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Office of Energy Efficiency & Renewable Energy

National Renewable Energy Laboratory

Innovation for Our Energy Future

PHEV Energy Storage Performance/Life/Cost Trade-off Analysis

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Outline

- Purpose and Goal
- Approach
- Basis for Performance, Life, and Cost Models
- Preliminary Results
- Alternative Approach
- Conclusion
- Next Steps

Purpose

Linking Battery Performance/Life/Cost Models

Goal: Develop linked parametric modeling tools to mathematically evaluate battery designs to satisfy challenging operational requirements for a PHEV.

- Reduce risk of
  - Premature battery failure
  - Falling short of consumer expectations
- Reduce incremental cost
  - Use data to minimize necessary energy/power margin
- Accelerate market penetration to achieve significant fuel savings

- The battery requirements were selected based on two sets of electric range and time frame:
  - A 10-mile all-electric-range (over UDDS) for a crossover vehicle in the mid-term (2012)
    - » Supporting potential early market experience

    High Power to Energy Ratio (P/E) Battery
  - A 40-mile all-electric-range (over UDDS) for a midsize car in the long-term (2015-2016)
    - » Supporting the President's Initiative

    High Energy to Power Ratio (E/P) Battery

USABC PHEV Battery Targets

Supporting simulations assumed degradation in Power (~30%) and Energy (~20%) from Beginning of Life (BOL) to End of Life (EOL)

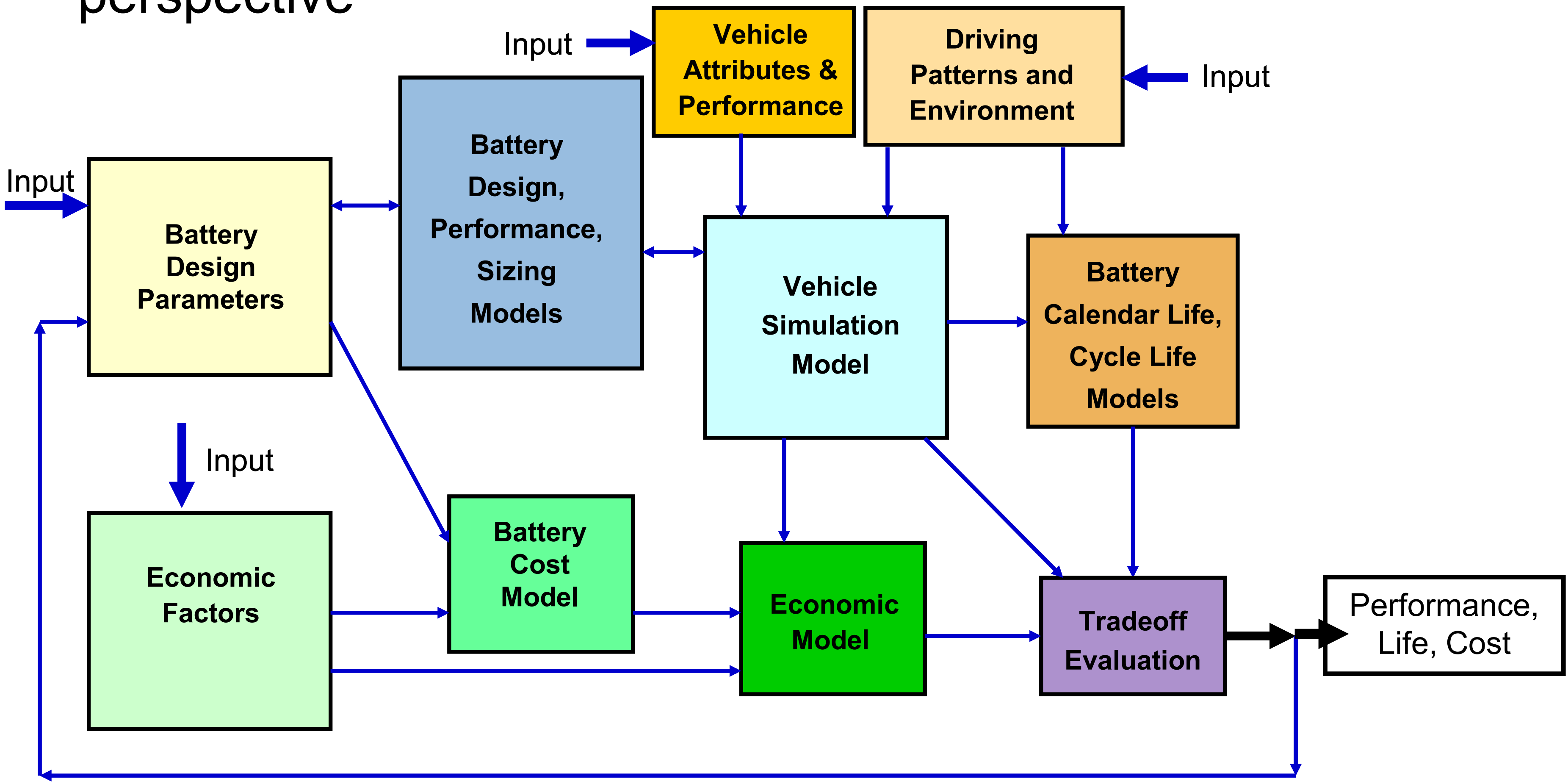
Requirements of End of Life Energy Storage Systems for PHEVs

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

www.uscar.org/commands/files_download.php?files_id=118

Objective

- Develop a process to optimize PHEV battery designs for performance, life, and cost from vehicle system perspective



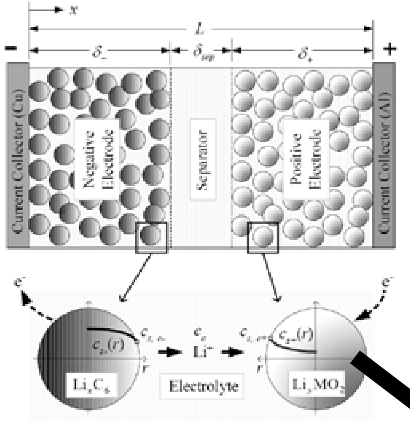
PHEV Battery Tradeoff Study: Approach

- Use physics-based battery models to:
  - Improve understanding of battery design/performance/life tradeoffs
  - Develop capability to predict battery life under any usage scenario
  - Reduce the number of iterations in the prototype battery design & testing process
  - Reduce the experimental burden of technology life verification
- Use credible battery cost models developed by others
- Use vehicle simulation tools
- Run optimization routine to come up with designs that have best combination of performance, life, and cost

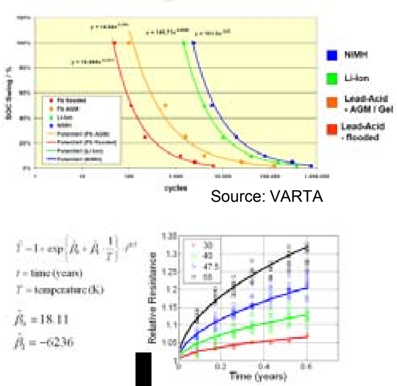
PHEV Battery Design Optimization

Designing PHEV batteries to meet requirements, such as DOE/USABC, at minimum cost.

Performance Model



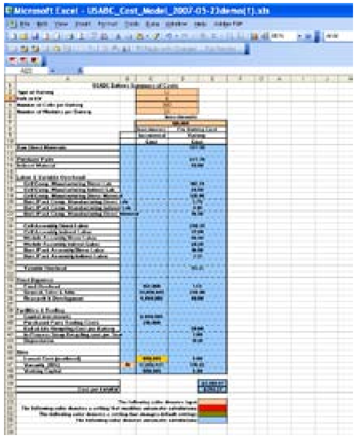
Life Model



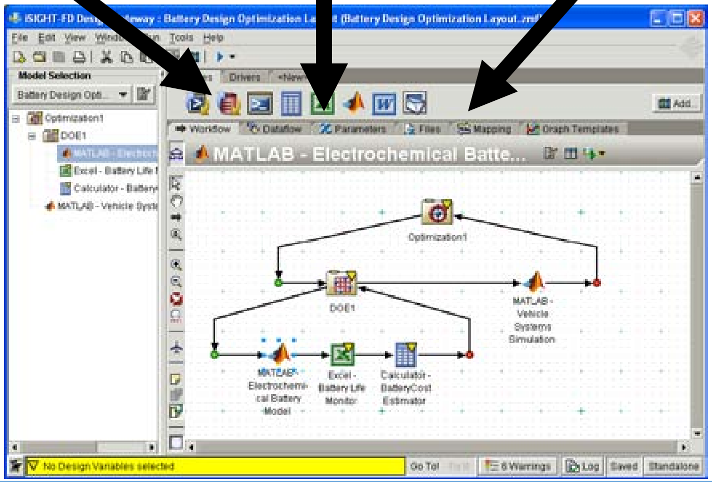
Source: VARTA

Source: INL, LBNL

Cost Model



Optimization



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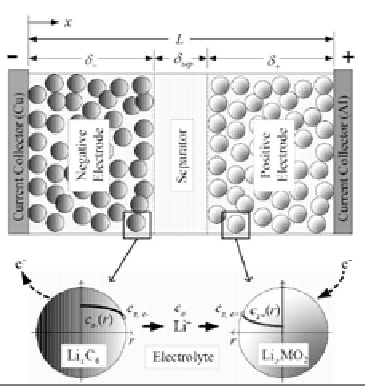
Electrochemical Performance Model

- Used Newman-type model – coded in Matlab
- Chose electrochemical input parameters representative of current technology
- Tuned to constant current data (below) & INL HPPC data (not shown)

