U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – ARMY RESEARCH LABORATORY

Enabling Greater Flight Endurance for sUASs—

Alternative Batteries, What Makes ‘Em Tick… and How to Abuse Them

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U.S. Army Research Laboratory-Sensors & Electron Devices Directorate (ARL-SEDD)

Energy & Biotechnology Division-Energy Storage Group

25 Mar 2020

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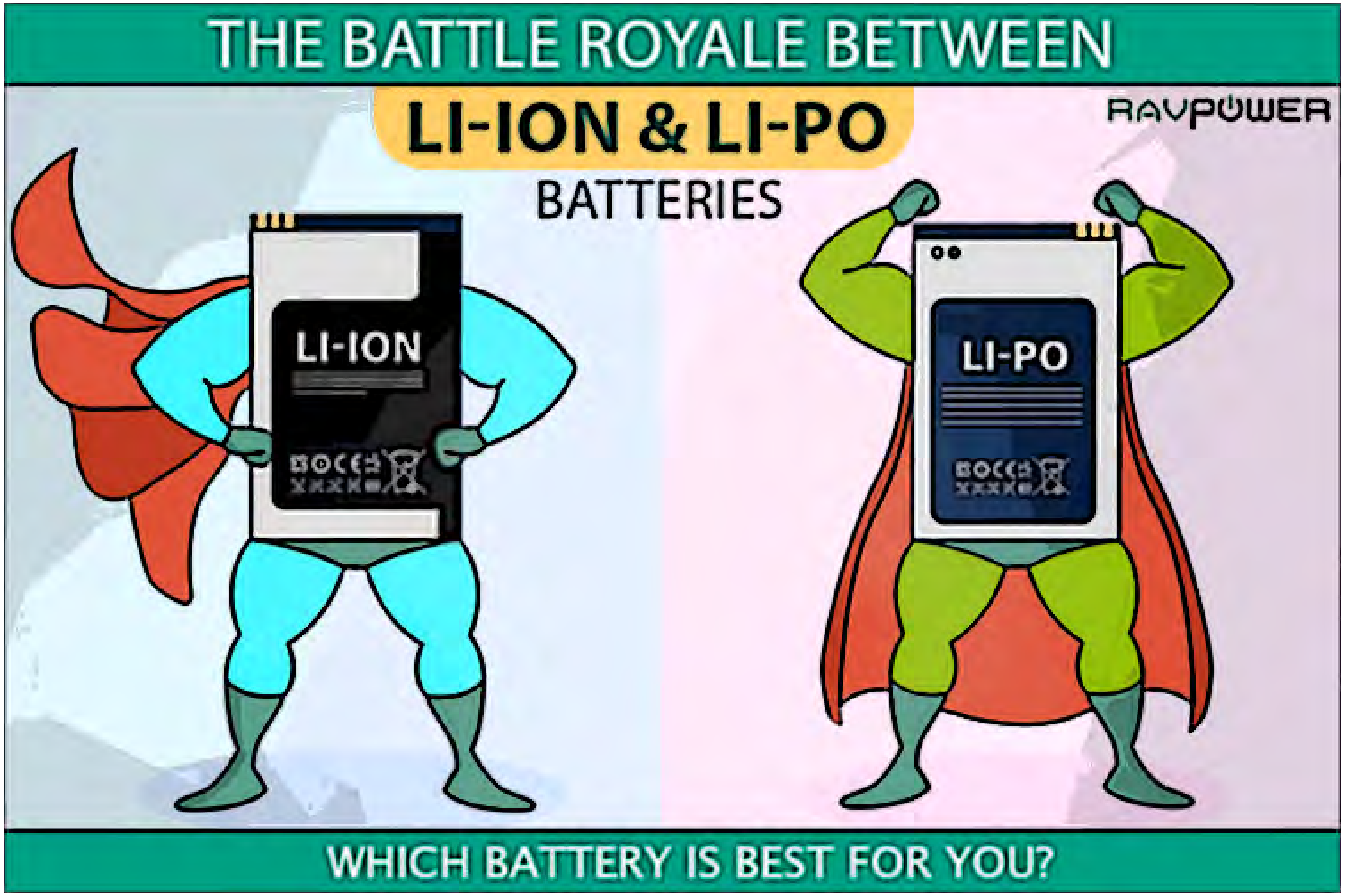


https://blog.ravpower.com/2017/06/lithium-ion-vs-lithium-polymer-batteries/

Battery Basics
“Li-ion” vs. “LiPo”

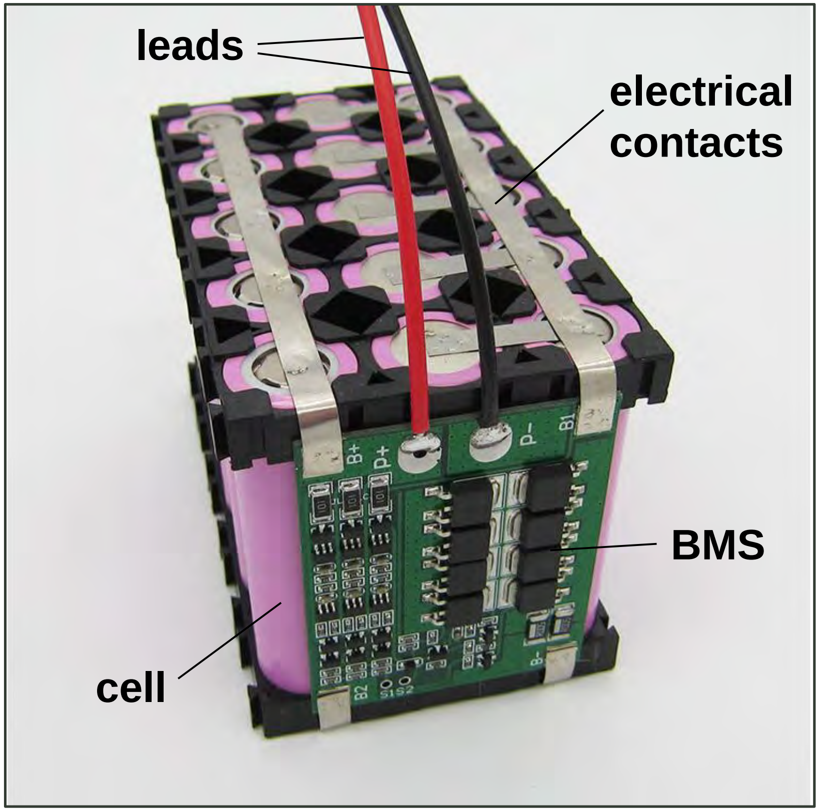
Li-Ion Batteries—Battery Packs & Cells

Li-ion batteries (or battery packs) are composed of individual Li-ion cells (one, several… or many)

typical battery components:

- **cells**
- **electrical contacts/leads**
- **BMS (battery management system)**
- **thermal sensors (thermistors)**

Li-ion battery (pack)



Li-Ion Batteries—Cell Types/Formats

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There are 3 primary cell formats used for larger Li-ion battery cells:

Cylindrical | **Prismatic** | **Pouch**

both are prismatic (hard vs. soft packaging)

i.e., "Li-ion" battery cells

i.e., what's inside "LiPo" batteries

NOTE: All of these 3 formats are Li-ion cells—the chemistry inside is often nearly identical

Li-Ion Batteries—Pouch Cells

Pouch cell sizes are not standardized—there are many different shapes, thicknesses, differences in tab (electrical contacts) locations, etc.

Li-Ion Batteries—Cylindrical Cells

Cylindrical cell sizes are standardized

cathode material identifier:

$LiCoO_2$ (LCO)	$LiMn_2O_4$ (LMO)	$LiNi_xMn_yCo_zO_4$ (NMC)	$LiFePO_4$ (LFP)
"ICR"	"IMR"	"INR"	"IFR"

https://batterybro.com/blogs/18650-wholesale-battery-reviews/18880255-battery-chemistry-finally-explained

NOTE: Cathode materials may be mixed/blended in commercial cells

Samsung 35E 18650 3500mAh 8A

- Samsung 35E → name
- 18650 → cell type
- 3500mAh → capacity (energy) or 3.5 Ah
- 8A → max. (continuous) power rating

Li-Ion Batteries—Activate Materials

active materials:
materials involved in cell reactions (intentionally)

cathode material identifier:

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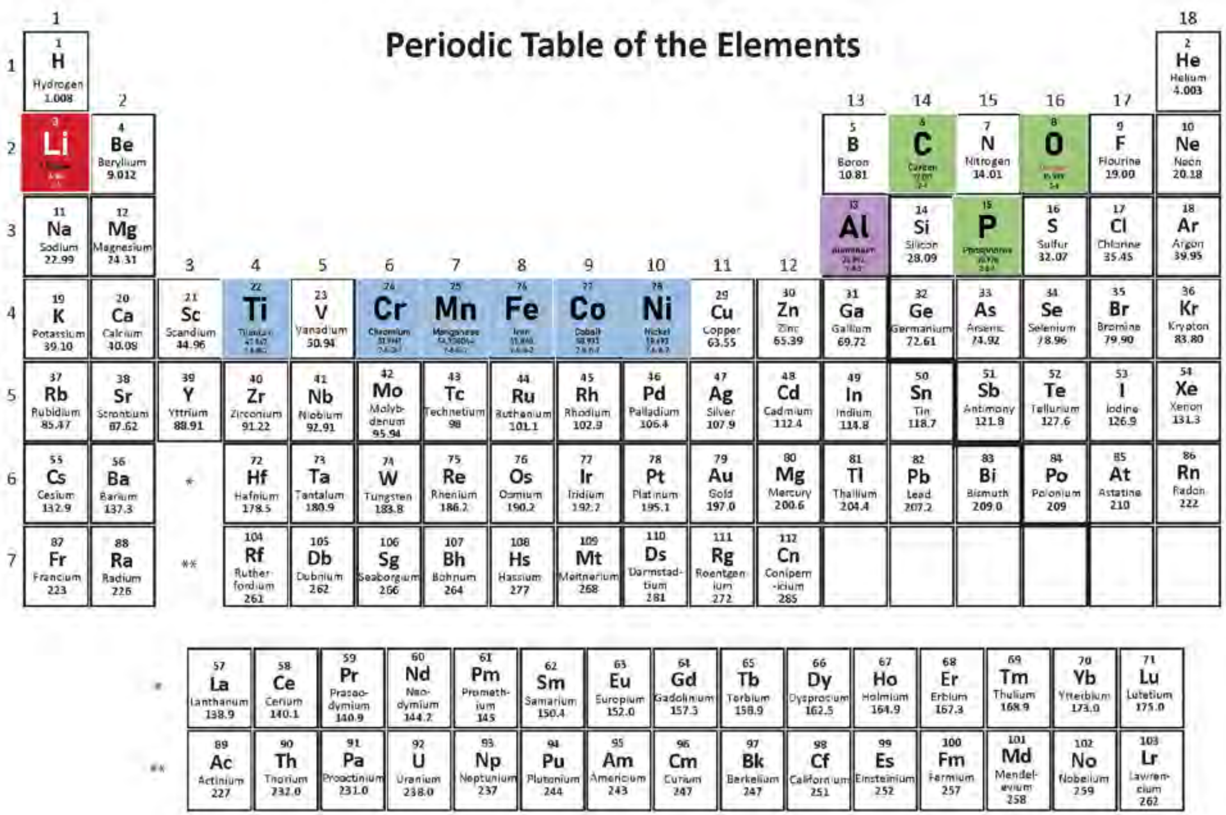
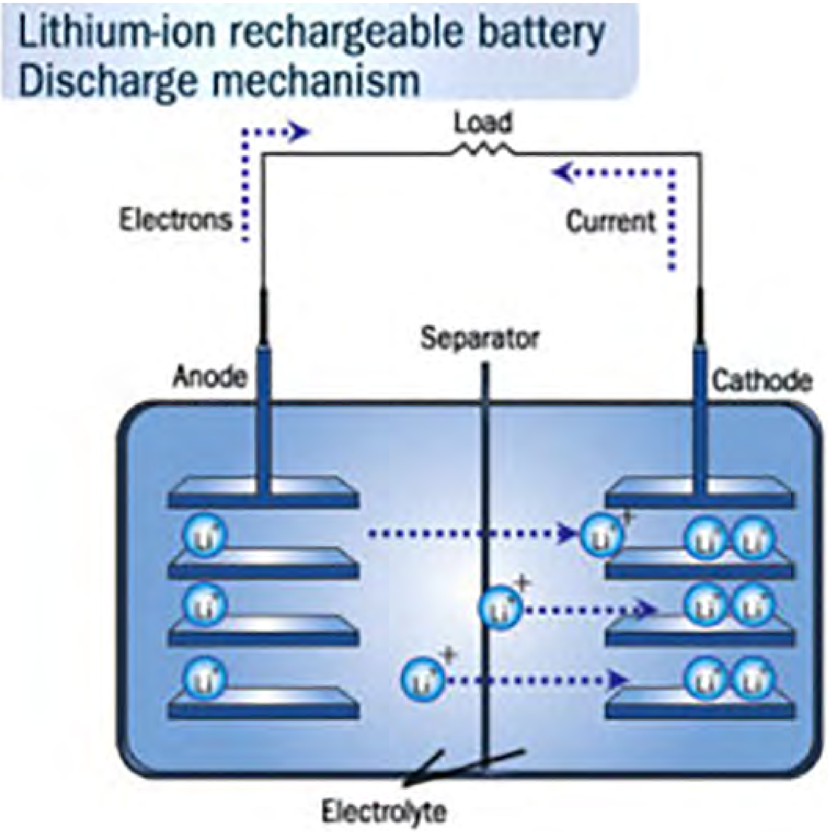


