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

Ahmad Pesaran, Ph.D.
Principal Engineer
National Renewable Energy Laboratory
Golden, Colorado, USA

NREL

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    - Electrochemical Energy Storage Tech Team
    - Vehicle System Analysis Tech Team

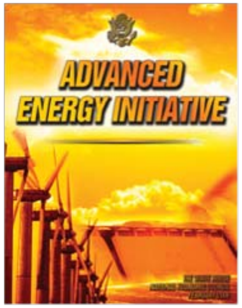
UNITED STATES ADVANCED BATTERY CONSORTIUM

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

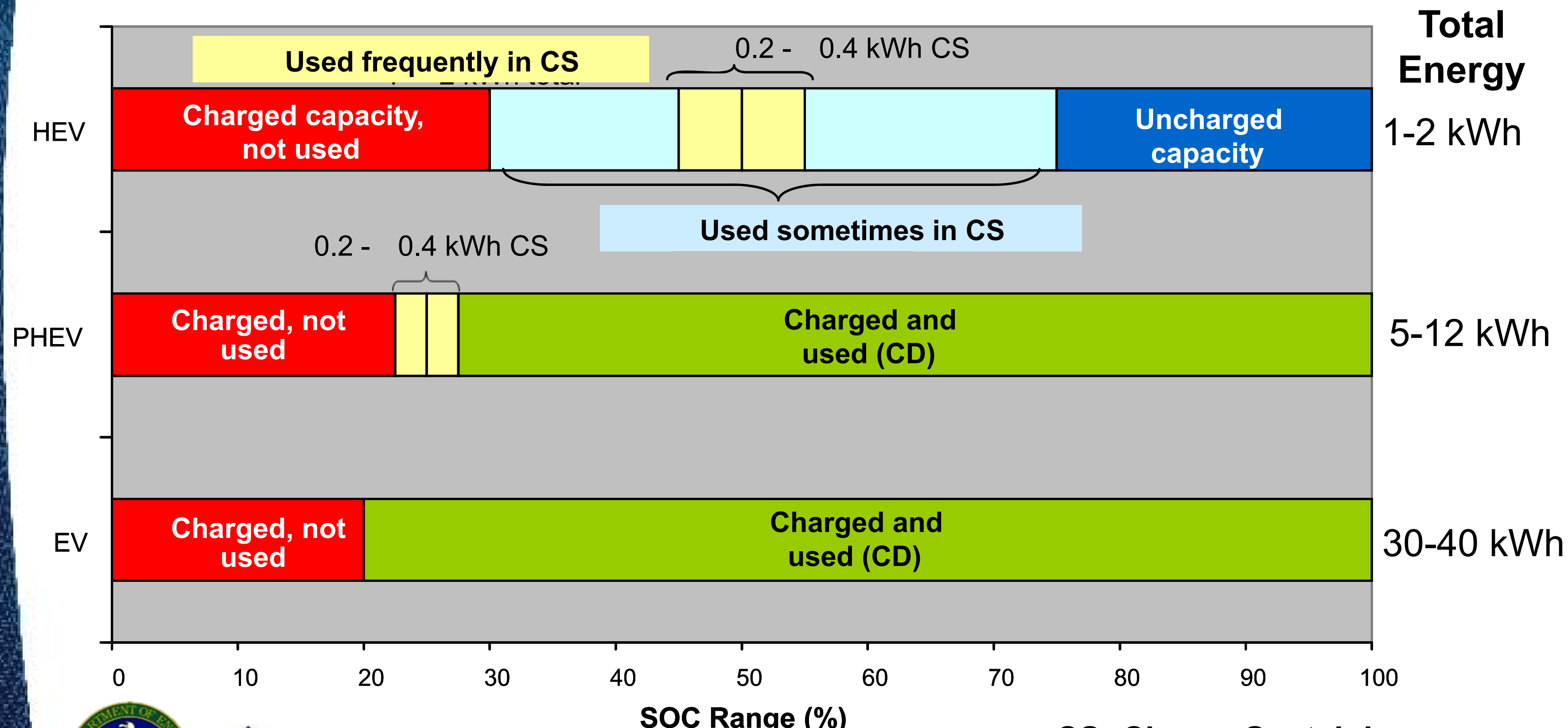
- The purpose of this paper/presentation is to present and document
  - Rationale behind the approach used
  - Rationale for selecting assumptions
  - Results of the analysis for power and energy
  - Rationale for selecting other requirements
  - Resulting PHEV battery requirements