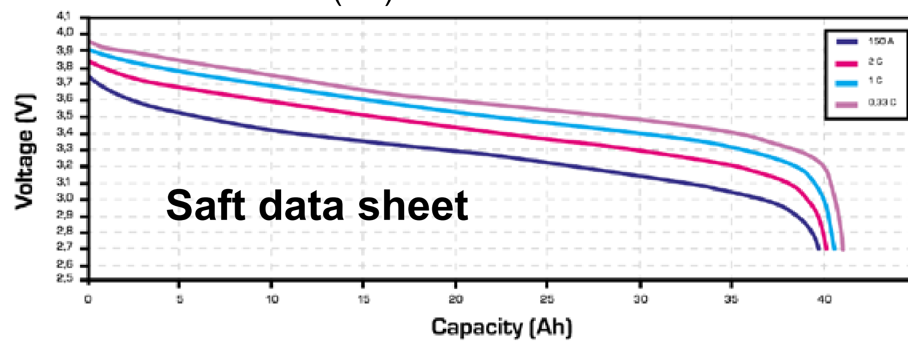
Saft VL41M: Graphite negative/ NCA positive

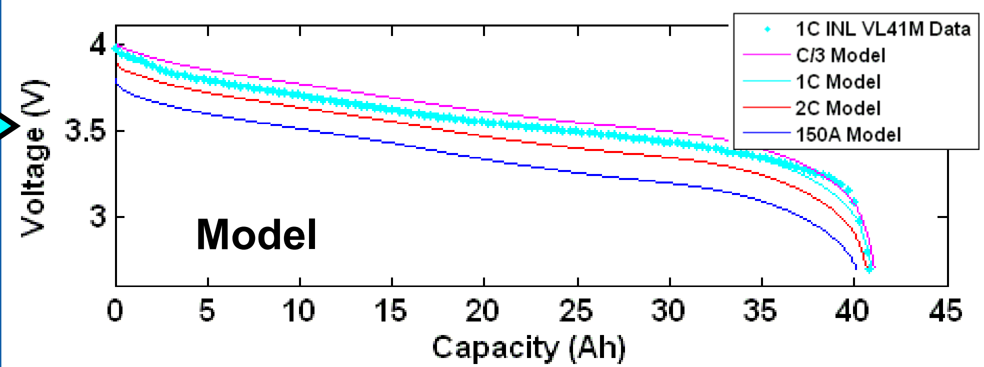
Electrochemical Performance Model



Constant current discharge:

- Saft data sheet (C/3, 1C, 2C, 150A)
- INL data (1C)

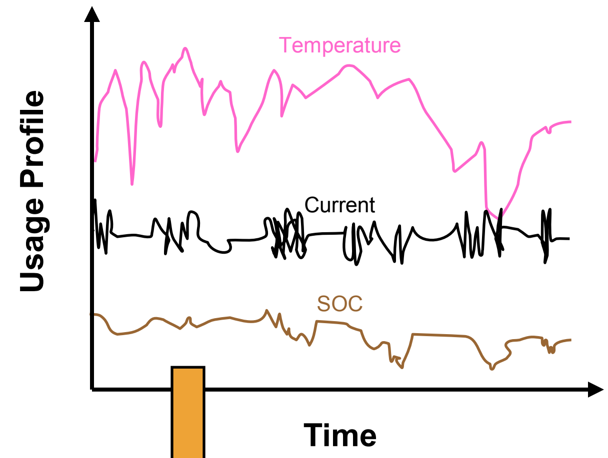




Approach for Developing Semi-Empirical Life Model

Objective: Quantify degradation for any given usage profile

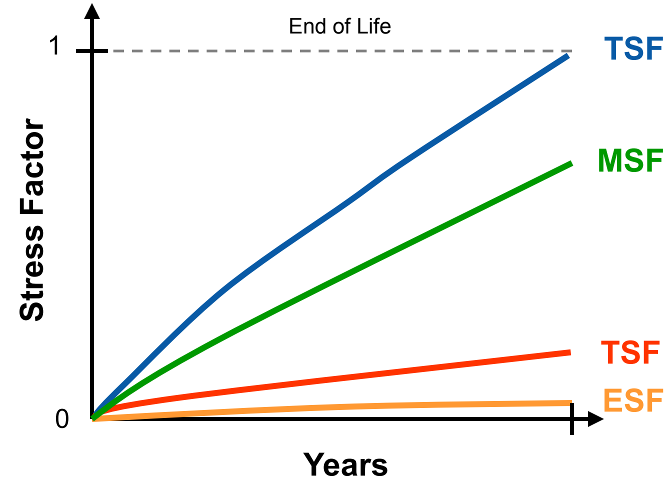
- Time at *T*
- Time at *SOC*
- # cycles at ΔDOD_i
- rate dependency



Method: Include various stress factors

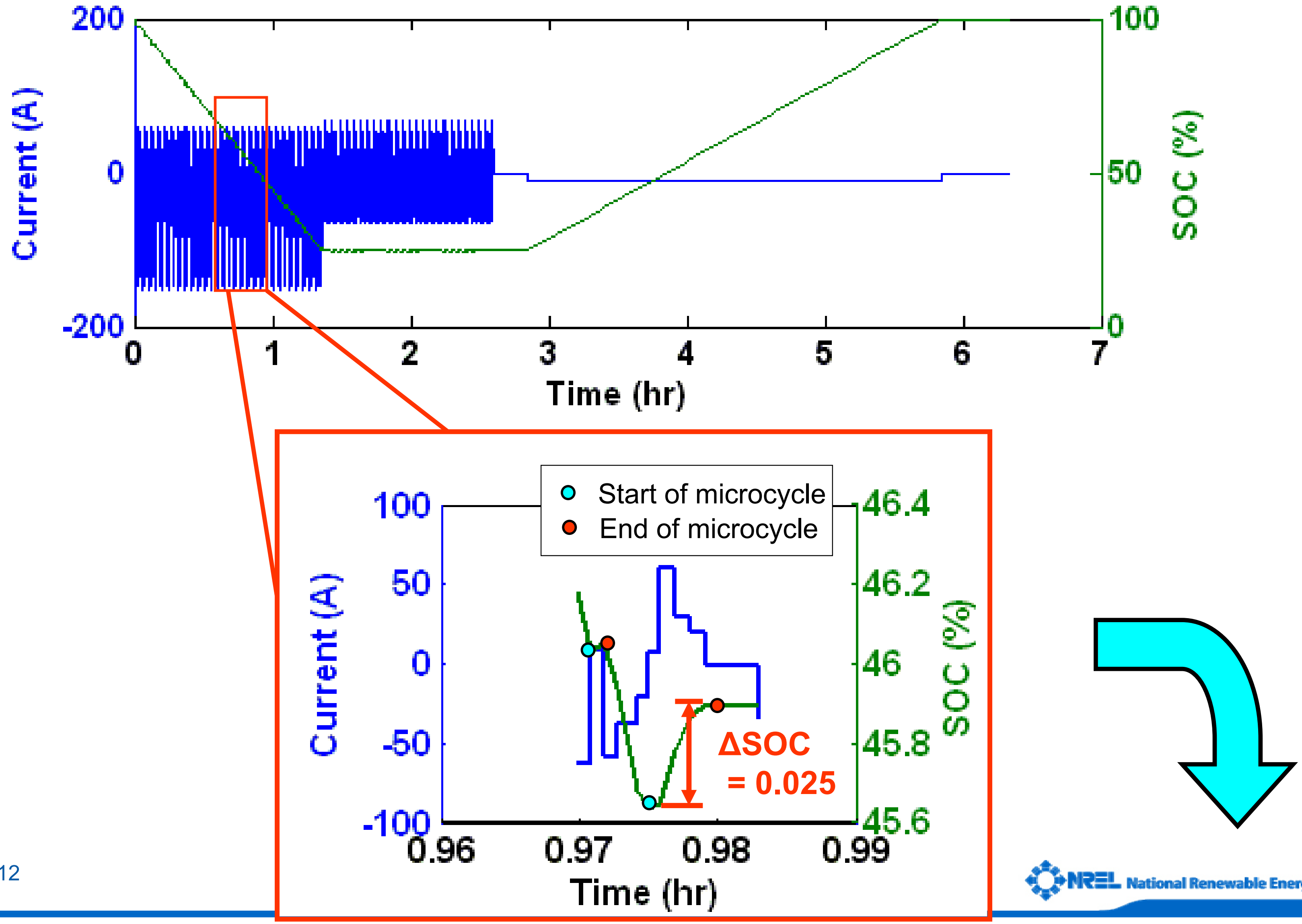
Mechanical (cycling stress, expansion/contraction)
Thermal (chemical reactions at T, SOC)
\+ Electrochemical (side reactions in use)

= Total Stress Factor (TSF)



Example: EPRI/SCE PHEV Cycling profile decomposed into Ncycles @ ΔDOD and Time @ T, OCV

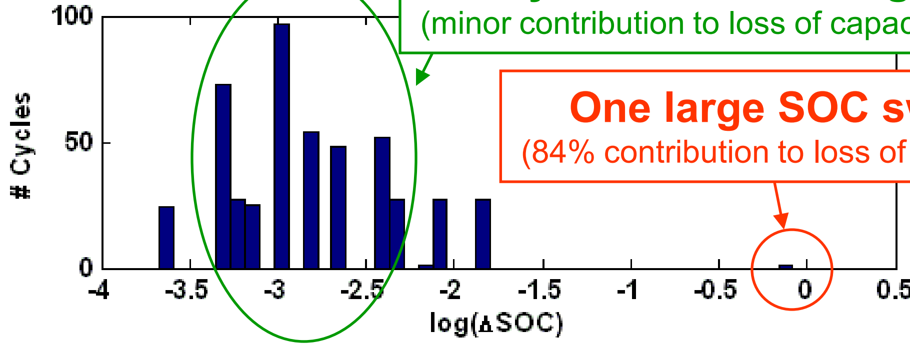
SCE Accelerated Testing Experimental Data for Sprinter Li-Ion Module



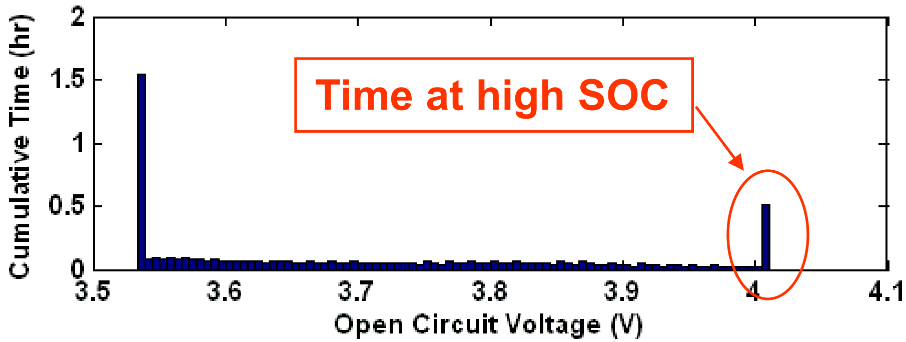
Continued Example: Extracting Cycle Statistics for use with Life Model

Many small SOC swings
(minor contribution to loss of capacity)

One large SOC swing
(84% contribution to loss of capacity!)