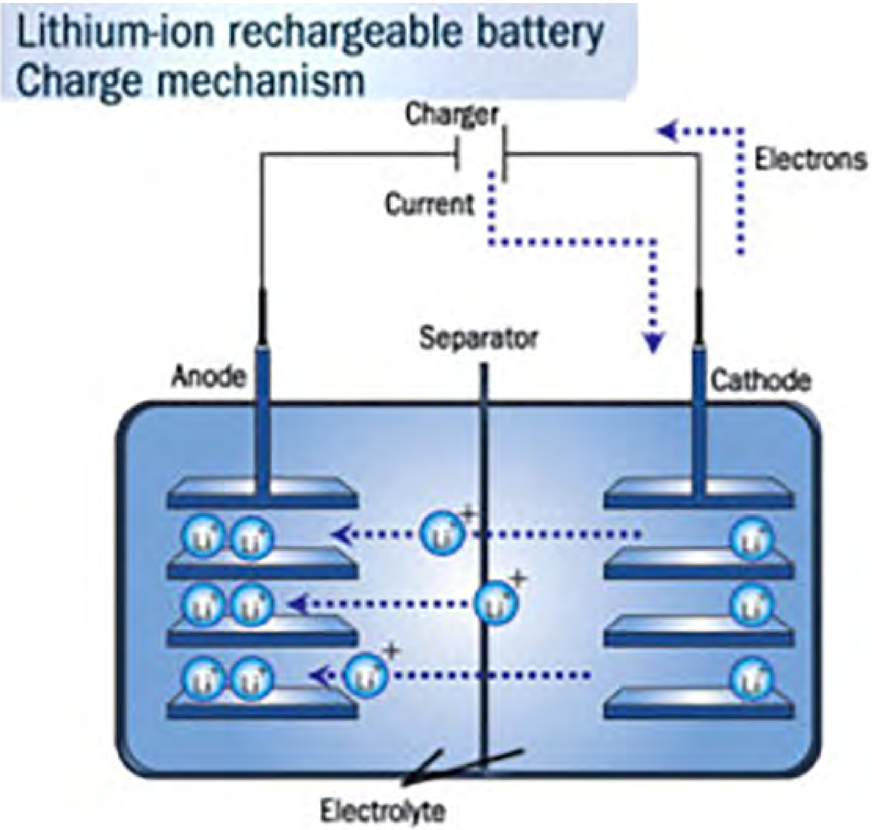
Using lighter elements (i.e., those near the top of the Periodic Table) for battery materials maximizes the battery energy density

Li-Ion Batteries—A Look Inside

battery/cell discharge



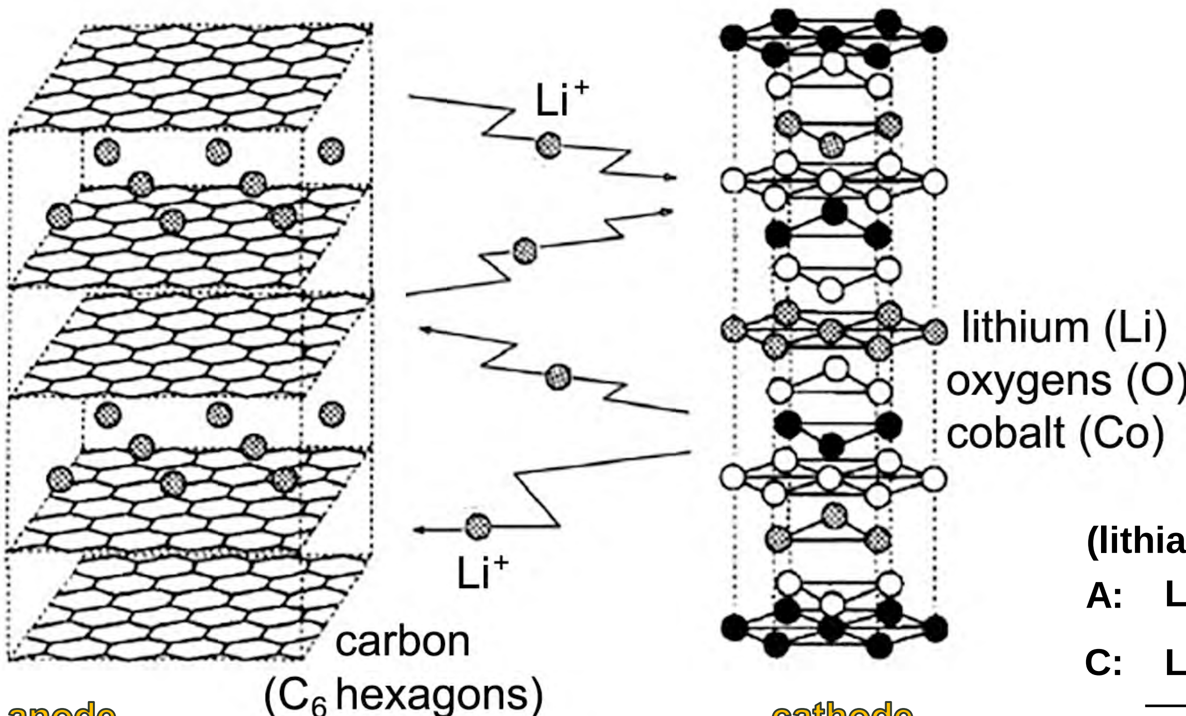
battery/cell (re)charge



https://electronics.howstuffworks.com/everyday-tech/lithium-ion-battery1.htm

Li-Ion Batteries—A Look Inside

more details...



anode
(negative electrode)

graphite

cathode
(positive electrode)

during cell discharge:

(lithiated graphite) **(graphite)**

A: $LiC_6 \longrightarrow Li^+ + e^- + C_6$

C: $Li^+ + e^- + Co^{+4}O_2 \longrightarrow LiCo^{+3}O_2$

$LiC_6 + CoO_2 \longrightarrow C_6 + LiCoO_2$

↓

NOTE: The $LiCoO_2$ is never fully delithiate (to prevent degradation)—i.e., $Li_{1-x}CoO_2$ (x ~ 0.5 for full discharge)

Li-Ion Batteries—Cylindrical Cells

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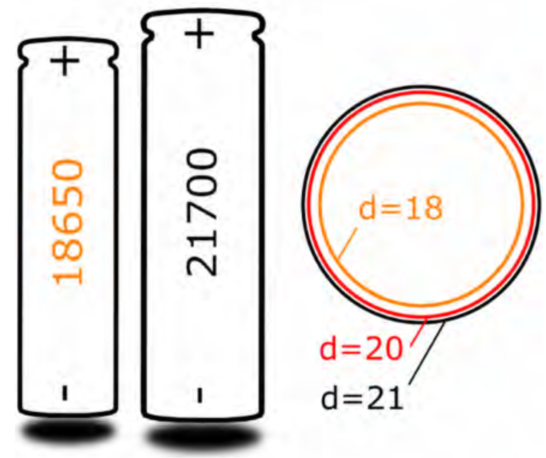
Cylindrical cell formats are standardized

Samsung 35E 18650 3500mAh 8A

Samsung 50E 21700 5000 mAh 9.8 A



http://jes.ecsdl.org/content/165/14/A3284/F1.expansion.html

A123 26650 ANR26650M1A 2500 mAh 3.3 V $LiFePO_4$ cell

Li-Ion Batteries—Point of Interest

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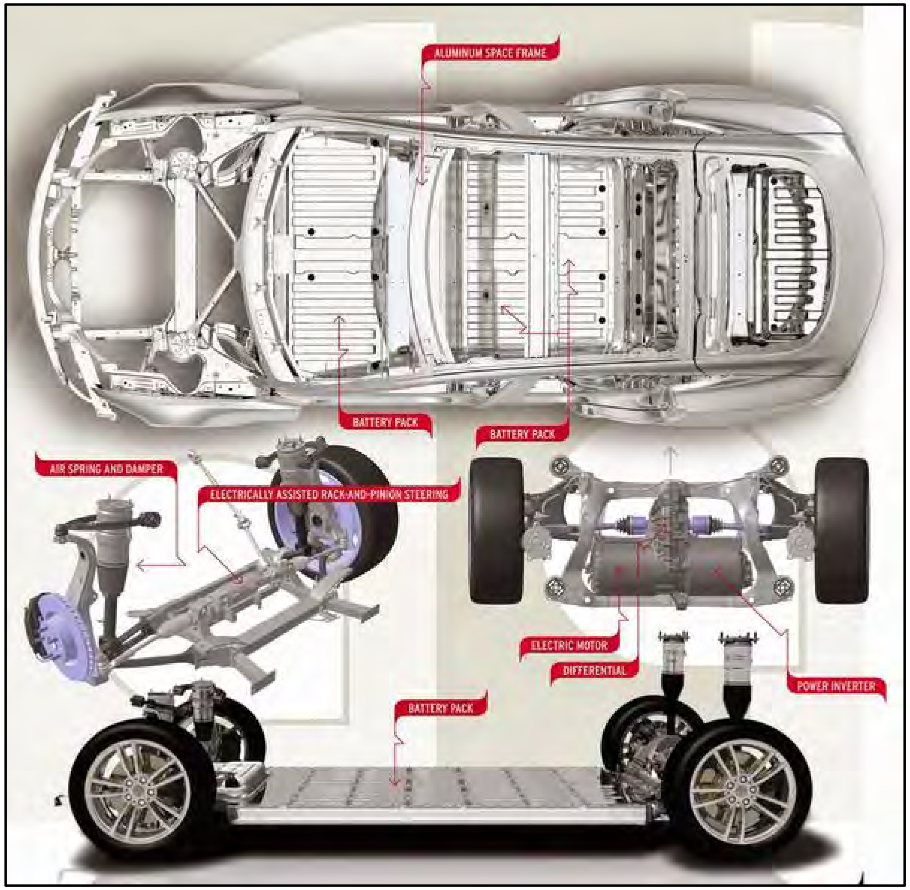
**Tesla is the only major car manufacturer using cylindrical cells...
all others are using prismatic cells (either hard case or pouch)**

Panasonic is the cell manufacturer for Tesla

18650 cells made in Japan → Tesla Model S, Tesla Model X

2170 (i.e., 21700) cells made in the Gigafactory in Nevada → Tesla Model 3



https://evannex.com/blogs/news/how-does-an-electric-car-work

Li-Ion Batteries—Cell Chemistry

https://batteryuniversity.com/learn/article/bu_216_summary_table_of_lithium_based_batteries

