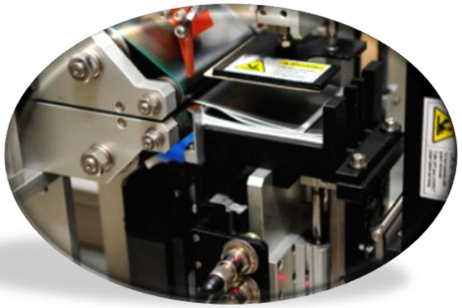
Advantages & Marine Applications of Various Lithium Ion Battery Chemistries

Mitch Mabrey – Spear Power Systems

MARAD META Battery Propulsion Conference, December 15, 2016

Lithium-ion Experts



-1989 -

Kokam Founded in Korea

- 2005 -

Kokam America Founded

- 2008 -

US Production Lithium Pouch Cells

- 2009 -

Joint Venture with Dow Chemical

- 2012 -

600 MWh Large Format Plant

- 2013 -

Spear Power Systems Formed

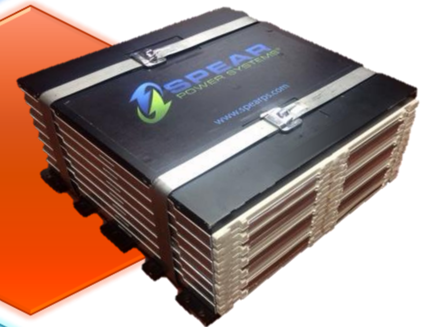
Spear Solutions

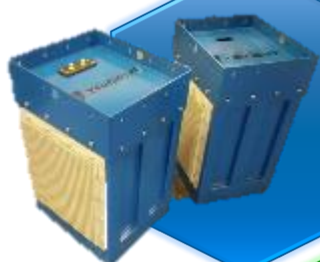
SBMS
Battery Management System

All Lithium Ion Chemistries (LTO, LFP, NMC) to 5V/cell
Modular – 3S to 24S Modules, 12 to 1250VDC Strings, Parallel Strings
High Data Rates & Resolution – Accurate SOC, SOH
Low Quiescent Current – Longer Shelf Life

SMOD
Prismatic Cell Modules

Low Resistance, Laser Welded Bus Connections
High Cell to Packaging Weight & Volume Ratio
Enhances Cycle Life
Air & Liquid Cooling
Managed Cell Venting
Cell Group to Group Propagation Protection





Standard ESS

Trident™ Modules for Marine Sector
Power Bore™ Modules for Mining & Industrial Sectors
Air or Liquid Cooling
Rack or Stackable Module Configurations

TRIDENT™

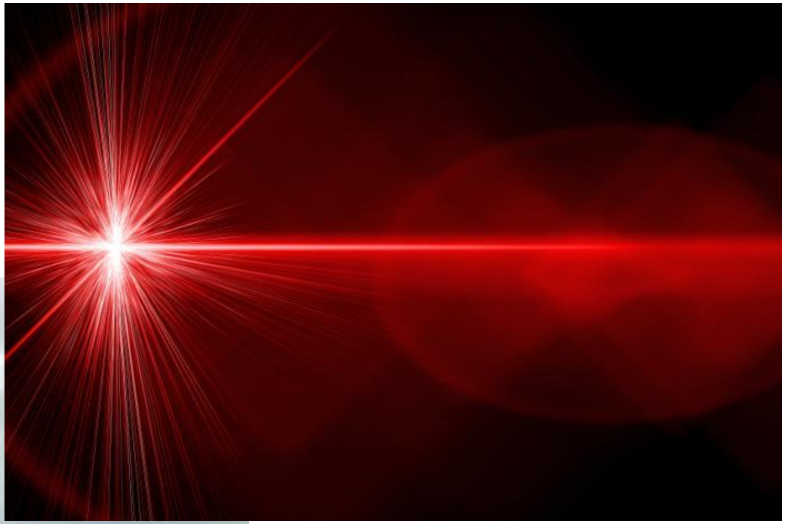
POWER BORE™

Custom ESS

High Density Packaging
Quick Design Cycle due to SBMS & SMOD
Custom Thermal Management
Application Specific Enclosures

Technology is changing…

Not all batteries are the same...

