Innovation for Our Energy Future

Impact of the 3Cs of Batteries on PHEV Value Proposition: Cost, Calendar Life, and Cycle Life

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Funded by Energy Storage R&D (David Howell) Vehicle Technologies Program U.S. Department of Energy

Overview

- Introduction and background
- Motivation for PHEV battery trade-off analysis
- Battery calendar and cycle life models
- Battery cost model
- Battery life/cost trade-off results
- Impact of temperature on battery life and cost
- Summary

Introduction

- PHEVs have the potential to significantly reduce (imported) petroleum consumption (and GHG emissions) by improving efficiency and use of electricity
- <u>Capacity, c-rate, cost, cycle life, and calendar life are all</u> critical in making batteries for PHEVs commercially viable
- Incremental cost of the long-lasting batteries could be offset with government incentives and high petroleum prices



Introduction

- PHEVs have the potential to significantly reduce (imported) petroleum consumption (and GHG emissions) by improving efficiency and use of electricity
- <u>Capacity, c-rate, cost, cycle life, and calendar life are all</u> critical in making batteries for PHEVs commercially viable
- Incremental cost of the long-lasting batteries could be offset with government incentives and high petroleum prices
- <u>Cost, calendar life, and cycle life are the least known and have the biggest impact on PHEV value proposition</u>
- Cost, fuel savings, and battery degradation characteristics at beginning of life vs. end of life must be evaluated
- The spectrum of battery degradation rates due to both cycle life and calendar life in various climates and operating states of charge (SOCs) are needed
- NREL has been studying trade-offs between the performance, life, and cost of batteries

Major Battery Requirements (5Cs)



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

Major Battery Requirements (5Cs)



Requirements of End of Life Energy Storage Systems for PHEVs

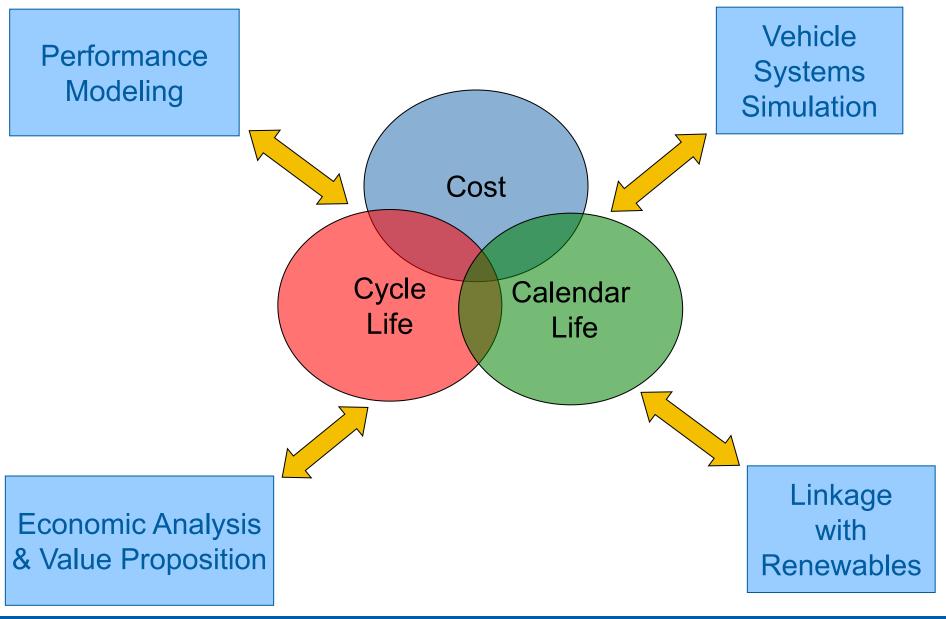
Requirements of End of Energy Storage Systems for THE VS				
Peak Power Discharge (2S/	10S) = 46/38	kW /Energy Ratio	High Energy/Power Ratio Battery	
Refer C-rate ~ 10-15 kW			40	
Peak Purse Disenarge Power 2 See 10 See	ΛΨ	<u> </u>	46 / 38	
Peak Regen Pulse Power (10 sec)	kW	30	25	
Available Energy = 11.6 (ACOC = 700 () 3.4 11.6				
Ava Available Energy = 11.6 kWh (Δ SOC = 70%) 0.5 0.3			0.3	
Min Capacity (EOL) = 16	6.6 kWh	90	90	
Cold cranking power at -30°C, 2 sec - 3 Pulses	kW	7	7	
CD Life / Discharge Throughput	Cvcles/MWh	5,000 / 17	5,000 / 58	
CS Cycle Life (depleting) = 3K-5K cycles				
Cal Cycle Life (sustaining) =200k	15	15		
Ma Cycle Life (Sustaining) –200K-500K Cycle		60	120	
Maximum System Volume	Liter	40	80	
Maximum Operating Voltage	at	400	400	
Minimum Opera Maximum Self Calendar Life at 35°C = 15 Years		>0.55 x Vmax	>0.55 x Vmax	
Maximum Self-	is reals	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	(system) = \$	3,400	-46 to +66	
Maximum System Production Price @ 100k units/yr	\$	\$1,700	\$3,400	
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The Three Important Cs of Batteries

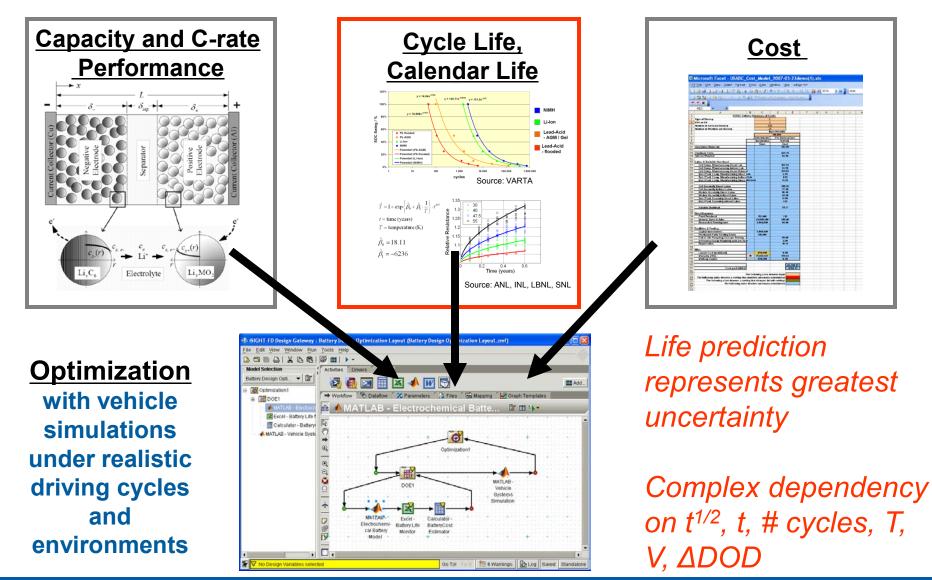
- <u>C</u>ost
- <u>Cycle Life</u>
- <u>Calendar Life</u>

These three attributes vary significantly from supplier to supplier, are not consistently reported, and dramatically affect the market potential of PHEVs and EVs.

