The Enabling Role of Nanomaterials in Lithium Battery Technology for Improved Energy Utilization

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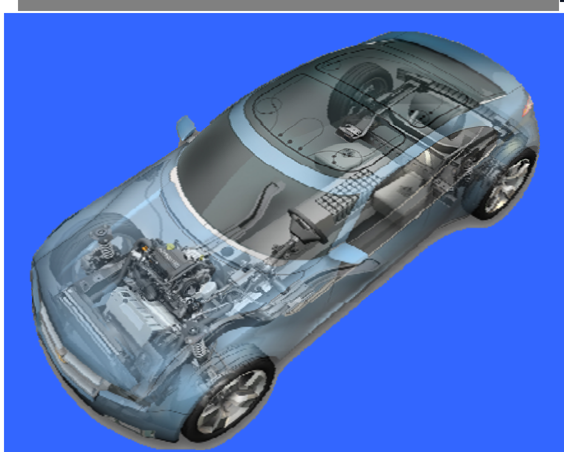
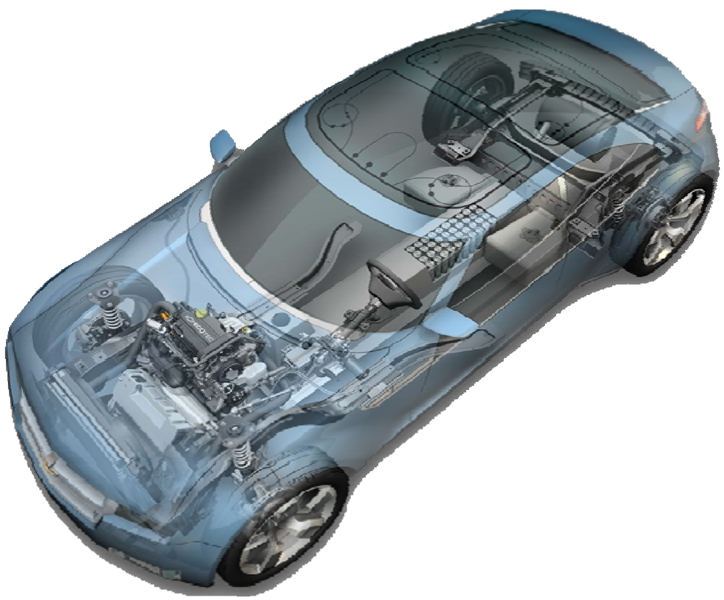


Where we are, and where we need to be

Lithium-ion cells for portable devices

- Volumetric energy is the key metric
- 300 charge/discharge cycles (1 yr life)
- Slow charge/discharge, ~1C rate (1hr) or slower
- Small (<5 Wh) cell size
- In market place since early 1990's; billions produced
- Still, >50 million batteries recalled over the past 2 years for safety reasons

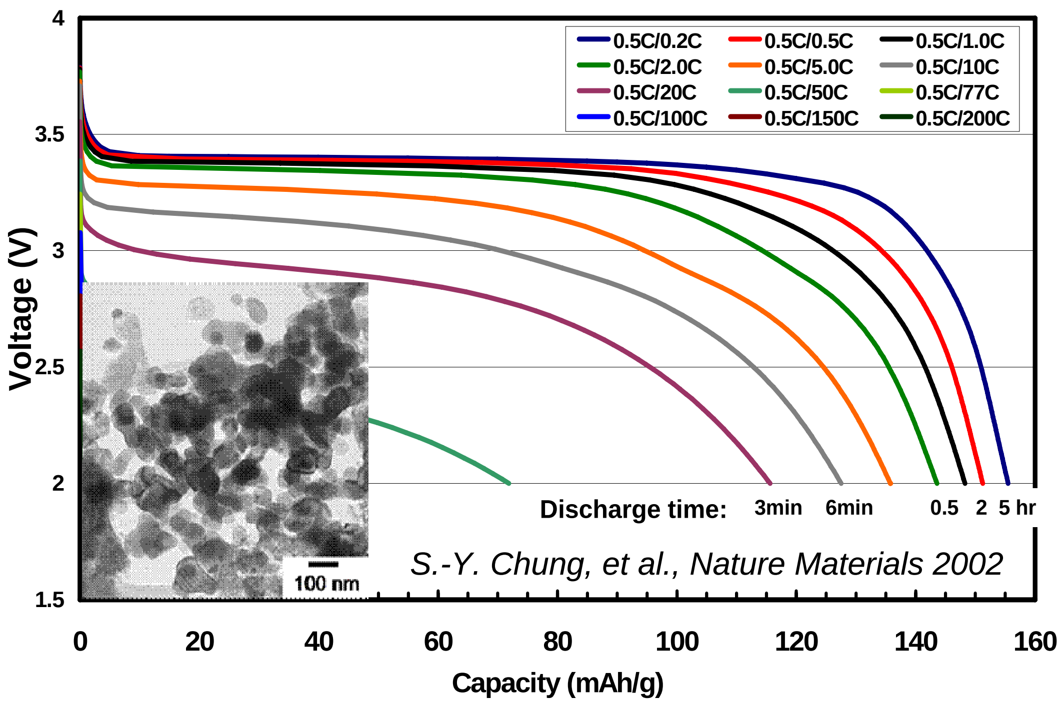
The 2010 Chevy Volt

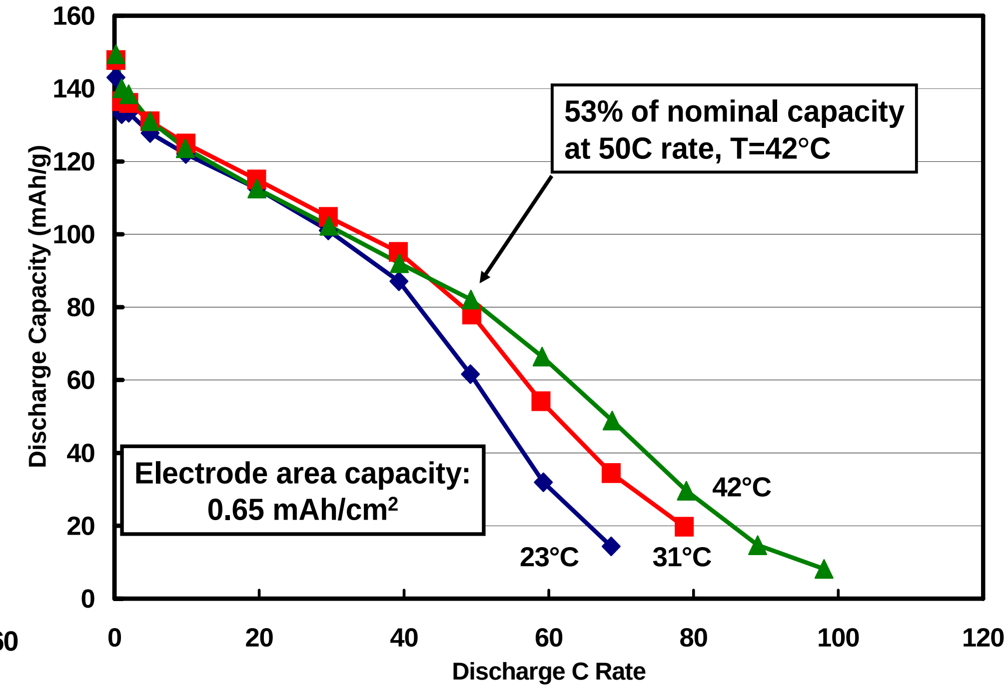


Advanced batteries for transportation

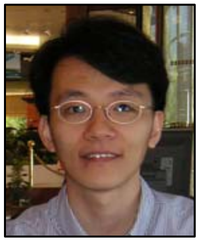
- Gravimetric power and energy are key, and favor lithium chemistry
- 6000 deep cycles for PHEV
- 300,000 shallow cycles for HEV
- 3C to >50C pulse charge/discharge rates
- 15 year calendar life
- Extreme safety in large packs (>5 kWh)
- Affordable

