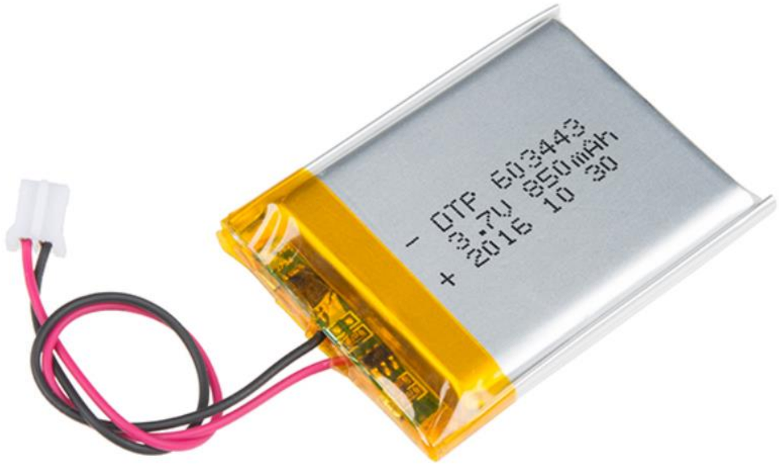
Modeling, Management and Application of Lithium-Ion Battery Energy Storage Systems



Tutorial for

2023 CURENT Industry Conference

Apr. 2023

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Agenda

- Battery Mechanism & Operating Principles;
- Battery Management Systems;
- Battery Modeling and Characterization;
- Future Development.

Battery

Chemica … Cell

A … B

A … B

A … B

… B

A + E … B

Free energy diss … ed to electrical energy

The first battery was invented by Alessandro Volta in 1800: : Zn-Cu

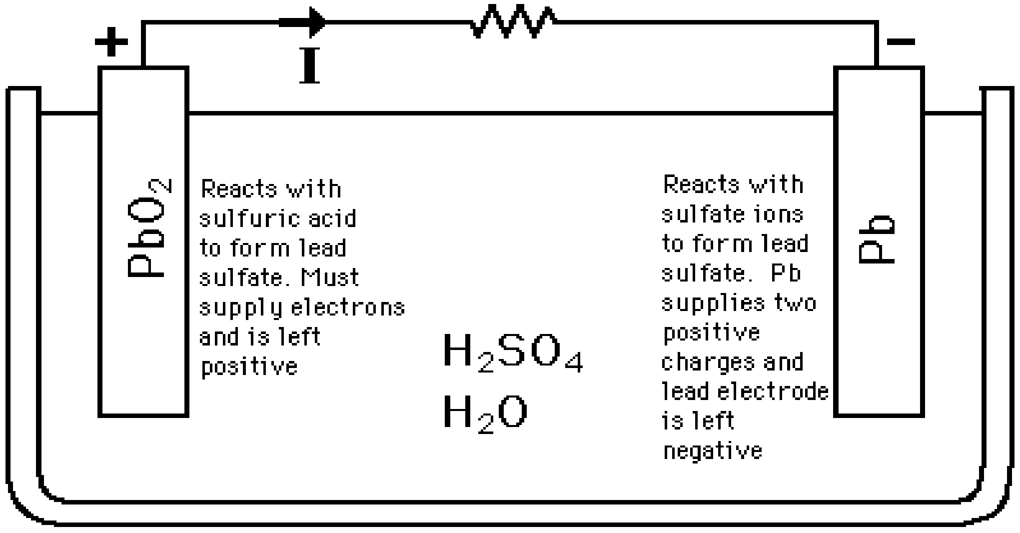
Example: PbA Battery

Discharging

Negative Plate: $Pb + HSO_4^- \rightarrow PbSO_4 + H^+ + 2e^-$

Positive Plate: $PbO_2 + HSO_4^- + 3H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O$

Overall: $PbO_2 + Pb + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$



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Periodic Table of the Elements 2005

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H 1.01																	2 He 4.00
3 Li 6.94	4 Be 9.01											5 B 10.81	6 C 12.01	7 N 14.01	8 O 15.99	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 25.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.87	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.41	31 Ga 69.72	32 Ge 72.64	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.90	54 Xe 131.29
55 Cs 132.91	56 Ba 137.33	57 La 138.91	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (261)	105 Db (262)	106 Sg (266)	107 Bh (264)	108 Hs (270)	109 Mt (268)	110 Ds (281)	111 Rg (272)							

58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.97	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

Molecular Research Institute

Example: PbA Battery

Overall: $PbO_2 + Pb + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$

Charge 2e-

Mass 239 207 196

Relative mass:
Pb: 207
O:16
S: 32

Other info:
1. One electron: $-1.602*10^{-19}$C
2. One hydrogen atom: $1.667*10^{-27}$kg

To transfer $Q=2*1.602*10^{-19}$C charge, we need the mass $M=(239+207+196)*1.667*10^{-27}$kg, yielding Q/M/3600=83Ah/kg

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Li-ion Battery Inventions

2019 Nobel Prize in Chemistry: development of lithium-ion batteries

John B. Goodenough — *1980s battery positive material*

M. Stanley Whittingham — *1972 1st Li battery*

Akira Yoshino — *1980s 1st Li-ion Battery*

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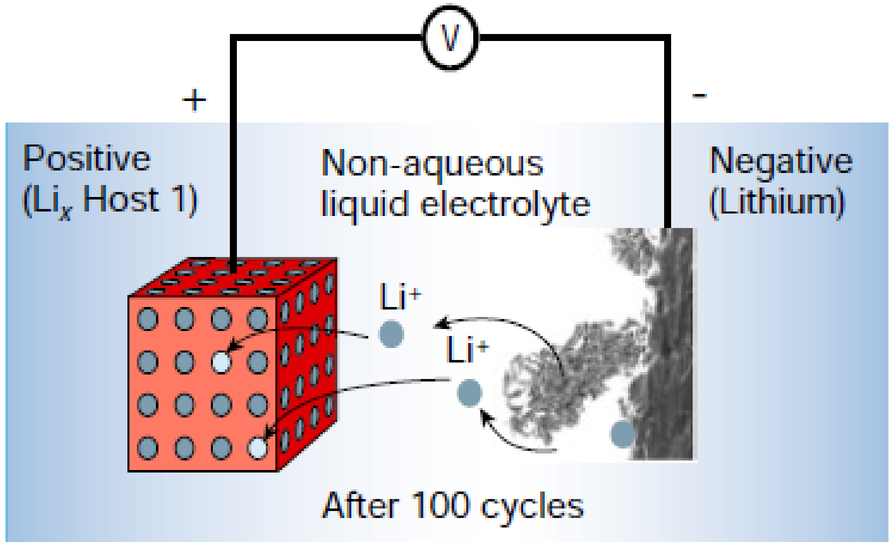
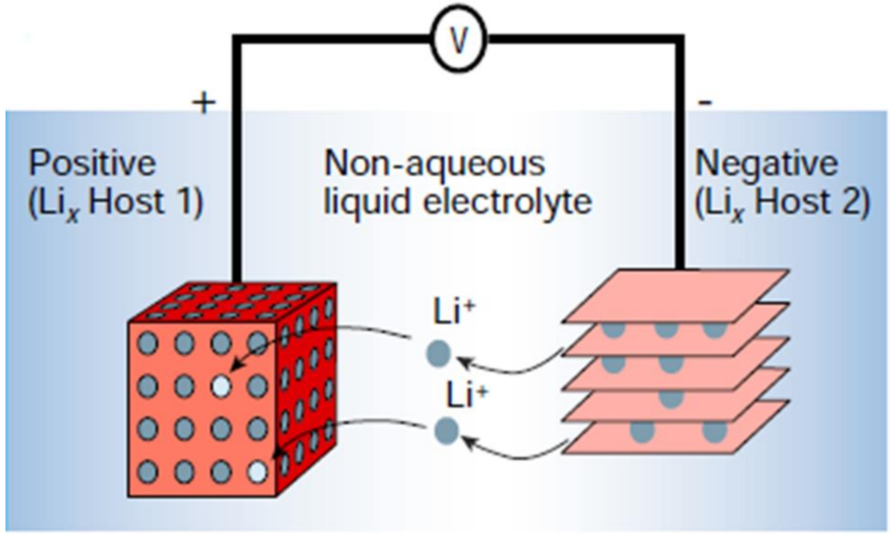
Li-ion Battery History



Lithium-metal Battery(Primary)



Rechargeable Li-ion battery (Secondary)

In 1972, Whittingham (Exxon): TiS_2 (Low voltage, layered-type structure)+ Li metal

Early 1980s, Goodenough proposed the families of compounds:Li_xMO_2 (where M is Co, Ni or Mn)

*Started in 1981 and invented in 1985***,** *Yoshino: substitute metallic Li for a second insertion material (carbon-rich anode, so-called Li-ion or rocking-chair technology)*

1991, Sony commercialized C/$LiCoO_2$ (3.6V, 120-150 Wh/kg)

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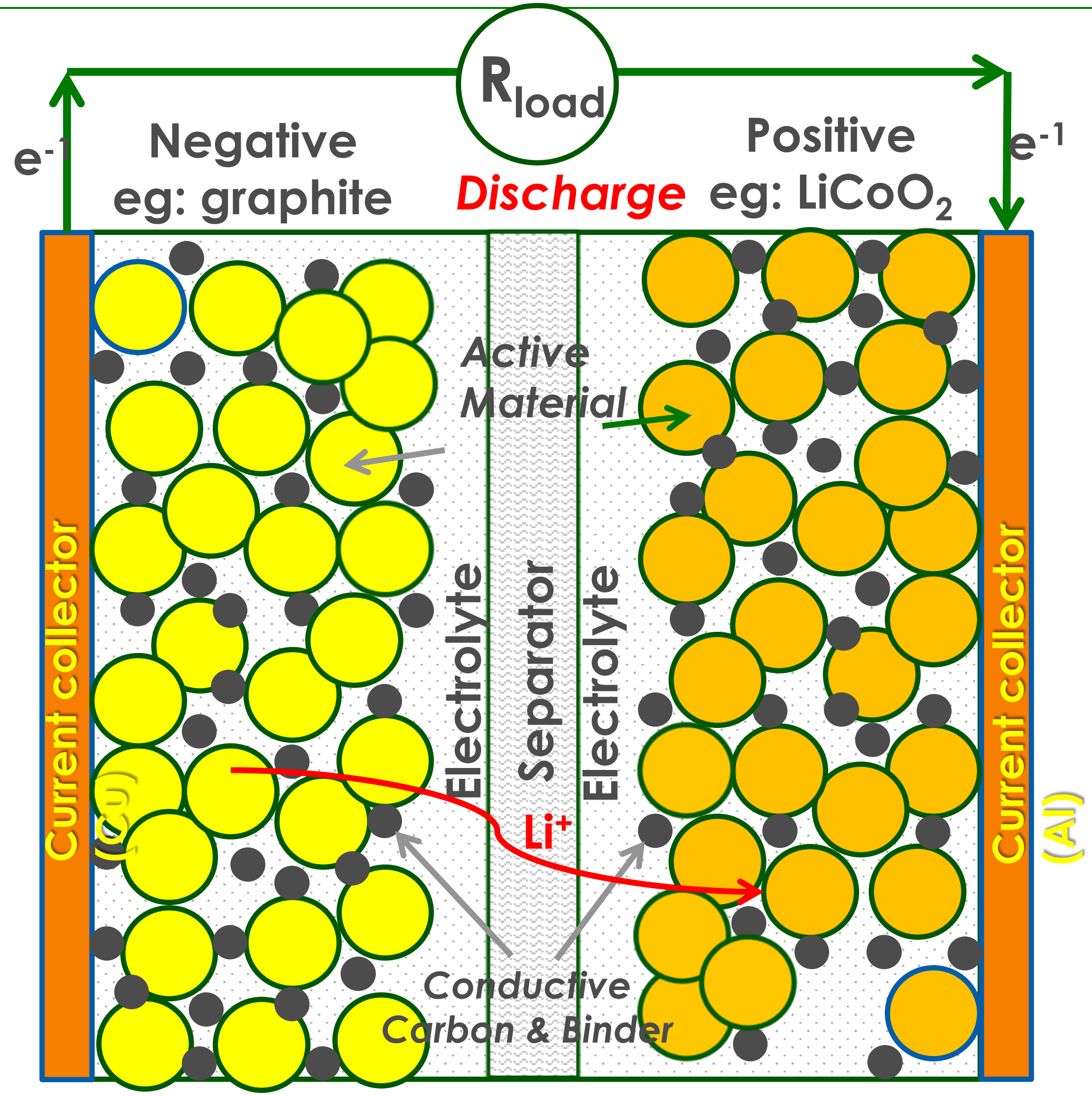
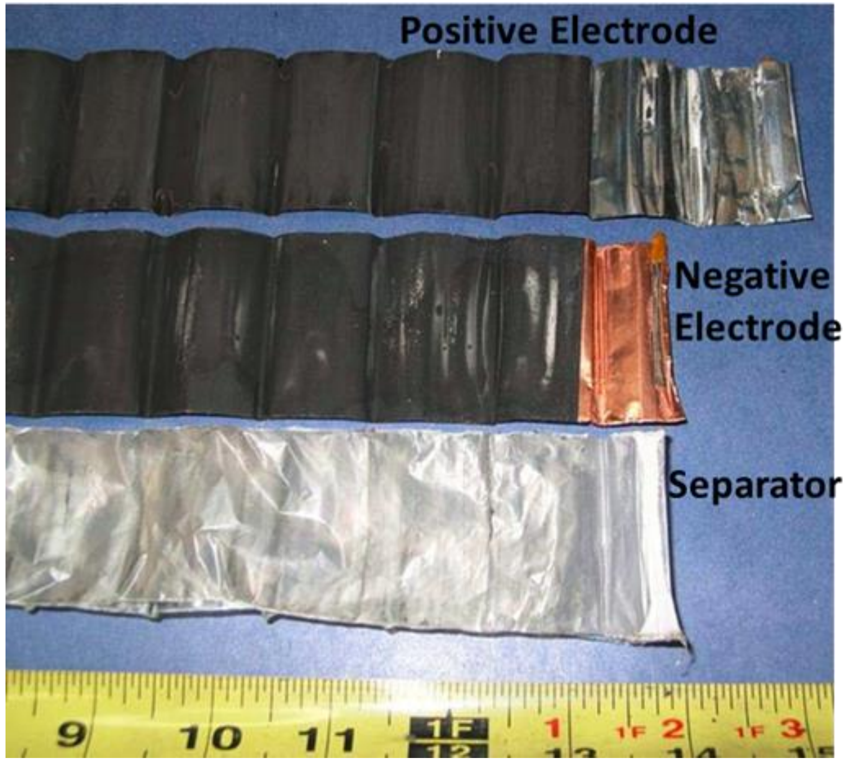
J.M. Tarascon, M. Armand, Issue and challenges facing rechargeable lithium batteries, *Nature*, 414(2001)359

Li-ion Battery



$LiC_6 \rightarrow Li^+ + e^{-1} + 6C$ $\quad$ $Li^+ + e^{-1} + CoO_2 \rightarrow LiCoO_2$



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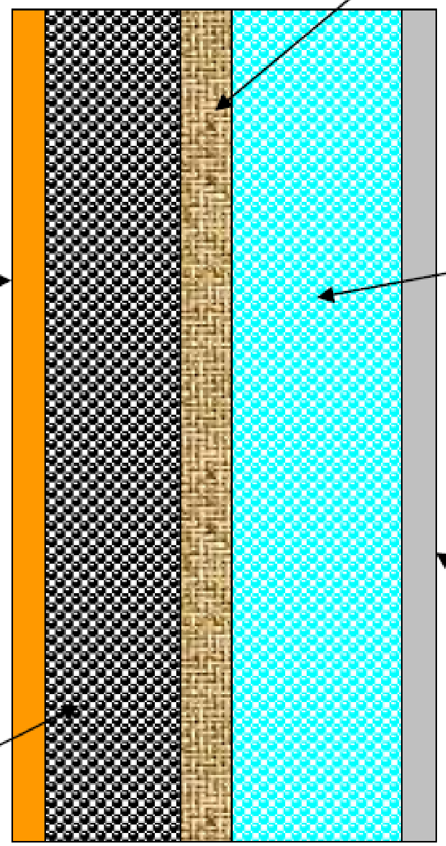
Li-ion Battery Structure

Separator: Typically microporous polyolefin, 20-25 microns thick, 40-50% porous

Anode current collector: Copper, ~12-16 microns thick

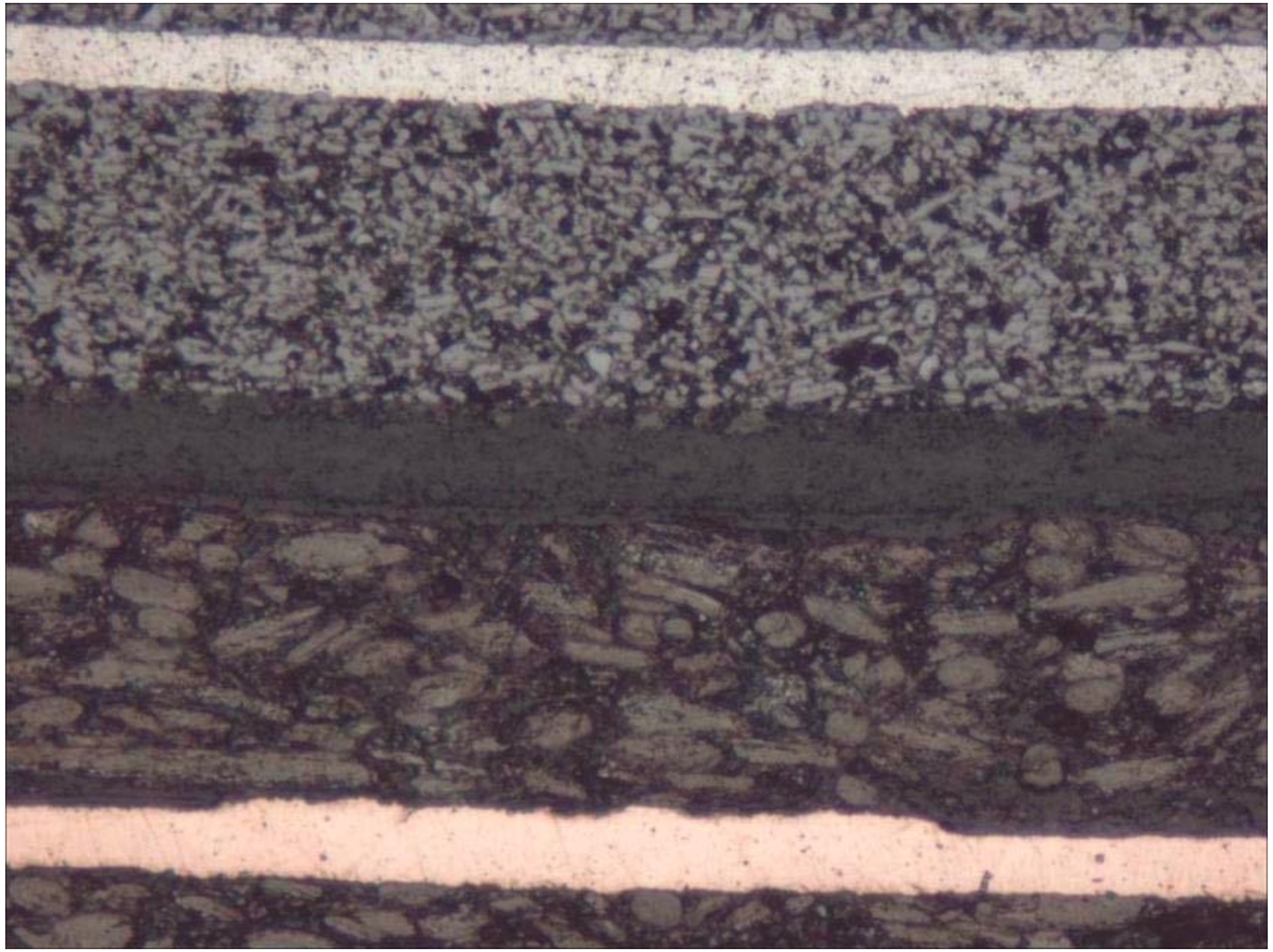


Cathode: up to 95% active material, remainder conductive carbon + binder, 25-30% porous, 30-100 microns thick depending on battery characteristics