C³ Data Is Critical to Many Analysis Efforts



PHEV Battery Design Optimization Design/size PHEV batteries to meet USABC technical goals/requirements at minimum cost.



Motivation: Minimize Battery Cost, Maximize Life

How?

0) Select a high-quality, low-cost cell

- 1) Size battery appropriately so as not to overstress/overcycle, but with minimum cost and mass
 - 1) Accelerated calendar and cycle life testing
 - 2) Accurate life and DOD predictive models

2) Minimize time spent at high temperatures

- 1) Standby thermal management (vehicle parked!)
- 2) Active thermal management (vehicle being driven)
- 3) Use proper electrical management, control design

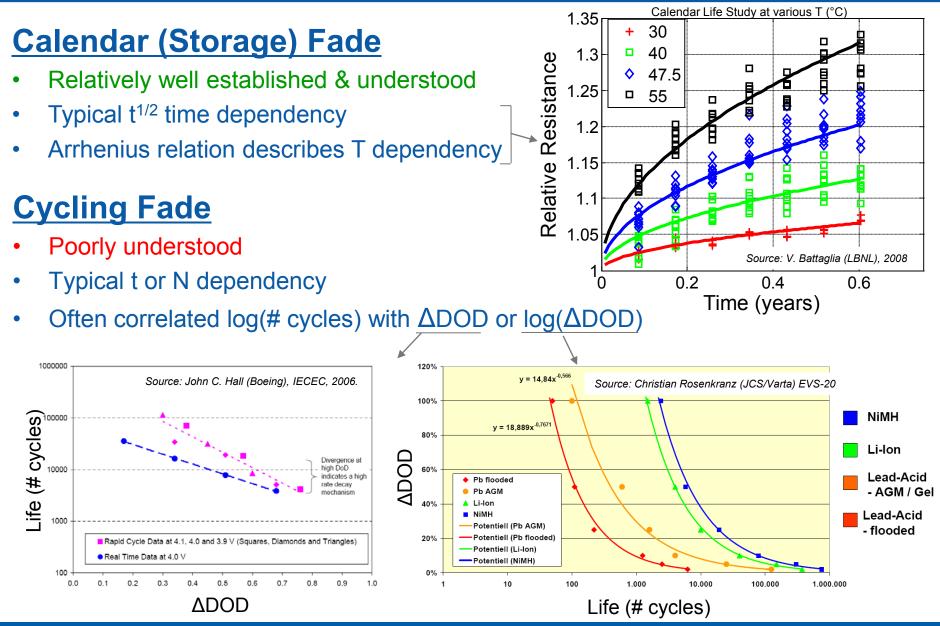
Component design/ selection

System design

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Modeling to Predict Battery Life



Objectives for Battery Life Modeling

1.35

Develop a power and energy degradation model that —

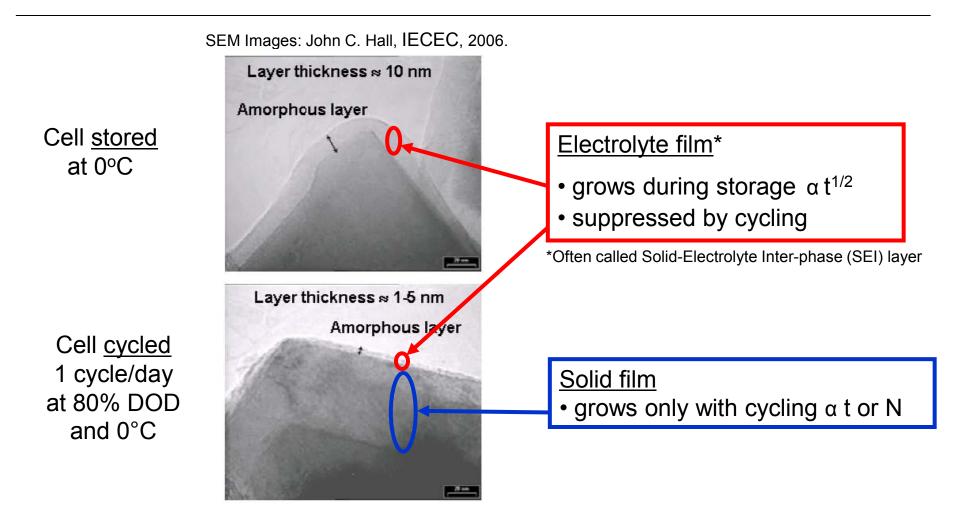
- 1. Uses both accelerated and real-time calendar and cycle life data as inputs.
- 2. Is mathematically consistent with all calendar and cycle life empirical data.
- 3. Is extendable to arbitrary usage scenarios (i.e., it is predictive).