High Power Doped Nanoscale $LiFePO_4$ Olivine (2002)





NYTimes reporter: *So how long do you think it will be before real batteries will be made using these new materials?*



MIT Team
Circa 2002

Power Tool Applications of Nanophosphate™ Began 2 yrs Ago

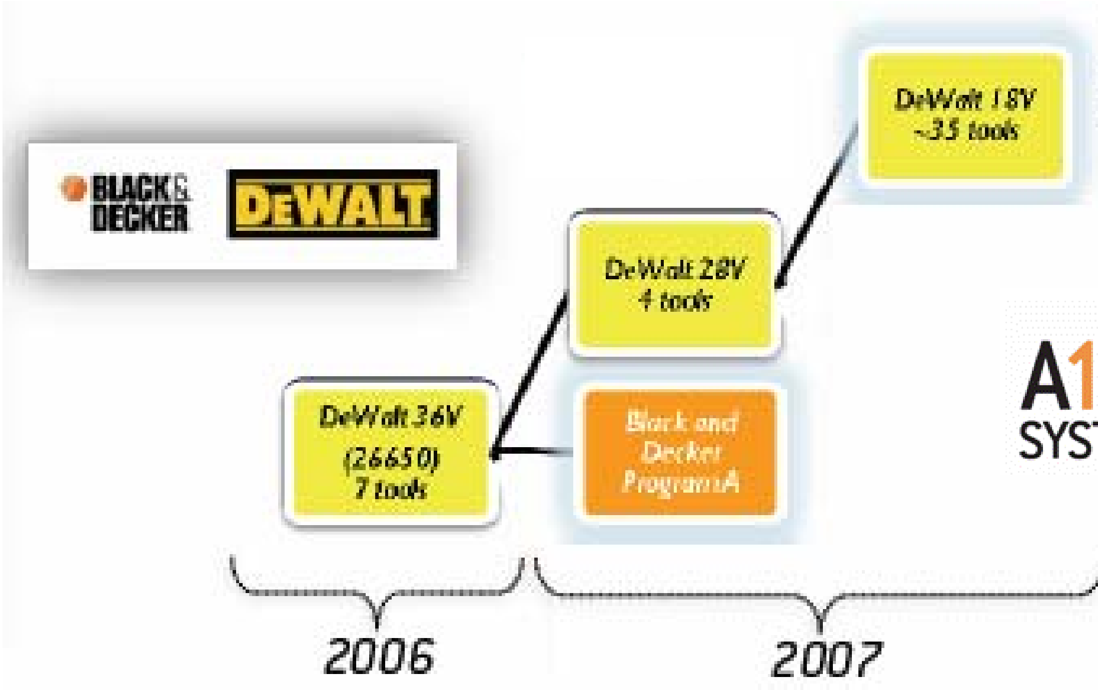
From 600-700W in 1.1kg (18V NiCd battery pack)

to 3000W in 1.1 kg (36V Li-ion battery pack)

→ 2x the peak power of corded power tools

- 3.3V, 2.3 Ah (7.2 Wh) cell of 26650 format
- >3000 W/kg peak power
- 110Wh/kg specific energy >150A pulse current
- 2000 cycles @100% depth of discharge
- >300,000 hybrid pulse power cycles
- Extremely low impedance growth

R&D 100



A123 SYSTEMS

From Power Tools to Vehicles

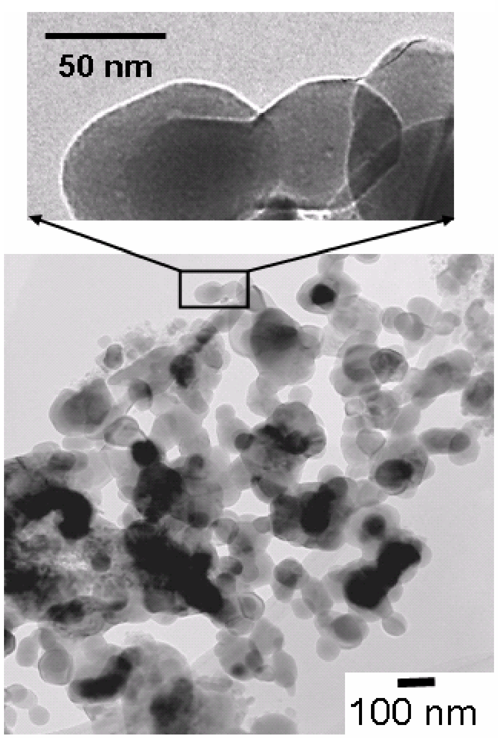
What enables high power in Li*M*PO4 olivines?

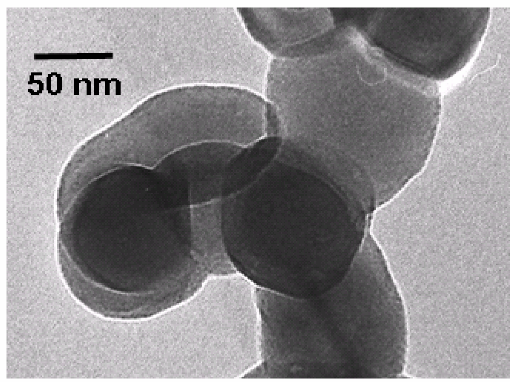
Are there fundamental changes in properties at the nanoscale?

