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SUSTAINABILITY:
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# Battery Requirements for Plug-In Hybrid Electric Vehicles – Analysis and Rationale

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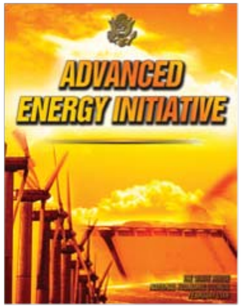
  - FreedomCAR PHEV Battery Work Group
    - Electrochemical Energy Storage Tech Team
    - Vehicle System Analysis Tech Team

# 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 green house 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

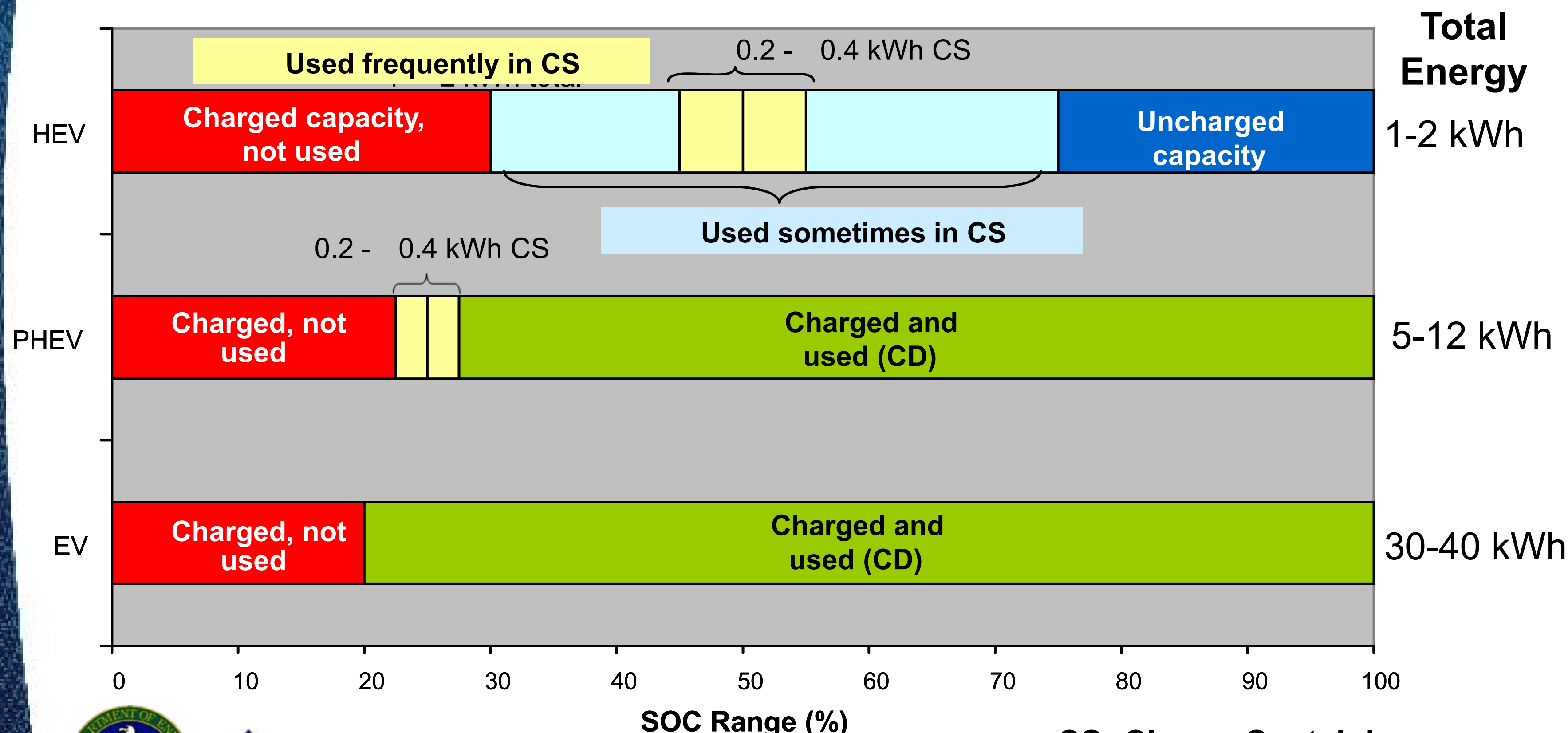
- The purpose of this paper/presentation is to present and document
  - Rationale behind the approach used
  - Rationale for selecting assumptions
  - Results of the analysis for power and energy
  - Rationale for selecting other requirements
  - Resulting PHEV battery requirements

