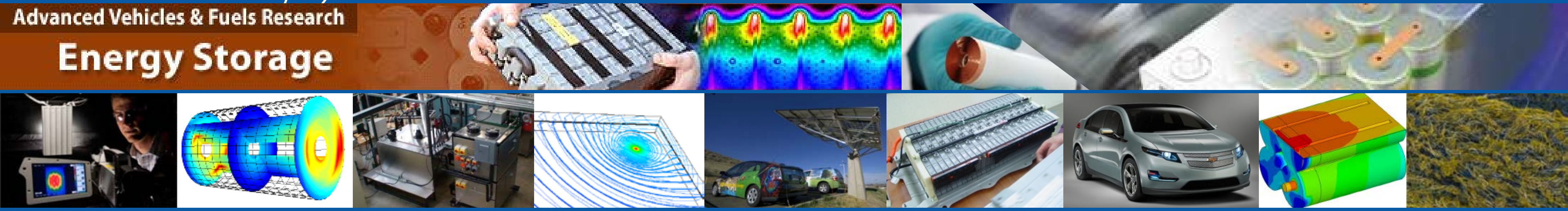
Optimizing Battery Usage and Management for Long Life



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Transportation and Hydrogen Systems Center
National Renewable Energy Laboratory
Golden, Colorado

Advanced Automotive Battery Conference
Detroit, Michigan June 16, 2016

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

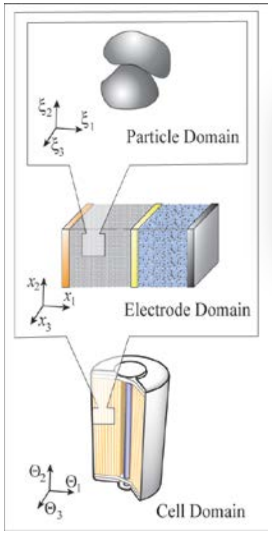
Outline

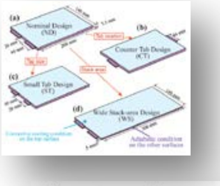
1) Models & methods

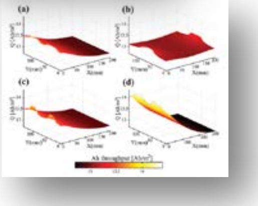
2) Analysis: PHEV 10 year / 150k mile life

3) Battery control research projects

NREL Battery Modeling Tools



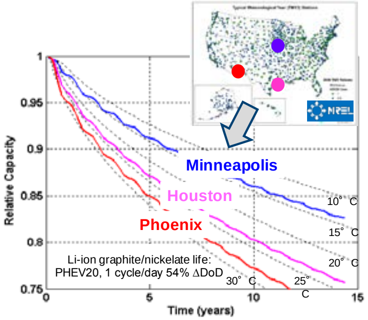




1) Multi-Scale Multi-Domain Model

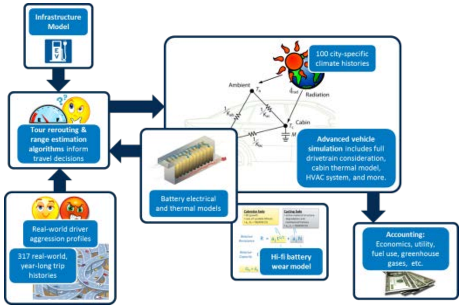
- 3D electrochemical/thermal physics
- 3D thermal/electrical/mechanical abuse

DOE Computer Aided Eng. of Batteries (CAEBAT) program



2) Battery Life Predictive Model

- Energy/power performance degradation as function of time, N_{cycles}, T, SOC, ΔSOC, C-rate
- Integrated in BLAST



Infrastructure Model

Tour rerouting & range estimation algorithms inform travel decisions

Real-world driver aggression profiles

317 real-world, year-long trip histories

100 city-specific climate histories

Advanced vehicle simulation includes full drivetrain consideration, cabin thermal model, HVAC system, and more.

Battery electrical and thermal models

Hi-fi battery wear model

Accounting: Economics, utility, fuel use, greenhouse gases, etc.

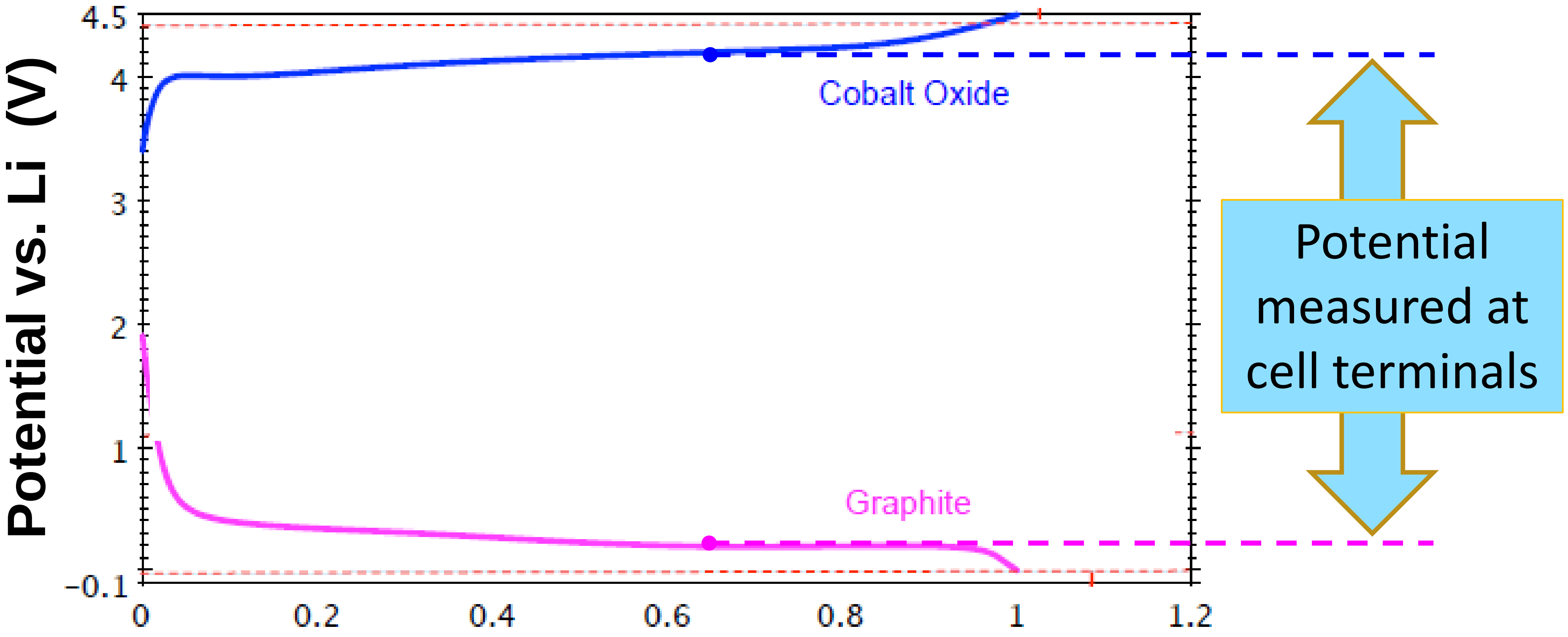
3) BLAST (Battery Lifetime Analysis and Simulation Tool)

- Load profile, climate & thermal simulation (vehicles, stationary)

