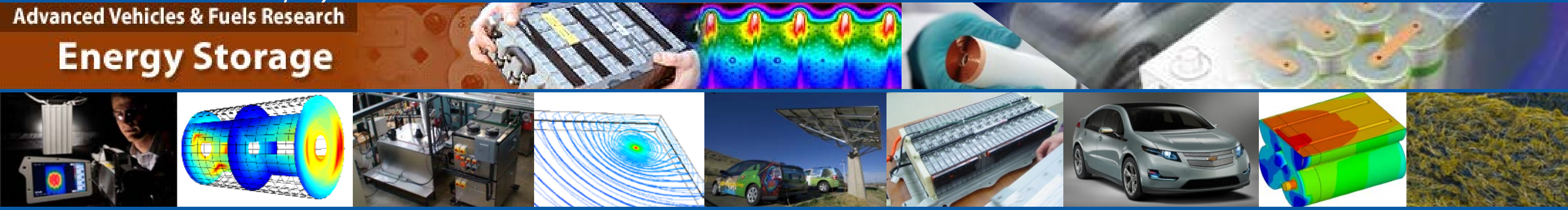
Optimizing Battery Usage and Management for Long Life



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NREL/PR-5400-66708

Outline

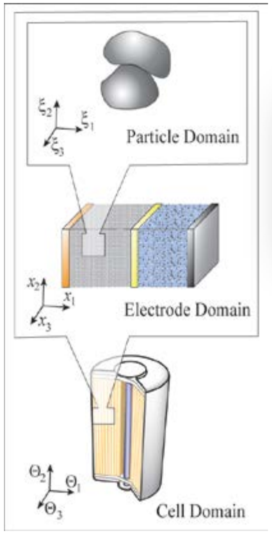
1) Models & methods

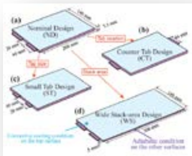
2) Analysis: PHEV 10-year / 150k-mile life

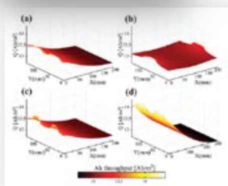
3) Battery control research projects

PHEV: plug-in hybrid electric vehicle

NREL Battery Modeling Tools



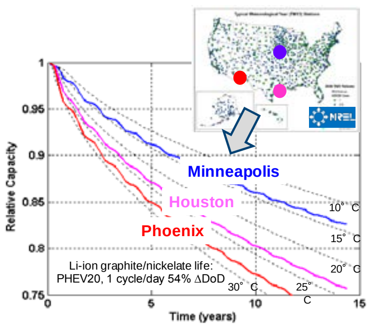




1) Multi-Scale Multi-Domain Model

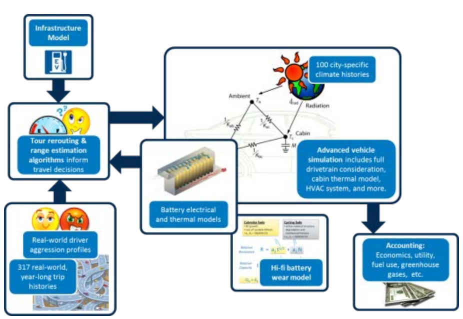
- 3D electrochemical/thermal physics
- 3D thermal/electrical/mechanical abuse

DOE Computer-Aided Eng. of Batteries (CAEBAT) program



2) Battery Life Predictive Model

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



3) BLAST (Battery Lifetime Analysis and Simulation Tool)

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

SOC: state of charge

Electrochemical Operating Window

0% SOC — charge → 100% SOC

← discharge

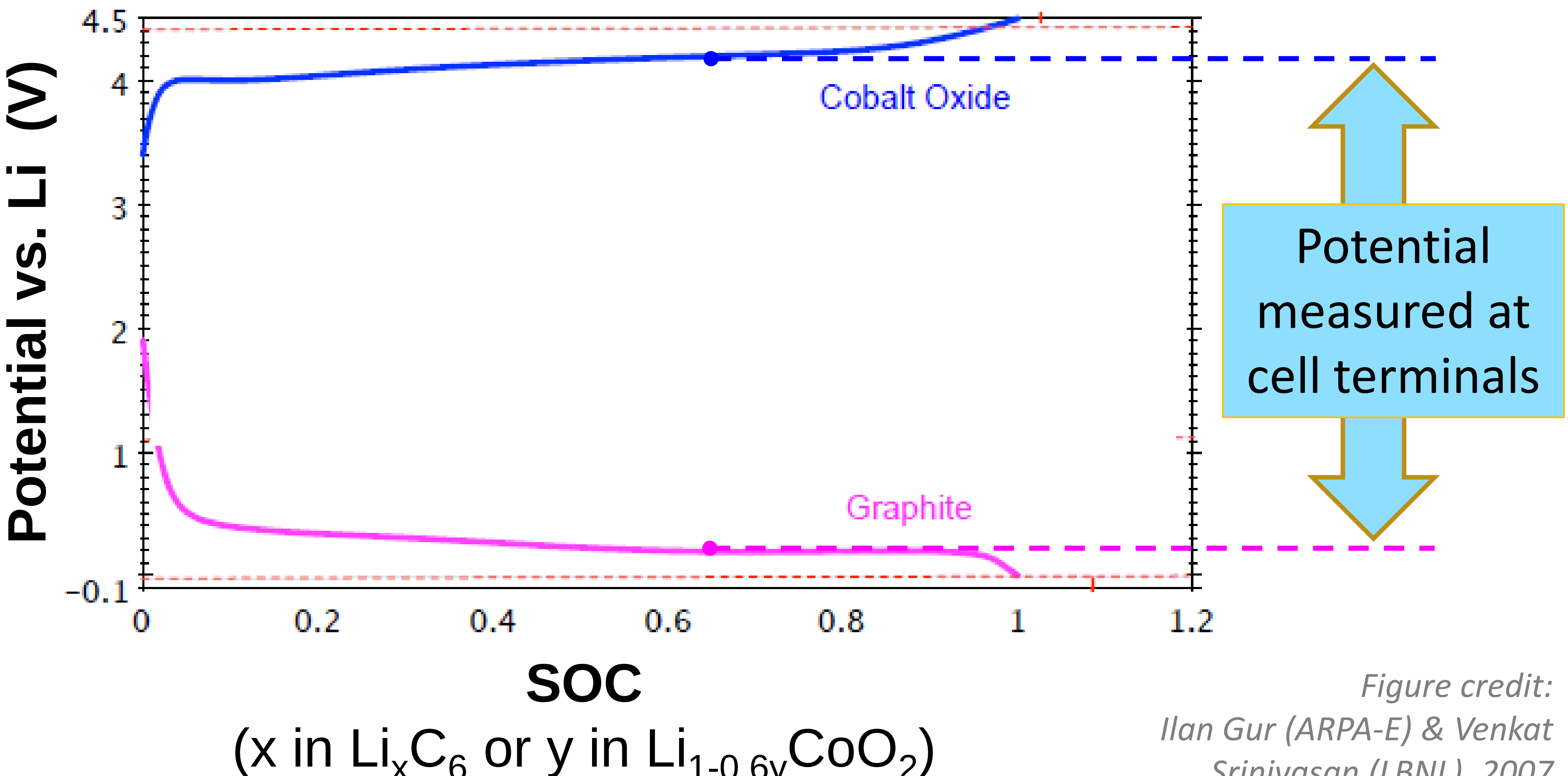
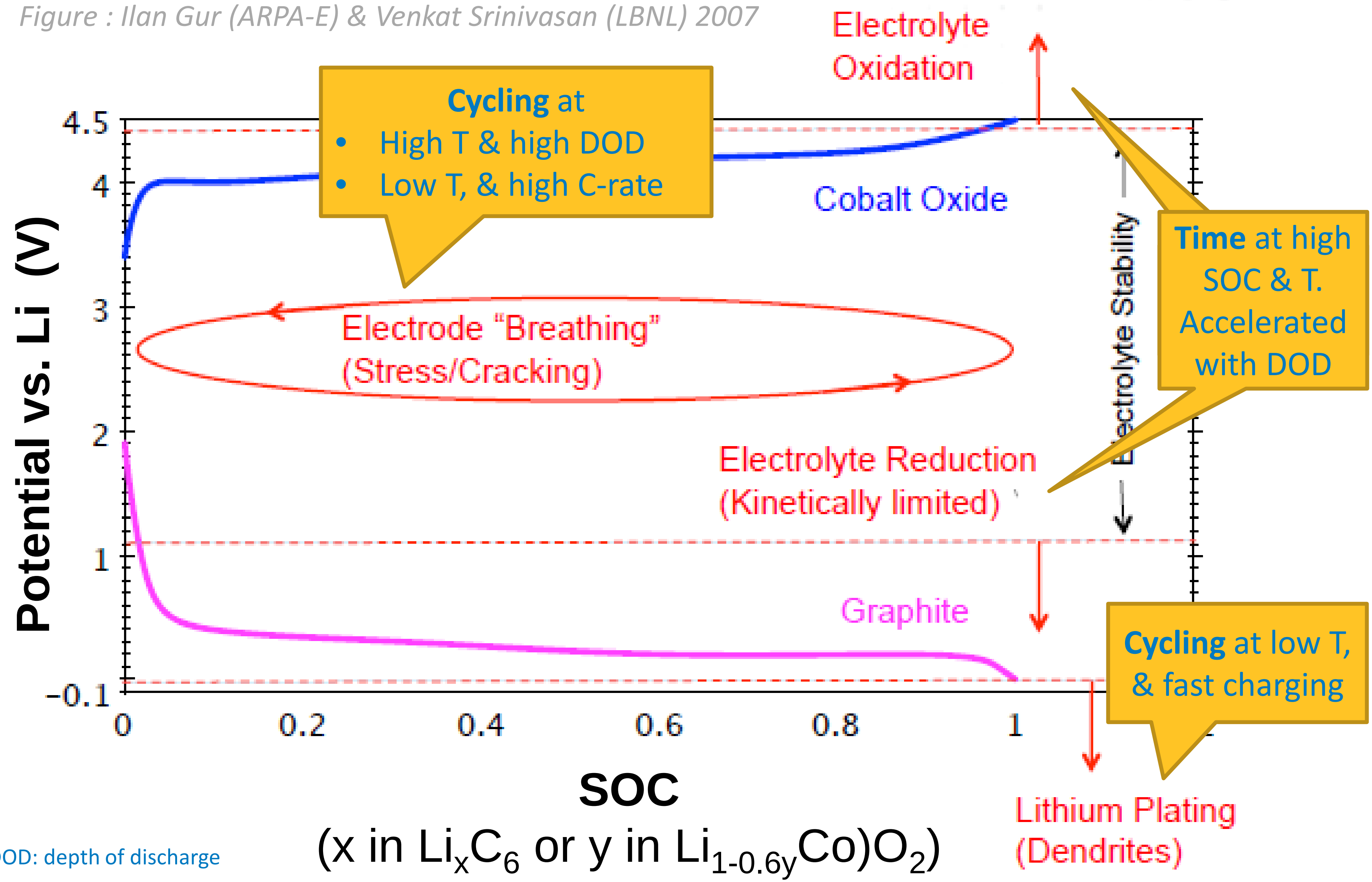