# 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.




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

| Parameter | Units | Midsize Car | Midsize Crossover UV | Midsize SUV |
|---|---|---|---|---|
| Approximate Glider Mass | kg | 940 | 1100 | 1200 |
| Approximate Vehicle Test Mass | kg | 1600 | 1950 | 2000 |
| Frontal Area | $m^2$ | 2.22 | 2.69 | 2.89 |
| Drag Coefficient | | 0.308 | 0.417 | 0.42 |
| Rolling Resistance | | 0.009 | 0.010 | 0.011 |
| Accessory Electrical Load | W | 800 | 1000 | 1200 |

## Vehicle performance parameters

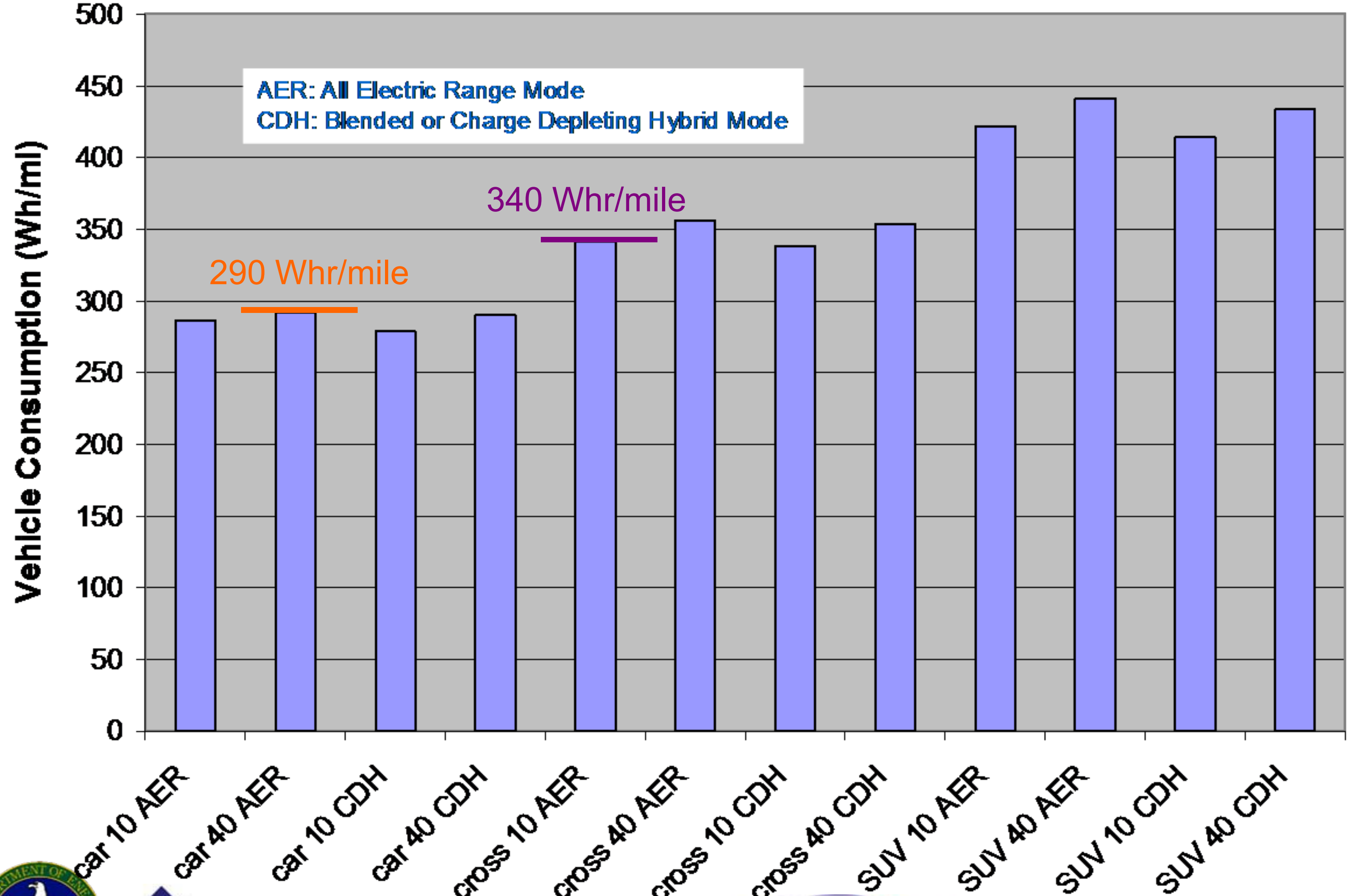
| Parameter | Value |
|---|---|
| Acceleration from 0 to 60 mph | 9 s |
| Top Speed | 100 mph |
| Grade at 55 mph | 6% |

