Prospects of Batteries for PHEV Applications

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Thesis

- Electric vehicles (EVs) are substantially more efficient than other advanced-technology vehicles. Based on the same primary sources and vehicle miles, EVs use less energy, generate less greenhouse gases, and cause fewer emissions of pollutants.

  In principle, electricity and EVs are the energy-strategic and environmentally superior links for coupling individual transportation to future energy sources.

But:

Batteries required for EVs to match the technical (especially range) and cost characteristics of market competitive CVs and HEVs do not presently exist, nor are there realistic prospects for their development in the foreseeable future.

Batteries and EVs with lesser attributes are feasible but unlikely to capture mass markets and generate nationally and globally significant energy-strategic and environmental benefits.

Thesis

- PHEVs offer the best prospects among advanced-technology vehicles to achieve a large portion of EV benefits while offering market competitive attributes and life cycle costs in the foreseeable future.

  The main challenge for PHEVs is the battery, but compared to EVs battery size and cost issues are much reduced.

NiMH Prospects for PHEVs

Advantages:

- NiMH technology for HEVs is readily upscaled to PHEVs
- PHEV operating and market experience can be acquired rapidly with appropriately modified HEVs

But:

- Ability of NiMH to achieve more than 2000-2500 deep cycles in PHEV service is questionable
- NiMH weight and cost also are issues for AER>10 miles

Conclusion:

- NiMH batteries of relatively small capacity (e.g. ≤ 3-4 kWh) might find application in PHEVs with short AER but only if batteries deliver >2500-3000 deep cycles

Thesis

- Among known battery types, only lithium ion technologies have good prospects to meet the performance, life, and safety requirements - as well as the life cycle cost constraints - for a wide range of PHEV architectures and applications.