Figure credit: Ilan Gur (ARPA-E) & Venkat Srinivasan (LBNL), 2007

Electrochemical Window – Degradation

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



DOD: depth of discharge

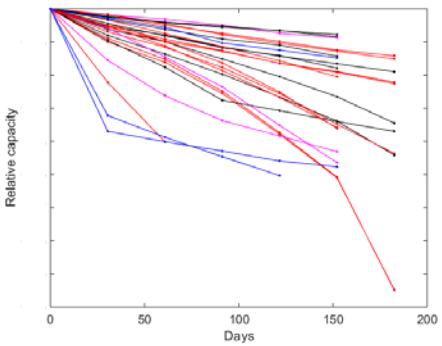
NREL Life Predictive Modeling – Approach

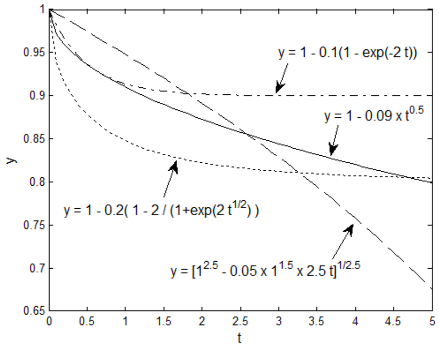
Set of trial equations representing physical fade mechanisms, e.g.:

- Solid-electrolyte interphase (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)





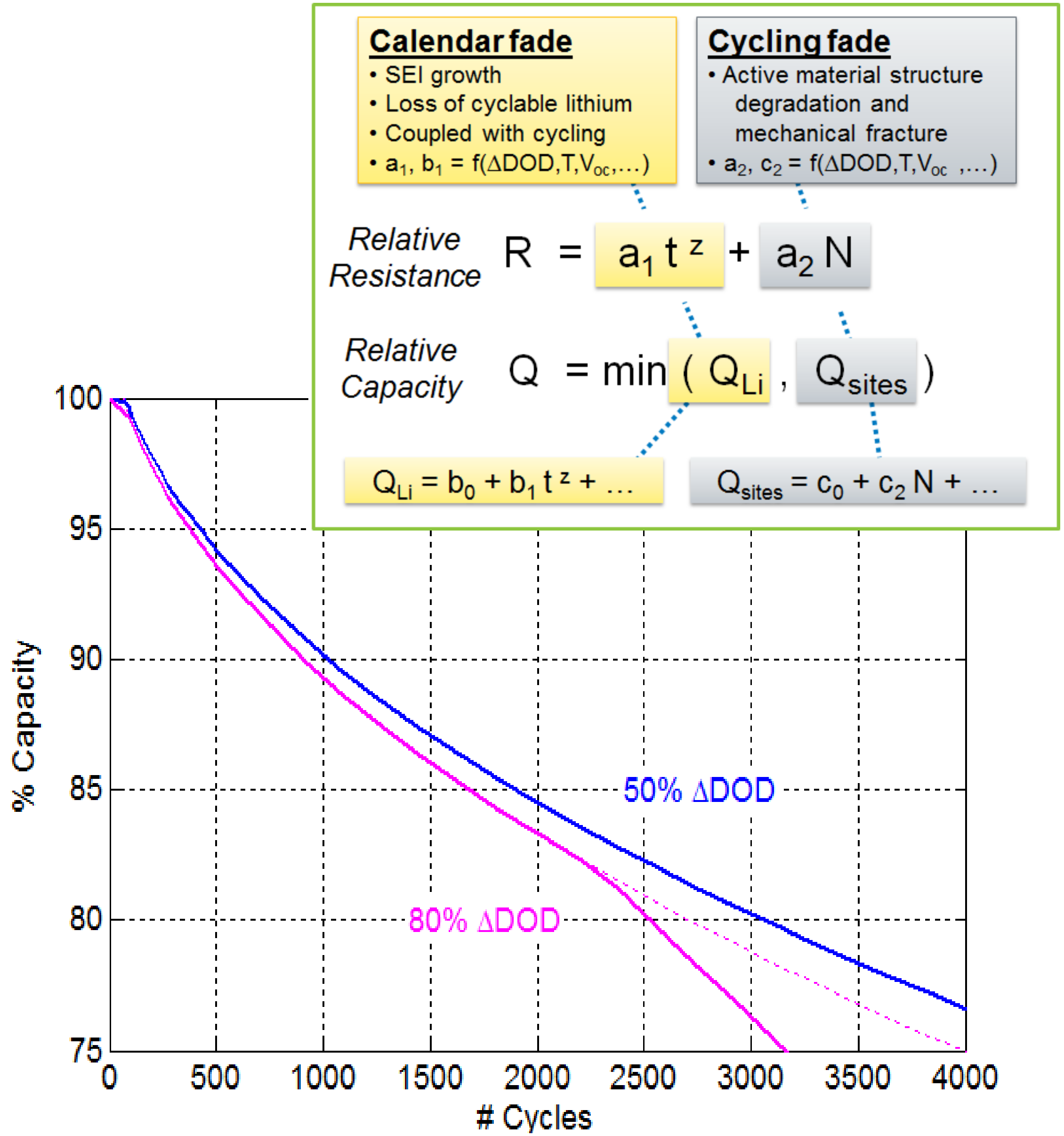
Mechanism	Trajectory equation	State equation	Parameters
Diffusion-controlled reaction	$x(t) = kt^{1/2}$	$\dot{x}(t) = \frac{k}{2}\left(\frac{k}{x(t)}\right)$	k – *rate* (p=1/2)
Kinetic-controlled reaction	$x(t) = kt$	$\dot{x}(t) = k$	k – *rate* (p=1)
Mixed diffusion/ kinetic	$x(t) = kt^{p}$	$\dot{x}(t) = kp\left(\frac{k}{x(t)}\right)^{\left(\frac{1-p}{p}\right)}$	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