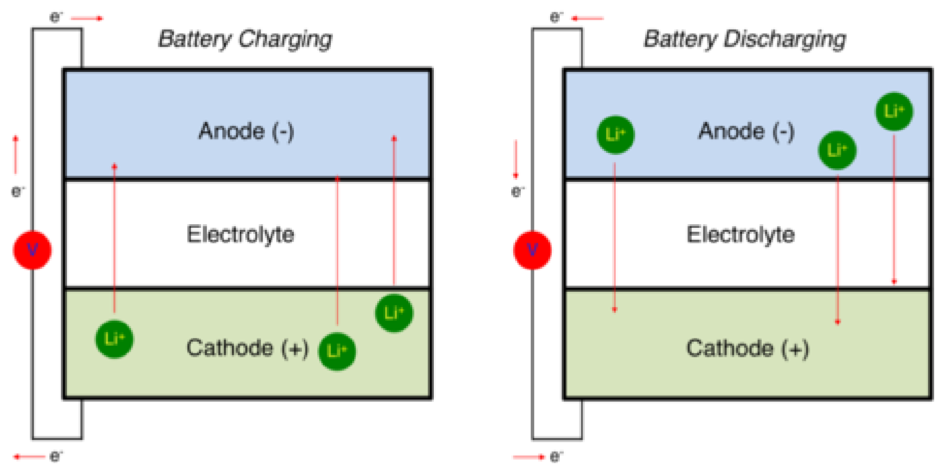


What’s Lithium-ion?

Lithium-ion is a generic, umbrella term – chemistries are unique in their advantages & limitations, named for their active materials