Electrochemical Operating Window

0% SOC $\xrightarrow{\text{charge}}$ 100% SOC

0% SOC $\xleftarrow[\text{discharge}]{}$ 100% SOC



Potential measured at cell terminals

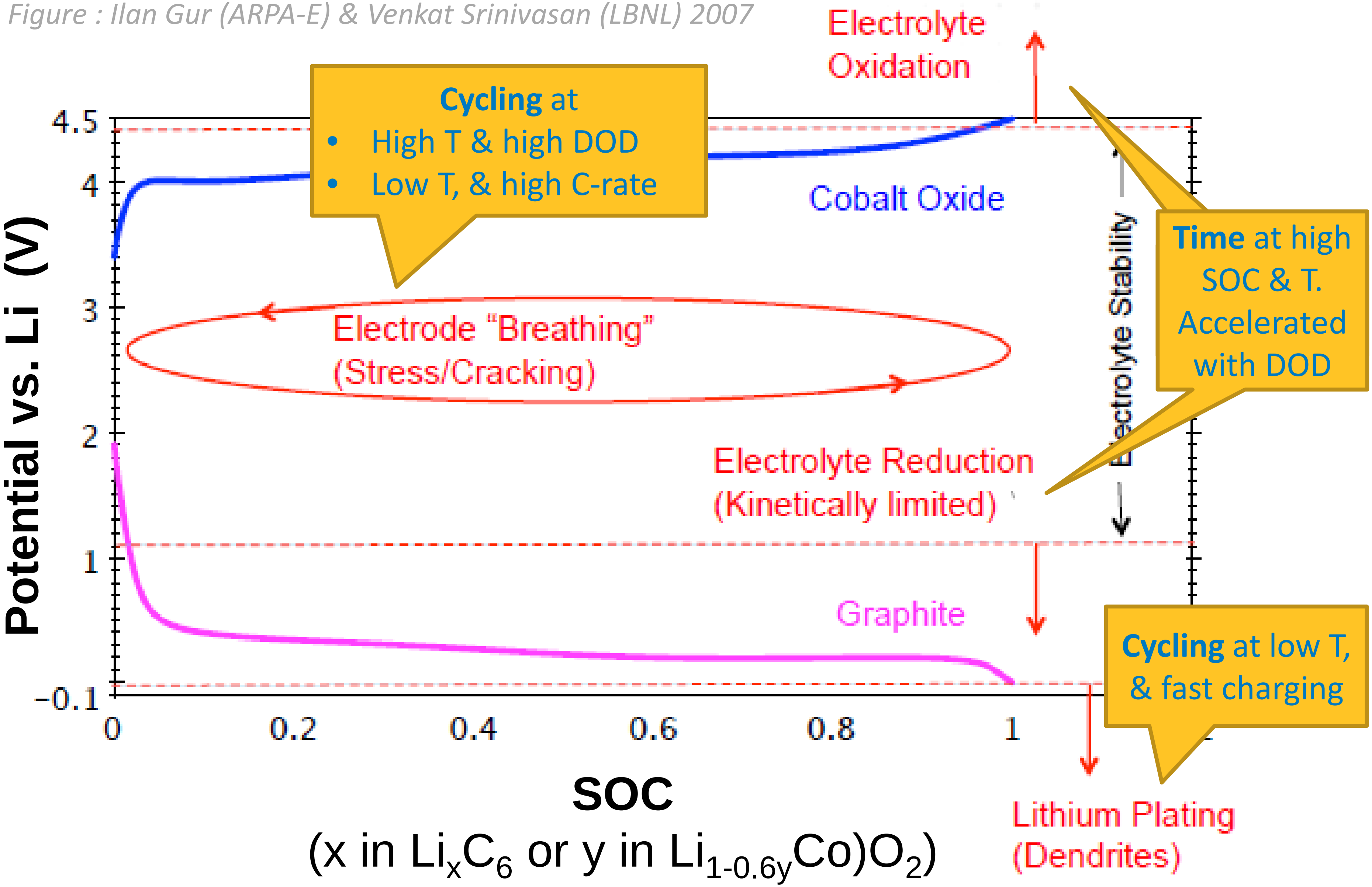
SOC

(x in Li_xC_6 or y in $Li_{1-0.6y}CoO_2$)

Figure credit: Ilan Gur (ARPA-E) & Venkat Srinivasan (LBNL), 2007

Electrochemical Window – Degradation

Figure : Ilan Gur (ARPA-E) & Venkat Srinivasan (LBNL) 2007



Cycling at

- High T & high DOD
- Low T, & high C-rate

Time at high SOC & T. Accelerated with DOD

Cycling at low T, & fast charging

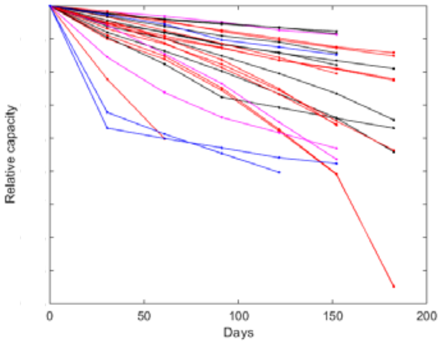
NREL Life Predictive Modeling – Approach

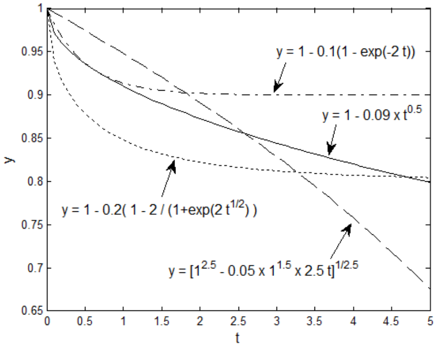
Set of trial equations representing physical fade mechanisms, e.g.

- SEI growth & damage
- Particle fracture
- Electrode isolation
- Electrolyte decomposition
- Gas generation, delamination
- Li plating

(Non)linear combinations of mechanisms describe performance metrics changes with time & cycles

- Capacity (generally min. of several limiting mechanisms)
- Resistance (generally additive)





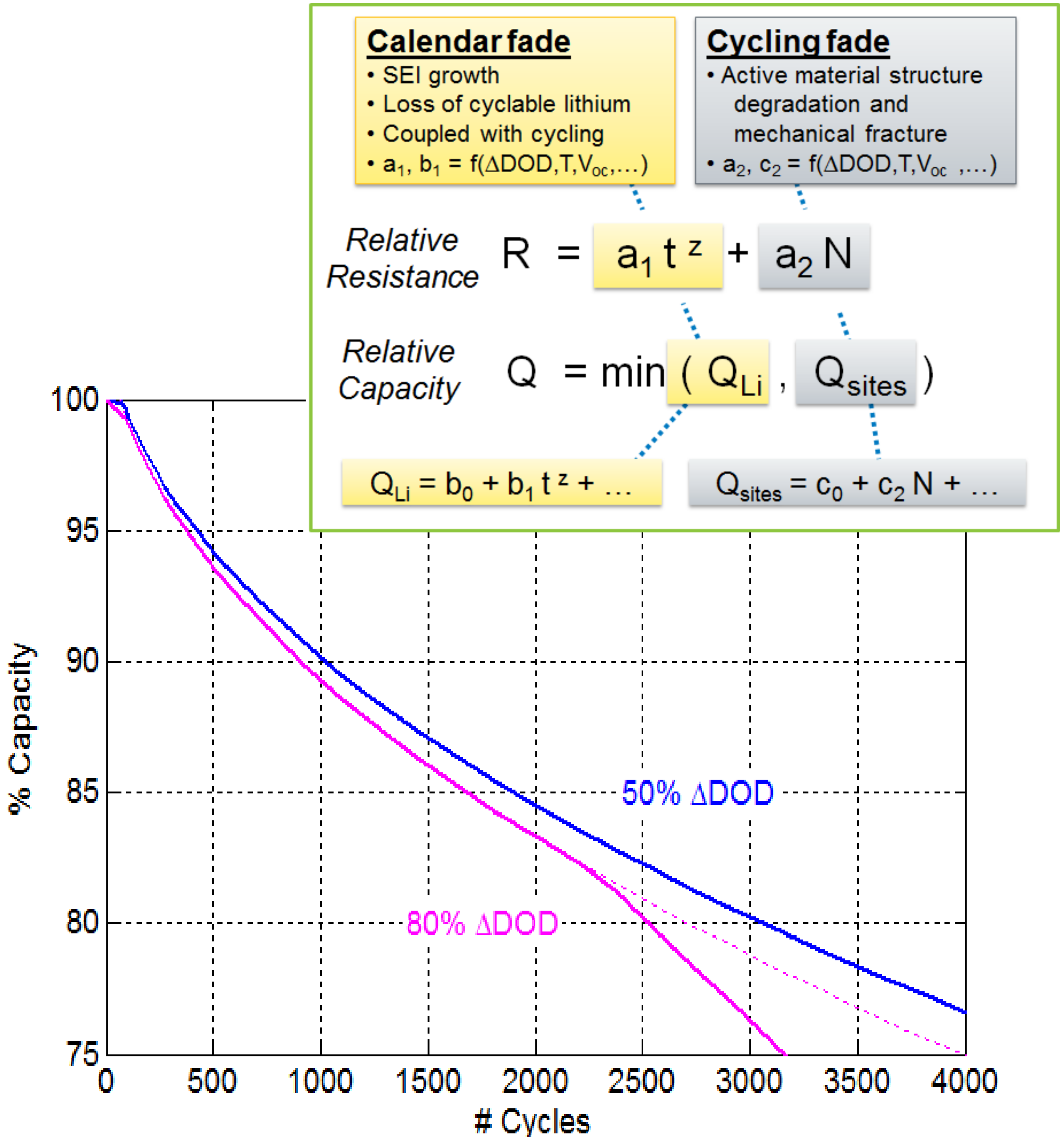
Mechanism	Trajectory equation	State equation	Parameters
Diffusion-controlled reaction	$x(t) = kt^{1/2}$	$\dot{x}(t) = \frac{k}{2}\left(\frac{k}{x(t)}\right)$	k – *rate* *(p=1/2)*
Kinetic-controlled reaction	$x(t) = kt$	$\dot{x}(t) = k$	k – *rate* *(p=1)*
Mixed diffusion/ kinetic	$x(t) = kt^p$	$\dot{x}(t) = kp\left(\frac{k}{x(t)}\right)^{\left(\frac{1-p}{p}\right)}$	k – *rate* p – *order*, *0.3<p<1*
Diffusion controlled reaction with mechanical damage	See Appendix A	$\dot{D} = \frac{dN}{dt} k_D \cdot \left(\sqrt{D}\right)^p$ $\dot{x}_0(t) = \frac{k}{2}\left(\frac{k}{x(t)}\right)$ $\dot{x}_j(t) = D\frac{k}{2}\left(\frac{k}{x(t)}\right)$	k – *rate* p – *order*
Cyclic fade – linear	$x(N) = kN$	$\dot{x}(N) = k$	k – *rate* *(p=0)*
Cyclic fade – accelerating.	$x(N) = \left[x_0^{1+p} + kx_0^{p}(1+p)N\right]^{\frac{1}{1+p}}$	$\dot{x}(N) = k\left(\frac{x_0}{x(N)}\right)^p$	k – *rate* p – *order*, $0 \geq p > 3$
Break-in process	$x(t) = M(1-\exp(-kt))$ or $x(N) = \ldots$	$\dot{x}(t) = k(M - x(t))$	M – *maximum fade* k – *rate*
Sigmoidal reaction	$x(t) = M\left[1 - \frac{2}{1+\exp(kt^p)}\right]$ or $x(N) = \ldots$	$\dot{x}(t) = \frac{2MkpX(t)\exp(kX(t))}{[1+\exp(kX(t))]^2}$ $X(t) = \left\{\frac{1}{k}\ln\left(\frac{2}{1-x(t)/M} - 1\right)\right\}^{\frac{1}{p}}$	M – *maximum fade* k – *rate* p – *order*

x, D: state variables
k, k_D: fade rates
p: order
M: maximum extent of fade

S. Santhanagopalan, **K. Smith**, J. Neubauer, G.-H. Kim, A. Pesaran, M. Keyser, Design and Analysis of Large Lithium-Ion Battery Systems, Artech House, 2015