Chemistry	$LiCoO_2$ (LCO)	$LiMn_2O_4$ (LMO)	$LiNi_xMn_yCo_zO_4$ (NMC)	$LiNi_xCo_yAl_zO_4$ (NCA)	$LiFePO_4$ (LFP)	$Li_4Ti_5O_{12}$ (LTO)
Nominal Voltage (V)	3.6	3.7-3.8	3.6-3.7	3.6	3.2-3.3	2.4
Full Charge (V)	4.2	4.2	4.2 (or higher)	4.2	3.65	2.85
Full Discharge (V)	3.0	3.0	3.0	3.0	2.50	1.80
Min. Voltage (V)	2.5	2.5	2.5	2.5	2.00	1.50
Specific Energy (kW/kg)	150-200	100-150	150-220	200-260	90-120	70-80
Cell Packaging (typical)	18650 prismatic pouch	prismatic	18650 prismatic pouch	18650	26650 prismatic	prismatic

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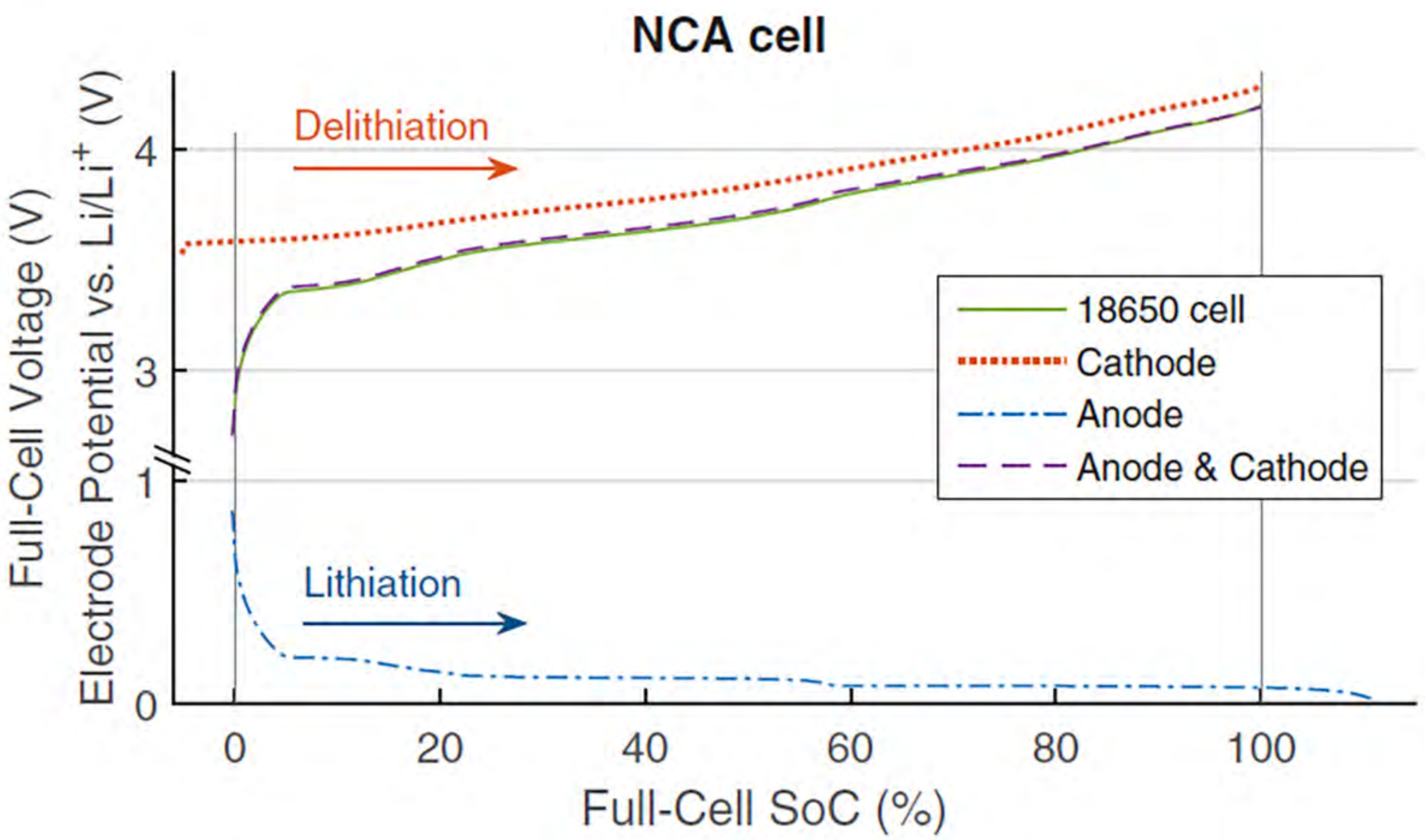
Li-Ion Batteries—Electrode/Full Cell Voltages



P. Keil and A. Jossen, *J. Electrochem. Soc.* **2017**, *164*, A6066.
Calendar Aging of NCA Lithium-Ion Batteries Investigated by Differential Voltage Analysis and Coulomb Tracking.

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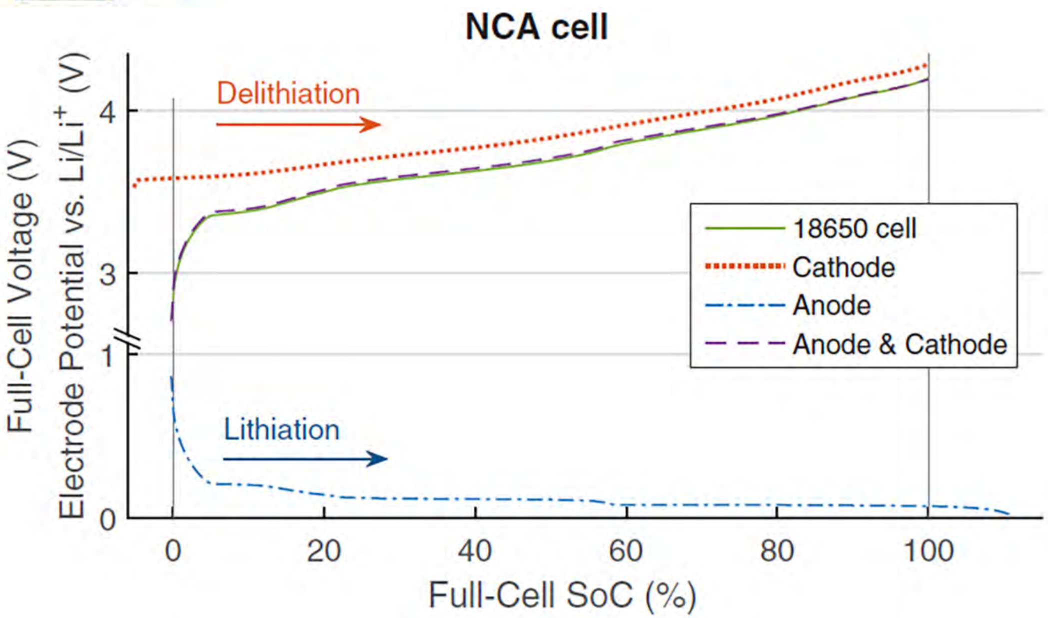

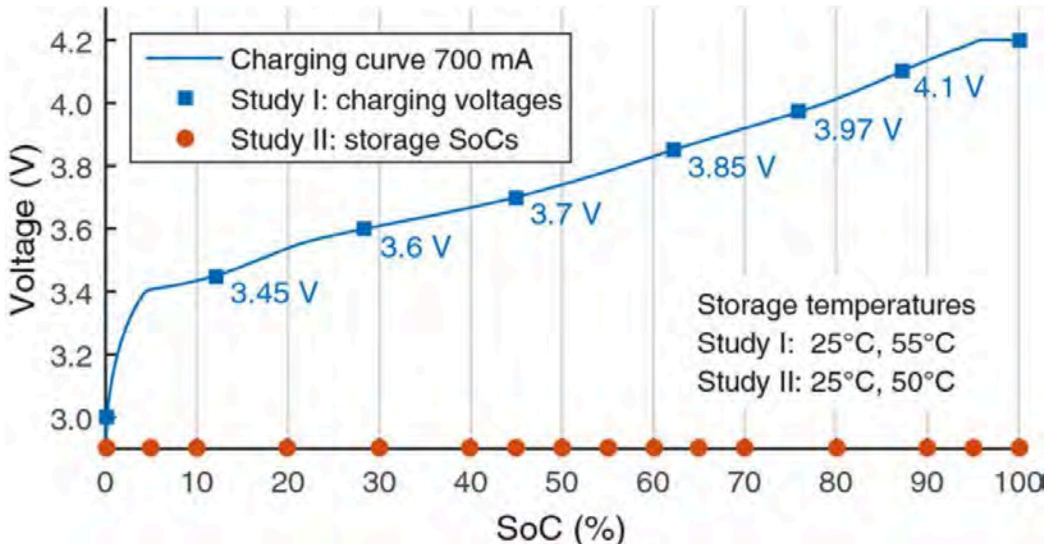

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specific energy (Wh/kg) = specific capacity (mAh/g) x voltage (V)

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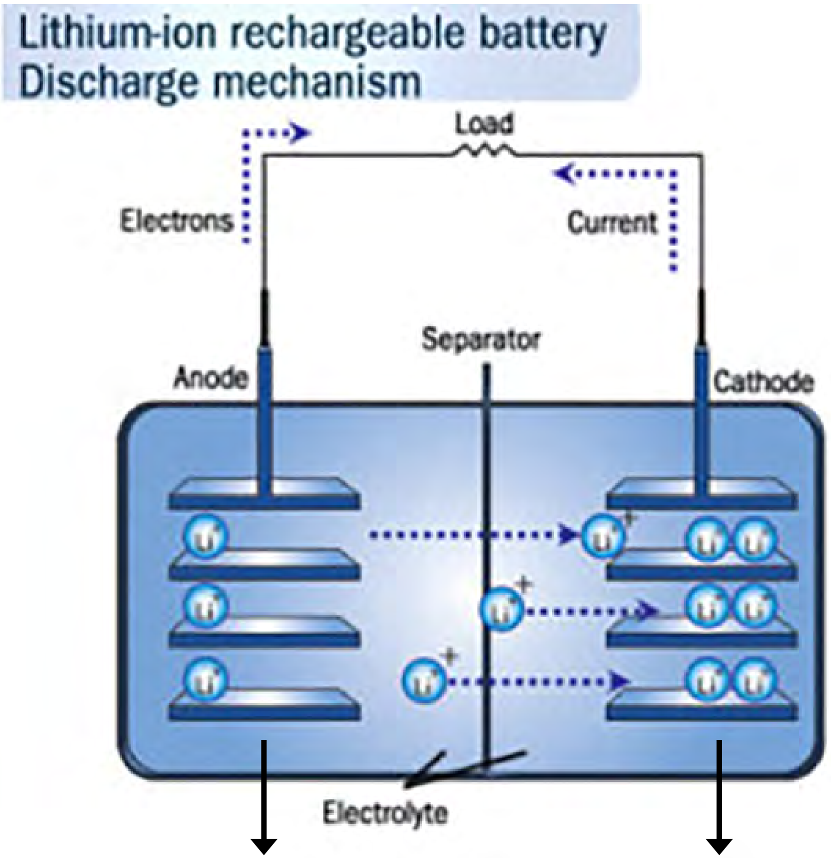
Li-Ion Batteries—Schematic

battery/cell discharge



graphite
LTO

LCO
LMO
NMC
NCA
LFP

LTO is an anode material – replacement for graphite. It can be paired with any of the cathode materials, but NMC is commonly used