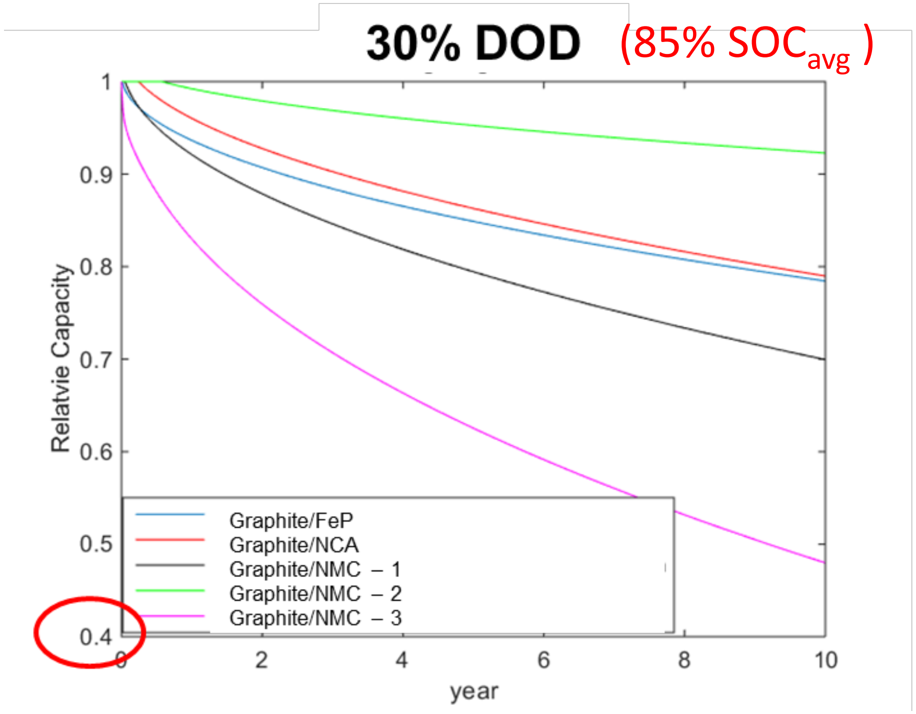


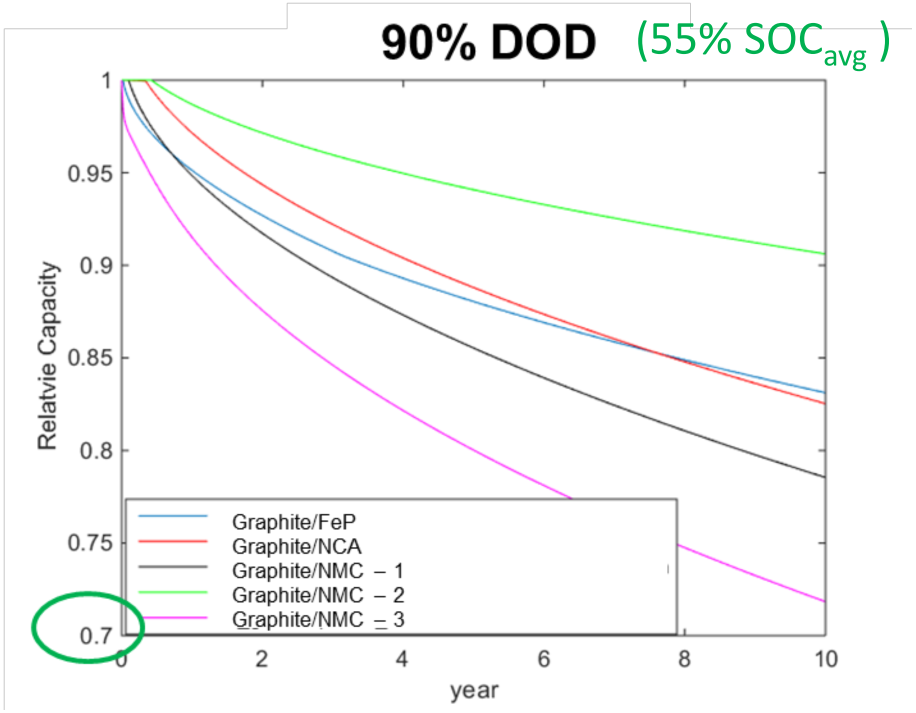
FeP: iron-phosphate
NCA: Ni-Co-Al
NMC: $LiNi_{0.4}Mn_{0.4}Co_{0.2}O_2$

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





Temperature and electrical cycling assumptions:

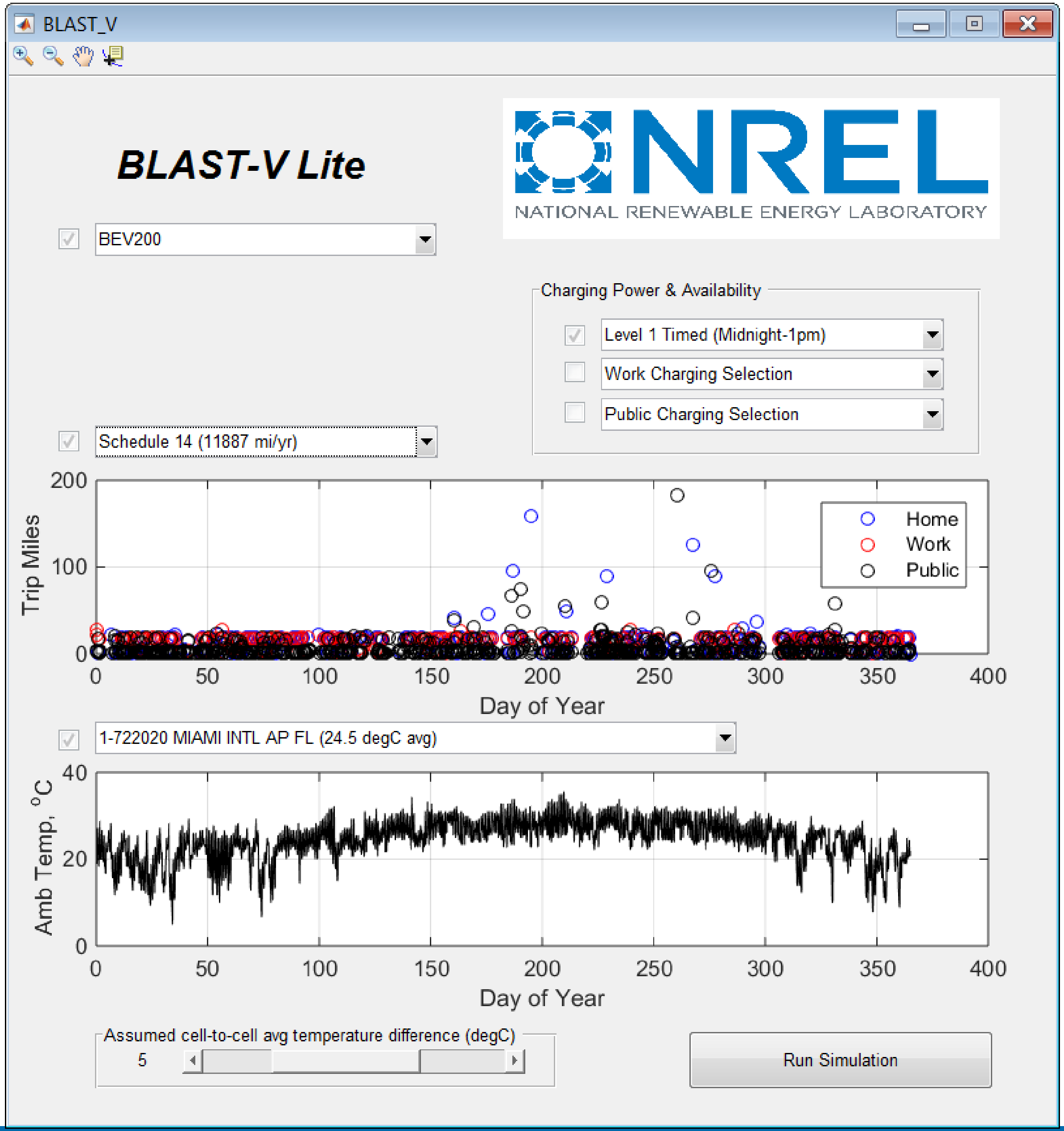
- Temperature: 28°C
- Cycling: 2-hr charge to 100% SOC; 10-hr rest; 2-hr dischg; 10-hr rest

