

PHEV Battery Trade-Off Study *and Standby Thermal Control*



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Overview

- Motivation for PHEV battery trade-off analysis
- Battery life model
 - Calendar life vs. cycle life: Complex interdependency
 - An empirical model capturing major degradation factors (temperature, time, # cycles, Δ DOD*, voltage)
- Battery life/cost interactions
 - Lowest cost system that meets technical requirements
 - Life sensitivity to different temperatures
- Battery standby thermal management
 - Concept
 - Vehicle-battery thermal interactions
 - Benefits of temperature management
- Conclusions
 - Future test needs

* DOD = depth of discharge



USABC PHEV Battery Goals

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



USABC PHEV Battery Goals

Requirements of End of Life Energy Storage Systems for PHEVs

Characteristics at EOL (End of Life)		High Power/Energy Ratio	High Energy/Power Ratio Battery
Reference Equivalent Electric Range			40
Peak Pulse Discharge Power - 2 Sec / 10 S			46 / 38
Peak Regen Pulse Power (10 sec)			25
Available Energy for CD (Charge Depletion)			11.6
Available Energy for CS (Charge Sustain)			0.3
Minimum Round-trip Energy Efficiency (%)			90
Cold cranking power at -30°C, 2 sec - 3 P			7
CD Life / Discharge Throughput	Cycles/MWh	5,000 / 17	5,000 / 58
CS HEV Cycle Life, 50 V		300,000	300,000
Calendar Life, 35°C			15
Maximum System Weight	kg	60	120
Maximum System Volume	L	40	80
Maximum Operating Voltage	V	400	400
Minimum Operating Voltage	V	>0.55 x Vmax	>0.55 x Vmax
Maximum Self-discharge	%/yr	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
Maximum System Production Price @ 100k units/yr			\$3,400

Available Energy = 11.6 kWh
 SOC Swing = 70%
 Total EOL Energy = 16.6 kWh
 Fade over Life = 20%
 Total BOL Energy = 20.7 kWh

Calendar Life at 35°C = 15 Years

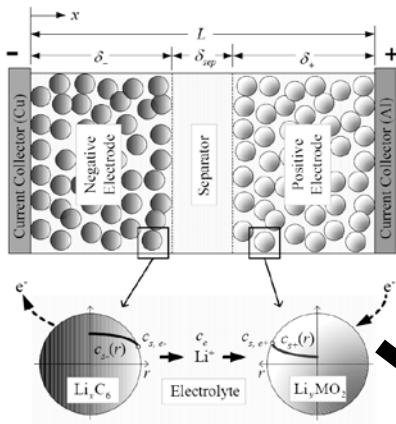
Max Weight = 120 kg
 Max Volume = 80 L

System Price = \$3,400

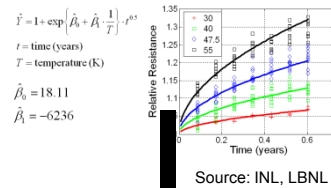
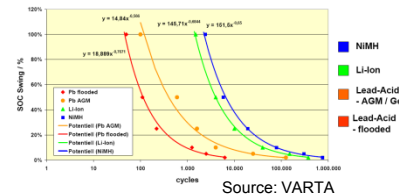
PHEV Battery Design Optimization

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

Battery Performance



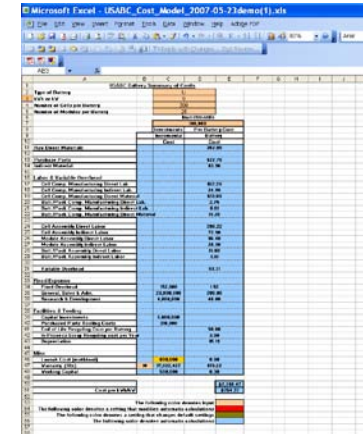
Battery Life



$$\hat{r} = 1 + \exp\left(\hat{\beta}_0 + \hat{\beta}_1 \frac{1}{T}\right) t^{\hat{\beta}_2}$$

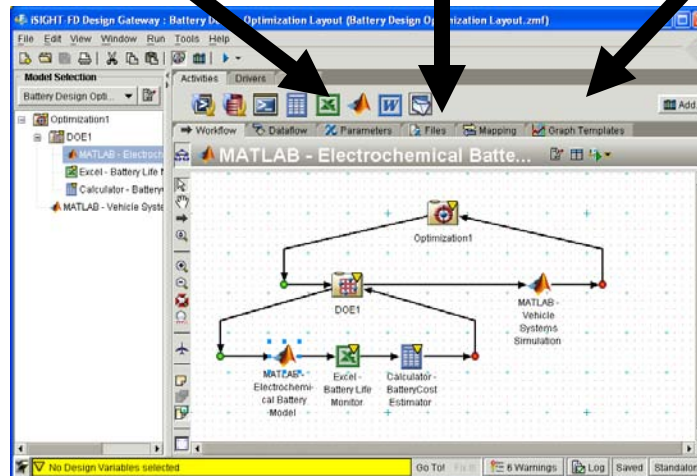
$\hat{\beta}_0 = 18.11$
 $\hat{\beta}_1 = -6236$

Battery Cost



Optimization

with vehicle simulations under realistic driving cycles and environments



Life prediction represents greatest uncertainty.

Complex dependency on $t^{1/2}$, t , # cycles, T , V , ΔDOD

Motivation: Minimize Battery Cost, Maximize Life

How?

- 0) Select a high-quality, low-cost cell.
- 1) Size battery appropriately so as not to overstress/over-cycle, but with minimum cost and mass**
 - 1) Accelerated calendar & 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 driving)
- 3) Proper electrical management, control design
- :

Component
design/
selection

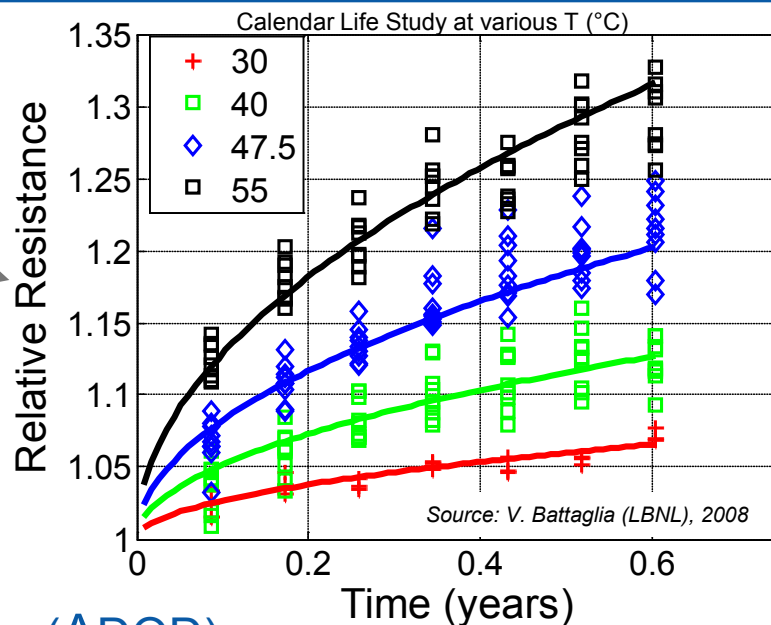
**System
design**



How Can We Predict Battery Life?

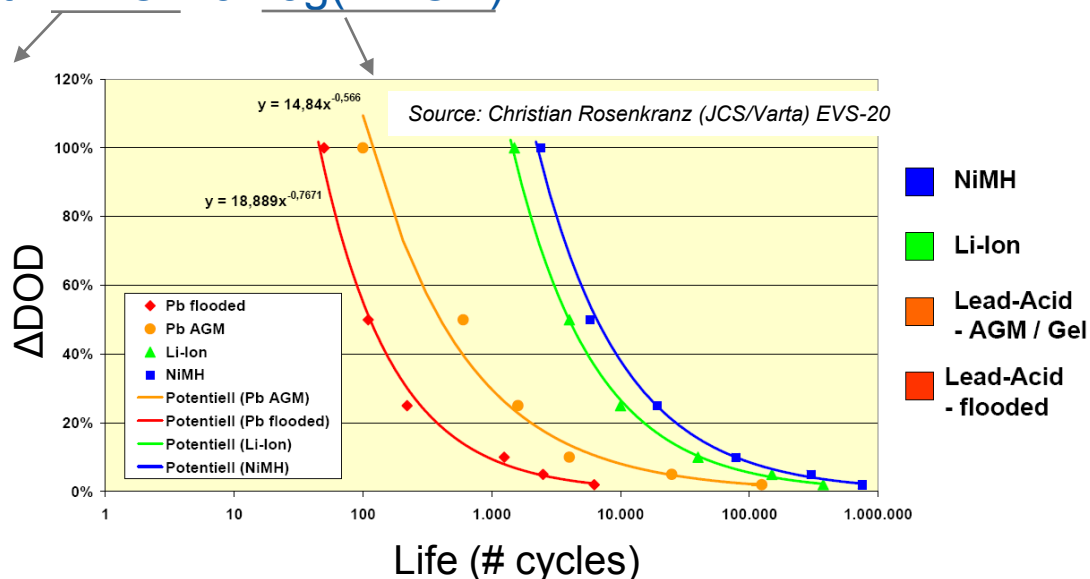
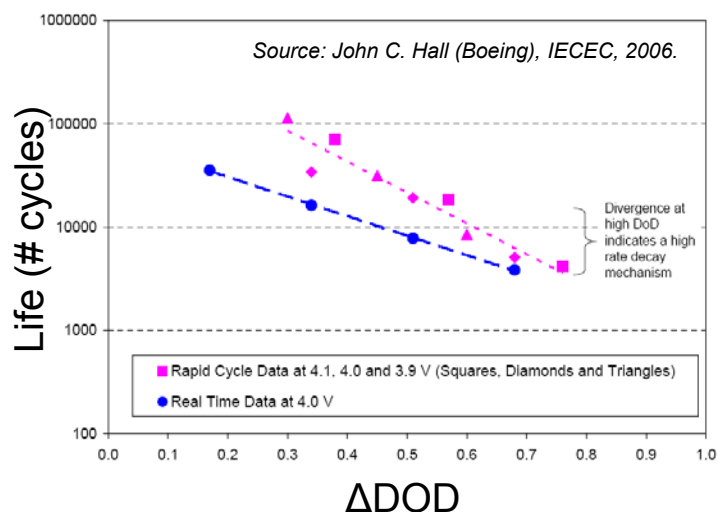
Calendar (Storage) Fade

