Accelerated Life Testing of Advanced Battery Technologies for EV, HEV, and PHEV Applications

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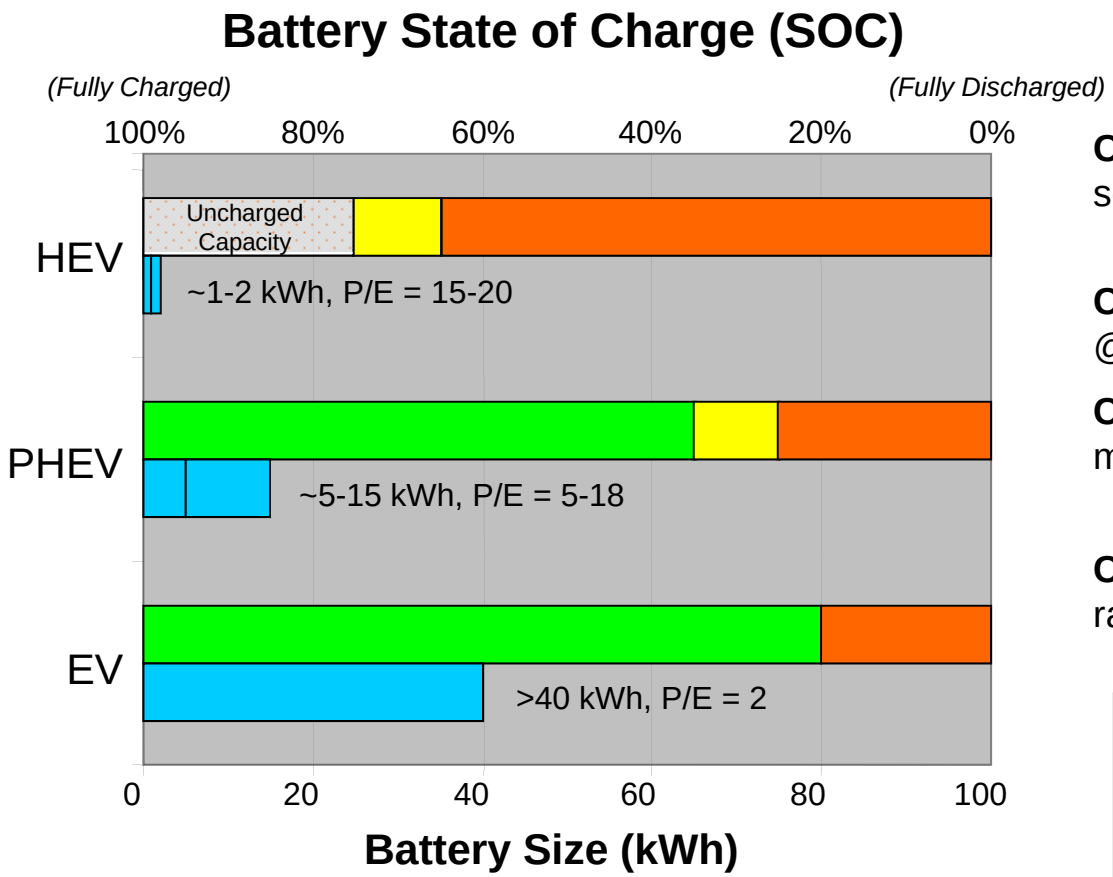
Background

- Energy Storage Technologies Laboratory

- We are a world leader in the testing of advanced energy storage technologies for future automotive applications.
- We are the lead Department of Energy (DOE) lab for hybrid electric and plug-in hybrid electric vehicle energy storage testing.
- We support DOE's effort to reduce national dependence on foreign oil through:
  - Vehicle energy storage testing
  - Vehicle system testing
- We are in independent source of energy storage performance data for:
  - U.S. DOE
  - U.S. car companies
  - Battery and ultracapacitor developers