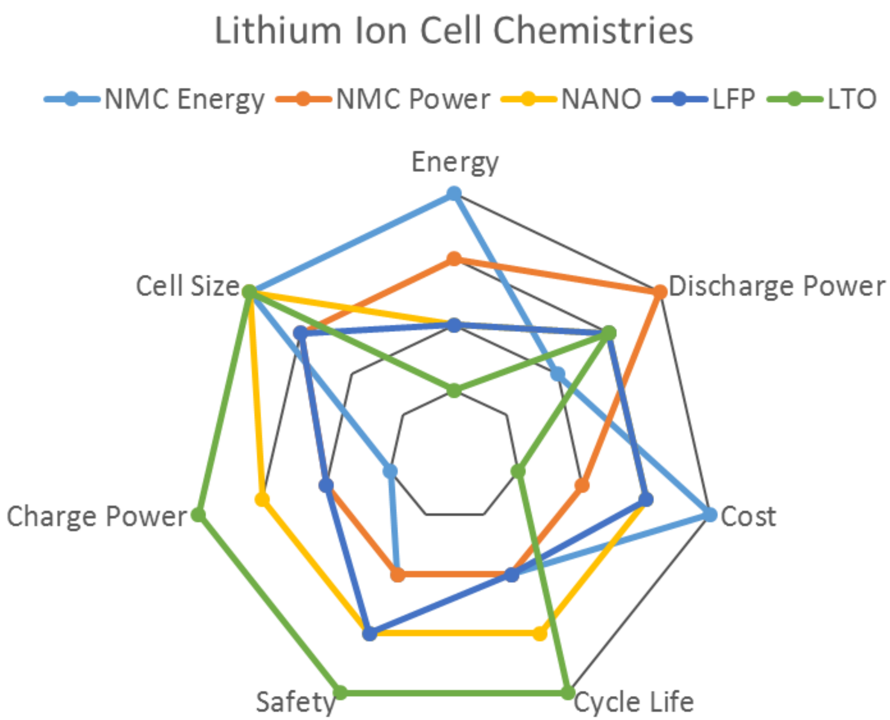
Lithium-ion Comparison

Lithium-Ion Chemistry	Chemical Composition	Cathode (+)	Anode (-)	Nominal Voltage
Nickel Manganese Cobalt (NMC)	$Li(NiMnCo)O_2$	Nickel Manganese Cobalt	Graphite	3.6/3.7 V
Lithium Iron Phosphate (LFP)	$LiFePO_4$	Lithium Iron Phosphate	Graphite	3.2/3.3 V
Lithium Titanate Oxide (LTO)	$Li_4Ti_5O_{12}$	NMC, NCA, LMO	LTO	2.2/2.3 V



SOURCE: *https://cdn.shopify.com/s/files/1/0674/3651/files/battery_large.png?7800179505369118554*

Marine Value Drivers



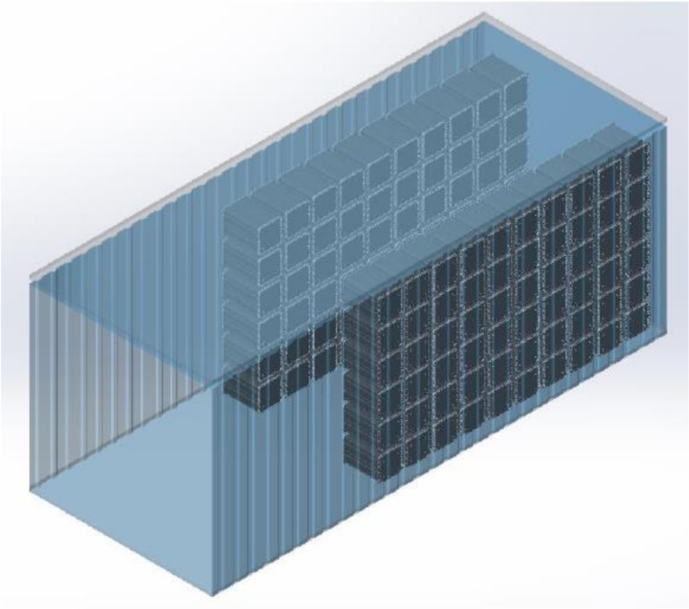
Spider plot ratings are relative to the other chemistries listed. The farther out along the plot axes, the higher performing the solution.

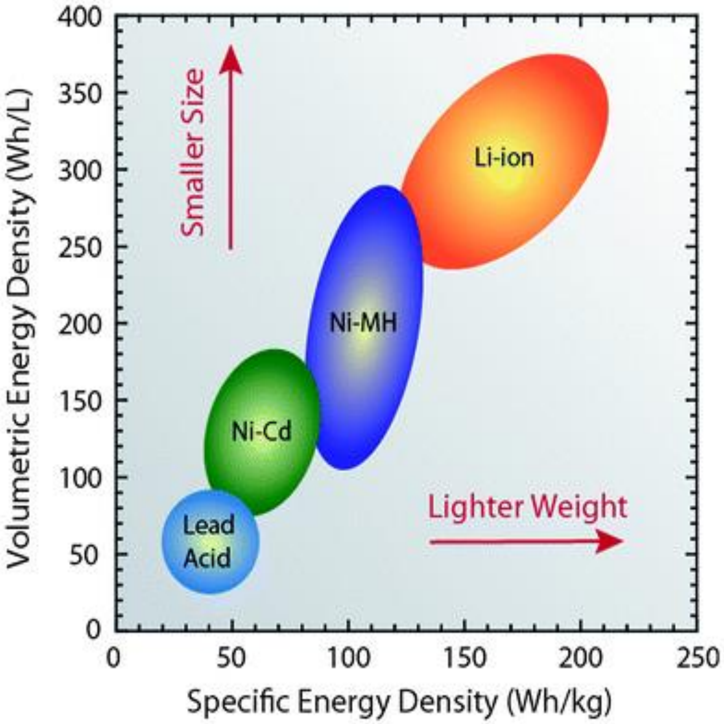
- **Energy** – specific energy & energy density
- **Discharge Power** - maximum continuous discharge rate
- **Cost** - production volume cell cost. Farthest out = lowest cost
- **Cycle life** – # cycles at the same DOD and temperature
- **Safety** – aggregate of the cell's ability to tolerate destructive overcharge, short circuit, heating, or mechanical abuse.
- **Charge Power** - maximum continuous charge rate
- **Cell Size** - maximum capacity cells commercially available in high quality serial production