■ Rapid Cycle Data at 4.1, 4.0 and 3.9 V (Squares, Diamonds and Triangles) ● Real Time Data at 4.0 V	20% — Potentiell (Pb flooded) — Potentiell (Li-lon) — Potentiell (NIMH)
	0% (1 10 100 1.000 10.000 1.000.000
DOD	Life (# cycles)

Calendar Life Study at various T (~C

Impedance Growth Mechanisms: Complex Calendar and Cycling Dependency

NCA chemistry: Different types of electrode surface film layers can grow. (1) "Electrolyte film" or SEI layer (2) "Solid film"



Life Model Summary (equations & coefficients)

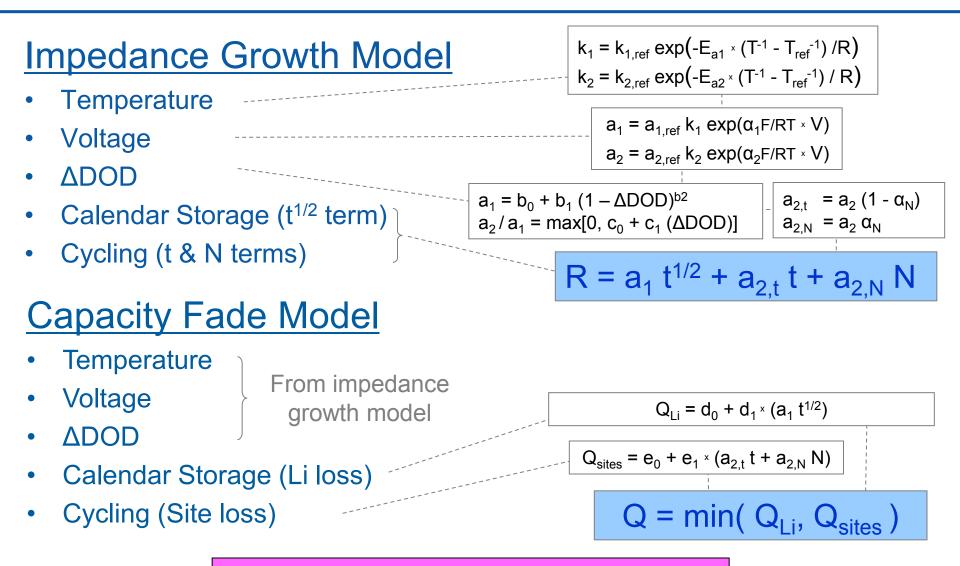
Impedance Growth Model

- Temperature
- Voltage
- ADOD
- Calendar Storage (t^{1/2} term)
- Cycling (t & N terms)

Capacity Fade Model

- Temperature
- Voltage
- ADOD
- Calendar Storage (Li loss)
- Cycling (Site loss)

Life Model Summary (equations & coefficients)



Reasonably fits available data

Actual interactions of degradation mechanisms may be more complex.

Details of Calendar and Cycle Life Models Are Presented by Kandler Smith in the Poster Session forAABC-09



NREL is a national laboratory of the U. S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Atliance for Sustainable Energy, LLC.

Modeling of Nonuniform Degradation in Large-Format Li-ion Batteries Kandler Smith · Kandler.Smith@nrel.gov, Gi-Heon Kim · Gi-Heon.Kim@nrel.gov, Ahmad Pesaran · Ahmad.Pesaran@nrel.gov - National Renewable Energy Laboratory Abstract Degradation Model Results Conclusions An empirical degradation model, sapturing the effects of both starage and cycling, was Empirical model fit to test data for the Li-ion NCA chemistry** Modeling investigation: Accelerated cycling of 20 Ah PHEV-type cylindrical cell For 20 Ah cylindrical cell with good thermal developed for the Li-ion Nickel-Cobalt-Aluminum chemistry". The degradation model is ADOD Effect & cycling uniformity at beginning of life ... Voltage and temperature acceleration - Cell Dimensions: 48 mm diameters: 120 mm height + 5000: 90% SOC_ 10 30% SOC_ 20 M coupled with NEEL's multi-dimensional multi-scale (MIME) cell model to explore the impacts Model indiates (** 1-storage) · increased decrudation due to elevated Well designed for thermal & cycling uniformity, low capacity fade rate * Actel. Cycling: Various discharge Shown below). Indulance proves throughout Me (7, Ah throughout, of nonuniform curling and temperature inside a cylindrical 20 Ah PNEV cell over the course and Nit-cyclingl impendencies voltage and temperature described Thermal: 30°C ambient, h = 20 Win/K 10 mm rest, 1C charge, 60 min rest, repeat. capacity low of an accelerated cycle life test. Basufts show significant differences compared to a lumped a, (-storage) and a, (-cycling) using Tafet and Arrhenius equations Asselection mechaniam apparent for high-rate analysis that neglects the cell's real geometry. coefficients vary with 5000 EVEND CAME Capacity fade & resistance growth for various repeated discharge profiles (VC, SC, 10C, US06) **Background and Approach** Roa to + a N Fector degradation Temperature rise accelerates degradation Major factors leading to nonuniform degradation Point For 1 (printing, N = 1) Background Nonuniform temperature (degrades inner cote) AT MED, A surface Context: Trend towards larger cells Nonuniform potential (degrades terminal regions) - Objectives HEV-+ HEV-+ IV Understand impact of large-format cell. Regions heavily used at beginning of Me linner care design features on battlery useful life Reduced off sourt reduces cost & complexity terminal report) are used less and less as Me proceeds. 100.000.00 ARC 148. 148 Improve battery engineering models to Drawback; Greater Internal nonumber mity 1-D othern fumped thermal model not suited to include realistic geometry and physics predict performance degradation for large cells Begins of localized ricking ? --- Degradation Reduce make-and-break iterations For a given electrode-level degradation accelerate design cycle ium, overpredicts cell-level capacity fade and impedance growth No accelerating trend observed for loss sale IX dasharge cycles · Significant growth in internal temperature during (106 and 300 44 10 44 40 Multiscale approach for computational efficiency Char accelerating trend observed for high-rate USDS and 100 cases discharge cycling Acknowledgements · Internal temperature remains - constant for 10 discharge carding WELL's Multi-Scale Multi-Dimensional (MUMD) Model"* U.S. Department of Energy, Office of Whicle Dance President 60 Longth scales: 2180514-8 11481,0-1 US06 - Nonuniform degradation - Manufact -Dave Howell, Energy Storage Program tunters 4 3.3ml/p-7 grade 210 Y. Linformation II (1-100 upon Relative Capacity Alt Imbalance 12 bets thinker a management practice 2. Heat & electron transport - try Lingla-4 . Tilling J work · Begions near terminals suffer most · Early in life, somer core and terminal areas are 1x1-30 cmi significant casacity loss cooled the most + Later in the, those same areas are most degraded Gene asseptiential -- taxania tabea Li-ion (C/NCA) degradation model summary and are cycled least References + Inner core loses capacity faster than impedance Growth Model + Initialance continually prives throughout life outer cylinder wall Time scales nigh temperature --- Material implations E. A. Kim, K. South, "Thrap-Dimensional Lithuan ion Batheric 1. Repeated cycling profile invinuted 2. Descadation effects incential h, - K, mp(4, + 011 - E, 3.40 · Tempetature Model[®] 48h International Symposium on Large Lifebase lise 8, + 8, exp(6, +17'-1, 7/4) Return Schentings and Application, Tampa, PL, May 10 VK, 2008 I north: N nonthe 2. 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Kithe, "Revolution $R=a_i\,t^{i+j}+a_{j,i}\,t+a_{j,i}\,N$ · Cycling & & N termü Growth or Lithium the Salettine Dalls. I New Destructive Data · Storage (Calendar) Rada - Cycling Fade Analyses," 2089. Electroniham Soc. Mild., Lins Angelies, CX. Detailar 16:21, 2005. Typical t or It dependency. Typical 1¹⁴ time dependency L18 (histophenes,) Black, LV Noise, KL Gene, GL **Capacity Fade Model** Often correlated log (# cycles) with (2000) Nonuniform degradation effects important for predicting cell performance fade Arthuman relation describes Trissendency Harrison, VS. Buttapla, (): Nousel, 'Advanced fact + Temperature Development Program for Literate text Batteries COC Gen 2 Performance Evolution from Report, * Idelto Rational Labora Socy, 26,1(21-0)-00012, july, 2006. 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Life Model Summary