- Relatively well established & understood
- Typical $t^{1/2}$ time dependency
- Arrhenius relation describes T dependency

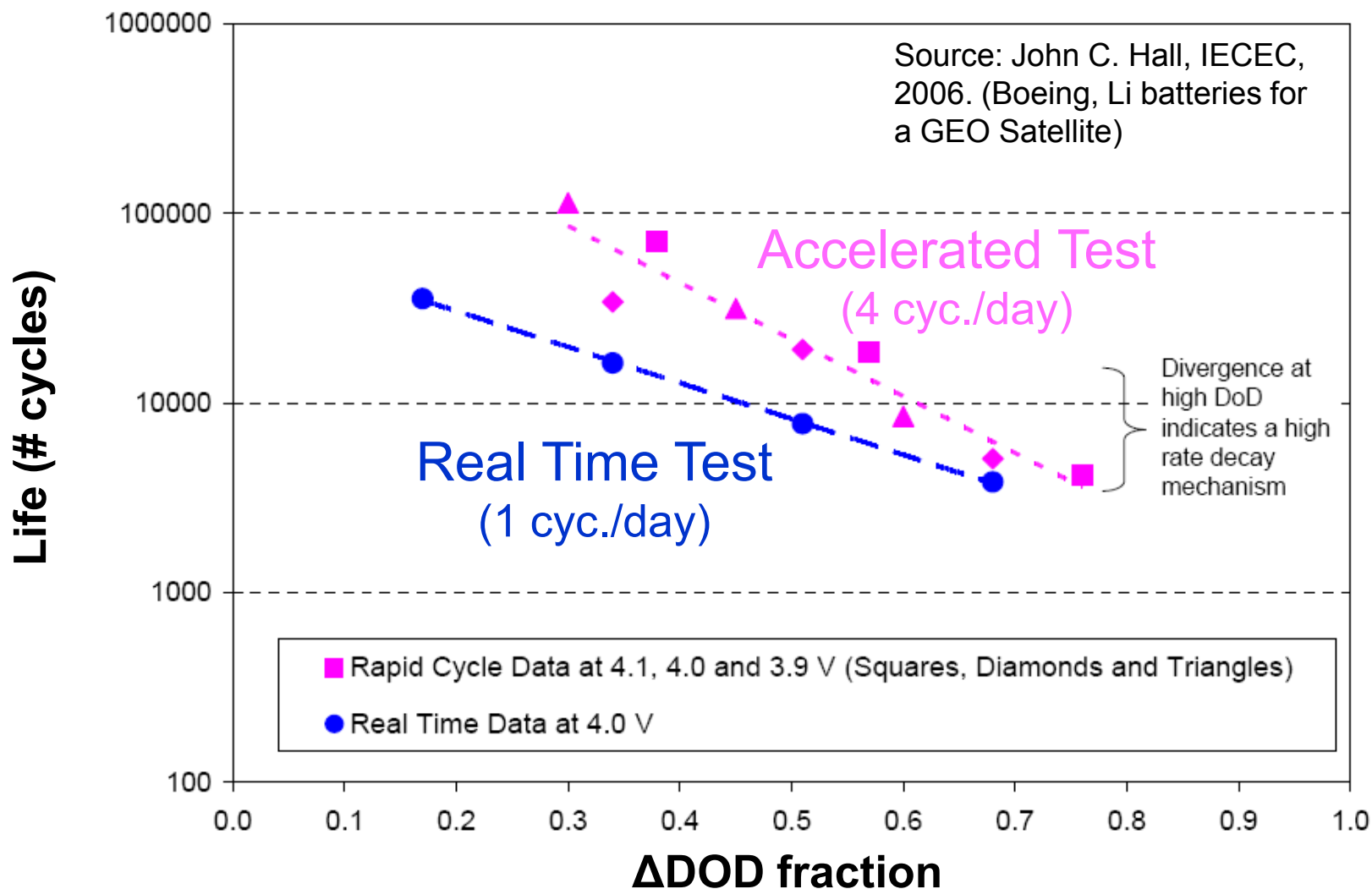


Cycling Fade

- Poorly understood
- Typical t or N dependency
- Often correlated $\log(\# \text{ cycles})$ with ΔDOD or $\log(\Delta\text{DOD})$



Accelerated Cycle Life Tests Are Not Always Conservative!

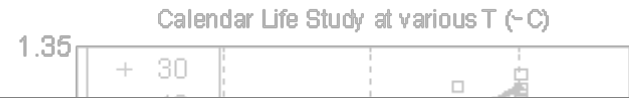


- Li-ion – high-voltage, nonaqueous chemistry – calendar life effect important
- Real-time tests necessary for proper extrapolation of accelerated results

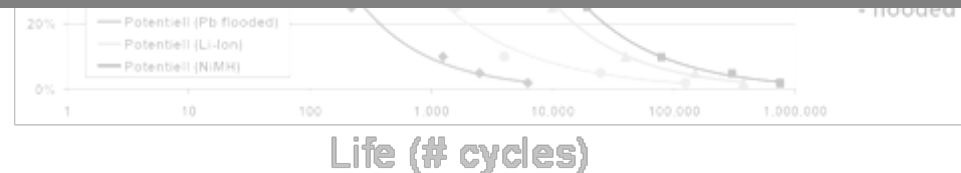
Our Objectives for Battery Life Modeling

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).

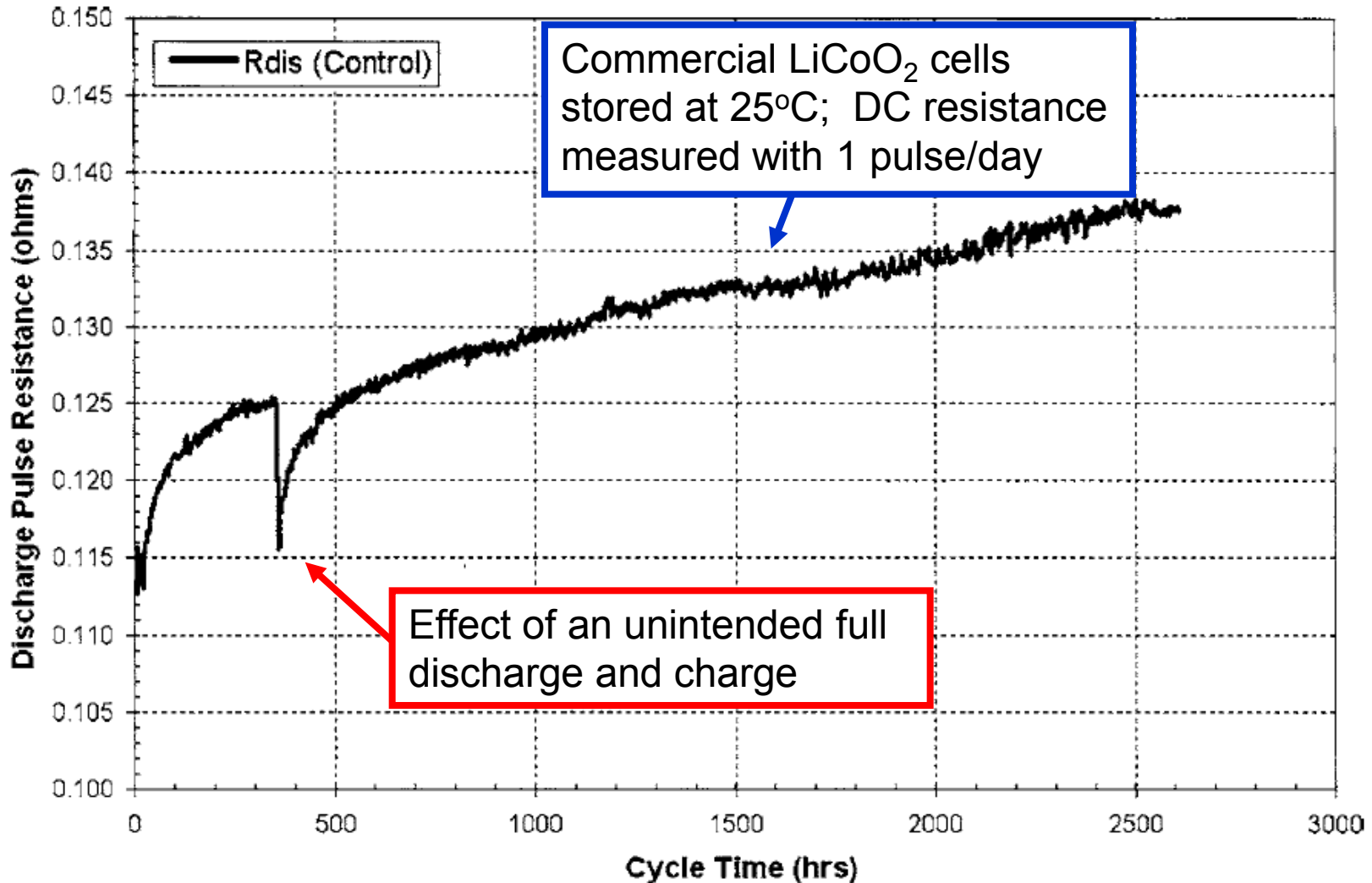


Life (# cycles)



Impedance Growth Mechanisms: Complex Calendar and Cycling Dependency

Cycling has been shown to suppress impedance growth.



Source: J.P.Christopersen, J. Electrochem. Society, 2006.

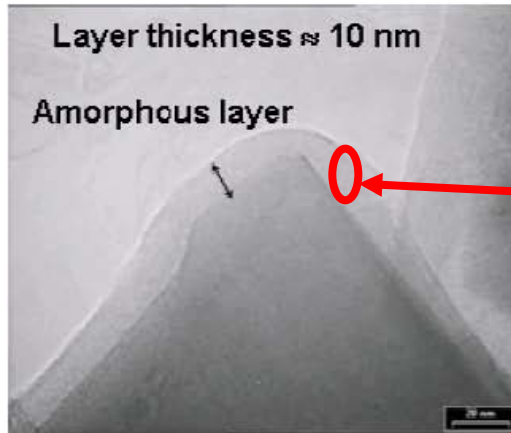
Impedance Growth Mechanisms: Complex Calendar and Cycling Dependency

NCA chemistry: Different types of electrode surface film layers can grow.