Time at high SOC

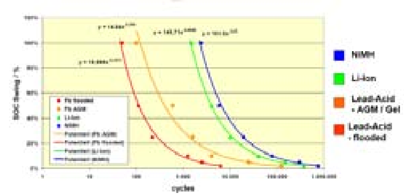


Operation Attributes

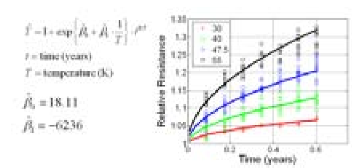
N_{cycles} @ ΔDOD

Time @ T, SOC

Life Model



Source: VARTA



Source: INL, LBNL

Model Forecasts Capacity Loss and Impedance Growth From Operational Data

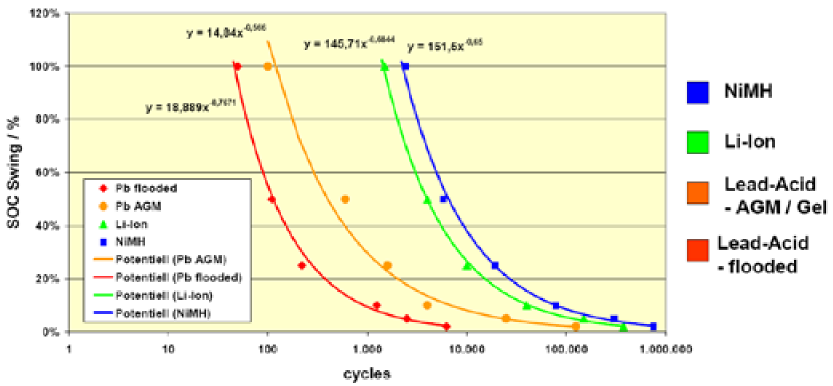
N_{cycles} @ ΔDOD

Time @ T, SOC

Life Model

Mechanical Stress

(cycling stress, expansion/contraction)
(at fixed temperature)



Christian Rosenkranz (JCS/Varta) EVS-20

Thermal Stress

(chemical reactions at various T, SOC)

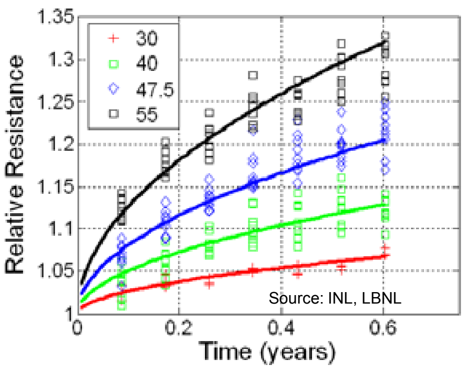
$$\hat{Y} = 1 + \exp\left\{\hat{\beta}_0 + \hat{\beta}_1 \cdot \frac{1}{T}\right\} \cdot t^{0.5}$$

t = time (years)

T = temperature (K)

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

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

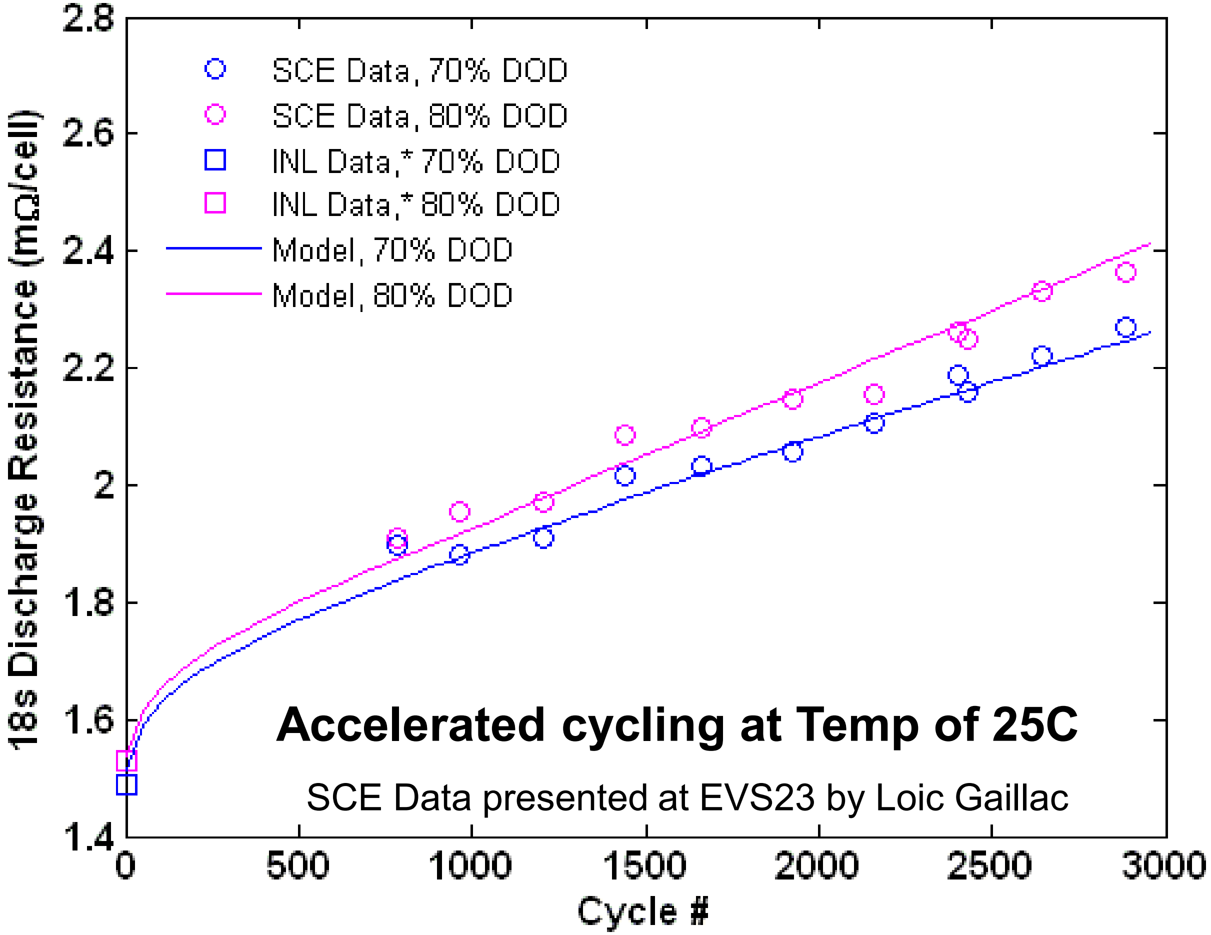


Vince Battaglia (DOE/TLVT)

