Battery Choices and Potential Requirements for Plug-In Hybrids

Plug-In Hybrid Electric Truck Workshop
Hybrid Truck Users Forum
Los Angeles, CA

February 13, 2007

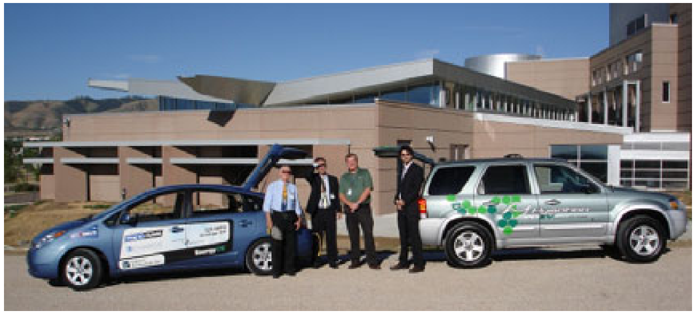
Ahmad Pesaran, Ph.D.
National Renewable Energy Laboratory

With support from
U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
FreedomCAR and Vehicle Technologies Program

NREL/PR-540-41328

NREL’s Plug-in Hybrid R&D Activities

- Battery Level
  - R&D support to developers
  - Testing and evaluation – Sprinter PHEV testing
  - Thermal characterization and design
  - Requirement analysis in support of EES Tech Team
- Vehicle Level
  - Simulated real-world PHEV fuel economy
  - Support development of test procedures and MPG reporting
  - Route-based control
  - PHEV design cost-benefit analysis
- Utility Level
  - Assessment of PHEV impacts on utilities
  - Exploring synergies between PHEVs and wind power
  - V2G opportunities for PHEVs in regulation services
- National Level
  - Benefits assessment - oil use and emissions
  - Renewable community – linking PHEV to homes/communities
- Analysis support to DOE, OEMs, and others
  - Working to identify and overcome barriers to PHEV adoption



NREL’s Heavy Hybrid Vehicle Activities

- Technical Monitor of DOE’s Advanced Heavy Hybrid Propulsion System Program
  - **GM – Allison Transmission** (Heavy hybrid transit bus application & orototype validation) – parallel hybrid
  - **Eaton/International** (Class 4-6 vehicle applications & prototype validations) – parallel hybrid
  - **Oshkosh** (Class 7-8 vehicle application & prototype validation) – Series hybrid; extremely demanding duty-cycle
  - **Caterpillar** (Focus on thermoelectric waste heat recovery)
- Technical Contributions
  - ReFUEL Lab (Chassis and engine dynamometers)
    - Vehicle fuel economy and emissions testing
    - Vehicle drive cycle characterization and analysis
  - Thermal testing, analysis, and management
    - Power electronics
    - Batteries and ultracapacitors

ReFUEL Laboratory

Topics of This Presentation

- **Battery Technologies for PHEVs**
  - State-of-the-art
  - Advances
- **Impact of Vehicle Attributes on Battery**
  - EV Range
  - System Architecture
  - Driving cycles and profiles
- **Concluding Remarks**

Key Messages

- There is a broad spectrum of PHEV designs leading to different battery requirements

- Batteries are available that could meet the energy and power demands for PHEVs, but cost and limited cycle/calendar life are major barriers for affordable PHEV introduction:
  - NiMH could do the job – volume and weight are concerns
  - Li-ion are potentially best candidates
  - All li-ions are not “created equal”

- For heavy-duty PHEV, combining low-cost, high-energy batteries (such as NaNiCl or ZnAir) with high power ultracapacitors may have potential

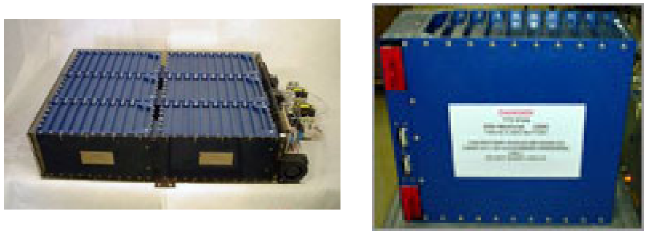
- There is a trade of between high fuel economy and emissions benefits
  - Engine-off during EV operation reduces the petroleum consumption
  - Too many engine-off cycles lead to cold starts and higher emissions

- PHEVs are the most-cost-effective choice in a scenario of projected low battery costs and high fuel costs.

Batteries in Current PHEVs

NiMH

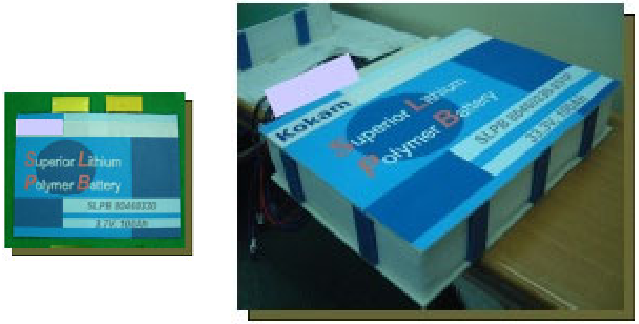
Johnson Controls / Varta



Electro Energy Inc.