https://electronics.howstuffworks.com/everyday-tech/lithium-ion-battery1.htm

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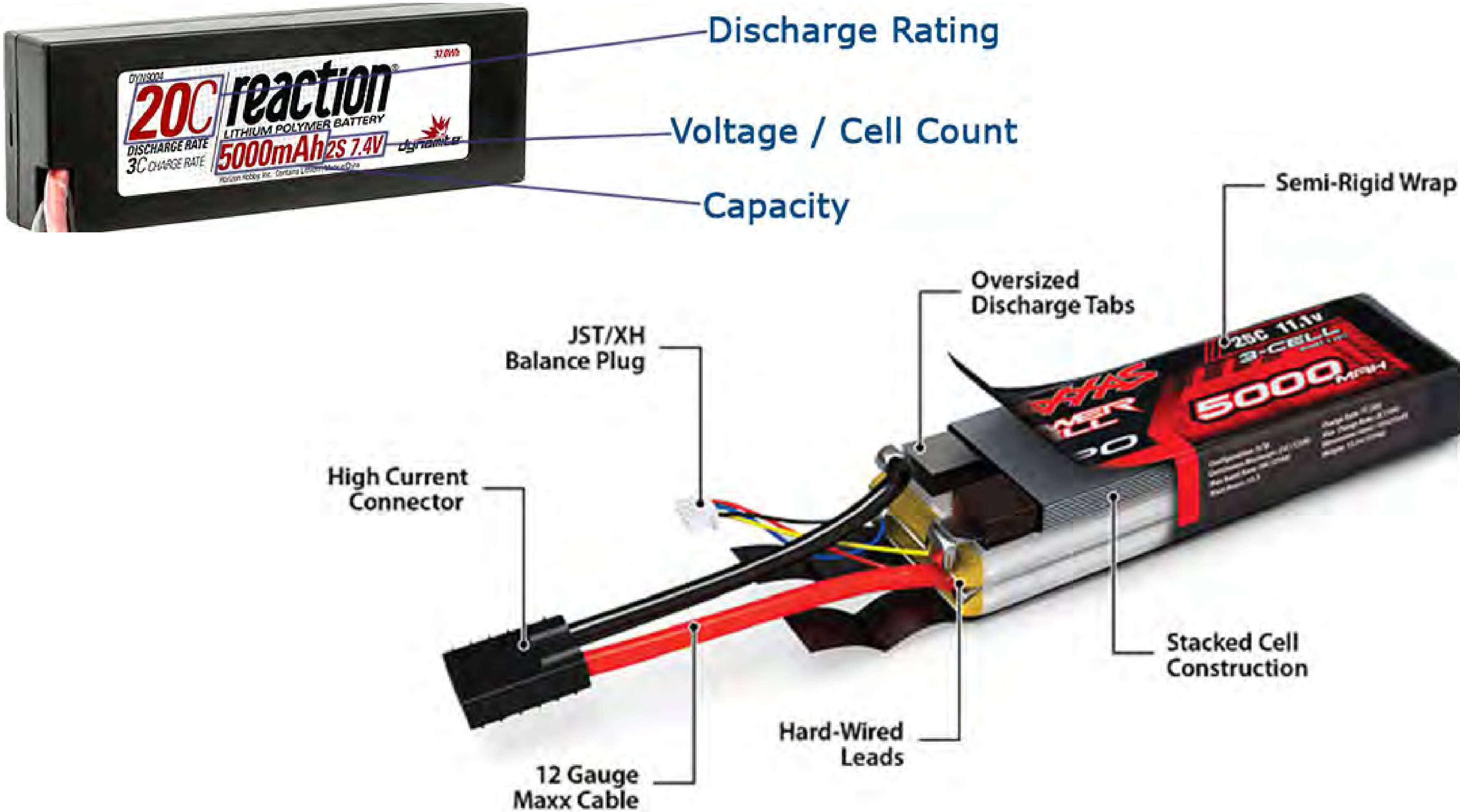
long cycle life

fast discharge (high power)

fast(er) recharge

UAS Batteries

LiPo Batteries



http://eduardochamorro.github.io/beansreels/workshops/beandrone.html

Li-Ion Batteries—C Rates

Power (W) = Current (A) x Voltage (V)

Discharge Current (A) = C-Rating x Capacity (Ah)

1C rate = full discharge of the battery capacity in 1 hr

Rate	(Full) Discharge Time
0.05C or C/20	20 hr
0.10C or C/10	10 hr
0.20C or C/5	5 hr
0.50C or C/2	2 hr
1C	1 hr
2C	30 min
5C	12 min
10C	6 min
20C	3 min
60C	1 min

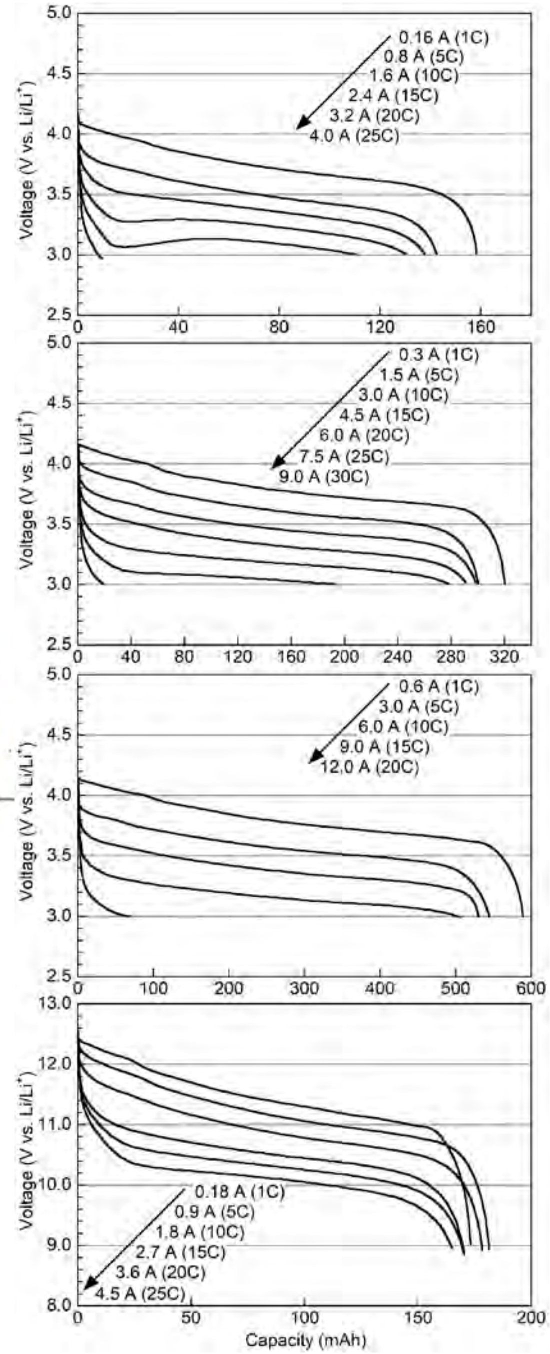
LiPo Batteries

1S: 3.7 V
160 mAh
25-40C

1S: 3.7 V
300 mAh
45-90C

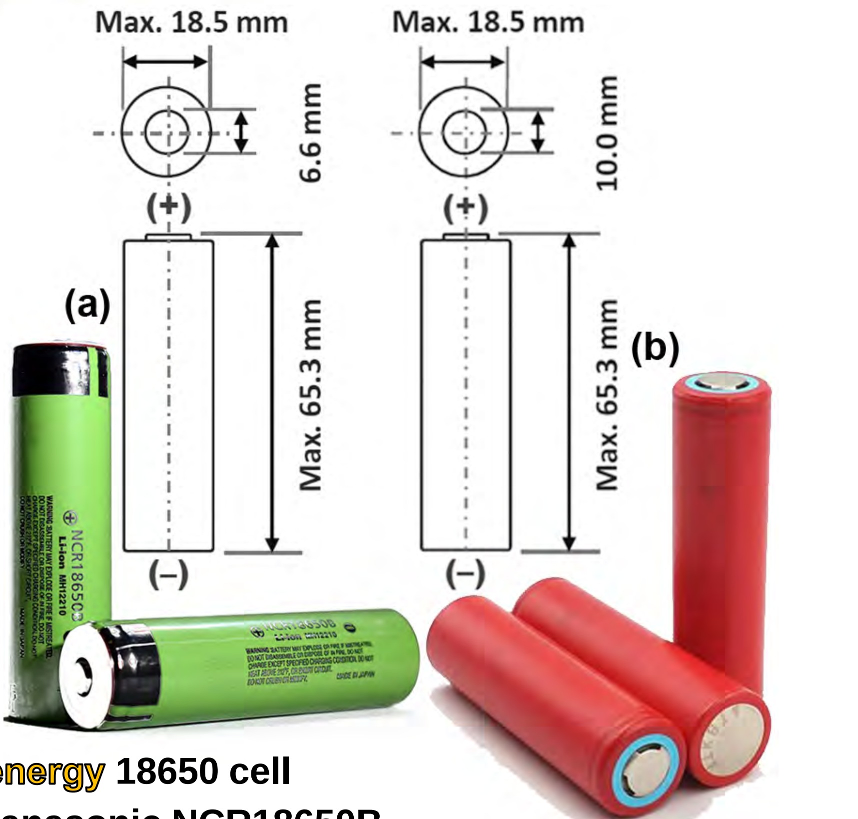
1S: 3.7 V
600 mAh
35-70C

3S: 11.1 V
180 mAh
25-40C



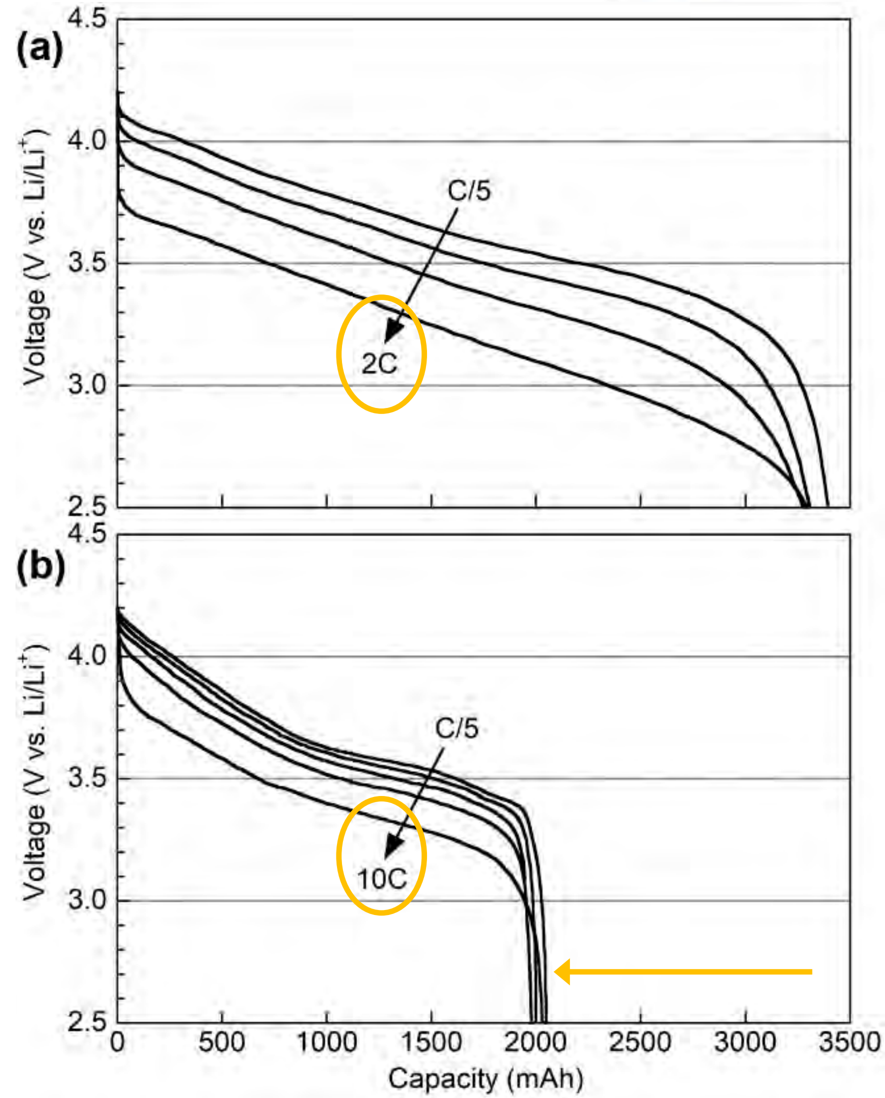
https://rightbattery.com/lipo-liion-life-batteries/

"Li-Ion" (i.e., Cylindrical) Batteries



energy 18650 cell
Panasonic NCR18650B

power 18650 cell
Panasonic UR18650RX



Cells can generally be optimized for either energy or power, but not both simultaneously

Cell Discharge Rate Limitations

Power cells are optimized by having **thinner electrodes, more current collector, more conductive carbon** (added with active materials)—to **aid in getting the electrons where they need to go** throughout the cell

cells are typically specified by their **maximum continuous power rating** (A or C-rate)

the discharge rate which the cells are capable of without a significant loss of capacity (due to poor utilization of active materials) and/or exceeding an internal temperature cutoff

high internal temperature results in more rapid cell degradation (due to side reactions) and can **initiate thermal runaway**

