Battery Requirements for Plug-In Hybrid Electric Vehicles – Analysis and Rationale
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Acknowledgements

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  - David Howell (U.S. Department of Energy)

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  - Tien Duong (U.S. Department of Energy)
  - FreedomCAR PHEV Battery Work Group
    - Electrochemical Energy Storage Tech Team
    - Vehicle System Analysis Tech Team
Outline

- Background
- Objectives
- Approach
- Results of Analysis
- Battery Requirements
- Summary
Background - PHEVs

- Plug-in Hybrid Electric Vehicles (PHEVs) have received considerable attention in recent years because they
  - Reduce gasoline consumption
  - Reduce dependence on imported oil
  - Decrease greenhouse gas emissions

- President Bush’s Initiatives on PHEVs
  - Advanced Energy Initiative in 2006
    - $14M appropriated for PHEV R&D in FY07
  - “20-in-10” in the 2007 State of the Union Address
    - $27.5M requested for PHEV R&D in FY08

- FreedomCAR Tech Teams worked together to develop requirements for PHEV batteries
Background – Batteries

- In 2006, the FreedomCAR Electrochemical Energy Storage Tech Team (EESTT) and USABC formed a Work Group to identify the requirements of batteries for PHEVs.
- NREL and ANL performed vehicle simulations in support of the Work Group to identify the energy and power requirements for various vehicle platforms, PHEV strategies, and electric range.
- Other requirements such as all electric range, calendar and cycle life, cost, cold cranking power, volume, and weight were identified and discussed by the EESTT/USABC participants of the Work Group.
- The Work Group recommended that safety attributes of PHEV batteries should be similar to power-assist HEV batteries.
- In the Spring of 2007, USABC issued request for proposals that included the battery requirements recommended by the Work Group.
FreedomCAR PHEV Battery Work Group

- **Electrochemical Energy Storage Tech Team Participants**
  - Cyrus Ashtiani (Chrysler)
  - Jeff Belt (INL)
  - Ron Elder (Chrysler)
  - Ahsan Habib (GM)
  - Gary Henriksen (ANL)
  - David Howell (DOE)
  - Josephine Lee (Ford)
  - Naum Pinsky (SCE)
  - Ahmad Pesaran (NREL)
  - Harshad Tataria (GM: Team Lead)

- **Vehicle System Analysis Tech Team Participants**
  - Lee Slezak (DOE)
  - Tony Markel (NREL)
  - Aymeric Rousseau (ANL)
  - Neeraj Shidore (ANL)
  - Jeff Gonder (NREL)
Objective

- The purpose of this paper/presentation is to present and document
  - Rationale behind the approach used
  - Rationale for selecting assumptions
  - Results of the analysis for power and energy
  - Rationale for selecting other requirements
  - Resulting PHEV battery requirements
Definitions and Terminologies

- **PHEV**: An HEV with the ability to plug-in its energy storage system to get recharged with electricity from the grid.
- **Charge-depleting (CD) mode**: An operating mode in which the energy storage state-of-charge (SOC) may fluctuate but, on average, decreases while the vehicle is driven.
- **Charge-sustaining (CS) mode**: An operating mode in which the energy storage SOC may fluctuate but, on average, is maintained at a certain level while the vehicle is driven. This is the common operating mode of commercial HEVs.
- **All-electric range (AER) mode**: The vehicle is driven with motor only (with the combustion engine off), range is the total miles driven electrically before the engine turns on for the first time.
- **Blended or charge-depleting hybrid (CDH) mode**: An operating mode in which the energy storage SOC decreases, on average, while the vehicle is driven; the engine is used occasionally to support power requests.
- **Zero-emission vehicle (ZEV) range**: The same as AER; there are no tailpipe emissions when the vehicle is in electric vehicle mode.
PHEV Battery Operation

A PHEV battery typically operates in either of 2 modes: the continuous discharge (charge depleting) mode of an electric vehicle and the shallow, high-power cycling (charge sustaining) mode of a power-assist hybrid vehicle.