Vehicle Battery Operation



CS only: 300-500 Wh, 25-40 kW (10 sec) @70% SOC, 300,000 cycles

CS: 300-500 Wh, 25-40 kW (10 sec) @30% SOC, 300,000 cycles

CD: Energy scaled for range (10-40 miles), 5,000 deep discharge cycles

CD only: Energy scaled for 100+ mile range, 1,000+ deep discharge cycles

- Charge Depleting (CD)
- Charge Sustaining (CS)
- Unused Energy

- Battery Size (kWh)

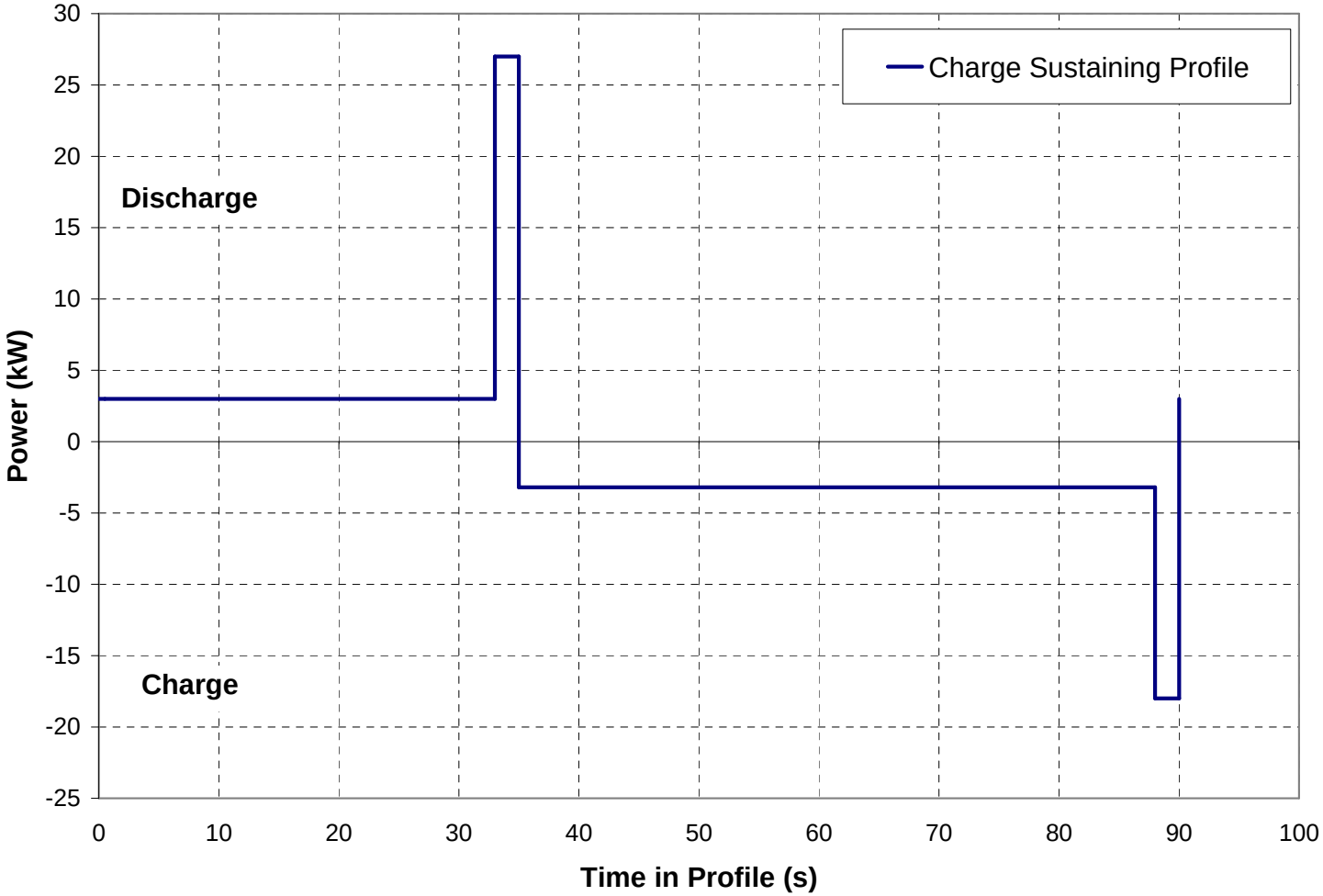
Source: Duong, BES Workshop, Apr. 2, 2007