# 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.

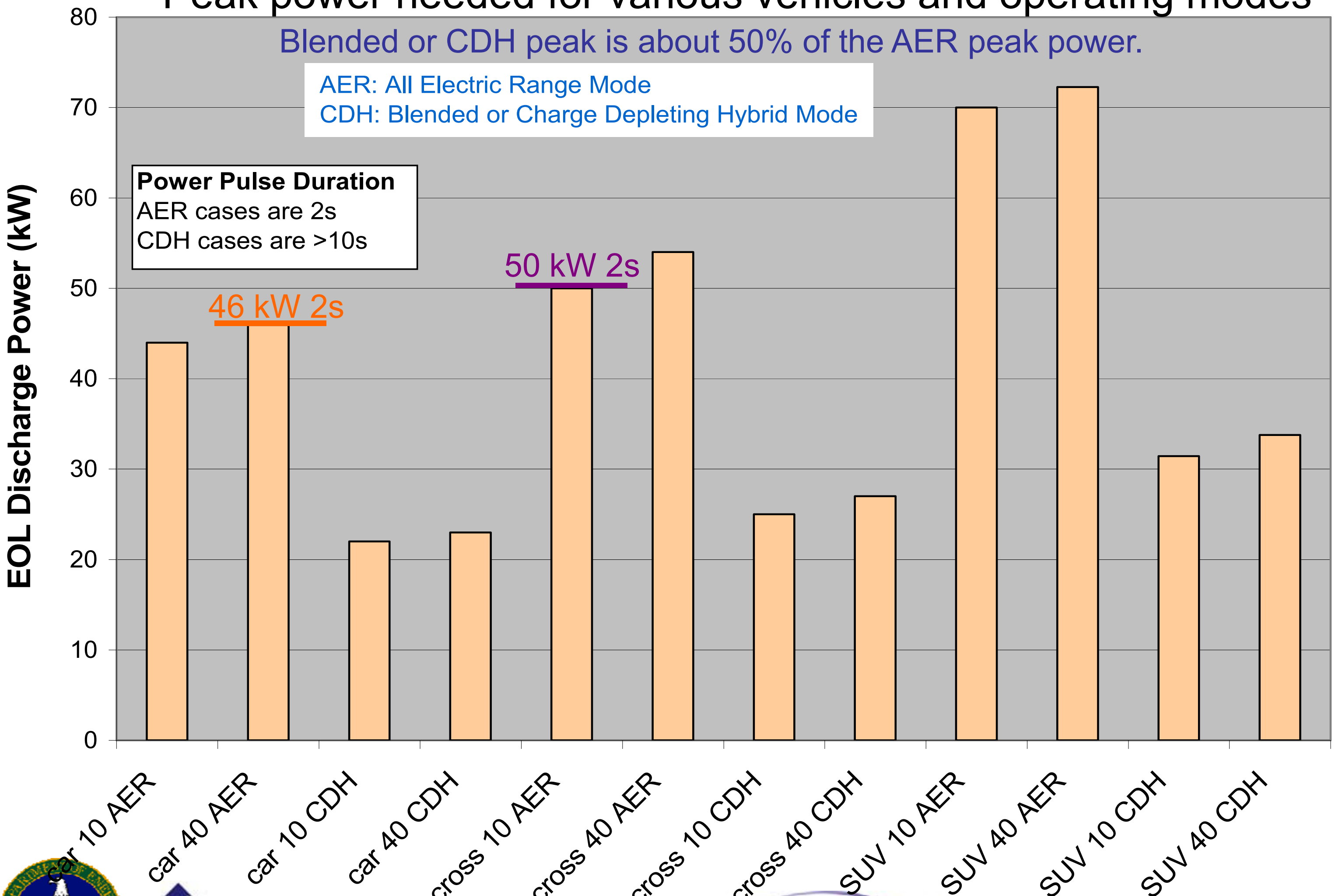
# Analysis Results for Energy - UDDS

Electric energy consumed per mile for various vehicles and operating modes



# Analysis Results for Power - UDDS

Peak power needed for various vehicles and operating modes



# 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

**High Power to Energy Ratio (P/E) Battery** (applies to the 10-mile case)

**High Energy to Power Ratio (E/P) Battery** (applies to the 40-mile case)

# Power and Energy Requirements For Charge-Depleting Mode

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

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

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.

| Characteristics at EOL (End of Life) | | High Power/Energy Ratio Battery | High Energy/Power Ratio Battery |
|---|---|---|---|
| Available Energy for CS (Charge Sustaining) Mode | kWh | 0.5 | 0.3 |
| Cold Cranking Power at -30°C, 2 s, 3 pulses (10 s rest between) | kW | 7 | 7 |

# Calendar & Cycle Life Requirements

| Characteristics at EOL (End of Life) | | High Power/Energy Ratio Battery | High Energy/Power Ratio Battery |
|---|---|---|---|
| Calendar Life, 35°C (a) | year | 15 | 15 |
| Charge Depleting (CD) Cycle Life (b) | cycles | 5,000 | 5,000 |
| Discharge Throughput Energy through CD Cycles (c) | MWh | 17 | 58 |
| Charge-Sustaining HEV Cycle Life, 50 Wh Profile (d) | cycles | 300,000 | 300,000 |

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

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

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

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