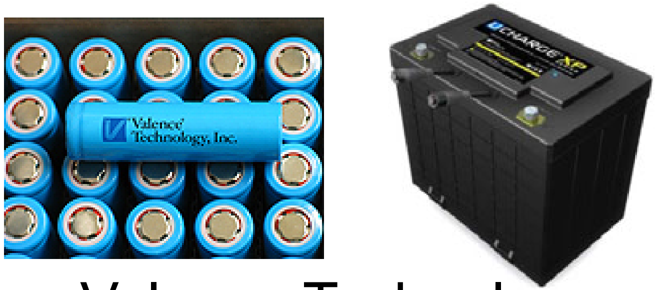
Co/Ni based Li-Ion

Johnson Controls / SAFT



Kokam

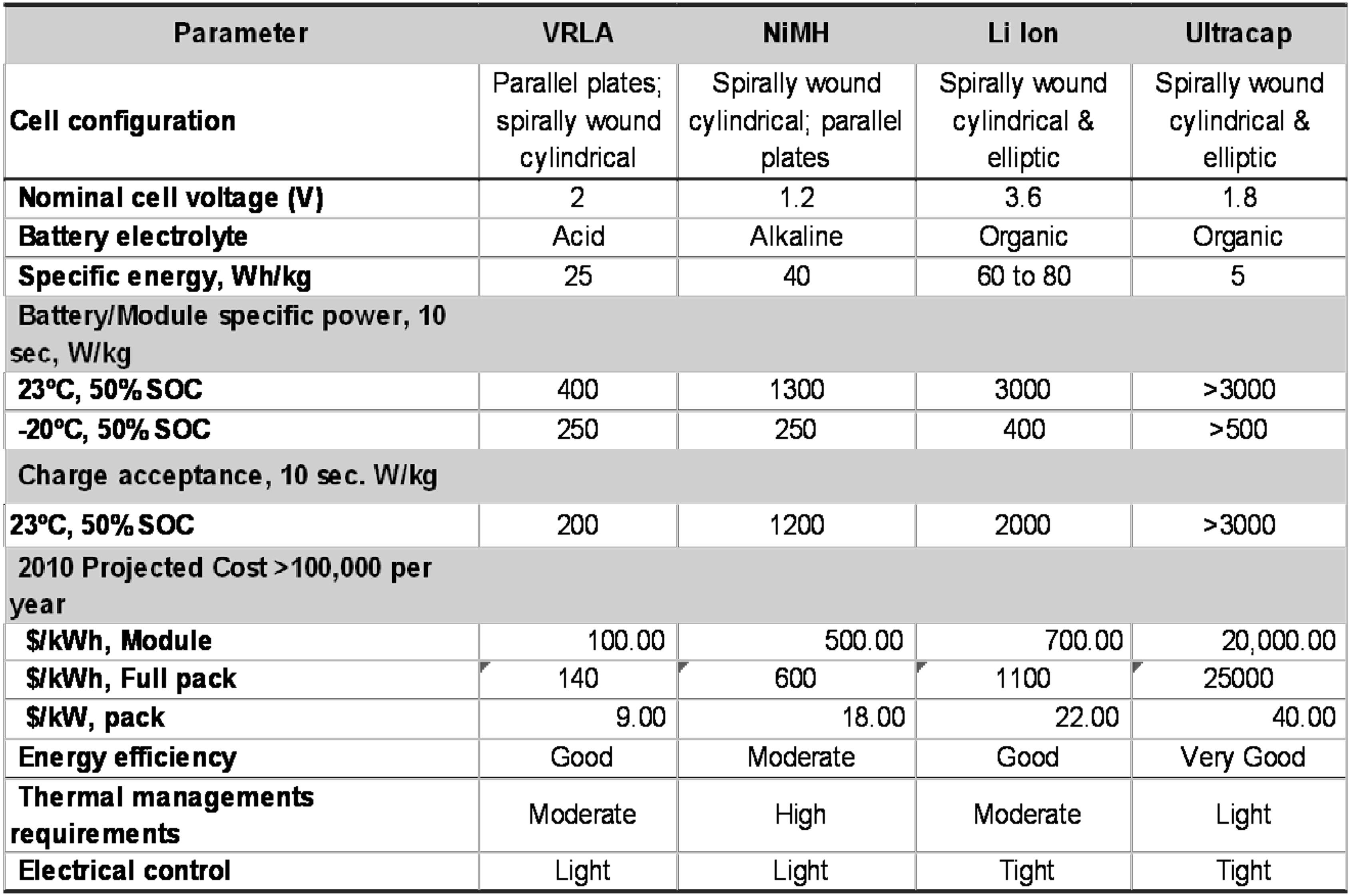
Iron phosphate based Li-Ion



Valence Technology

A123 Systems

High Power Battery and Ultracapacitor Characteristics



Parameter	VRLA	NiMH	Li Ion	Ultracap
Cell configuration	Parallel plates; spirally wound cylindrical	Spirally wound cylindrical; parallel plates	Spirally wound cylindrical & elliptic	Spirally wound cylindrical & elliptic
Nominal cell voltage (V)	2	1.2	3.6	1.8
Battery electrolyte	Acid	Alkaline	Organic	Organic
Specific energy, Wh/kg	25	40	60 to 80	5
Battery/Module specific power, 10 sec, W/kg				
23°C, 50% SOC	400	1300	3000	>3000
-20°C, 50% SOC	250	250	400	>500
Charge acceptance, 10 sec. W/kg				
23°C, 50% SOC	200	1200	2000	>3000
2010 Projected Cost >100,000 per year				
$/kWh, Module	100.00	500.00	700.00	20,000.00
$/kWh, Full pack	140	600	1100	25000
$/kW, pack	9.00	18.00	22.00	40.00
Energy efficiency	Good	Moderate	Good	Very Good
Thermal managements requirements	Moderate	High	Moderate	Light
Electrical control	Light	Light	Tight	Tight

Source: M. Anderman, AABC-04 Tutorial, San Francisco, CA June 2004

Qualitative Comparison of Existing Energy Battery Technologies for PHEVs

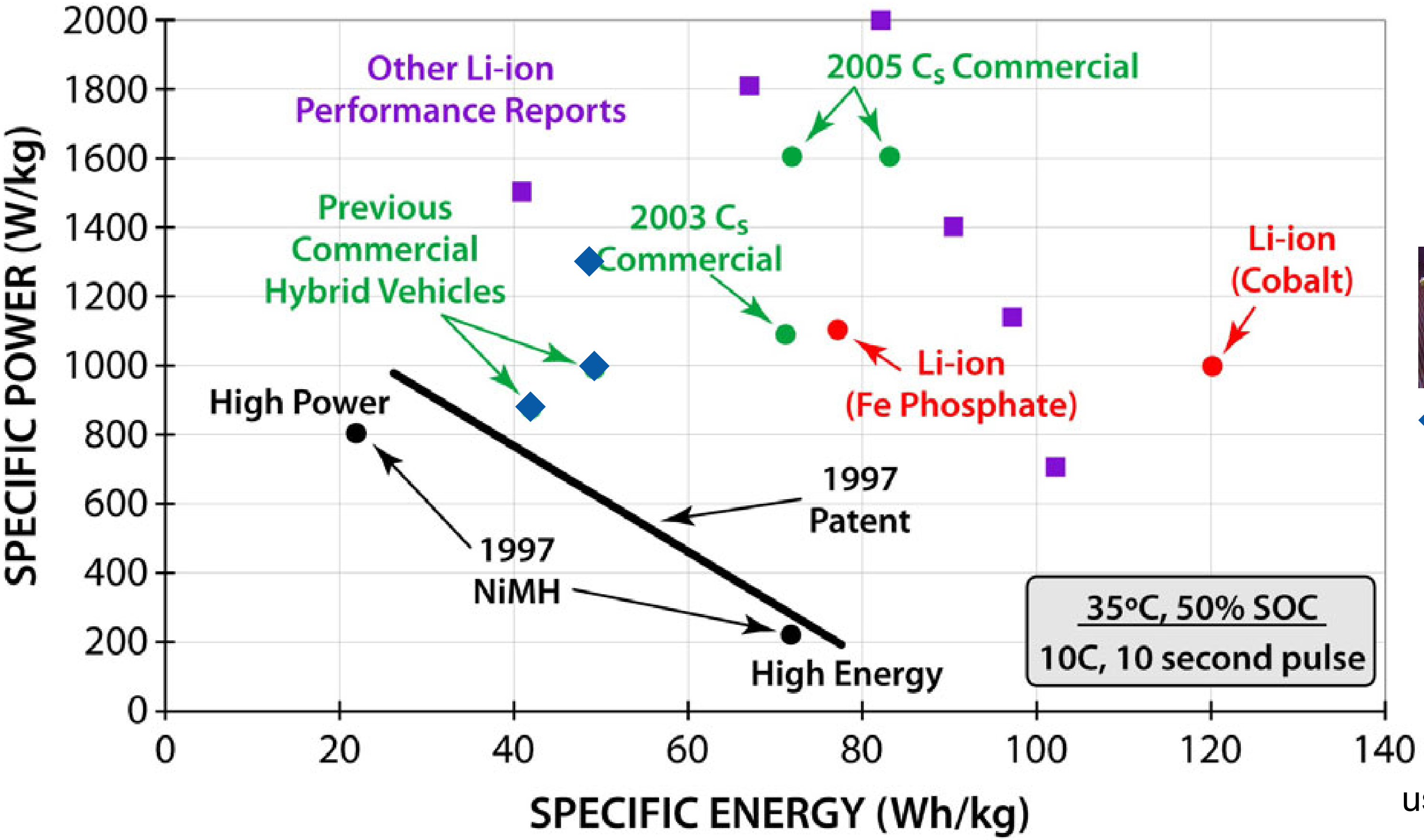
Key

Key
🟥 Poor
🟨 Fair
🟩 Good

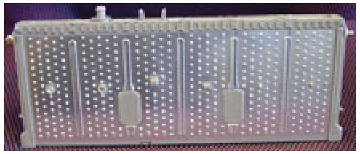
Attribute	Lead Acid	NiMH	Li-Ion
Weight (kg)	🟥	🟨	🟩
Volume (lit)	🟥	🟩	🟩
Capacity/Energy (kWh)	🟥	🟨	🟩
Discharge Power (kW)	🟩	🟨	🟩
Regen Power (kW)	🟩	🟩	🟩
Cold-Temperature (kWh & kW)	🟩	🟨	🟥
Shallow Cycle Life (number)	🟩	🟩	🟩
Deep Cycle Life (number)	🟥	🟩	🟨
Calendar Life (years)	🟥	🟨	🟨
Cost ($/kW or $/kWh)	🟩	🟥	🟥
Safety- Abuse Tolerance	🟩	🟩	🟨
Maturity - Technology	🟩	🟩	🟨
Maturity - Manufacturing	🟩	🟨	🟥

NiMH has Matured in Power and Energy

Specific energy ranging from 45 Wh/kg to 80 Wh/kg depending on the power capability.



● **Ovonic**



◆ **Panasonic EV**

95 Ah EV module used in Toyota RAV 4

Source: Reproduced from A. Fetcenko (Ovonic Battery Company) from the 23rd International Battery Seminar & Exhibit, March 13-16, 2006, Ft. Lauderdale, FL.