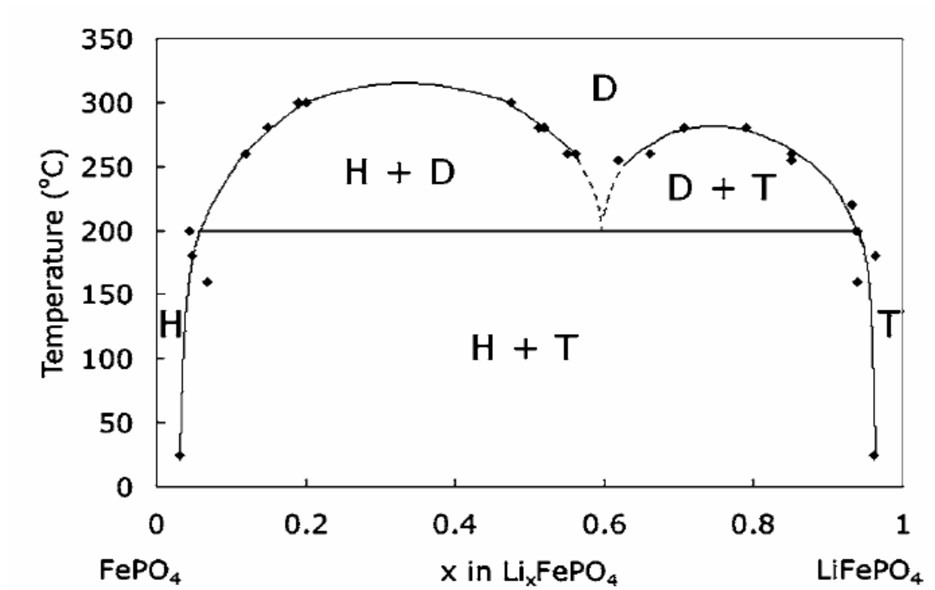
(Is this really nanotechnology?)

Or just Fickian diffusion kinetics at small length scale?

- Olivines like many intercalation compnds undergo 1st order transition upon cycling.
  $\rightarrow$ Maximizing power = maximizing rate of the phase transition
- Charge/discharge kinetics are a direct measure of the rate of phase transformation
- Something besides transport (electronic, ionic) rate-limiting?
- Focus on the elastic misfit and phase transformation kinetics