<table>
<thead>
<tr>
<th>SOC Range (%)</th>
<th>Total Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 100</td>
<td>1-2 kWh</td>
</tr>
<tr>
<td>30 - 40</td>
<td>5-12 kWh</td>
</tr>
<tr>
<td>5-12</td>
<td>30-40 kWh</td>
</tr>
</tbody>
</table>

**HEV**
- **Charged capacity, not used**
- **Uncharged capacity**

**PHEV**
- **Charged, not used**
- **Used sometimes in CS**

**EV**
- **Charged, not used**
- **Charged and used (CD)**

**CS:** Charge Sustaining
**CD:** Charge Depleting
What Strategy to Select for CD Mode?

- Charge-depleting operation could be done either with **all-electric** or **blended** modes, each having advantages and disadvantages, with impact on size and cost of the battery system.
- Having the full capability of **all-electric** mode in all drive cycles has the advantage of displacing more gasoline and reducing more vehicle emissions but the disadvantage of having a larger and costlier energy-storage system.
- With **blended** mode, in most real driving, the energy storage size and cost are more manageable, but gasoline fuel saving decreases and tailpipe emissions increase slightly.
- The Urban Dynamometer Driving Schedule (UDDS) drive cycle is the basis for qualifying for ZEV or AT PZEV credits with minimum of 10 miles AER.

**Final strategy that was selected:**

- Ability to operate in **all-electric** mode over the UDDS drive cycle to qualify for ZEV or AT PZEV credits.
- Ability to operate in **blended** mode over all other aggressive drive cycles and real driving to keep the battery size and cost manageable.
Approach for Defining Battery Power and Energy

- Previous analysis by NREL and ANL indicated that sizing of energy storage power and energy for PHEVs depend on the
  - vehicle platform,
  - vehicle performance attributes,
  - hybrid vehicle configuration,
  - drive cycle,
  - electric range,
  - operating strategy, and
  - level of electric only performance on various drive cycles.

- Requirements are not intended to be specific or to depend on a particular control strategy. Rather, they intended to be flexible enough to allow being applied to different vehicles and operating strategies.
Analysis for Power and Energy

- Process included defining
  - vehicle platforms (mass, aerodynamic, and rolling resistance)
  - vehicle performance targets (acceleration, top speed, grade)
  - the desired equivalent electric range
  - the operating strategy (all-electric and blended)
  - the usable SOC window.

- The analysis and simulations provided
  - electric vehicle consumption (Wh/mile)
  - peak power requirements for a particular drive cycle
  - peak power requirements during charge-sustaining operation.
Vehicle Assumptions

Vehicle attributes used for simulations and component sizing

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Midsize Car</th>
<th>Midsize Crossover UV</th>
<th>Midsize SUV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approximate Glider Mass</td>
<td>kg</td>
<td>940</td>
<td>1100</td>
<td>1200</td>
</tr>
<tr>
<td>Approximate Vehicle Test Mass</td>
<td>kg</td>
<td>1600</td>
<td>1950</td>
<td>2000</td>
</tr>
<tr>
<td>Frontal Area</td>
<td>m²</td>
<td>2.22</td>
<td>2.69</td>
<td>2.89</td>
</tr>
<tr>
<td>Drag Coefficient</td>
<td></td>
<td>0.308</td>
<td>0.417</td>
<td>0.42</td>
</tr>
<tr>
<td>Rolling Resistance</td>
<td></td>
<td>0.009</td>
<td>0.010</td>
<td>0.011</td>
</tr>
<tr>
<td>Accessory Electrical Load</td>
<td>W</td>
<td>800</td>
<td>1000</td>
<td>1200</td>
</tr>
</tbody>
</table>

Vehicle performance parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration from 0 to 60 mph</td>
<td>9 s</td>
</tr>
<tr>
<td>Top Speed</td>
<td>100 mph</td>
</tr>
<tr>
<td>Grade at 55 mph</td>
<td>6%</td>
</tr>
</tbody>
</table>
Vehicle Simulations & Analysis