Capacity Loss, Impedance Growth

Fitting the Life Model to Data- Impedance Growth Model Using SCE Data

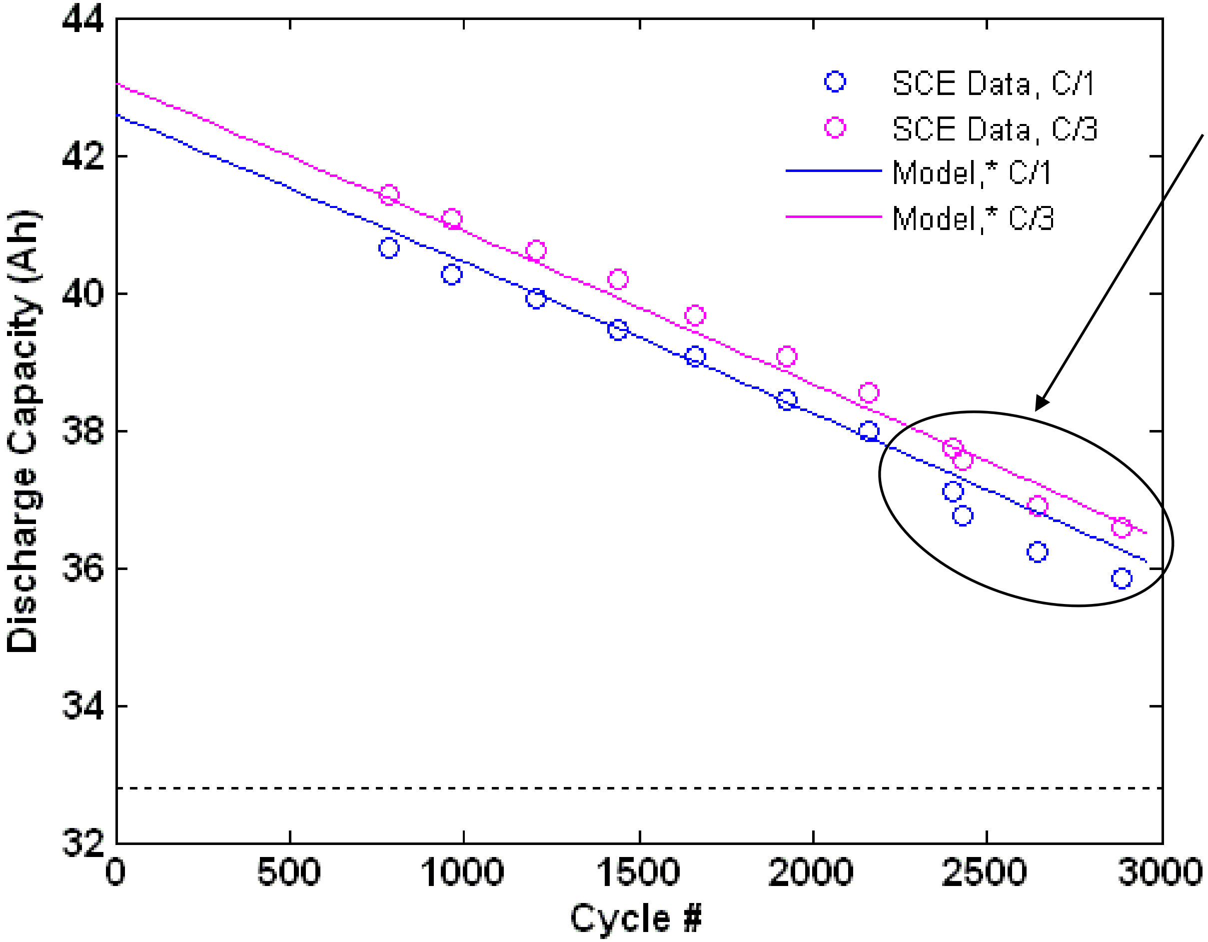
Thermal Stress (impedance growth ~$t^{1/2}$) and Mechanical Stress (capacity loss) models simultaneously fit to accelerated cycling data.



Calendar life and Cycle life testing being done on these cells in parallel would allow accurate separation of Mechanical and Thermal Stress contributions.

* INL Data: 10s resistance scaled to 18s.

Capacity Loss Prediction Using SCE Data

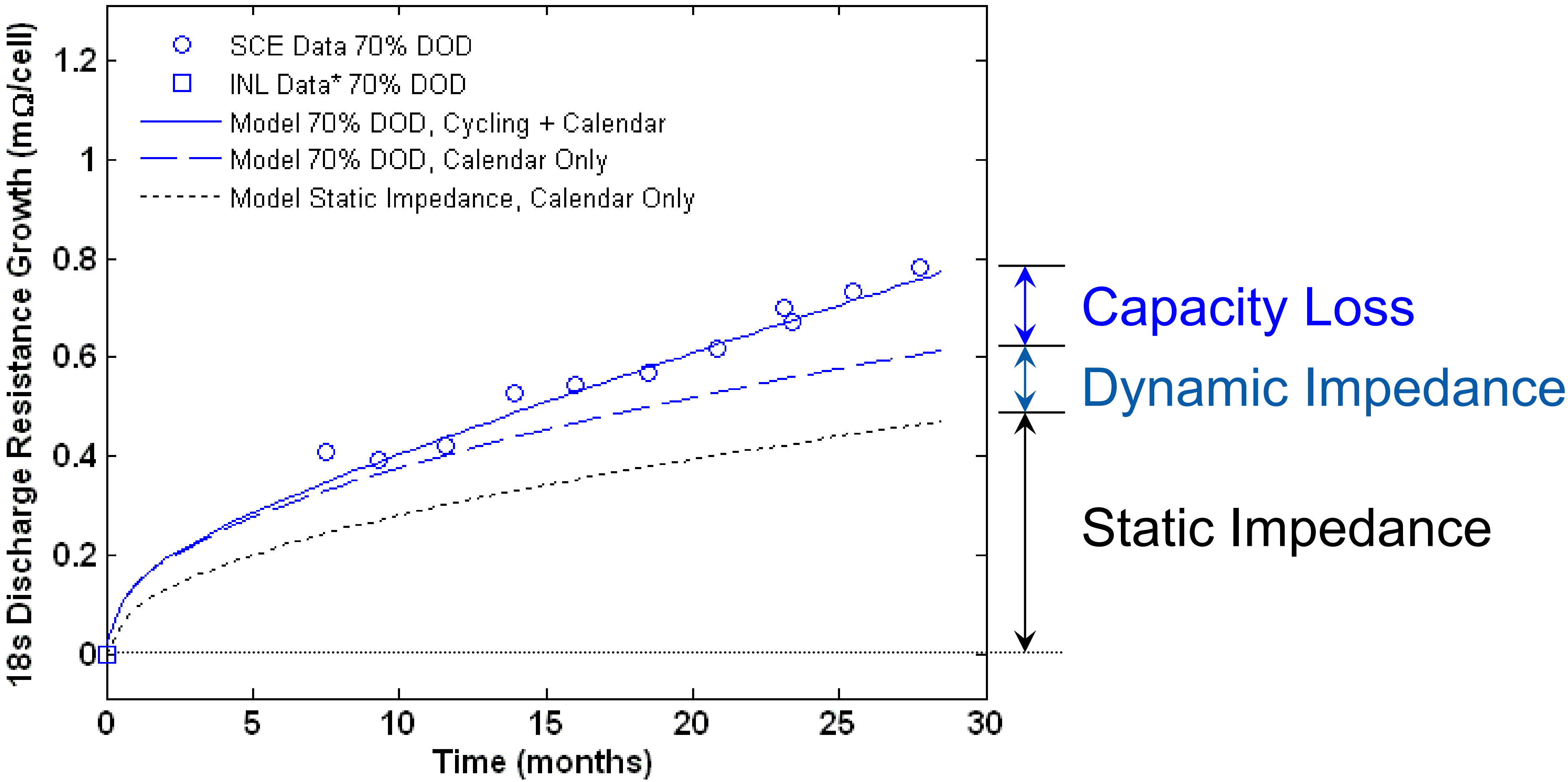


This Mechanical Stress (capacity loss) model fails to capture apparent accelerating trend.

Small accelerating influence predicted by model due to increase of ΔSOC cycling severity with capacity loss.

Impedance contributions to apparent capacity (underdischarging & undercharging) investigated as accelerating trend but effects found negligible.

Capacity loss (cycling) has appreciable impact on measured discharge resistance growth

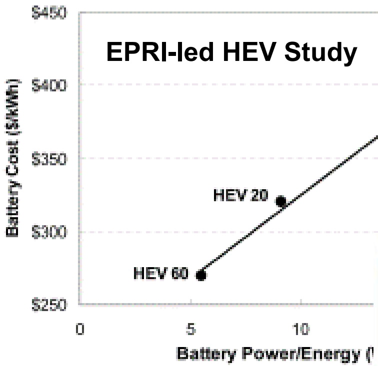


* INL Data: 10s resistance scaled to 18s.

Developing Simplified Cost Model

Estimating Manufacturer Pack Cost

- Battery cost estimates from EPRI-led HEV study as original source[1]
- EPRI HEV Cost model used for NREL's EVS-22 paper on PHEV Cost Benefit Analysis[2]
- DOE-sponsored TIAX study reviewed cost details of two li-ion cathodes (NCA and NCM) manufacturing[3]
- Modified fixed costs to include a per cell component based on TIAX estimates [this study]



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

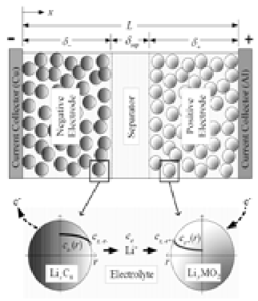
Simplified Pack Cost Model

$/pack = 11.1*kW + 224.1*kWh + 4.53*BSF + 340

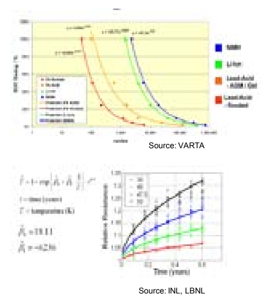
1. Graham, R. et al. "Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options," Electric Power Research Institute (EPRI), 2001.
2. Simpson, A., "Cost Benefit Analysis of Plug-In Hybrid Electric Vehicle Technology," *22^{nd} International Electric Vehicle Symposium*, Yokohama, Japan, Oct.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

Summary of Components for Performance/Life/Cost Modeling Effort

Performance Model



Life Model



Cost Model

- Developed performance model representative of Saft VL41M data
- Employed simplified cost model based on kWh, P/E ratio and cell number connected in series (BSF) representative for NCA chemistry
- Life model representative of hypothetical design :
  - Mechanical Stress
    - » fit with SCE capacity loss
  - Thermal Stress
    - » using TLVT impedance growth method