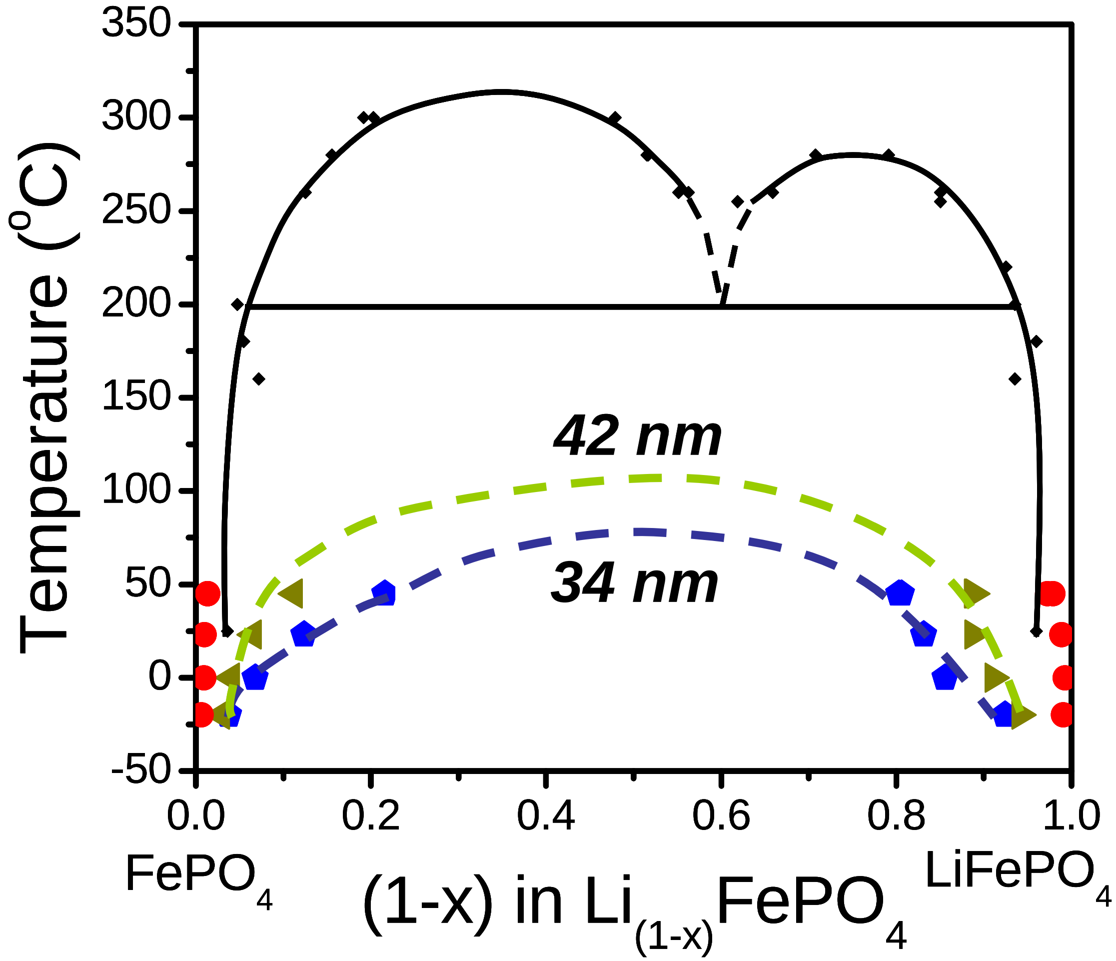


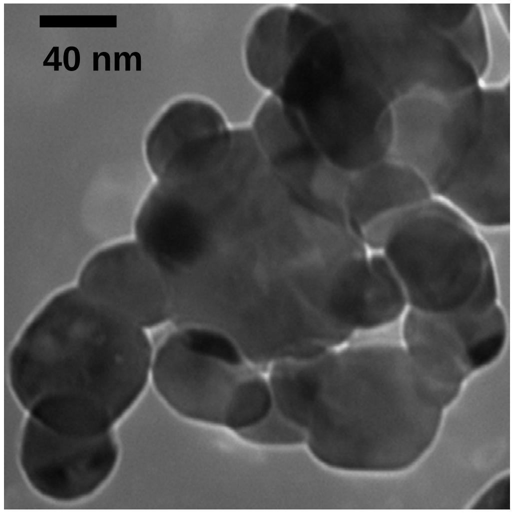


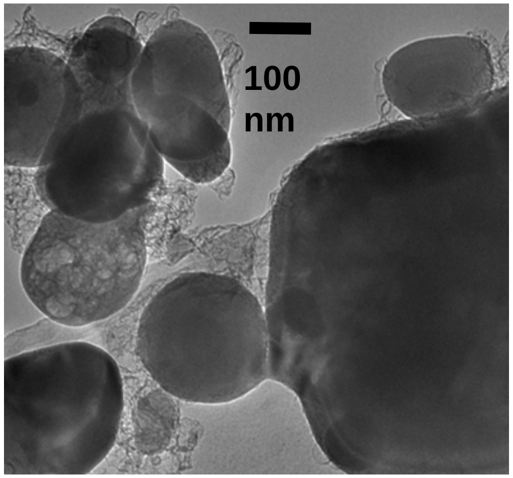


Dodd et al., ESSL 2006

Nanoscaling and Doping of Olivines Radically Shrinks the Miscibility Gap

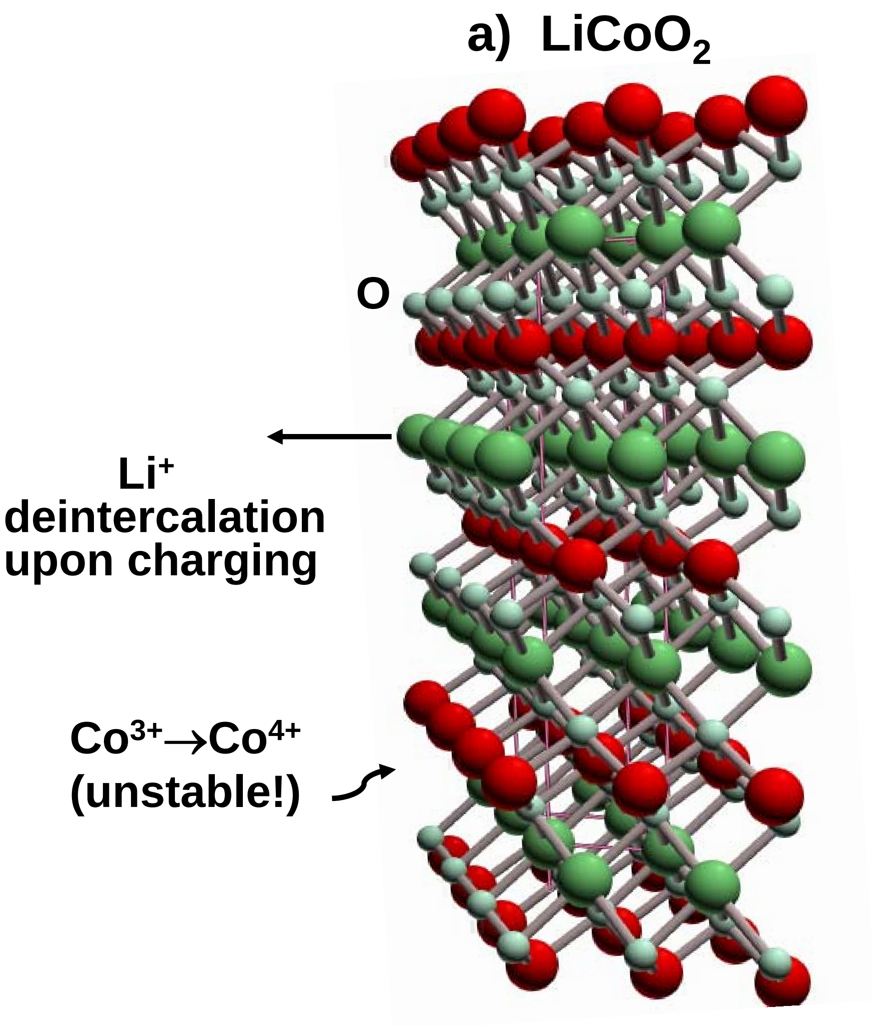


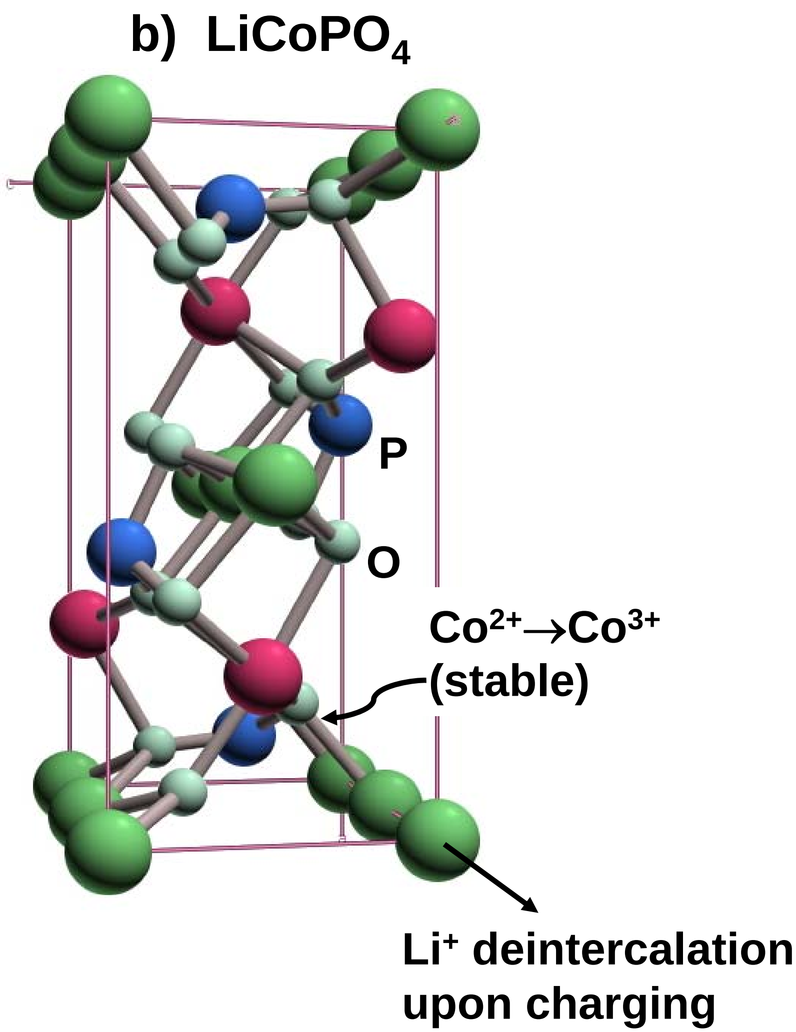




N. Meethong *et al.*, *Electrochem. Solid State Lett.*, 10[5] 134-138, 2007
(Undoped phase diagram from *Dodd et al., ESSL 2006)*

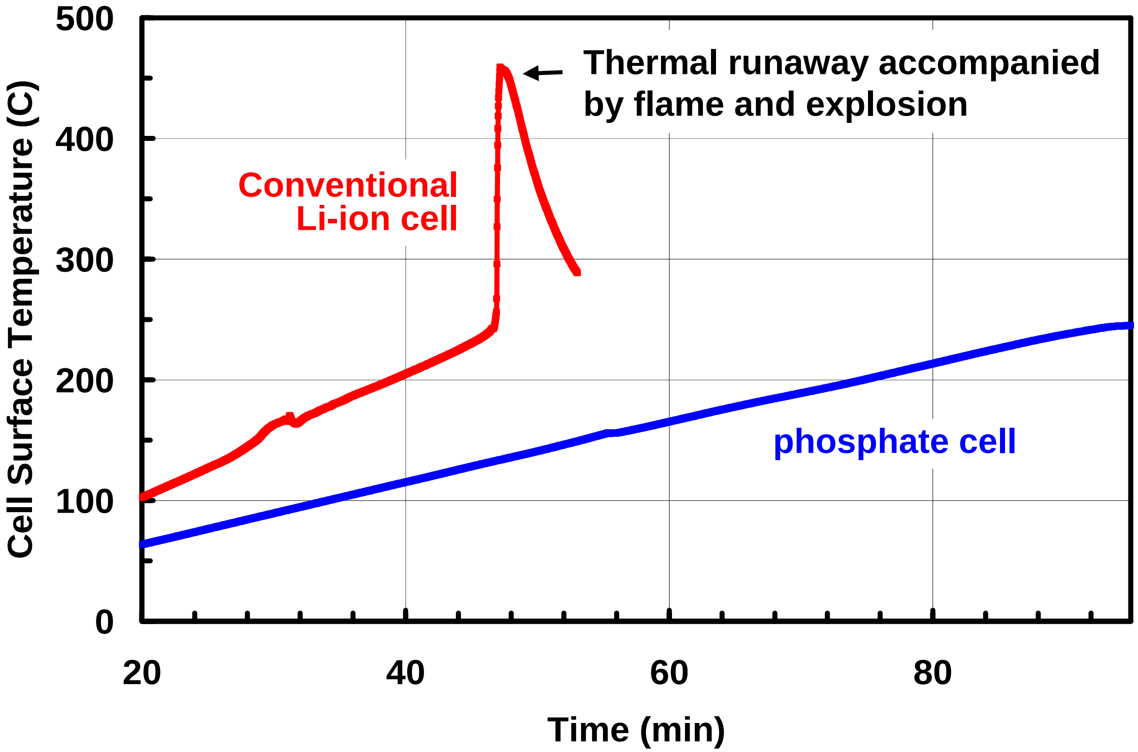
Lithium Ion Battery Safety: The positive electrode in the charged state has been of greatest concern