(1) “Electrolyte film” (2) “Solid film”

SEM Images: John C. Hall, IECEC, 2006.

Cell stored
at 0°C

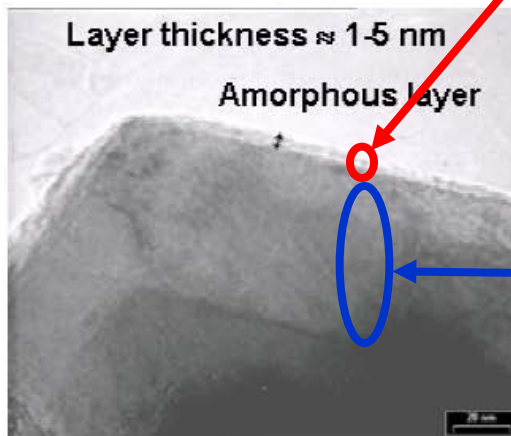


Electrolyte film*

- grows during storage $\propto t^{1/2}$
- suppressed by cycling

*Often called Solid-Electrolyte Interphase (SEI) layer

Cell cycled
1 cycle/day
at 80% DOD



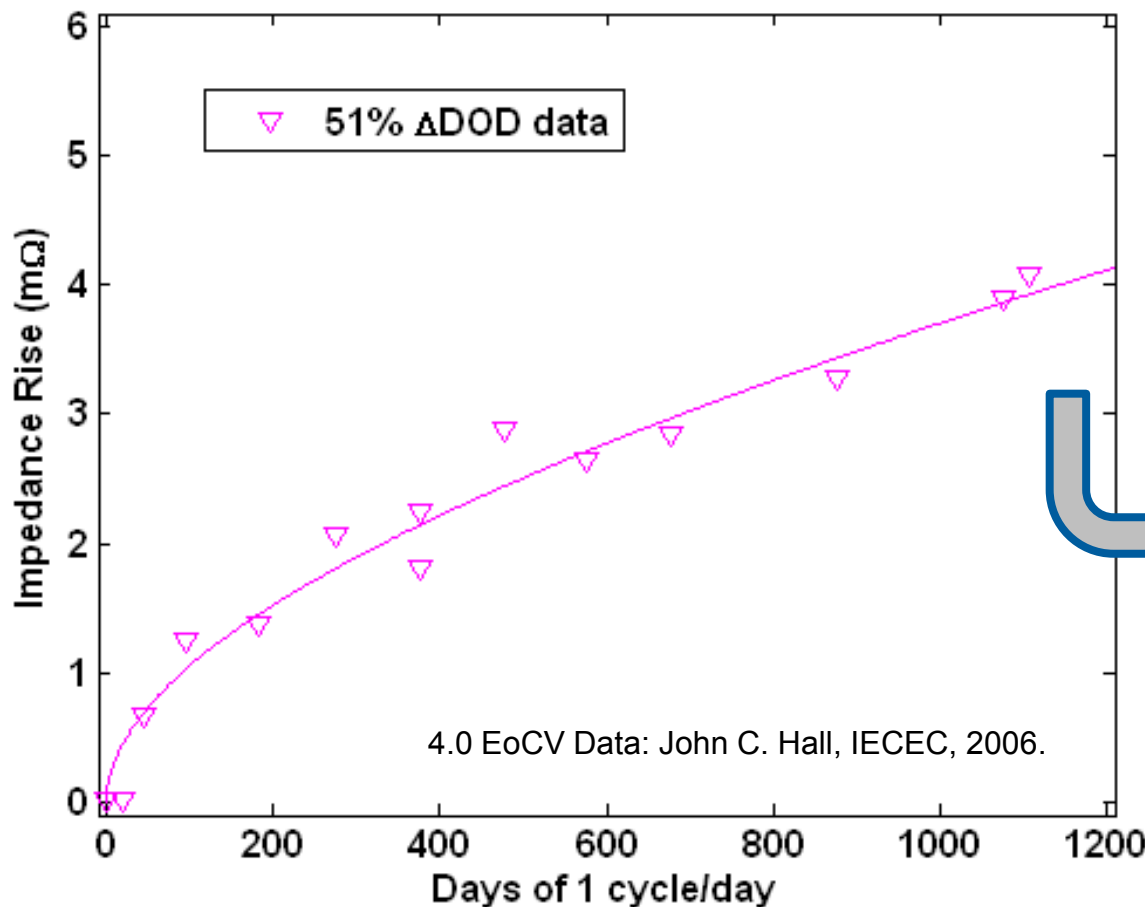
Solid film

- grows only with cycling $\propto t$ or N

Impedance (R): Cycling at Various Δ DODs

Fitting $t^{1/2}$ and N Components

- Simple model fit to cycling test data: Boeing GEO satellite application, NCA chemistry
- Model includes $t^{1/2}$ (~storage) and N (~cycling) component.



$$R = a_1 t^{1/2} + a_2 N$$

(Note: For 1 cycle/day, $N = t$)

Curve-fit at 51% Δ DOD:

$$a_1 = 1.00001e-4 \text{ } \Omega/\text{day}^{1/2}$$

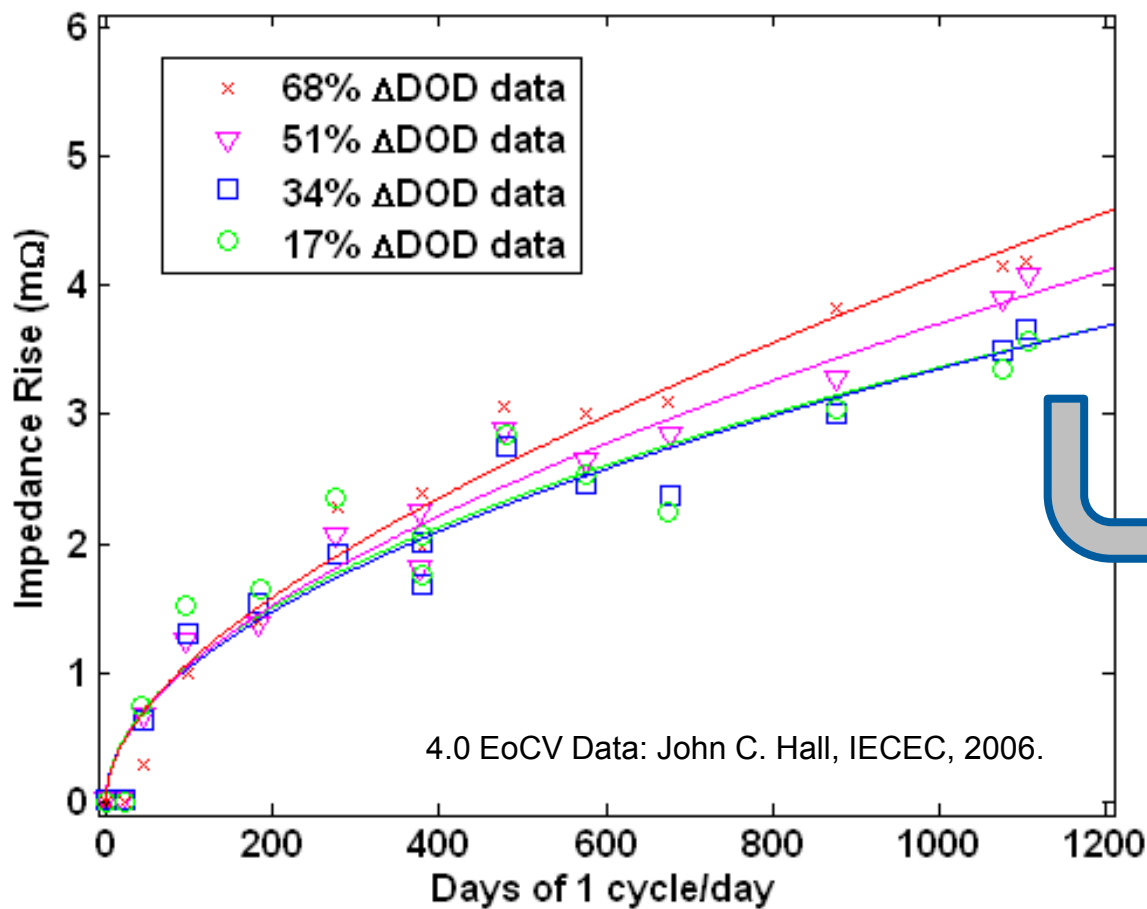
$$a_2 = 5.70972e-7 \text{ } \Omega/\text{cyc}$$

$$R^2 = 0.9684$$

Impedance (R): Cycling at Various Δ DODs

Fitting $t^{1/2}$ and N Components

- Simple model fit to cycling test data: Boeing GEO satellite application, NCA chemistry
- Model includes $t^{1/2}$ (~storage) and N (~cycling) component.



$$R = a_1 t^{1/2} + a_2 N$$

(Note: For 1 cycle/day, $N = t$)

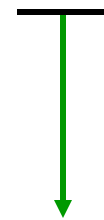
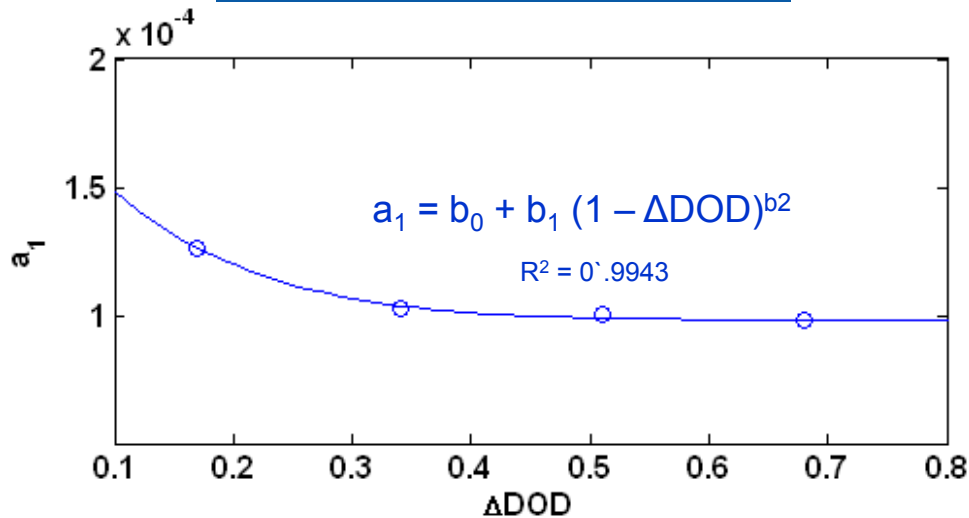
Δ DOD	a_1 ($\Omega/\text{day}^{1/2}$)	a_2 (Ω/cyc)	R^2
68%	0.98245e-4	9.54812e-7	0.9667
51%	1.00001e-4	5.70972e-7	0.9684
34%	1.02414e-4	0.988878e-7	0.94928
17%	1.26352e-4	-7.53354e-7	0.9174