**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.*

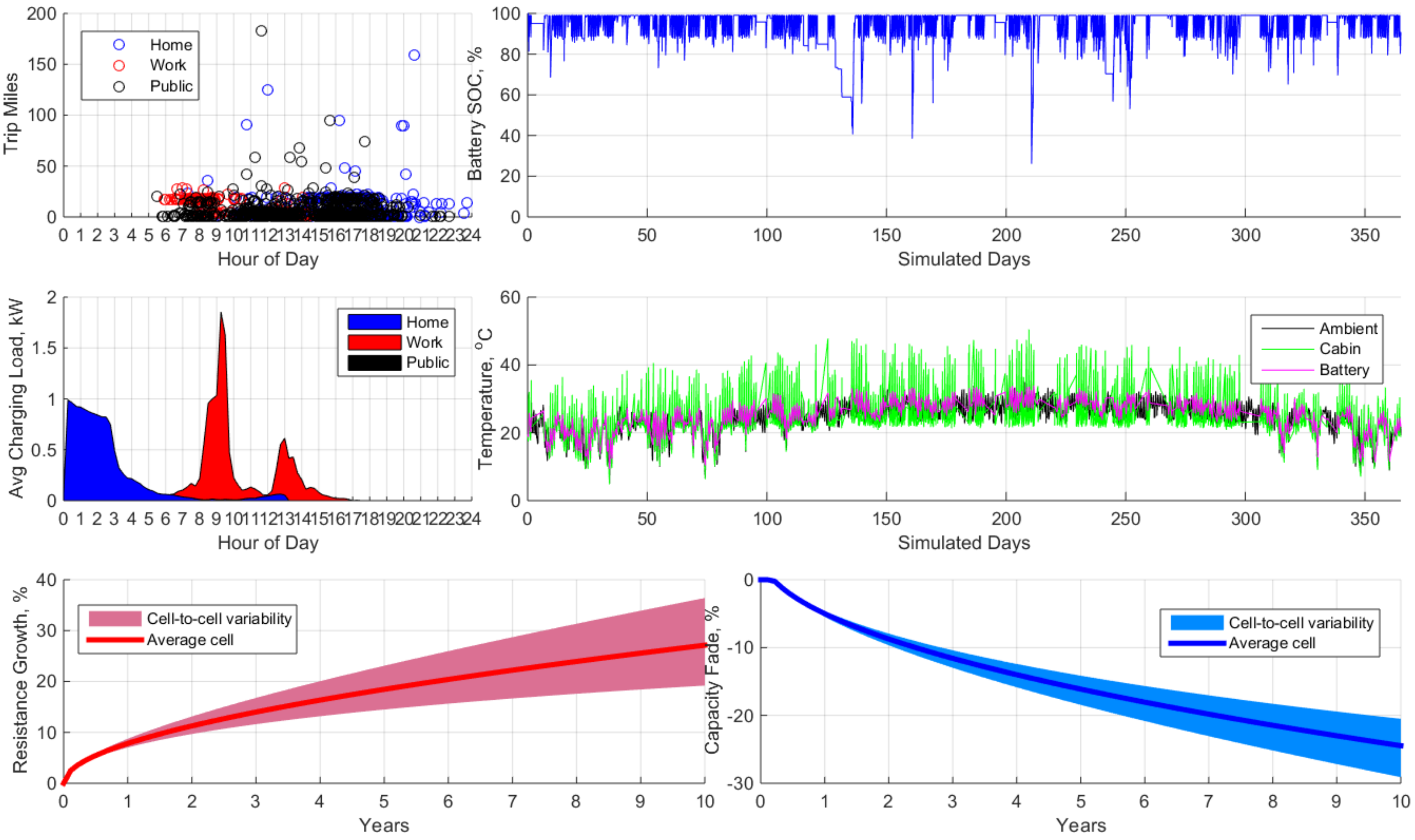
BLAST-Lite Standalone Model GUI

- **Versions for vehicle (shown) and stationary energy storage applications**

- **Downloadable from NREL website later this year**

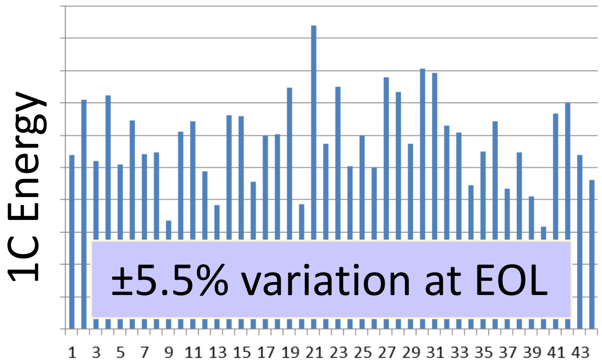


BLAST-Lite Sample Model Results

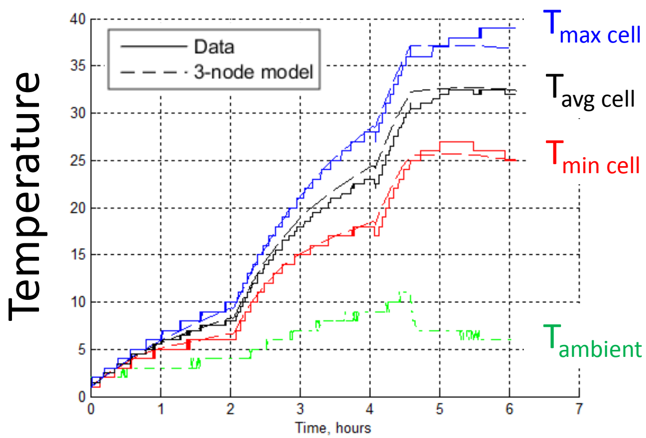