- Model structure set by Boeing satellite battery dataset^{1,2}
 - Difficult to decouple ΔDOD and voltage degradation effects from cell-level dataset
- Model adjusted to reflect more recent experience with NCA-graphite cells from various Labs ³⁻⁶
 - 4.5 years storage at 40°C, 50% SOC \rightarrow 10%
 - \rightarrow 10% capacity fade⁴

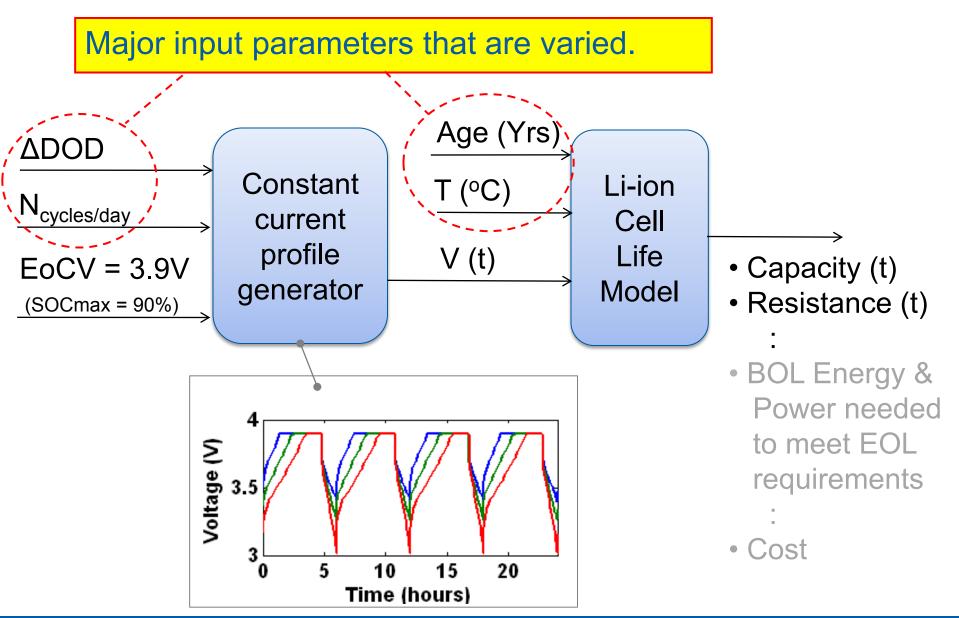
• 13.7 years storage at 35°C

- → 110% resistance growth⁵
- 2700 PHEV charge depletion cycles at 25°C → 8% capacity fade, 50% resistance growth⁶
- The following analysis illustrates trade-offs for a cell with low capacity fade but high resistance growth over life.

References:

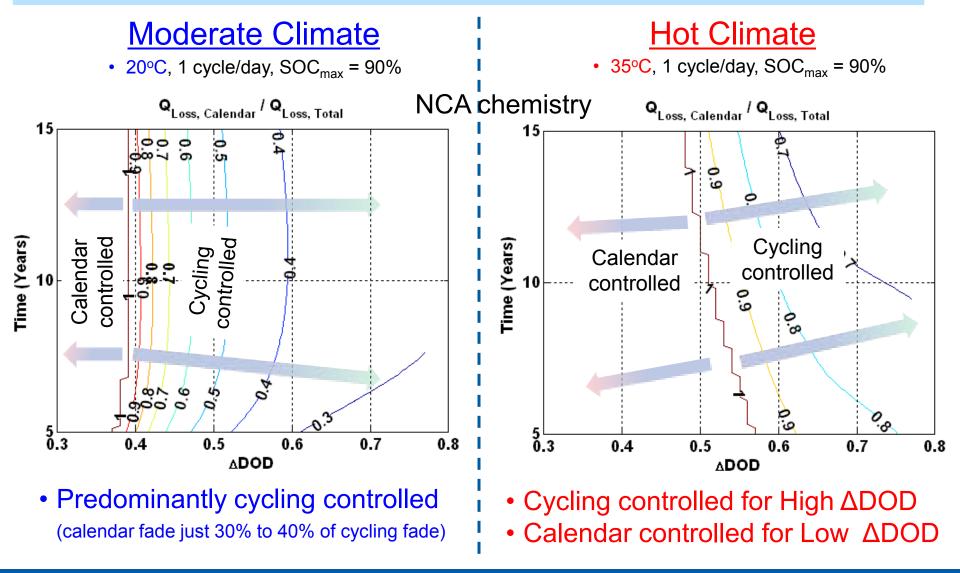
- 1. J. Hall, T. Lin, G. Brown, "Decay Processes and Life Predictions for Lithium Ion Satellite Cells," 4th International Energy Conversion Engineering Conference & Exhibit, San Diego, CA, June 26-29, 2006.
- 2. J. Hall, A. Schoen, A. Powers, P. Liu, K. Kirby, "Resistance Growth in Lithium Ion Satellite Cells. I. Non Destructive Data Analyses," 208th Electrochem. Soc. Mtg., Los Angeles, CA, October 16-21, 2005.
- 3. J.P. Christophersen, I. Bloom, E.V. Thomas, K.L. Gering, G.L. Henriksen, V.S. Battaglia, D. Howell, "Advanced Technology Development Program for Lithium-Ion Batteries: DOE Gen 2 Performance Evaluation Final Report," Idaho National Laboratory, INL/EXT-05-00913, July, 2006.
- 4. M.C. Smart, K.B. Chin, L.D. Whitcanack, B.V. Ratnakumar, "Storage Characteristics of Li-Ion Batteries," NASA Aerospace Battery Workshop, Huntsville, AL, November 14-16, 2006.
- 5. P. Biensan, Y. Borthomieu, "Saft Li-Ion Space Batteries Roadmap," NASA Aerospace Battery Workshop, Huntsville, AL, November 27-29, 2007.
- 6. L. Gaillac, "Accelerated Testing of Advanced Battery Technologies in PHEV Applications," 23rd Electric Vehicle Symposium, Anaheim, CA, December 2-5, 2007.