Impedance (R): Cycling at Various Δ DODs

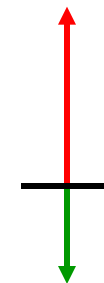
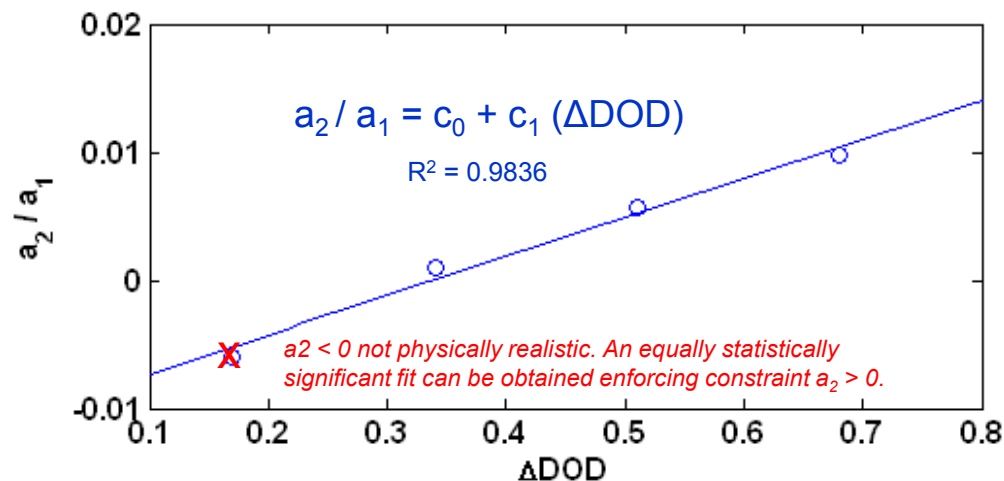
Capturing Parameter Dependencies on Δ DOD

$$R = a_1 t^{1/2} + a_2 N$$

Additional models are fit to describe a_1 and a_2 dependence on Δ DOD.



High $t^{1/2}$ resistance growth on storage is suppressed by cycling.



High DOD cycling grows resistance $\propto N$.

Low DOD cycling reduces resistance $\propto N$.

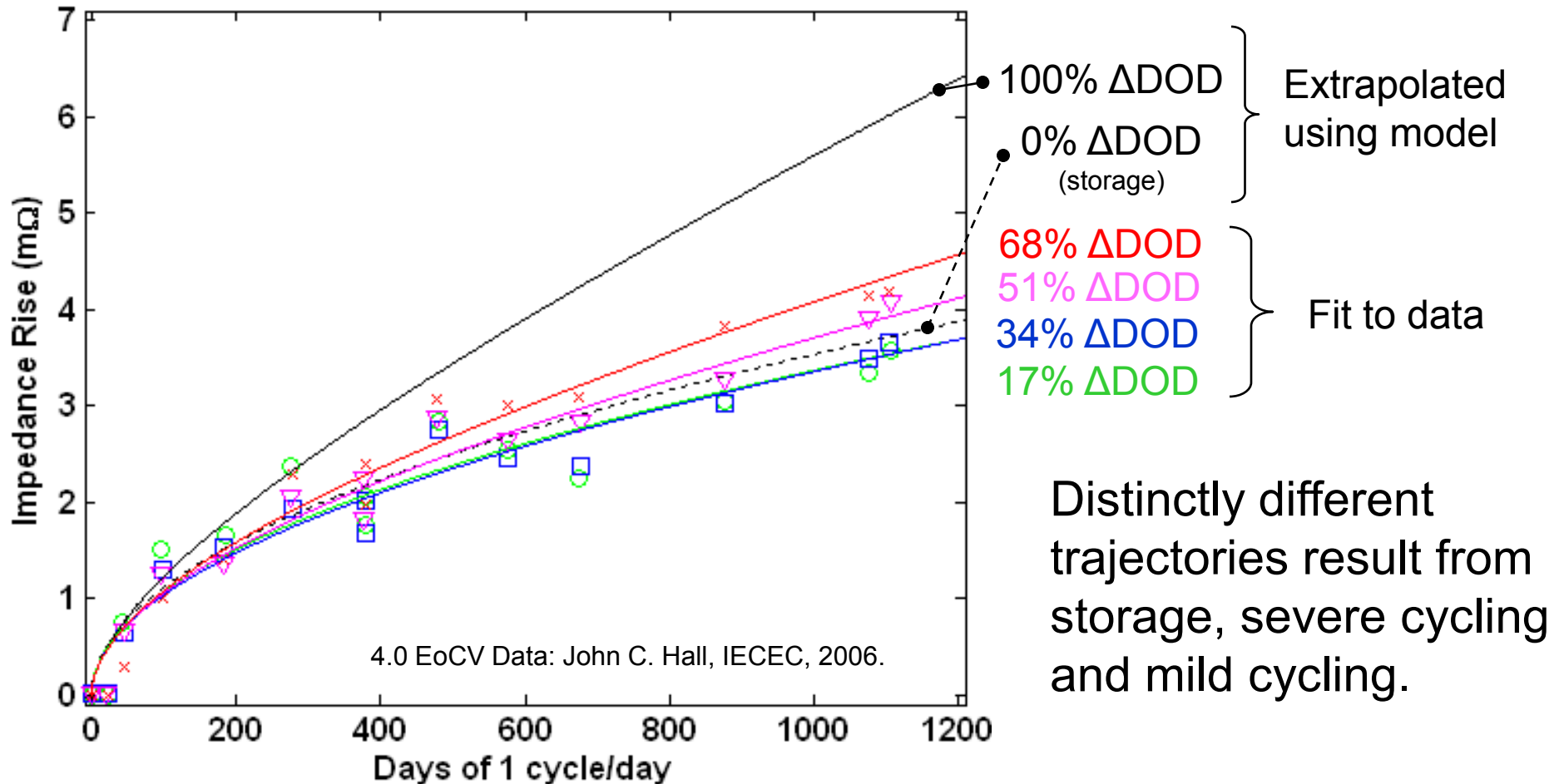
Impedance: Cycling at Various Δ DODs

Example Model Projections

$$R = a_1 t^{1/2} + a_2 N$$

$$a_1 = b_0 + b_1 (1 - \Delta\text{DOD})^{b_2}$$

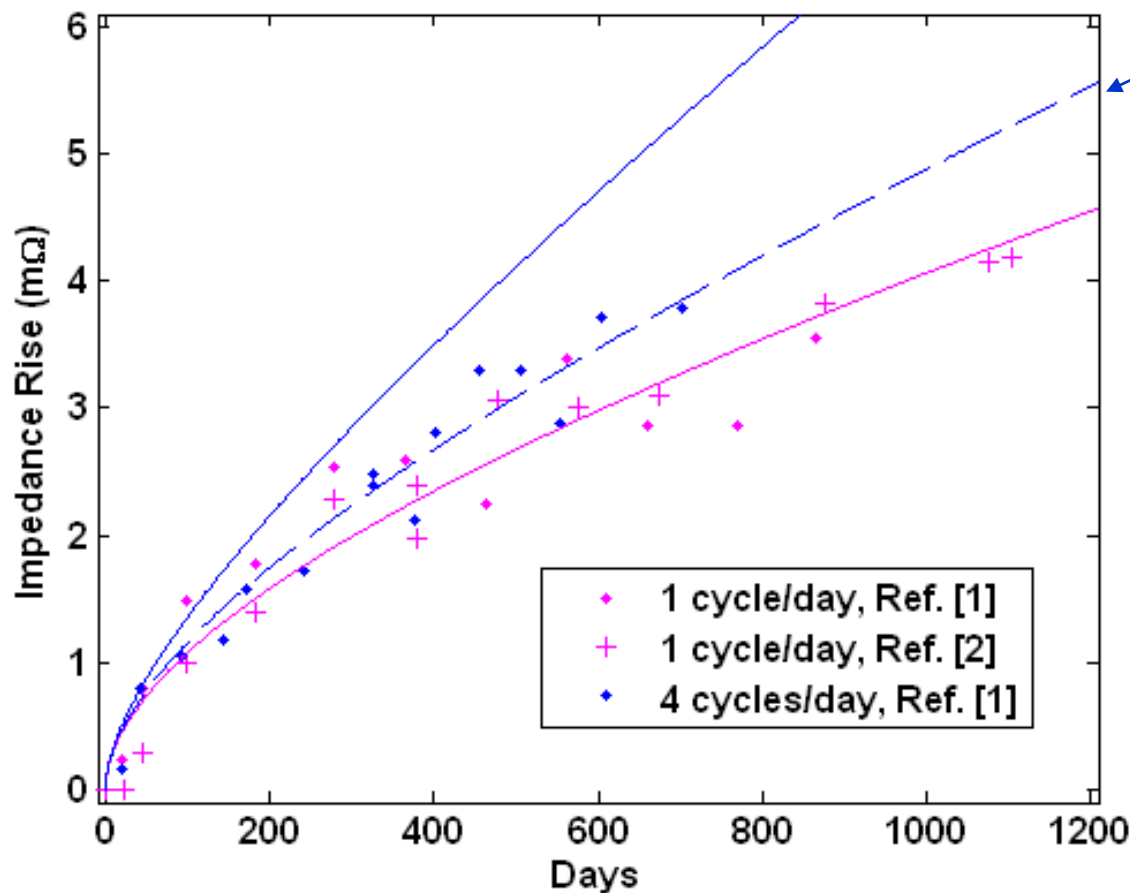
$$a_2 / a_1 = \max[0, c_0 + c_1 (\Delta\text{DOD})]$$



Impedance: Multiple Cycles per Day

Dependence on $t^{1/2}$, N model
overpredicts effect of
accelerated cycling.
(not used)

~~$$R = a_1 t^{1/2} + a_2 N$$~~



$$R = a_1 t^{1/2} + a_{2,t} t + a_{2,N} N$$

$$a_{2,t} = a_2 (1 - \alpha_N)$$

$$a_{2,N} = a_2 \alpha_N$$

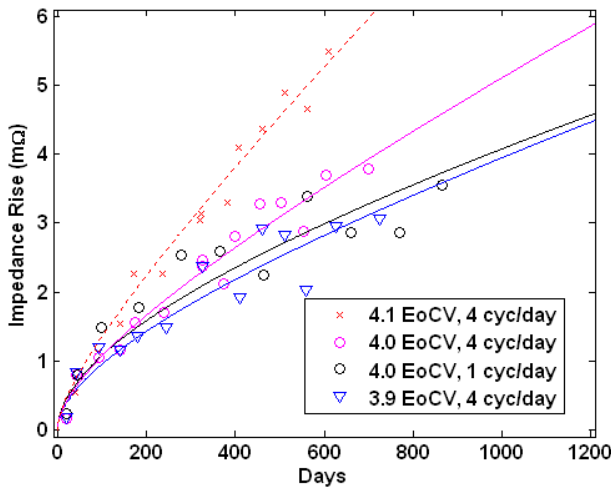
$$\alpha_N = 0.285, R^2 = 0.9488$$

Dependence on
 $t^{1/2}$, t , N model
predicts
accelerated and
real-time cycling
much better.