Cathode current collector: Aluminum, ~12-16 microns thick

Anode: 90-95% active material, 3-5% conductive carbon, 3-5% binder, 25-30% porous, 25-90 microns thick depending on intended battery characteristics

Li-ion Battery Structure



Al

Cathode

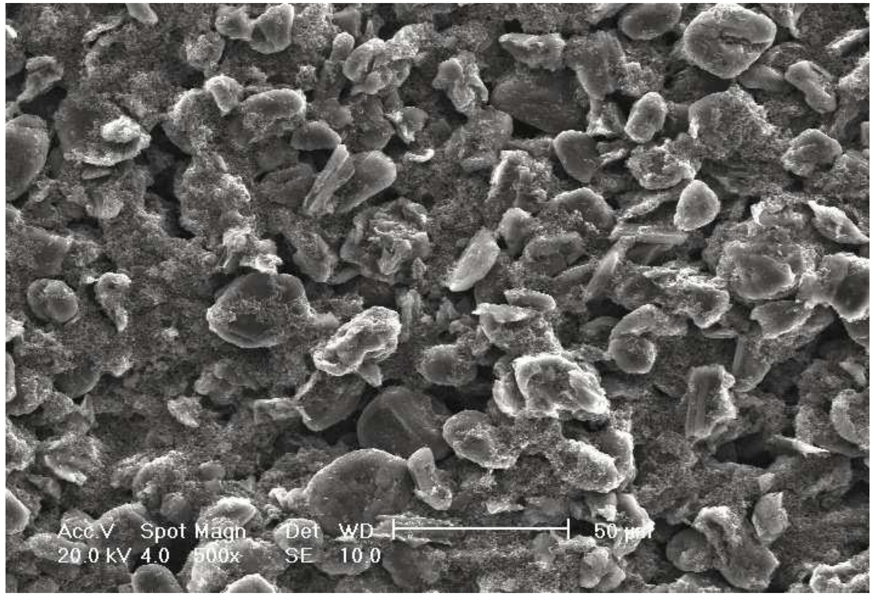
Separator

Anode

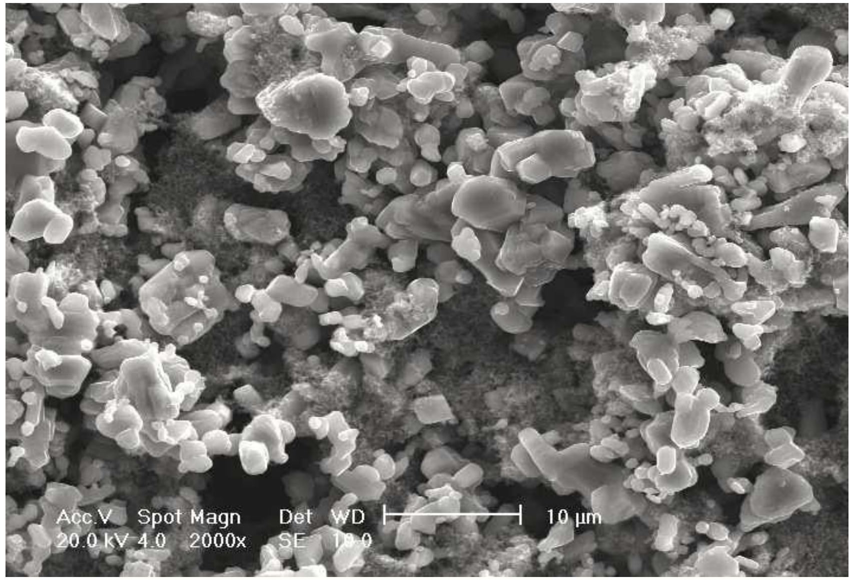
Cu

Optical microscope image

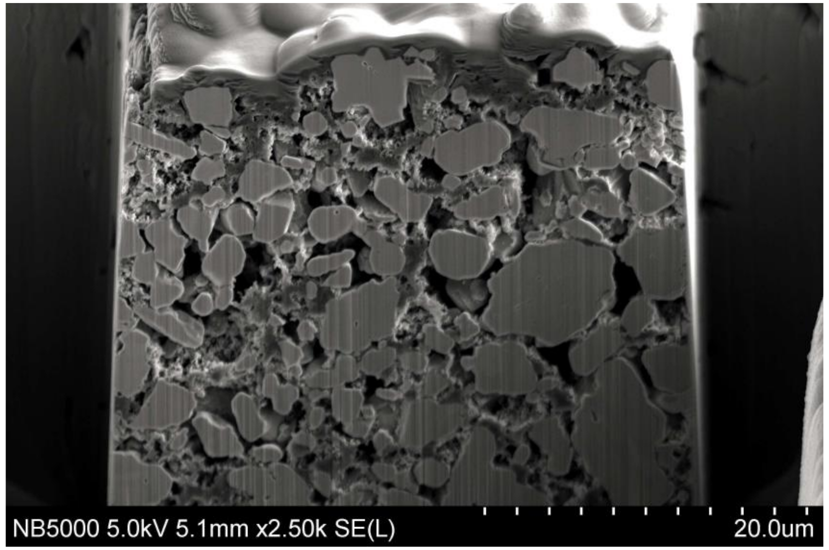
Morphology of Battery Materials



Carbonaceous spheres (graphite, negative electrode)



Lithium manganese oxide (positive electrode)



Cross-sectional slice of electrode material

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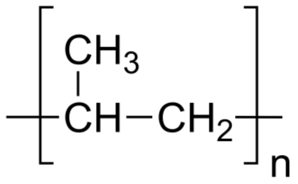
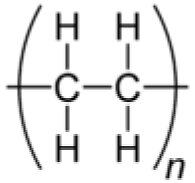
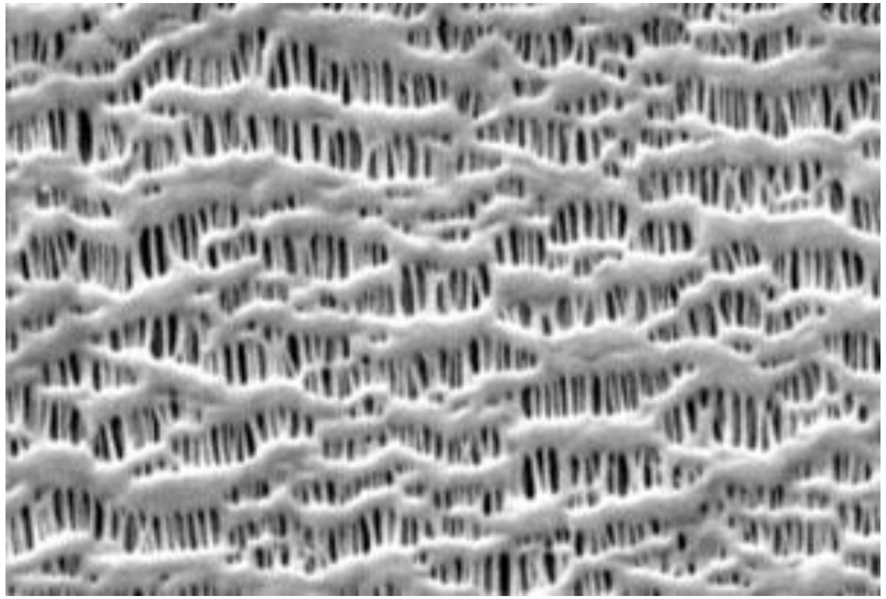
Separator



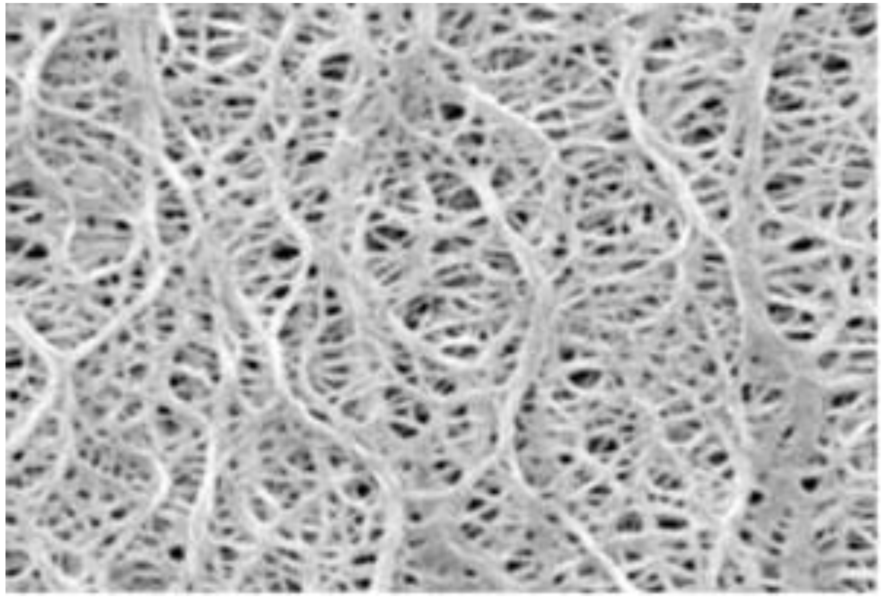
$(C_3H_6)_n$ Polypropylene (PP)



$(C_2H_4)_n$ Polyethylene (PE)

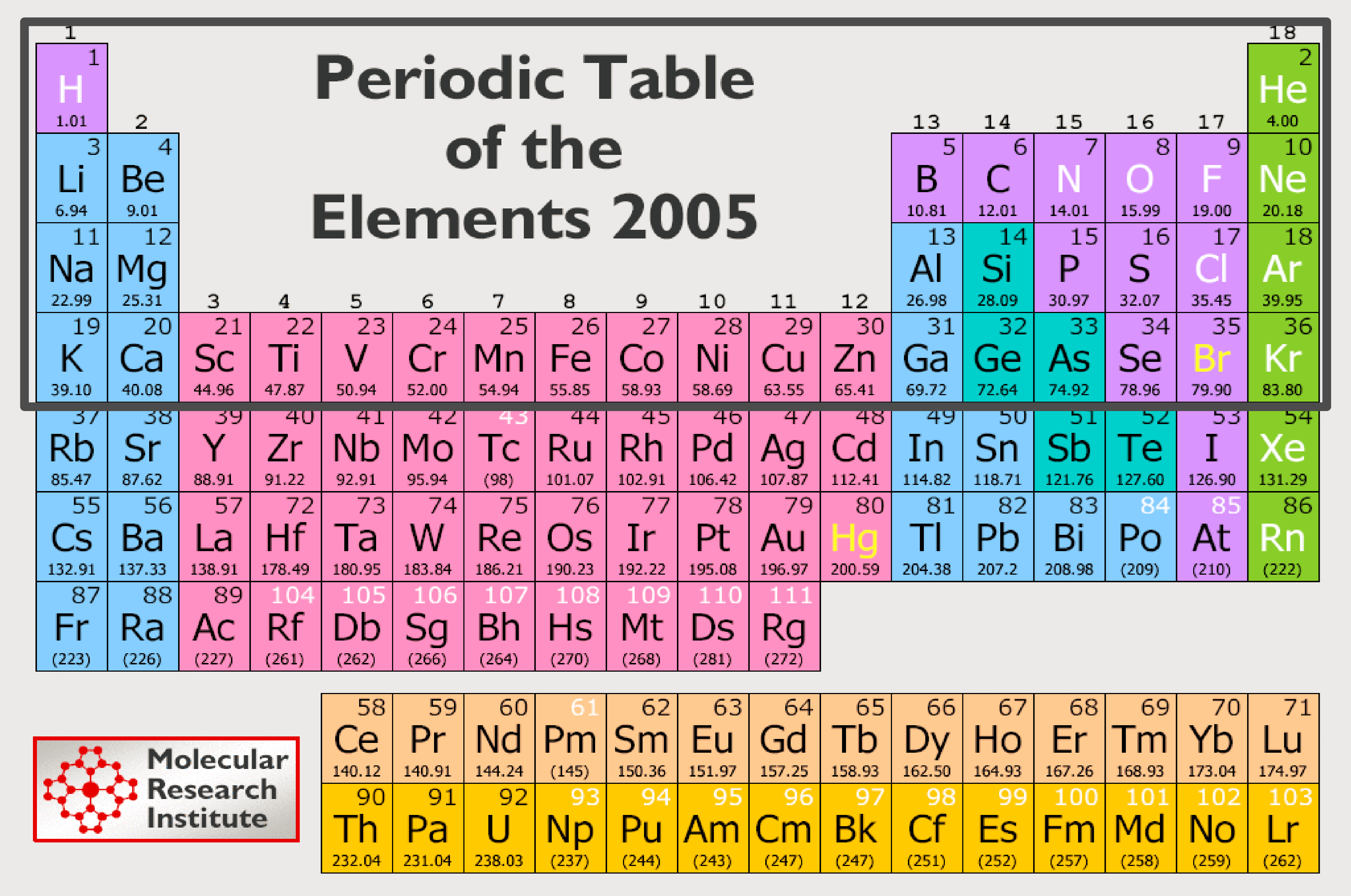


SEM Surface Photomicrograph of Celgard® Monolayer PP Battery Separator



SEM Surface Photomicrograph of Celgard® Monolayer PE Battery Separator

Why Li-ion? (1)


Periodic Table of the Elements 2005
Molecular Research Institute

Why Li-ion? (2)

Stronger oxidizing agent ↑ / Weaker oxidizing agent

Weaker reducing agent ↓ / Stronger reducing agent

Reduction Half-Reaction		E° (V)
$F_2(g) + 2e^-$	$\longrightarrow 2F(aq)$	2.87
$H_2O_2(aq) + 2H^+(aq) + 2e^-$	$\longrightarrow 2H_2O(l)$	1.78
$MnO_4^-(aq) + 8H^+(aq) + 5e^-$	$\longrightarrow Mn^{2+}(aq) + 4H_2O(l)$	1.51
$Cl_2(g) + 2e^-$	$\longrightarrow 2Cl^-(aq)$	1.36
$Cr_2O_7^{2-}(aq) + 14H^+(aq) + 6e^-$	$\longrightarrow 2Cr^{3+}(aq) + 7H_2O(l)$	1.33
$O_2(g) + 4H^+(aq) + 4e^-$	$\longrightarrow 2H_2O(l)$	1.23
$Br_2(l) + 2e^-$	$\longrightarrow 2Br^-(aq)$	1.09
$Ag^+(aq) + e^-$	$\longrightarrow Ag(s)$	0.80
$Fe^{3+}(aq) + e^-$	$\longrightarrow Fe^{2+}(aq)$	0.77
$O_2(g) + 2H^+(aq) + 2e^-$	$\longrightarrow H_2O_2(aq)$	0.70
$I_2(s) + 2e^-$	$\longrightarrow 2I^-(aq)$	0.54
$O_2(g) + 2H_2O(l) + 4e^-$	$\longrightarrow 4OH^-(aq)$	0.40
$Cu^{2+}(aq) + 2e^-$	$\longrightarrow Cu(s)$	0.34
$Sn^{4+}(aq) + 2e^-$	$\longrightarrow Sn^{2+}(aq)$	0.15
$2H^+(aq) + 2e^-$	$\longrightarrow H_2(g)$	0
$Pb^{2+}(aq) + 2e^-$	$\longrightarrow Pb(s)$	−0.13
$Ni^{2+}(aq) + 2e^-$	$\longrightarrow Ni(s)$	−0.26
$Cd^{2+}(aq) + 2e^-$	$\longrightarrow Cd(s)$	−0.40
$Fe^{2+}(aq) + 2e^-$	$\longrightarrow Fe(s)$	−0.45
$Zn^{2+}(aq) + 2e^-$	$\longrightarrow Zn(s)$	−0.76
$2H_2O(l) + 2e^-$	$\longrightarrow H_2(g) + 2OH^-(aq)$	−0.83
$Al^{3+}(aq) + 3e^-$	$\longrightarrow Al(s)$	−1.66
$Mg^{2+}(aq) + 2e^-$	$\longrightarrow Mg(s)$	−2.37
$Na^+(aq) + e^-$	$\longrightarrow Na(s)$	−2.71
$Li^+(aq) + e^-$	$\longrightarrow Li(s)$	−3.04

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Example: Li-ion Battery

A fully charged Li-ion battery has positive electrode as CoO_2 and negative electrode as LiC_6

<M> + <HLi> → <MLi> + <H>

Here M= CoO_2, <HLi>=LiC_6

Therefore the overall chemical reaction when discharging is

$$CoO_2 + LiC_6 \rightarrow LiCoO_2 + 6C$$

Relative mass:

Li: 6.9

Co:59

O: 16

C: 12

Other info:

1. One electron: $-1.602*10^{-19}C$
2. One hydrogen atom: $1.667*10^{-27}kg$

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Example: Li-ion Battery

$$CoO_2 \quad + \quad LiC_6 \quad \rightarrow \quad LiCoO_2 \quad + \quad 6C$$

Relative mass   59+16*2   6.9+12*6

To generate $Q=1.602*10^{-19}$C, we need $M=169.9*1.667*10^{-27}$kg. Therefore the gravimetric charge density is Q/M/3600=157Ah/kg.

The energy density is 3.4V*151Ah/kg=534Wh/kg

What are those parameters of the Pb-Acid Battery?