NREL Life Predictive Modeling – NCA Example

- Experience with 8-10 NCA, FeP, NMC technologies
- NCA model, shown here, implemented in BLAST



Calendar fade

- SEI growth
- Loss of cyclable lithium
- Coupled with cycling
- $a_1, b_1 = f(\Delta DOD, T, V_{oc}, \ldots)$

Cycling fade

- Active material structure degradation and mechanical fracture
- $a_2, c_2 = f(\Delta DOD, T, V_{oc}, \ldots)$

Relative Resistance $R = a_1 t^z + a_2 N$

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

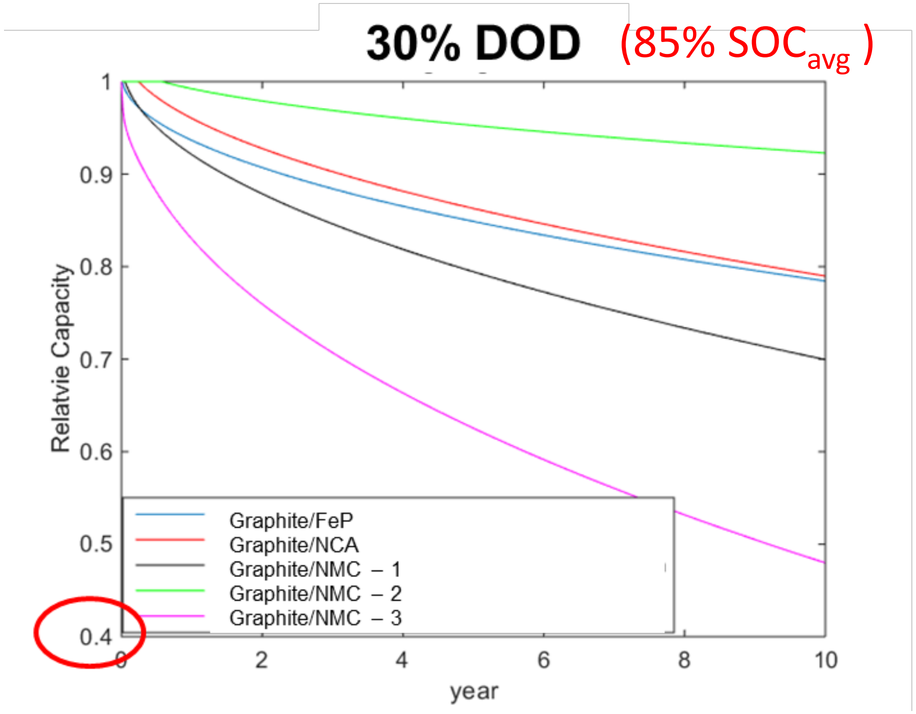
$Q_{Li} = b_0 + b_1 t^z + \ldots$

$Q_{sites} = c_0 + c_2 N + \ldots$

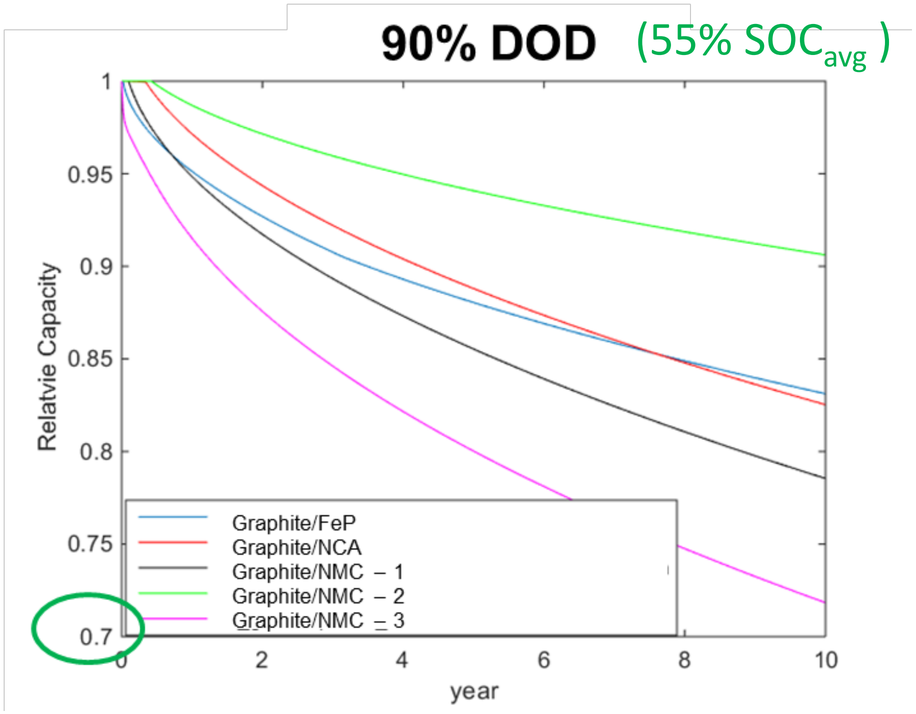
Life comparison of 5 Li-ion technologies

In addition to aging condition, life changes significantly with Li-ion technology

- Power/energy ratio
- Chemistry
- Design heritage



30% DOD (85% SOC_{avg})



90% DOD (55% SOC_{avg})

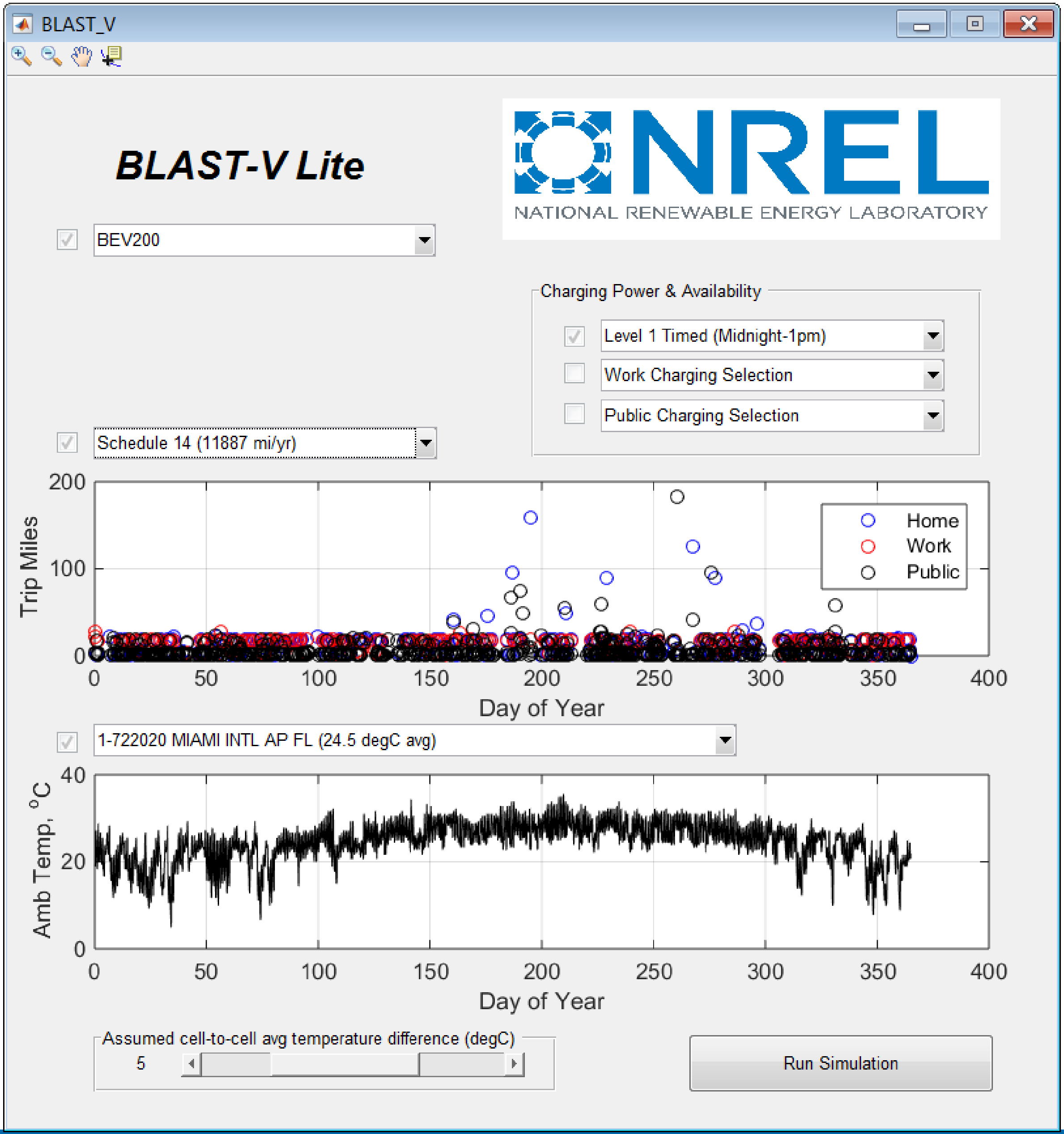
Temperature and electrical cycling assumptions:

- Temperature: 28^{o}C
- Cycling: 2-hr charge to 100% SOC; 10-hr rest; 2-hr dischg; 10-hr rest

**Faster fade at 30% DOD relative to 90% DOD in this scenario is due to longer dwell time at high SOC for the 30% DOD case*

BLAST-Lite standalone model GUI

- **Versions for vehicle (shown) and stationary energy storage applications**
- **Downloadable from NREL website later this year**



BLAST-V Lite

☑ BEV200

Charging Power & Availability

☑ Level 1 Timed (Midnight-1pm)

☐ Work Charging Selection

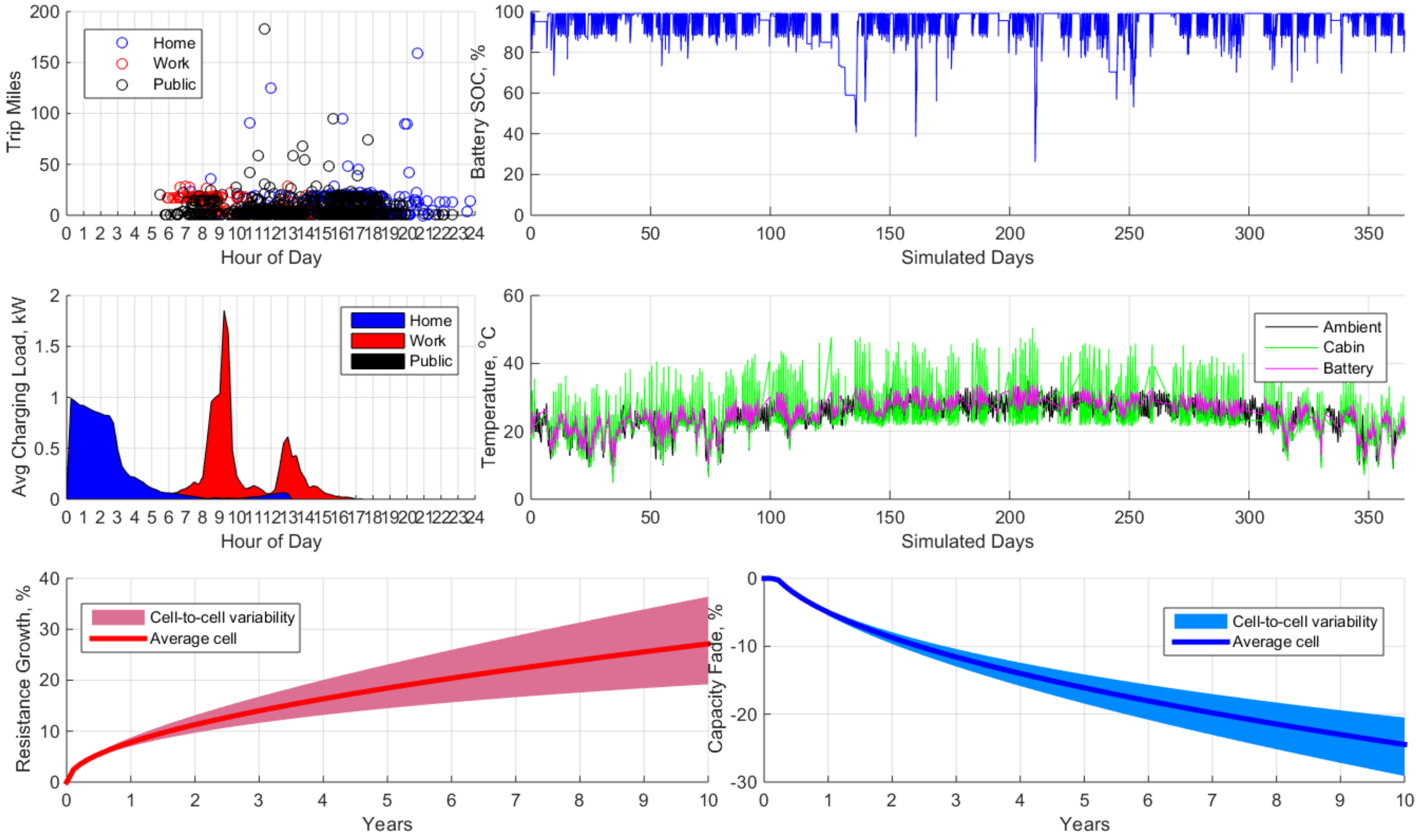
☐ Public Charging Selection

☑ Schedule 14 (11887 mi/yr)

☑ 1-722020 MIAMI INTL AP FL (24.5 degC avg)

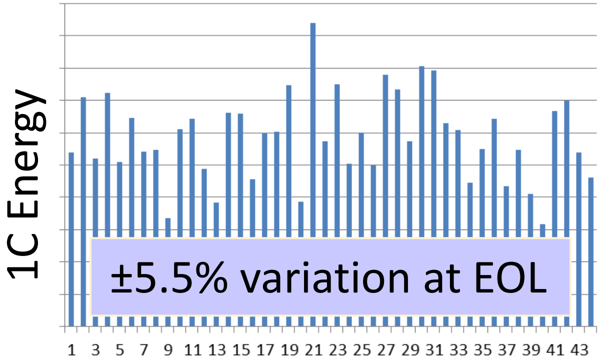
Assumed cell-to-cell avg temperature difference (degC): 5

BLAST-Lite sample model results

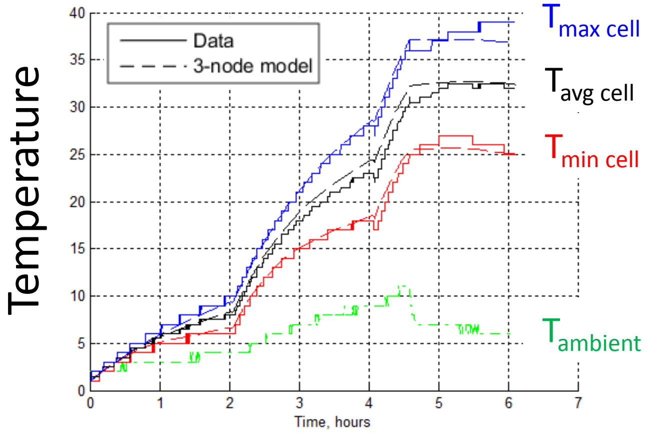


Cell-to-cell capacity imbalance

- Expert interviews & teardown analysis of NCA automotive pack aged to 70% remaining energy