Cell-to-Cell Capacity Imbalance

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

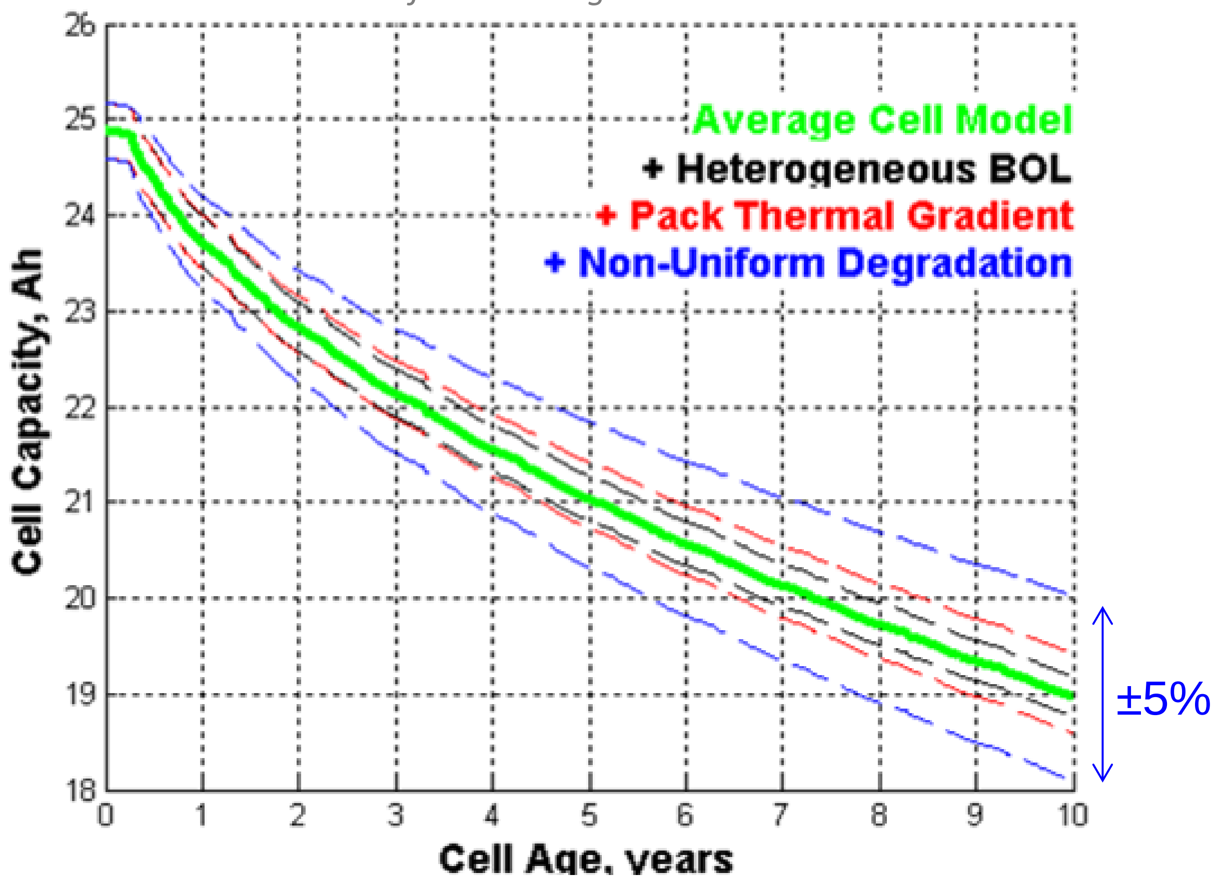


- Pack thermal imbalance testing and simulation



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

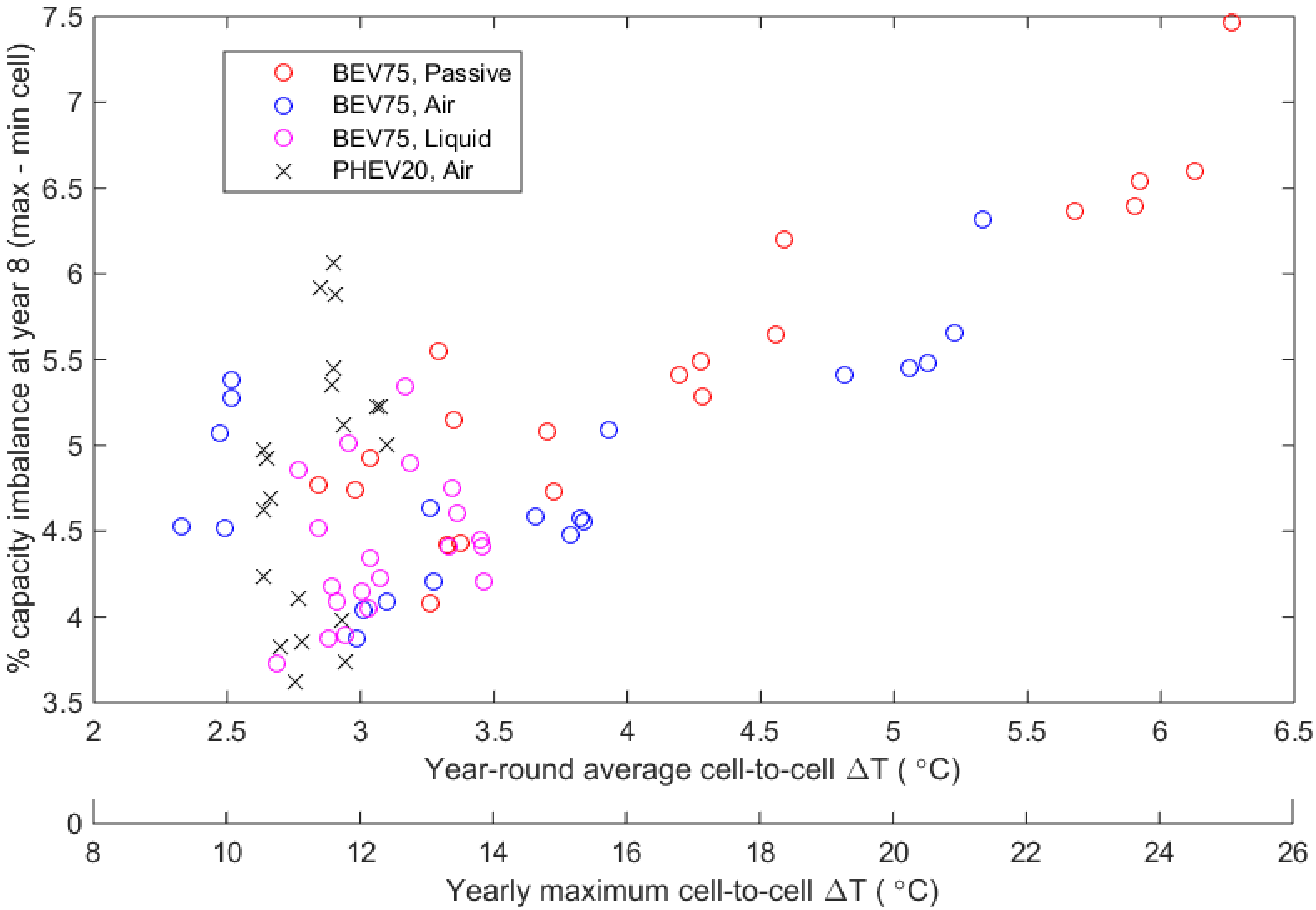
Non-uniform degradation includes ±10% random perturbation on life model degradation rates