83Ah/kg
174Wh/kg

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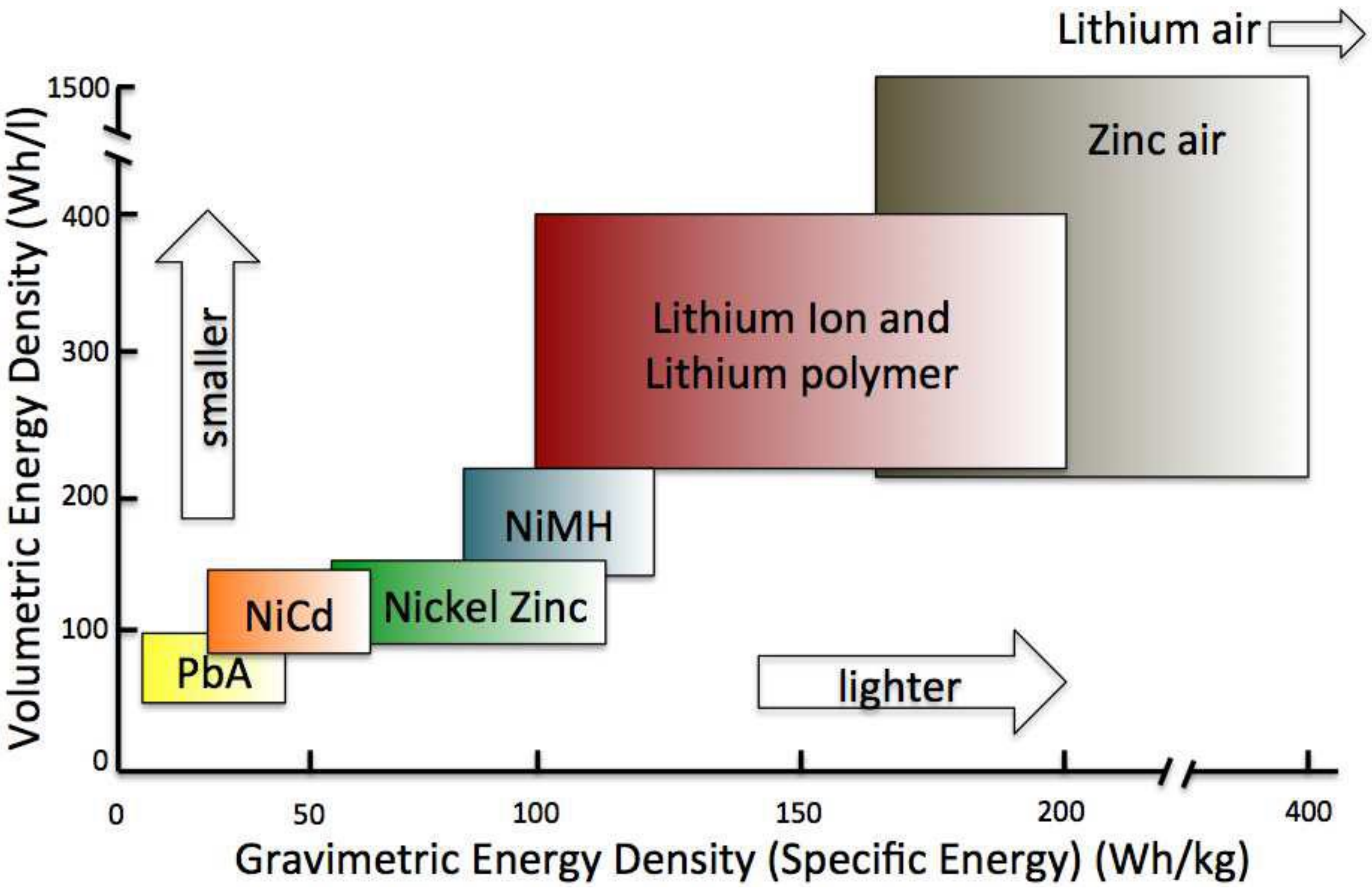
However…



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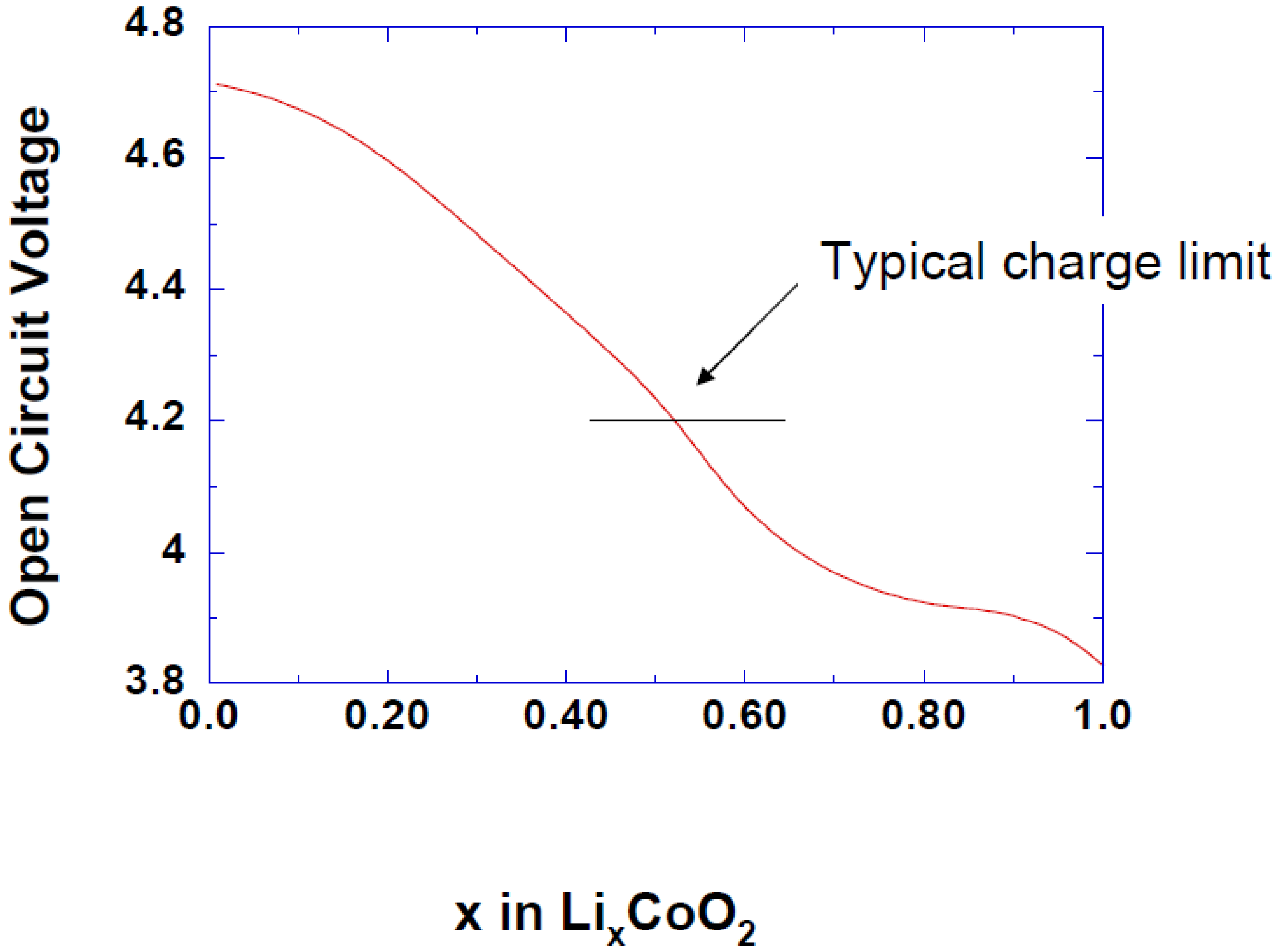
Why?

Cathode Voltage vs. Degree of Li+ Intercalation C/LiCoO2 Cell



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Why?

- **Electrolyte stability**
  - –Standard commercial Li-ion electrolytes only stable to ~4.5V vs. Li/Li+

- **Li_xCoO_2 thermodynamic stability**
  - –X = 0.5-1.0 →stable compound
  - –x<0.5 →Li_xCoO_2→$Li_2O/Co_2O_3/Co_3O_4/O_2$

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Battery vs Others

- **What do I need to Travel 1 mile, in a vehicle?**

- 80g of CNG
- 96g of Gasoline
- 200g of chocolate

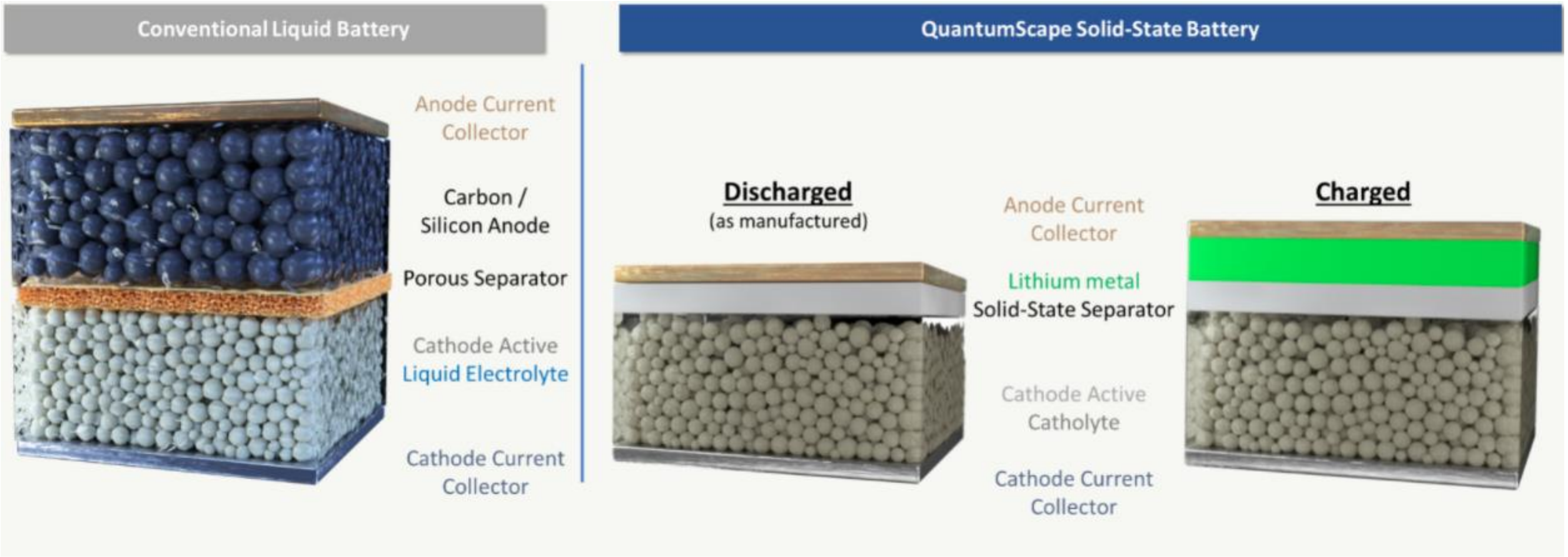
These utilize thermal processes

- 1600g of a lithium-ion cell
- 6900g of a lead-acid cell
- **20g of lithium metal!**

These utilize electrochemical processes

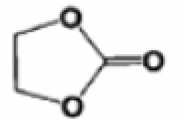
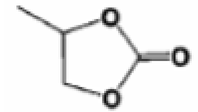
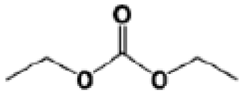
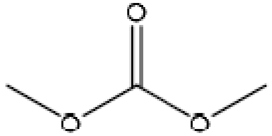
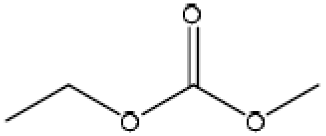
Solid and liquid fuels have much higher energy density than the battery using electrochemical reactions

Solid-state Battery



Li-ion Battery Electrolyte

- Solvent: Blend of organic carbonates

Chemical name	Chemical structure	Viscosity (cP)	Dielectric constant	Melting Point (°C)	Flash Point (°C)
Ethylene carbonate (EC)		1.9 (40 °C)	89	37	160
Propylene carbonate (PC)		2.5	65	-49	132
Diethyl carbonate (DEC)		0.75	2.8	-74	31
Dimethyl carbonate (DMC)		0.59	3.1	4.6	18
Ethyl methyl carbonate (EMC)		0.65	3.9	-53	25
Water		0.88	78	0	Non-flammable

The **flash point** of a volatile material is the lowest temperature at which it can vaporize to form an ignitable mixture in air.

Solid-state Battery

Pros:

- High safety: no dendrite piercing through the separator; low flaming possibility;
- High energy density: no need for carbon to collect Li; 300 - 400Wh / kg;
- Long cycling lifespan: ideally up to 45000 cycles.

Cons:

- High resistance：due to not close contact between solid and solid; slow ion movement in the solid;
- High cost.

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Solid-state Battery

Polymer

SES Beyond Li-Ion™
SEEO
BOLLORÉ
Solid Power
ionic MATERIALS

Sulfide

BMW
SAMSUNG
HONDA The Power of Dreams
CATL 宁德时代
TOYOTA
Panasonic

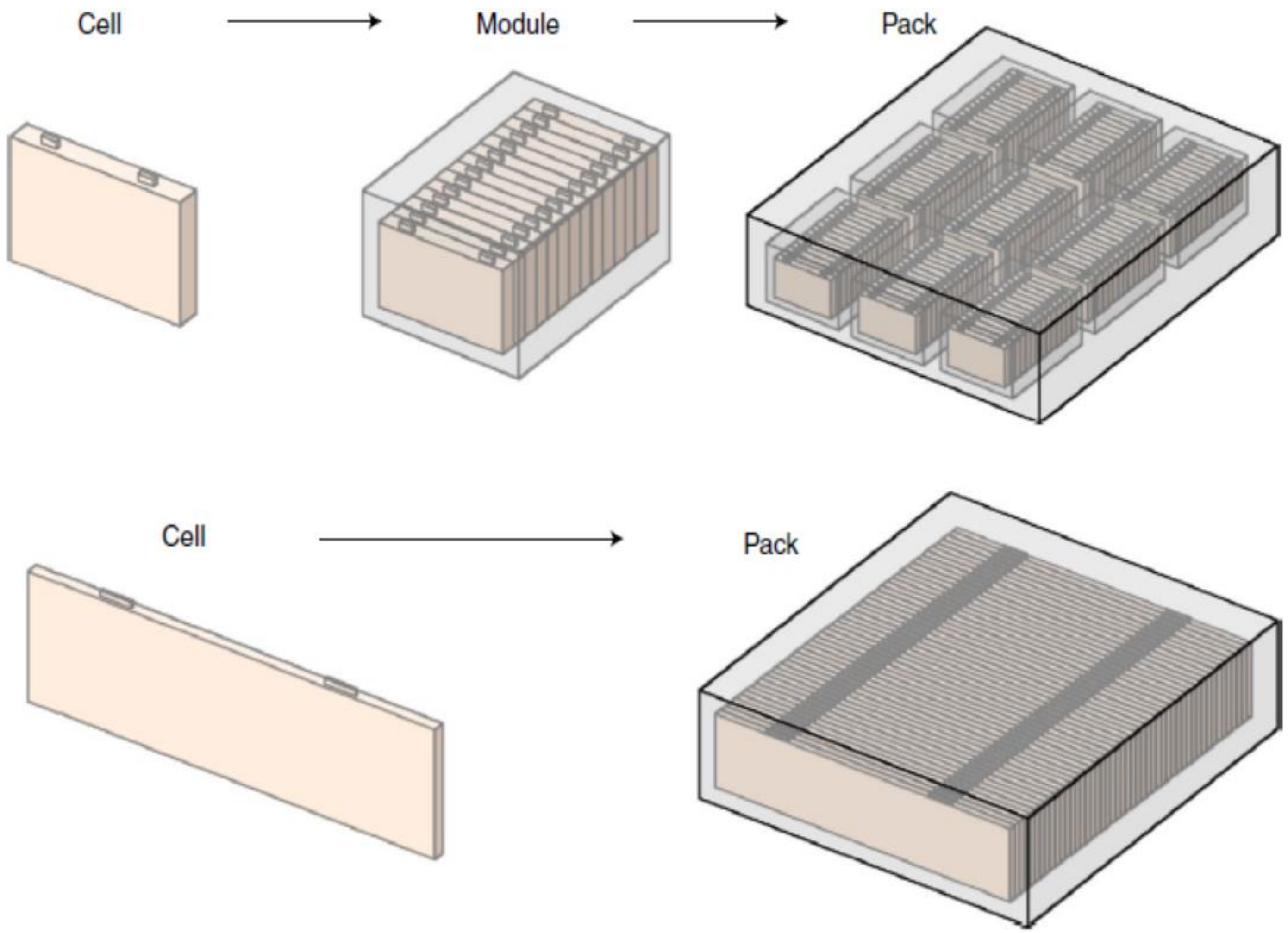
Oxide

VW
赣锋锂业 GanfengLithium
LG Chem
清陶发展
SAKTI3
ProLogium
QuantumScape
SONY

Cell, Module and Pack

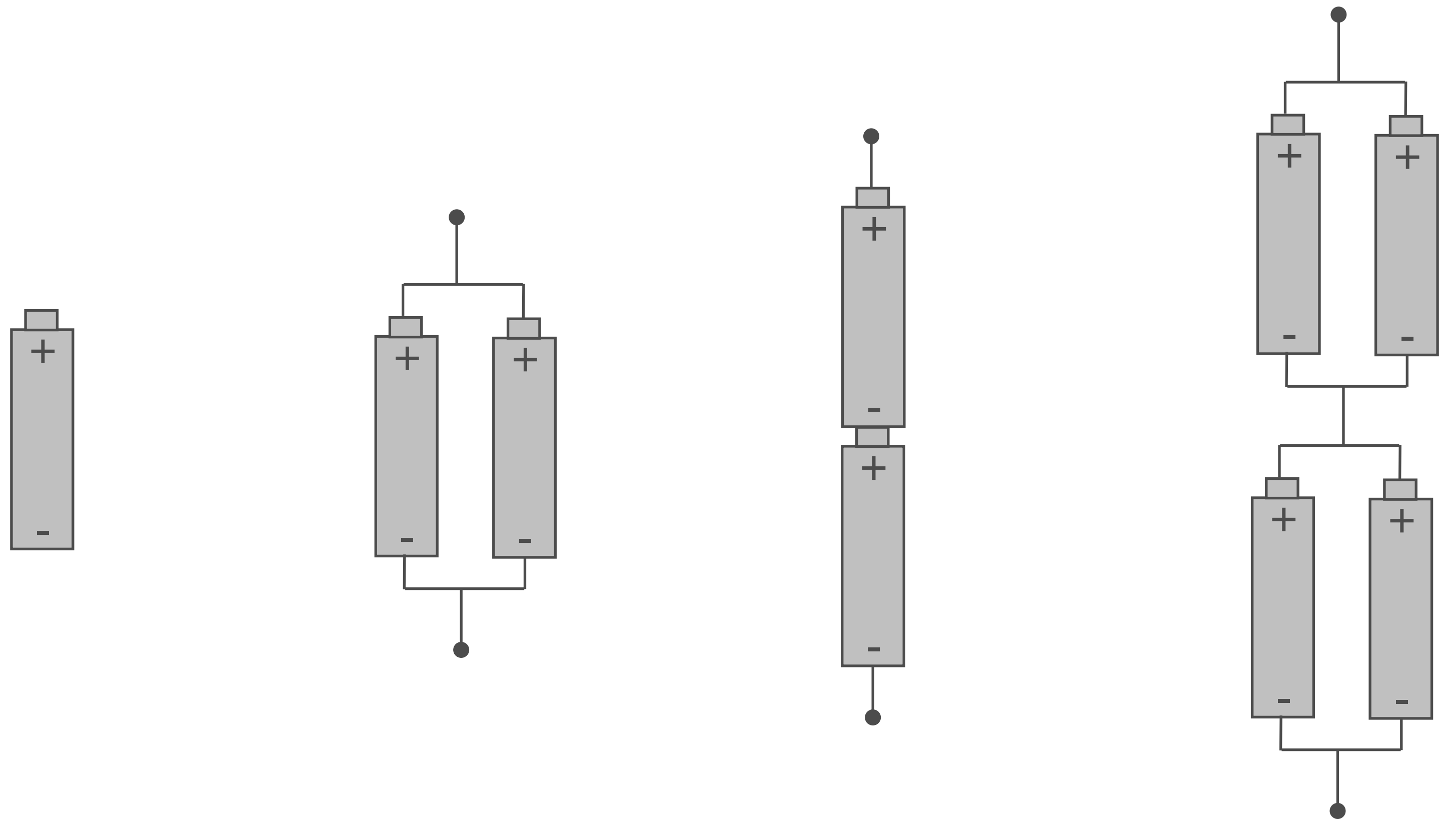
- The conventional battery pack uses cells to build module and then assembles modules to a pack.

- A blade battery pack builds on wide and short cells and assembles them directly into a pack, thereby having much higher mass and volume integration efficiencies than the conventional pack.



Yang, XG., Liu, T. & Wang, CY. Thermally modulated lithium iron phosphate batteries for mass-market electric vehicles. Nat Energy 6, 176–185 (2021).

Cell, Module and Pack

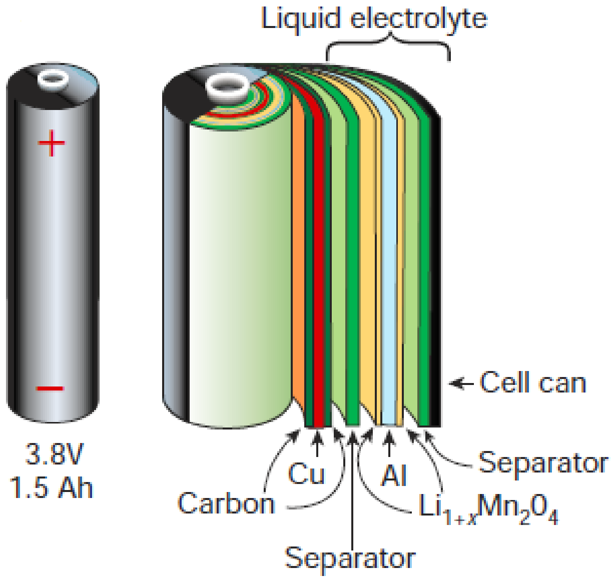


Single Cell	Parallel Cells	Series Cells	2S2P
1.5 V, 2.2 Ah	1.5 V, 4.4 Ah	3.0 V, 2.2 Ah	3.0 V, 4.4 Ah

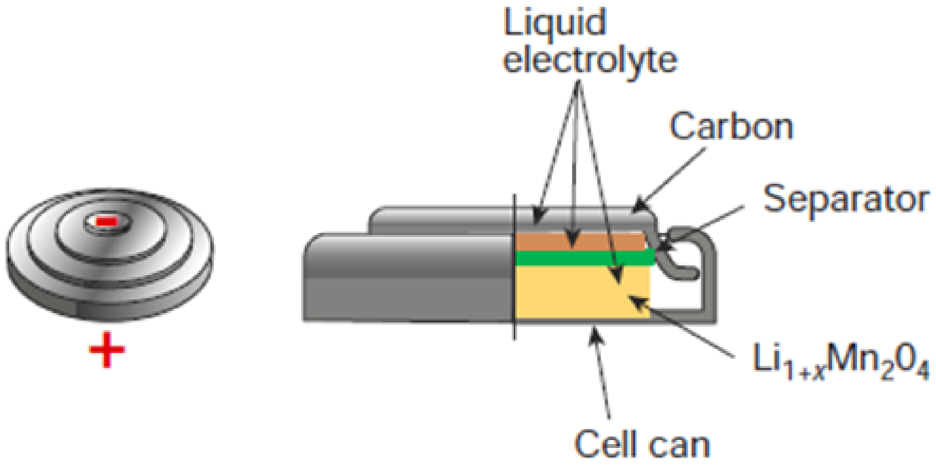
Use the AA Alkaline cells as a starting point – 1.5 V, 2.2 Ah cell

1. Series connection increases voltage;
2. Parallel connection increases Ah-capacity;
3. Combinations increase both voltage and Ah capacity.