- Vehicle analysis (ANL’s Powertrain Simulation Toolkit and power-flow calculations) were used to size the various components, including battery, engine, and motor.
- Component sizes were selected to satisfy the performance constraints for each vehicle type.
- Each vehicle’s consumption of gasoline and electricity over various driving cycles was calculated.
- The vehicle’s performance and energy use were coupled to vehicle mass for mass compounding.
- The required electric drive system size was based on completing the given distance over UDDS drive cycle.
- The required engine size was based on meeting a 6% grade requirement at 55 mph and two-thirds of peak power.
Analysis Results for Energy - UDDS

Electric energy consumed per mile for various vehicles and operating modes

- 290 Whr/mile
- 340 Whr/mile

AER: All Electric Range Mode
CDH: Blended or Charge Depleting Hybrid Mode
Analysis Results for Power - UDDS

Peak power needed for various vehicles and operating modes

Blended or CDH peak is about 50% of the AER peak power.

AER: All Electric Range Mode
CDH: Blended or Charge Depleting Hybrid Mode

Power Pulse Duration
AER cases are 2s
CDH cases are >10s

EOL Discharge Power (kW)

- 46 kW 2s
- 50 kW 2s

Vehicle Types:
- 10 AER
- 40 AER
- 10 CDH
- 40 CDH
- Car 10 AER
- Car 40 AER
- Car 10 CDH
- Car 40 CDH
- Cross 10 AER
- Cross 40 AER
- Cross 10 CDH
- Cross 40 CDH
- SUV 10 AER
- SUV 40 AER
- SUV 10 CDH
- SUV 40 CDH
Bases for Selection of Battery Requirements

- The battery requirements were recommended based on two sets of electric range and time-frame
  - A 10-mile all-electric-range (over UDDS) for a crossover vehicle in the mid-term (2012)
    - Supporting potential early market experience
  - A 40-mile all-electric-range (over UDDS) for a midsize car in the long-term (2015-2016)
    - Supporting President’s Initiative
### Power and Energy Requirements For Charge-Depleting Mode

30°C battery power and energy requirements at end of life

<table>
<thead>
<tr>
<th>Characteristics at EOL (End of Life)</th>
<th>High Power/Energy Ratio Battery</th>
<th>High Energy/Power Ratio Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology Readiness Target year</td>
<td>2012</td>
<td>2015-2016</td>
</tr>
<tr>
<td>Reference Equivalent Electric Range miles</td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>Peak Pulse Discharge Power - 2 s kW</td>
<td>50</td>
<td>46</td>
</tr>
<tr>
<td>Peak Pulse Discharge Power - 10 s kW</td>
<td>45</td>
<td>38</td>
</tr>
<tr>
<td>Peak Regen Pulse Power - 10 s kW</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>Available Energy for Charge Depleting Mode, 10 kW Rate (c) kWh</td>
<td>3.4 (a)</td>
<td>11.6 (b)</td>
</tr>
</tbody>
</table>

- **a:** Based on 340 Whr/mile as suggested by vehicle simulations
- **b:** Based on 290 Whr/mile as suggested by vehicle simulations
- **c:** Discharge rate of 10 kW (roughly one-fourth of peak power) during charge depleting portion was based on approximate power needed to propel either of the vehicles at a constant speed of 25 to 30 mph.
Considerations for SOC

- It was felt that a SOC window should NOT be specified since it depends on technology or chemistry limits.
- Battery developer/supplier should recommend the SOC window based on the limits of their technology considering the trade-off between weight and life.
- However, in most of the Work Group discussions and calculations, a 70% SOC window was assumed.
- Although battery power and energy fading is technology specific, a fade factor of 20% for energy and 30% for power were assumed for sizing of beginning of life.

**SOC: State of Charge = Capacity Left for Discharge / Total Capacity**
Power and Energy Requirements for Charge-Sustaining HEV Mode

- The battery must support charge-sustaining HEV operation (both power and available energy) at the minimum state-of-charge (SOC).
- USABC has defined battery requirements for power-assist HEVs that are charge-sustaining. Similar power and available energy requirements were selected.
- Data indicates that if a battery system meets the AER peak power targets, it also meet the CS HEV needs, so no additional peak power target for a CS HEV was selected.