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

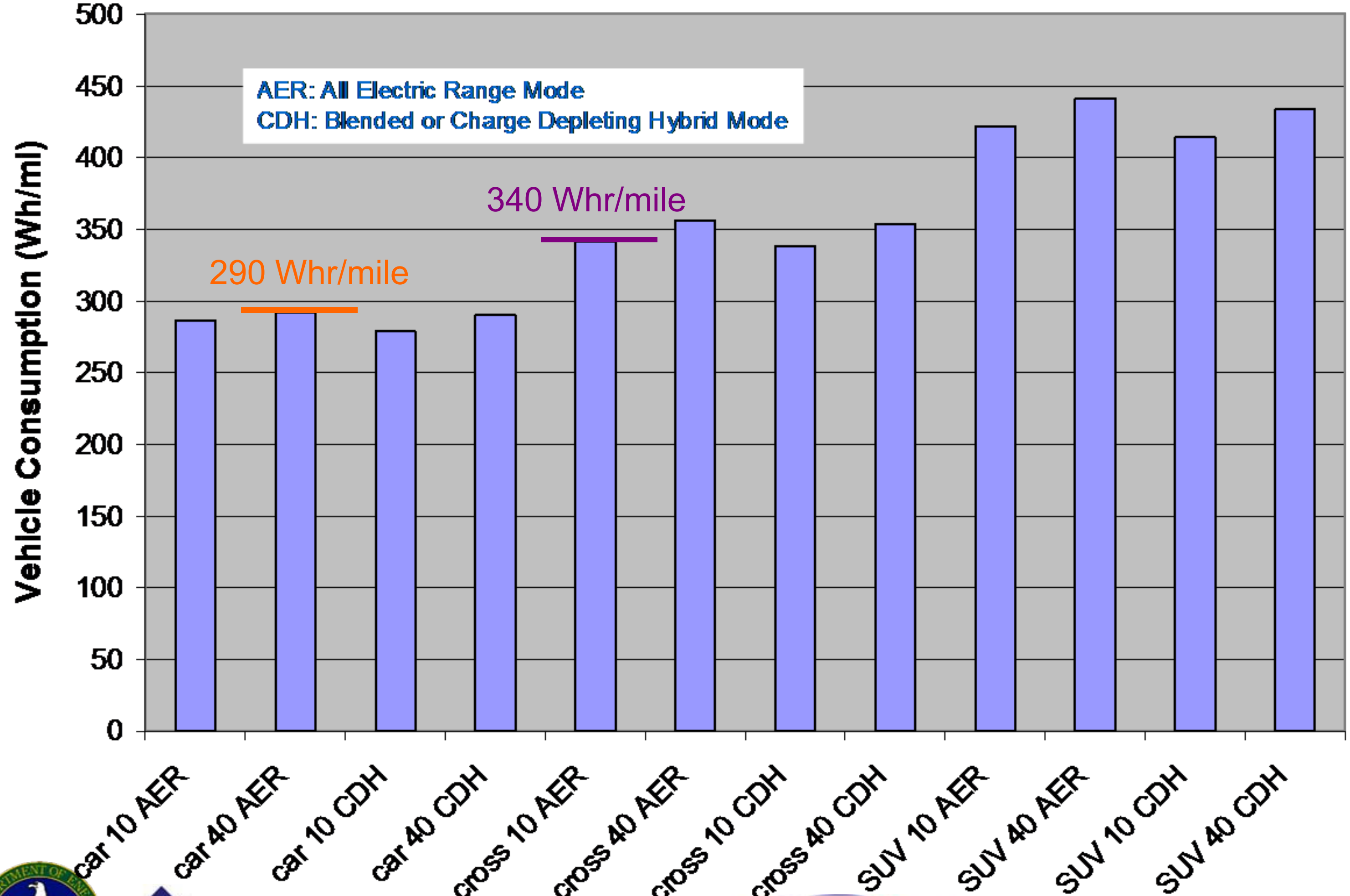
Parameter	Value
Acceleration from 0 to 60 mph	9 s
Top Speed	100 mph
Grade at 55 mph	6%

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.