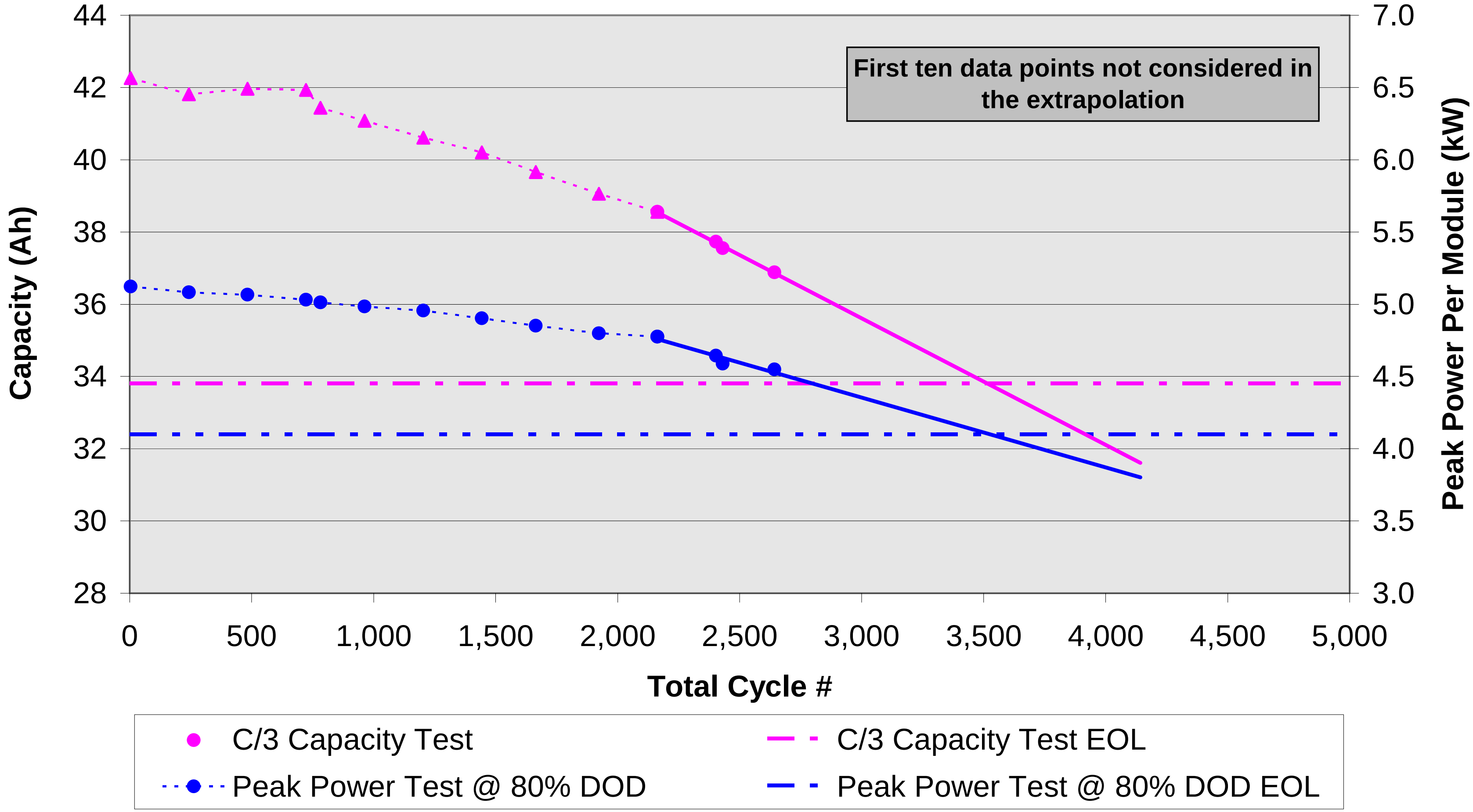
Li Ion Prospects for PHEVs: Performance

ATV Type **Battery Type**	Weight (max. kg)	Peak Power (min. kW)	Power Density (min. W/kg) **Battery Capability**	ES Capacity (min. kWh)	Energy Density (min.Wh/kg) **Battery Capability**
Full HEV	50	40-60	800-1200	1.5-2.5	30-50
PHEV-20	**120**	**50**	**~400**	**7**	**~60**
PHEV-40	**120**	**65**	**~540**	**14**	**~120**
Li Ion (battery)	**n.a.**	**n.a.**	**500-900**	**n.a.**	**75-120**
NiMH (module)	**n.a.**	**n.a.**	**250-400**	**n.a.**	**50-60**
EV (midsize)	250	100	400	40	160

Li Ion Prospects for PHEVs: Cycle Life

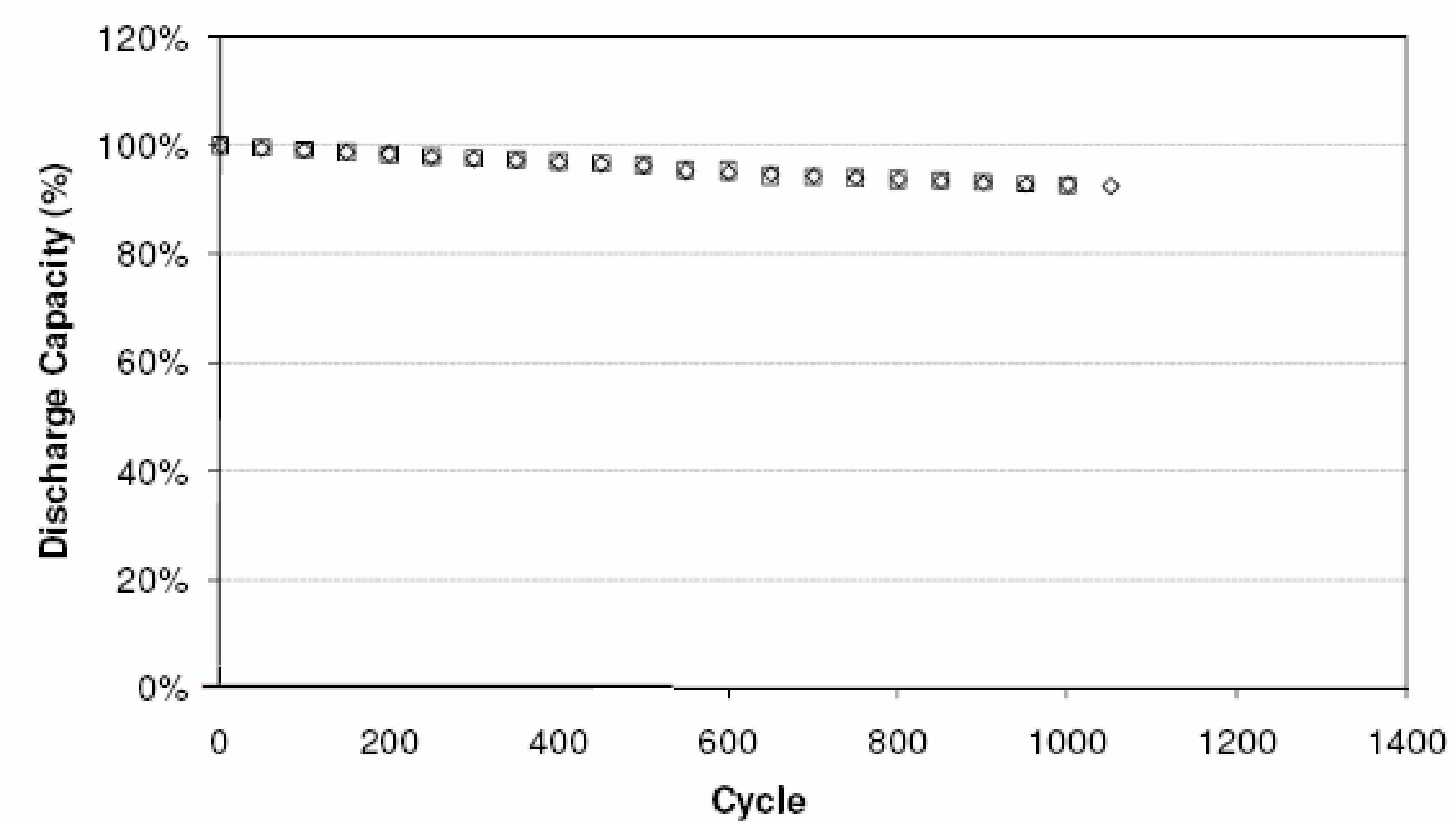
- PHEV batteries need to deliver >2500-3000 deep cycles over battery life
- More than 3000 deep cycles reported by at least four Li Ion battery developers/manufacturers
  - different chemistries
  - different cell designs
- Cycling results very promising even for simulated PHEV battery operating conditions