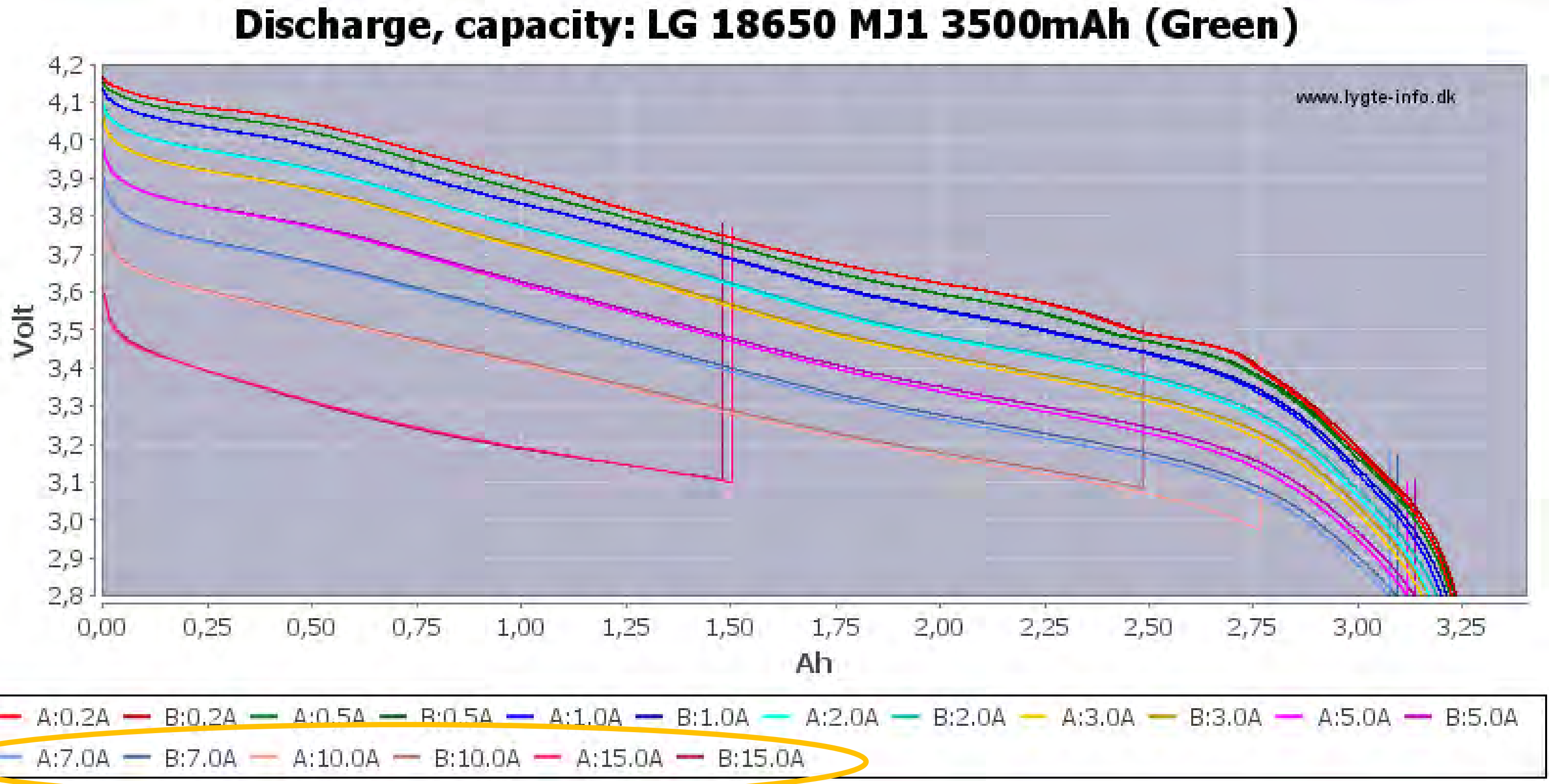
we'll get to that—wait for it

sometimes a **burst or pulse rating** (A or C-rate) is also given

this is what the cells can handle for **short periods of time** (e.g., 4-10 sec)

Cell Discharge Rate Limitations

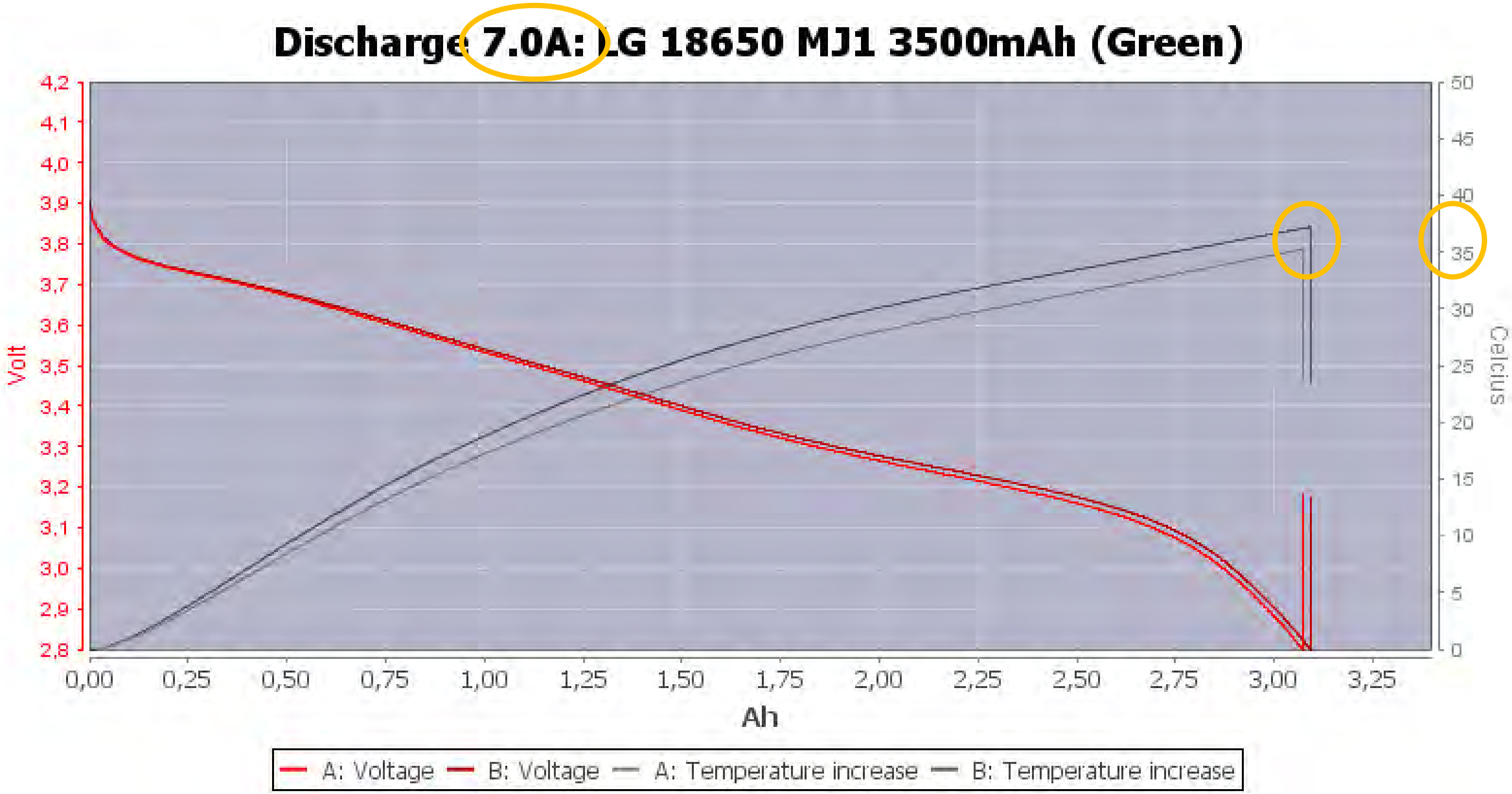
LG Chem 18650 cells (MJ1)



https://lygte-info.dk/review/batteries2012/LG%2018650%20MJ1%203500mAh%20(Green)%20UK.html

Cell Discharge Rate Limitations

2 different 18650 cells evaluated



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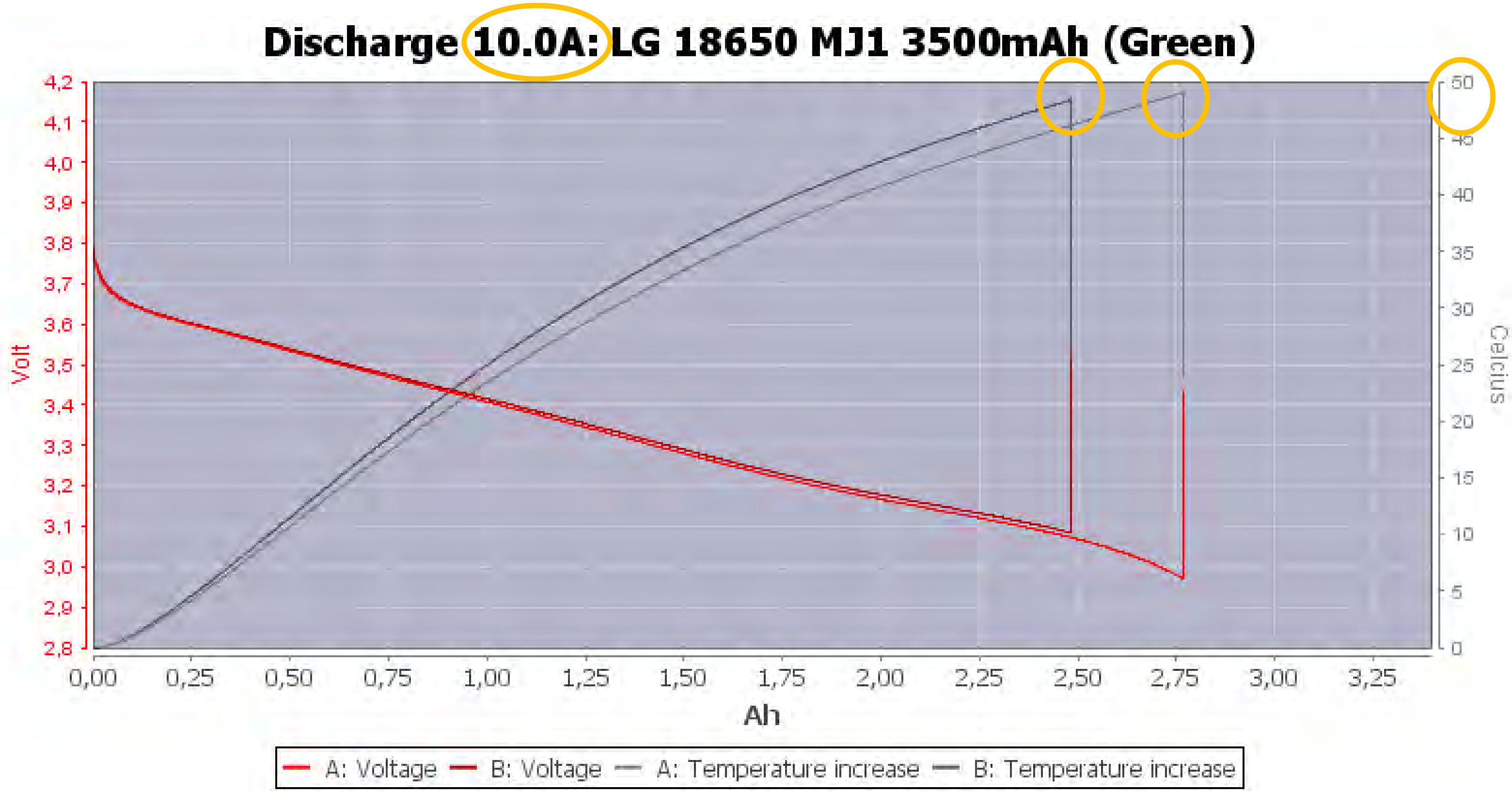