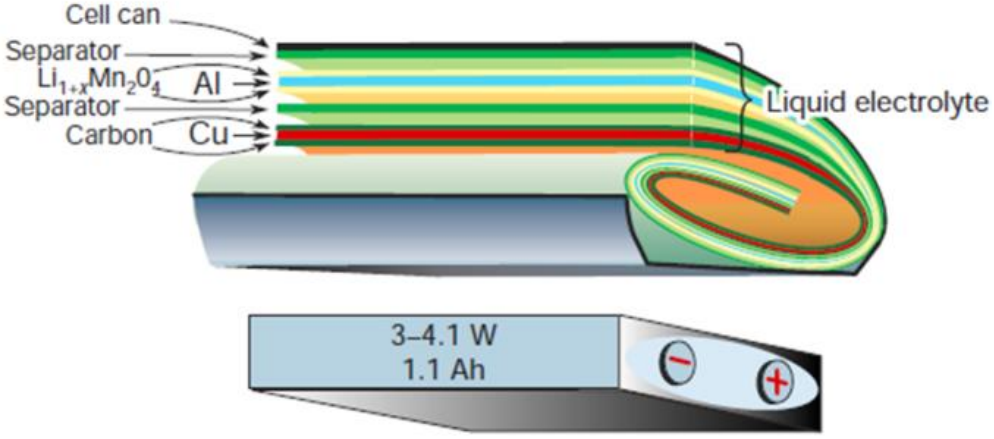
Cells



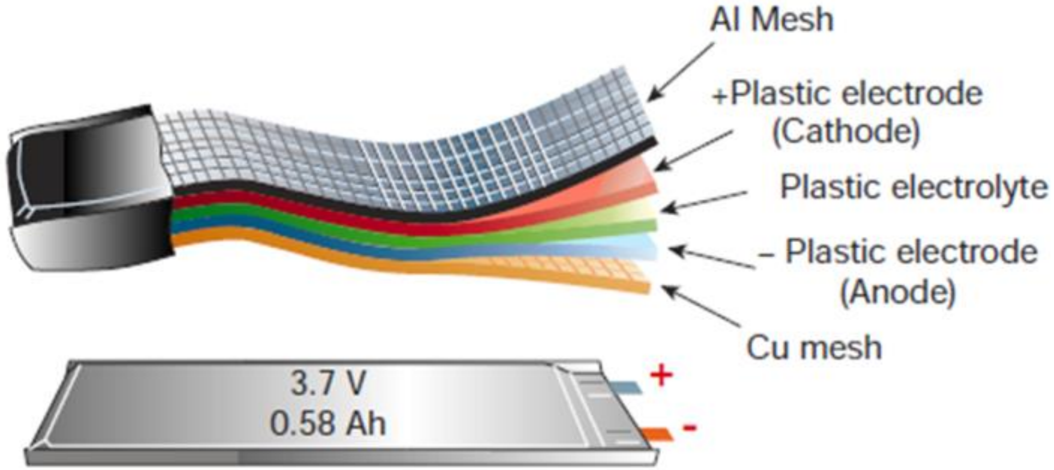
Cylindrical



Coin cell

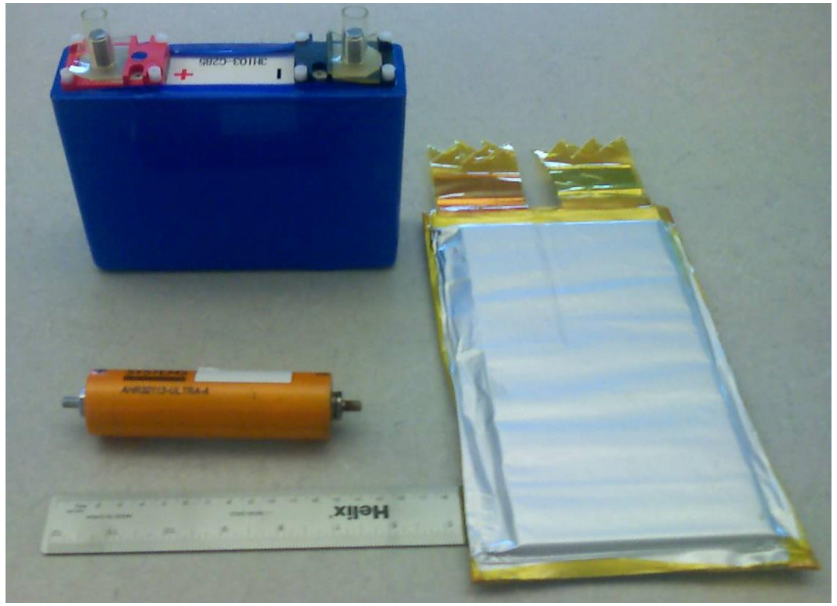


Prismatic (Hard Can)



Pouch

Cell, Module and Pack

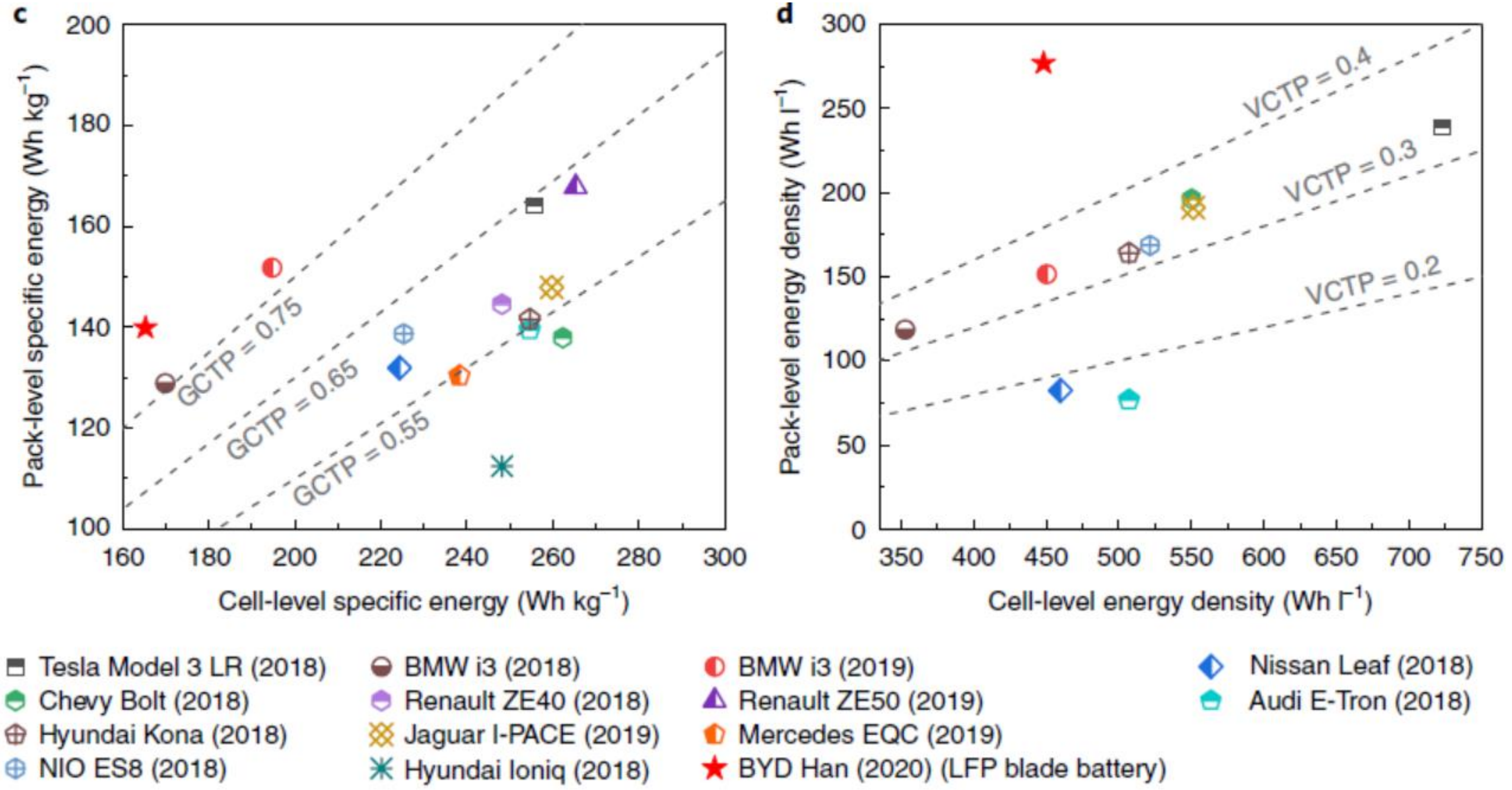


Individual Cells

A prismatic Li-ion module by A123 system

Battery Pack by A123 system

Pack vs Cell

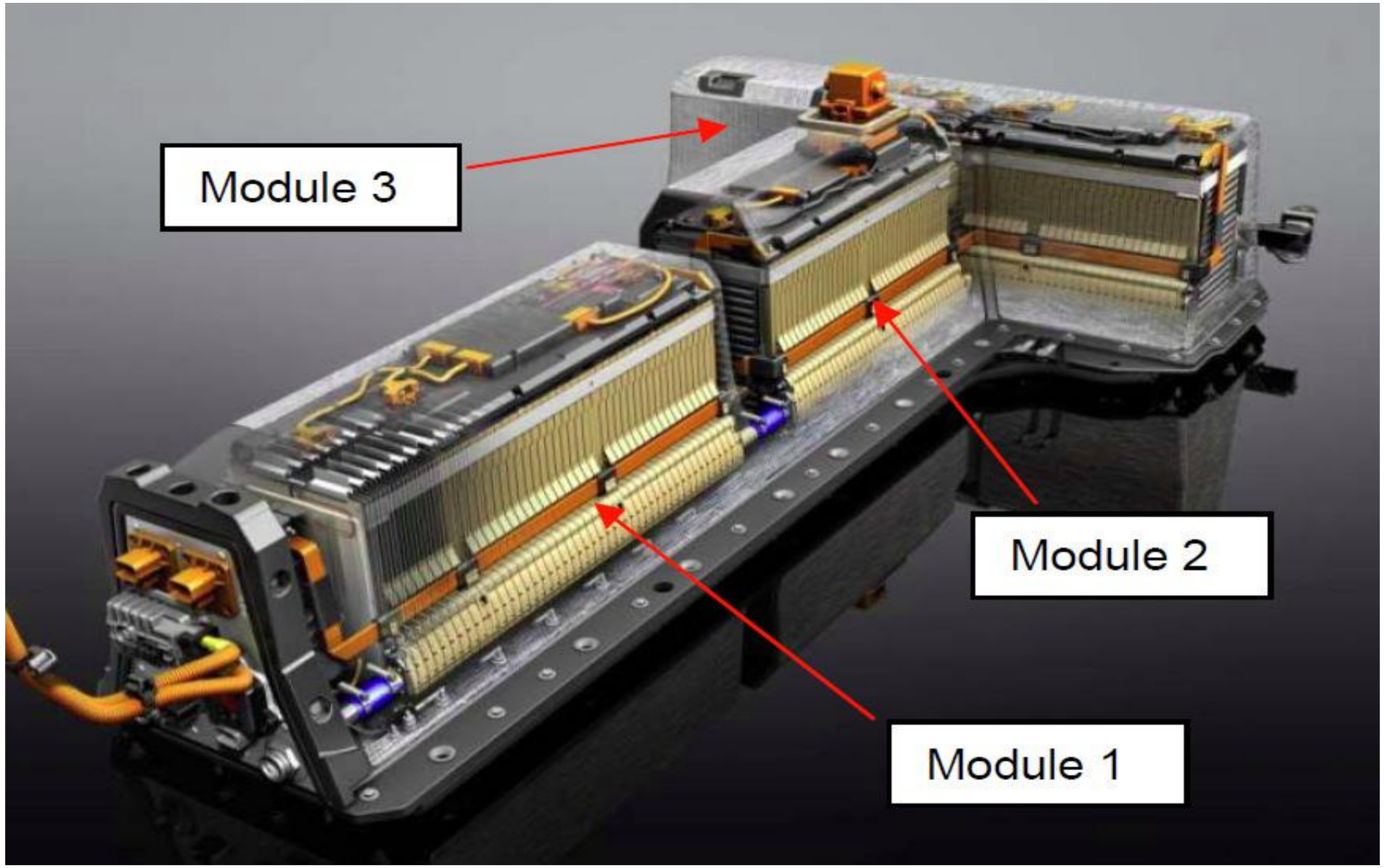


- Gravimetric cell-to-pack ratio (GCTP, the ratio of specific energy at the pack level to that at cell level)
- Volumetric cell-to-pack ration (VCTP)

Yang, XG., Liu, T. & Wang, CY. Thermally modulated lithium iron phosphate batteries for mass-market electric vehicles. Nat Energy 6, 176–185 (2021).

Chevrolet Volt battery pack

T shape, 288 LG P1 pouch cell



“Chevrolet Volt Battery Pack Tests, Final Report” Rept. No. GTL-DOT-11-VOLTBAT, 20-Jan-2012, by General Testing Laboratories, Inc., Colonial Beach, Virginia, for USDOT.

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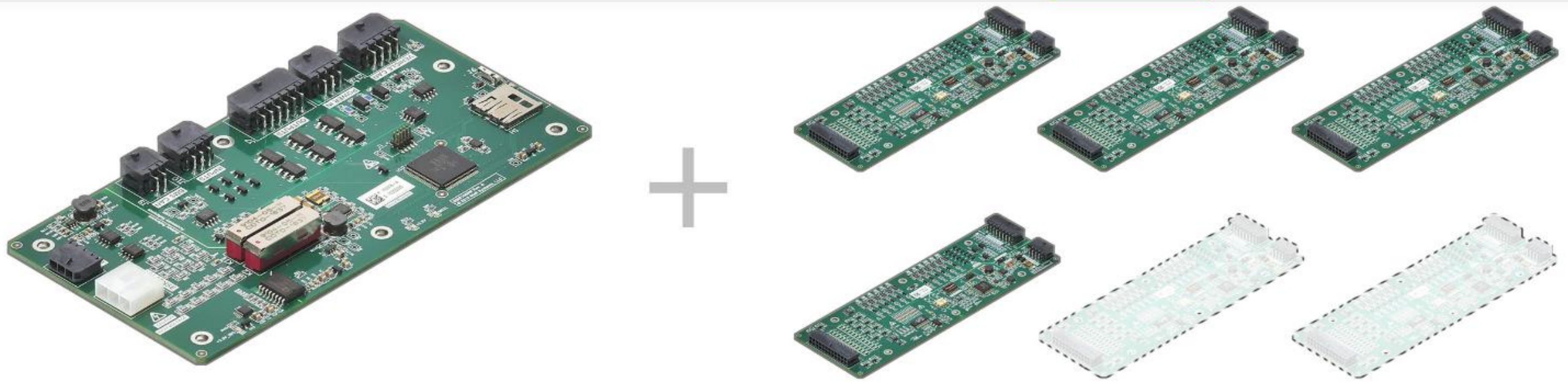
Battery Management Systems

An embedded system (purpose-built electronics plus processing to enable a specific application)



1X **Master BMS** Unit

- Communicates with outside system via CAN 2.0B
- Manages pre-charging and contactors
- Monitors pack voltages

1-64X **Monitor BMS** Units

- Measures cell voltages and temperatures
- Balances cells
- Communicates with Master BMS via internal data link

Why Managing? (1)

Imbalance in voltage, state-of-charge and temperature among cells

- Reduces the capacity of the battery
- Reduces the lifetime of the battery
- Increases with large charge/discharge cycles

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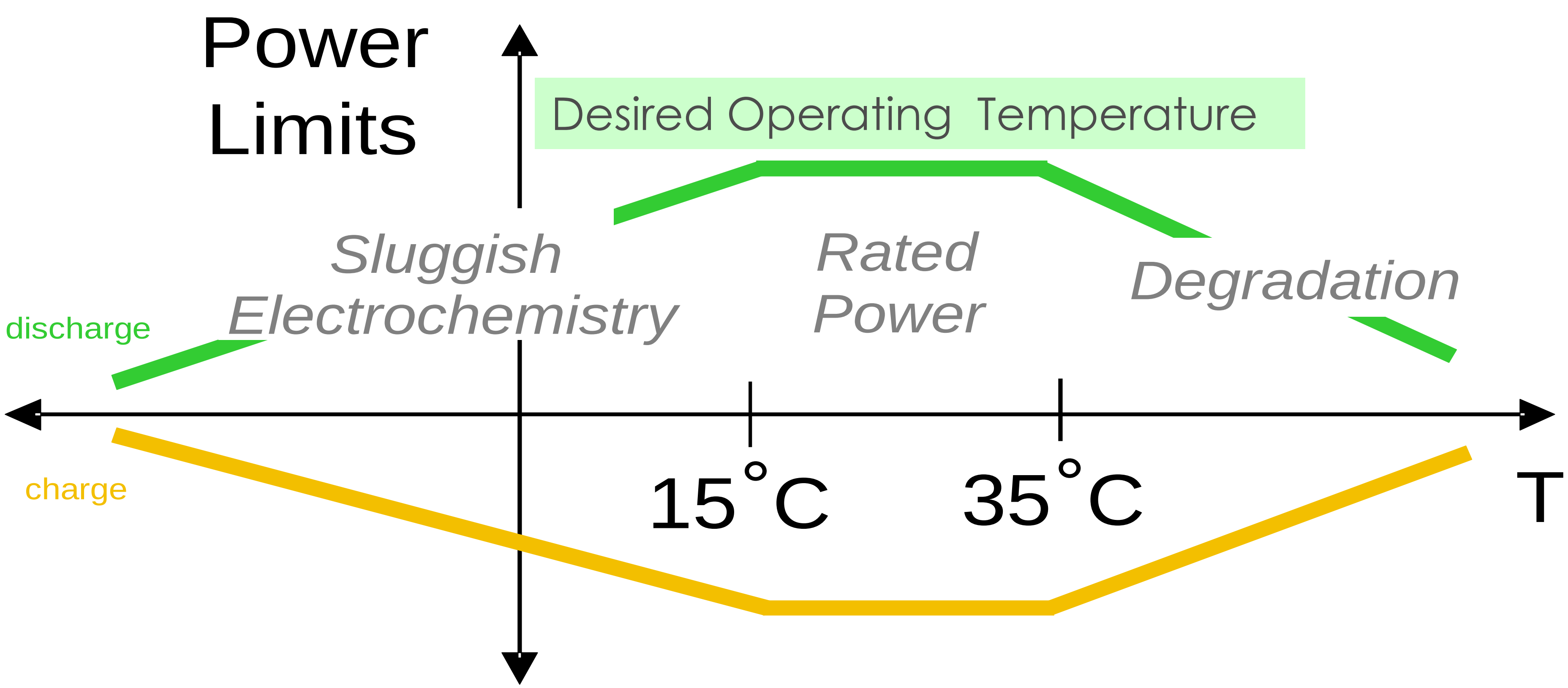
Why Managing? (1)



Kandler Smith, NREL Milestone Report, 2008

Why Managing? (2)