Life Analysis Conducted Using Simplified Cycling Profiles



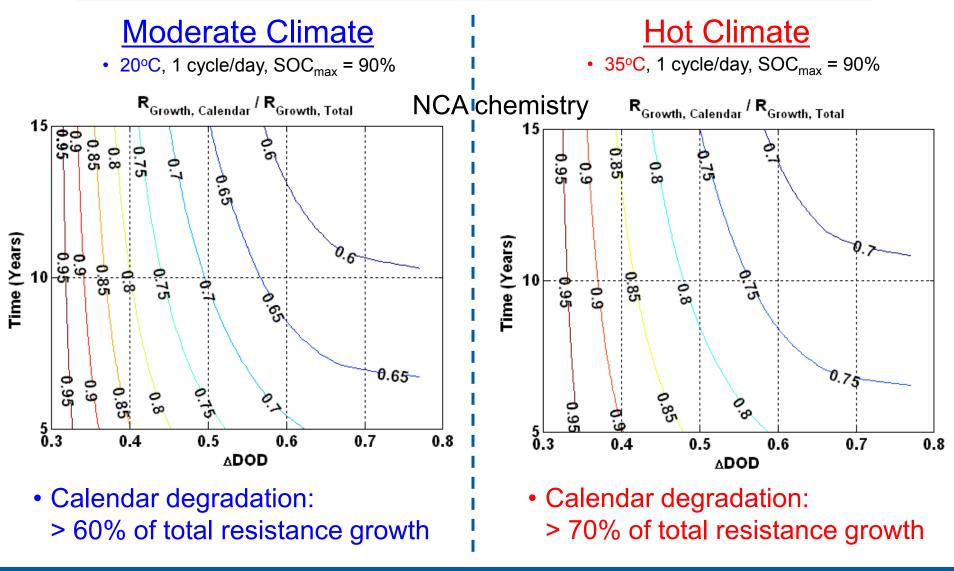
Results: Which Dominates — Calendar or Cycling? Capacity Fade – Energy

Generally cycling controlled, though it depends on temperature



Results: Which Dominates — Calendar or Cycling? Resistance Growth – Power

Calendar effect dominates, though both are important.

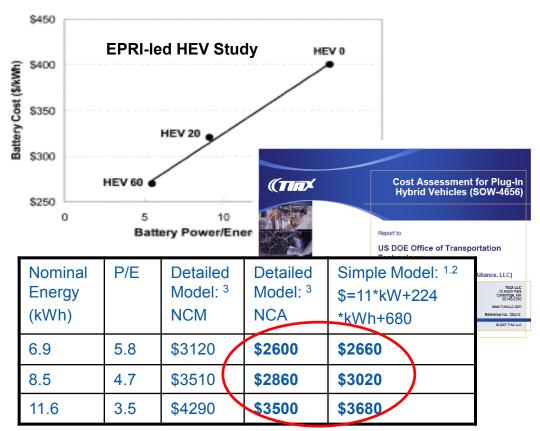


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Developing a Simplified Cost Model Estimating Manufacturer Pack Cost

- Battery cost estimates from EPRIled HEV study as original source¹
- EPRI HEV cost model used for NREL's EVS-22 paper on PHEV Cost Benefit Analysis²
- DOE-sponsored TIAX study reviewed cost details of two Li-ion cathodes (NCA and NCM) manufacturing³
- Modified fixed costs to include a per-cell component based on TIAX estimates (this study)
- Cost at volume manufacturing at 2007 materials' prices



NCA - Nickel Cobalt Alumina; NCM- Nickel Cobalt Manganese

Simplified Pack Cost Model \$/pack = 11.1*kW + 224.1*kWh + 4.53*BSF + 340

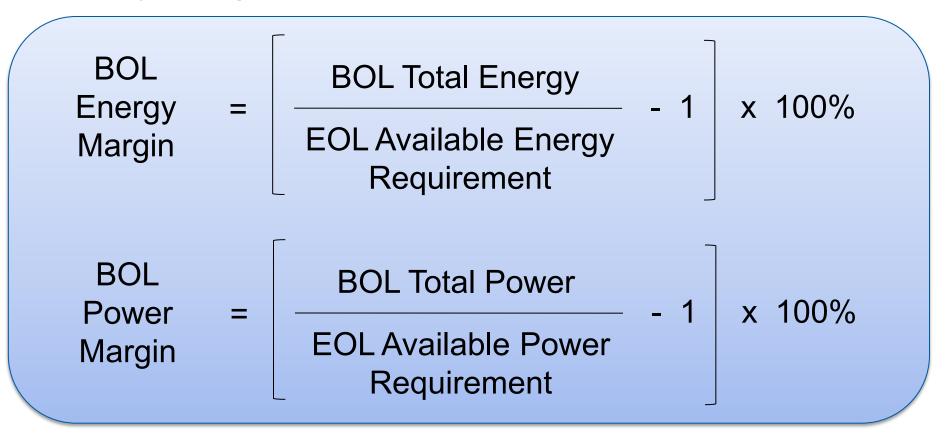
- BSF = Battery Size Factor
- 1. Graham, R. et al. "Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options," Electric Power Research Institute (EPRI), 2001.
- 2. Simpson, A., "Cost Benefit Analysis of Plug-In Hybrid Electric Vehicle Technology," 22nd International Electric Vehicle Symposium, Yokohama, Japan, Oct. 2006.
- 3. "Cost Assessment for Plug-In Hybrid Vehicles," *TIAX LLC*, Oct. 2007.