Minimum HEV and PHEV Targets

Characteristics	Units	Minimum HEV Battery	Minimum PHEV Battery
Peak Discharge Pulse Power (2 sec /10 sec)	kW	NA/25	50/45
Peak Regen Pulse Power (10 sec)	kW	20	30
Max. Current (10 sec pulse)	A	NA	300
Available Energy for CD (Charge-Depleting) Mode, 10 kW Rate	kWh	NA	3.4
Available Energy for CS (Charge-Sustaining) Mode, 10 kW Rate	kWh	0.3	0.5
Minimum Round-trip Energy Efficiency (CS 50 Wh profile)	%	90	90
Cold cranking power at -30°C, 2 sec, 3 Pulses	kW	5	7
CD Life / Discharge Throughput	Cycles/ MWh	NA	5,000 / 17
CS HEV Cycle Life	Cycles	300,000	300,000
Calendar Life	year	15 (30°C)	15 (35°C)
Maximum System Weight	kg	40	60
Maximum System Volume	Liter	32	40
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
Maximum System Recharge Rate at 30°C	kW		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	$	500	1,700

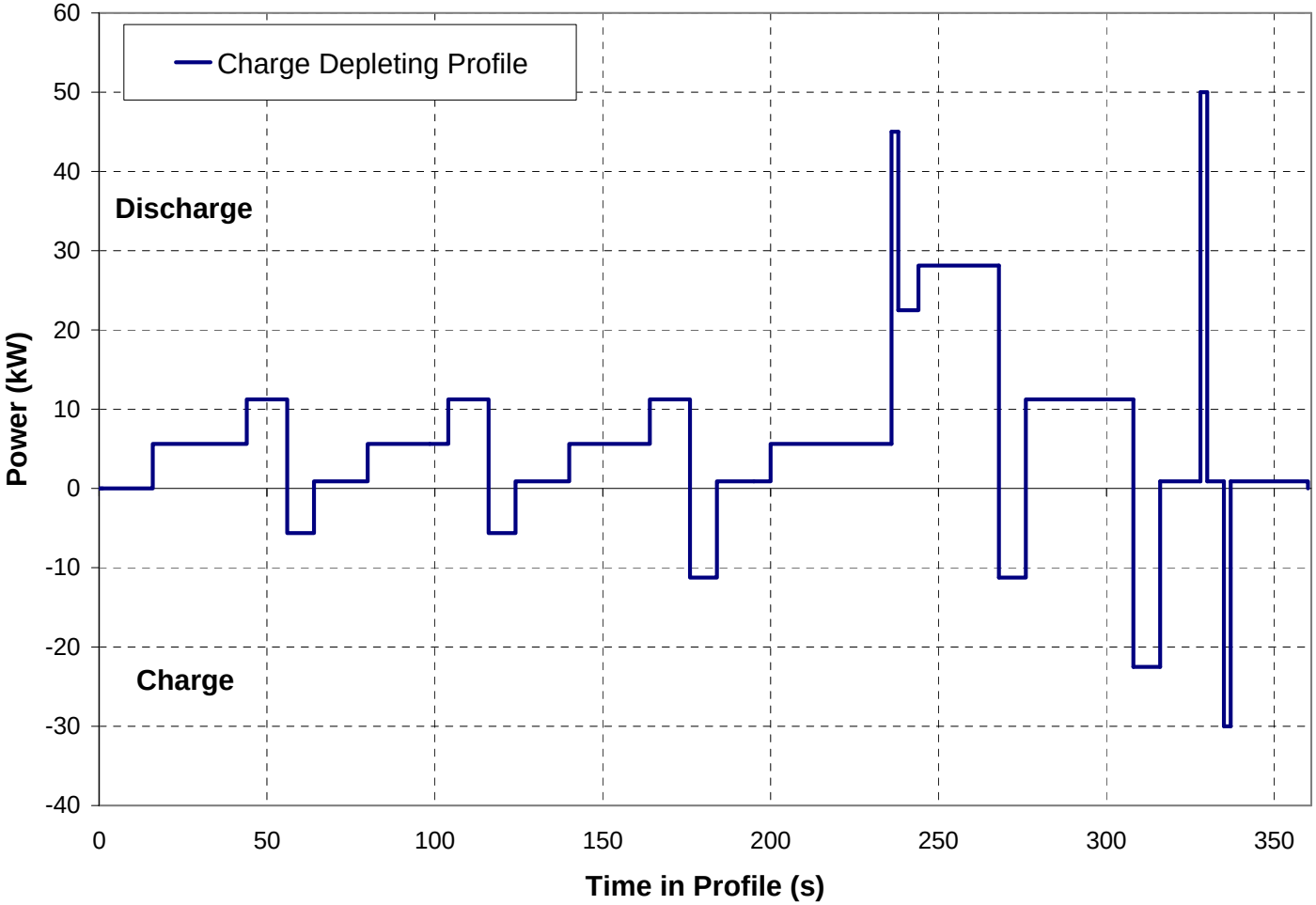
INL Energy Storage Laboratories

- Charge Sustaining Cycle Life Profile:



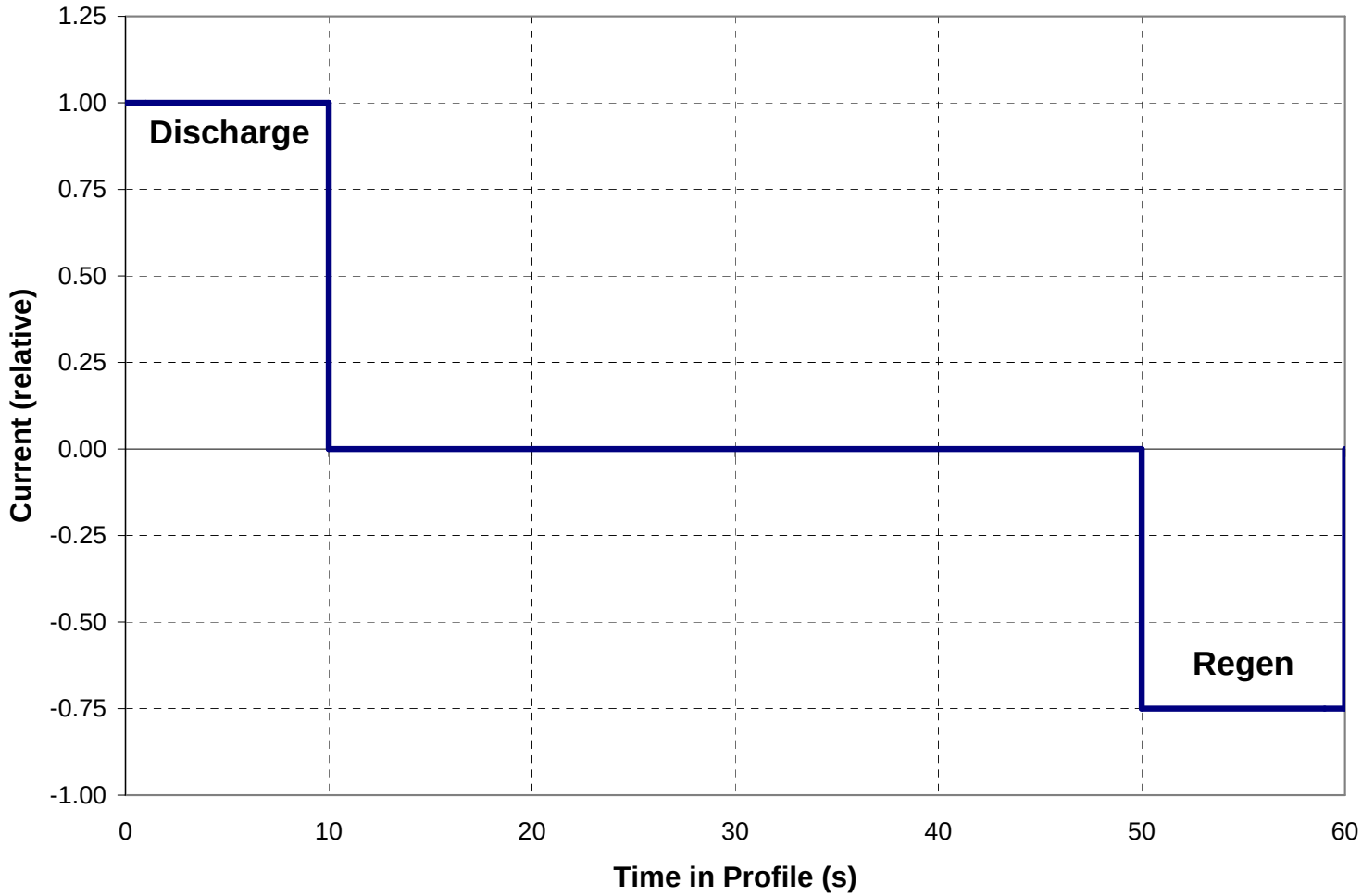
INL Energy Storage Laboratories (cont.)