NiMH technology is forecasted to have a major market share in hybrid market until Li-Ion takes off

Panasonic

6.5 Ah Battery for Toyota Prius

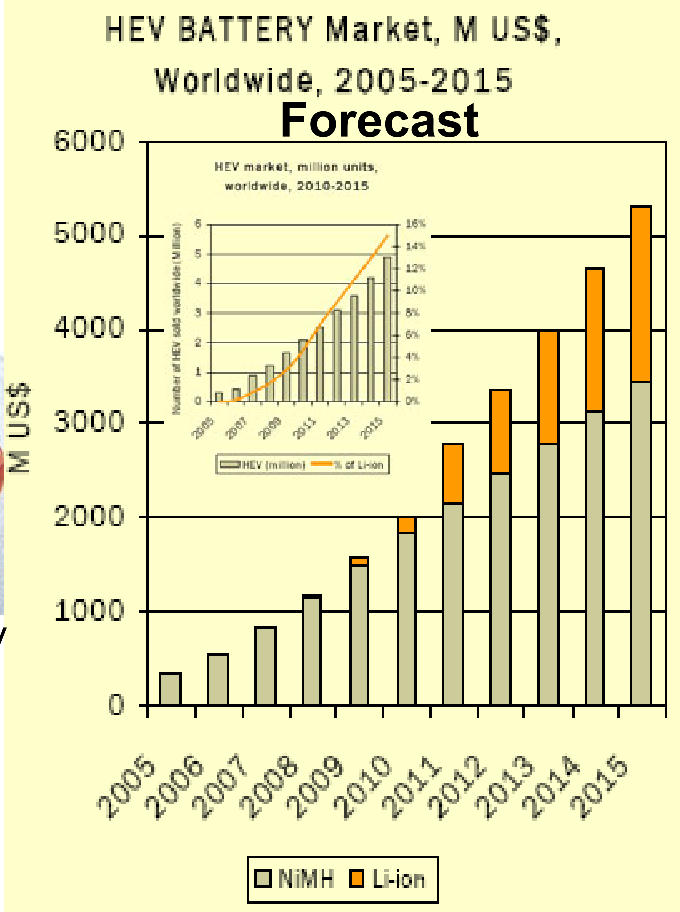
Sanyo

6.5 Ah HEV cells in Ford Escape HEV

Source: Sanyo website news

Cobasys

EV module (left) and 42V HEV batteries



Source: C. Pillot (Avicenne) from the 23rd International Battery Seminar & Exhibit, March 13-16, 2006, Ft. Lauderdale, FL.

Electro Energy

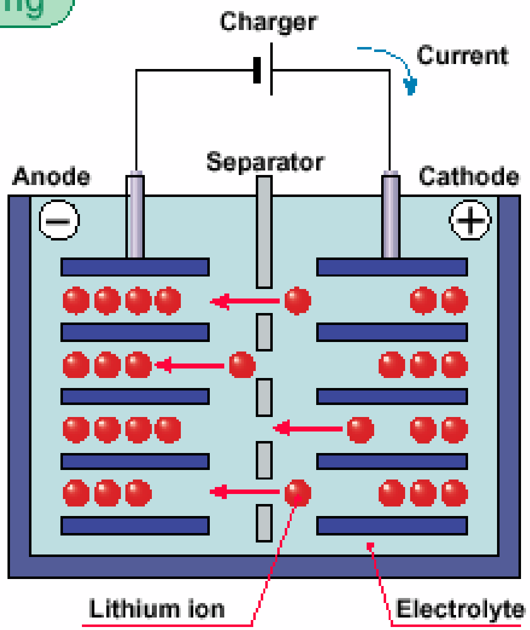
Pack with bipolar Cells/Modules

Bipolar pack in a Plug-In Prius

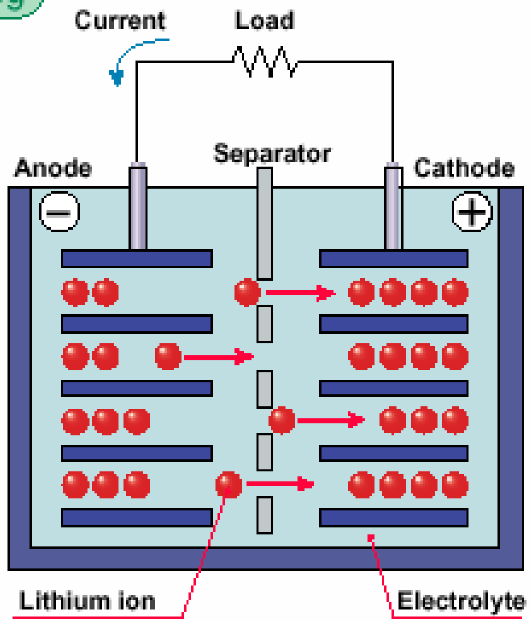
Source: Images provided by James Landi of Electro Energy Inc.

Li-Ion Technology – Diverse Chemistry & Opportunity

Charging



Discharging



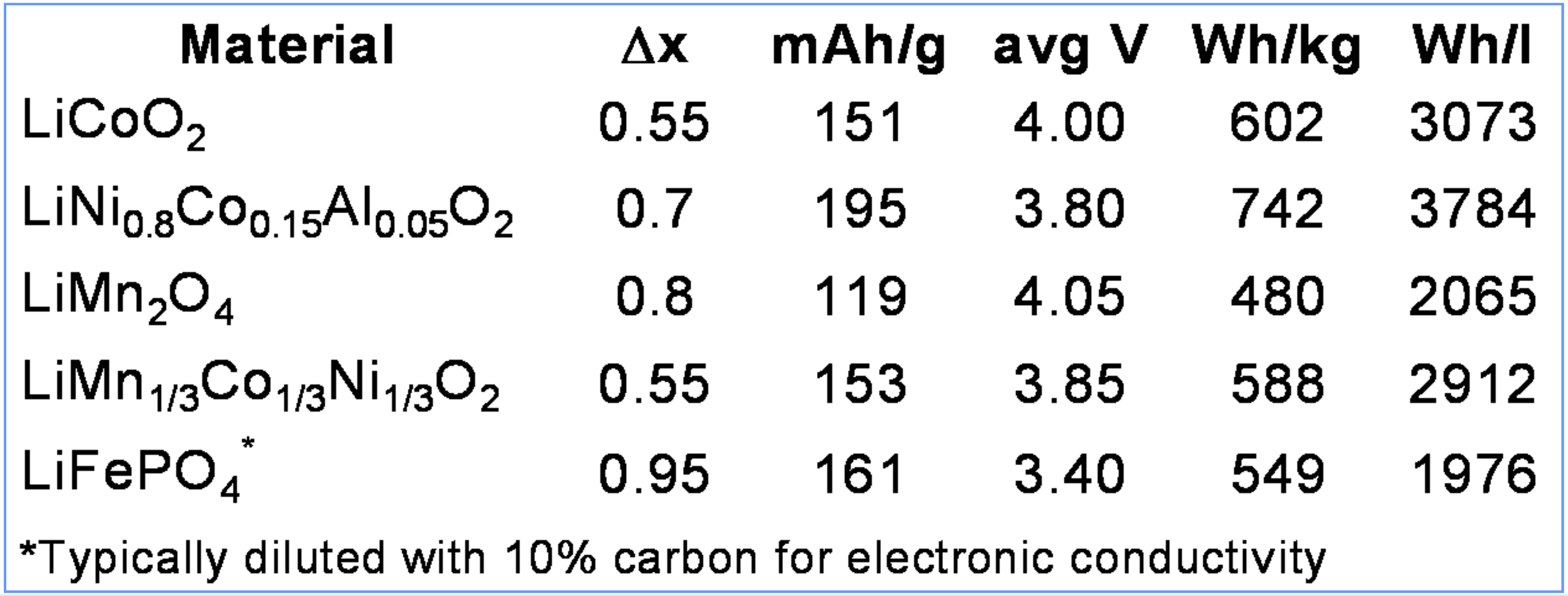
Voltage ~3.2-3.8 V
Cycle life ~1000-3000
Wh/kg >150
Wh/l >400
Discharge -30 to 60°C
Shelf life <10%/year

Many anodes are possible	**Many electrolytes are possible**	**Many cathodes are possible**
Carbon/Graphite	$LiPF_6$ based	Cobalt oxide
Titanate ($Li_4Ti_5O_{12}$)	$LiBF_4$ based	Manganese oxide
Titanium oxide based	Various solid state electrolytes	Mixed oxides with Nickel
Tin Oxide based	Polymer electrolytes	Iron phosphate
Tungsten oxide	(+ some salts)	Vanadium oxide based