Cycling Performance of JC-SAFT VLM41 Li Ion Technology



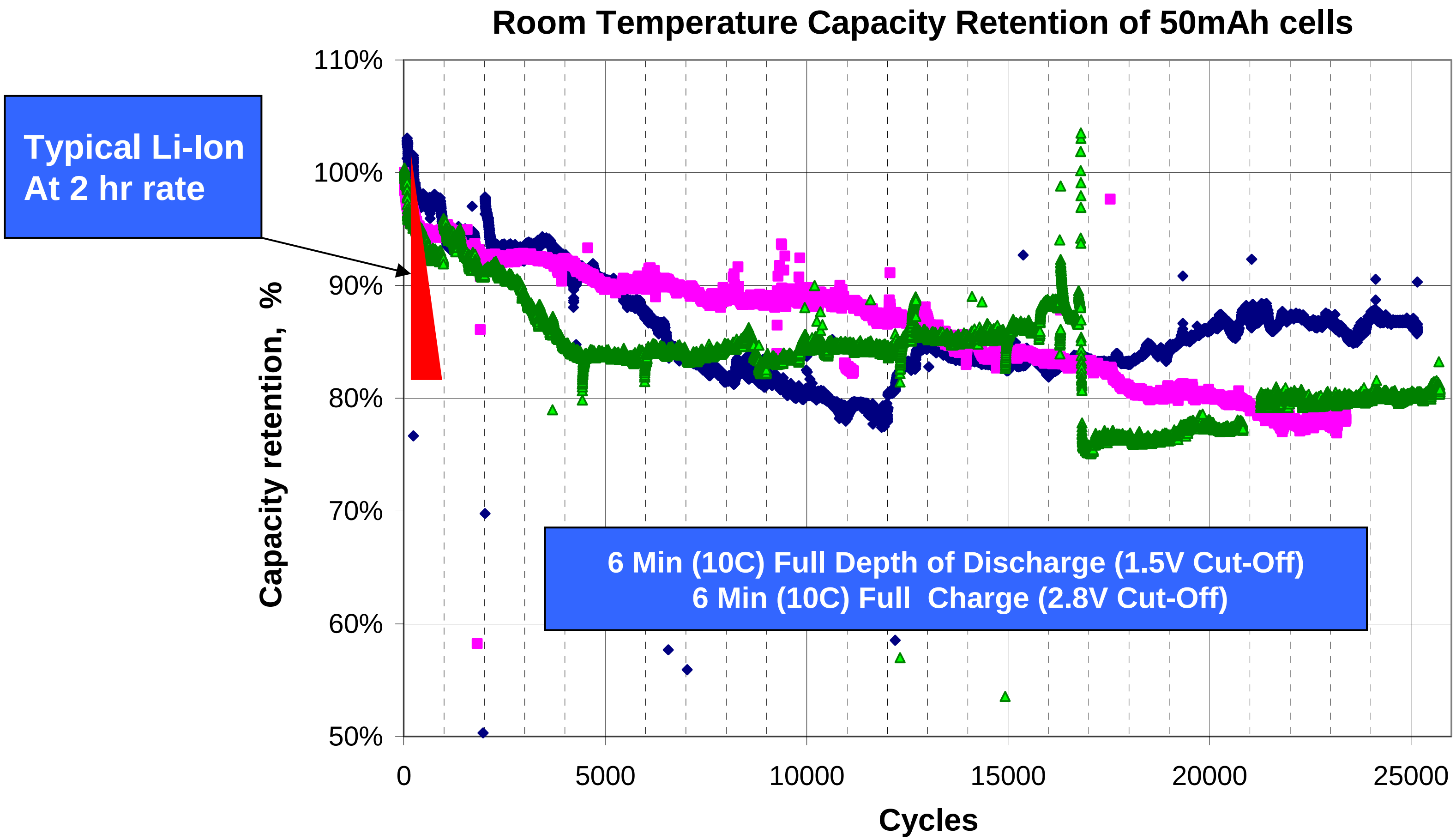
(module pack cycled to 75% DoD in simulated PHEV operating mode)