Acronym	Cathode (+ Electrode)	Anode (- Electrode)	Nominal Voltage (V)
NMC Energy	Nickel Manganese Cobalt	Graphite	3.7
NMC Power	Nickel Manganese Cobalt	Graphite	3.7
NANO	NMC w/ LFP Coating	Graphite w/ LTO	3.7
LFP	Lithium Iron Phosphate	Graphite	3.3
LTO	NMC, LMO, NCA, or LFP	Lithium Titanate	2.3

Energy Density

- Lower energy density leads to a larger and heavier battery system
- Limits propulsion power
- Large difference between cell-level energy density and system-level energy density → **robust packaging necessary**





SOURCE: *http://www.epectec.com/batteries/cell-comparison.html*

Energy Density Example

Cell

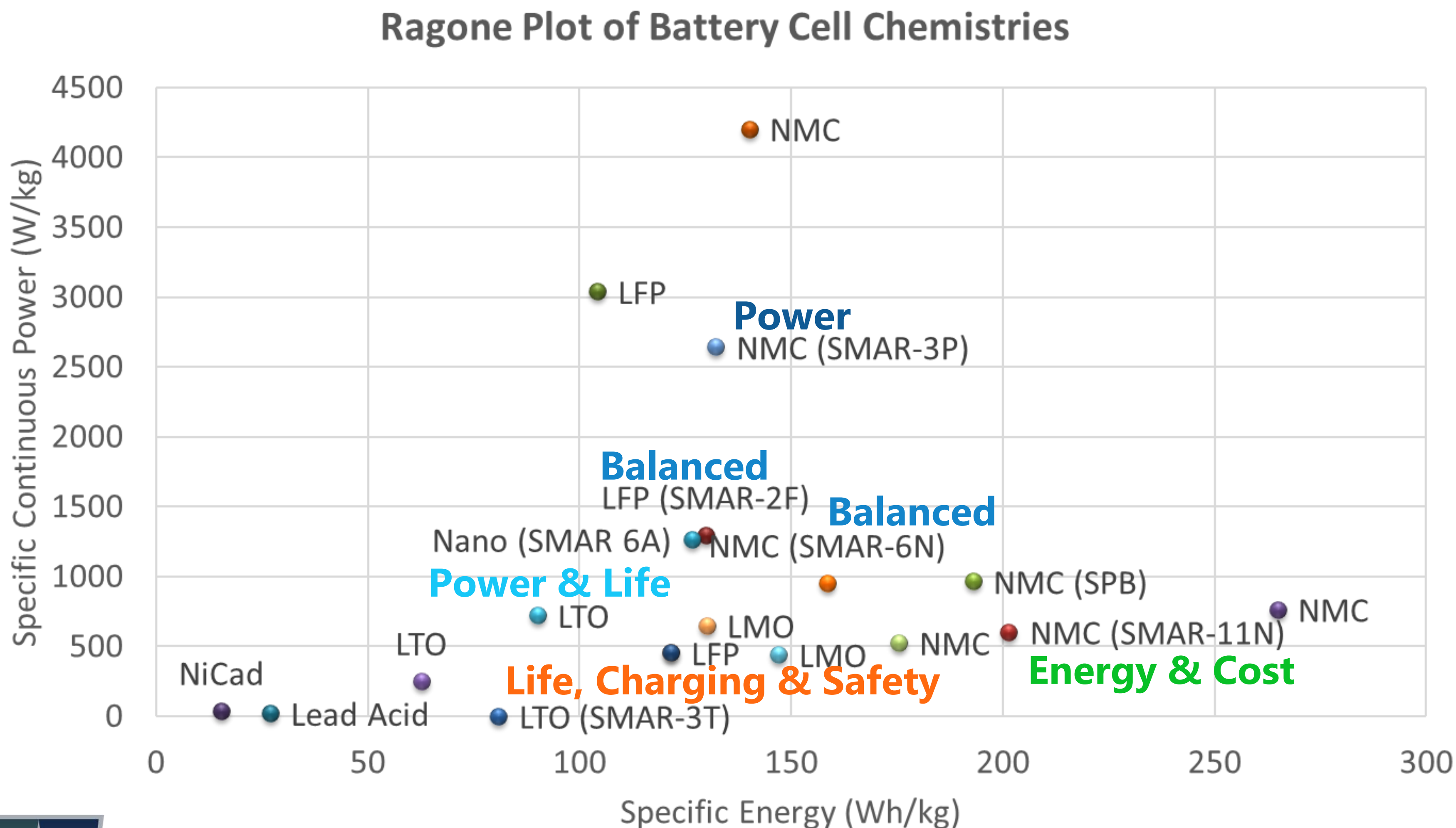
BMS

LEVEL	ENERGY DENSITY
Cell	414 Wh/L
Module	134 Wh/L
String	**101 Wh/L**

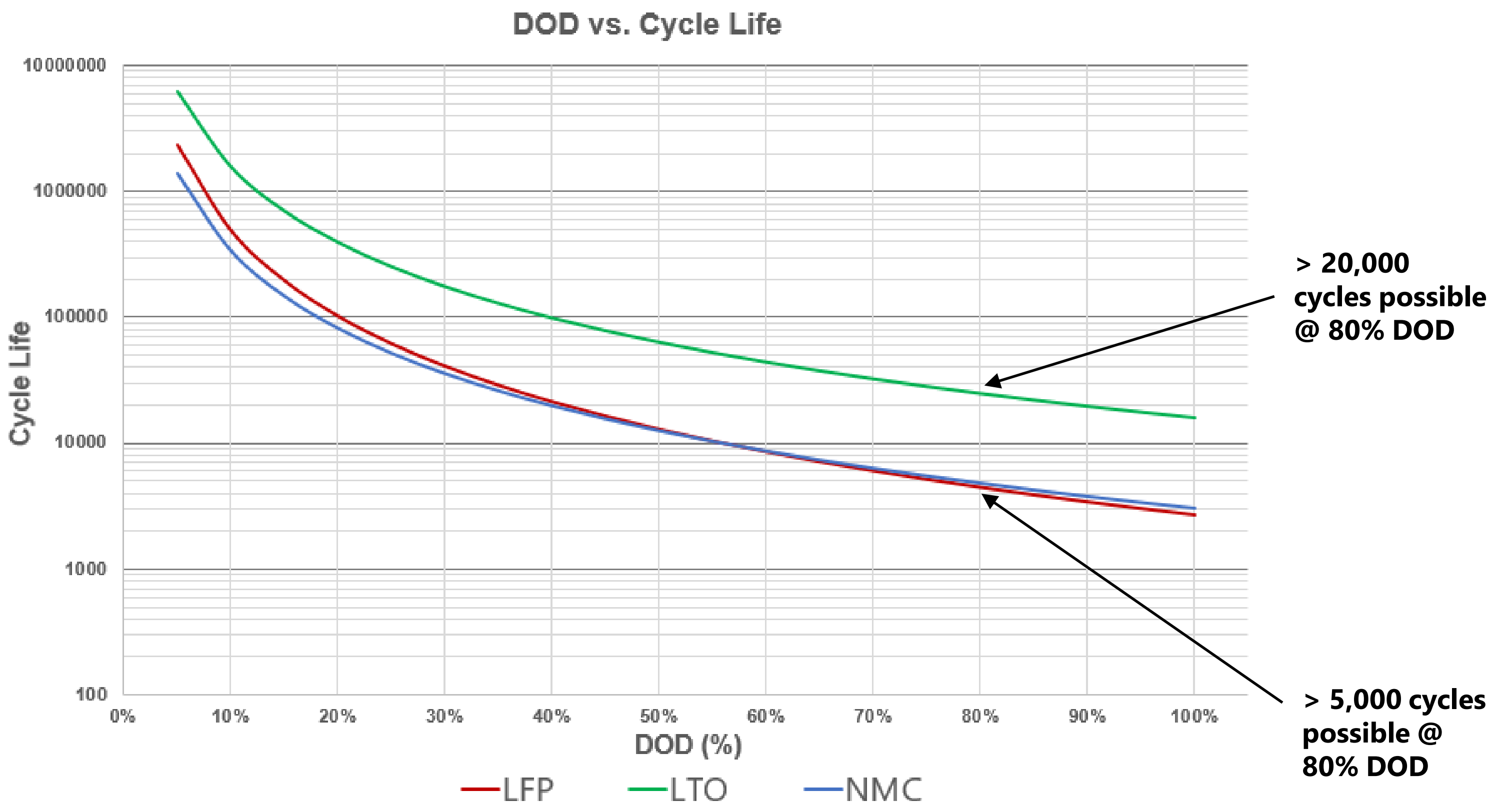
Module

String

Li Ion Cell Power vs. Energy



Cycle Life



- One of the key aging factors of a lithium-ion battery system
- Most lithium cell manufacturers specify cycle life to 80% original capacity (lead acid standard)

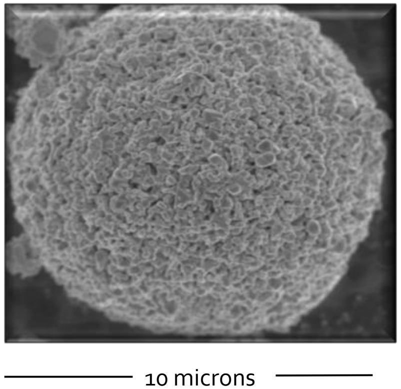
Cycle Life Example

- **Passenger Ferry (full-electric):**
  - 100 kWh energy consumption each crossing (20 minutes in duration)