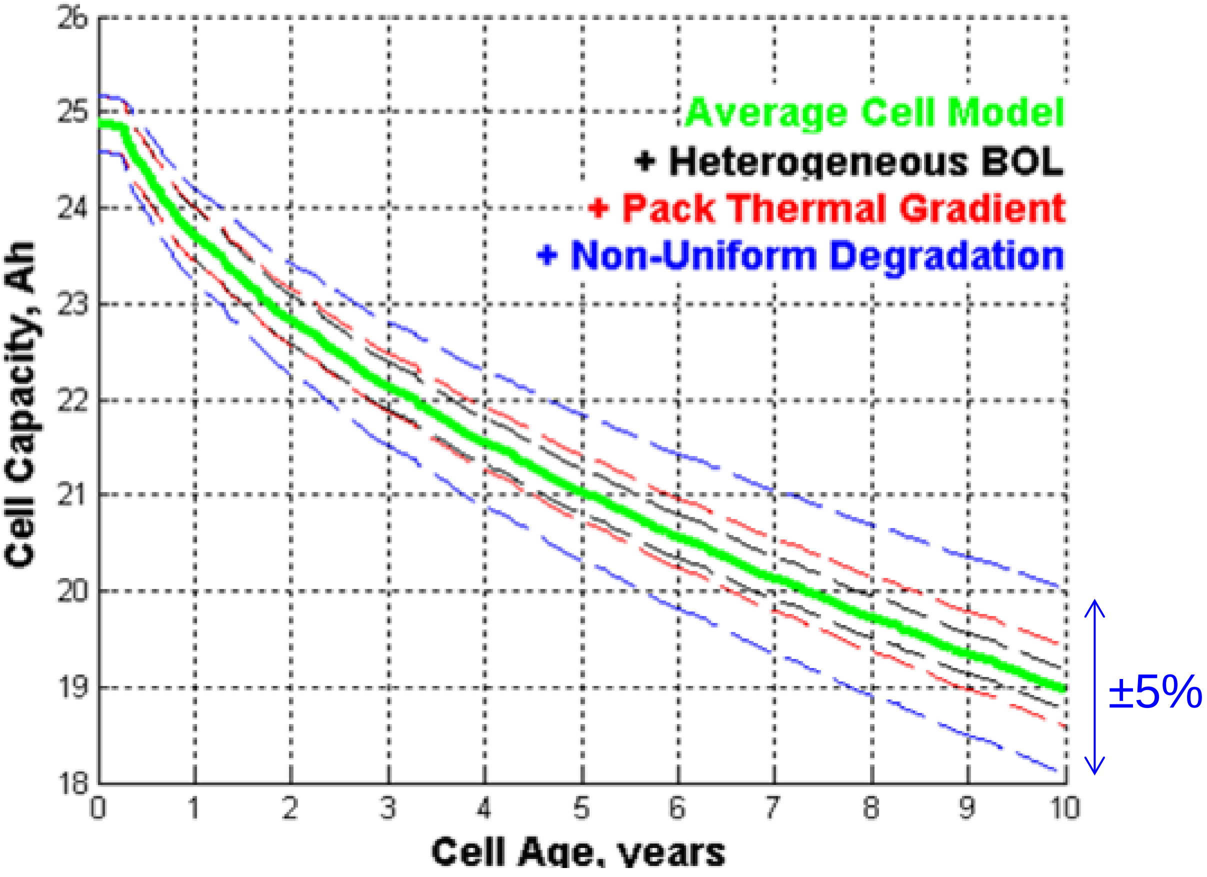


- Pack thermal imbalance testing and simulation



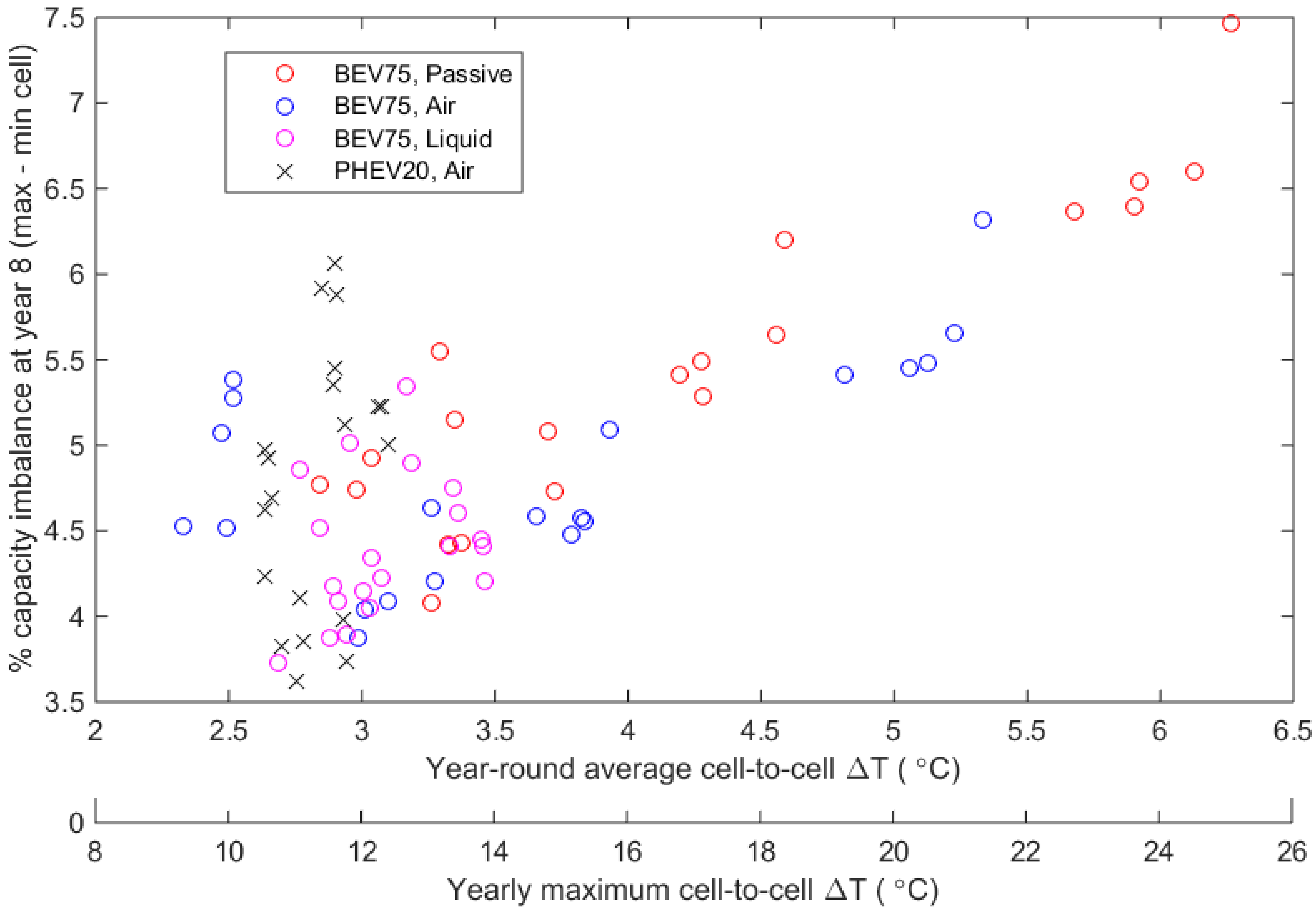
- Simulation of sources of cell-to-cell aging variability

Non-uniform degradation includes ±10% random perturbation on life model degradation rates



Cooling system impact on cell aging imbalance

BLAST simulation of xEVs across 5 driving patterns, 4 climates



1) Lifetime models & methods

2) Analysis: PHEV 10 year / 150k mile life

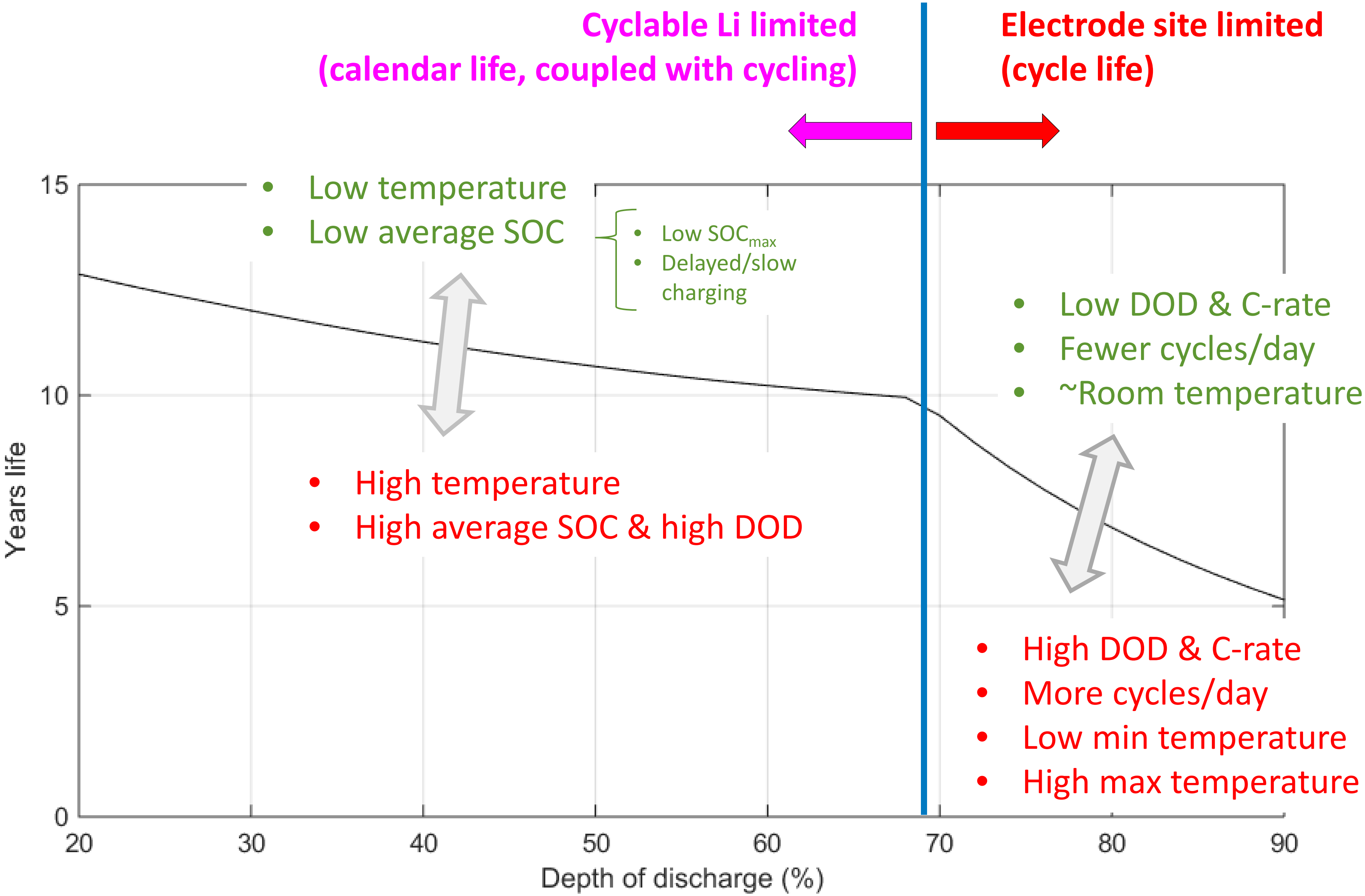
3) Battery control research projects

Impacts on PHEV lifetime

- **AT-PZEV 10yr/150kmi warranty**
- **Presently no remaining capacity requirement**
- **But important for long term customer satisfaction and resale value**

- **Nominal assumptions** (variations noted on each slide)
  - Graphite/NCA life model
  - 20°C
  - 90% SOC_{max}
  - Average cell degradation (margin required for worst cell if passive balancing)
  - 1 cycle per day
  - 2/3 of rest time spent at SOC_{max}
  - 1/3 of rest time spent at SOC_{min}

Calendar versus cycle limitations on years life



Cyclable Li limited
(calendar life, coupled with cycling)

Electrode site limited
(cycle life)