BOL: beginning of life
EOL: end of life

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

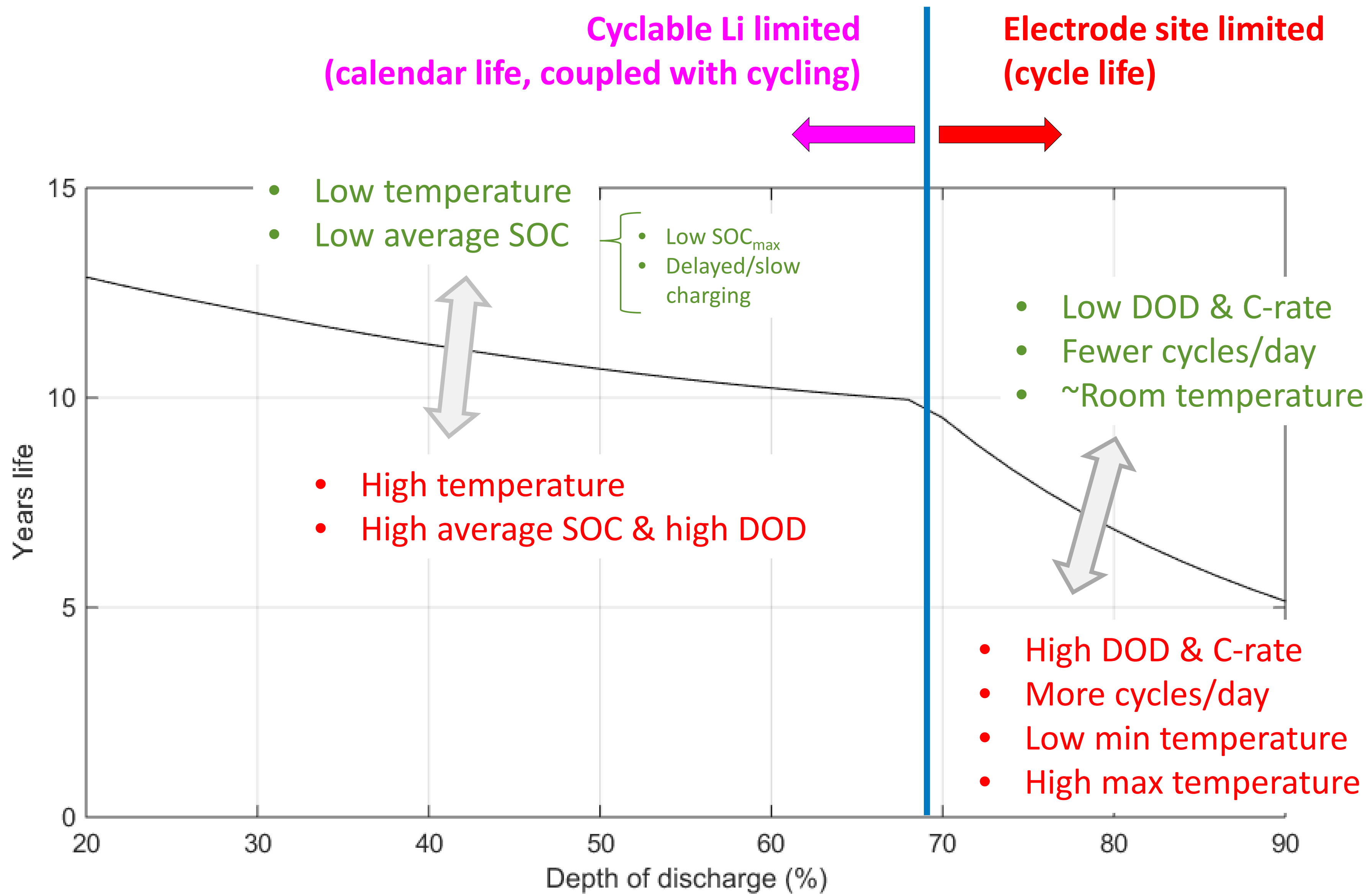
3) Battery control research projects

Impacts on PHEV Lifetime

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

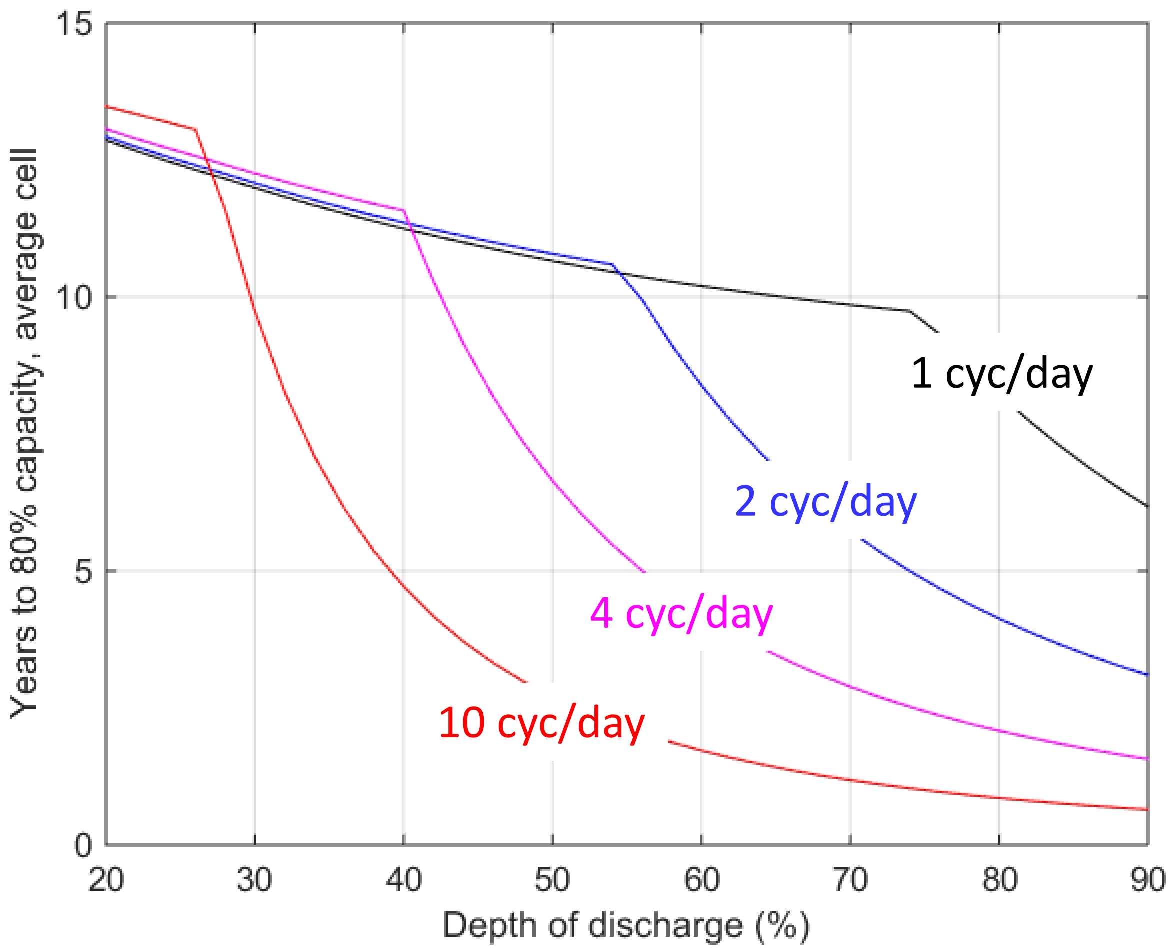
- **Nominal assumptions** (variations noted on each slide)
    - Graphite/NCA life model
    - 20^{o}C
    - 90% SOC_{max}
    - Average cell degradation (margin required for worst cell if passive balancing)
    - 1 cycle per day
    - 2/3 of rest time spent at SOC_{max}
    - 1/3 of rest time spent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