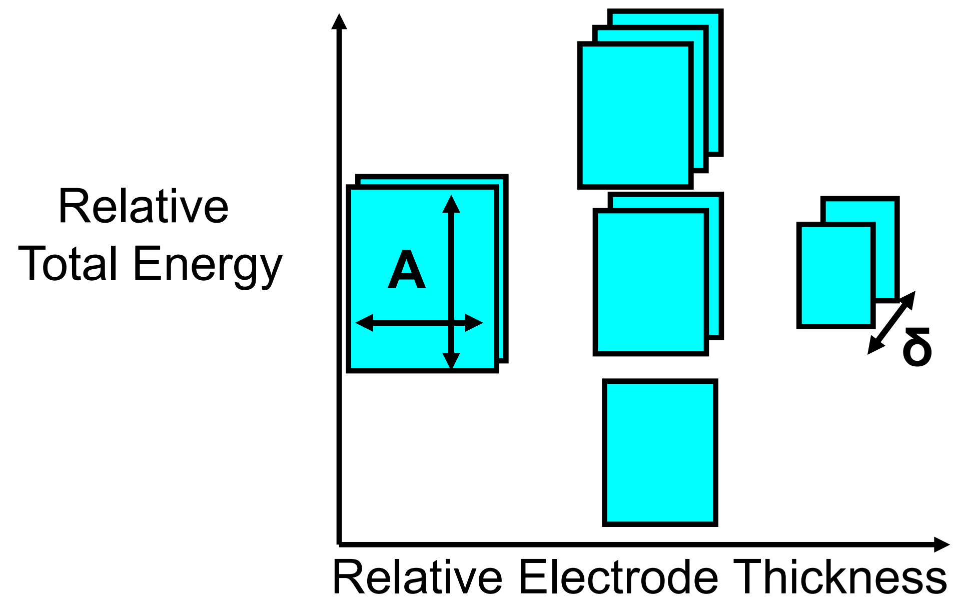
TLVT – Technology Life Verification Test

Preliminary Trade-off Study – Approach

- Parametric study on number of cells connected in series (BSF), cell capacity, and electrode thickness
  - Calculated BOL and EOL (15 years @ 35C; 5,000 CD cycles; 300,000 CS cycles)† characteristics

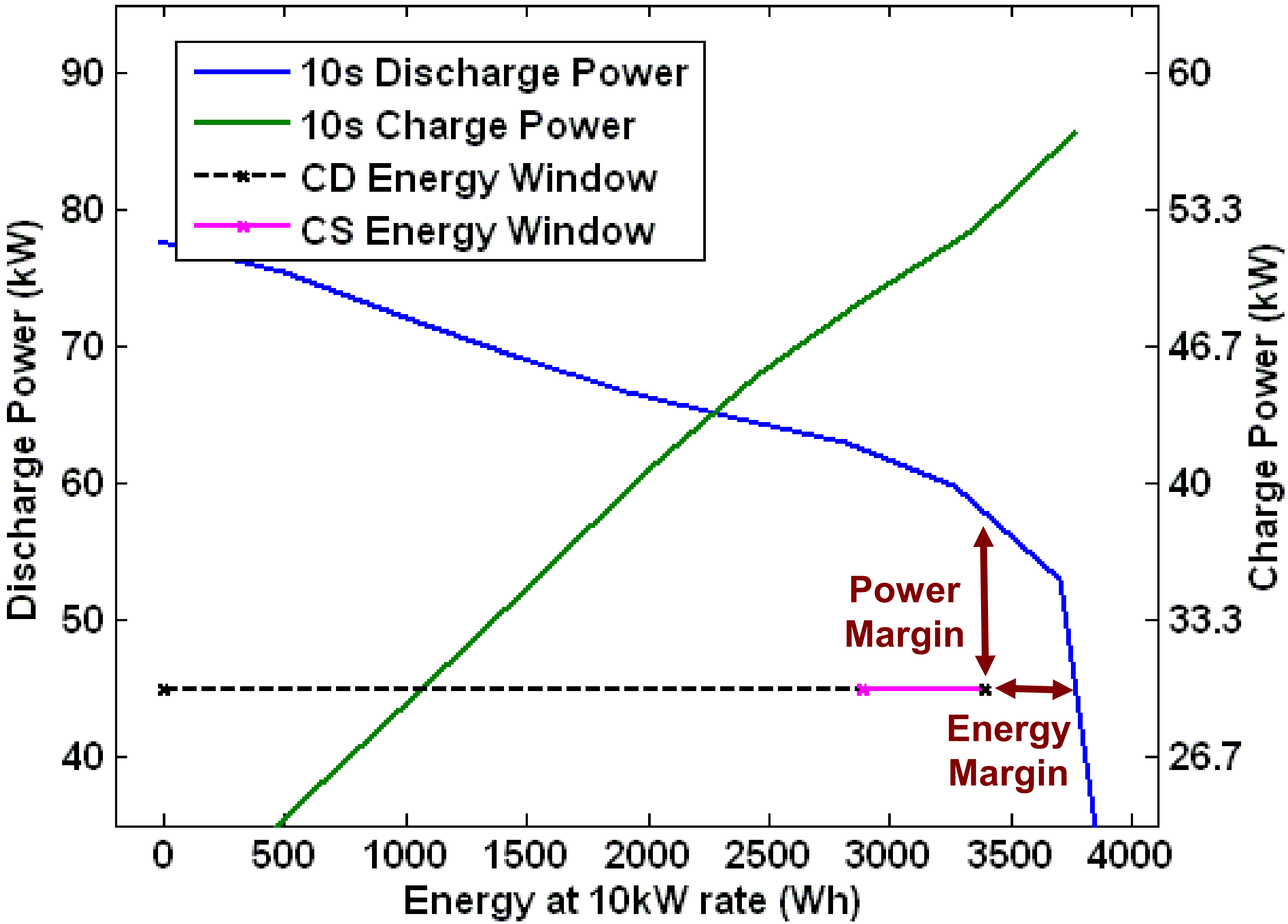
As electrode thickness varies, cell dimensions vary to provide <u>equivalent total energy</u> for each constant energy scenario

Electrode impedance ∝ δ/A
Electrode capacity ∝ δ*A



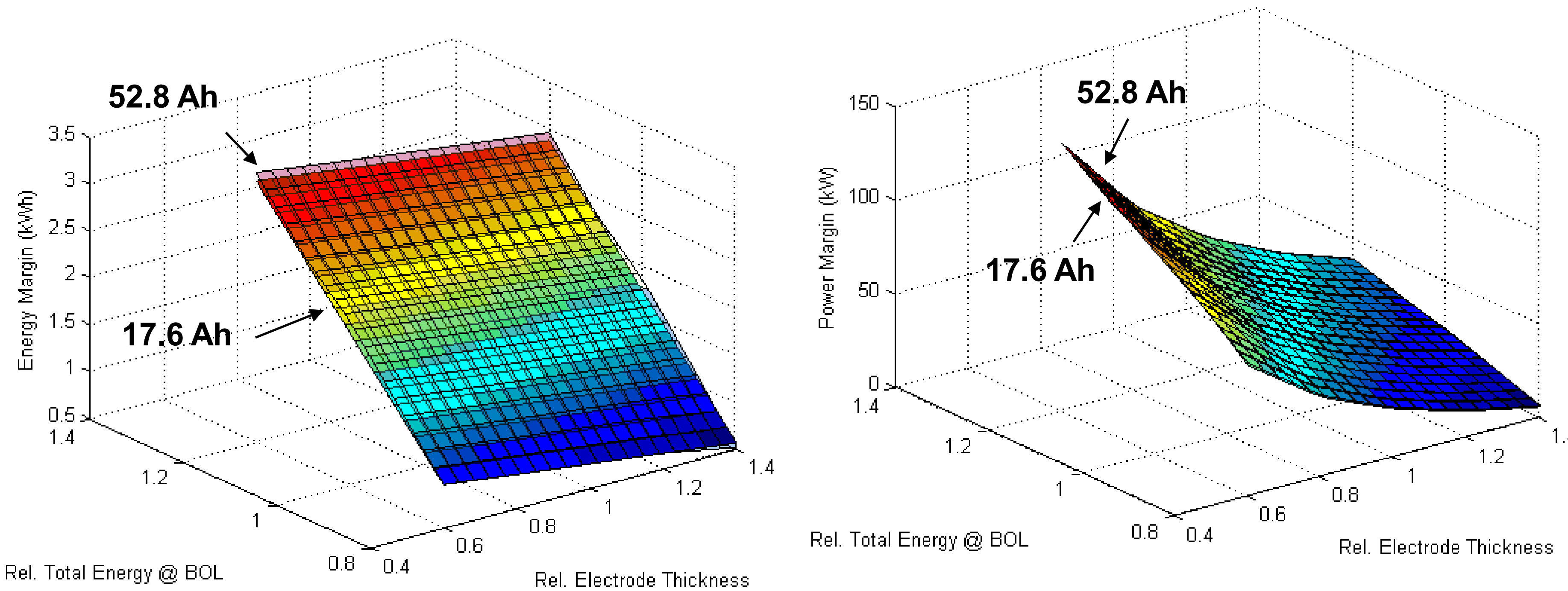
†USABC PHEV Battery Test Manual
CD: Charge Depleting; CS: Charge Sustaining

Power and Energy Margin With Respect to USABC Hybrid Pulse Power Characterization Testing