- Low temperature
- Low average SOC
  - Low SOC_{max}
  - Delayed/slow charging

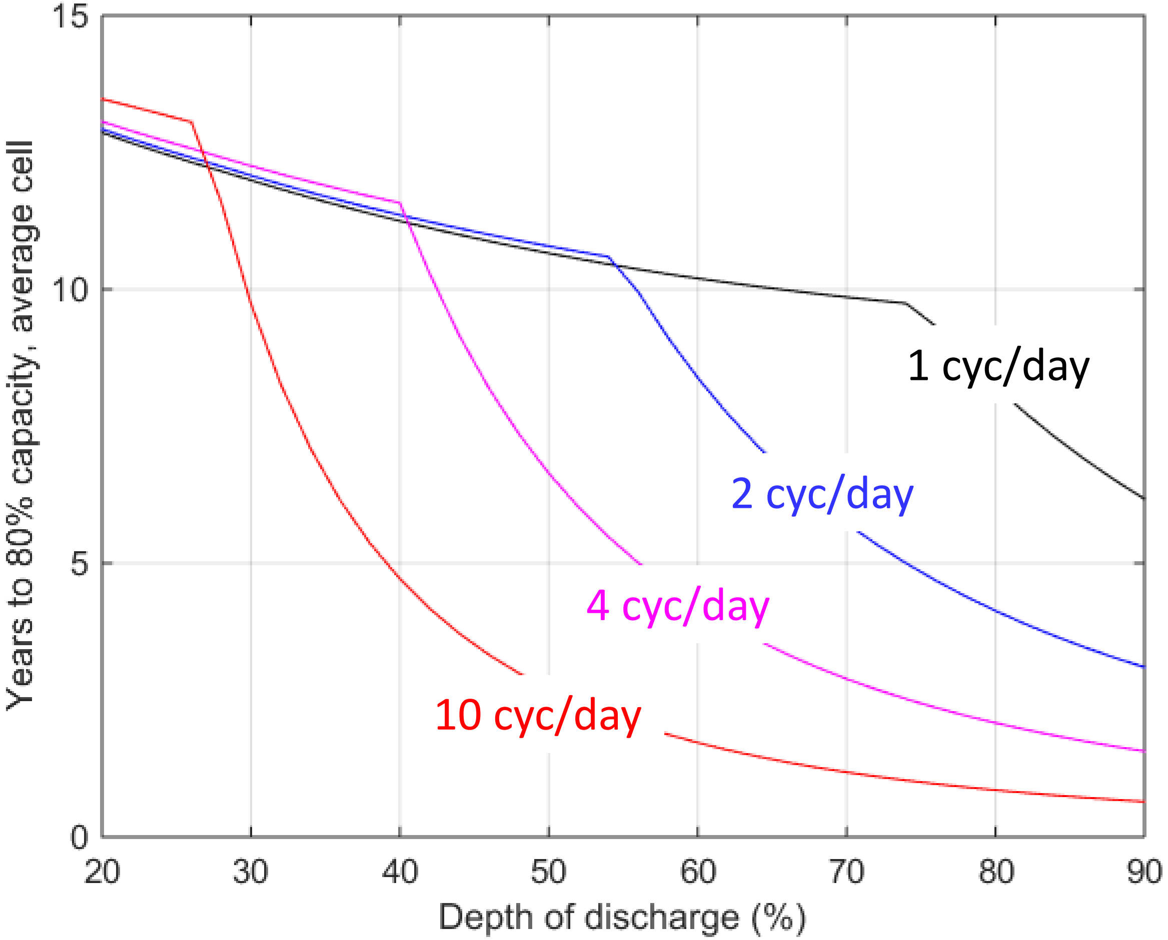
- High temperature
- High average SOC & high DOD

- Low DOD & C-rate
- Fewer cycles/day
- ~Room temperature

- High DOD & C-rate
- More cycles/day
- Low min temperature
- High max temperature

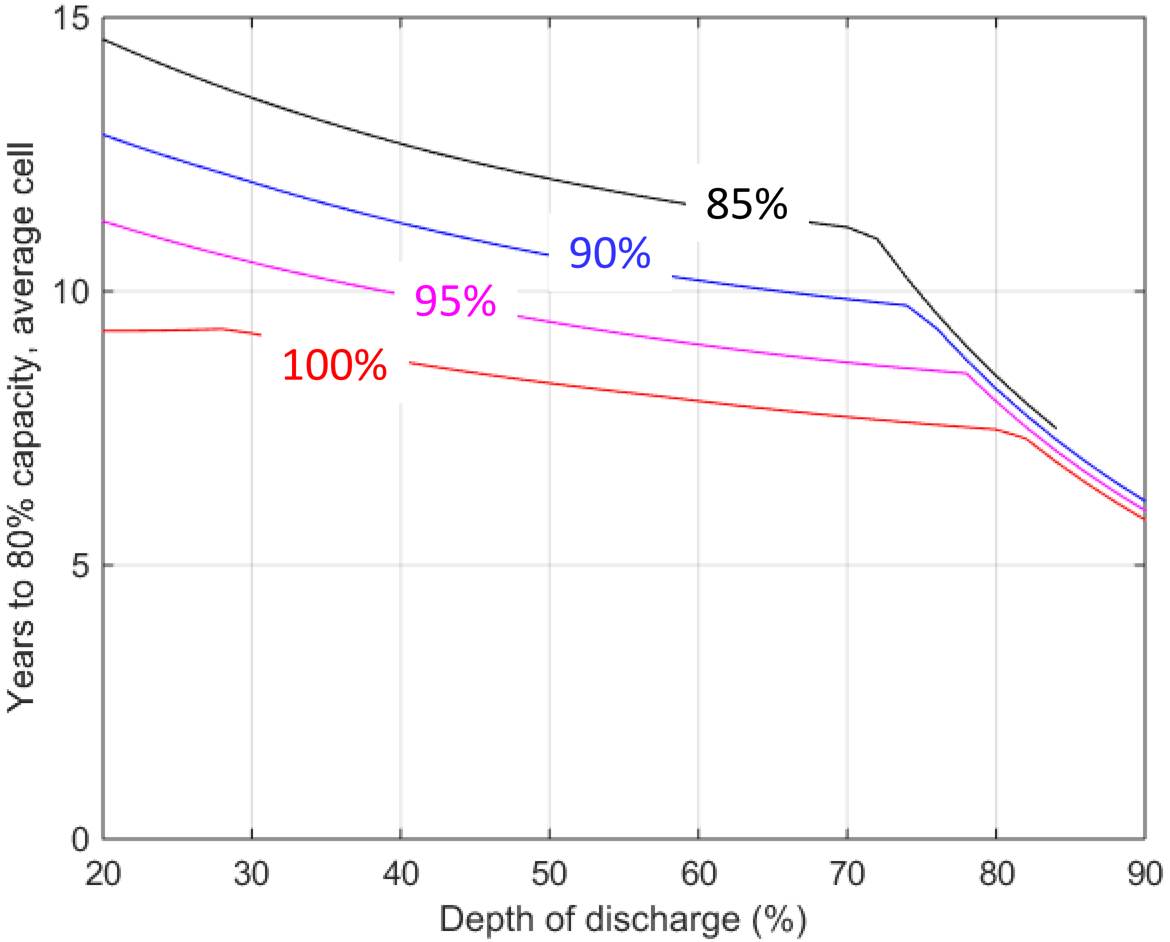
Impact of number of cycles per day

- **PHEV40 typical worst case is 1 cyc/day: 10 yrs ~ 68% DOD**
- **PHEV20 could experience 2 cyc/day: 10 yrs ~ 56% DOD**
- **PHEV10 could experience 4 cyc/day: 10 yrs ~ 43% DOD**



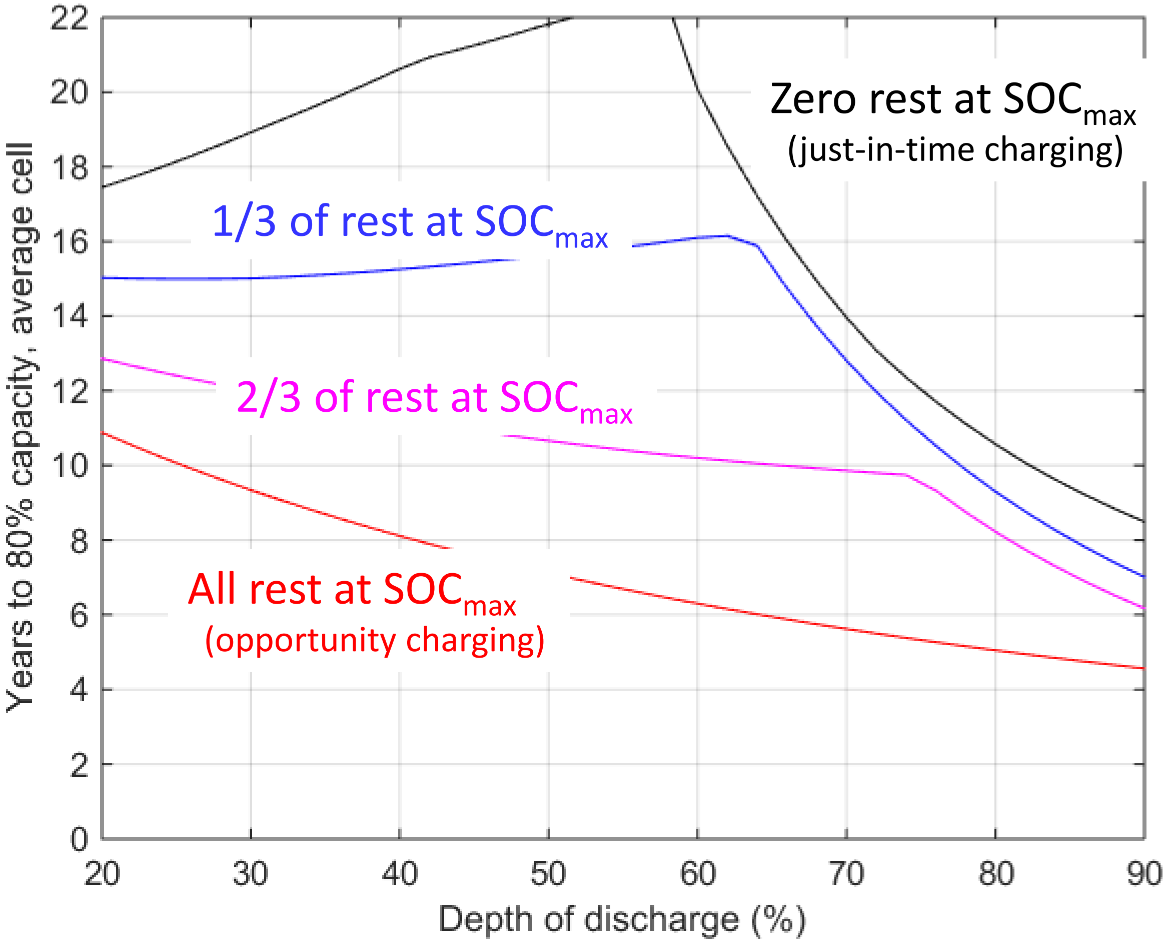
Impact of maximum SOC

- **Plot below assumes constant SOC_{max}. Alternately, can be varied with**
  - Seasonal or battery temperature (e.g. low in summer, high in winter)
  - Service life (e.g. gradually increasing SOC_{max} to maintain available energy)