[1] Corrected data from J.C. Hall et al., 208th ECS Mtg., Oct. 16-21, Los Angeles, CA.

[2] Data from J.C. Hall et al., 4th IECEC, June 26-29, San Diego, CA.

Impedance: Voltage and Temperature Acceleration



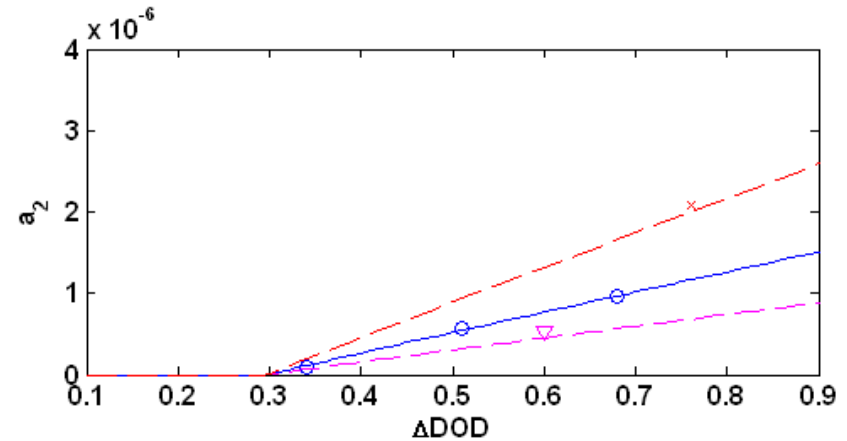
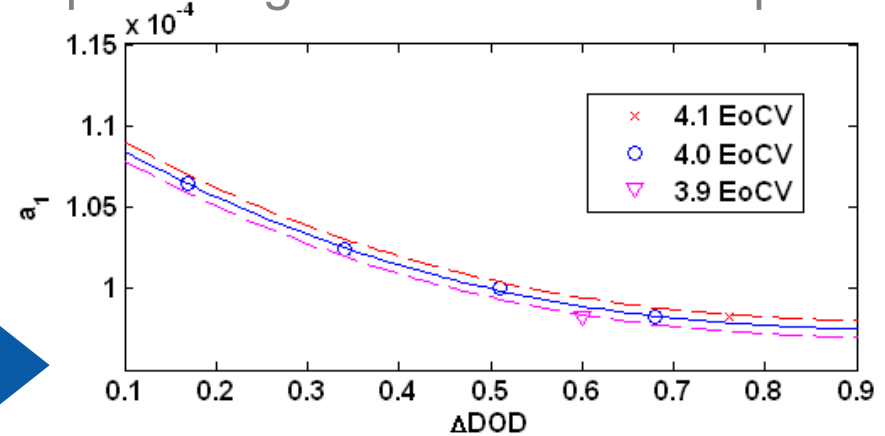
- Increased impedance growth due to elevated voltage & temperature fit using Tafel & Arrhenius-type equations.
- Dedicated lab experiments required to fully decouple voltage- Δ DOD relationship.

$$a_1 = a_{1,ref} k_1 \exp(\alpha_1 F/RT \times V)$$

$$a_2 = a_{2,ref} k_2 \exp(\alpha_2 F/RT \times V)$$

$$k_1 = k_{1,ref} \exp(-E_{a1} \times (T^{-1} - T_{ref}^{-1}) / R)$$

$$k_2 = k_{2,ref} \exp(-E_{a2} \times (T^{-1} - T_{ref}^{-1}) / R)$$

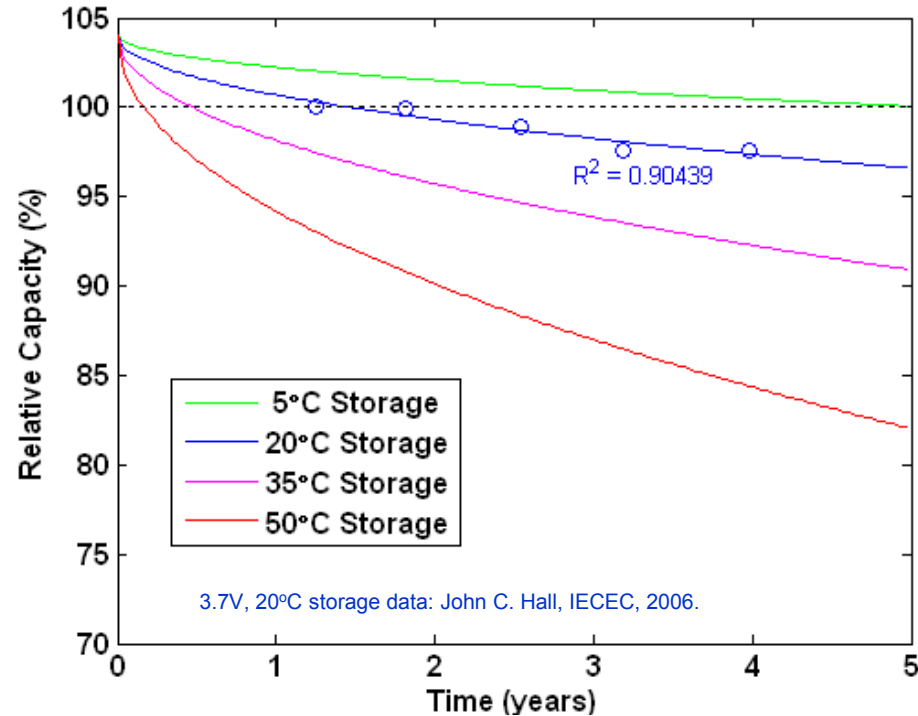


• This work assumes values for k_1 & α_1 .
 • Activation energies, E_{a1} and E_{a2} , are taken from similar chemistry.

Capacity Fade: Calendar (storage) and Cycling Effects

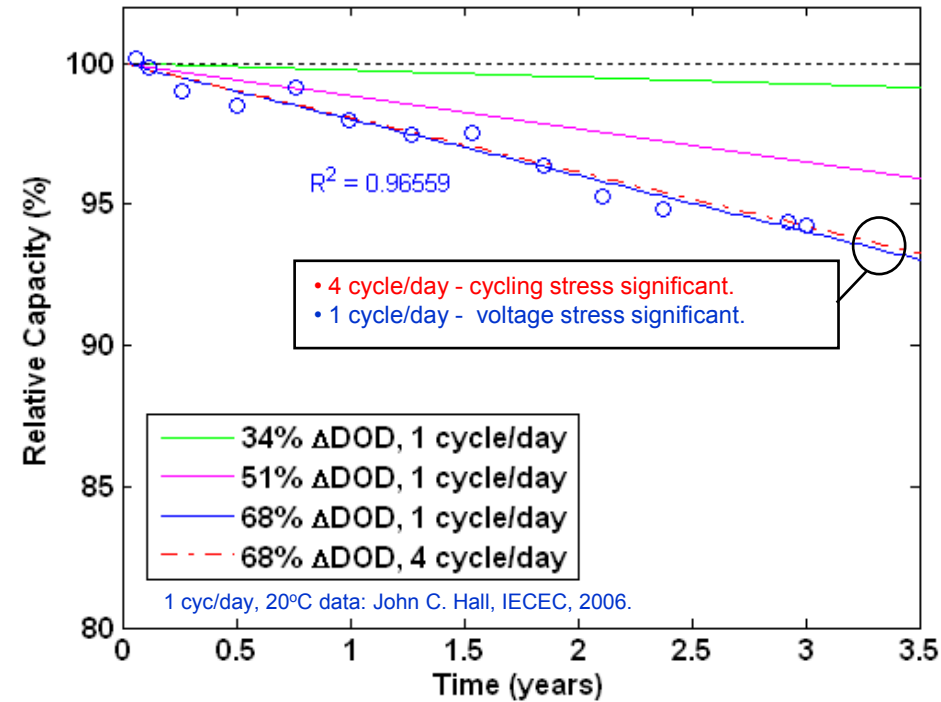
Capacity Loss During Storage

Loss of cyclable Li



Capacity Loss During Cycling

Isolation of active sites



$$Q_{Li} = d_0 + d_1 \times (a_1 t^{1/2})$$

$$Q_{sites} = e_0 + e_1 \times (a_{2,t} t + a_{2,N} N)$$

Q = Relative Capacity

$$Q = \min(Q_{Li}, Q_{sites})$$

a_1 and a_2 capture temperature, ΔDOD , and voltage dependencies (previous slides).

Life Model Summary (equations & coefficients)

Impedance Growth Model

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

$$k_1 = k_{1,ref} \exp(-E_{a1} \times (T^{-1} - T_{ref}^{-1}) / R)$$

$$k_2 = k_{2,ref} \exp(-E_{a2} \times (T^{-1} - T_{ref}^{-1}) / R)$$

$$a_1 = a_{1,ref} k_1 \exp(\alpha_1 F / RT \times V)$$

$$a_2 = a_{2,ref} k_2 \exp(\alpha_2 F / RT \times V)$$

$$a_1 = b_0 + b_1 (1 - \Delta DOD)^{b2}$$

$$a_2 / a_1 = \max[0, c_0 + c_1 (\Delta DOD)]$$

$$a_{2,t} = a_2 (1 - \alpha_N)$$

$$a_{2,N} = a_2 \alpha_N$$

$$R = a_1 t^{1/2} + a_{2,t} t + a_{2,N} N$$

Capacity Fade Model

- Temperature
 - Voltage
 - ΔDOD
 - Calendar Storage (Li loss)
 - Cycling (Site loss)
- From impedance growth model

$$Q_{Li} = d_0 + d_1 \times (a_1 t^{1/2})$$

$$Q_{sites} = e_0 + e_1 \times (a_{2,t} t + a_{2,N} N)$$

$$Q = \min(Q_{Li}, Q_{sites})$$

Reasonably fits available data

Actual interactions of degradation mechanisms may be more complex.