| Characteristics at EOL (End of Life) | | High Power/Energy Ratio Battery | High Energy/Power Ratio Battery |
|---|---|---|---|
| Reference Equivalent Electric Range | miles | **10** | **40** |
| Peak Pulse Discharge Power - 2 Sec / 10 Sec | kW | **50 / 45** | **46 / 38** |
| Peak Regen Pulse Power (10 sec) | kW | **30** | **25** |
| Available Energy for CD (Charge Depleting) Mode, 10 kW Rate | kWh | **3.4** | **11.6** |
| Available Energy for CS (Charge Sustaining) Mode | kWh | **0.5** | **0.3** |
| Minimum Round-trip Energy Efficiency (USABC HEV Cycle) | % | **90** | **90** |
| Cold cranking power at -30°C, 2 sec - 3 Pulses | kW | **7** | **7** |
| CD Life / Discharge Throughput | Cycles/MWh | **5,000 / 17** | **5,000 / 58** |
| CS HEV Cycle Life, 50 Wh Profile | Cycles | **300,000** | **300,000** |
| Calendar Life, 35°C | year | **15** | **15** |
| Maximum System Weight | kg | **60** | **120** |
| Maximum System Volume | Liter | **40** | **80** |
| Maximum Operating Voltage | Vdc | **400** | **400** |
| Minimum Operating Voltage | Vdc | **>0.55 x Vmax** | **>0.55 x Vmax** |
| Maximum Self-discharge | Wh/day | **50** | **50** |
| System Recharge Rate at 30°C | kW | **1.4 (120V/15A)** | **1.4 (120V/15A)** |
| Unassisted Operating & Charging Temperature Range | °C | **-30 to +52** | **-30 to +52** |
| Survival Temperature Range | °C | **-46 to +66** | **-46 to +66** |
| Maximum System Production Price @ 100k units/yr | $ | **$1,700** | **$3,400** |

http://www.uscar.org/commands/files_download.php?files_id=118

# 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 <u>energy density</u> targets for 40-mile, long-term are expected to be very challenging.

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