Beginning of Life: Energy and Power Margin

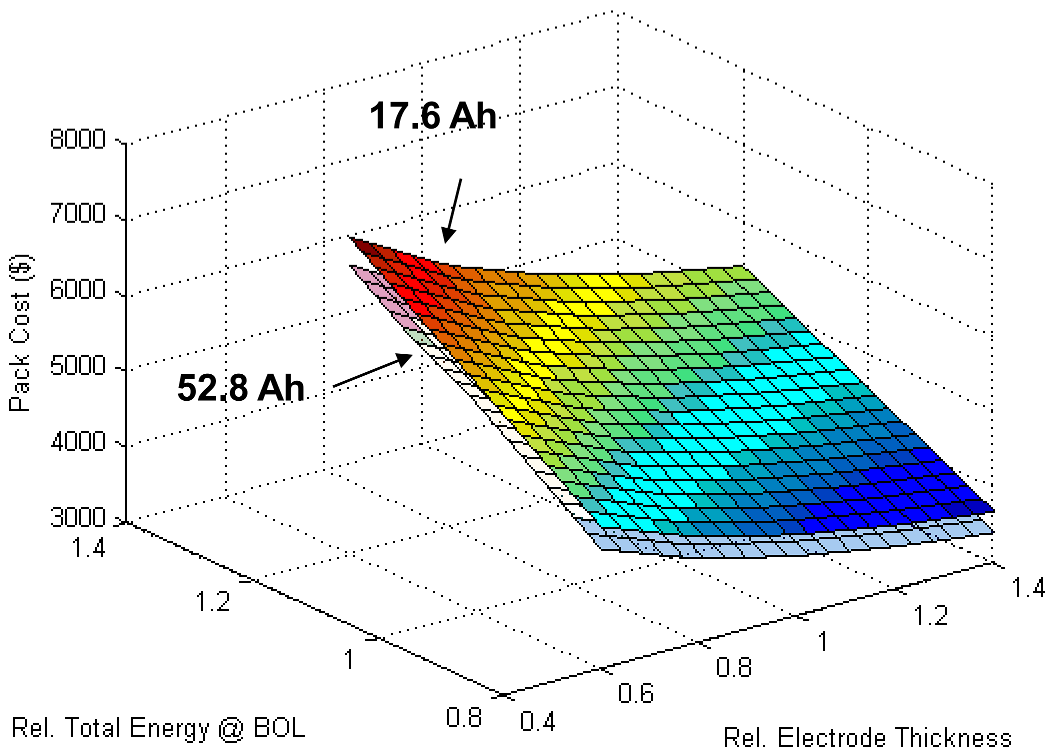
Rel Total Energy=1 and Rel Electrode Thickness=1 is baseline VL41M design with BSF = 44



- USABC energy & power margin both increased with:
  - Increased total energy (# cells or cell capacity)
  - Decreased electrode thickness (more power)
- Cell capacity has negligible influence on energy & power margin

Beginning of Life: Cost

- Cell capacity, electrode thickness, number of cells in series all have strong influence on cost



Observations

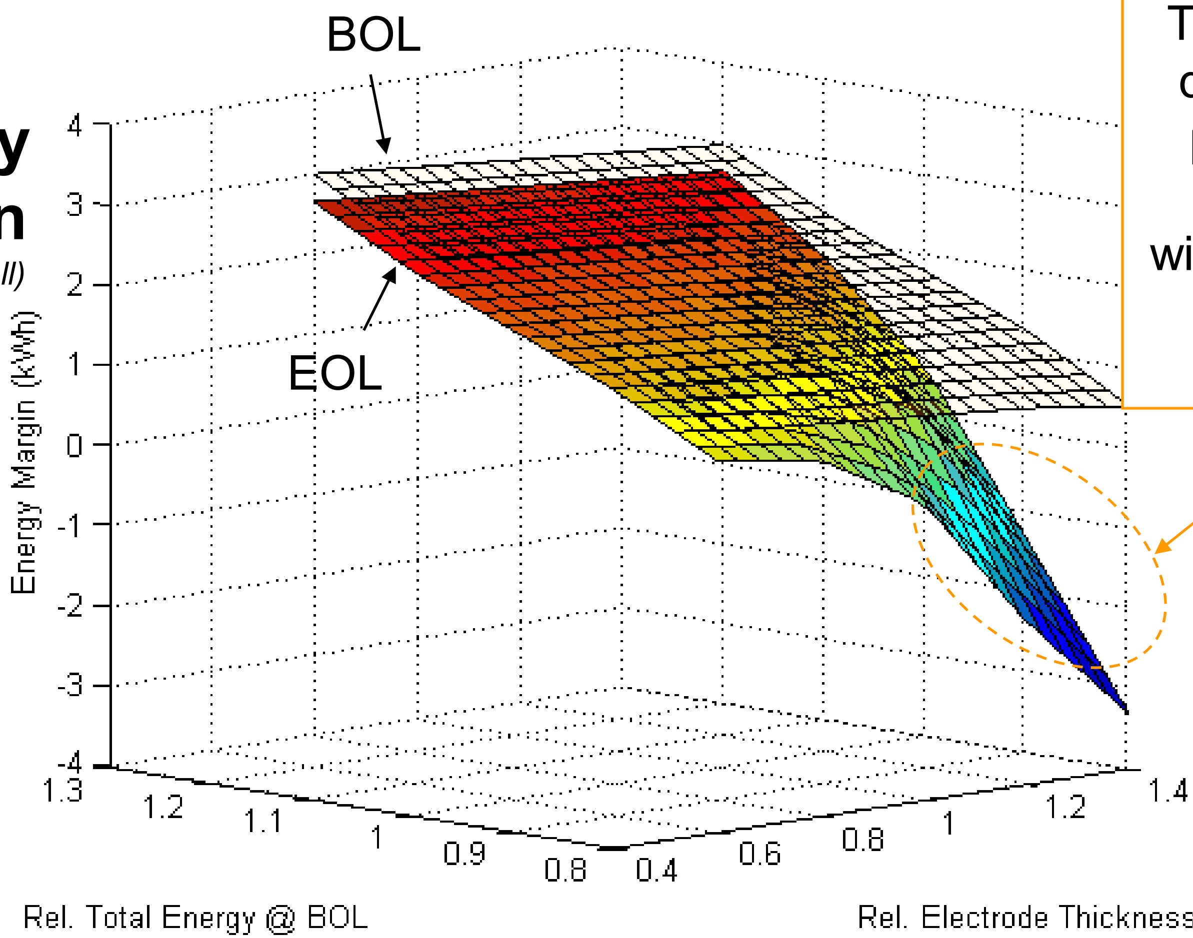
→ Using the largest capacity cell results in pack ~$310 cheaper than the smallest capacity cell.

→ Use largest capacity cell possible that still meets pack voltage constraints.

Combined Cycling + Calendar Scenario
Energy Margin

- End of Life energy margin calculated at
  - 5000 CD cycles; 300,000 CS cycles; 15 years at 35˚C

Energy Margin
(for 41 Ah cell)



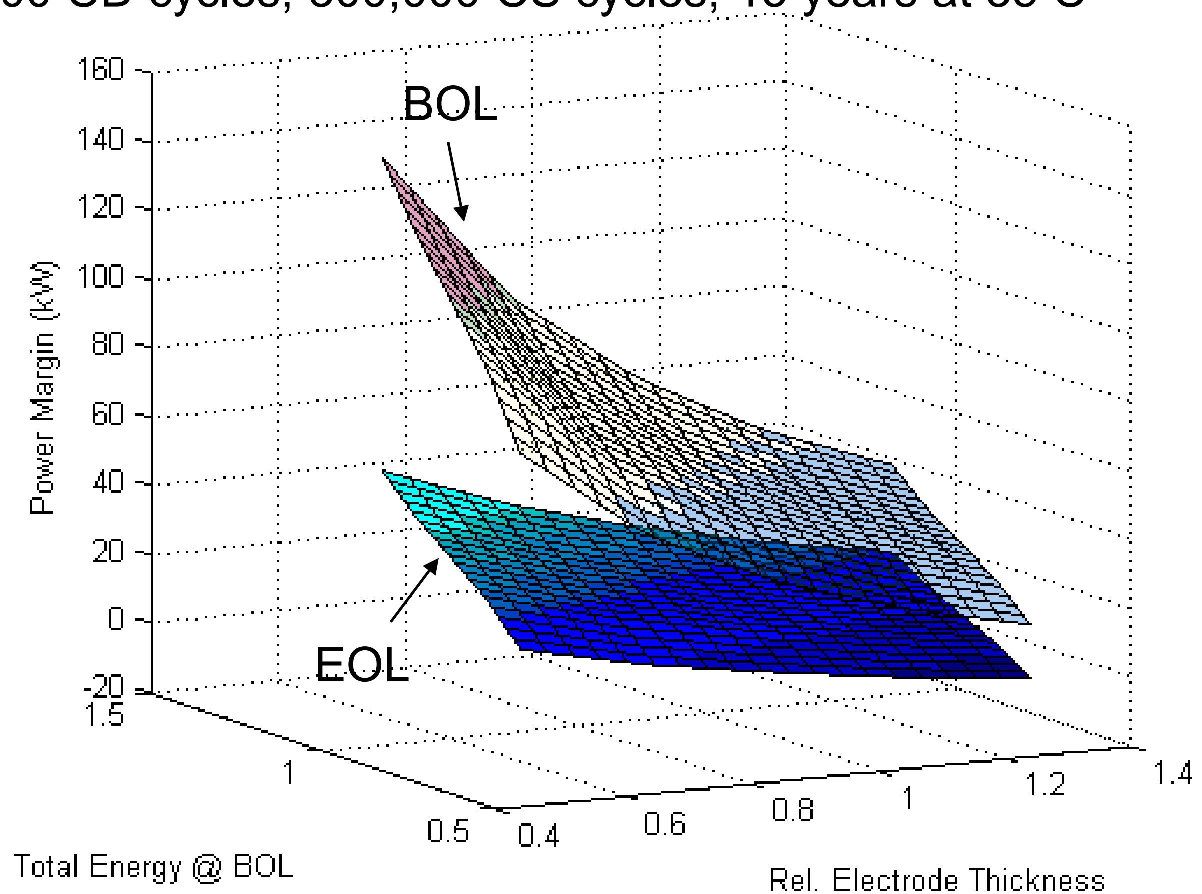
These thick electrode designs with smaller plate area have too small an energy window (power-limited) at EOL and cannot meet life goal.