$LiCoO_2$ and its nickel-containing derivatives used as the positive electrode in lithium-ion batteries experience an oxidation of Co^{3+} to unstable Co^{4+} (or Ni^{3+} to unstable Ni^{4+}) as Li^+ ions are removed from the lattice upon charging. In contrast, a phosphate-based cathode such as $LiCoPO_4$ undergoes oxidation of Co^{2+} to a stable Co^{3+} state (or Mn^{3+}, or Fe^{3+}), resulting in a safer, fault-tolerant cell chemistry.

Comparison: Conventional $LiCoO_2$ vs. New Phosphates



Sandia National Lab test chamber

Comparison of conventional lithium-ion battery exhibiting thermal runaway followed by flaming and explosion, with intrinsically safer phosphate-based lithium ion cells. (Test data performed at Sandia National Laboratory on full-size cylindrical cells. Charged cells are instrumented with thermocouples and heated at constant rate to seek thermal events.)

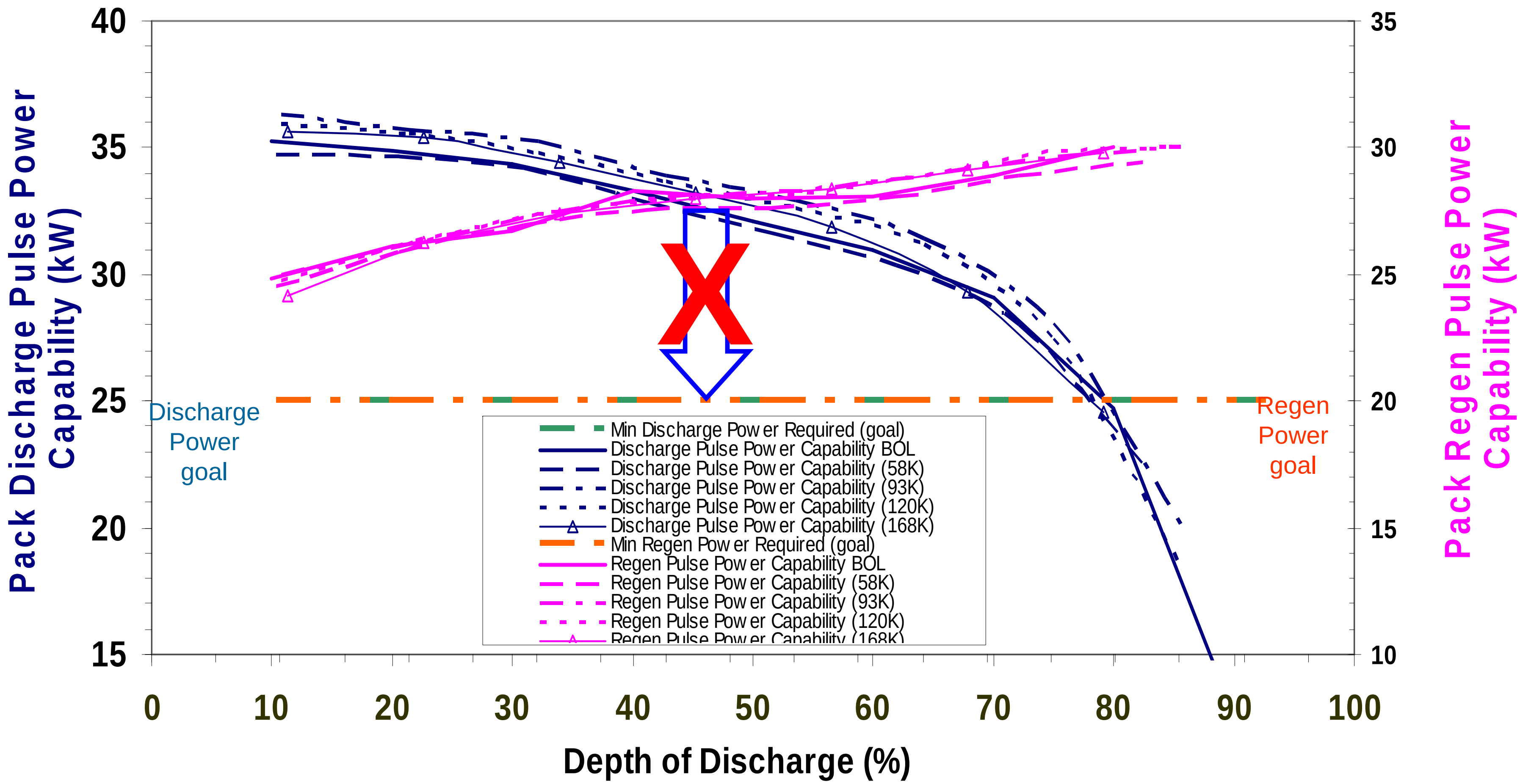
Applications Using High Power Cells

Truck and bus Hybrid packs

Aviation packs

BAE HybriDrive Propulsion System for the 2008 Daimler Chrysler Orion VII Bus

For HEVs, higher power and longer life translates to smaller packs, less “oversizing,” lower cost