  - 10 minutes at the shore to charge battery system
  - Vessel operates for 15 hours/day = 30 cycles/day = 10,950 cycles/year
  - 7 year life desired → **76,650 cycles/life**

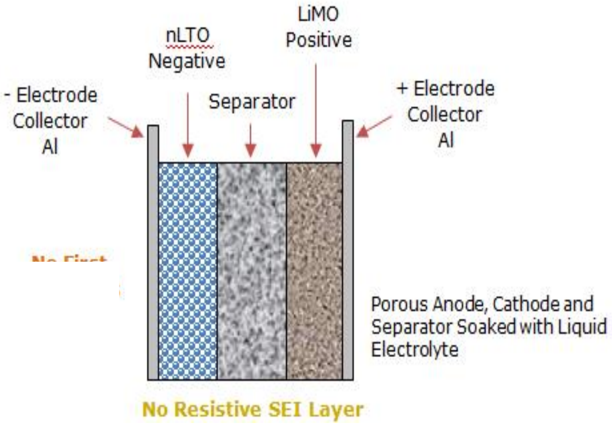
SOURCE: Green City Ferries

Lithium-ion Chemistry	NMC	LFP	LTO
Typical Energy Consumed Between Charges	100 kWh		
Number of Cycles (7 year life)	76,650 cycles		
Maximum Allowable DOD	21 %	23 %	48 %
Minimum Embedded Energy	486 kWh	441 kWh	207 kWh
Lowest Cost Solution			✓
Lowest Weight Solution			✓
Smallest Volume Solution			✓