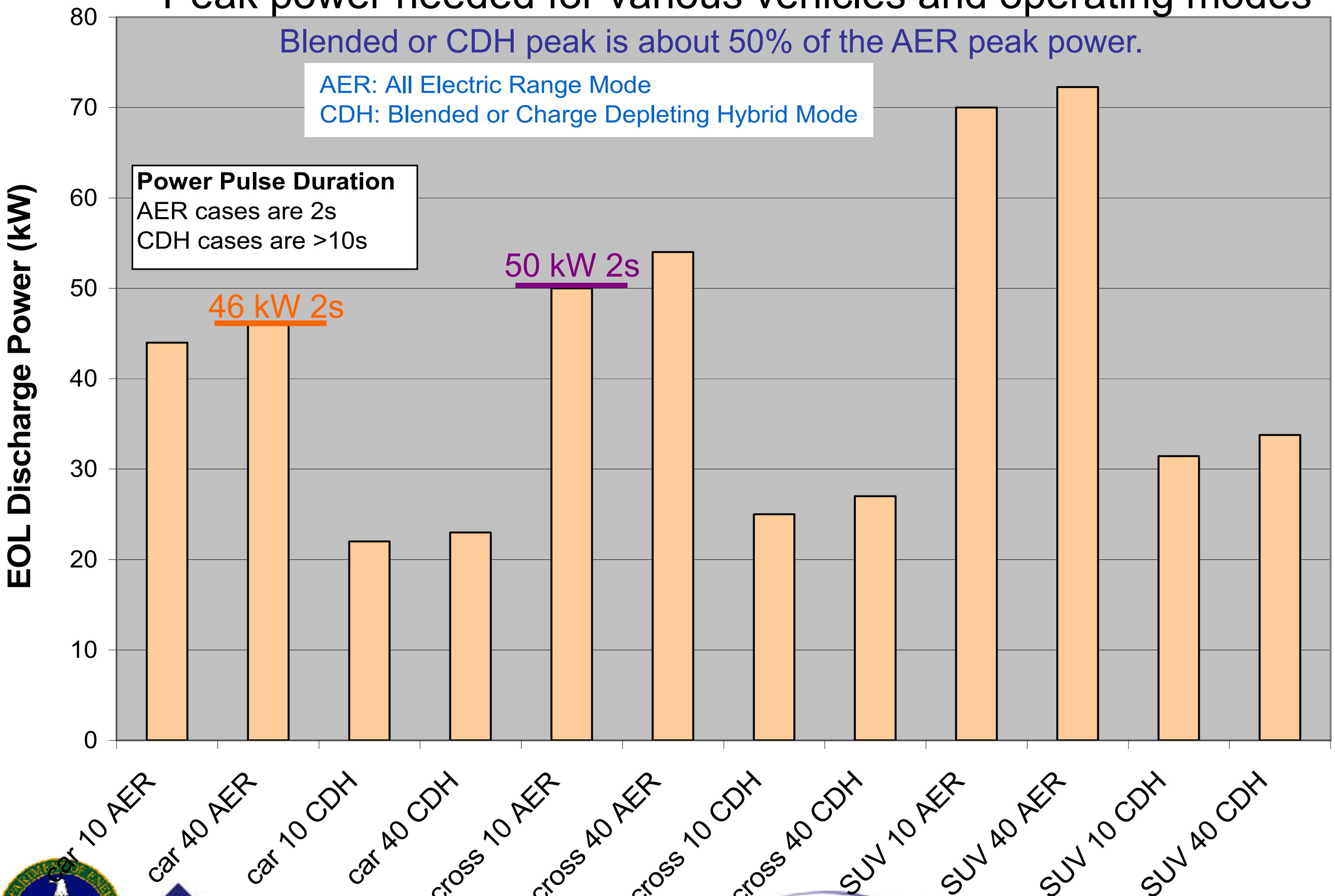
Analysis Results for Energy - UDDS

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 (10-mile case)

High Energy to Power Ratio (E/P) Battery (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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