In typical systems, curves shift down due to impedance growth

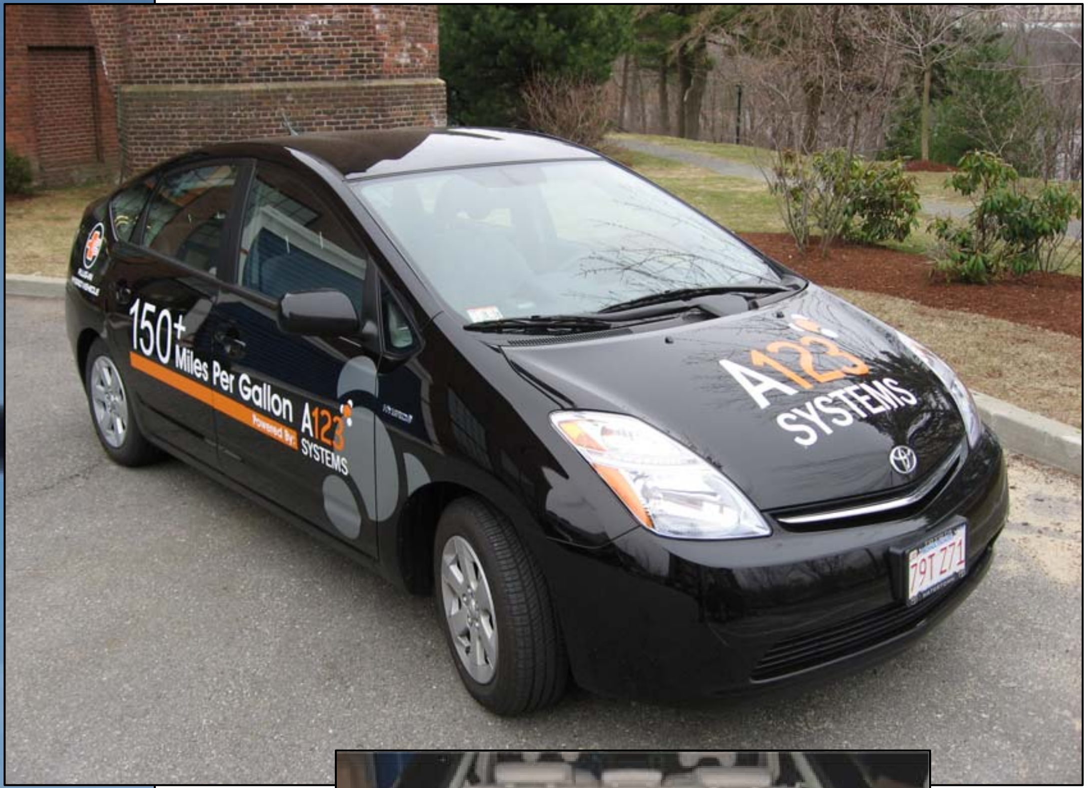
$\frac{\$ \Downarrow}{kW \Uparrow}$ Reduce cost / Increase power

Nanophosphate™ cells exhibit minimal impedance growth: no substantial loss of power with cycling

Improving power *reduces* system cost.

A123 SYSTEMS

Plug-in Hybrids:
The vehicle of the future

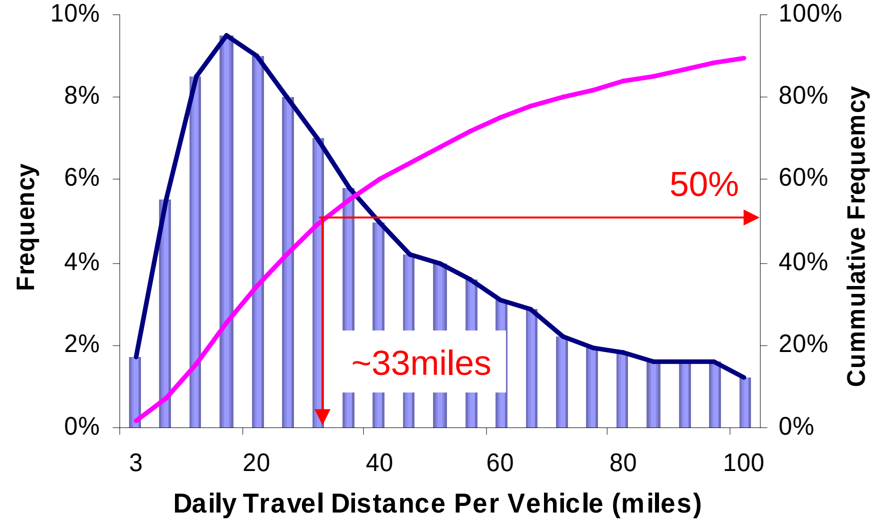


Lucy Sanna, EPRI

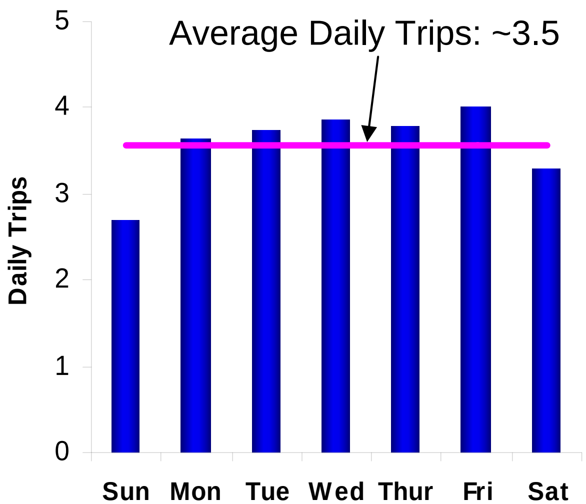
How Americans Drive

- Half the cars are driven less than 40 miles
  - Median daily travel distance is ~33 miles
- Average vehicle travel ~3.5 trips per day
- Most of the daily trips are less than 10 miles
- 10% of vehicles travel >100 miles daily