Source: Robert M. Spotnitz, Battery Design LLC, "Advanced EV and HEV Batteries," 2005 IEEE Vehicle Power and Propulsion Conference, September 7-9, 2005, IIT, Chicago, IL

Characteristics of Cathode Materials

Theoretical values for a battery system relative to graphite anode and $LiPF_6$ electrolyte



Material	Δx	mAh/g	avg V	Wh/kg	Wh/l
$LiCoO_2$	0.55	151	4.00	602	3073
$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	0.7	195	3.80	742	3784
$LiMn_2O_4$	0.8	119	4.05	480	2065
$LiMn_{1/3}Co_{1/3}Ni_{1/3}O_2$	0.55	153	3.85	588	2912
$LiFePO_4$*	0.95	161	3.40	549	1976

*Typically diluted with 10% carbon for electronic conductivity

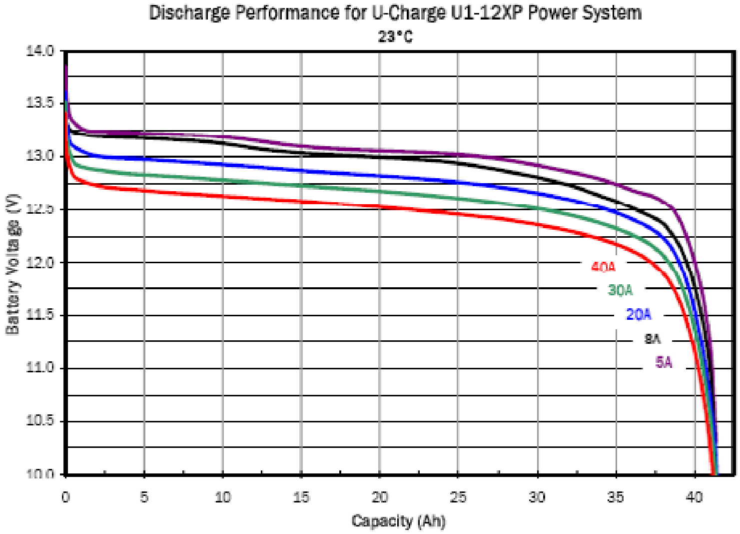
- Cobalt oxide most widely used in consumer cells but recently too expensive
- $LiMn_{1/3}Co_{1/3}Ni_{1/3}O_2$ newer than $LiNiCoO_2$
- Mn_2O_4 around for many years – not competitive for consumer – good for high power
- Oxide cathodes with cobalt are more energetic
- $LiFePO_4$ – very new – too low energy density for consumer electronics
  - safe on overcharge but need electronics to prevent under-voltage
  - may require larger number of cells due to lower cell voltage

Source: Robert M. Spotnitz, Battery Design LLC, “Advanced EV and HEV Batteries,” 2005 IEEE Vehicle Power and Propulsion Conference, September 7-9, 2005, IIT, Chicago, IL

Many Commercial Oxide Based Li-Ion Batteries are Available

- Johnson Control - Saft
- LG Chem
- Electrovaya
- Kokam
- SK Corp
- NEC Lamilion Energy
- GS Yuasa
- Sony
- Sanyo
- Samsung
- Panasonic
- Nissan
- Lishen
- Pionics
- Altair Nanotechnologies
- Chinese companies

Lithium Iron Phosphate ($LiFePO_4$) Cathodes



Source: On line brochures from Valence Technolo
http://www.valence.com/ucharge.asp

+ High stability and non-toxic
+ Good specific capacity
+ Flat voltage profile
+ Cost effective (less expensive cathode)
+ Improved safety
– Lower voltage than other cathodes
– Poor Li diffusion (D_{Li}~ 10^{-13} cm^2/Sec)
– Poor electronic conductivity (~ 10^{-8} S/cm)

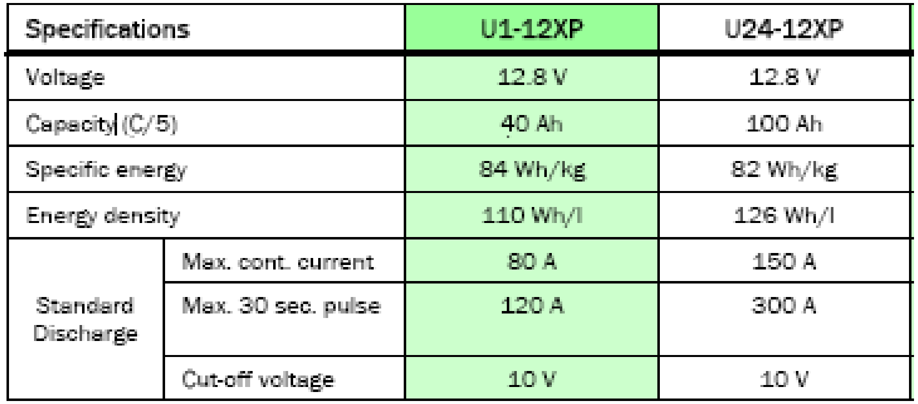
- Approach many use to overcome poor characteristics
  - Use nano $LiFePO_4$ – carbon composite
  - Use larger number of cells
  - Nano structured materials

Source: Various papers from the 23rd International Battery Seminar & Exhibit, March 13-16, 2006, Ft. Lauderdale, FL.

Improvements in Iron Phosphate Li-Ion Batteries

Valence Technology 18650 Cells
100 Wh/kg in cell 84 Wh/kg in U Charge module

The battery with standard lead acid battery form factor includes a battery management system.



Specifications		U1-12XP	U24-12XP
Voltage		12.8 V	12.8 V
Capacity (C/5)		40 Ah	100 Ah
Specific energy		84 Wh/kg	82 Wh/kg
Energy density		110 Wh/l	126 Wh/l
Standard Discharge	Max. cont. current	80 A	150 A
	Max. 30 sec. pulse	120 A	300 A
	Cut-off voltage	10 V	10 V

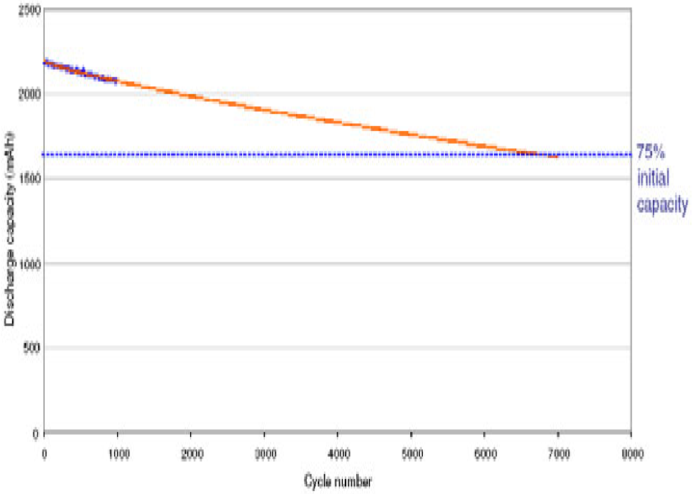
Source: 2006 On line brochures from Valence Technology, http://www.valence.com/ucharge.asp

Power Density (<3Ah cy cells)	Weight to discharge @1500W	Safety	Life at 100% DoD 1C rate	Environmental
3600 W/Kg	0.9 lbs	✓	~7000	✓

Based on: Novel nano scale doped phosphate active materials (pat. pending)
Low impedance cell design and electrolyte (pat. pending)

A123 Systems with 26650 Cells 100 Wh/kg

Source: Andrew Chu (A123 Systems) from the 23rd International Battery Seminar & Exhibit, March 13-16, 2006, Ft. Lauderdale, FL.