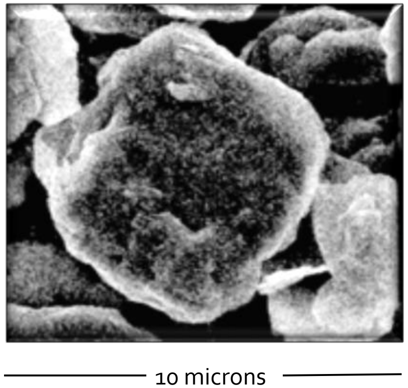
Charge Rates



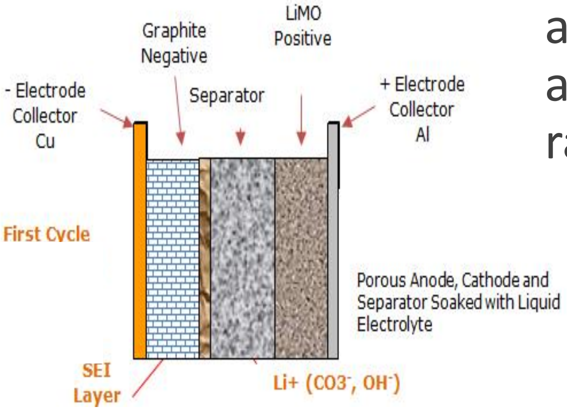
LTO molecules have more than 1000 times the surface area of graphite molecules



LTO battery



Ordinary Graphite Particle



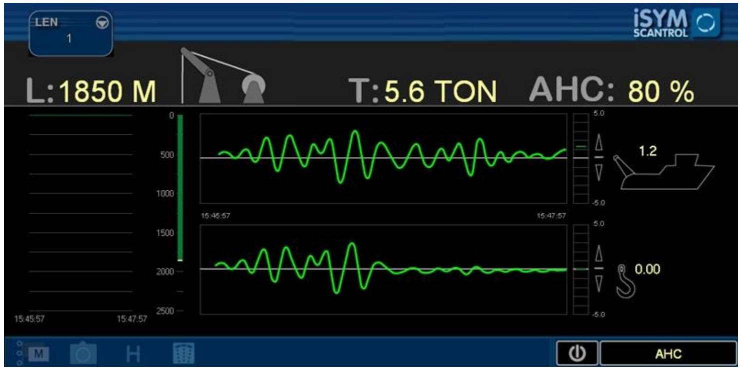
Ordinary Li-Ion battery

- Carbon-based anodes are limited to 3C charge rates → exceeding can lead to lithium plating
- In LTO cells, anode is replaced with lithium titanate → larger surface area = better charge acceptance = higher charge rates possible
  - Enables symmetrical cell designs, with similar power in and out
  - >10C continuous charge
  - >20C peak charge rates

Charge Rate Example

- Power regeneration on offshore cranes with AHC, for cases when not allowed to supply generated power back to ship's grid
- Battery acts as efficient, cost-effective energy storage
- Average power is low, but (bidirectional) peak power is high