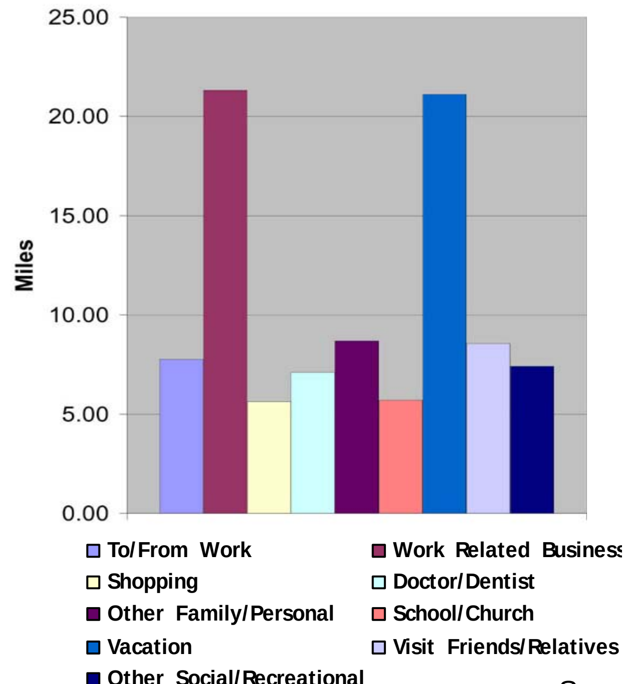
1995 NPTS
Daily Vehicle Travel Pattern



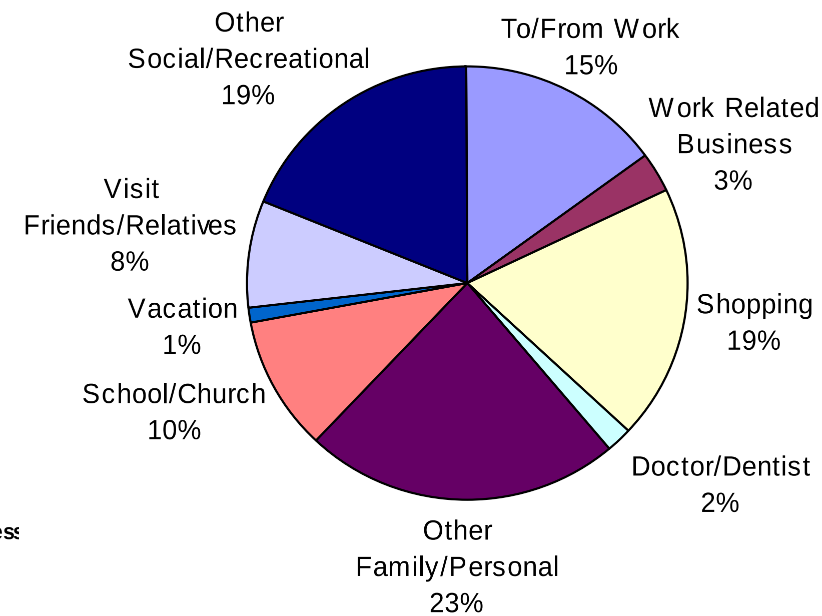
Average Daily Trips



Average Trip Length by Trip Purpose



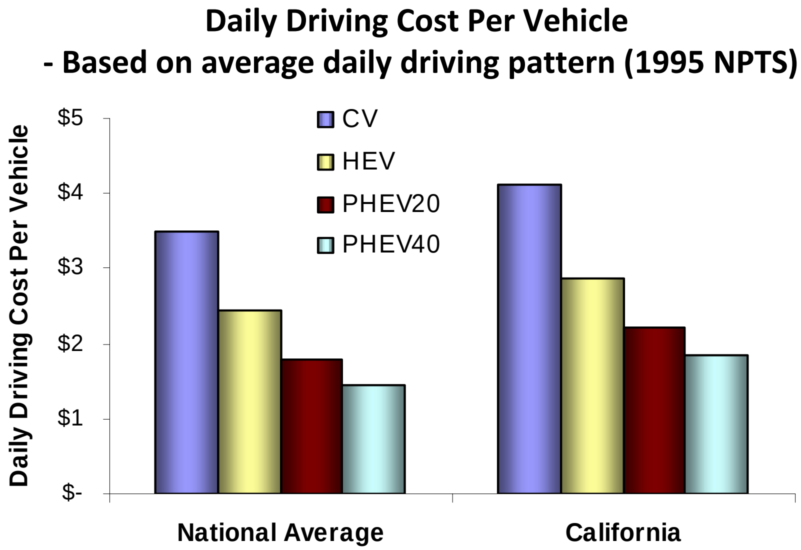
Percentage of Daily Trip Purpose



Source: 2001 National Household Travel Survey

Operating Cost Analysis

- PHEV have lower daily operating cost everywhere
- PHEV operating cost is sensitive to the local electricity price



Assumptions (also used in later studies):

National average retail electricity price: **10** cents/kWh

National average retail gasoline price: **2.5** $/gal

CA average retail electricity price: **13.84** cents/kWh

CA average retail gasoline price: **2.95** $/gal

Passenger vehicle weight: ~3500 lb

Gasoline Engine CV: **25** miles/gal

HEV: **35** miles/gal

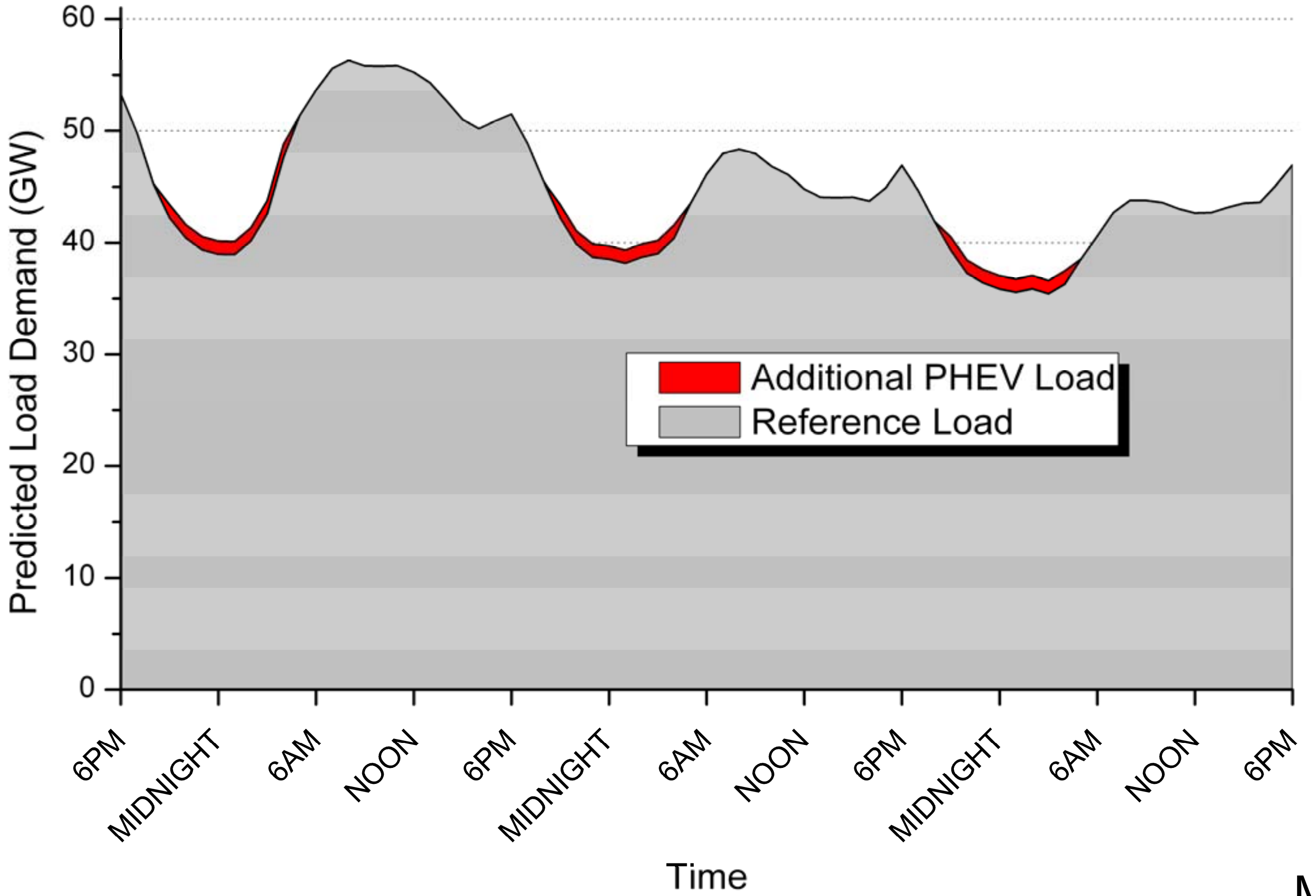
EV: **3.4** miles/kWh

State	Retail Residential Electricity [1] (cents/kWh)	Retail Gasoline [2] ($/gal)	CV (cents/mile)	HEV (cents/mile)	PHEV20 cents/mile)	PHEV40 (cents/mile)
New York	16.35	2.75	10.98	7.84	**6.0**	**4.8**
Illinois	8.32	2.69	10.77	7.69	**4.5**	**2.4**
Texas	12.43	2.34	9.36	6.68	**4.8**	**3.7**
California	13.84	2.85	11.39	8.14	**5.7**	**4.1**
Hawaii	23.15	3.50	14.00	10.00	**8.1**	**6.8**