- Charge Depleting Cycle Life Profile:



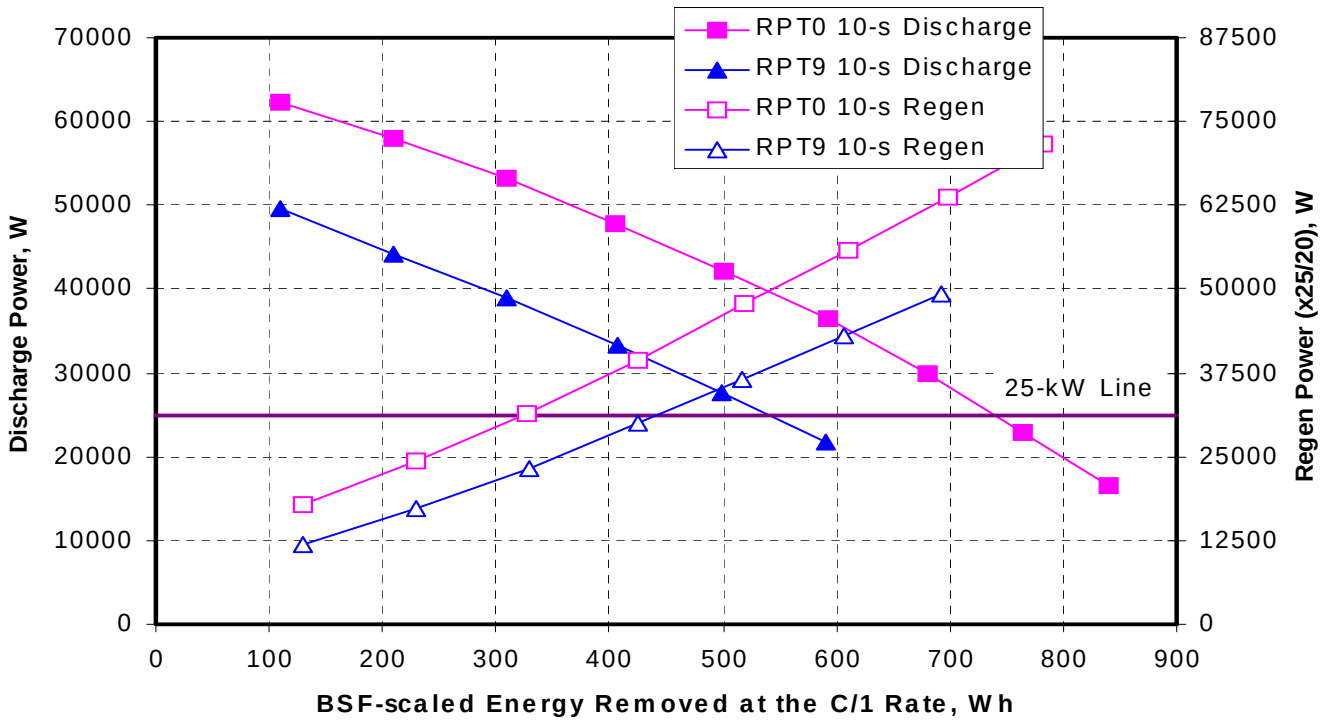
INL Energy Storage Laboratories (cont.)