Energy Margin: Amount of Power left above the EOL requirements

Combined Cycling + Calendar Scenario
Power Margin

- End of Life power margin calculated at
  - 5000 CD cycles; 300,000 CS cycles; 15 years at 35˚C

Power Margin
(for 41 Ah cell)

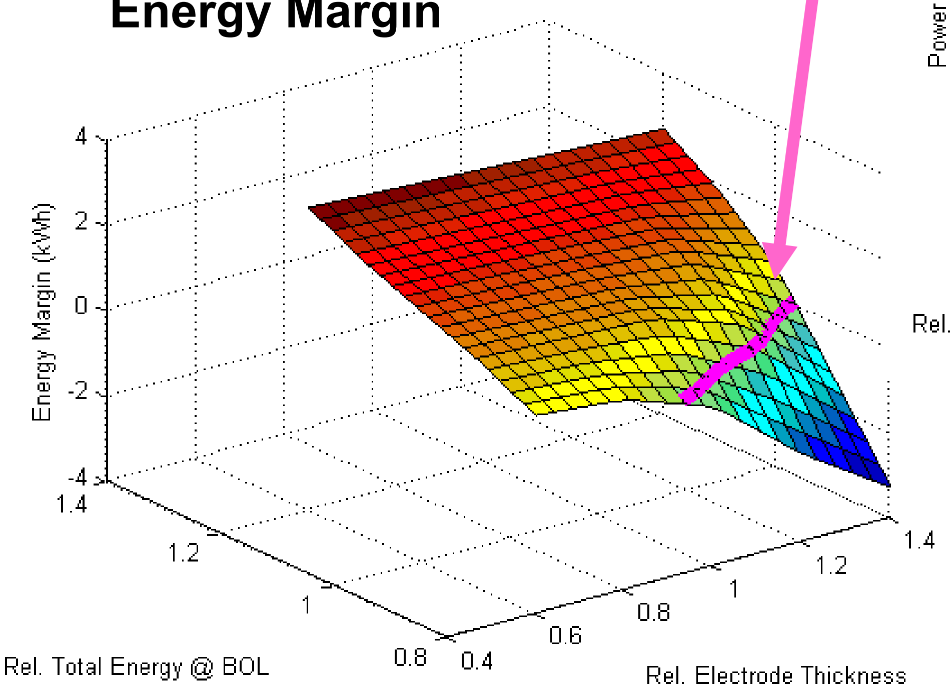


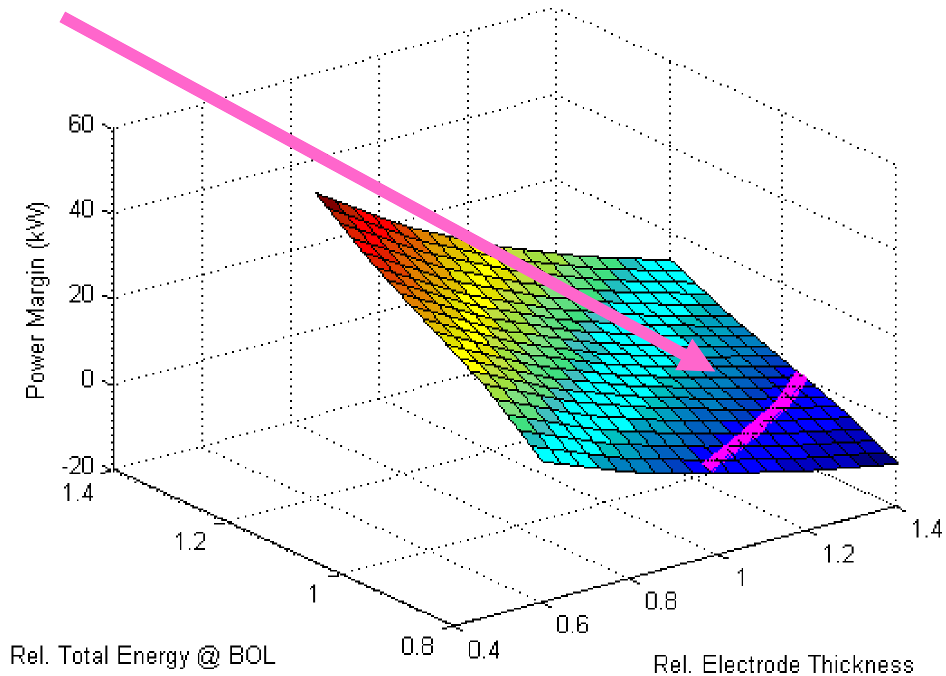
- All designs have excess power margin at beginning of life.
- The ideal (least expensive) design will have zero power & energy margin at end of life.

Combined Cycling + Calendar Scenario

Zero Energy/Power Margin Designs at End of Life

- Designs on this line have zero margin at end of life

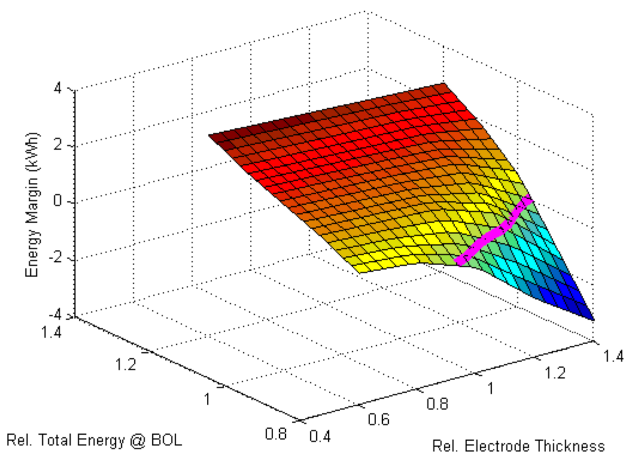




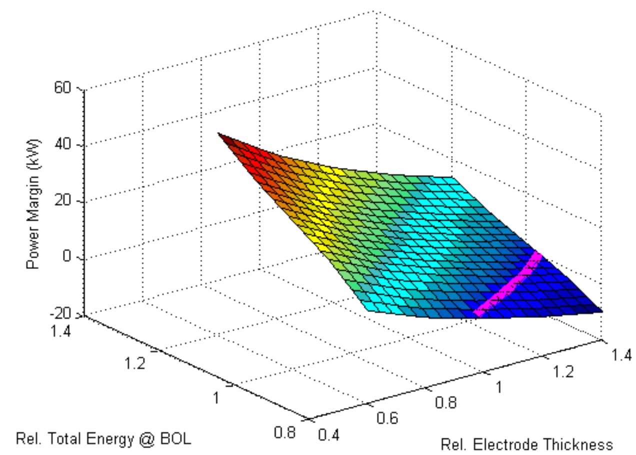
Combined Cycling + Calendar Scenario

Impact of Design Options on Pack Cost

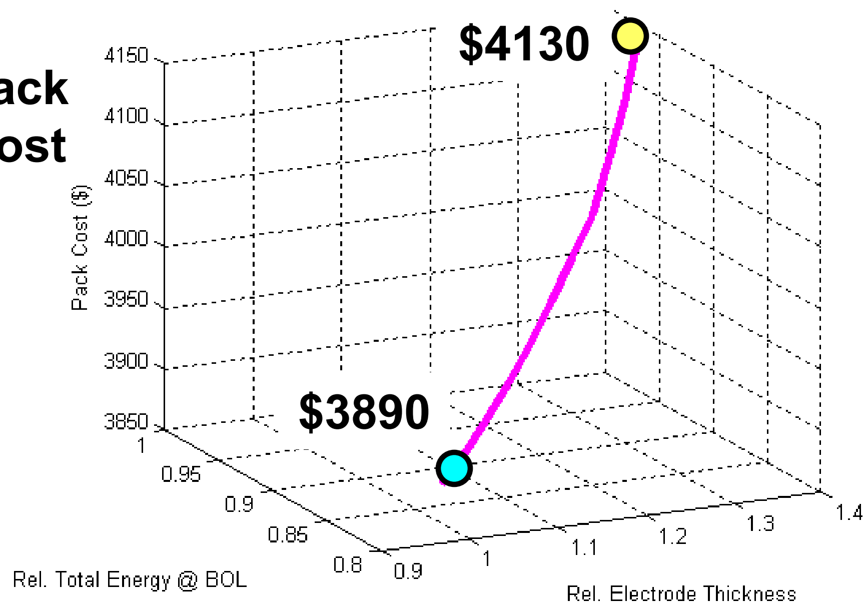
Energy Margin



Power Margin



Pack Cost



- Amongst these "zero margin" designs, the highest P/E design is cheapest.