Life-Cost Trade-Off Study: Approach

- Choose a cycle life model and a calendar life model
 - We picked curve fits from slide 13 for NCA chemistry
- Choose a <u>cost model</u>
 - Manufacturing cost of a complete pack at high-volume production
 - We picked the equation on slide 18 for NCA chemistry
- Select the required battery energy and power
 - Energy: 3.4 kWh PHEV10; 11.6 kWh PHEV40 (USABC requirements)
- Select the required battery life
 - Cycles (charge depleting): 5000 CD cycles (USABC requirements)
 - Calendar life: 10 years at 30°C (less aggressive than 15-year USABC)
- Perform analysis to answer the following questions:
 - What ΔDOD & P/E meet life at minimum cost?
 - Which controls life? Calendar or cycle life?
 - What environmental parameters cause greatest life sensitivity?

Life-Cost Trade-Off: Energy and Power Margin to Meet EOL Performance Requirements

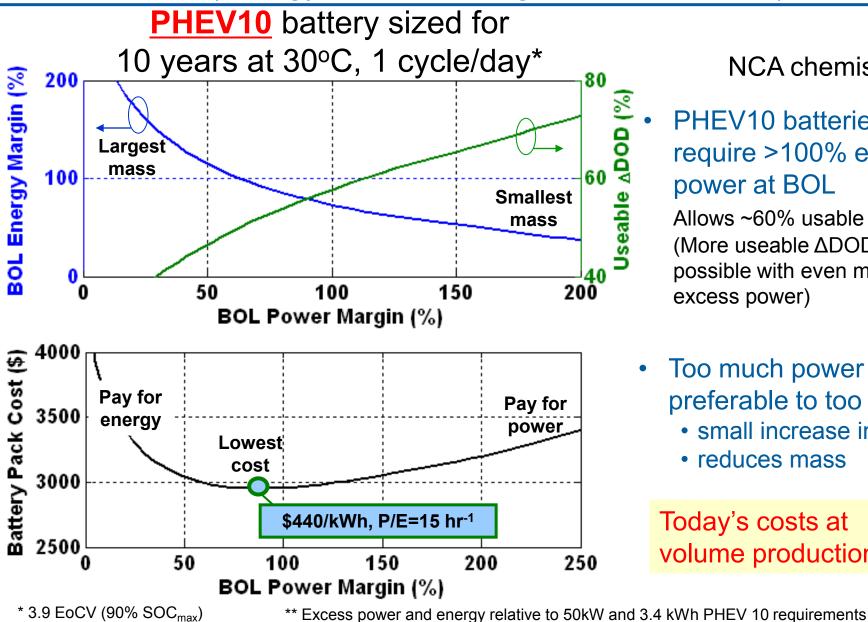
Battery Sizing Metrics:



BOL = Beginning of Life EOL = End of Life Next slides give results for **typical** Li-ion NCA chemistry and include fade for a chosen ΔDOD window (1 cycle/day, 30°C).

Example Results: Life-Cost Trade-Off Study

(Energy & Power Margin, Usable ΔDOD)



NCA chemistry

PHEV10 batteries can require >100% excess power at BOL

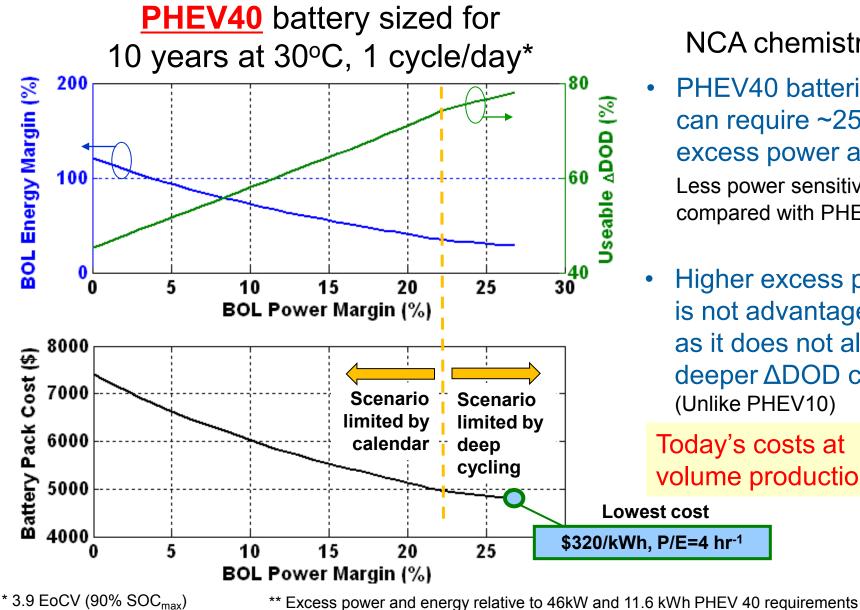
Allows ~60% usable ΔDOD (More useable ΔDOD is possible with even more excess power)

- Too much power is preferable to too little
 - small increase in cost
 - reduces mass

Today's costs at volume production

Example Results: Life-Cost Trade-Off Study

(Energy & Power Margin, Usable ΔDOD)