- Hybrid Pulse Power Characterization (HPPC) Pulse:



Example Results - Battery Power & Energy Fade

Power level decreases with time
Energy window at constant power decreases with time



Accelerated Life Testing

- Technology Life Verification Testing (TLVT)

- Accelerated life testing consists of designing a test matrix that adequately covers the identified stress factors.
  - Temperature, SOC, energy throughput, pulse power, etc.

- The stress factor level should not be increased to a point where the battery failure rate is different than anticipated normal-use conditions.

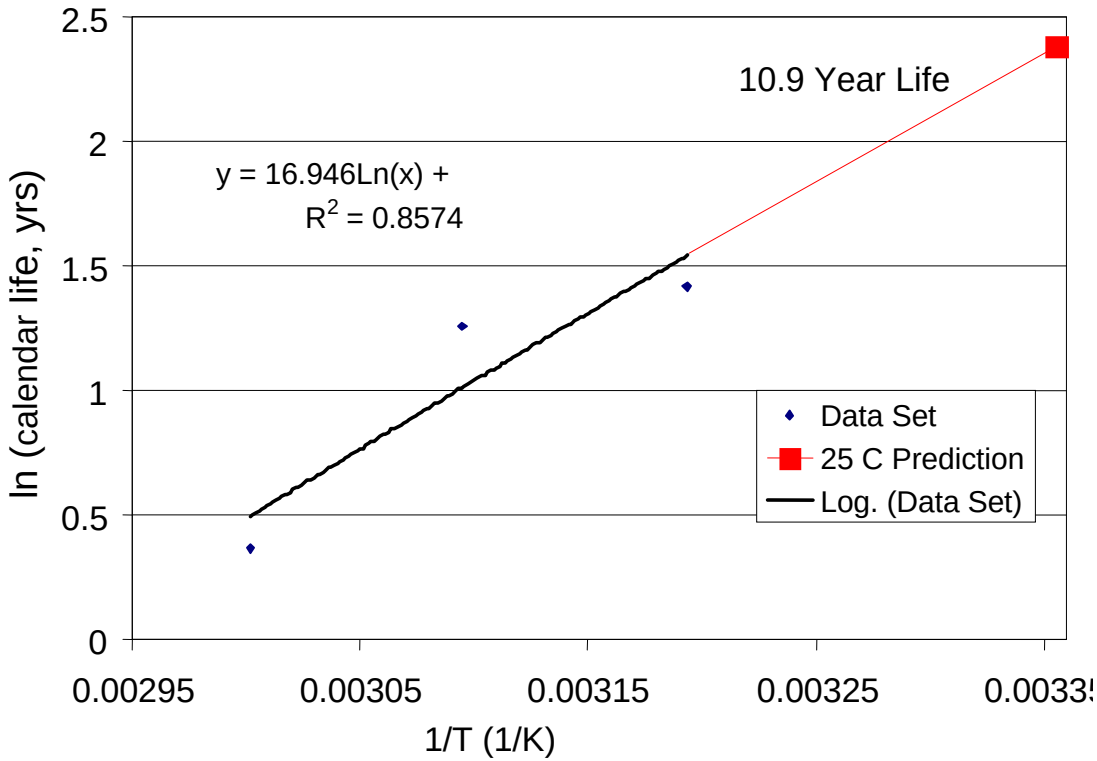
- Life estimates can be achieved through a known battery model and Monte Carlo simulations.
  - Monte Carlo simulations generate a large number of independent simulation trials with random perturbations to model parameters, measurement error, and manufacturing variability.