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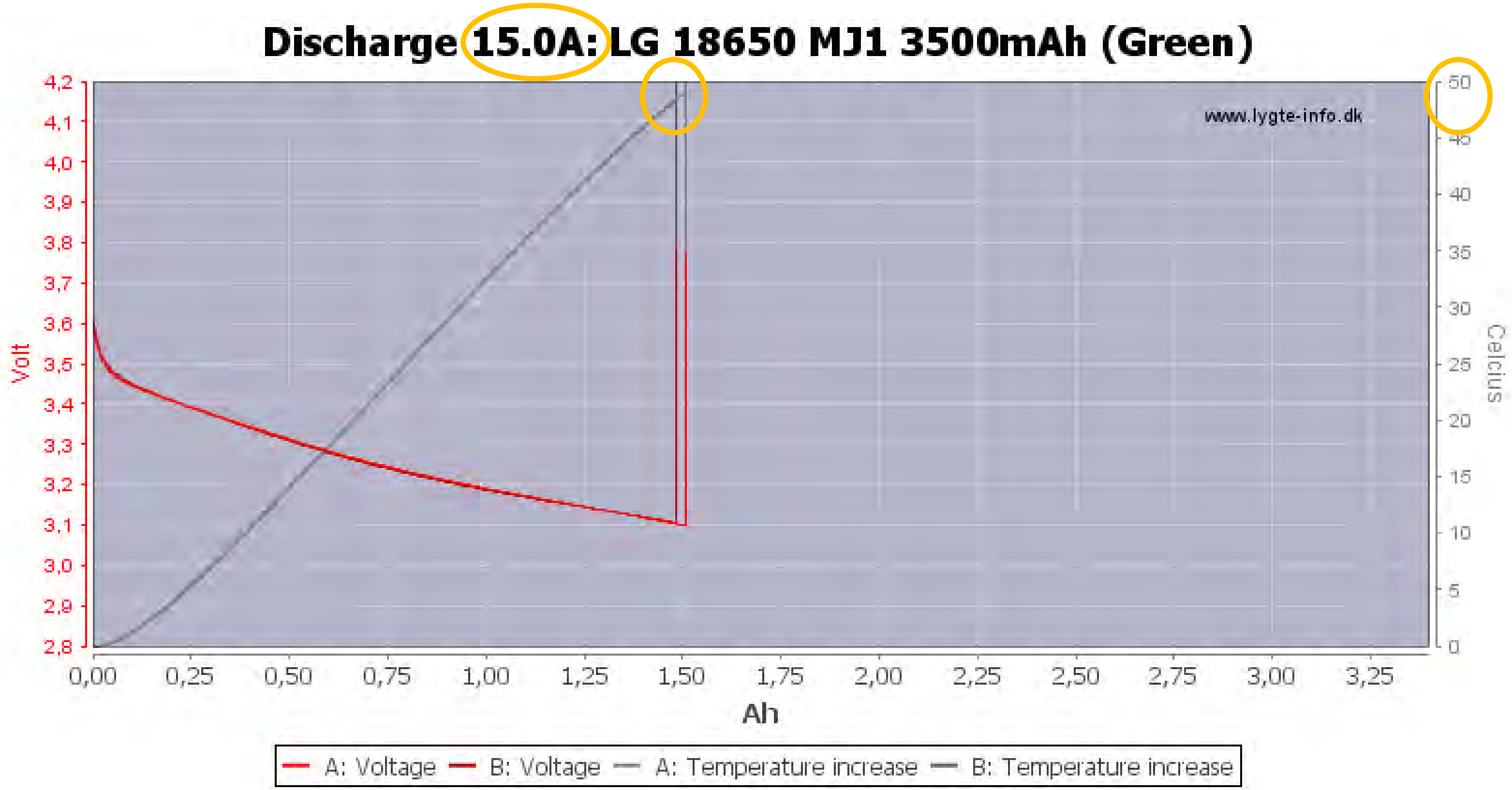

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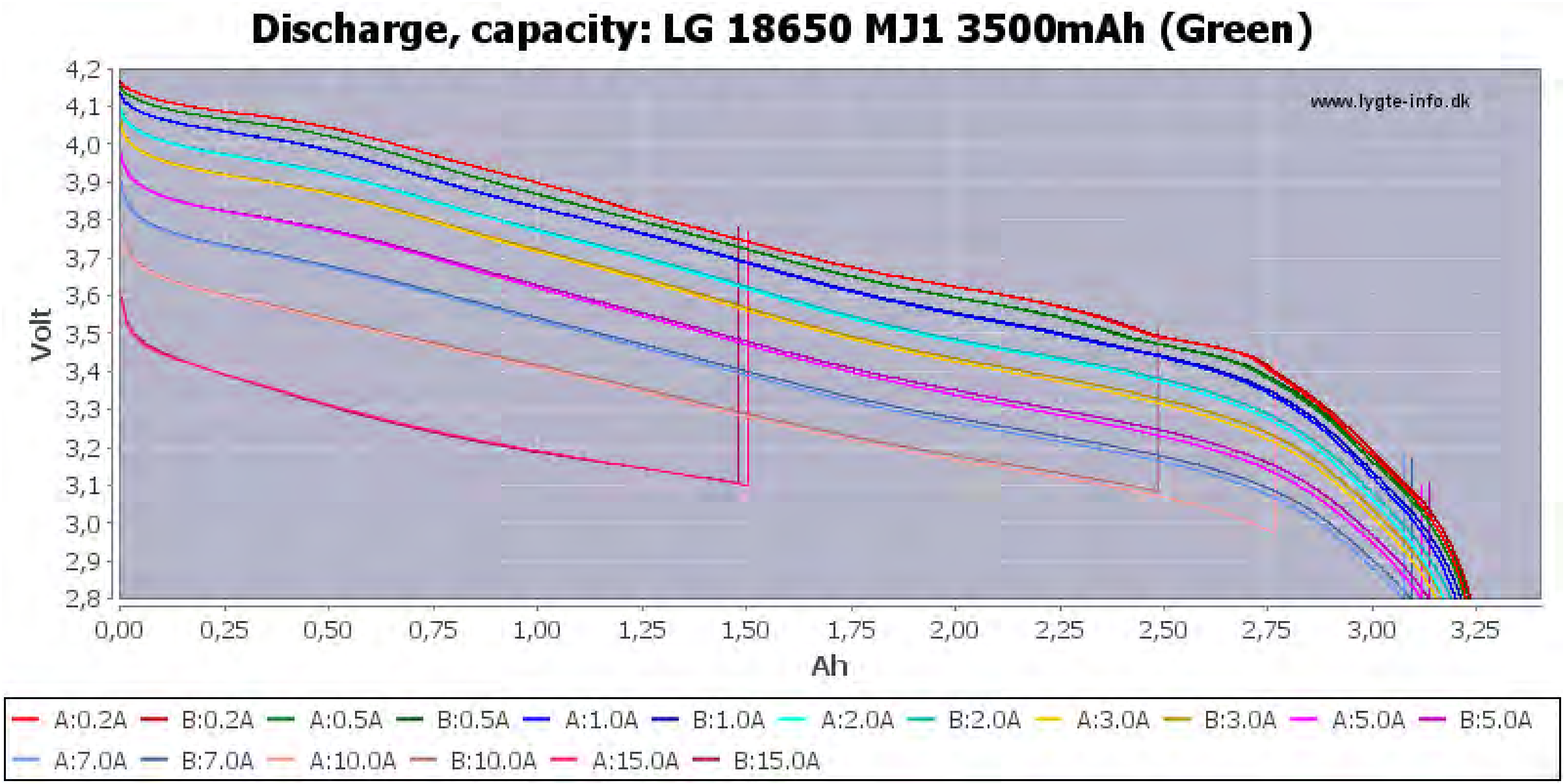
Cell Voltage Variations

The cell voltage at any given time is a function of many factors.
The 3 main ones are:

- **Depth of Discharge (DoD) or SoC—how much energy is left in the cell**
- **discharge rate/current—higher rates results in lower voltage**
- **temperature—low temperatures (below room temperature) result in lower voltage**



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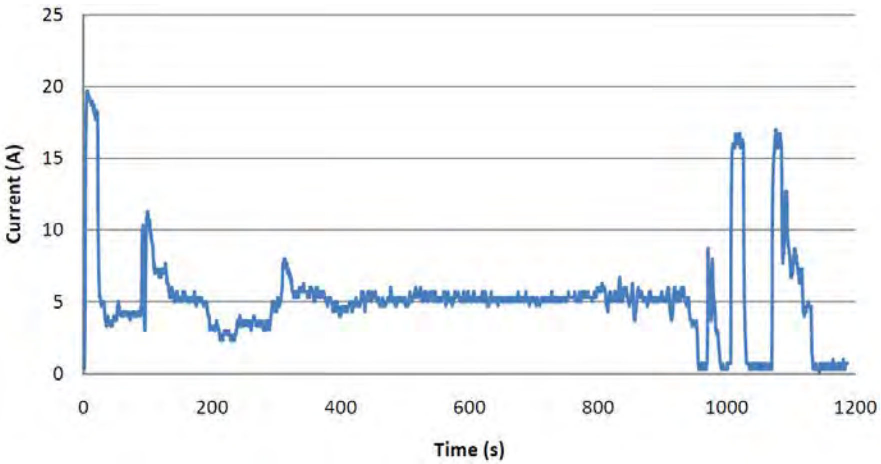
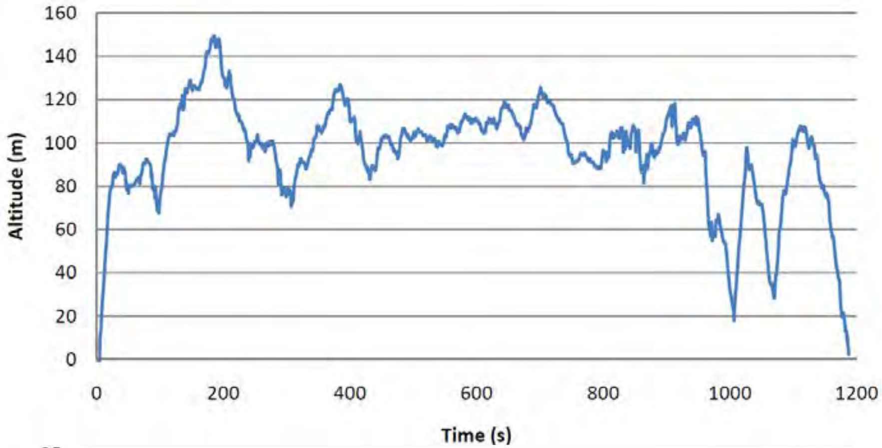
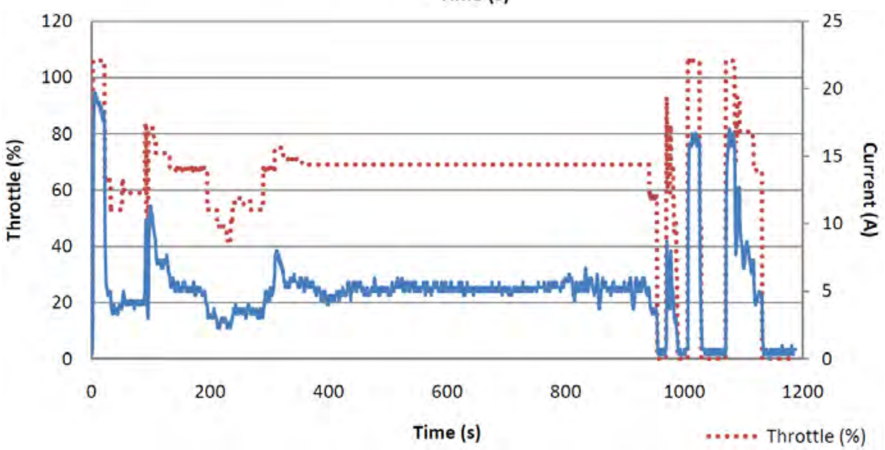
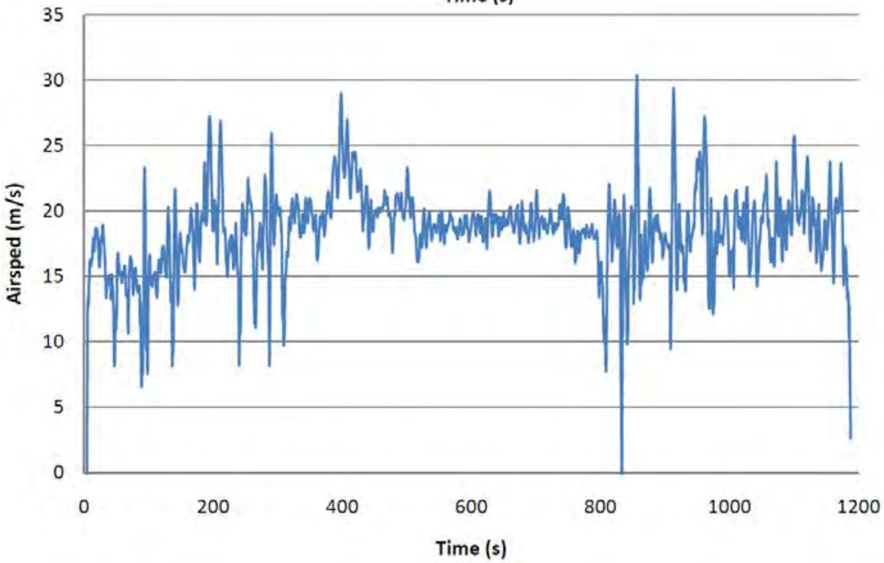
UAS Flight Data