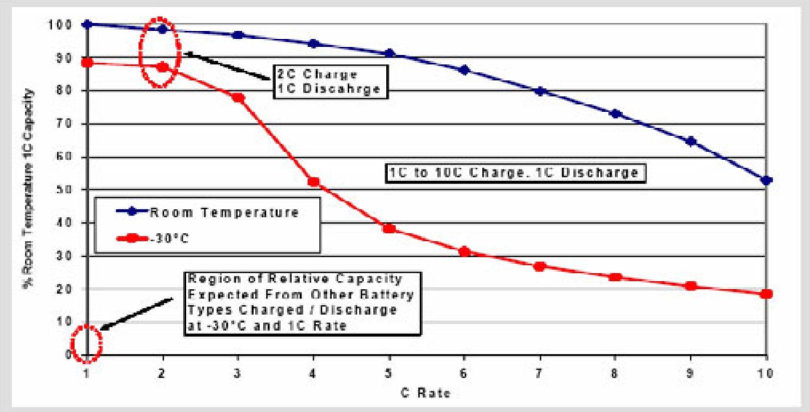


100%DOD 1C charge, 1C discharge cycling data.
Using first 1000 cycles, extrapolated cycle life: ~7000 cycles.

NREL National Renewable Energy Laboratory

Improving Li-Ion Batteries with Titanate Anode

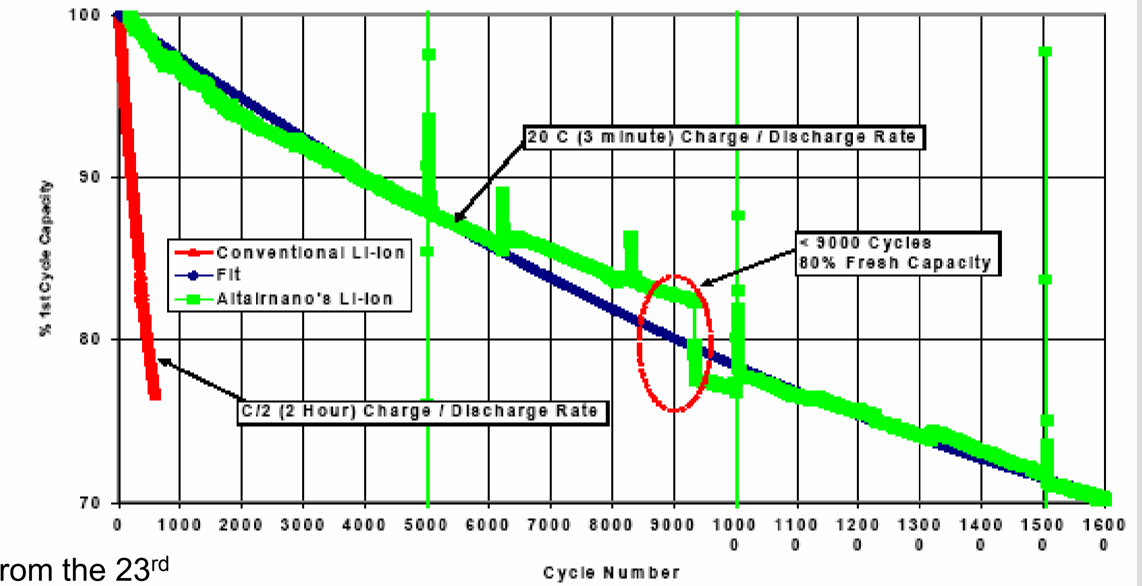
Characteristic	Traditional Li Ion Batteries	Li Ion Batteries Using Altairnano materials
Electrode Materials		
Anode	Graphite	Lithium titanate spinel
Cathode	Cobaltate	Nano-Structured oxides
Performance		
Charge rate	½ C	20 C and greater
Discharge rate	4 C	40 C and greater
Cycle life	300-500 cycles	9,000 cycles (full DOD)
Calendar life	2-3 years	10-15 years



~90% SOC of RT Cell at -30°C and 1-2C Charge Rate!

Altaire Nanotechnologies Inc.

- Improved low temperature performance
- Faster charge acceptance
- Longer cycle life
- 80-100 Wh/kg
- 2000-4000 W/kg



Source: E. House (Altair Nanotechnologies) from the 23rd International Battery Seminar & Exhibit, March 13-16, 2006, Ft. Lauderdale, FL.

Exciting Times for Li-Ion Batteries

- New Cathodes
  - Lower cost
  - Higher power
  - Better safety
  - Improved life
- New Anodes
  - Faster charge rate
  - Improved life
- New Electrolyte
  - Improved safety
  - Improved low temperature performance
- New Separator
  - Lower cost
  - Improved safety

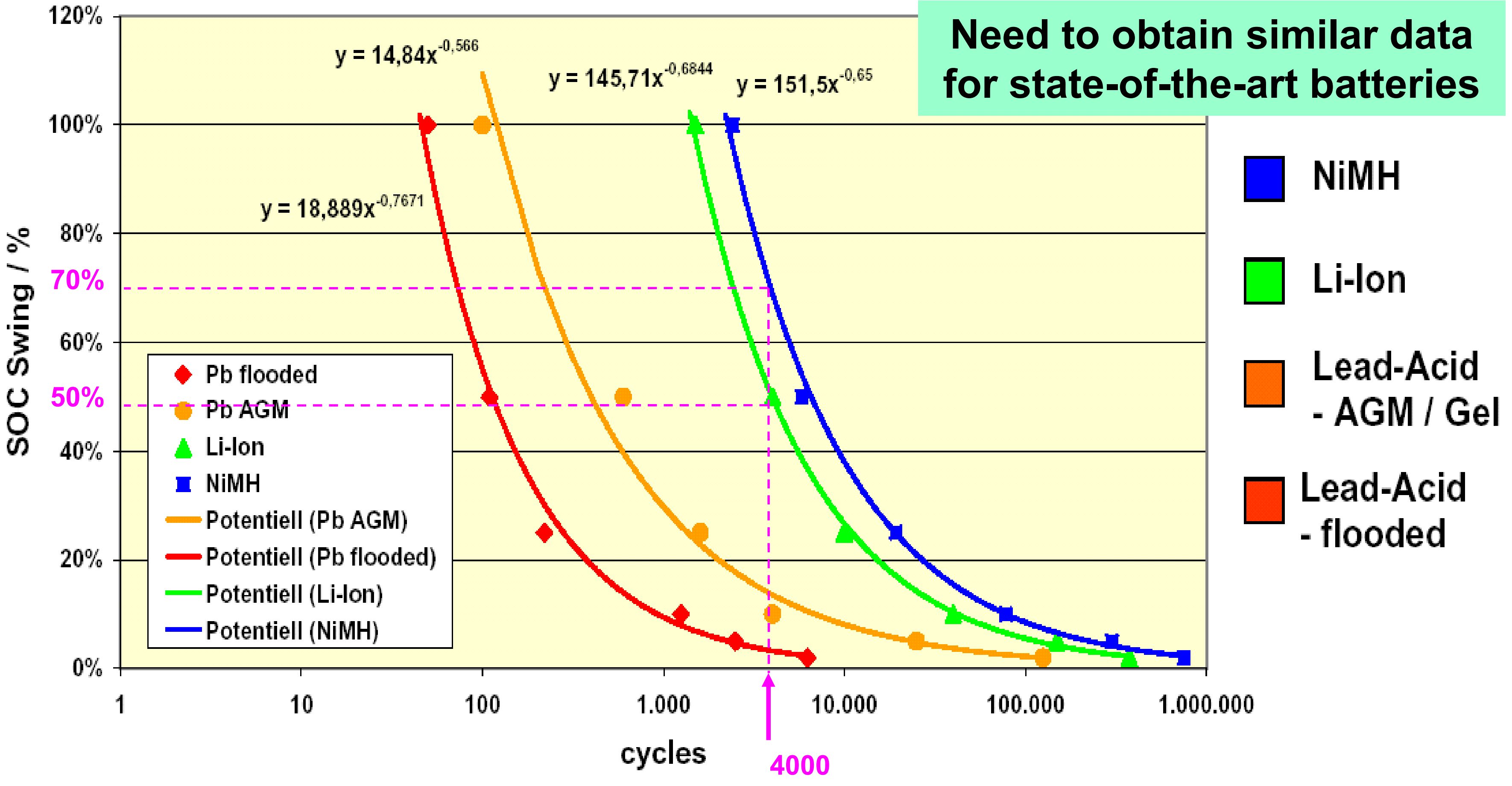
Main barrier is cost!