- Simulated results are verified with actual battery testing and assessed for lack-of-fit statistics.

Example Results – Arrhenius Fit

With an Arrhenius fit, battery life
at the target reference point can be estimated.

Calendar Life Model for Saft HP-12 Li-Ion Cells.



Example Results* - Battery Life Estimation

- The default model was applied to a set of cells that were calendar-life aged at various temperatures.
- The 30°C data were not used to construct the model.

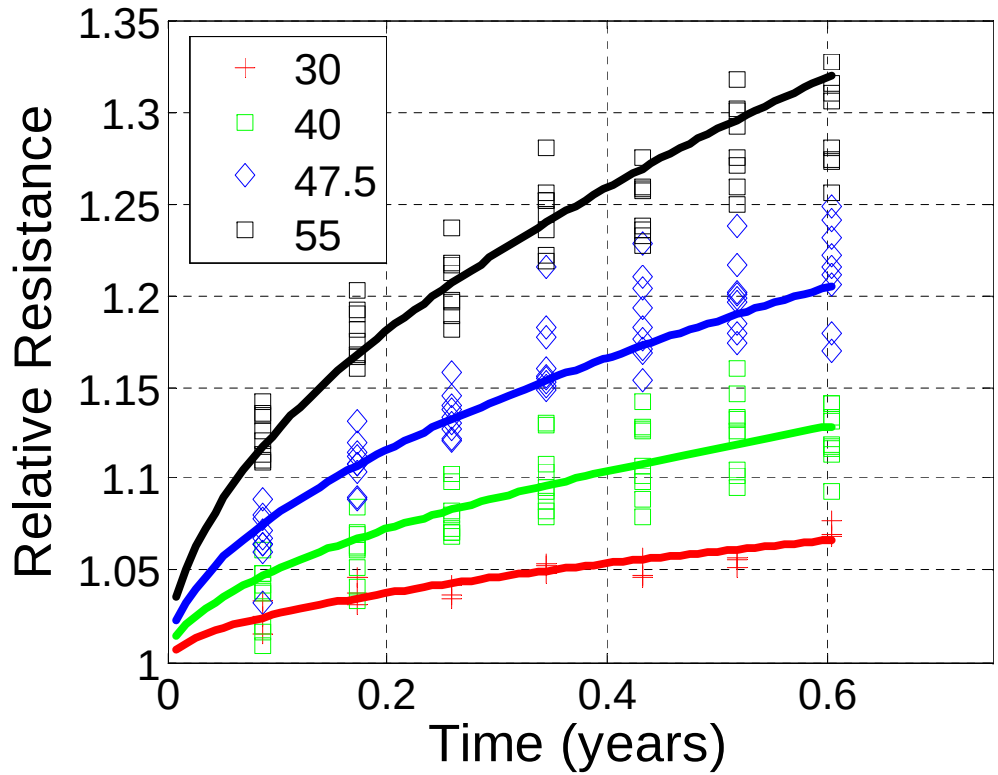
$$\hat{Y} = 1 + \exp\left\{\hat{\beta}_0 + \hat{\beta}_1 \cdot \frac{1}{T}\right\} \cdot t^{0.5}$$