Example: UAS flight characteristics ⟶ …for a battery pack (not an individual cell)









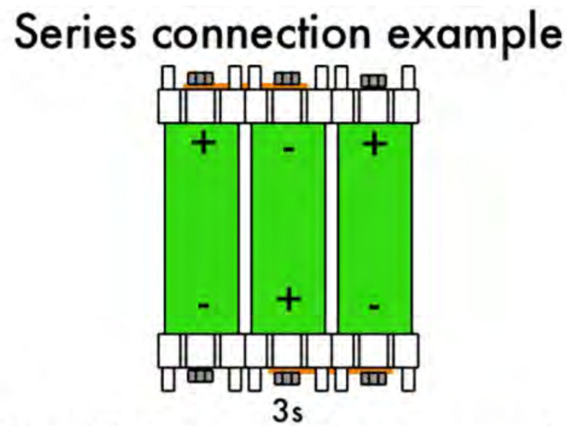
Li-Ion Battery Packs

SERIES connections (increases voltage)

1S: 3.6 V (1 x 3.6 V)

2S: 7.2 V (2 x 3.6 V)

3S: 10.8 V (3 x 3.6 V)

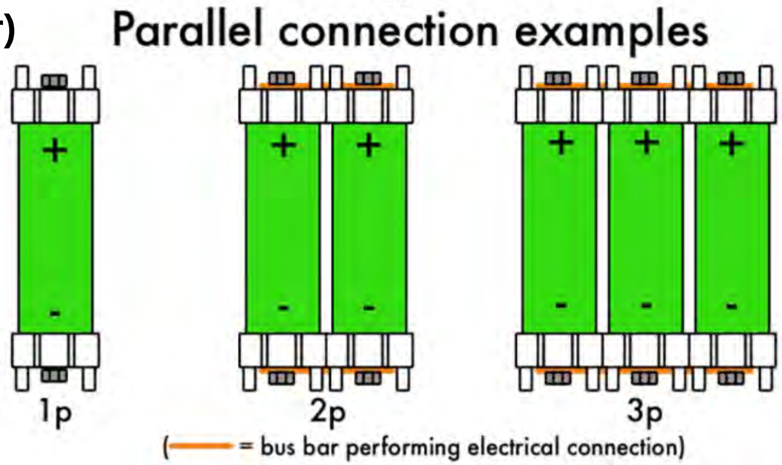


PARALLEL connections (increases capacity/power)

1P: 3000 mAh / 10 A

2P: 6000 mAh / 20 A

3P: 9000 mAh / 30 A



NOTE: If the cells used have:
nominal voltage of 3.6 V
capacity of 3000 mAh (or 3 Ah) and
max. cont discharge current (rate capability) of 10 A

https://vruzend.com/tech-center/what-are-parallel-and-series-connections/
https://www.electricbike.com/introduction-lithium-18650-batteries/

Li-Ion Battery Packs

LiPo battery packs → **usually only connected in series (S) (e.g., 3S)**

pack capacity is increased by using larger pouch cells

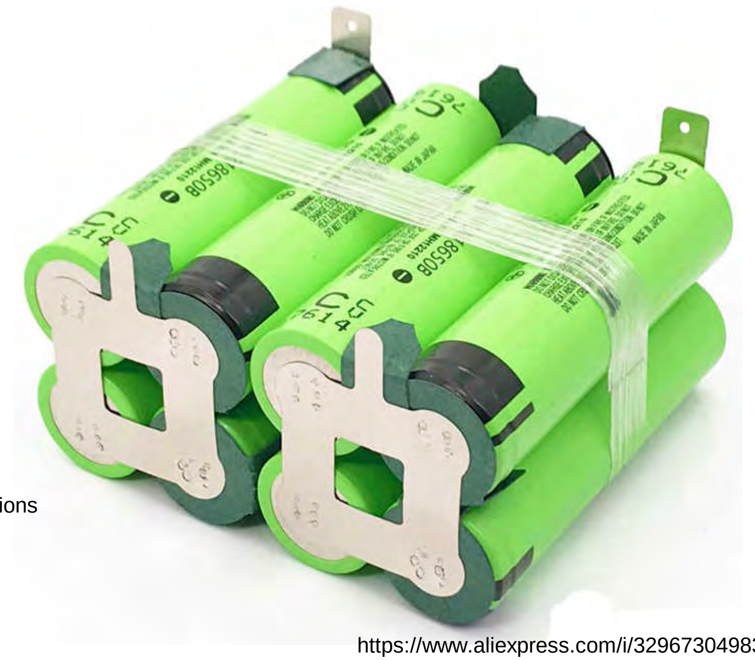
cylindrical cell battery packs → **usually connected both in series (S) and in parallel (P) (e.g., 3S2P)**

pack capacity is increased via parallel connections and using more cells

connecting multiple cells in parallel effectively makes one larger cell

…but the individual cells need to be nearly identical in properties

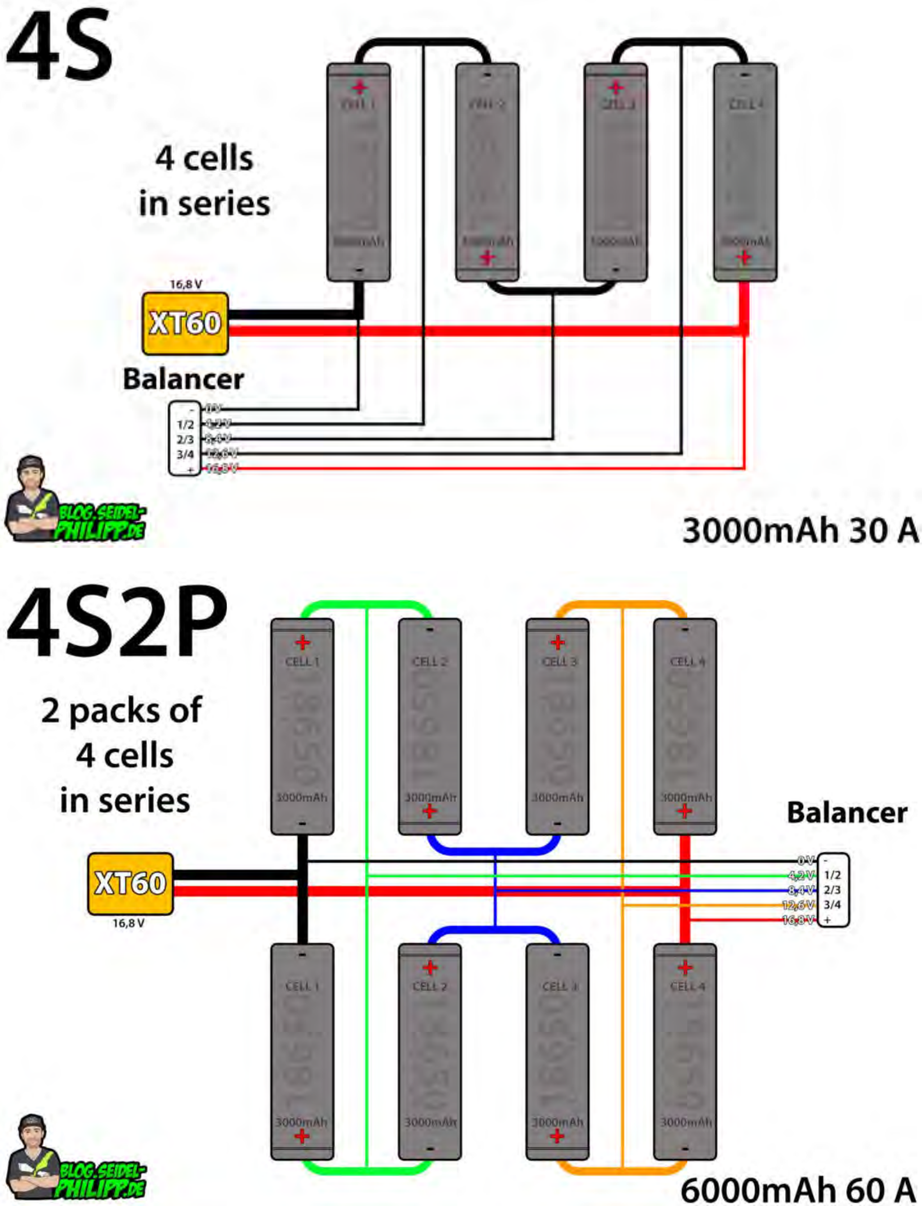
https://batteryuniversity.com/learn/article/serial_and_parallel_battery_configurations



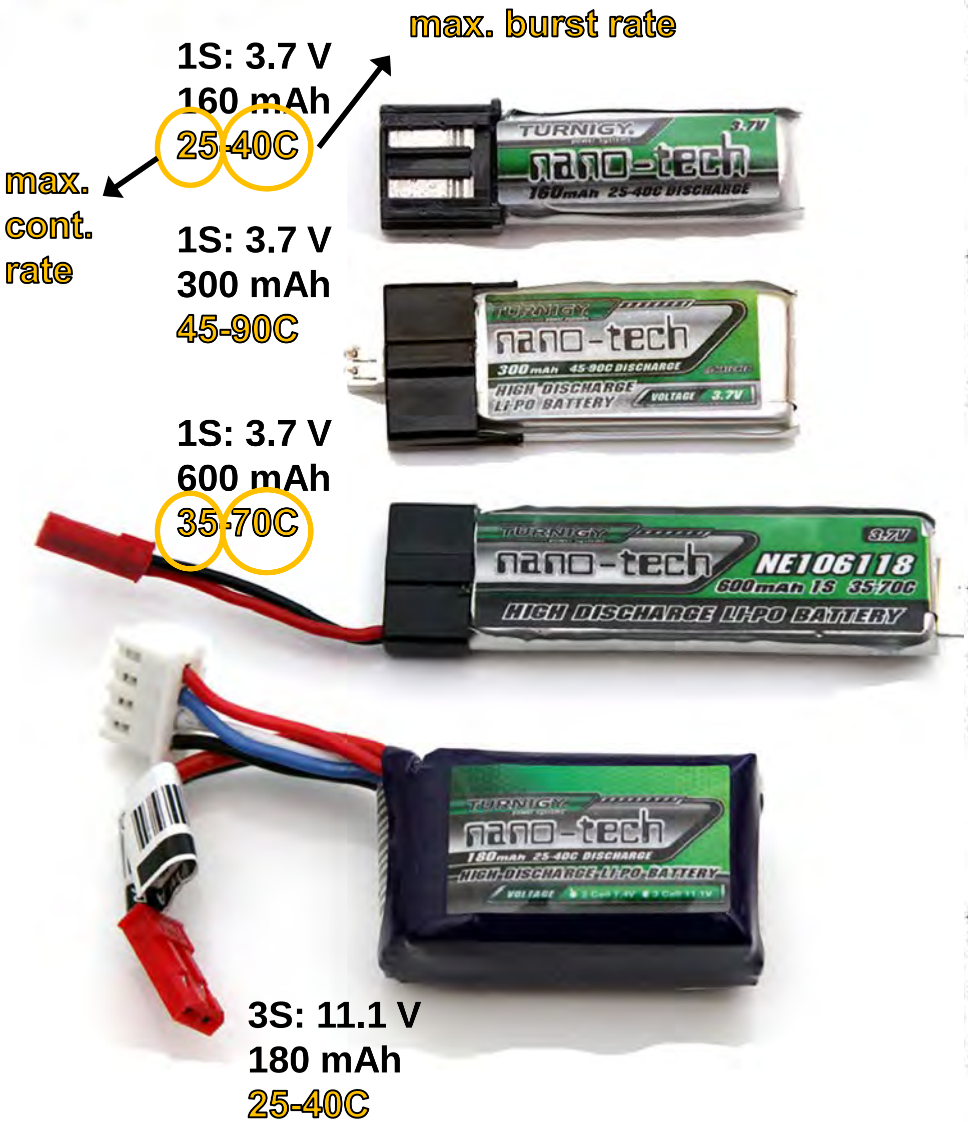
https://www.aliexpress.com/i/32967304983.html