Calendar versus Cycle Limitations on Years Life



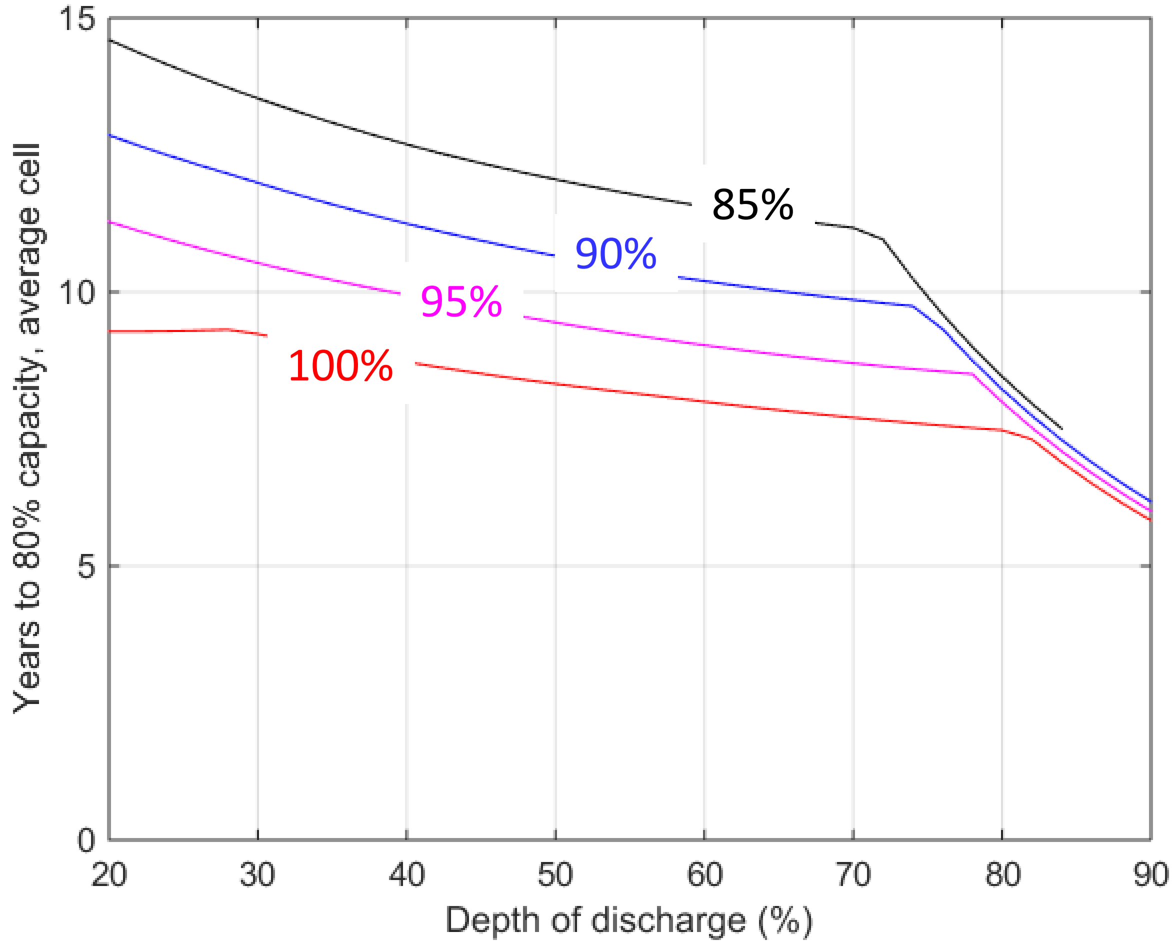
Impact of Number of Cycles per Day

- 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



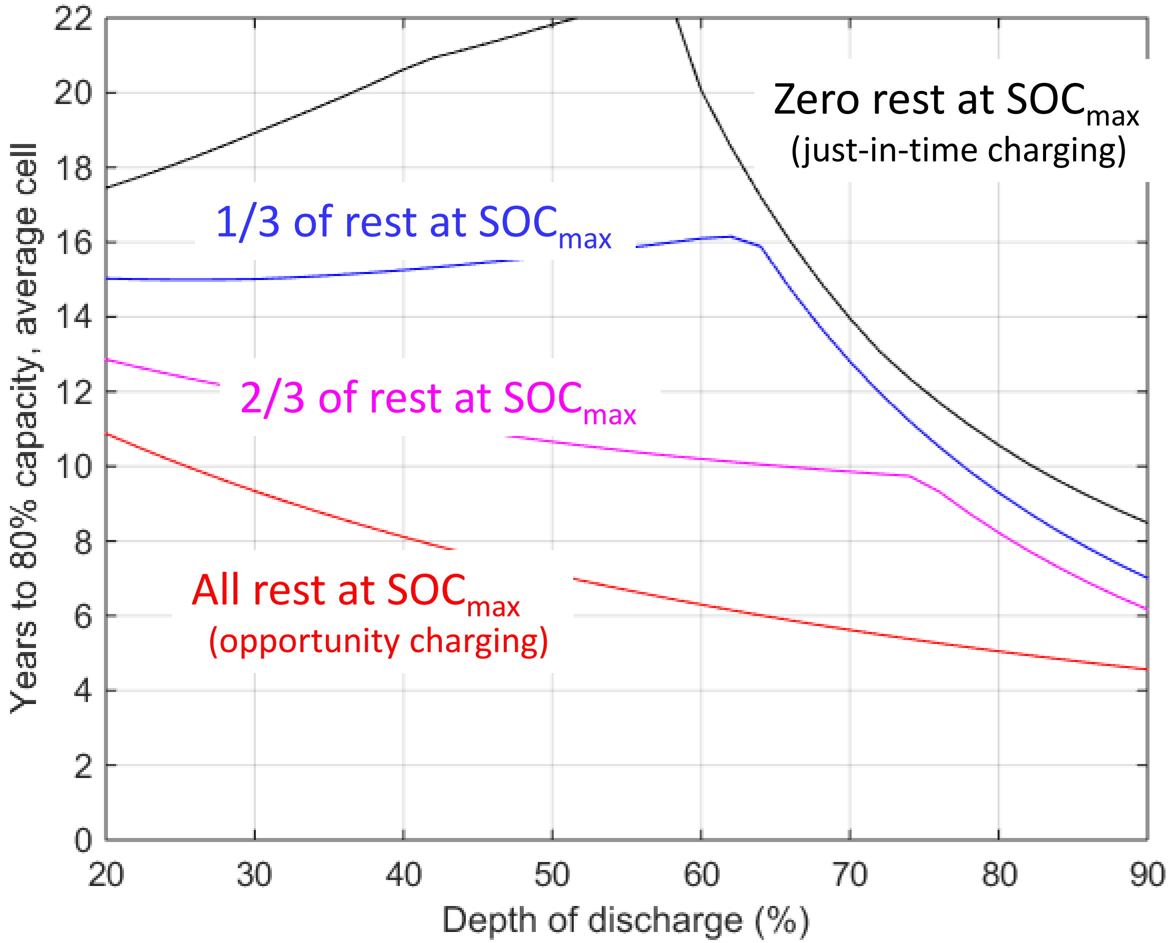
Impact of Maximum SOC

- **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)



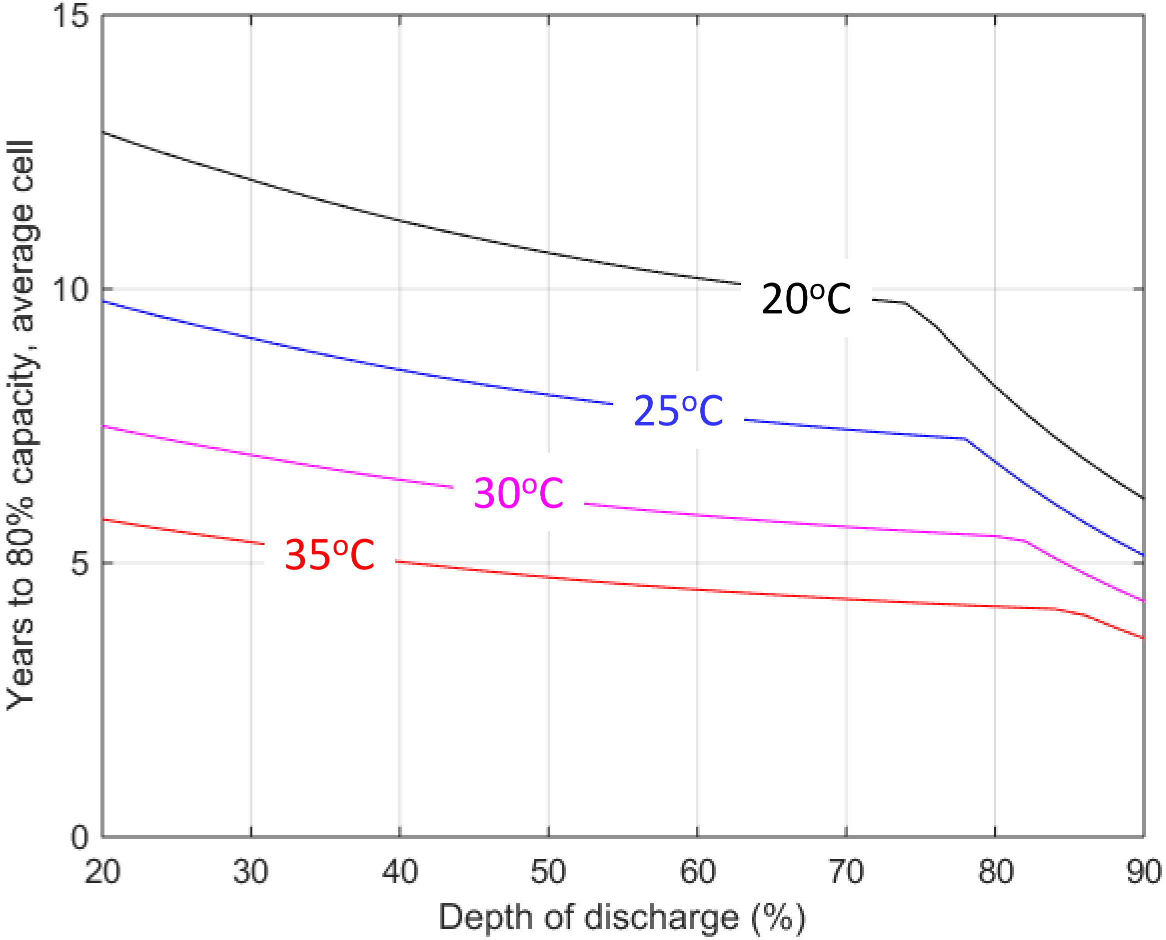
Impact of rest time at maximum SOC

- **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

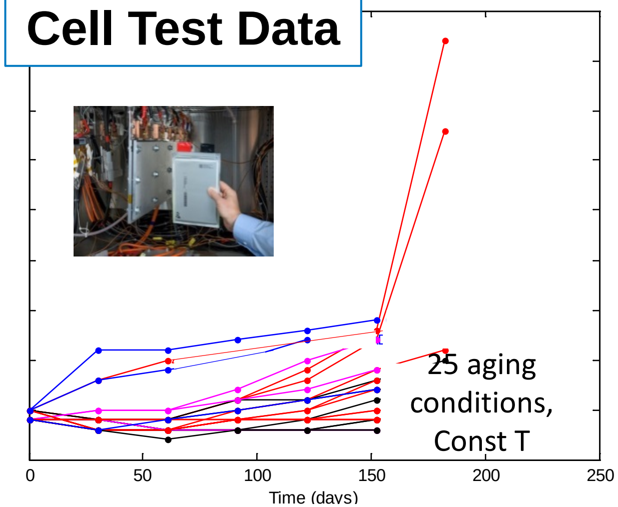
3) Battery control research projects

Battery Prognostic-Based Control for xEVs

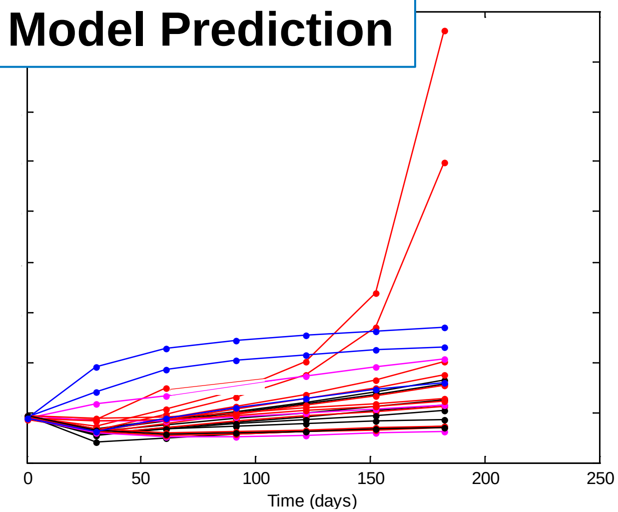
Figure: http://www.eaton.com/Eaton/ … ProductsServices/HybridPower/Applications/index.htm