Note: Assuming 33 miles driving distance

Sourcse:
http://www.eia.doe.gov/cneaf/electricity/epm/table5_6_b.html#_ftn1
http://www.eia.doe.gov/oil_gas/petroleum/data_publications/wrgp/mogas_home_page.html

PHEV Electricity Demand Likely in Off-Peak



Model: IPM

- Additional load from PHEVs is small
- PHEVs could be charged mostly via base-load filling during evenings and nights, when electricity costs are low

Advances In Battery Technology Are Enabling PHEVs

Forbes: *Why not do the Volt three years ago, when the EV1 was cancelled?*

Bob Lutz (General Motors, Vice Chairman): *The reason we're working on the Volt now is that lithium ion batteries have made huge progress in the last three years. One of the companies we're working with has very big lithium ion batteries it uses in power tools, and we're working with that company, A123 in Massachusetts.*

40 Mile PHEV Module	Lead Acid	NiMH	Lithium Ion
Size (Cubic Ft)	23	10.5	4
Weight (Lbs)	1,100	600	180

Commuting Distance	Measured City MPG	Measured Hwy MPG
20 miles	174	117
40 miles	153	103
60 miles	124	90

Independent performance testing of modules at Argonne National Labs

E-Flex: Electric drive with flexible generator choice (i.c. engine, fuel cell, etc.)

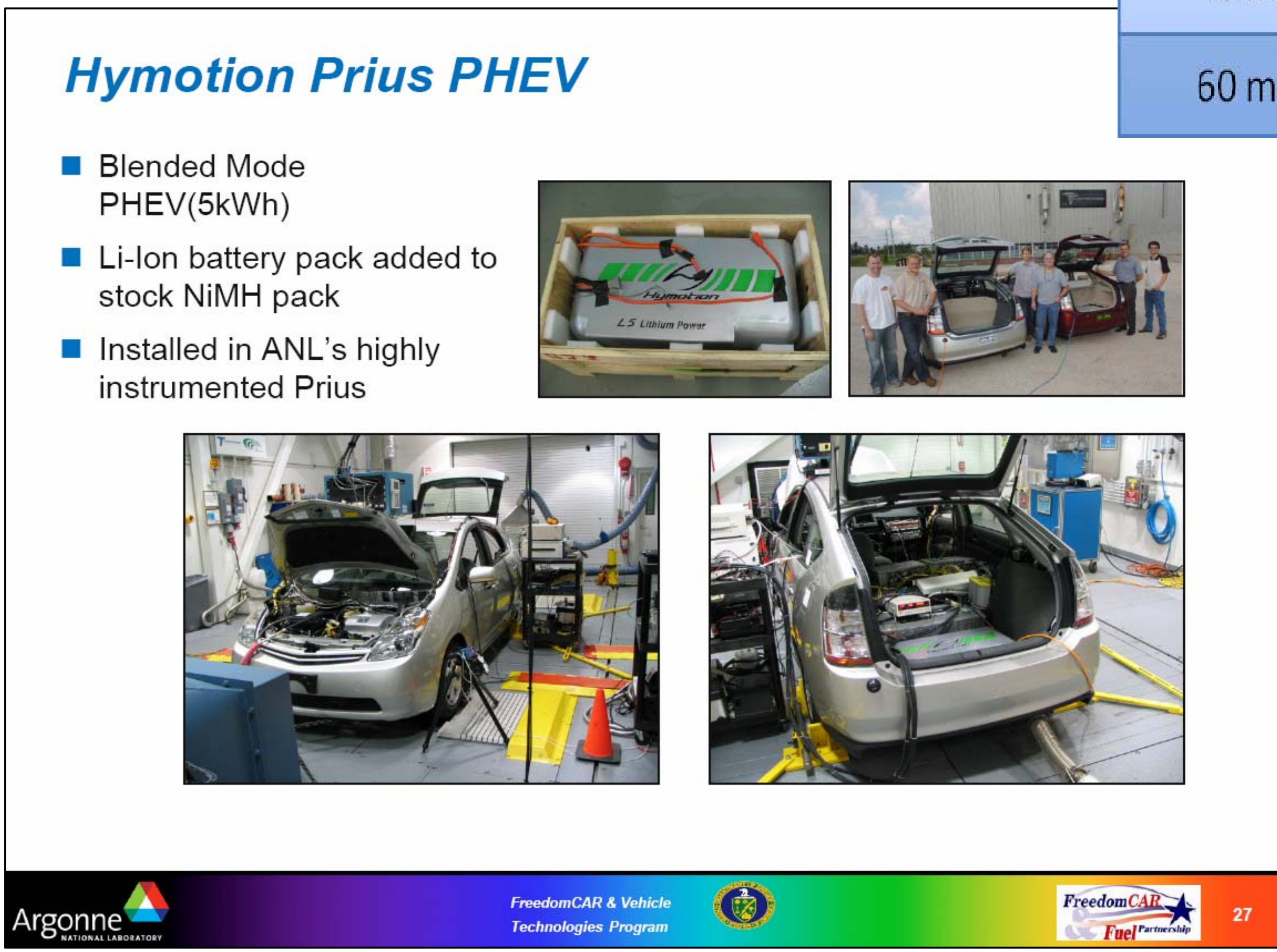
GM Saturn VUE Plug-In HEV

World's first production PHEV program

Prius PHEV Conversion tested at Argonne National Labs

• 80% lower gas consumption
• 50% lower greenhouse gas emission
Compared to 25 mpg gasoline powered car

Commuting Distance	Measured City MPG	Measured Hwy MPG
20 miles	174	117
40 miles	153	103
60 miles	124	90



Hymotion

Summary

- Nanomaterials innovations are driving advances in battery technology. Enormous leverage can result from advances in cathodes, anodes, electrolyte, etc.
- Lithium ion batteries have come a long way in the past few years, and now provide realistic levels of power, energy, safety and life for deployment in large-scale systems (>1 kWh) ranging from aircraft engine start to hybrid buses to automotive HEV and PHEV
- There are three key benefits to this technology:
  - Reduced operating cost to the consumer
  - Reduced greenhouse gas emissions
  - Reduced dependence on foreign oil
  - What's not to like?
- This is version 1.0 of a technology that will continue to grow and improve.
- Cost reduction is key to widespread adoption, and in this field *improved performance translates directly to lower cost*.

Thank you for your attention!