Life/Cost Trade-Offs: Approach

- Life model adjusted slightly to reflect experience with present-day PHEV battery technology (NCA chemistry).
- Cost model from previous work:
 - Manufacturing cost of a complete pack at high volume production

$$\$/\text{pack} = 11.1 \cdot \text{kW} + 224.1 \cdot \text{kWh} + 4.53 \cdot \text{BSF} + 340$$

BSF = Battery Size Factor

• Requirements from USABC/DOE

- Energy: 3.4 kWh PHEV10; 11.6 kWh PHEV40
- CD Cycle Life: 5000 CD cycles
- Calendar Life: 15 years at 35°C
 - Too aggressive for present-day technology
 - Instead used 10 years at 30°C for analysis (next two slides)

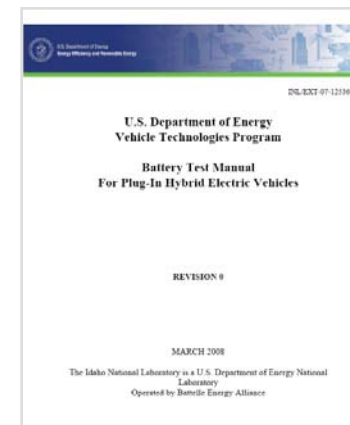
• Questions:

- What Δ DOD & P/E meet life at minimum cost?
- Which controls life? Calendar or cycle life?
- What environmental parameters cause greatest life sensitivity?



Nominal Energy (kWh)	P/E	Detailed Model: ³ NCM	Detailed Model: ³ NCA	Simple Model: ^{1,2} \$=11*kW+224*kWh+680
6.88	5.8	\$3120	\$2600	\$2660
8.46	4.7	\$3510	\$2860	\$3020
11.46	3.5	\$4290	\$3500	\$3680

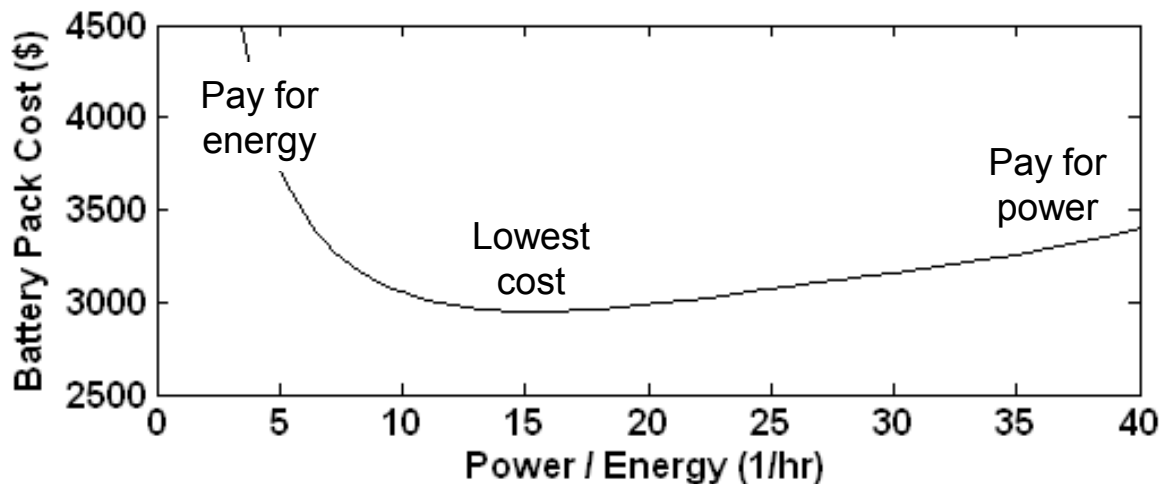
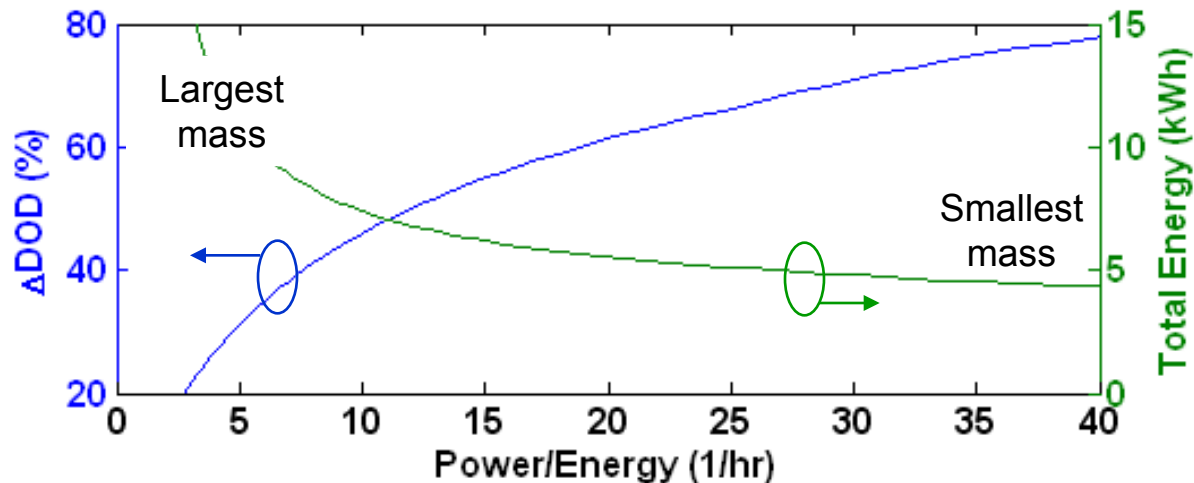
NCA - Nickel Cobalt Alumina; NCM- Nickel Cobalt Manganese



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-Offs: Usable Δ DOD

PHEV10 battery sized for
10 years at 30°C, 1 cycle/day*



- Expanding Δ DOD window
 - reduces total battery energy & mass
 - requires higher P/E to meet power requirements at low SOC

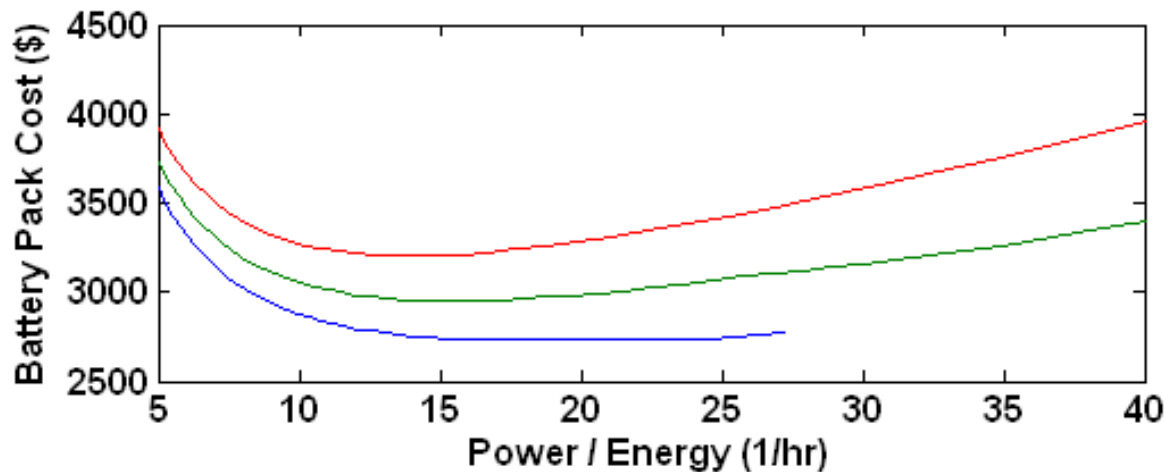
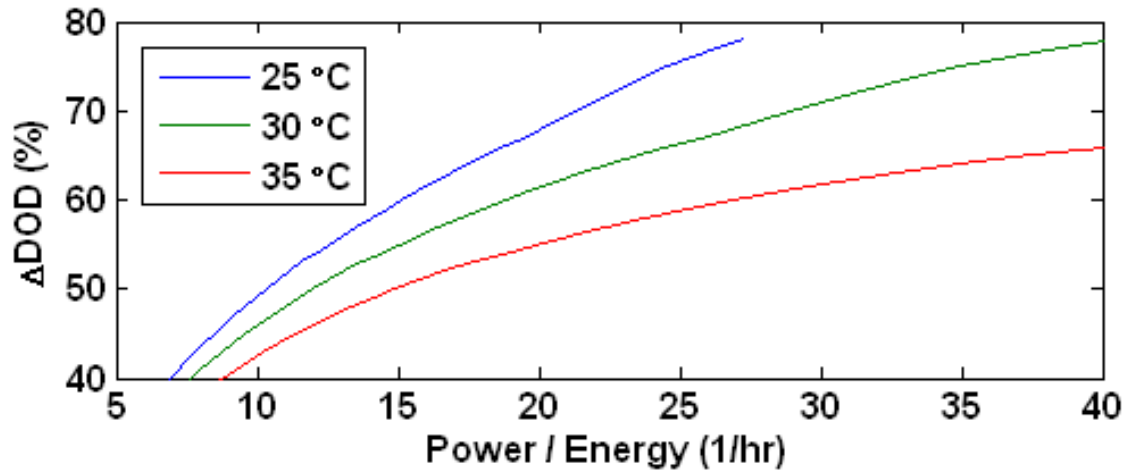
- Optimal P/E ratio ($\sim 15 \text{ hr}^{-1}$) yields lowest cost battery

- Too much P/E is preferred to too little P/E
 - small increase in cost
 - reduces mass

* using 3.9 EoCV (90% SOC_{max})

Life/Cost Trade-Offs: Temperature Sensitivity

PHEV10 battery sized for
10 years at **25°C**, **30°C**, & **35°C***



- Temperature exposure drastically impacts system size necessary to meet goals at end of life.