Catastrophic failure rate in commercial Li-ion batteries ~ 1 in 5-10 million

- Equates to ~1 in 1 million laptops
- BUT also equates to ~1 in 1000 Tesla Roadsters

90 Wh

2 kWh

4 kWh

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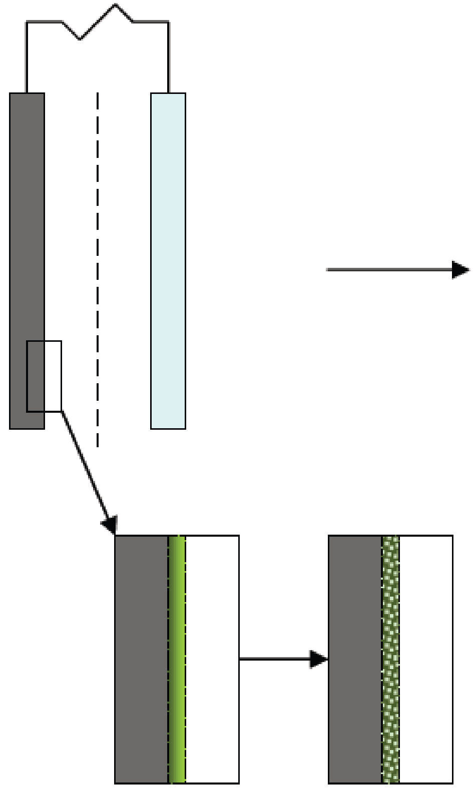
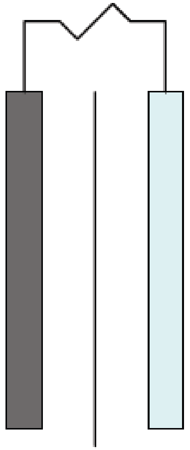
Why Managing? (2)

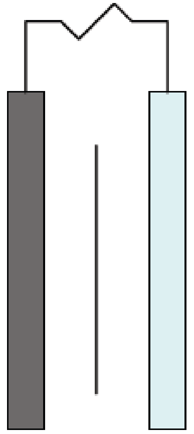
~80°C:
Passivating layer on anode begins to break down
Exothermic reaction between anode and electrolyte



~135°C:
Heating continues, separator pores close
Exothermic reaction at anode continues



~160-180°C:
Separator loses mechanical integrity & shrinks
Massive internal short develops
Rapid heating ensues



~180-250°C:
Highly exothermic reactions between cathode & electrolyte
Rapid temp & pressure rise
Battery vents flammable mist

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BMS Functions

1. ***Sensing and high-voltage control***

- voltage, current, temperature; control contactor, pre-charge; ground-fault detection, thermal management

2. ***Protection against***

- Over-charge, over-discharge, over-current, short circuit, extreme temperatures

3. ***Interface***

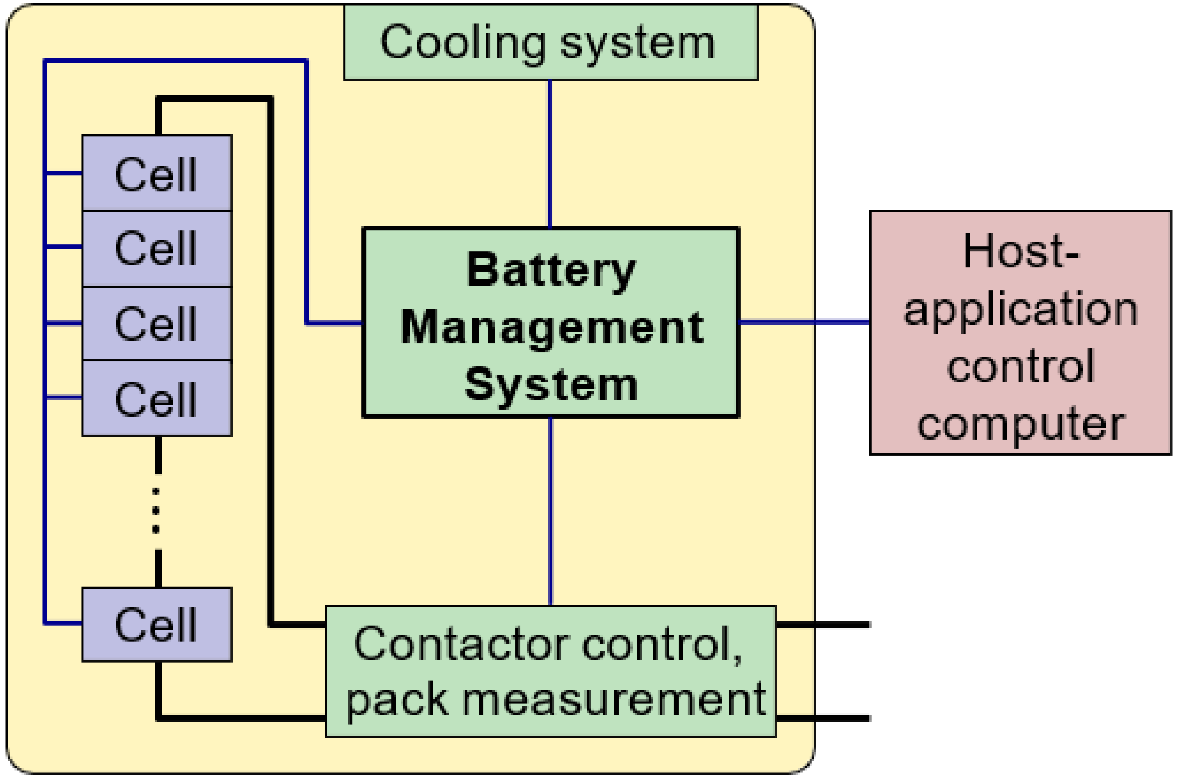
- Range estimation, communications, data recording, reporting

4. ***Performance management***

- State-of-charge (SOC) estimation, power-limit computation, balance/equalize cells

5. ***Diagnostics***

- Abuse detection, state-of-health (SOH) estimation, state-of-life (SOL) estimation



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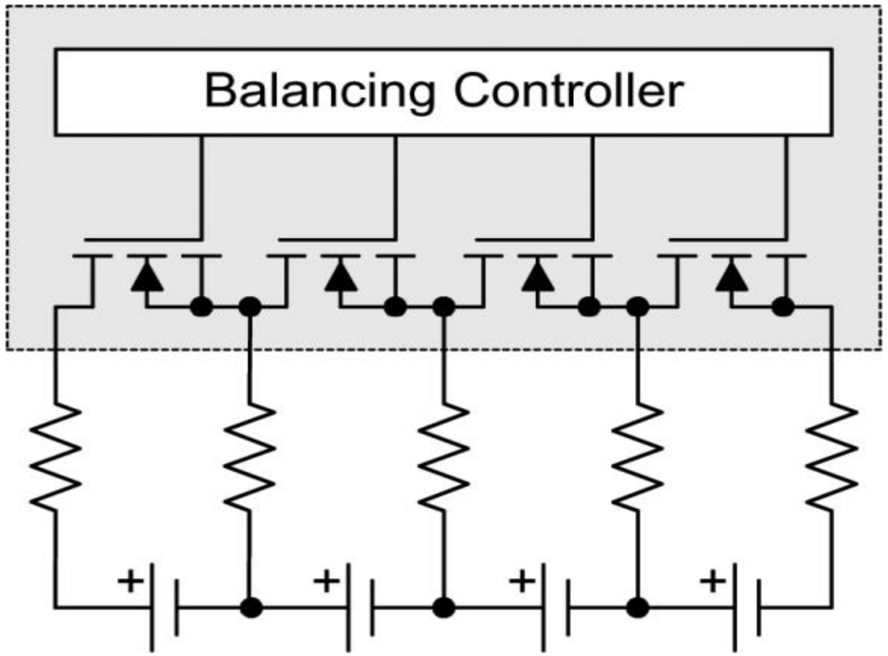
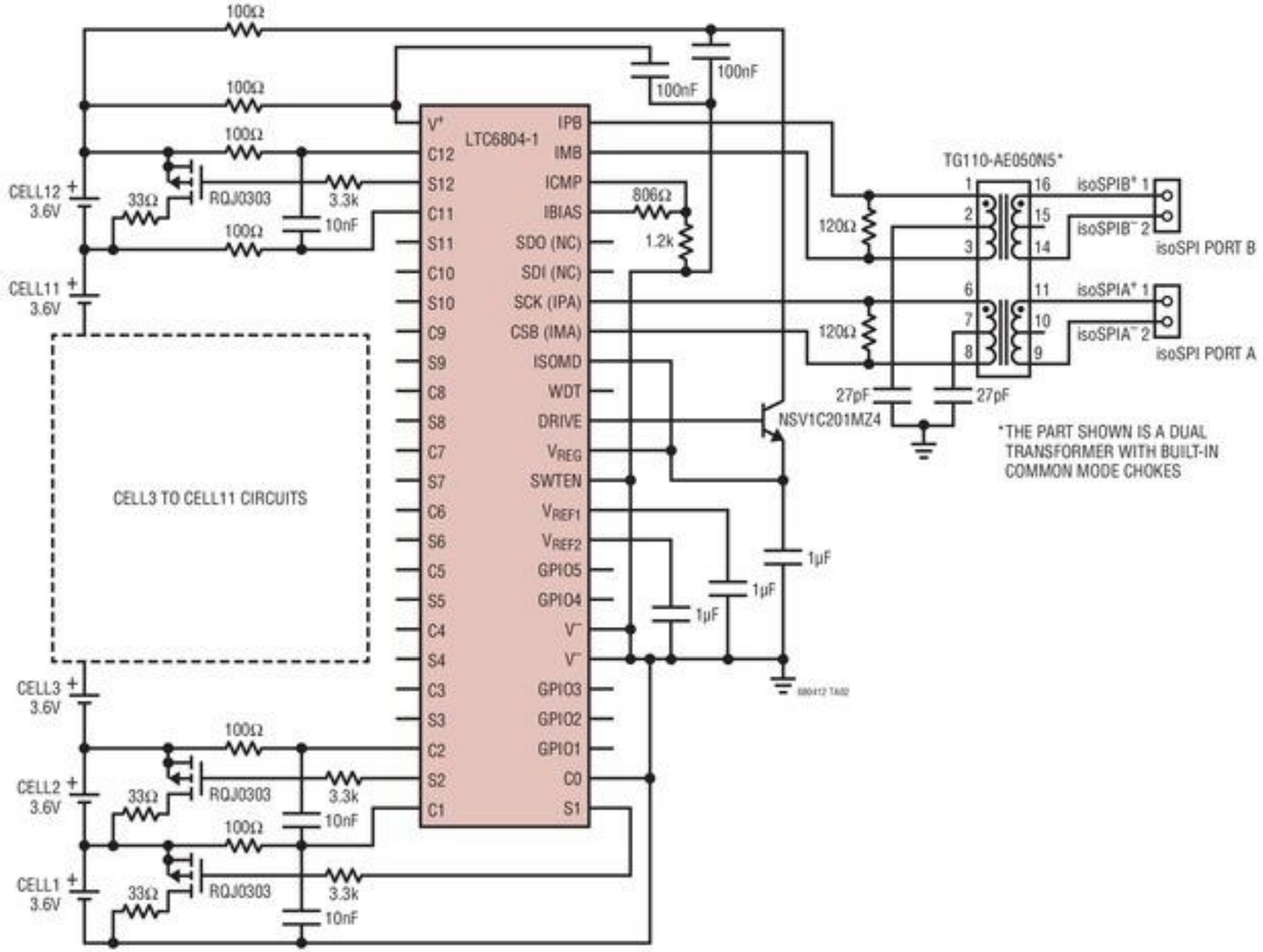
Passive Resistor Balancing

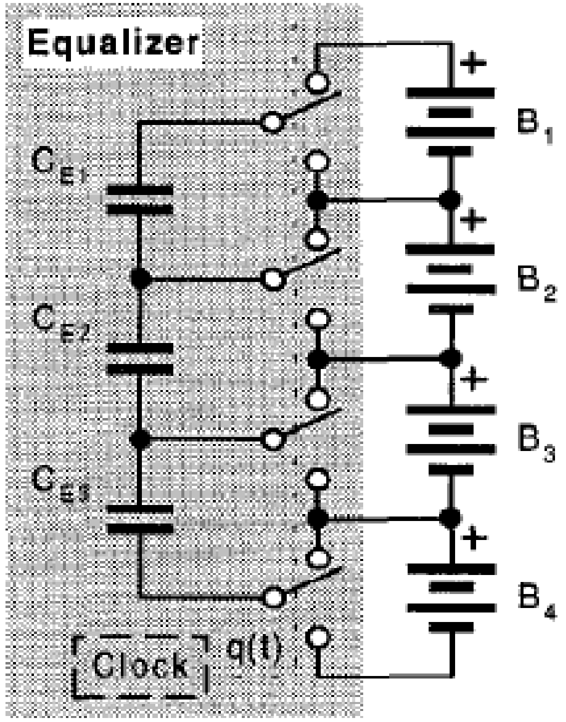


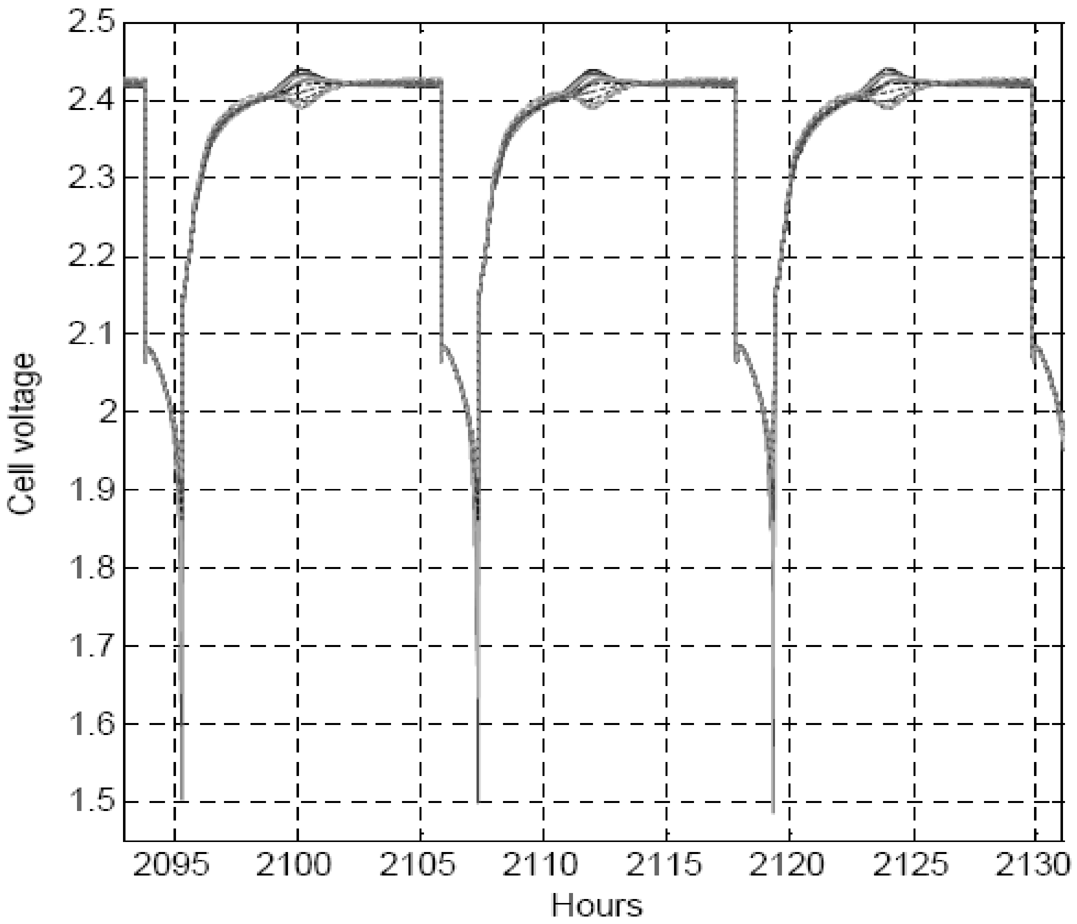
- Energy of high-voltage cells is consumed by resistors
- Loss of energy due to balance
- Hard to manage heat
- Can only balance the over-voltage cell

Example: LT Resistor Balancing



Capacitive Balancing





- Slow speed balancing: up to 20 hours
- Large size Capacitor
- Lack of enable/disable feature

P. T. Krein, R. Balog, "Life Extension Through Charge Equalization of Lead-Acid Batteries," ITELEC02, 2002

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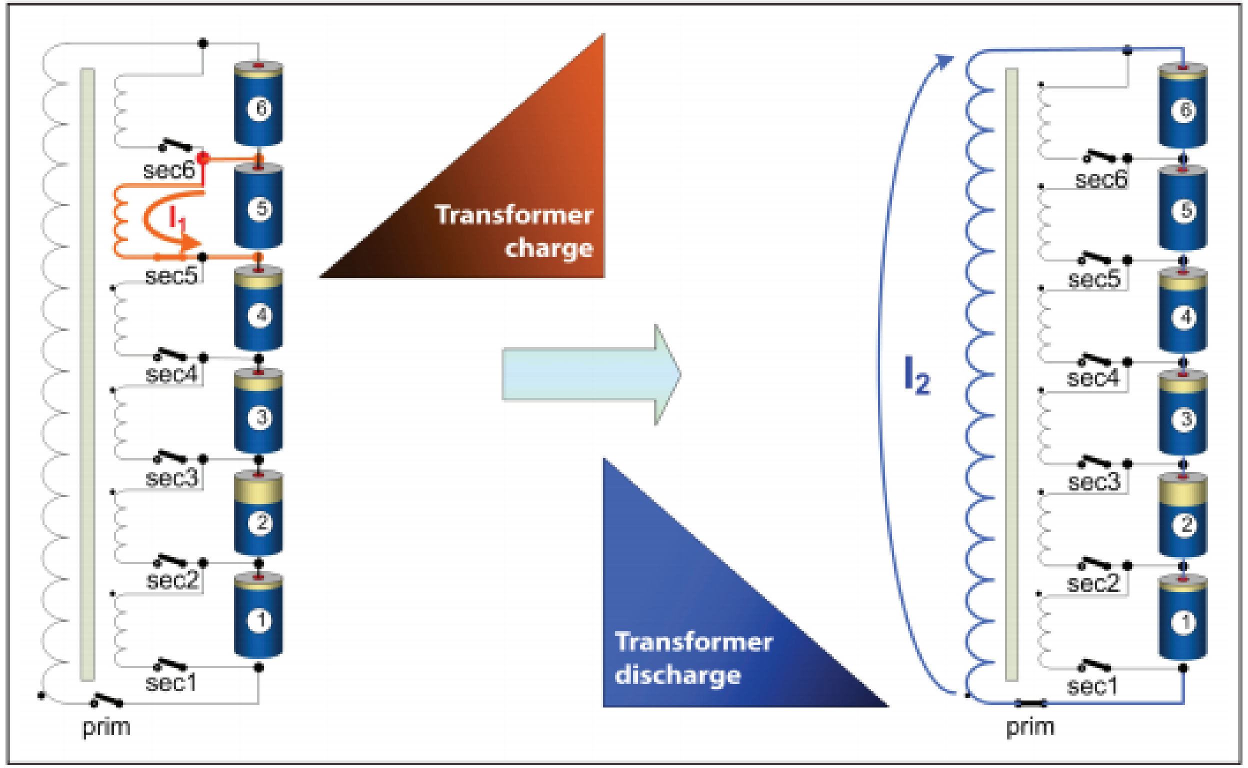
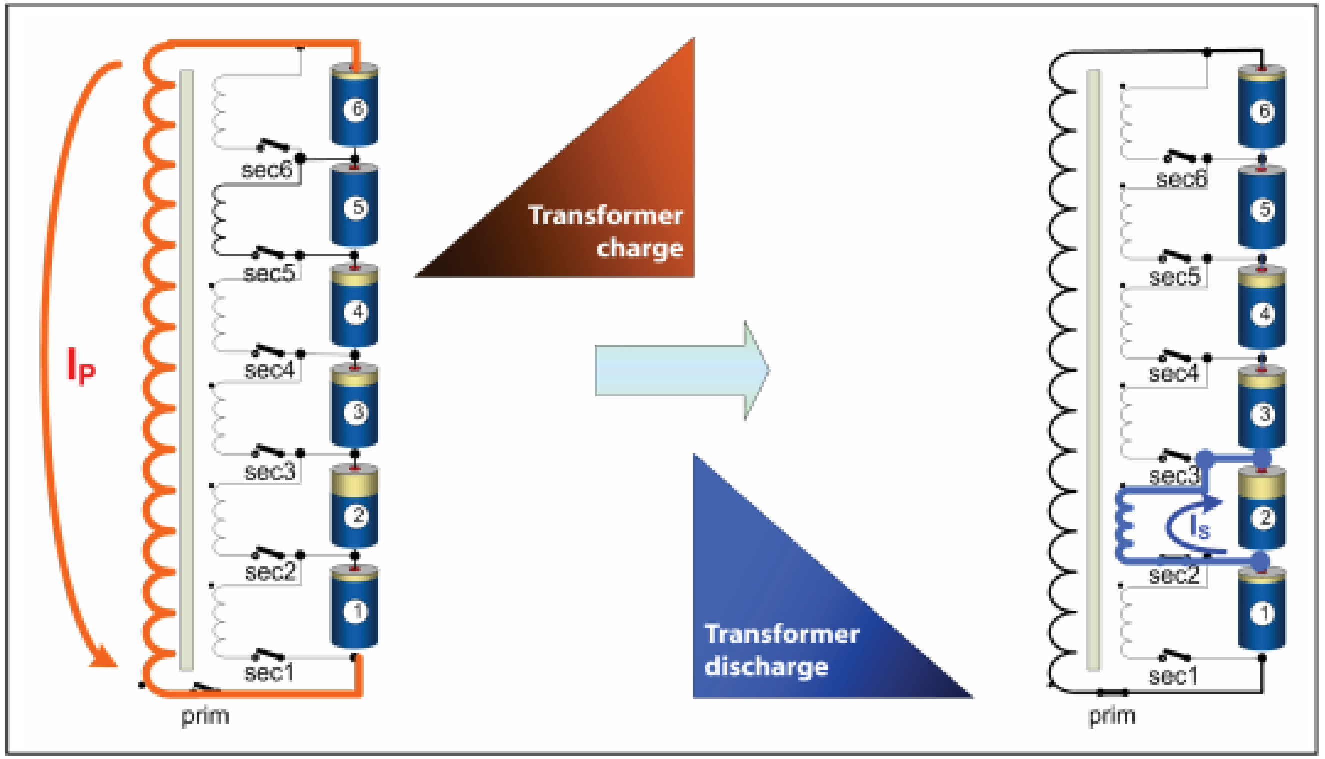
Inductive Balancing