NCA chemistry

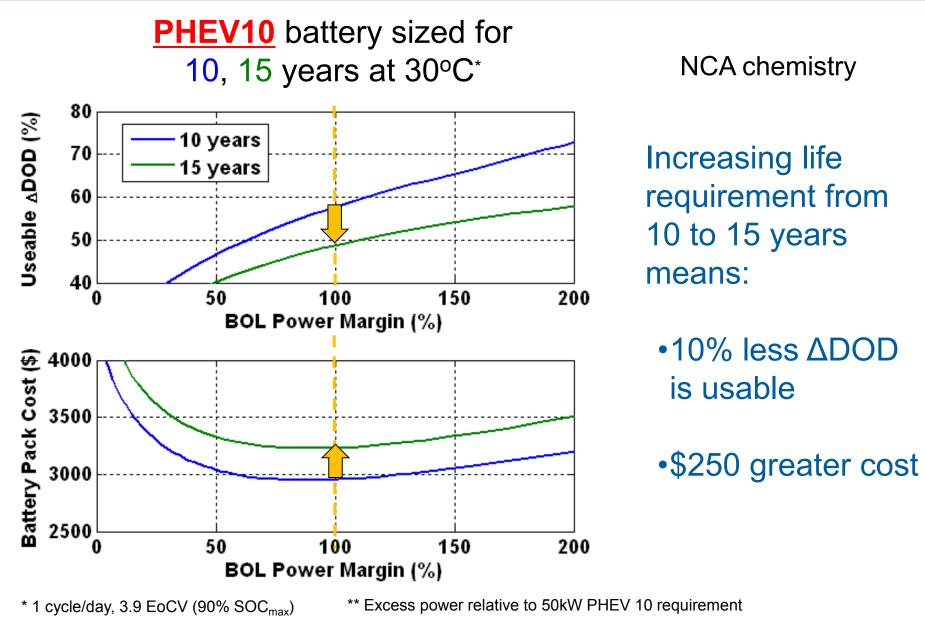
PHEV40 batteries can require ~25% excess power at BOL Less power sensitivity compared with PHEV10

Higher excess power is not advantageous as it does not allow deeper ΔDOD cycling (Unlike PHEV10)

Today's costs at volume production

Example Results: Life-Cost Trade-off Study

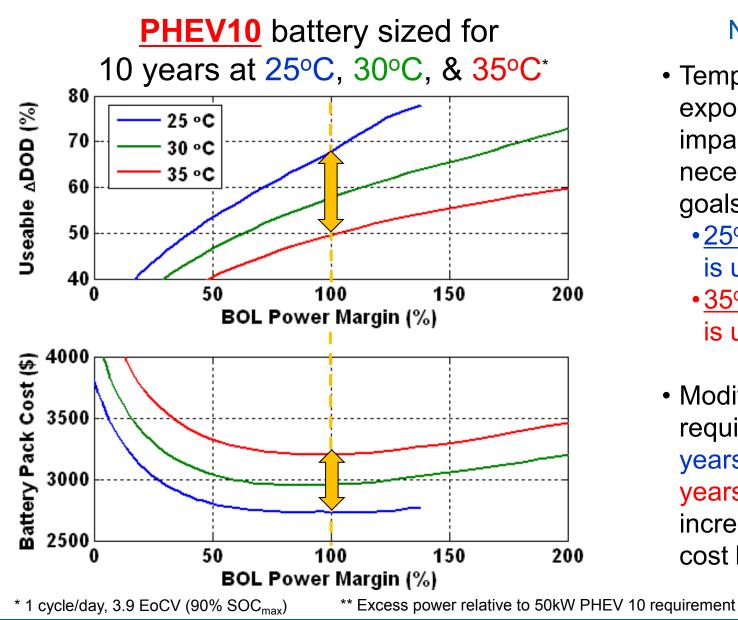
(Sensitivity to Years of Life)



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Example Results: Life-Cost Trade-Off Study

(Temperature Sensitivity)



NCA chemistry

 Temperature exposure drastically impacts system size necessary to meet goals at end of life
 <u>25°C</u>: 70% ΔDOD

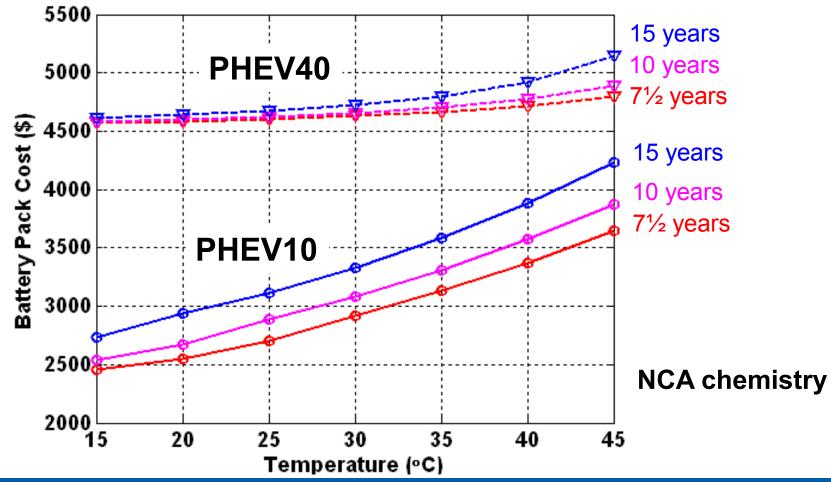
is usable
<u>35°C</u>: 50% ∆DOD
is usable

 Modifying life requirements from 10 years at 25°C to 10 years at 35°C increases battery cost by >\$500

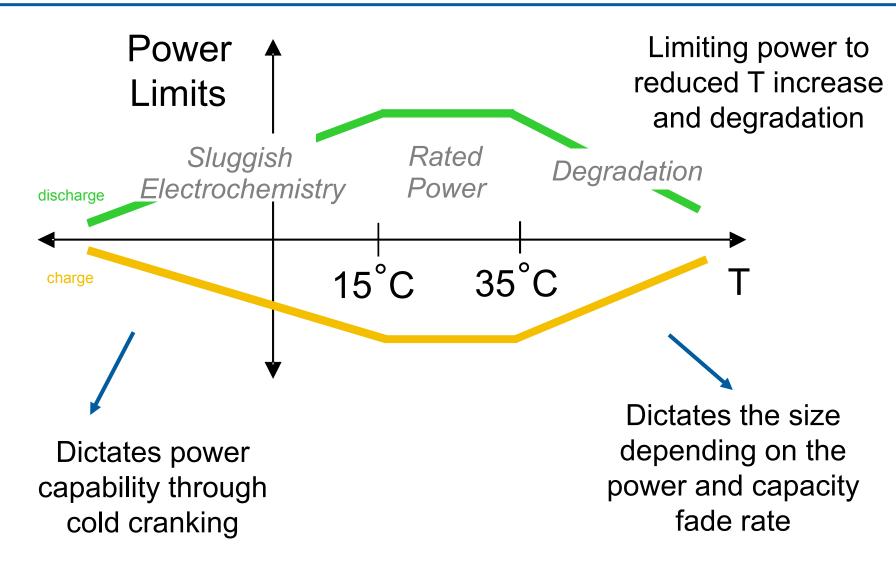
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Summary: Comparison of Battery Minimum Cost Designs for Varying Years of Life and Temperature