Other Energy Storage Potential Choices for Plug-In Hybrid Electric Trucks (PHET)

- Sodium Nickel Chloride battery (NaNiCl) – Zebra
  - High energy density
  - Low power density
  - Inexpensive
- Zinc Air battery/fuel cell (ZnAir)
  - Types
    - The “Refuellable” ZnAir Fuel Cell
    - The “Mechanically Rechargeable” ZnAir Fuel Cell
    - The Electrically Rechargeable ZnAir Battery
  - High energy density
  - Low power density
  - Inexpensive
- Ultracapacitors
  - High power density
  - Low energy density
  - Expensive now, could become lower in cost
- Combination of ultracapacitors with NaNiCl or ZnAir
  - The need for DC/DC converter may increase cost, volume/mass

Battery Cycle Life Depends on State of Charge Swing

- PHEV battery likely to deep-cycle each day driven: 15 yrs equates to 4000-5000 deep cycles
- Also need to consider combination of high and low frequency cycling

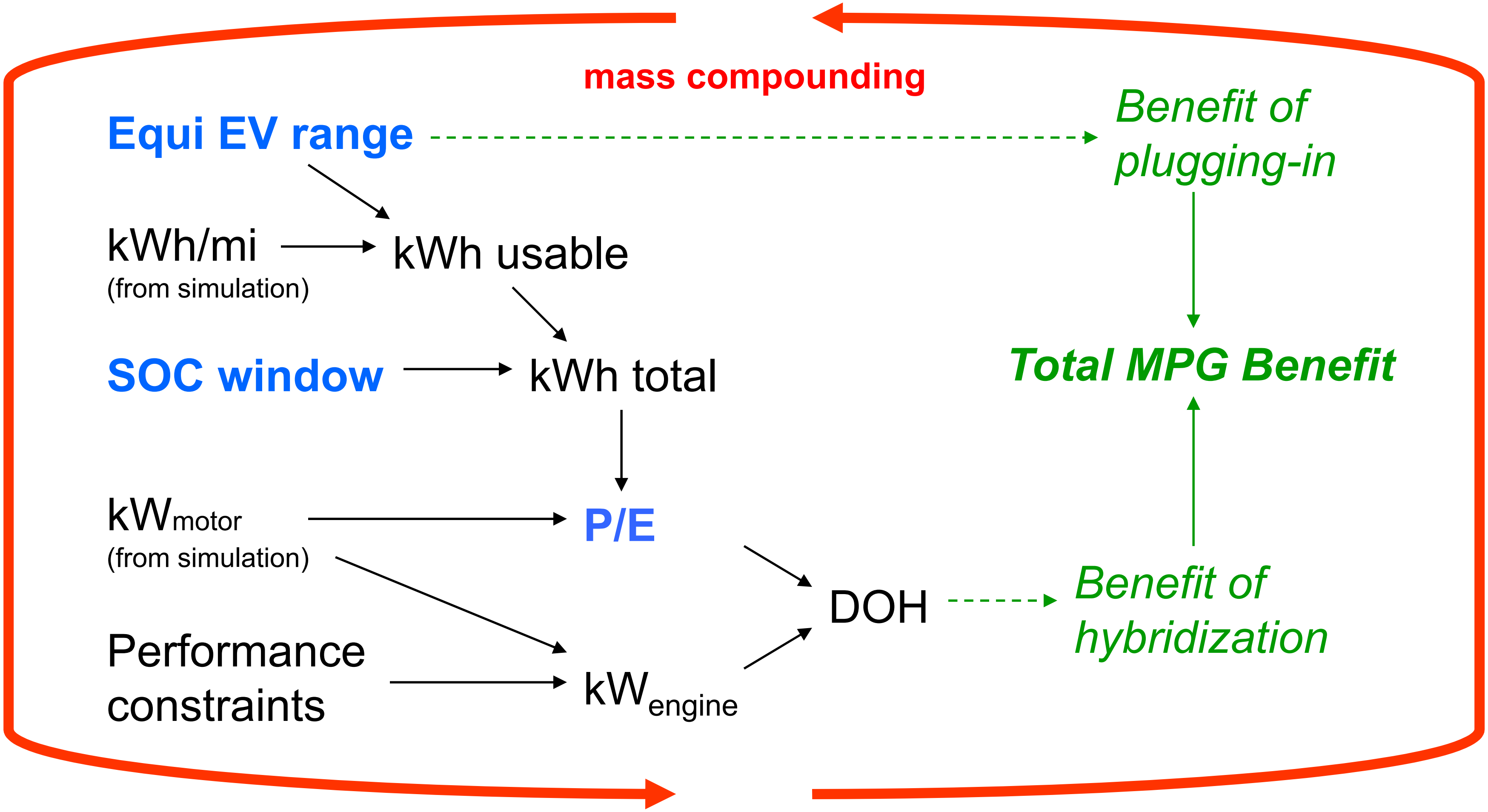


Need to obtain similar data for state-of-the-art batteries

Source: Christian Rosenkranz (Johnson Controls) at EVS 20, Long Beach, CA, November 15-19, 2003

Battery Sizing Depends on:

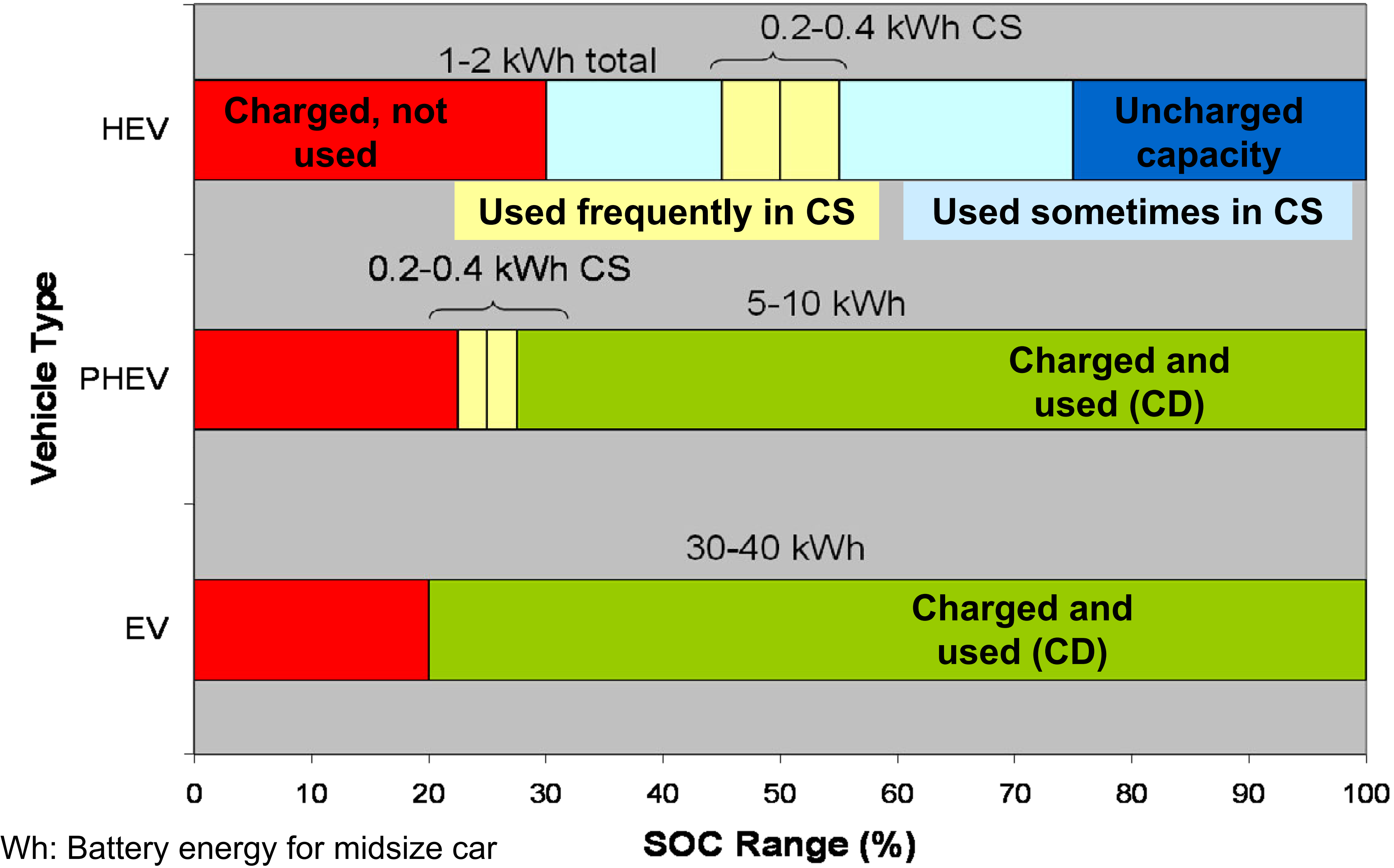
EV range, vehicle (mass, aerodynamic, etc.), drive cycle, strategy



DOH = degree of hybridization

Source: Tony Markel and Andrew Simpson, Milestone Report, National Renewable Energy Laboratory, Golden, CO, September 2005.