When some cell is high

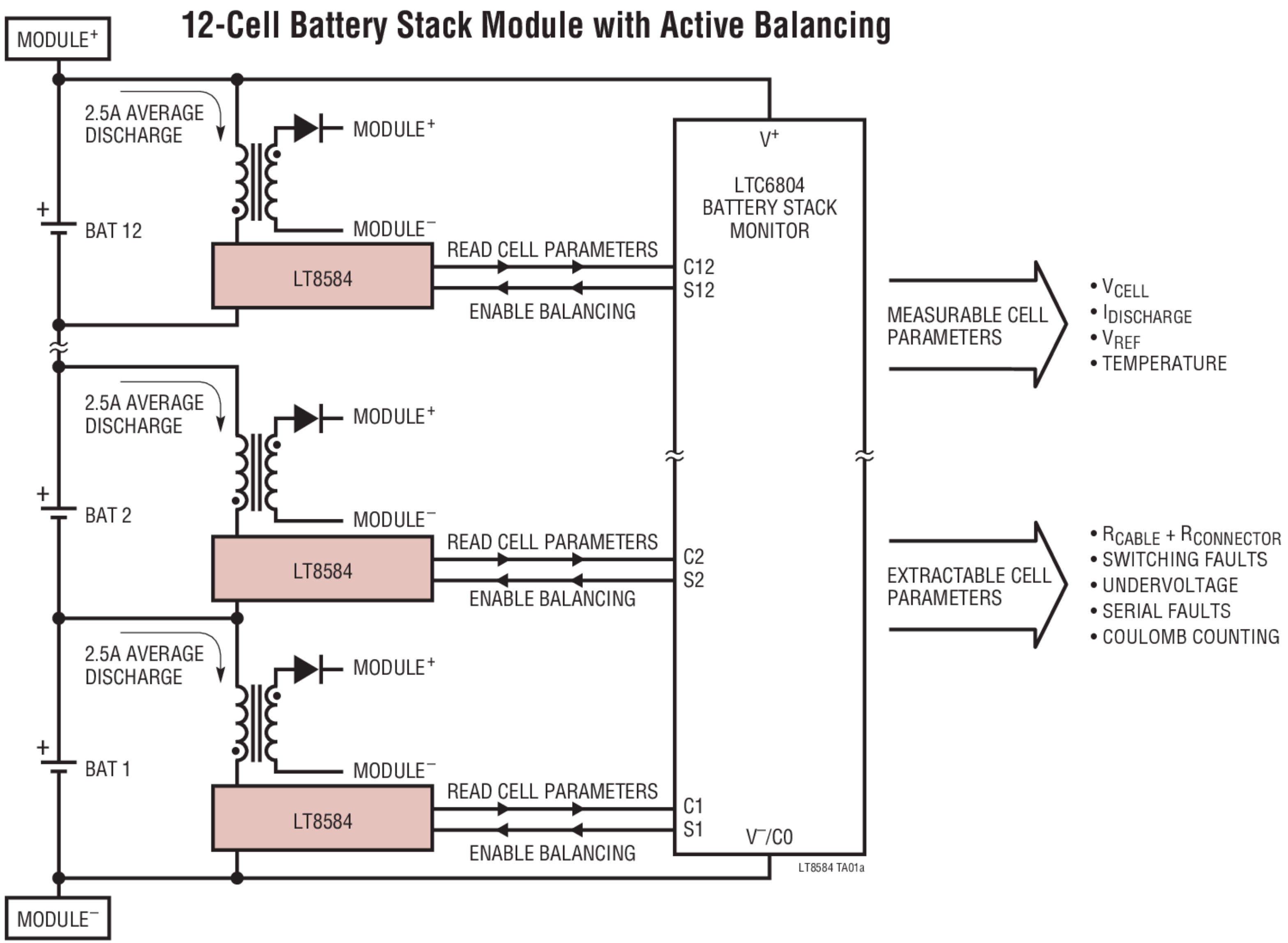


When some cell is low



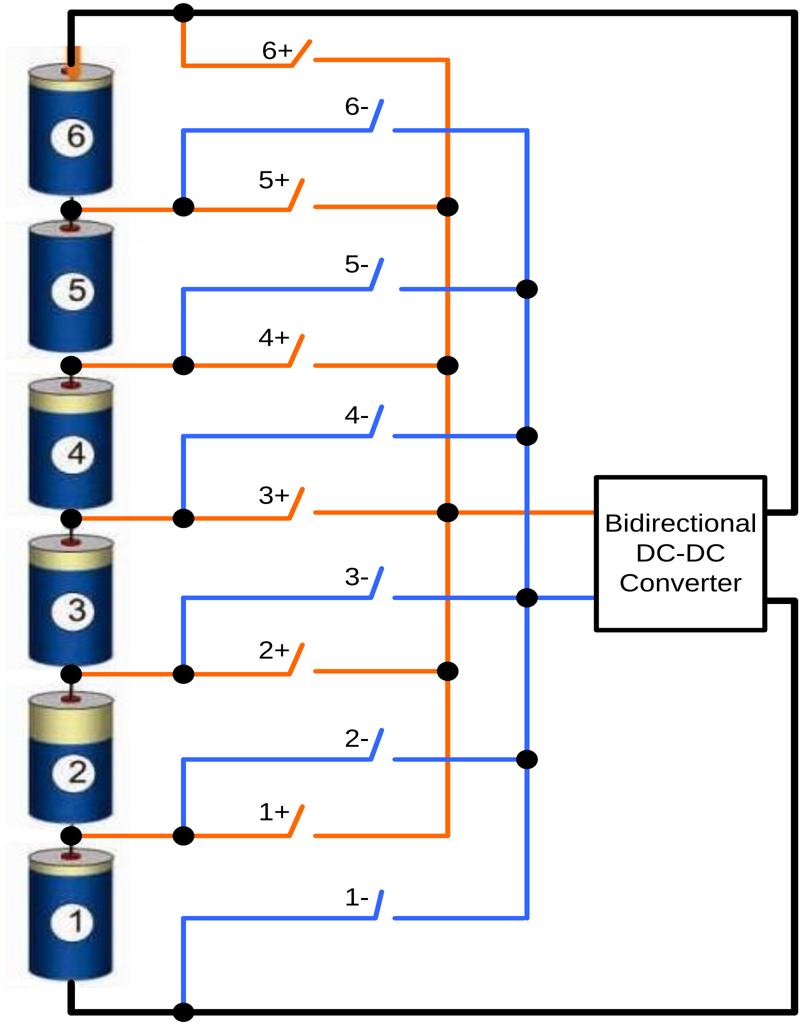
Werner Rößler, Boost battery performance with active charge-balancing, Infineon, EE Times India, 2008.
http://www.powerdesignindia.co.in/STATIC/PDF/200807/PDIOL_2008JUL24_PMNG_TA_01.pdf?SOURCES=DOWNLOAD

Example: LT Active Balancing



Dynamic Balancing

- The lowest row/cell is charged by the DC-DC converter using the pack voltage
- The highest cell is discharged to the whole pack
- Difficulty is the small duty ratio for large packs



Ziling Nie, and Chunting Mi, "Fast Battery Equalization with Isolated Bidirectional DC-DC Converter for PHEV Applications," the Fifth IEEE International Vehicle Power and Propulsion Conference (VPPC), Dearborn, Michigan, USA, September 7-11, 2009.

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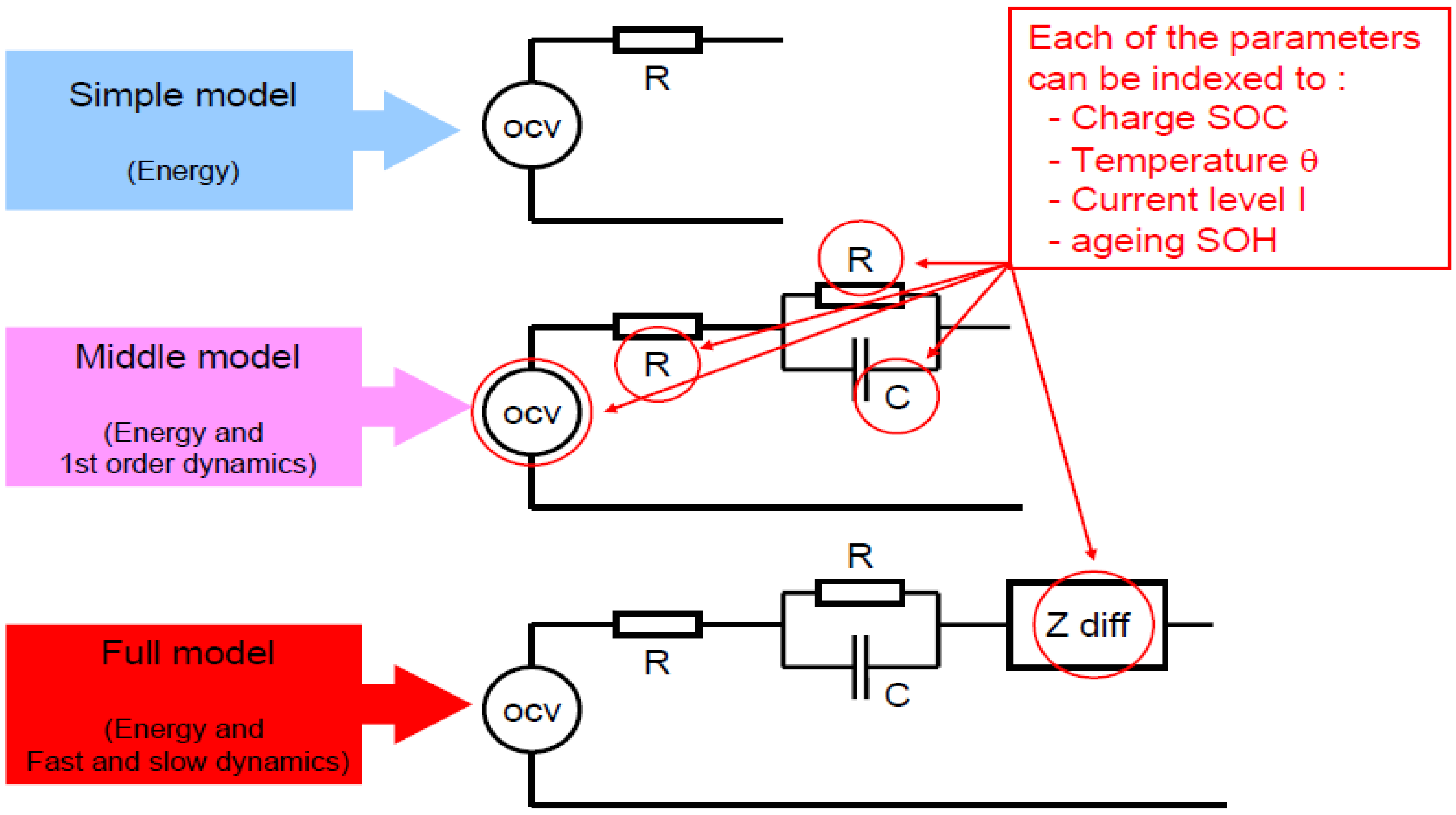
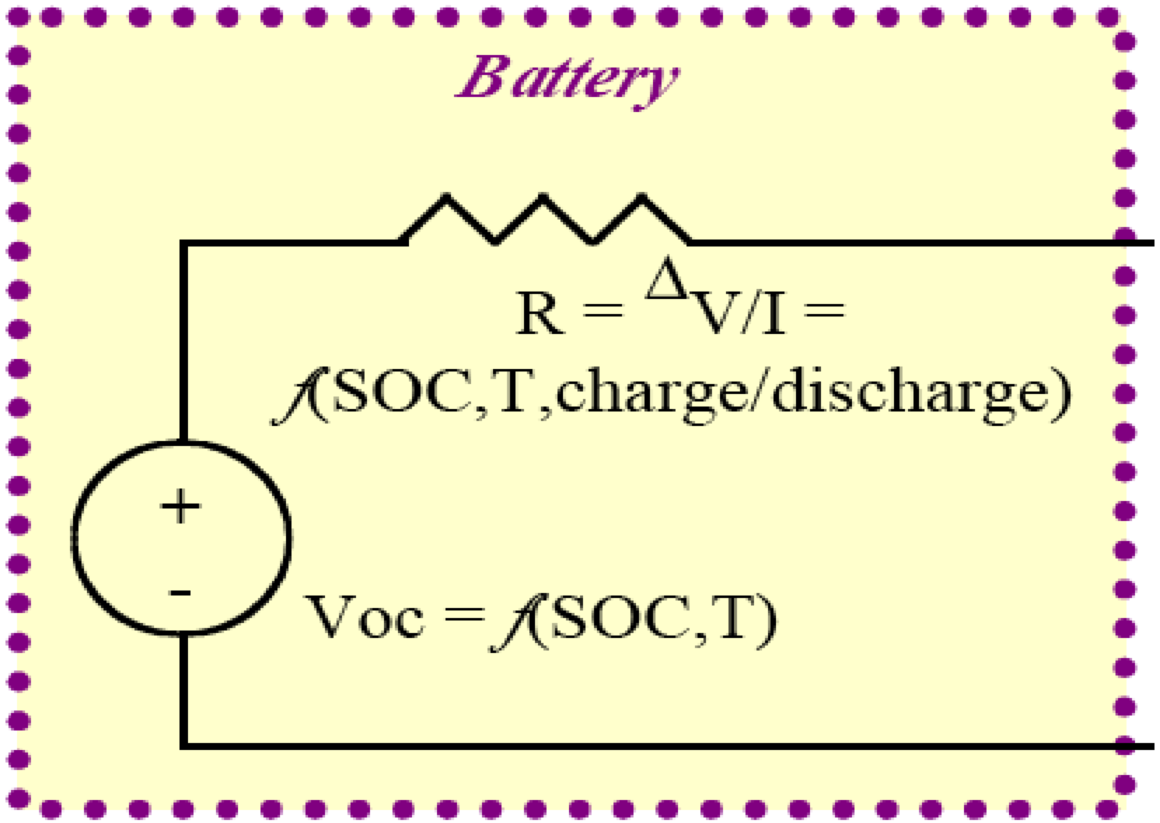
Battery Modeling