- Battery replacement not economically justified
- Cost can be <u>more sensitive to temperature than years life</u> (Especially true for small PHEV batteries with high power requirement)

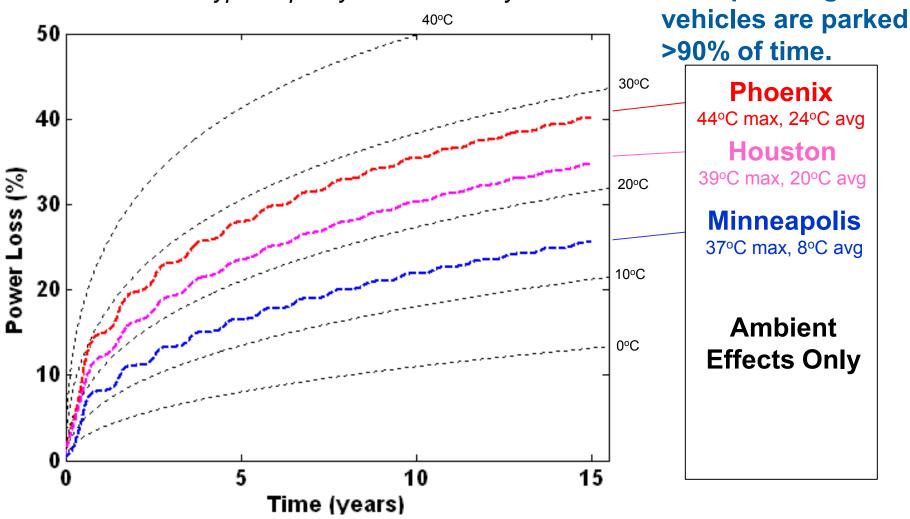


Temperature Impacts Cost (Sizing & Life)



Impact of Temperature on Battery in a Parked Car (Battery T = Ambient T)

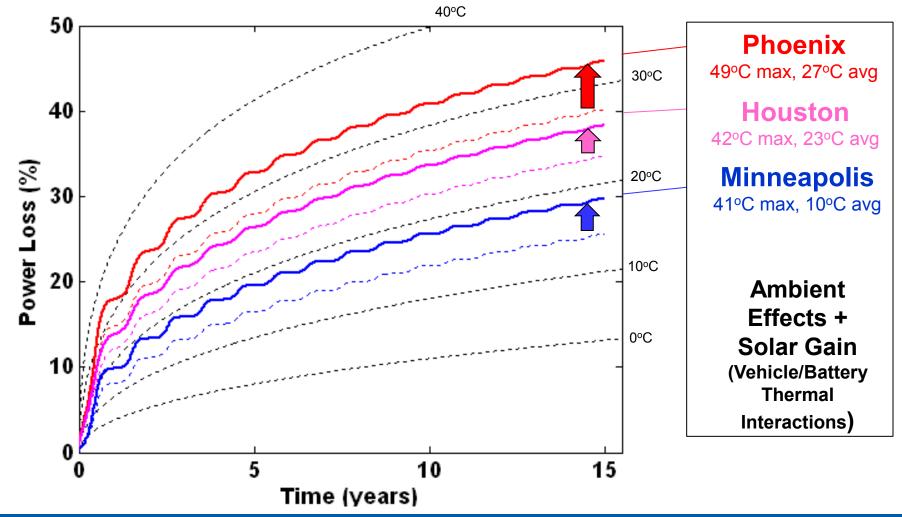
- Used typical metrological year (TMY) as the hourly temperature
- Power fade model reformulated as rate law, integrated for temperature profile.
- PHEV10 with a typical quality NCA chemistry.



Most passenger

Impact of Temperature on Battery in a Parked Car (Battery T = Ambient T + Solar Gain)

- The same as previous slide (PHEV10, NCA chemistry and TYM weather)
- Developed a vehicle-battery-ambient model to predict the battery temperature
- Results show significant fade due to the ambient temperature and solar gain



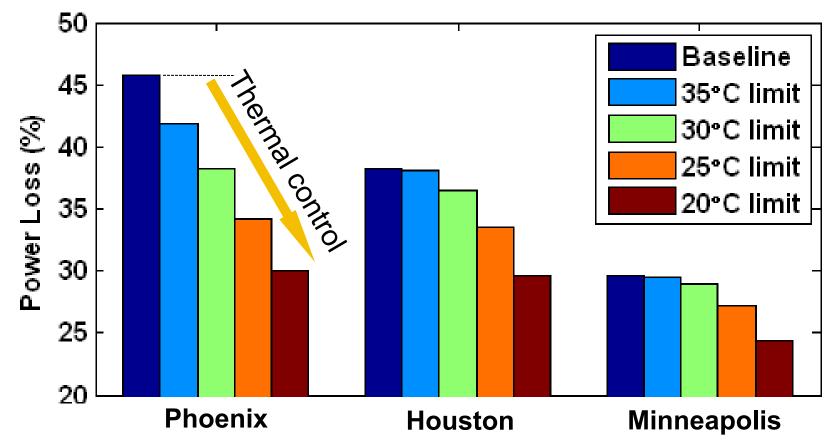
Analysis Shows Keeping Peak Battery Temperature below Extremes Could Greatly Improve Battery Life

PHEV10 – Power loss after 15 years

Ambient temperature & solar radiation climate data input to vehicle/battery thermal model. Assume peak battery temperatures can be eliminated.

Typical Quality Current NCA Li-ion Technology

How much is it worth to spend on thermal control (parked too)?



Summary

• Battery <u>cost</u>, <u>cycle life</u>, and <u>calendar life must be optimized to achieve maximum value for PHEV commercialization.</u>

A process/approach such as the one discussed here is needed.

 Useful life of a given pack design is dictated by complex interaction of parameters (t^{1/2}, t, N, T, V, DOD).

- Different chemistries have different behaviors.

- Battery life is extremely sensitive to temperature exposure; solar loading can cause further battery heating and lower life.
- Thermal control (when parked or driving) could be a cost-effective method to reduce oversizing of battery for the beginning of life.
- PHEV battery "standby" thermal control can reduce power loss, particularly for PHEV10.
- Accurate degradation prediction requires a large experimental matrix (for different chemistries).

www.nrel.gov/vehiclesandfuels/energystorage/

Thank You!