Various Standby Systems
can differ widely depending on cell chemistry, materials, and manufacturer

**Saft HP-12LC Cell**  
(Belt/INL, ECS Mtg. 2008)  
- low fade rate, high cost

5%-10% less power fade with Ins. + VC

**DOE/TLVT Cell**  
(Christopersen/INL, Battaglia/LBL, 2007 Merit Review)  
- moderate fade rate, lower cost

9%-22% less power fade with Ins. + VC

Lower cost cell preferred, provided it can meet life.

Next slide compares Δcosts of DOE/TLVT battery sized for 15 years in Phoenix, w/ and w/o insulation + VC system.
Savings from Downsized Battery Expected to Significantly Outweigh Cost of Added Components

DOE/TLVT cell sized for 15 years; in Phoenix, AZ, charged nightly.

Total savings assuming components represent additional cost:
- PHEV10: ($360)
- PHEV20: ($320)
- PHEV40: ($250)
Standby Thermal Management – Passive Techniques to Reduce Battery Temperatures

- Installed metalized solar reflective film on the glazings of a Toyota Prius in Phoenix
- Cabin air temperature reduced ~6°C
- Before: Battery daily max temp 1.5°C above ambient
- After: Battery daily max temp 2°C below ambient

Photo Credit: John Rugh, NREL
Thermal Preconditioning

**Issues:**
- For conventional vehicle and HEV platforms, A/C use leads to increased fuel consumption
- For PHEV and EV platforms, climate control energy is supplied by the traction battery
  - *Charge depletion (CD) range reduction*
- Batteries degrade rapidly at high temperatures and benefit from active cooling
- Batteries suffer from reduced power and energy at cold temperatures; their performance can be improved by preheating
  - *Battery wear and life impacts*

**Potential Solution:**
- Use grid power to thermally precondition cabin and battery
- Save valuable onboard stored energy for propulsion
Preconditioning, Driving & Charging Patterns Affect Battery Temperature and Duty-Cycle

24-hour profiles created to estimate impact of preconditioning on battery life.

PHEV40s, hwy cycle, 95°F (35°C) ambient.

Battery heat generation rates and SOC extracted from PSAT vehicle simulations of charge-depleting and charge-sustaining operation.
Thermal Preconditioning can Regain CD Range as well as Improve Thermal Comfort

<table>
<thead>
<tr>
<th>EDV Platform (Climate Control)</th>
<th>Fuel Consumption Impact*</th>
<th>CD Range Impact*</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHEV15 (heat)</td>
<td>-1.4%</td>
<td>+19.2%</td>
</tr>
<tr>
<td>PHEV15 (AC)</td>
<td>-0.6%</td>
<td>+5.2%</td>
</tr>
<tr>
<td>PHEV40 (heat)</td>
<td>-2.7%</td>
<td>+5.7%</td>
</tr>
<tr>
<td>PHEV40 (AC)</td>
<td>-1.5%</td>
<td>+4.3%</td>
</tr>
<tr>
<td>EV (heat)</td>
<td>NA</td>
<td>+3.9%</td>
</tr>
<tr>
<td>EV (AC)</td>
<td>NA</td>
<td>+1.7%</td>
</tr>
</tbody>
</table>

*Compared to no thermal preconditioning
Thermal Preconditioning Can Also Improve Battery Life

Battery capacity loss over time is driven by ambient temperature.

Thermal preconditioning has a small benefit in reducing battery capacity loss (2%–7%), primarily by reducing pack temperature (2%–6%) in the high ambient temperature (35°C/95°F) scenario.

<table>
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<tr>
<th>EDV Platform (Climate Control)</th>
<th>Capacity Loss Reduction*</th>
</tr>
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<tbody>
<tr>
<td>PHEV15(A/C)</td>
<td>+2.1%</td>
</tr>
<tr>
<td>PHEV40 (A/C)</td>
<td>+4.1%</td>
</tr>
<tr>
<td>EV (A/C)</td>
<td>+7.1%</td>
</tr>
</tbody>
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*Compared to no thermal preconditioning
Thermal Preconditioning Considerations

- **Timing**
  - avoid cooling or heating too early
  - does the heating/cooling coincide with peak demand on the grid?

- **Can the charge circuit provide power for simultaneous heating/cooling and charging?**

- **When not plugged in, is it worth using onboard stored energy for preconditioning?**
  - Trade stored energy (range) for battery life
Systems Approach - Options for Improving Electric Range with Climate Control

- Incorporate thermal preconditioning strategies
- Reduced heat transfer into/out of the cabin
- Use efficient HVAC equipment
- Reduce cooling capacity or heat load
  - Zonal climate control
  - Focus on occupant comfort
- HVAC controls
  - Eco mode (temporarily minimize energy use)
  - Eliminate inefficient HVAC control practices
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Tradeoff of Battery Cooling with Thermal Comfort

- NREL Integrated Vehicle Thermal Management task
- KULI thermal model
  - A/C and cabin
  - Battery cooling loop
  - Motor and power electronics cooling loop
- Nissan Leaf size EV
- Environment
  - 35 °C
  - 40% RH
- 0% recirc
- US06 drive cycle
- Cooldown simulation from a hot soak

Source: David Howell, DOE Vehicle Technologies Annual Merit Review
After 10 Minutes, the Battery Cools to Control Setpoint While the Cabin is Still Warm
Initially Less Than 50% of the A/C System Capacity is Going to the Cabin

![Graph showing heat transfer over time for Chiller and Evaporator]

- **Chiller**
- **Evaporator**

Heat Transfer (kW) vs. Time from start of cooldown (sec)
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Summary

• Temperature impacts the life, performance, and cost of batteries in HEVs, PHEVs, and EVs
• Battery life and performance are extremely sensitive to temperature exposure
• Thermal management is a must for batteries
• Thermal control of PHEVs and EVs (when parked or driving) could be a cost-effective method to reduce over-sizing of battery for the beginning of life
• Future trends
  – Some variation of today’s Li-ion chemistries
  – Same sized packs – larger range
  – Improved cell designs to solve life issues
Acknowledgments, Contacts, and Team Members

Special thanks to:

David Anderson
David Howell
Susan Rogers
Lee Slezak

*U.S. Department of Energy*
*Vehicle Technologies Program*

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