$t = \text{time (years)}$

$T = \text{temperature (K)}$

$$\hat{\beta}_0 = 18.11$$

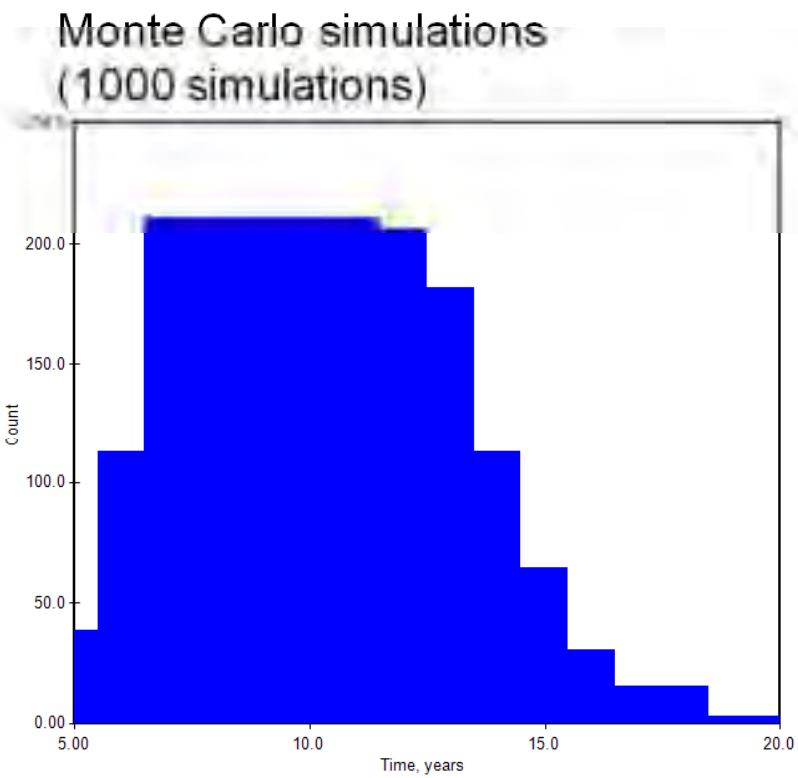
$$\hat{\beta}_1 = -6236$$



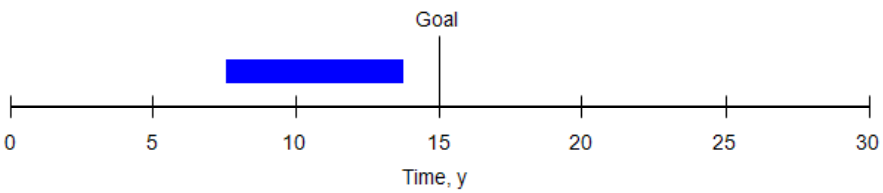
* E.V. Thomas, I. Bloom, J.P. Christophersen, V.S. Battaglia, *J. Power Sources*, 184 (2008) 312–317

Example Results - Battery Life Estimation (cont.)

- Life estimation was completed with 1000 Monte Carlo simulations using the default models.
- These cells were projected to have a life capability between 7.6 and 13.8 years.



Life estimate at 95% LCL= 7.6 y
Life estimate at 95% UCL= 13.8 y



Summary

- We are supporting DOE's effort to reduce national dependence on foreign oil through vehicle energy storage and system testing.
  - We provide an independent source of performance data to help DOE, US car companies, and manufacturers make informed decisions about future vehicle technologies.
- Performance targets and battery designs vary depending on the vehicle operation mode (HEV, PHEV, EV, etc.).
- Accelerated life aging should adequately cover the stress factor range while avoiding the onset of off-normal degradation mechanisms.
- Life estimates of energy storage devices with a statistical confidence window includes known models (empirical or physics-based) and Monte Carlo simulations.