Battery Usage in EVs, HEVs, and PHEVs



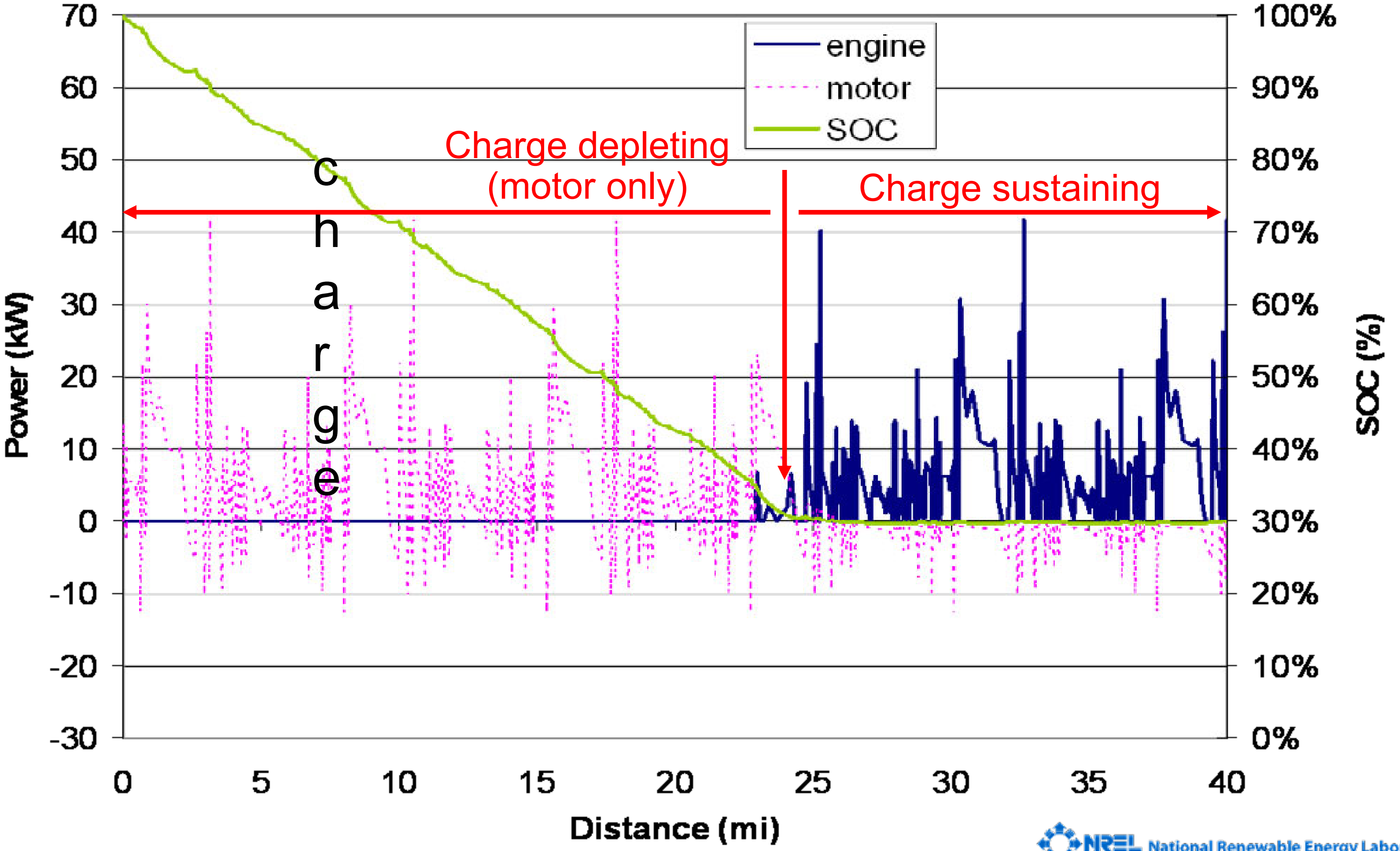
kWh: Battery energy for midsize car

CS: Charge Sustaining **CD: Charge Depleting**

Alternative PHEV Design Strategies: Charge Depleting EV vs. Charge Depleting HEV

- Engine turns on when battery reaches low state of charge
- Requires high power battery and motor

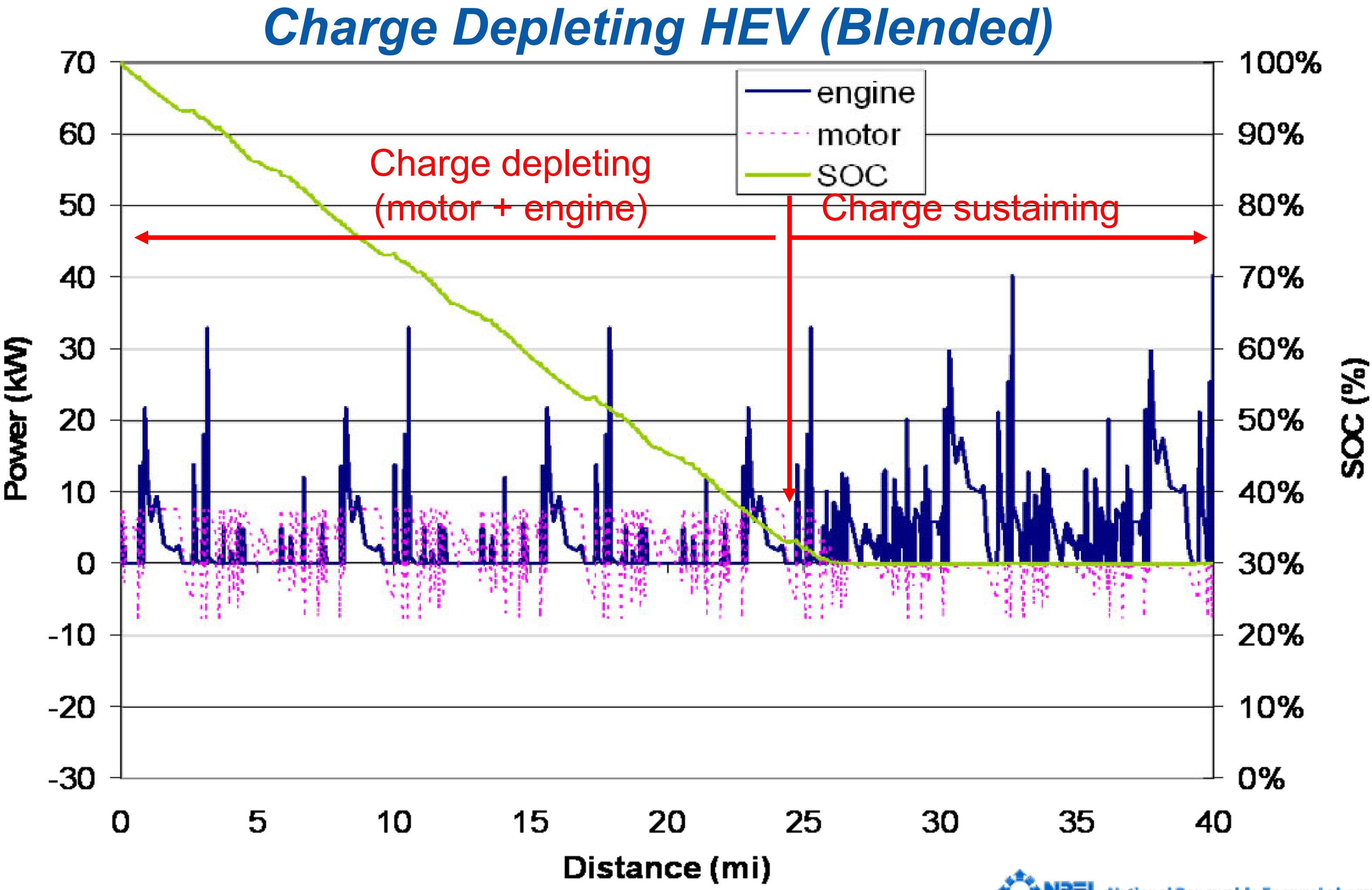
Charge-Depleting EV (All-Electric)