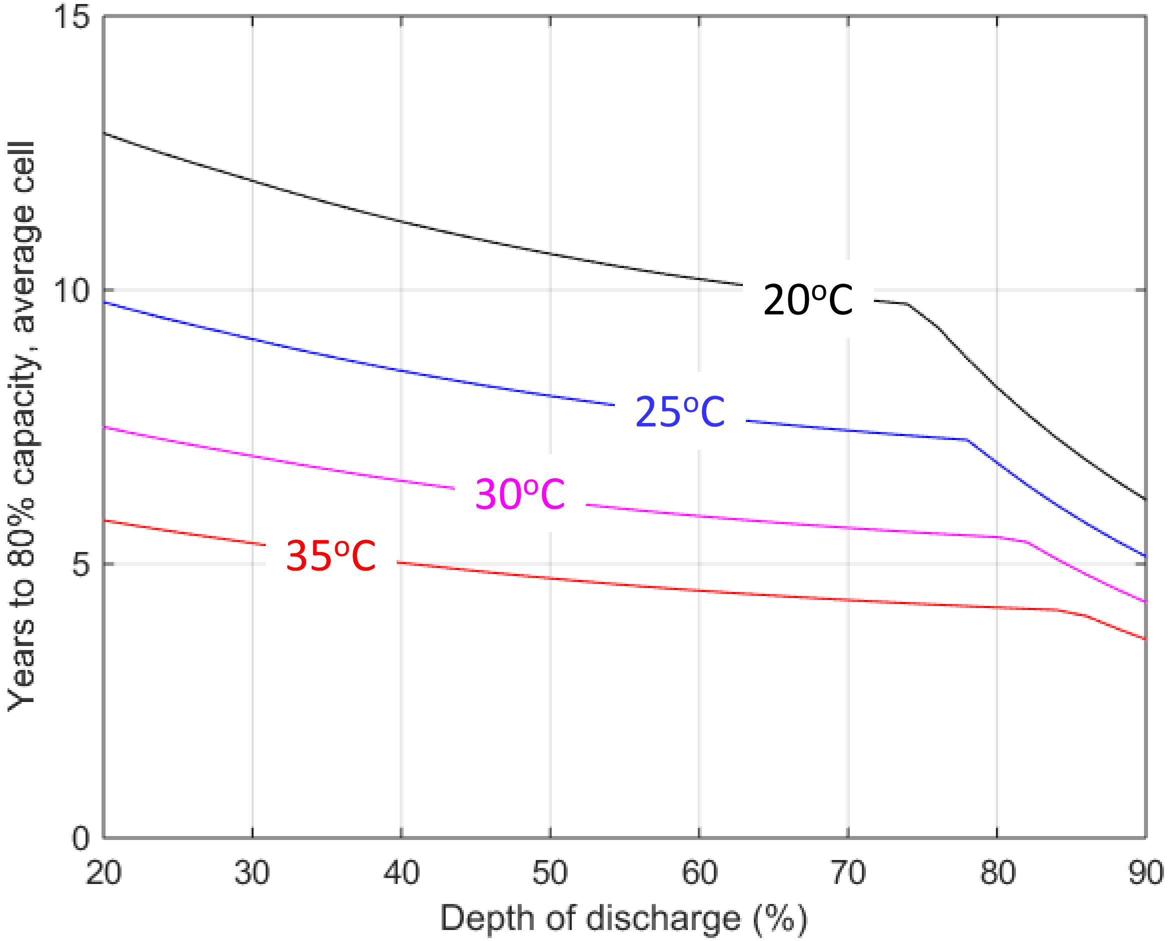
Impact of rest time at maximum SOC

- **Impacted by charging behavior**
- **Huge calendar lifetime benefit w/ delayed charging**
  - Must be traded with providing customer full charge just in time for next trip



Impact of lifetime average temperature

- **Hot climates require some combination of**
  - Chilled thermal management
  - Restricting $SOC_{max} < 90\%$ [when battery is hot and/or during hot seasons]
  - Increasing SOC window over 10 years
  - Delayed charging
  - Reducing 10 year remaining capacity requirement < 80%



1) Lifetime models & methods

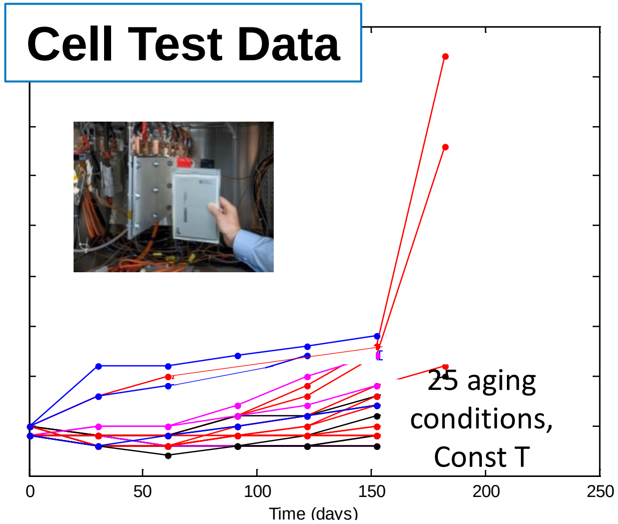
2) Analysis: PHEV 10 year / 150k mile life

3) Battery control research projects

Battery Prognostic-based Control for xEVs

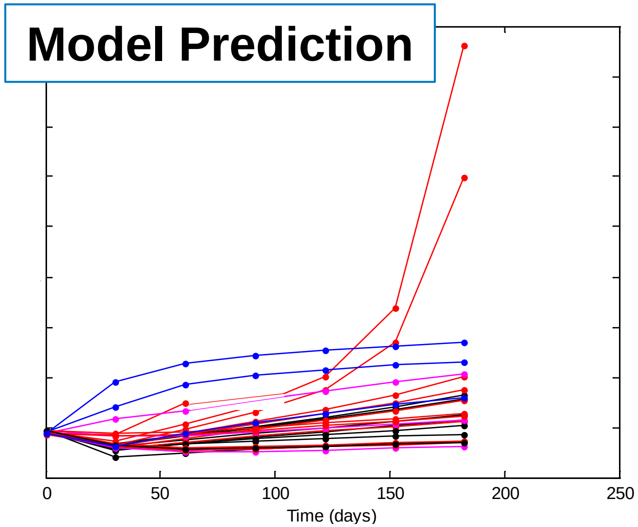
Figure: http://www.eaton.com/Eaton/ … ProductsServices/HybridPower/Applications/index.htm

- ARPA-E AMPED project led by Eaton Corporation
- Issue: xEV battery packs are oversized & controls are conservatively tuned to achieve typical life of 10 years. Oversizing is expensive
- Solution: 35% smaller HEV battery by providing vehicle controller with real-time knowledge of battery degradation
- NREL roles: Developed battery prognostic model with 6 months accelerated cell testing. Validated model and controls with 33 month 4-season HIL pack testing