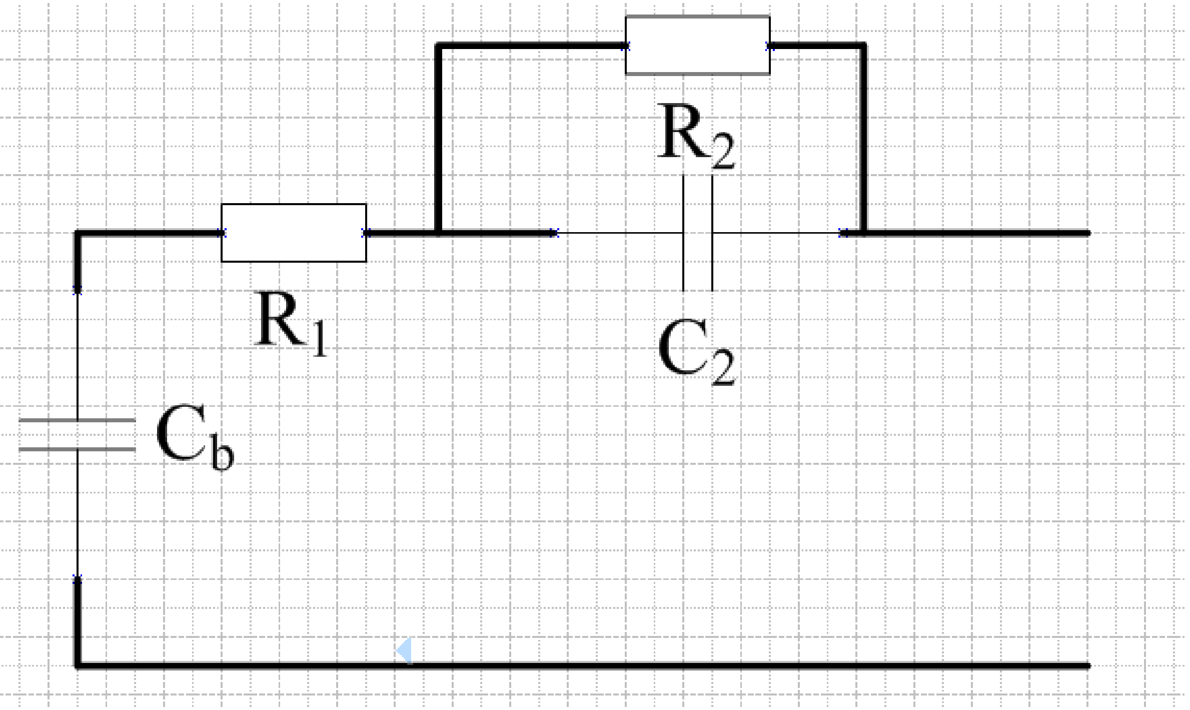


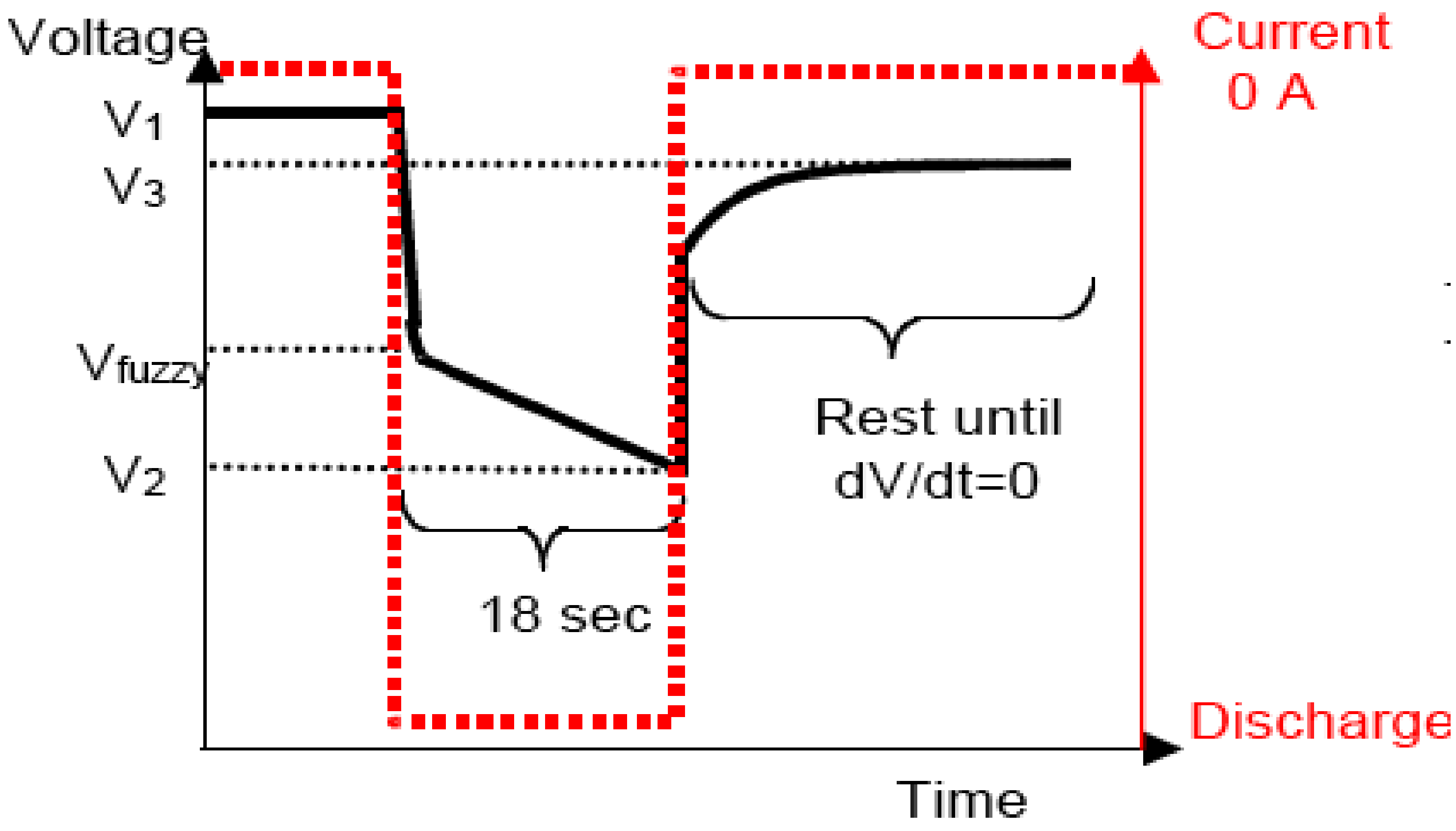
Simple Model



Simulink, ADVISOR

Middle Model





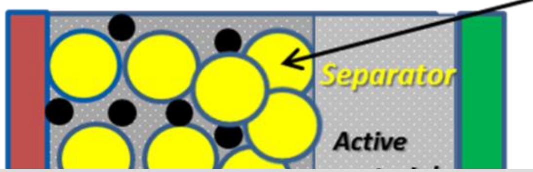
Physics-Based Model

Charge transport in solid sate

$$\sigma^{eff}\frac{\partial^2\phi_s}{\partial x^2}=a_s j^{Li}$$

Butler-Volmer Kinetic Equation

$$j^{Li}=a_s i_0\left(exp\left(\frac{\alpha_a F}{RT}\eta\right)-exp\left(\frac{-\alpha_c F}{RT}\eta\right)\right)$$



1. ***Cell geometries, particle sizes, material properties and even particle shape can be varied, in simulation, to optimize a cell's characteristics without the need to build numerous experimental cells***
2. ***Connection between battery external properties (SOC) and internal parameters (Li ion concentration)***

Charge transport in electrolyte

Ion transport in electrolyte

•Reference: M. Doyle, T.F. Fuller, and J. Newman, Journal of Electrochem. Soc., 140, 1526 (1993)
C. R. Pals and J. Newman Journal of Electrochem. Soc., 142 (10), 3274-3281 (1995)
M. Doyle, J. Newman, Journal of Electochem. Soc., 143, 1890 (1996)
Chaoyang Wang, Battery System Engineering, (2014)

State of Charge

1C: We define the discharging/charging current using one-hour to deplete/charge the battery from full/empty to empty/full as 1C;

SOC: a proportion of the charge available at that point compared to the total charge available when it is fully charged. Full:100%. Empty: 0%;

In EV, **SOC** evaluation is also known as *fuel gauge* due to its analogy to a gas car's fuel gauge.

Attention: Cell SOC ≠ Battery SOC

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Depth of Discharge

DOD: a measure of the charge removed from the battery or cell. DOD could be expressed either in Ah or %.

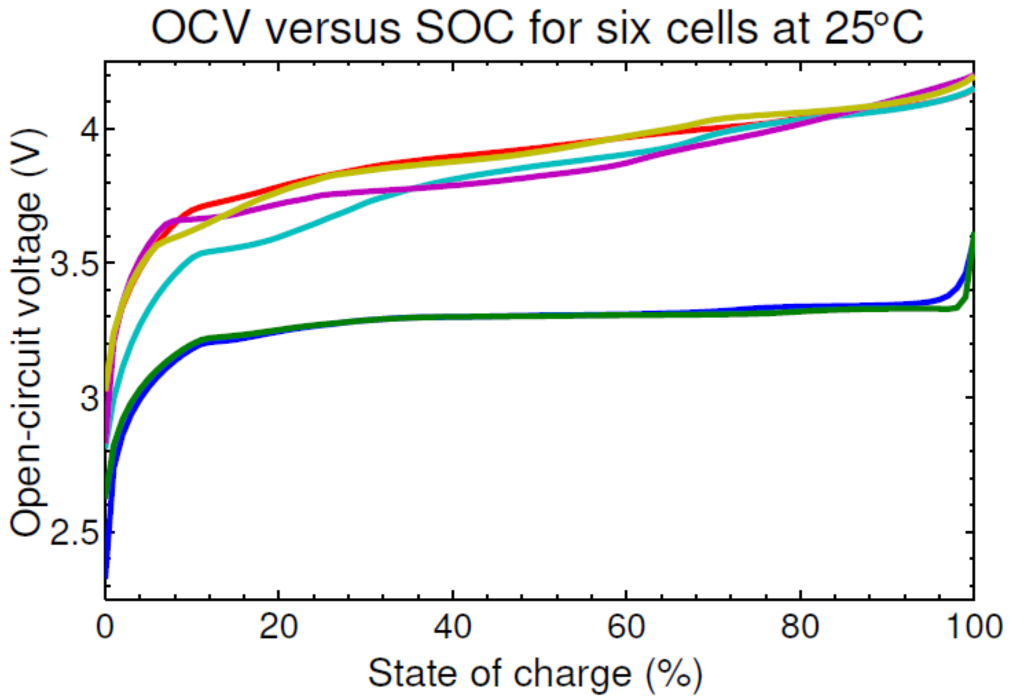
In most cases: DOD(%) = 1-SOC. This description is not always true.

A battery with 100Ah rated capacity could be further discharged even when its SOC is already 0 (not recommended though). This battery could discharged 105Ah, meaning over discharged. Using DOD(%) = 1-SOC, its SOC = 0% and its DOD is 100%, however although it actually released 105Ah charge.

Therefore for DOD, we prefer to using Ah instead of %.

SOC Estimation

OCV method



Voltage useful as indirect indicator of SOC, but not as measurement of SOC

Coulomb Counting

$$SOC\ (t) = SOC(0) - \frac{1}{Q}\eta\int_0^t I(t)dt$$

η is cell coulombic efficiency
Q is the cell total capacity in ampere seconds (coulombs)

Cons: Accumulating error could be severe

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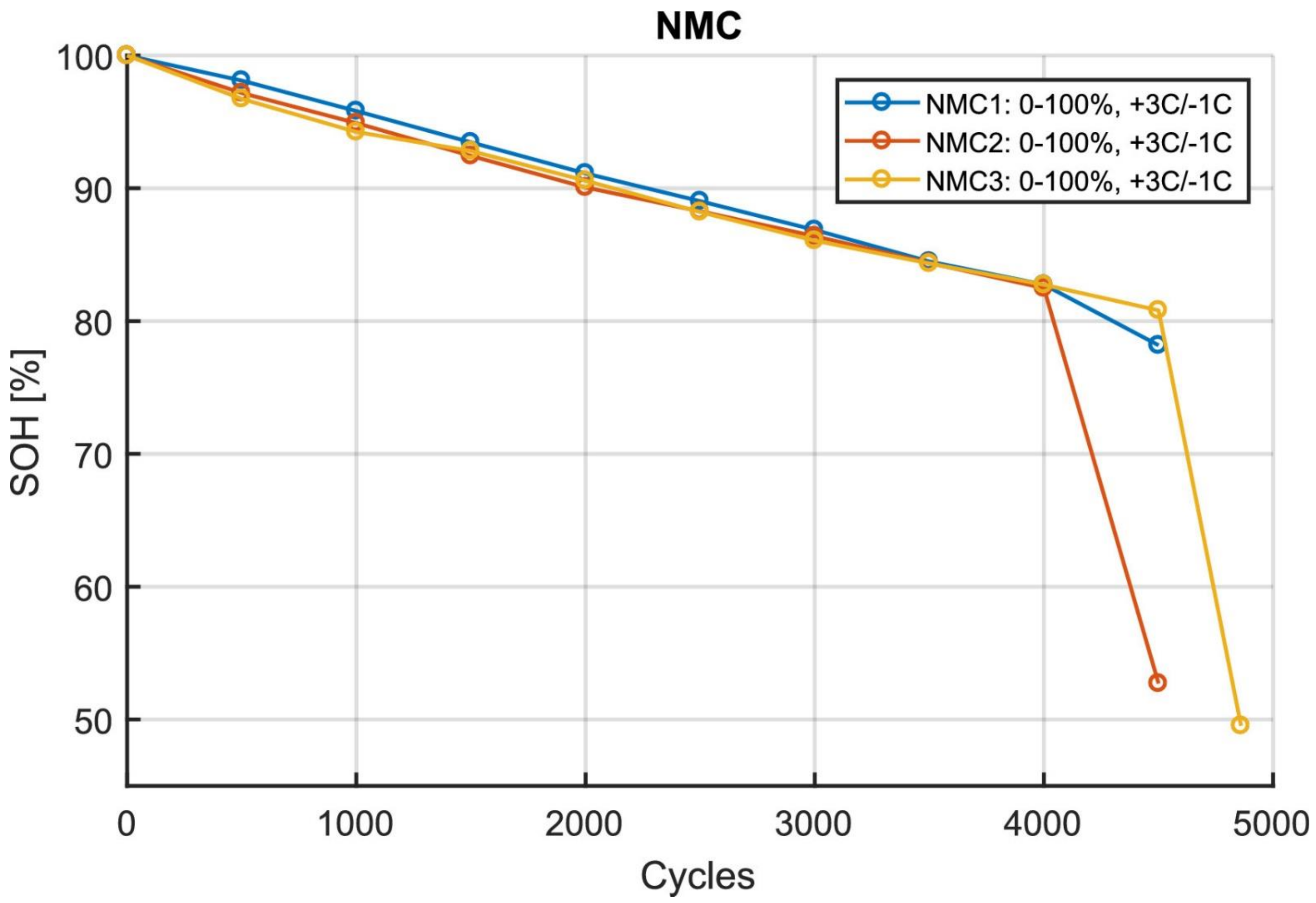
State of Health

No specific mathematical expression;

However in the real practice, capacity and resistance are the two major metrics.



State of health estimation of cycle aged large format lithium-ion cells based on partial charging, Journal of Energy Storage, Volume 46, February 2022.

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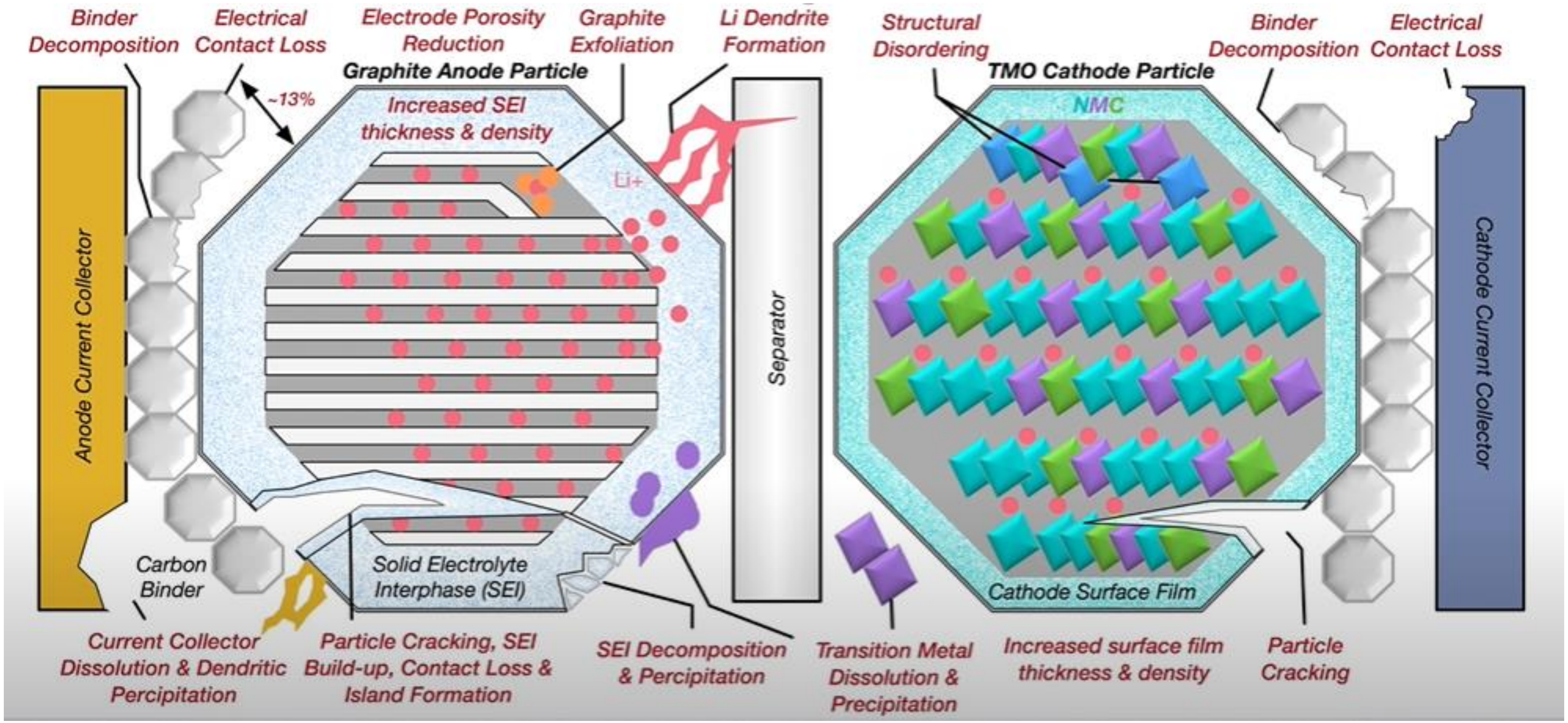
End of Life

- Battery Life requirements need to follow vehicle component requirements:

- 10 years and 150,000 miles.

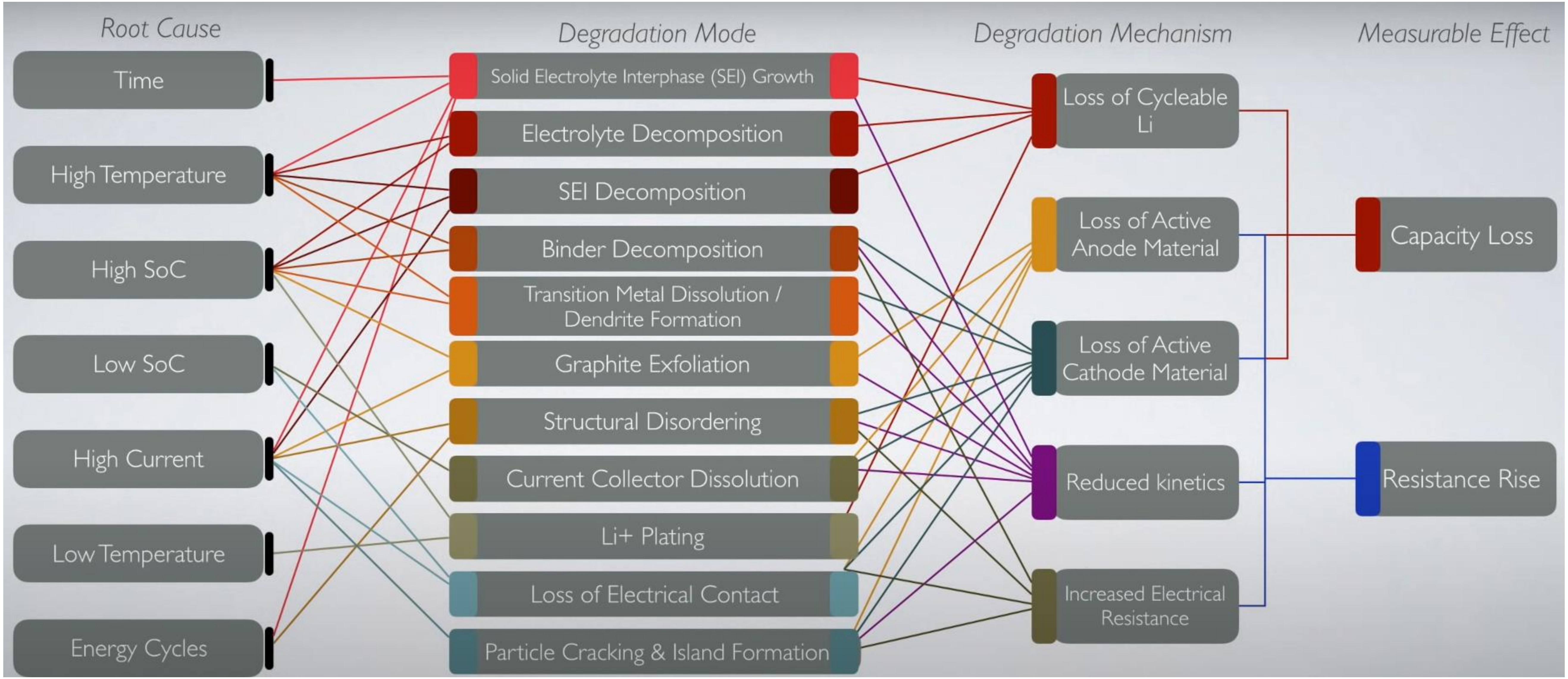
- USABC has set requirements, based on both cycle life and calendar life.
- A battery is considered at its end of life if it cannot provide at least 80% of its initial capacity/energy, or 70% of its initial power (~130% of its original resistance).