<table>
<thead>
<tr>
<th>Characteristics at EOL (End of Life)</th>
<th>High Power/Energy Ratio Battery</th>
<th>High Energy/Power Ratio Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available Energy for CS (Charge Sustaining) Mode kWh</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Cold Cranking Power at -30°C, 2 s, 3 pulses (10 s rest between) kW</td>
<td>7</td>
<td>7</td>
</tr>
</tbody>
</table>
## Calendar & Cycle Life Requirements

<table>
<thead>
<tr>
<th>Characteristics at EOL (End of Life)</th>
<th>High Power/Energy Ratio Battery</th>
<th>High Energy/Power Ratio Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calendar Life, 35°C (a)</td>
<td>year</td>
<td>15</td>
</tr>
<tr>
<td>Charge Depleting (CD) Cycle Life (b)</td>
<td>cycles</td>
<td>5,000</td>
</tr>
<tr>
<td>Discharge Throughput Energy through CD Cycles (c)</td>
<td>MWh</td>
<td>17</td>
</tr>
<tr>
<td>Charge-Sustaining HEV Cycle Life, 50 Wh Profile (d)</td>
<td>cycles</td>
<td>300,000</td>
</tr>
</tbody>
</table>

a: Calendar life is similar to USABC/FreedomCAR requirements for power-assist HEVs
   - Currently CARB requires 10 years warranty for AT PZEV batteries but most consumers expect the batteries to last the average life of vehicles, i.e., 15 years,
   - PHEV calendar life temperature is 35°C rather than 30°C of HEVs.

b: Assuming roughly 1 deep discharge per day per year (roughly 330 times/year) for 15 years.

c: Number of cycles in 15 years multiplied by the charge depleting available energy.

d: The same as requirements for power-assist HEVs as defined by USABC. Reflects typical shallow cycles experienced by a power-assist hybrid battery over a 15 year life, equivalent to about 150,000 miles.
System-Level Requirements

<table>
<thead>
<tr>
<th>Characteristics at EOL (End of Life)</th>
<th>High Power/Energy Ratio Battery</th>
<th>High Energy/Power Ratio Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum System Production Price @ 100,000 units/year (a)</td>
<td>$1,700</td>
<td>$3,400</td>
</tr>
<tr>
<td>Maximum System Weight (b)</td>
<td>60 kg</td>
<td>120 kg</td>
</tr>
<tr>
<td>Maximum System Volume (c)</td>
<td>40 liter</td>
<td>80 liter</td>
</tr>
<tr>
<td>System Recharge Rate at 30°C (d)</td>
<td>1.4 kW (120V/15A)</td>
<td>1.4 kW (120V/15A)</td>
</tr>
<tr>
<td>Minimum Round-trip Energy Efficiency (USABC Cycle) (e)</td>
<td>90%</td>
<td>90%</td>
</tr>
</tbody>
</table>

a: The battery cost targets reflect the mid and long term R&D cost goals of $500/(available) kWh in 2012 and $300/(available) kWh in 2015-2016.
b: Includes balance of the system such as enclosure and battery management.
c: Total volume of the system cells + packaging + electronics; selected to have enough space in the cargo area for consumer acceptance.
d: Nameplate residential electrical outlets (receptacles) are 120V and 15A in U.S. According to U.S. codes, the continuous power rating is 80% of the nameplate.
e: This is similar to the USABC requirements for power-assist HEV batteries.
### Battery System-Level Limits

**Characteristics at EOL (End of Life)**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>High Power/Energy Ratio Battery</th>
<th>High Energy/Power Ratio Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Current (10 sec pulse) (a)</td>
<td>A</td>
<td>300</td>
</tr>
<tr>
<td>Maximum Operating Voltage (b)</td>
<td>Vdc</td>
<td>400</td>
</tr>
<tr>
<td>Minimum Operating Voltage (b)</td>
<td>Vdc</td>
<td>&gt;0.55 x Vmax</td>
</tr>
<tr>
<td>Maximum Self-Discharge (c)</td>
<td>Wh/day</td>
<td>50</td>
</tr>
<tr>
<td>Unassisted Operating &amp; Charging Temperature Range (d)</td>
<td>°C</td>
<td>-30 to +52</td>
</tr>
<tr>
<td>Survival Temperature Range (d)</td>
<td>°C</td>
<td>-46 to +66</td>
</tr>
</tbody>
</table>