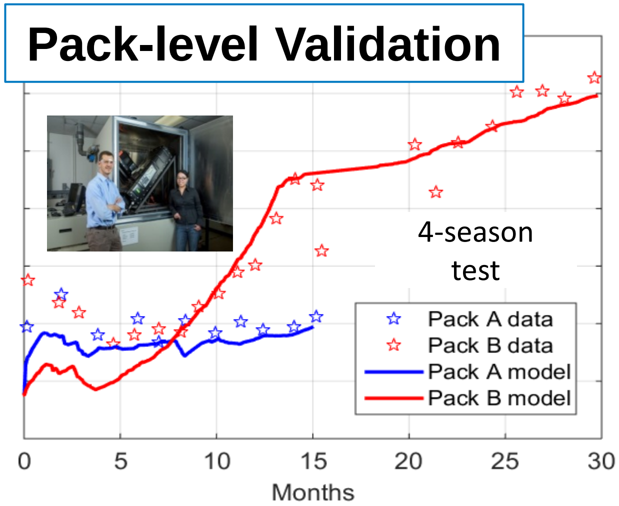


Cell Test Data

25 aging conditions, Const T



Model Prediction

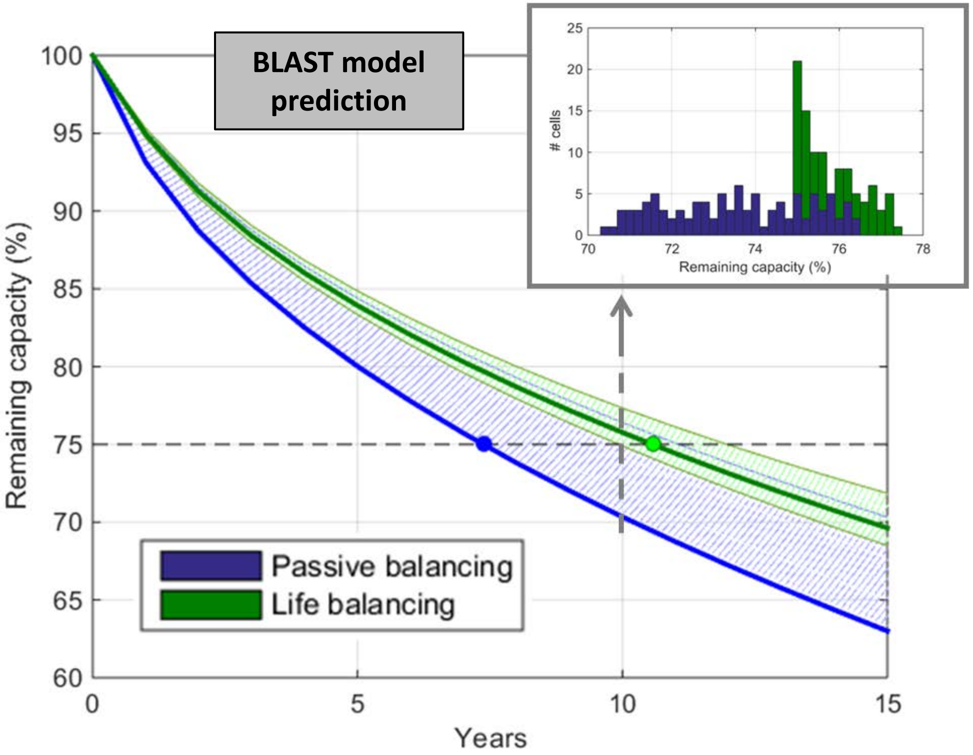


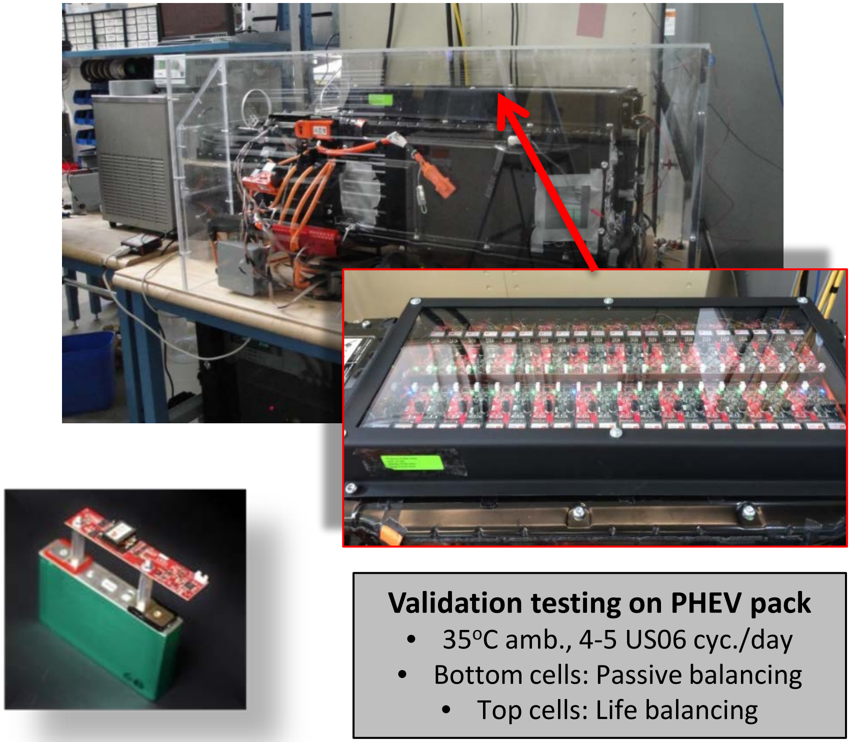
Pack-level Validation

4-season test

Robust Cell-level Control of xEV Batteries

- ARPA-E AMPED project led by Utah State, with Ford, CU-Boulder, UCCS, NREL
- Life extension: 30% to 45% xEV battery life extension using new hardware and controls to differentially cycle weak cells & extend their life
- Cost neutral: Active cell balancing hardware supplies vehicle auxiliary 12V loads. Replaces HV → 12V DC-DC converter (~$200 component)
- NREL roles: Benefits modeling, control strategy, validation w/ 1.5 year accel. aging

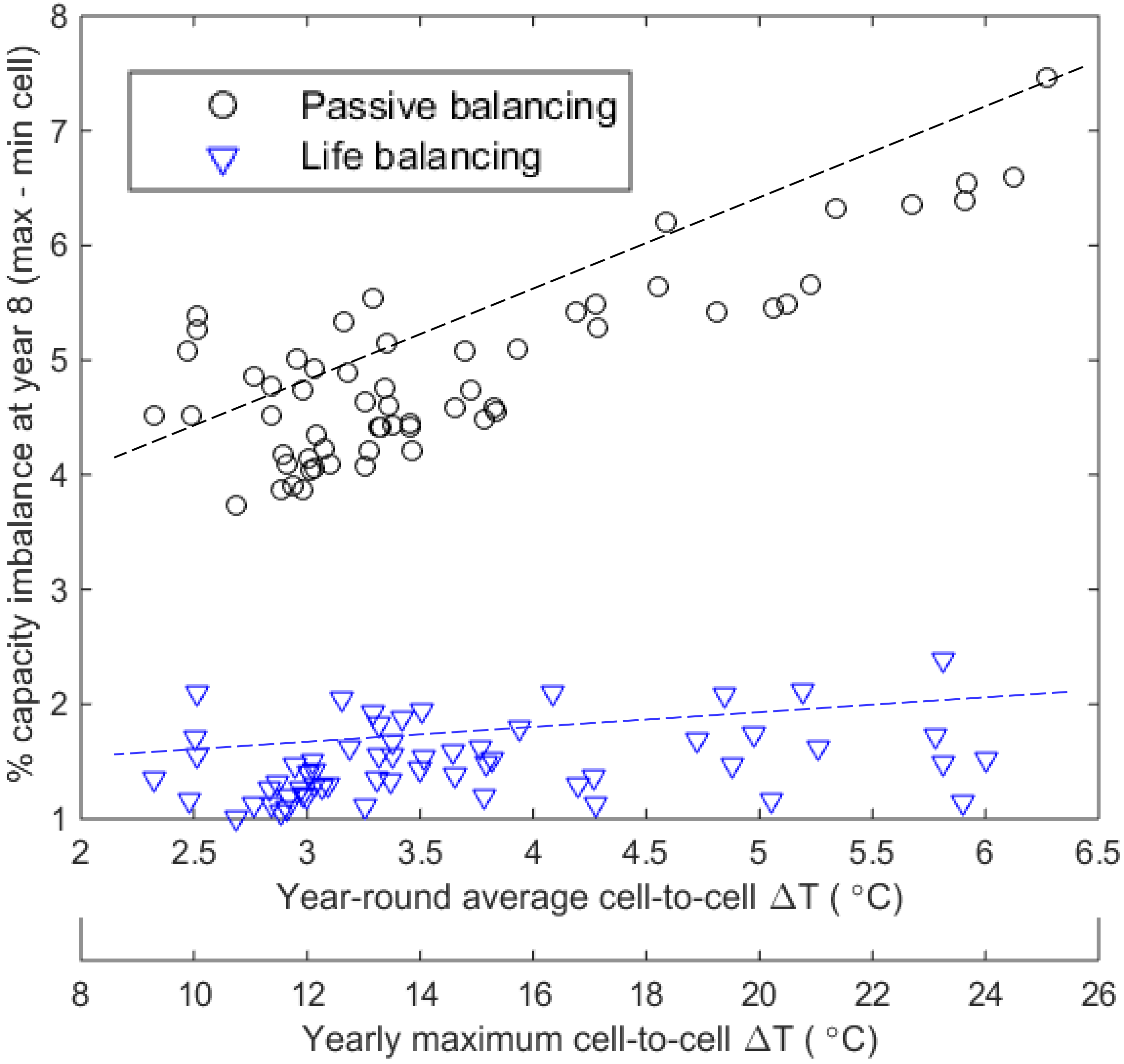

BLAST model prediction



Validation testing on PHEV pack
- 35°C amb., 4-5 US06 cyc./day
- Bottom cells: Passive balancing
- Top cells: Life balancing

Life balancing control strategy reduces need for tight cell-to-cell thermal control

BLAST simulation. Individual data points are same scenarios as shown on slide 12.



- **USU AMPED balancing system compensates for non-uniform cell aging**

- **Thermal management still needed to remove heat load and suppress maximum cell temperature**

Summary

- **Main calendar life factors: Average T & SOC**
  - DOD_{max} secondary (inverse correlation with avg. SOC)
- **Main cycle life factors: DOD & C-rate (max, RMS); high/low T extremes**
- **Today's life models reasonably extrapolate test data forward in time**
  - Extrapolation to untested duty cycles still uncertain
  - Integration with physics models needed to optimize next generation cell designs
- **Advanced controls show promise for**
  - 35% smaller HEV battery
  - 30-45% longer PHEV & BEV life

Acknowledgements

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  - Russell Ross
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  - Utah State Team – Regan Zane, Dyche Anderson, Dragan Maksimovic, Gregory Plett, Scott Trimboli,