25°C: 70% to 80%

ΔDOD is usable

35°C: 50% to 65%

ΔDOD is usable

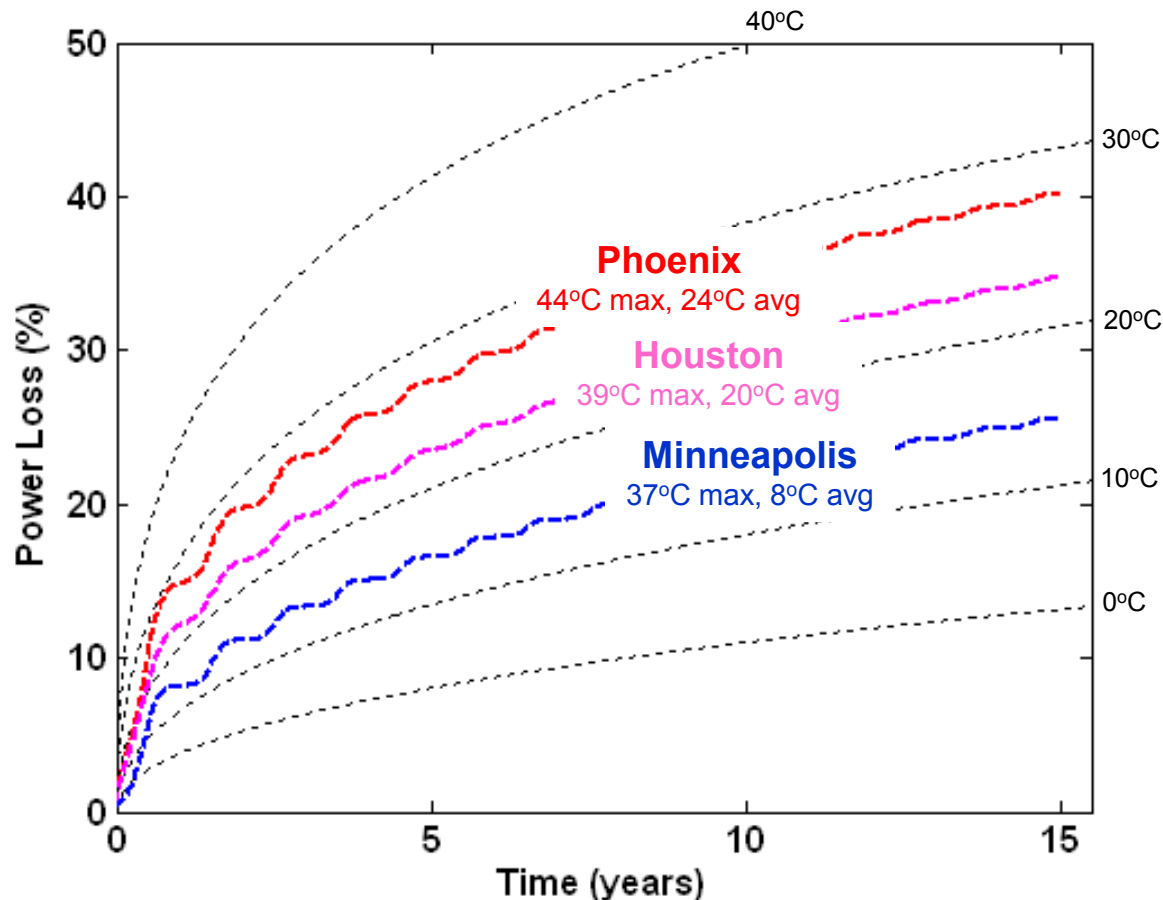
- Modifying life requirements from 10 years at 25°C to 10 years at 35°C increases battery cost by > \$500.

* 1 cycle/day, 3.9 EoCV (90% SOC_{max})

The Case for Thermal Control of PHEV Batteries

Storage at elevated temperatures responsible for significant impedance growth; most passenger vehicles are parked >90% of the time.

- Assume vehicle is always parked (storage calendar life effect only).
- Typical Meteorological Year (TMY) hour-by-hour geographic dataset used to provide ambient conditions.
- Assume $T_{\text{battery}} = T_{\text{ambient}}$ (*Realistic? No. Solar loading on vehicle cabin & battery will cause even more power loss.*)



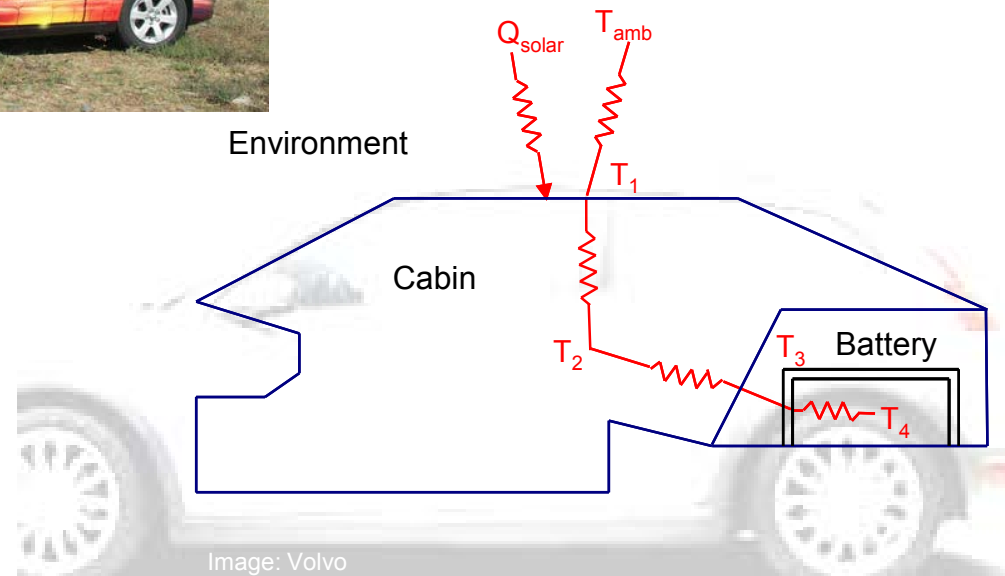
Current Li-ion technology can require 30% to 70% excess power to last 15 years.

Advanced Li-Ion technologies still could require 15% to 30% excess power to last 15 years.

Thermal control of PHEV batteries is needed even during standby.

Study of PHEV Battery Standby Thermal Control

- Investigate the technical and economic merits of various thermal control strategies during standby
 - Experiments using NREL PHEV Test Bed and other vehicles
 - Vehicle thermal modeling with various solar and ambient loads



On Sunny Days, Solar Warming of Cabin Can Cause Battery Temperature to Be Much Hotter than Ambient

NREL PHEV Test Bed instrumented to correlate solar radiation & ambient temperature with battery temperature

Rooftop pyranometer & RTD



Battery Pack RTD



Vehicle thermal model extracted for geographic scenario analysis

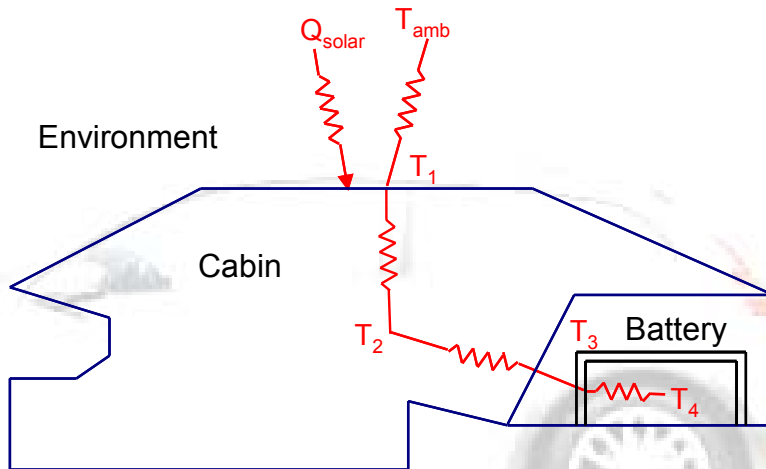
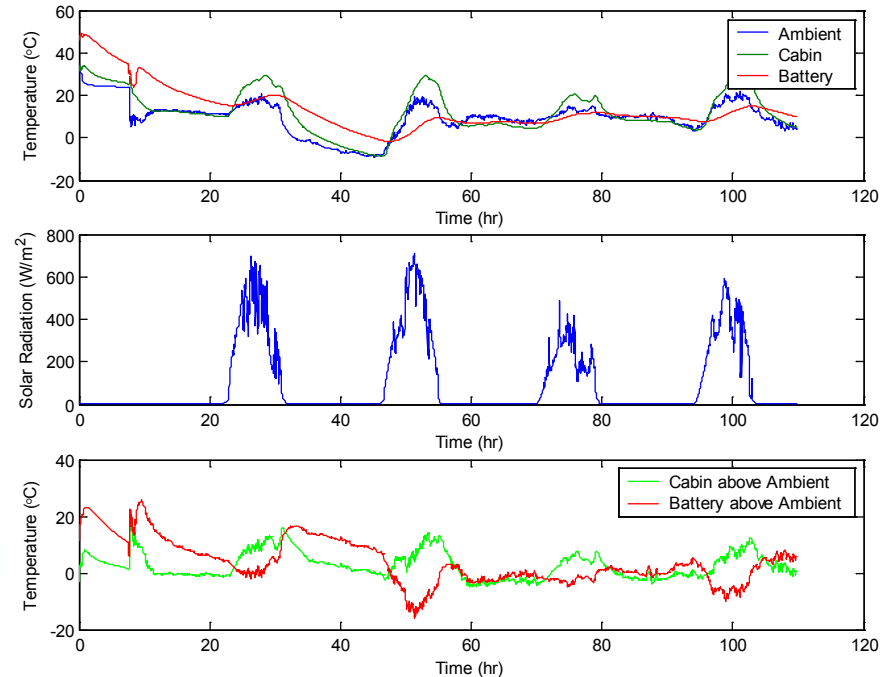