- **a:** Similar to power-assist HEV, dictated by vehicle wiring system
- **b:** Similar to power-assist HEV, dictated by vehicle electric drive system (inverter and motors)
- **c:** To ensure the high-voltage battery has sufficient energy and power to operate the vehicle in HEV mode unassisted after long parking period (normally 30 days).
- **d:** Similar to power-assist HEV battery requirements for reliability and consumer acceptance.
## Combined PHEV Battery Requirements

### Requirements of End of Life Energy Storage Systems for PHEVs

<table>
<thead>
<tr>
<th>Characteristics at EOL (End of Life)</th>
<th>High Power/Energy Ratio Battery</th>
<th>High Energy/Power Ratio Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Equivalent Electric Range</td>
<td>miles</td>
<td>10</td>
</tr>
<tr>
<td>Peak Pulse Discharge Power - 2 Sec / 10 Sec</td>
<td>kW</td>
<td>50 / 45</td>
</tr>
<tr>
<td>Peak Regen Pulse Power (10 sec)</td>
<td>kW</td>
<td>30</td>
</tr>
<tr>
<td>Available Energy for CD (Charge Depleting) Mode, 10 kW Rate</td>
<td>kWh</td>
<td>3.4</td>
</tr>
<tr>
<td>Available Energy for CS (Charge Sustaining) Mode</td>
<td>kWh</td>
<td>0.5</td>
</tr>
<tr>
<td>Minimum Round-trip Energy Efficiency (USABC HEV Cycle)</td>
<td>%</td>
<td>90</td>
</tr>
<tr>
<td>Cold cranking power at -30°C, 2 sec - 3 Pulses</td>
<td>kW</td>
<td>7</td>
</tr>
<tr>
<td>CD Life / Discharge Throughput</td>
<td>Cycles/MWh</td>
<td>5,000 / 17</td>
</tr>
<tr>
<td>CS HEV Cycle Life, 50 Wh Profile</td>
<td>Cycles</td>
<td>300,000</td>
</tr>
<tr>
<td>Calendar Life, 35°C</td>
<td>year</td>
<td>15</td>
</tr>
<tr>
<td>Maximum System Weight</td>
<td>kg</td>
<td>60</td>
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<td>Liter</td>
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<td>Vdc</td>
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<tr>
<td>Minimum Operating Voltage</td>
<td>Vdc</td>
<td>&gt;0.55 x Vmax</td>
</tr>
<tr>
<td>Maximum Self-discharge</td>
<td>Wh/day</td>
<td>50</td>
</tr>
<tr>
<td>System Recharge Rate at 30°C</td>
<td>kW</td>
<td>1.4 (120V/15A)</td>
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<td>°C</td>
<td>-30 to +52</td>
</tr>
<tr>
<td>Survival Temperature Range</td>
<td>°C</td>
<td>-46 to +66</td>
</tr>
<tr>
<td>Maximum System Production Price @ 100k units/yr</td>
<td>$</td>
<td>$1,700</td>
</tr>
</tbody>
</table>

Summary

- Vehicle analysis and battery sizing studies were performed in support of a Work Group to propose PHEV battery requirements.
- Two categories of batteries, one for a 10-mile all-electric range (high P/E) and one for a 40-mile all-electric range (high E/P) were selected.
- Four sets of requirements were defined:
  - charge-depleting HEV mode (available energy and power)
  - charge-sustaining HEV mode (available energy and cold cranking)
  - system-level (cost, volume/weight, calendar and cycle life)
  - battery limits (voltage, current and temperature)
- The USABC adopted these requirements and included them as goals in a request for proposals to developers of PHEV batteries.
- Meeting cost and life targets for 10-mile, mid-term batteries are expected to be very challenging.
- Meeting cost, life, and energy density targets for 40-mile, long-term are expected to be very challenging.
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