Battery Degradation



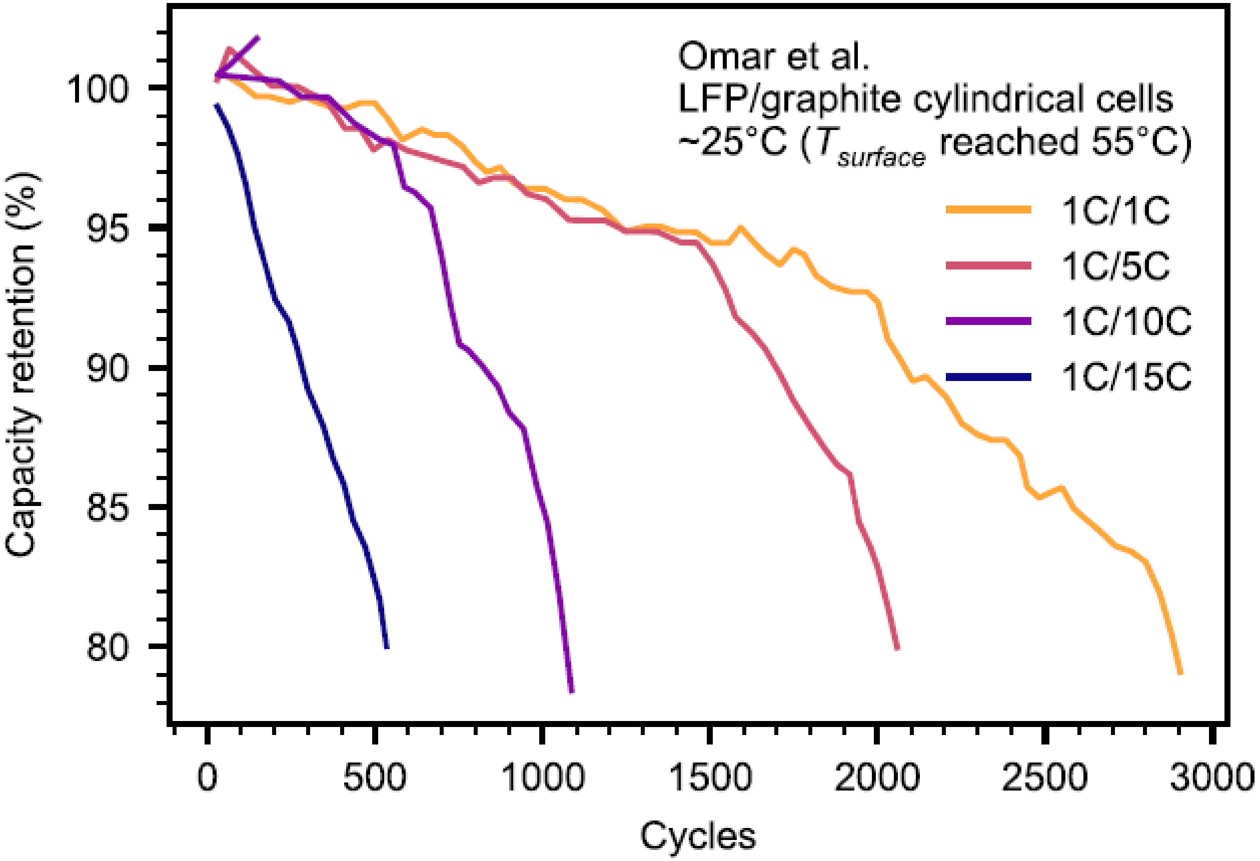
Battery Degradation Scientifically Explained - EV Battery Tech Explained (https://www.youtube.com/watch?v=XLnBg25JoHg)

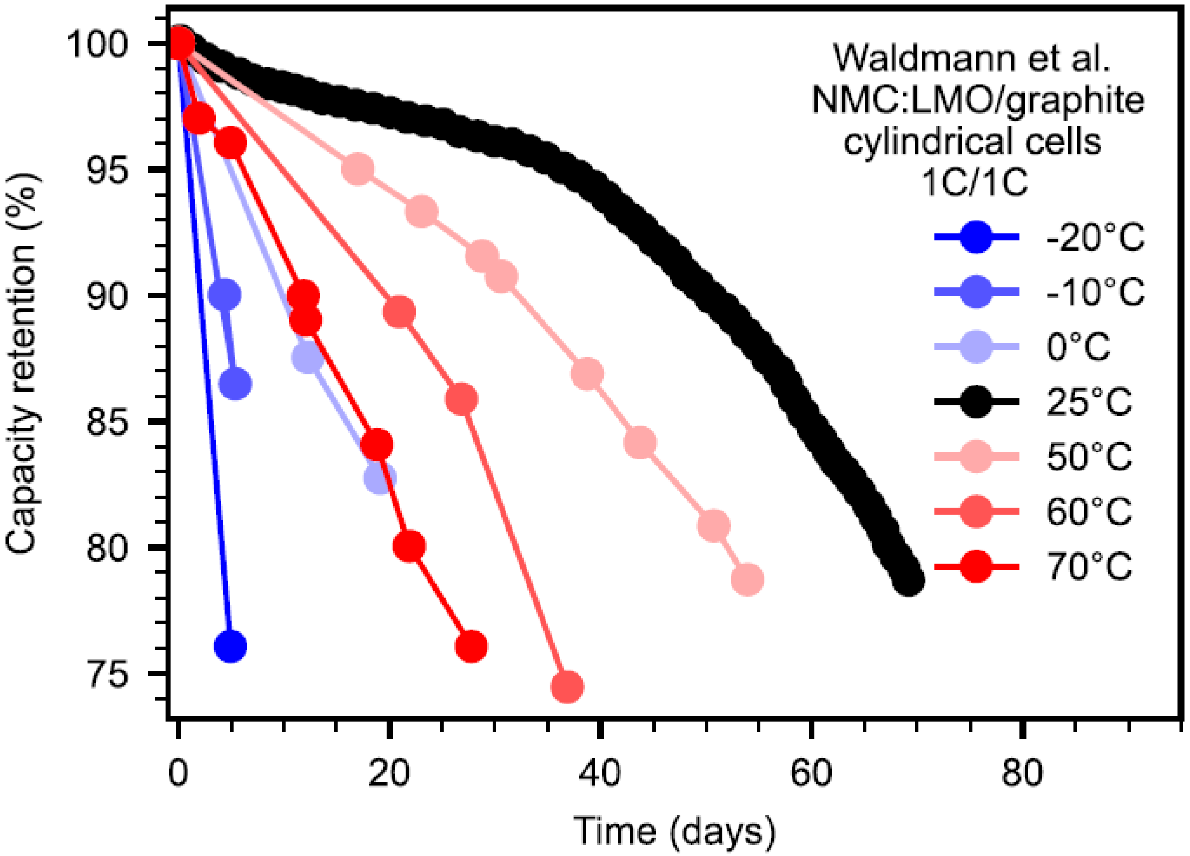
Battery Degradation



Battery Degradation Scientifically Explained - EV Battery Tech Explained (https://www.youtube.com/watch?v=XLnBg25JoHg)

State of Health





"State of health estimation of cycle aged large format lithium-ion cells based on partial charging", Journal of Energy Storage, Volume 46, February 2022.

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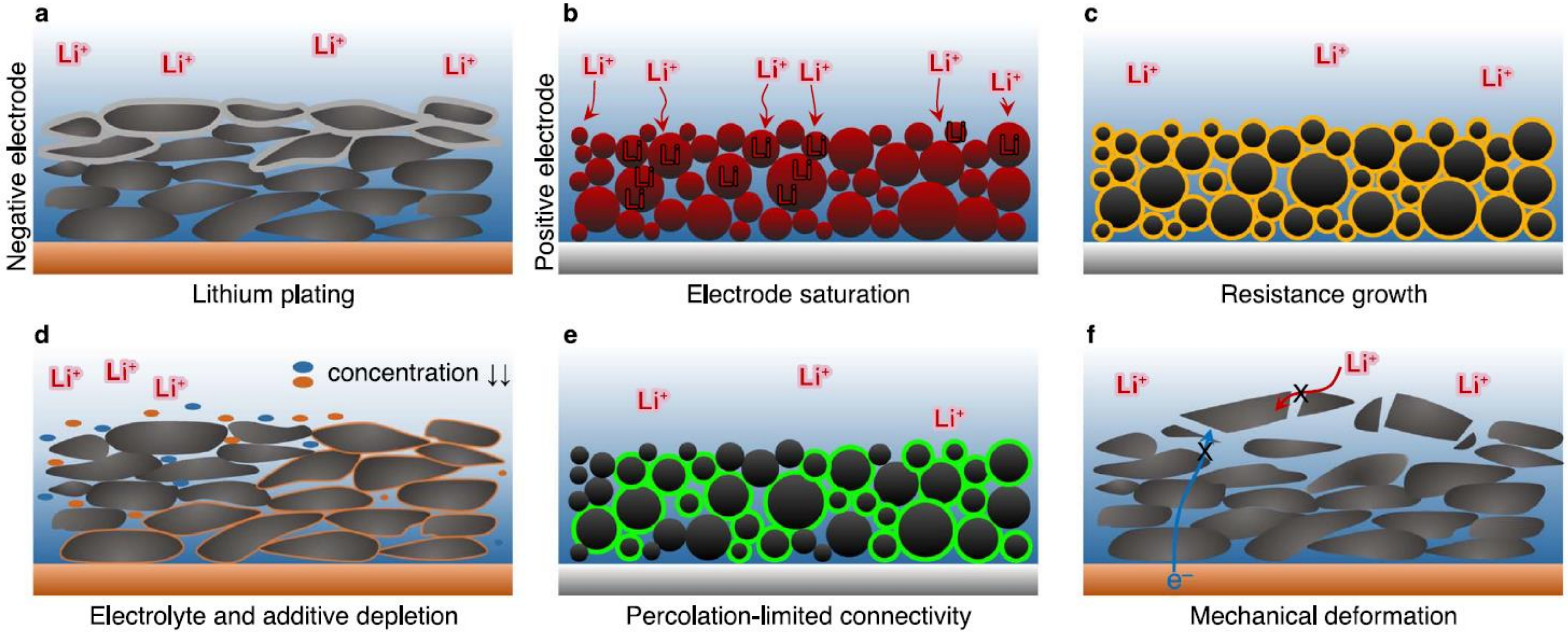
State of Health



Review—“Knees” in Lithium-Ion Battery Aging Trajectories, Peter M. Attia *et al* 2022 *J. Electrochem. Soc.* **169** 060517

Key Impact Factors

Charging rate	**High charging current expedites Li plating;**
Discharging rate	**Mixed**
Voltage limit	**Wide voltage window accelerates the onset of the knee point**
Temperature	**Studies found 25~35^{o}C is the best**
Rest time	**Mixed**
Pressure	**Optimized in the intermediate value**

Review—"Knees" in Lithium-Ion Battery Aging Trajectories, Peter M. Attia *et al* 2022 *J. Electrochem. Soc.* **169** 060517

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Grand Challenges

1. Can we extend battery life by >3 times (cycle, calendar)?
2. How fast can batteries be charged (<10min)?
3. Can we make batteries be completely safe?
4. How do we sense the battery health condition?
5. How do we make battery wearable, flexible and stretchable?
6. How high energy density can batteries go (Wh/kg, Wh/L)?
7. Can we reduce the battery cost down by 3 times?
8. What are the methods for battery reuse and recycle?
9. How do we do grid-scale and seasonal storage?

Yi Cui, Stanford University

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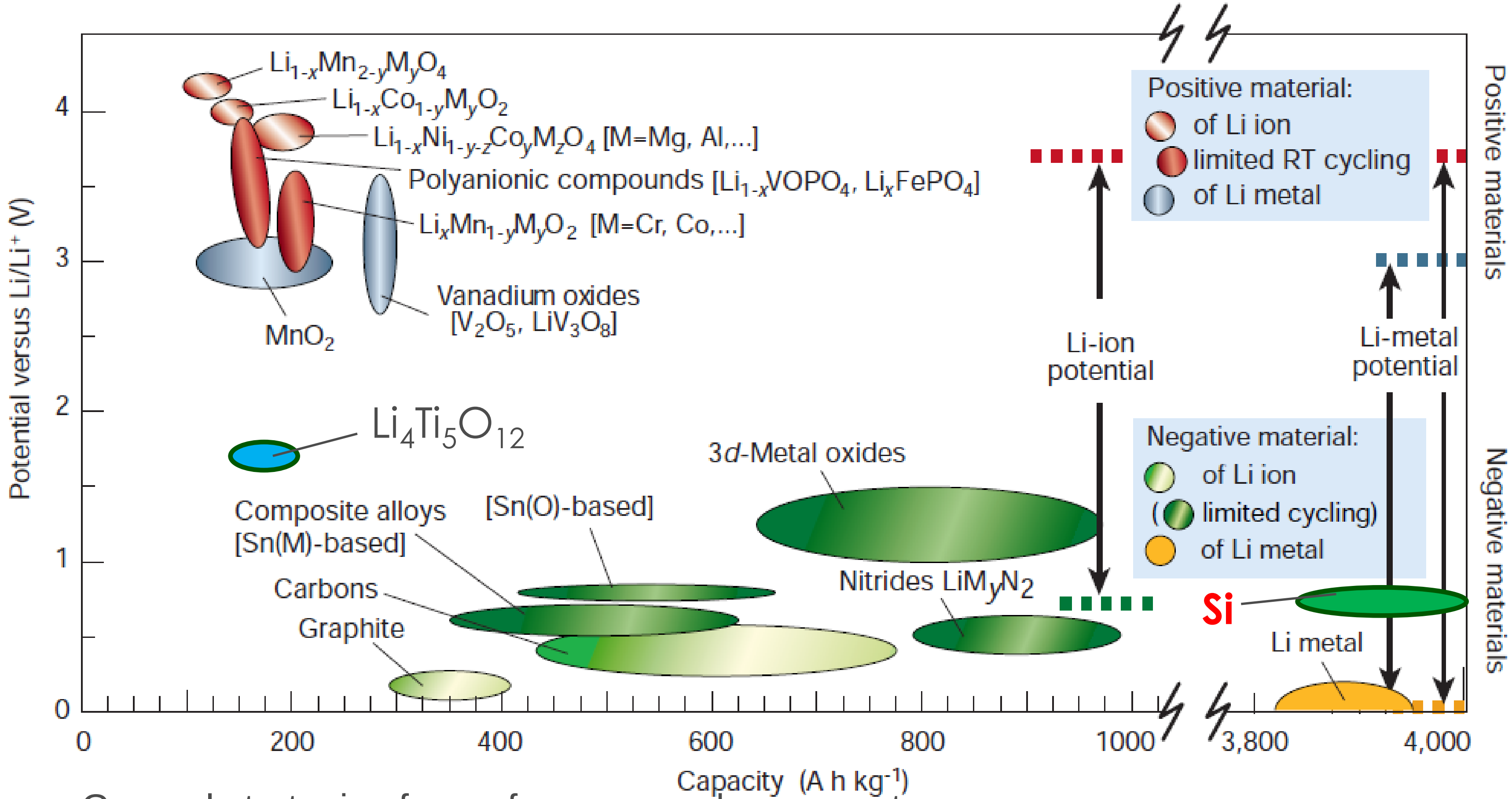
Li-ion Battery Present Development



General strategies for performance enhancement

1. Dimension Reduction
2. Composite Formation
3. Doping & Functionalization
4. Morphology Control
5. Coating & Encapsulation
6. Electrolyte Modification

N. Nitta, F. Wu et al., Li-ion battery materials: present and future, *Materials Today*, 18(2015)252

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Li-ion vs Na-ion

Electrical Vehicles

Large-scale ESS

Important Parameters

- High energy capacity
- High power capacity
- High cyclability
- High safety

Important Parameters

- Very long calendar life
- Very low cost
- High columbic efficiency

FARADION: Na-ion battery powered vehicle

Na-ion Battery

Why beyond Li-ion battery?

- **Limited resources of lithium raw materials**
- **Unevenly distributed (*mainly in South America*)**
- **Increasing demand**

Why Na-ion battery?

- **Unlimited resources**
- **Physical and chemical similarity**

	Li^+	Na^+
relative atomic mass (g/mol)	6.94	23
Shannon's Ionic radii ($\dot{A}$)	0.76	1.02
E^0 (vs SHE, V)	-3.04	-2.71
material abundance (ppm)	20	23,600
molar volume ($\dot{A}^3$)	21.3	39.3
theoretical capacity of $ACoO_2$ /mAh g^{-1}	274	235
theoretical capacity of $ACoO_2$/mAh cm^{-3}	1387	1193

N. Yabuuchi, et al., *Chemical Reviews*, 2014,114, 11636

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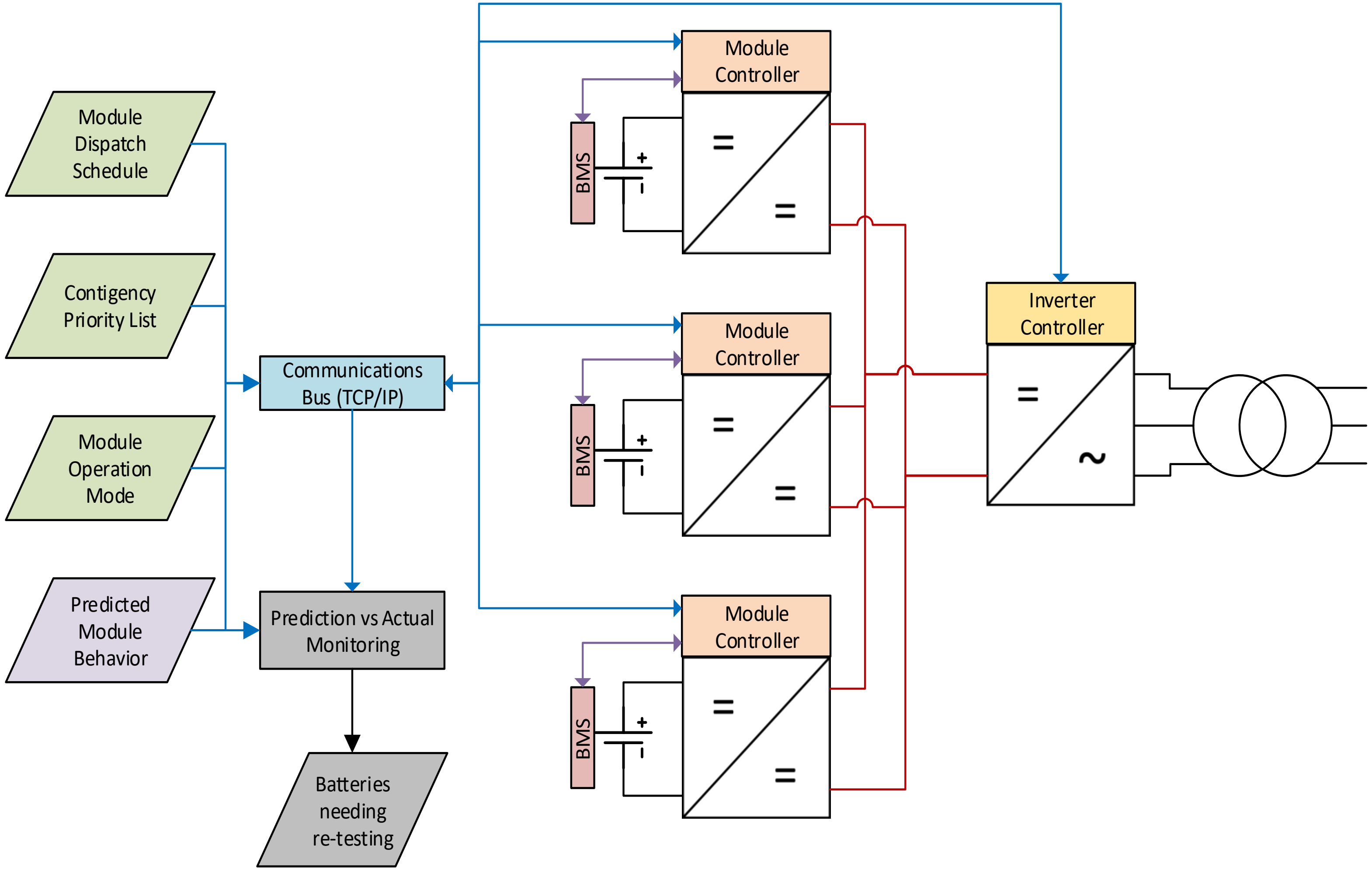
Second-life Battery



Mitchell T. Smith, Michael R. Starke, Madhu Chinthavali, and Leon M. Tolbert, “Architecture for Utility-Scale Multi-Chemistry Battery Energy Storage”, ECCE 2019.

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Battery Conventions

Time
C-rate
OCV
Capacity
SOC
DOD
Energy
Power
Cycle number
Equivalent full cycles (or capacity/energy throughput)
Calendar life
Cycling life
Self discharging current

SOH
EOL
Capacity knee point
Resistance elbow

Conclusion

1. Battery electrochemical equations determine charge & energy density;

2. Solid-state &Na-ion battery deserve attentions in the near future;

3. Battery SOH has many unknowns, due to not enough data available;

4. In EECS domain, BMS, SOH and SLB are still important topics.