- 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

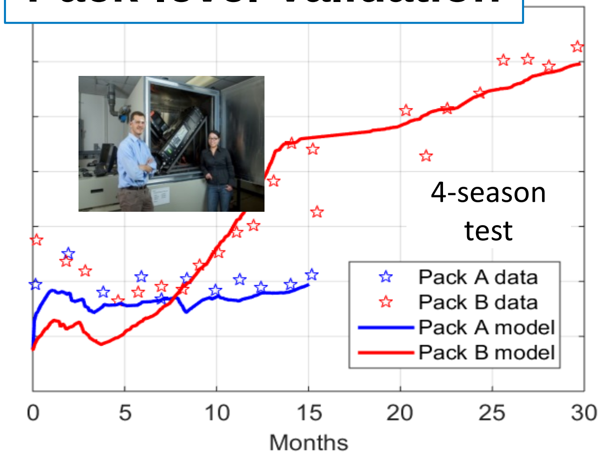
Cell Test Data



Model Prediction

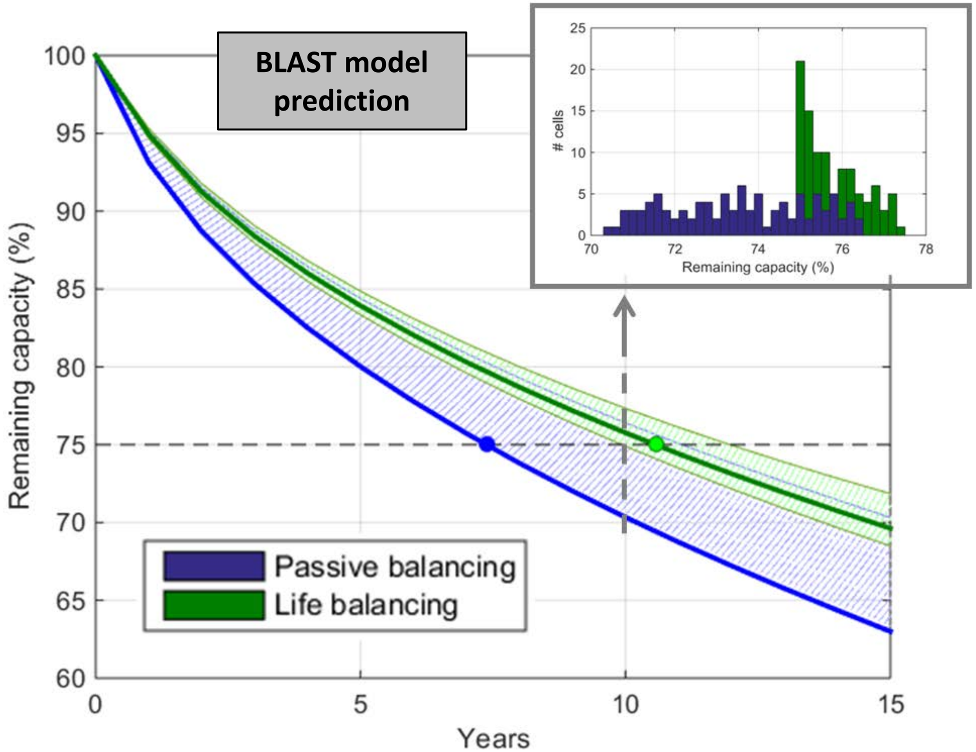


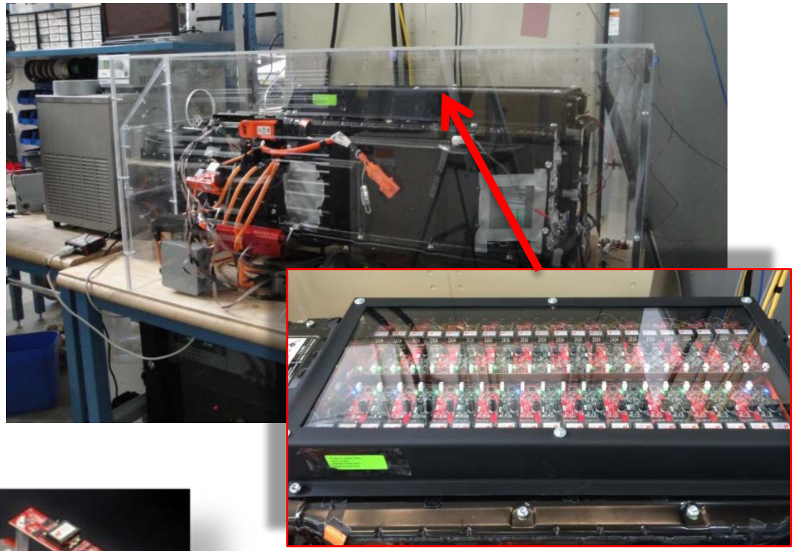
Pack-level Validation



Robust Cell-Level Control of xEV Batteries

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

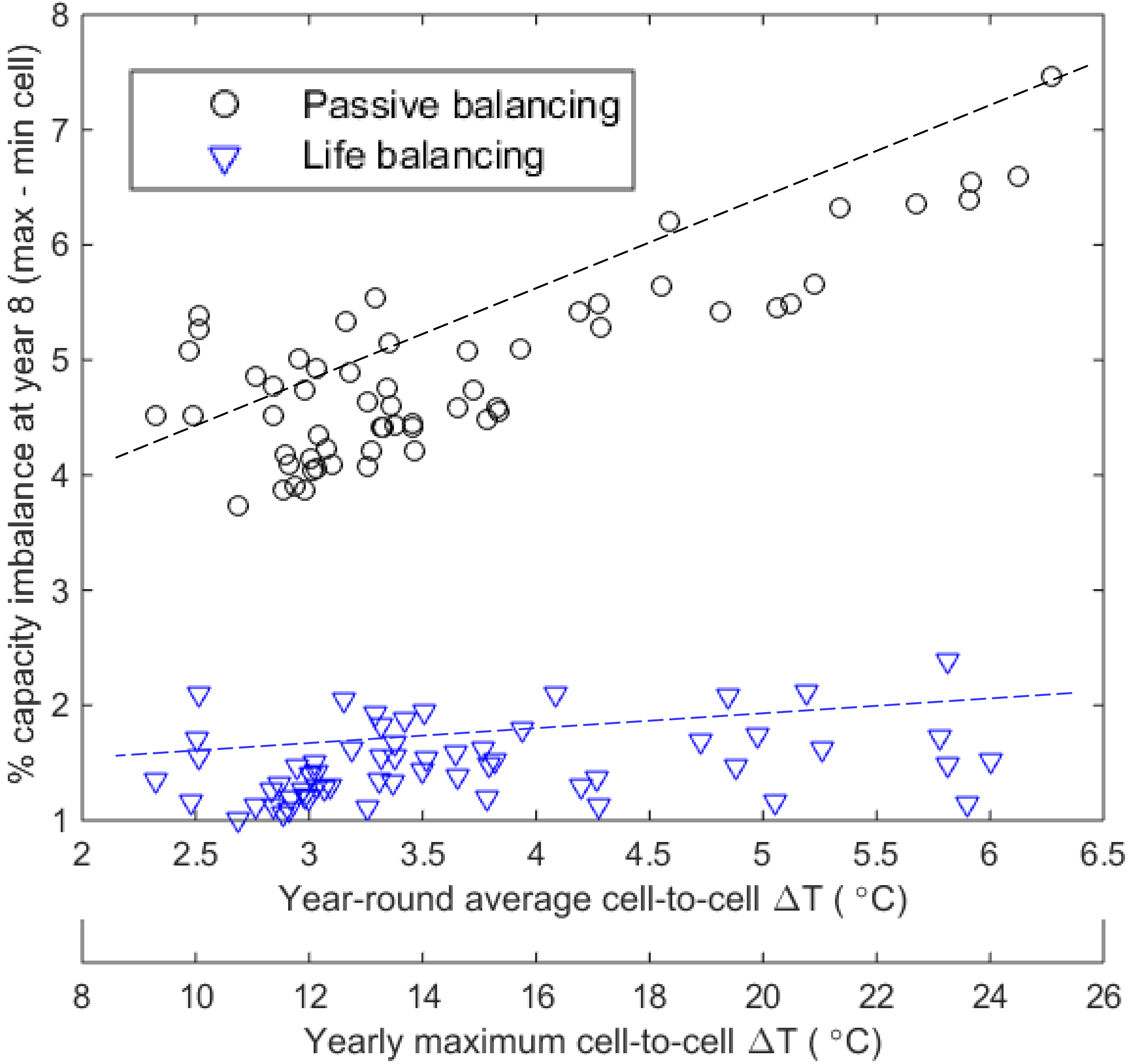




Validation testing on PHEV pack
- 35°C amb., 4-5 US06 cyc./day
- Bottom cells: Passive balancing
- Top cells: Life balancing

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.



- **Utah State University 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

- **DOE Vehicle Technologies Office**
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- **DOE ARPA-E AMPED Program**
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  - Russell Ross
  - Ilan Gur

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