Image: Volvo

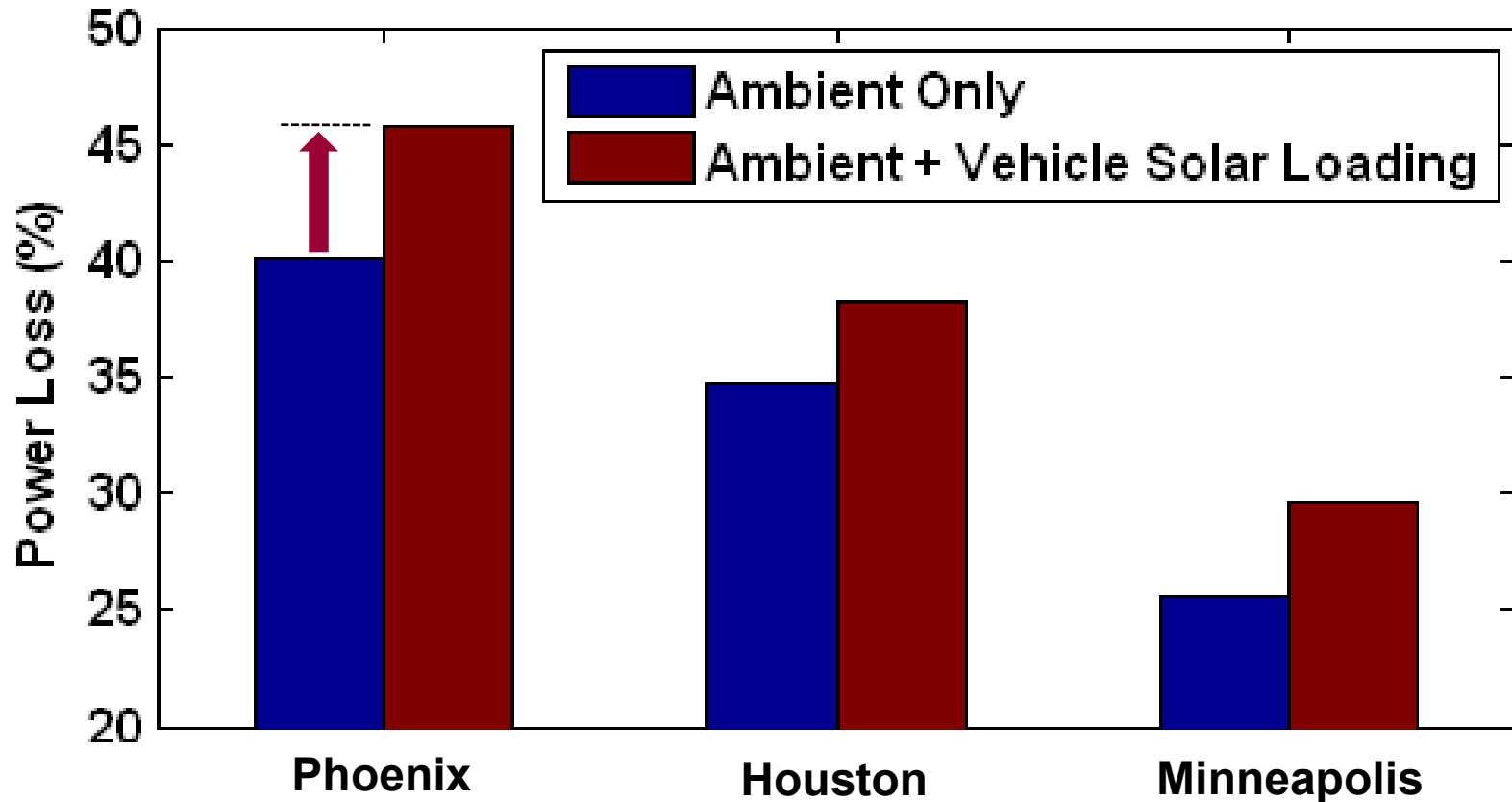


Model: Solar Warming of Cabin (and its effect on battery temperature) Is Important for Predicting Battery Degradation

PHEV10 – Power loss after 15 years

Degradation predictions with and without effects of vehicle solar loading.

Current Li-ion technology

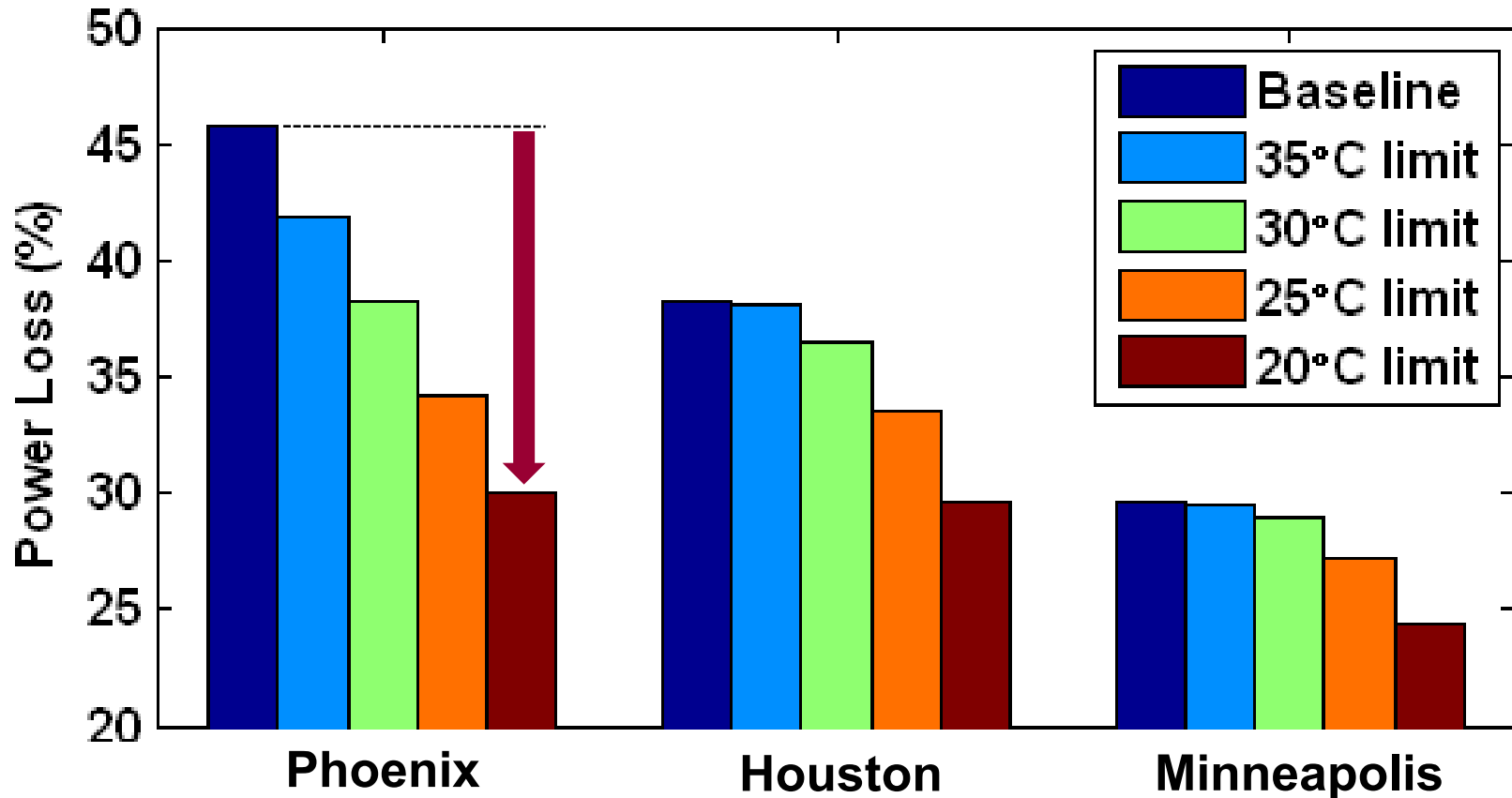


Eliminating Peak Battery Temperatures (e.g., battery insulation, active cooling, reducing solar load) Can Greatly Improve Battery Life

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.*

Current Li-ion technology



Conclusions

- Useful life of a given cell design is dictated by the complex interaction of parameters ($t^{1/2}$, t , N , T , V , DOD).
- Successful introduction of PHEV Li-ion technology requires careful consideration of
 - Design factors: battery DOD, end of charge voltage, ...
 - Real-world use: # cycles/day, temperature exposure.
- Battery life is extremely sensitive to temperature exposure; solar loading on cabin can cause severe battery heating.
- PHEV battery standby thermal control can reduce power loss by >15% over baseline 15-year Phoenix, AZ, scenario.
- Accurate degradation prediction requires large parametric dataset at the cell level (next slide) plus dedicated laboratory tests at the material level.

Need for Parametric Data on Li-ion Technologies:

Battery life model is only as good as the dataset populating it.

Special Considerations:

- Expose possible accelerating mechanisms:
 - high T material degradation
 - low T mechanical stress.

- Low Δ DOD cycling is important for decoupling $t^{1/2}$ and t dependencies.

- Test to $>V_{\max}$ to improve model fit at elevated voltages.

- When cells die:
 - destructive physical analysis, or
 - continue cycling at less severe rate (enable 2nd use/resale).

4 Cycles per Day at Average CD Current

- Size CD region

Capacity (Ah)		30	34	38	42
EoCV (V)		3.9	4	4.1	4.25
Δ DOD (%)	90	20°C	-10°C, 0°C, 20°C, 40°C	20°C	20°C, 40°C
	70	20°C	20°C	20°C	
	30	20°C	-10°C, 0°C, 20°C, 40°C	20°C	20°C, 40°C
	10	20°C	20°C	20°C	

1 Cycle per Day at Average CD Current

- Allow proper extrapolation of 4 cycle/day accelerated tests

Capacity (Ah)		30	34	38	42
EoCV (V)		3.9	4	4.1	4.25
Δ DOD (%)	90		0°C, 20°C, 40°C		20°C, 40°C
	80		20°C		
	65		0°C, 20°C, 40°C		20°C, 40°C
	30		20°C		

Open Circuit Storage

- Choose OCV to match CD & CS cycling scenarios

OCV (V)	3.4	4	4.1	4.25
	40°C	20°C, 40°C, 60°C	40°C	20°C, 40°C, 60°C

Continuous Cycling in Various CS Windows

- Find optimum CS region and window

Capacity (Ah)		30	34	38	42
SOC (%)		5%	10%	20%	50%
Δ DOD (%)	2	0°C, 20°C	0°C, 20°C	20°C	20°C
	5	0°C, 20°C	0°C, 20°C	20°C	20°C

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