Source: Tony Markel and Andrew Simpson (NREL), AABC-06, Baltimore, MD, May 19, 2006

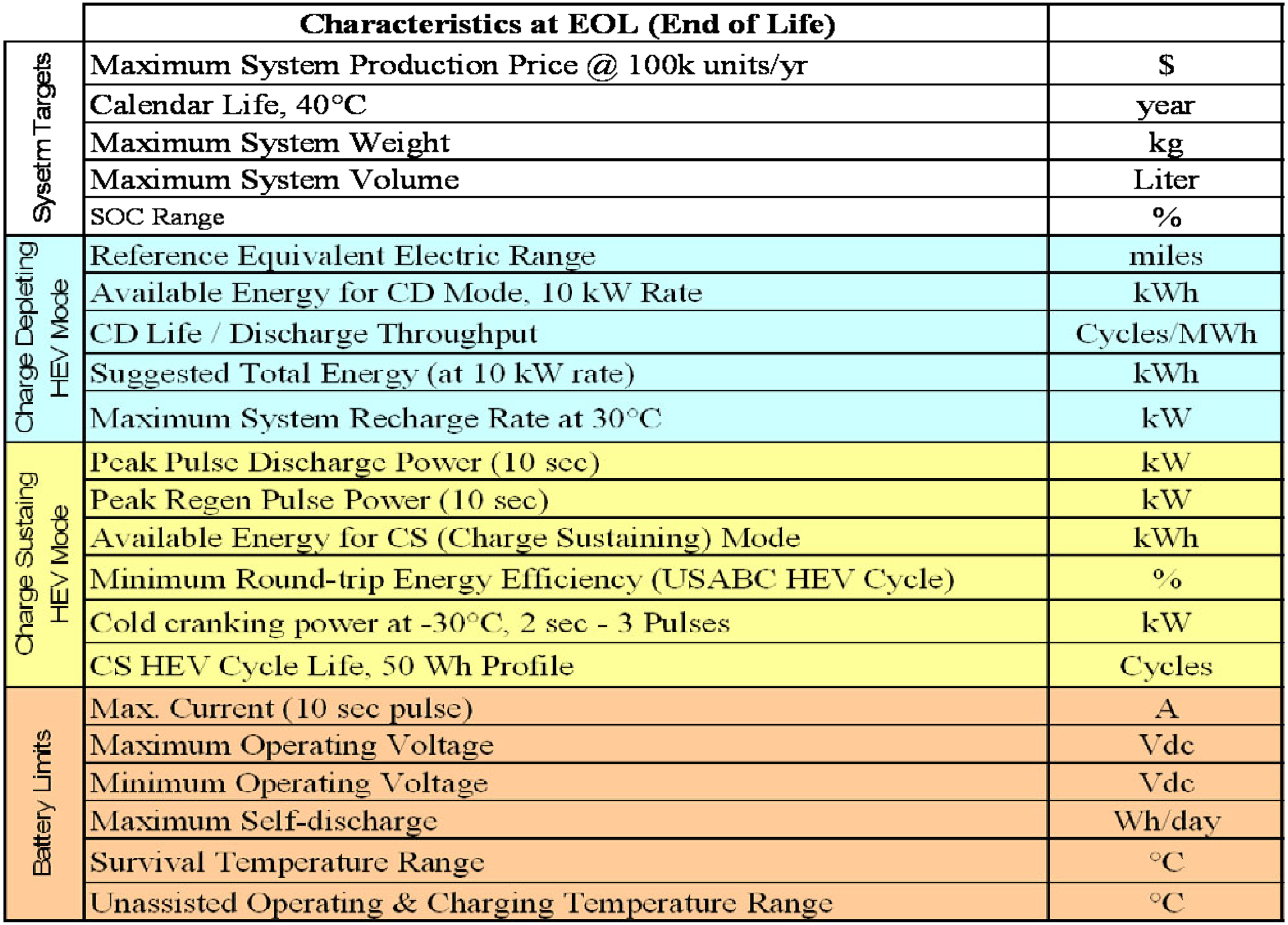
Alternative PHEV Design Strategies: Charge Depleting EV vs. Charge Depleting HEV

- Engine turns on when power exceeds battery power capability
- Engine only provides load that exceeds battery power capability



Source: Tony Markel and Andrew Simpson (NREL), AABC-06, Baltimore, MD, May 19, 2006

Example of Battery Requirements for Plug-in Hybrid Vehicles



	Characteristics at EOL (End of Life)	
Sysetm Targets	Maximum System Production Price @ 100k units/yr	$
	Calendar Life, 40°C	year
	Maximum System Weight	kg
	Maximum System Volume	Liter
	SOC Range	%
Charge Depleting HEV Mode	Reference Equivalent Electric Range	miles
	Available Energy for CD Mode, 10 kW Rate	kWh
	CD Life / Discharge Throughput	Cycles/MWh
	Suggested Total Energy (at 10 kW rate)	kWh
	Maximum System Recharge Rate at 30°C	kW
Charge Sustaing HEV Mode	Peak Pulse Discharge Power (10 sec)	kW
	Peak Regen Pulse Power (10 sec)	kW
	Available Energy for CS (Charge Sustaining) Mode	kWh
	Minimum Round-trip Energy Efficiency (USABC HEV Cycle)	%
	Cold cranking power at -30°C, 2 sec - 3 Pulses	kW
	CS HEV Cycle Life, 50 Wh Profile	Cycles
Battery Limits	Max. Current (10 sec pulse)	A
	Maximum Operating Voltage	Vdc
	Minimum Operating Voltage	Vdc
	Maximum Self-discharge	Wh/day
	Survival Temperature Range	°C
	Unassisted Operating & Charging Temperature Range	°C

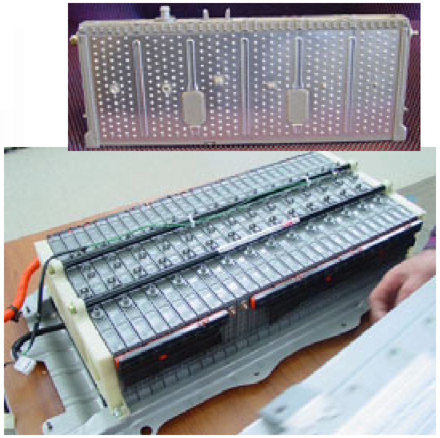
Battery Energy Requirements for Heavy-Duty PHET

- The energy efficiency of light-duty vehicles are about 200 to 400 Whr/mile
  - 5 to 12 kWhr battery for 30 mile
  - 2 Second power: 30 to 60 kW
  - Power to energy ratio (P/E) from 2 to 15
- Sprinter van delivery PHEV is estimated to consume about 600 Whr/mile in charge depleting (CD) mode
- Heavy-duty trucks could consume from 1000 to 2000 Whr/mile
  - 30 to 60 kWh battery for 30 mile range
  - Some may require additional kWh energy during idling or vocational operation
  - Power need: 50 to 150 kW or even more
  - Volume, weight, and cost are big issues
  - Thermal management is a concern

Battery Pack Packaging?

- Many small cells
    - Low cell cost (commodity market)
    - Improved safety (faster heat rejection)
    - Many interconnects
    - Low weight and volume efficiency
    - Reliability (many components, but some redundancy)
    - Higher assembly cost
    - Electrical management (costly)
    - Life?

- Fewer large cells
    - Higher cost
    - Increased reliability
    - Lower assembly cost
    - Higher weight and volume efficiency
    - Thermal management (tougher)
    - Safety ??
    - Better Reliability (lower number of components)
    - Life?



Concluding Remarks

- Batteries with low power to energy ratios are needed for PHEVs and PHETs
- Widening of the energy storage system usable state of charge window while maintaining life will be critical for reducing system cost and volume, but could decrease the life
- A blended operating strategy as opposed to an all electric range focused strategy may provide some benefit in reducing cost and volume while maintaining petroleum consumption benefits
- The key barrier to commercialization of PHEVs and PHETs are battery life, packaging, and cost.

Acknowledgments

- DOE Program Support
  - Dave Howell
  - Tien Duong

FreedomCAR & Fuel Partnership

- Technical Support
  - Tony Markel (NREL)