PHEV cycling of 32157 Cell from A123



* 8 DST mini-cycles per cycle
* SOC swing 74% (100-26% SOC)
* Total capacity measured every 50 cycles
* C/2 3.6V CCCV charge

100% DoD Cycling of Altairnano Cell



Li Ion Prospects for PHEVs: Safety

- Excellent on road safety experience with >5 year old Li Ion technology in ~ 100 EVs and HEVs
- Multiple sensing of key variables (temperature, pressure, voltages) and hierarchical levels of electric control enable safe system operation
- Newer cell chemistries have substantially higher levels of intrinsic safety (greater tolerance of abuse conditions)

Li Ion Battery Costs: Comparison of Projections with Propulsion Energy Cost Savings

Vehicle Type	Annual Mileage		Efficiency		NPV ($) Energy Cost Savings	Costs ($) Projected for Li Ion Batteries
	Gasoline (miles/yr)	Electric (miles/yr)	Hybrid Drive (mi/gal)	Electric Drive (mi/kWh)		
HEV	14,000	0	50	n.a.	2,878	3,025
PHEV-20	9,500	4,500	50	3.5	4,221	4,025
PHEV-40	8,000	6,000	50	3.5	4,669	5,585
EV	0	14,000	n.a.	3.5	7,056	8,395

Assumptions:
CV efficiency 36 mpg, gasoline cost $3.50/gal, electricity cost 12¢/kWh, battery life 10 years, production 100,000 packs/year, interest rate 6%

Final Thoughts

- Continuing concerns of carmakers may delay investment in Li Ion battery production and introduction of PHEVs
- There is much to do:

  Validation of best available Li Ion technologies:

  - Generate more life data (key variables SoC, ΔSoC, temperature)
  - Develop better tests (duty cycle simulation; accelerated testing)
  - Prove battery systems in vehicles (packaging; control/safety)

  Exploration/exploitation of advanced technologies:

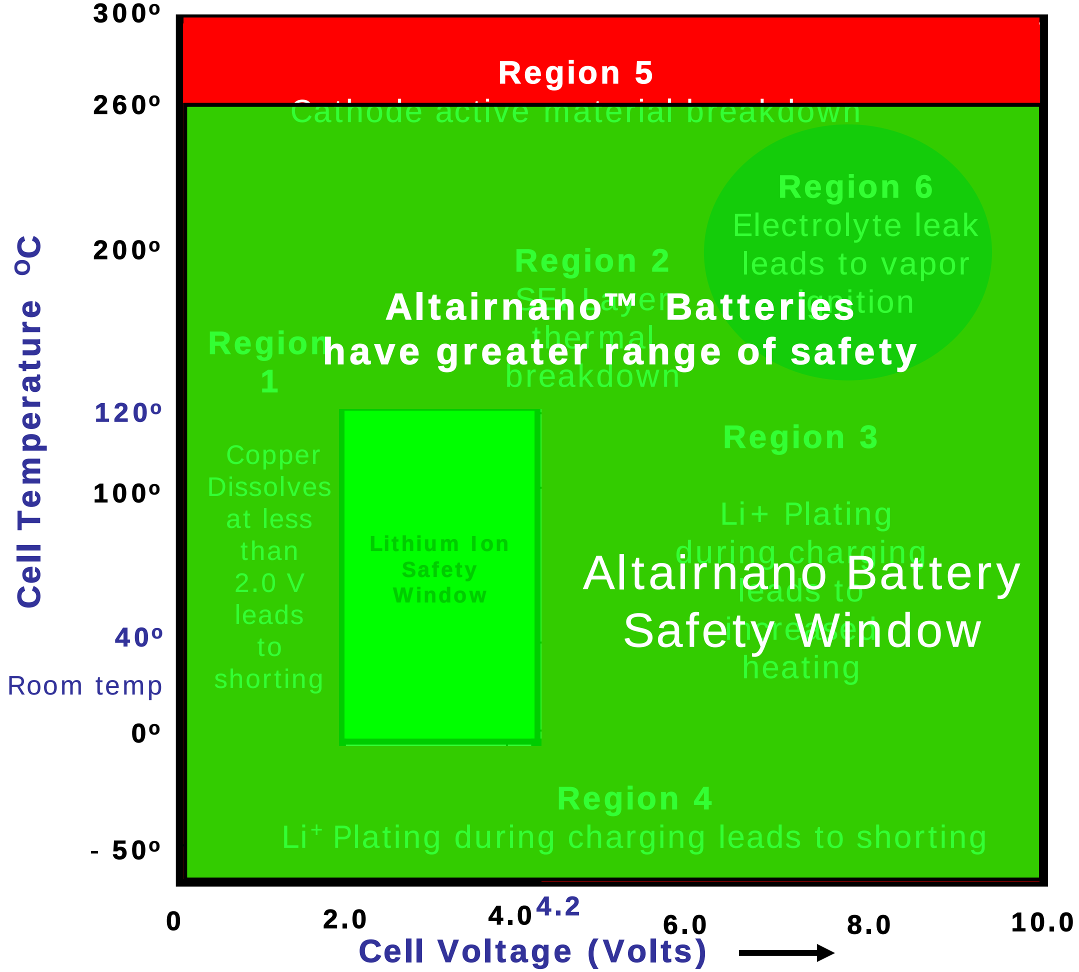
  - Develop and apply better screening test for durability & safety
  - Explore and optimize battery systems with parallel Li Ion cells
  - Explore advanced concepts (electrolytes; active materials; etc.)
- The next 2-3 years will do much to establish viability of Li Ion batteries for PHEV applications!

Projected Costs of Li Ion Batteries

Vehicle Type	Battery Capacity (kWh)	Cell Capacity (Ah)	2500 MWh/year 100k Batteries/Year		
			Production Rate (MWh/y)	Module Cost ($/kWh)	Battery Cost ($)
Full HEV	2	7	2500 200	550 1,010	1,650 3,025
PHEV-10	4	15	2500 400	395 605	2,240 3,445
PHEV-20	7	30	2500 700	295 405	2,750 4,025
PHEV-40	14	45	2500 1400	260 300	4,850 5,585
EV	40	120	2500 4000	195 175	9,285 8,395

Altairnano Products

The Altairnano battery solutions have minimal safety issues related to temperature and voltage due to the composition of the battery.