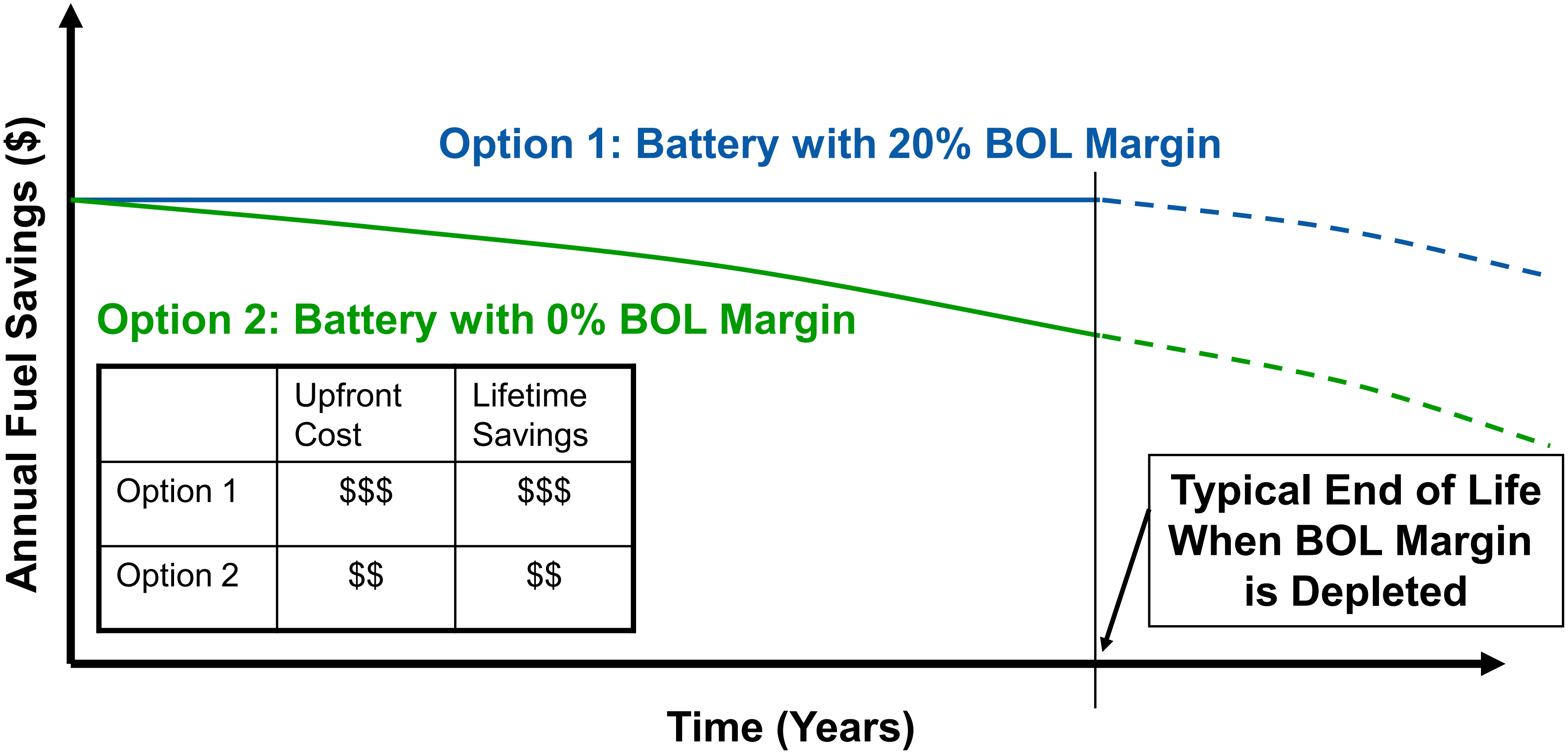
<u>Observations:</u>

- Battery packs should be designed with minimal energy content that satisfies life goals.
- Increasing P/E is effective in increasing useable energy.

Some Thoughts on Analysis toward USABC Requirements

- Modifications to the cell design attributes can be used to reduce cost and satisfy USABC requirements
- Is *"design for degradation"* the best approach?
- Why 20%-30% degradation?
- Linked performance/life/cost model tied to vehicle simulation could be used to evaluate the tradeoff between upfront cost of battery with margin vs. degraded long-term fuel savings for a *"just enough"* battery design

Margin or No Margin?



	Upfront Cost	Lifetime Savings
Option 1	$$$	$$$
Option 2	$$	$$

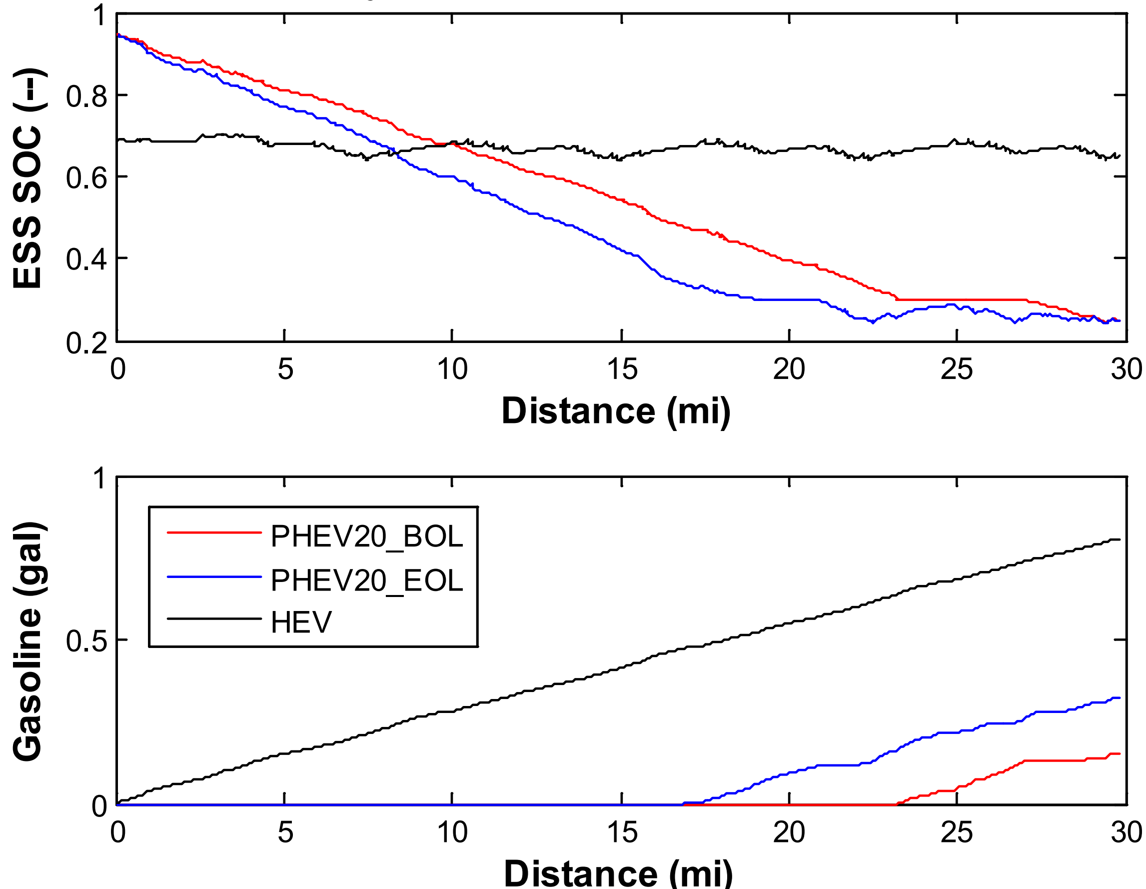
Lower upfront costs may lead to greater market share
Greater market share with slightly lower fuel savings may translate to **more fleet fuel savings** and **volume cost reductions sooner.**

Beginning of Life and End of Life Vehicle Simulations

- Vehicle simulation with 20% degradation in both Energy and Power,
  - CD range decreases from 22 to 17 miles
  - Over 30 miles, EOL fuel consumption is double BOL consumption however EOL consumption still only a fraction of HEV consumption

BOL cost savings likely more valuable than EOL fuel savings: \$1000 in year 1 ≠ \$1000 over 15 yrs

Battery life model linked with vehicle simulation will provide better estimate of change in operation and savings over vehicle lifetime



Summary and Conclusion

- NREL is developing tools, algorithms, and a framework for battery investigators to identify battery design options for PHEVs with trade-offs in mind

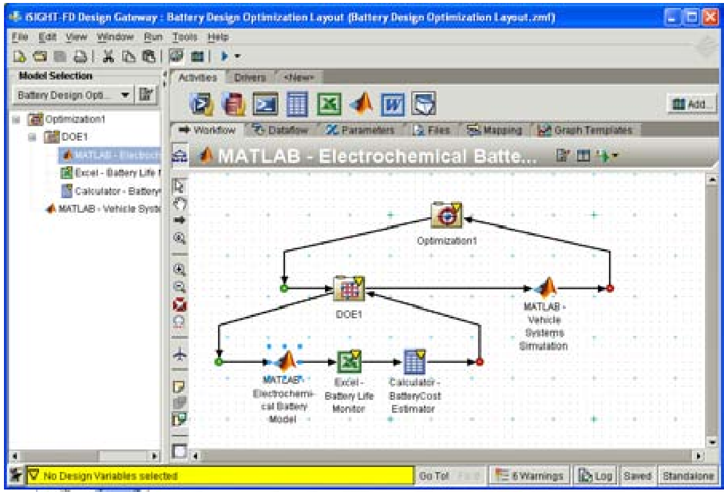
- It is possible to decrease initial battery cost with better understanding of life and performance impacts of design and usage pattern

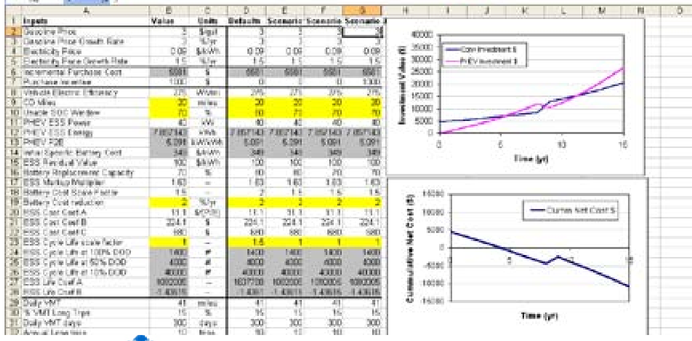
- First principals performance model clarifies degradation contributions due to cycling and calendar aspects

- Alternative designs may accelerate market growth

Next Steps

- Collaborate with battery providers and OEMs to refine the cost/life/performance models
- Develop performance models for other chemistries
- Incorporate climatic variation effects
  - — Cold → performance reduction
  - — Hot → calendar life
- Link vehicle simulation, performance, and life models to evaluate options
  - — Designed for end of life – no change in performance
  - — Designed for beginning of life with change in performance
- Employ optimization and robust design tools to identify key design attributes





Work with others to demonstrate usefulness of this trade-off analysis framework

Vision: How This Battery Trade-off Framework May be used by Companies with Confidential Models/Data?

- Exchange of model parameters and results through secure Internet firewalls.
- Confidential data/models maintained internally, key results shared to formulate optimum solutions