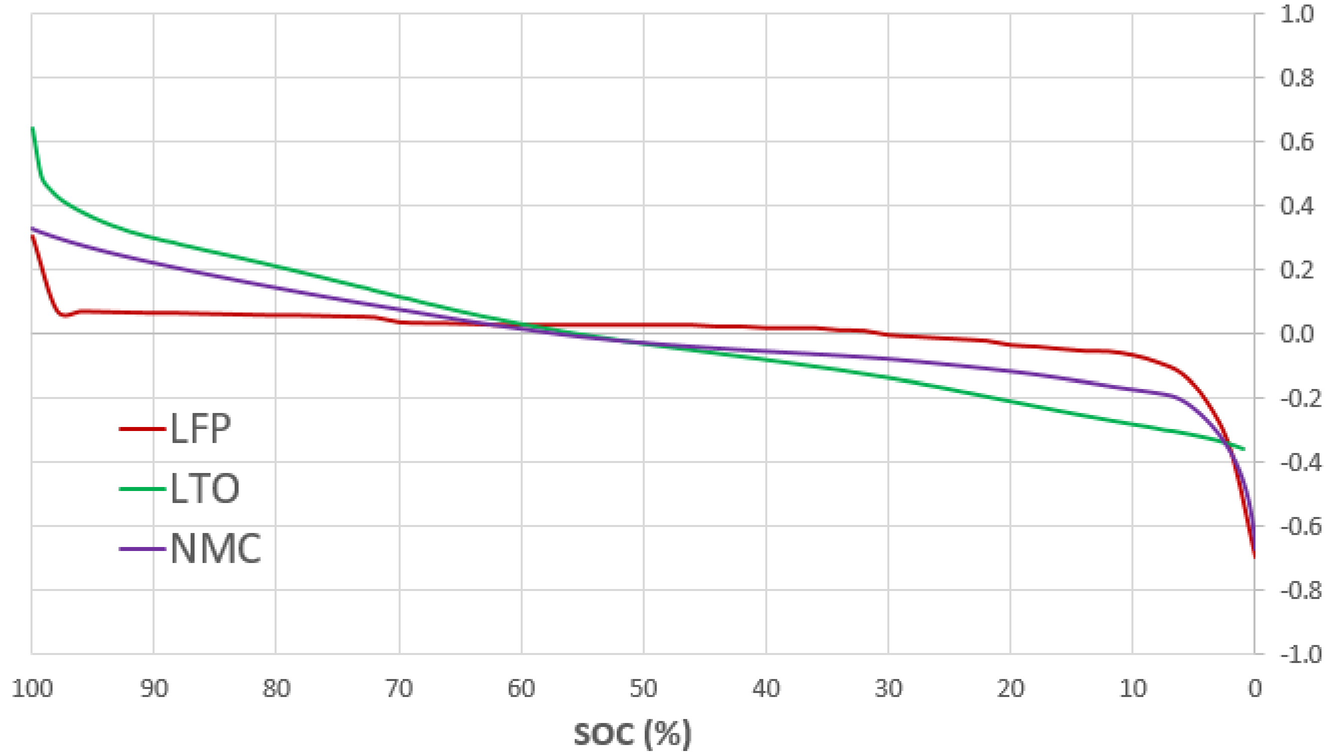
SOURCE: http://www.isys.uni-stuttgart.de/forschung/mechatronik/robo/AHC/index.en.html



SOURCE: http://www.oceanologyinternational.com/__novaimages/1041319?v=635875073609900000

Voltage Response Example

- LFP makes an excellent case for high power applications due to flat voltage response
  - ➢ LFP retains power capability at low SOC
  - ➢ Spinning reserve, UPS backup systems, dynamic positioning, etc.



Summary

Lithium-Ion Chemistry	Cell-Level Energy Density	Cycle Life (at 80% DOD)	Recharge Time (0-80% SOC)	Advantages	Applications
Nickel Manganese Cobalt (NMC)	**300-410 Wh/L**	> 6,000 cycles	≥ 20 mins	• Highest energy density • Power/energy balance	• HEV/PHEV ferries • Workboats • Yachts/Fishing/ Research vessels
Lithium Iron Phosphate (LFP)	200-250 Wh/L	> 6,000 cycles	≥ 20 mins	• Flat voltage response • Balanced chemistry	• Spinning reserve/UPS • Dynamic positioning
Lithium Titanate Oxide (LTO)	145-180 Wh/L	**> 20,000 cycles**	**≥ 6 mins**	• Highest cycle life • Highest continuous charge rates	• HEV/PHEV ferries • Offshore/port cranes • Peak shaving

Thank you!

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