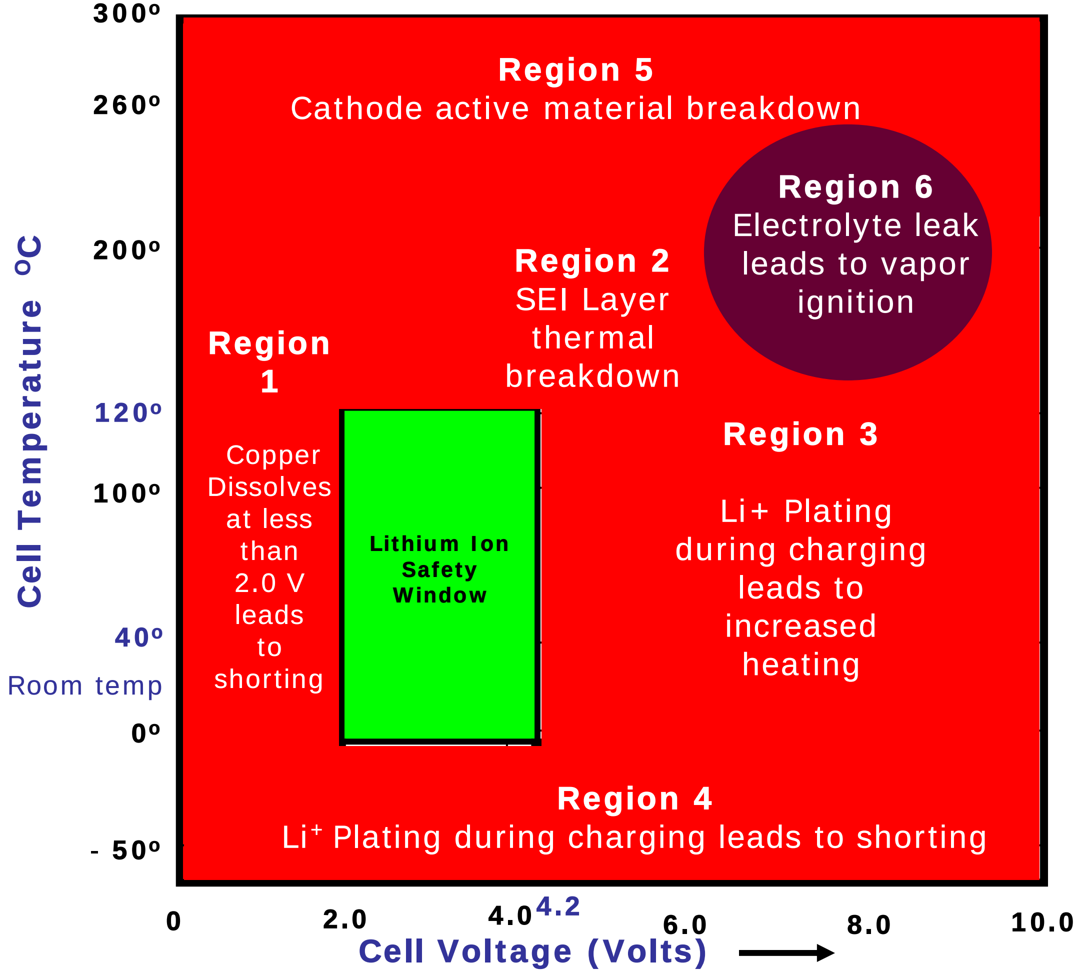


- **Region 1:** Uses no copper – batteries can be taken to very low discharge state
- **Region 2:** No dangerous SEI formed
- **Region 3:** Altairnano batteries "shut down" above 3.7V
- **Region 4:** Caused by SEI layer, Altairnano forms no dangerous SEI
- **Region 5:** Proprietary design removes this hazard
- **Region 6:** Eliminating dangers from other regions mitigates this hazard

Wide safety range for Altairnano products from -50° to 260°C

Lithium Ion Battery Safety

Lithium ion batteries require control of temperature & voltage to manage safety.



- **Region 1:** Dissolved copper re-plates on charge causing shorts
- **Region 2:** Thermal runaway virtually unavoidable once SEI layer breaks-down
- **Region 3:** Occurs at high-rates and can cause battery to explode
- **Region 4:** Lithium plating is unavoidable at cold temps; batteries can't charge
- **Region 5:** Combination of free oxygen, electrolyte, and exposed graphite leads to explosions
- **Region 6:** Runaway hazard from other regions enhances vapor exertion and ignition

Safe operation is confined to a relatively small range of V and T