Li-Ion Battery Packs

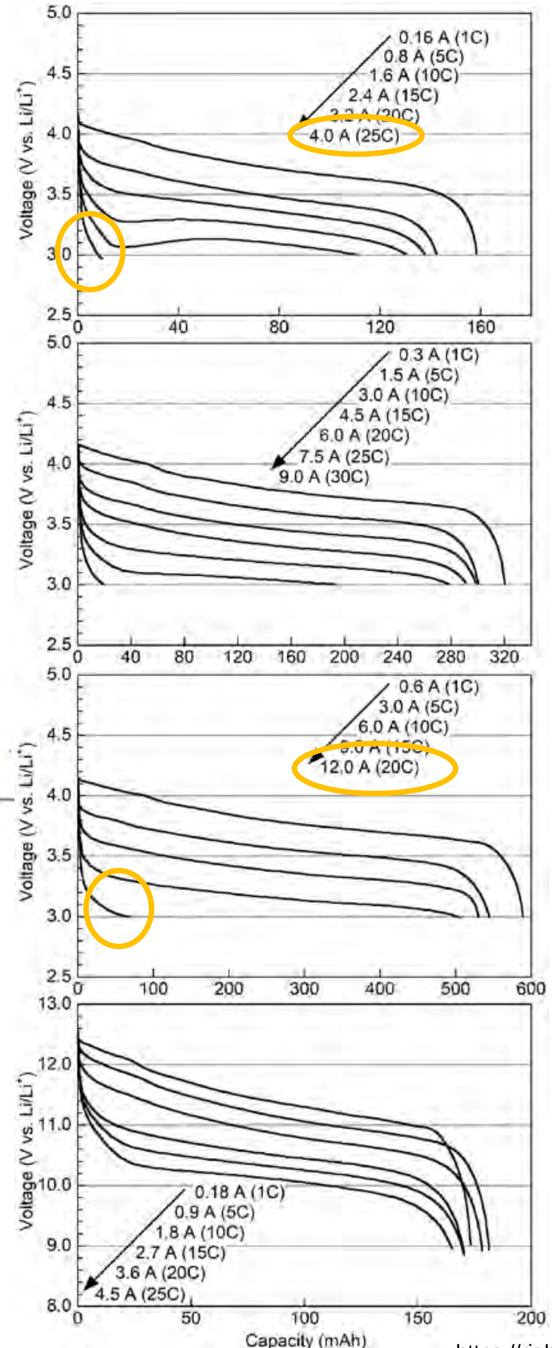
https://blog.seidel-philipp.de/diy-build-a-longrange-lithium-ion-battery/



Word(s) of Caution



https://rightbattery.com/lipo-liion-life-batteries/



https://rightbattery.com/lipo-liion-life-batteries/

LiPo battery packs rates are often grossly inaccurate

(too high)—this increases sales (most customers cannot measure this capability)

LiPo battery packs often use a 3.7 V (nominal) value for the cells

instead of the 3.6 V typically used for cylindrical cells… this also seems to be a selling point since the chemistry is similar

“Li-ion” vs. “LiPo” (for sUASs)

LiPo vs. Cylindrical Cell Batteries

Cylindrical cells have the highest energy density of any Li-ion cell format. Thus, replacing LiPo batteries from those assembled with cylindrical cells can result in a battery pack with a much higher capacity.

NOTE: Cylindrical cells may have a lower power rating than the LiPo pouch cells—ensure that the battery pack has the necessary power capability for high throttle (for take-off, climbing, maneuvering, etc.)

RECALL: Many commercial LiPo battery pack power ratings are inaccurate

LiPo vs. Cylindrical Cell Batteries

Turnigy
6S1P (6 cells)
3300 mAh capacity
30C or 99 A (cont) power
505 g
136 x 45 x 43 mm

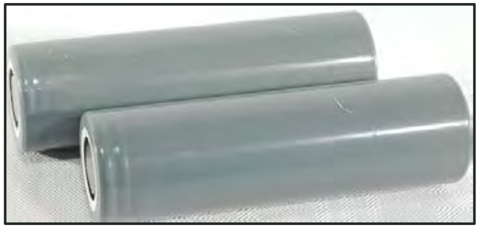
https://hobbyking.com/en_us/turnigy-3300mah-6s-30c-lipo-pack-xt-60.html?queryID=8bc236f2a2d4d59709657057eaf73cf8&objectID=69387&indexName=hbk_live_magento_en_us_products

Turnigy
6S1P (6 cells)
5000 mAh capacity
40C or 200 A (cont) power
805 g
144 x 51 x 56 mm

https://hobbyking.com/en_us/turnigy-5000mah-6s-40c-lipo-pack-xt90.html

LG Chem 18650 M36 (cylindrical) cells
6S2P (12 cells)
6500 mAh capacity
20 A (cont) power
582 g (+ BMS & connectors)

https://lygte-info.dk/review/batteries2012/LG%2018650%20M36%203600mAh%20(Cyan)%20UK.html



LG Chem 21700 M50 (cylindrical) cells
6S1P (6 cells)
5000 mAh capacity
10 A (cont) power
415 g (+ BMS & connectors)

https://lygte-info.dk/review/batteries2012/LG%2021700%20M50%205000mAh%20(Grey)%20UK.html

LG Chem 21700 M50 (cylindrical) cells
6S2P (12 cells)
10,000 mAh capacity
20 A (cont) power
830 g (+ BMS & connectors)

NOTE: These cylindrical cells can handle higher "burst" power rates for extended periods of time (before getting too hot internally)

…other considerations…

How to Abuse Your Puppy

APPROVED FOR PUBLIC RELEASE

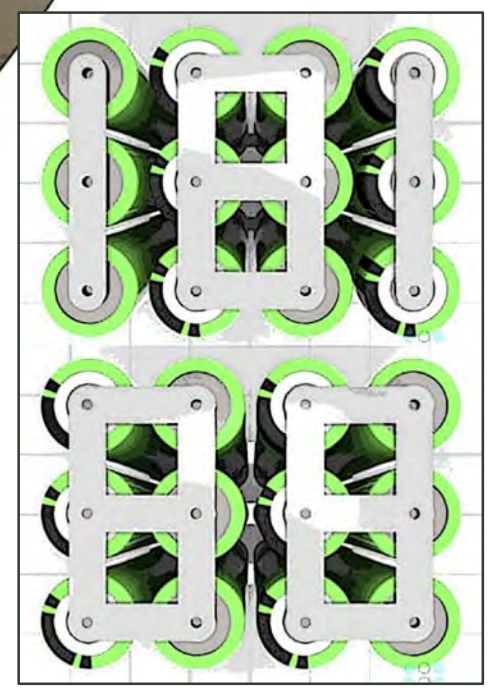
Your Puppy…

Your Puppy… Is a Li-Ion Battery

=

BB-2590/U

…contains twenty four (24) 18650 cells two (2) 4S3P packs that can be connected in series (to get a "24 V" battery) or in parallel (to get two (2) "12V" batteries, but with twice the capacity)



A Husky Puppy

But he's not just any puppy…
…he's a Husky puppy

How to Abuse Your Puppy

DEVCOM ARMY RESEARCH LABORATORY

TRANSLATION

He sleeps best when it's room temperature or lower… lower is better

Li-ion batteries degrade when stored at RT and above… especially at elevated temperature ("calendar aging")

He gets sick when he sits/sleeps with a full stomach… and he may throw up violently

Li-ion batteries degrade much faster when stored at a higher SoC ("calendar aging")… and thermal runaway (venting, fires, explosion) occurs more readily

If you do fill his stomach, have him pull the sled soon afterwards

If fully charging a Li-ion battery (100% SoC), it should be used relatively soon afterwards

Although he likes to sleep in the cold, don't feed him when it's cold… he'll get sick

Charging Li-ion batteries at temperatures $< 0^{o}C$ causes "Li plating" which degrades the battery capacity… and can result in a short-circuit (and perhaps venting, fires or an explosion)

Li-Ion Batteries—State-of-Charge (SoC)

Military Batteries: Storage & Shipping

The MIL-PRF for rechargeable batteries has always required them to be delivered to the U.S. Government fully charged (i.e., 100% SoC) In the latest spec, MIL-PRF-32383, paragraph 3.4.8. states:

> **"3.4.8 Battery condition for shipping. Each battery shall be furnished fully charged as indicated by five state of charge segments where applicable...."**

Q: If a specific state-of-charge (SoC) limitation is in place, who ensures that is followed?

DLA: If you mean a state-of-charge (SoC) limitation for transportation to a DLA depot and then into storage, the contractor. Once in a DLA Depot, the batteries are not maintained or recharged. They are not disturbed until they are ordered. At that point, no one opens the box or recharges the battery. The box is loaded onto a truck and taken to its destination. Additionally, the contractor would ensure the state-of-charge (SoC) limitation for a battery that is not stocked and delivered directly to the customer.

Li-Ion Batteries—State-of-Charge (SoC)

DEVCOM ARMY RESEARCH LABORATORY

Military Batteries: Storage & Shipping

NOTE: Storing batteries at very low SoC (< 20%) can have other undesirable results (side reactions w/ degradation and safety issues)

current DoD policy → GREAT! Right?

About 40-50% SoC is ideal (for extended storage)
…lower (30% SoC) if they will be used soon (or shipped)

No. Actually – this sucks (for storage/shipping)

The storage/shipping of Li-ion batteries at different SoC values has consequences…

Li-Ion Batteries—Safety

Deep Dive: Li-Ion Batteries— Transportation Challenges

https://www.asibrake.com/blog/lithium-ion-batteries-fire-hazard/

1

Deep Dive

Li-Ion Batteries— Transportation Challenges

Wesley Henderson
International Program Manager—
Energy Transport & Storage Program
(Tokyo, Japan)
U.S. Army Research Office (ARO)
wesley.a.henderson4.civ@mail.mil

LI-ION BATTERIES—INHERENTLY UNSAFE FOR TRANSPORTATION & STORAGE

"One of the largest trends in the growth of in-flight fires is due to the transportation of lithium batteries. **From March 1991 to August 2018, the FAA Office of Security and Hazardous Materials Safety recorded 225 cases of aviation incidents involving smoke, fire, extreme heat or explosion involving batteries and battery powered devices** (FAA, 2018). Lithium batteries were the majority of battery types in the incidents. Of particular concern is the increasing number of lithium battery fires onboard aeroplanes. **In 2018 between January and August there were 34 events, in 2017 there were 46 events, in 2016 there were 31, and in 2015 there were 16** (FAA 2018)."
https://www.skybrary.aero/bookshelf/books/2330.pdf
https://www.faa.gov/hazmat/resources/lithium_batteries/media/Battery_incident_chart.pdf

- **UPS Flight 006**
  https://www.aircargonews.net/region/fire-risk-lurking-in-containers/
  https://www.airspacemag.com/videos/category/new-label/were-lithium-batteries-the-cause-of-this-pla/
  https://flightsafety.org/files/RAESSFF.pdf
- **Boeing 747 on Fire Explodes Mid-Air | Asiana Airlines Flight 991**
  https://youtu.be/OCMRTRSdIYc
  https://en.wikipedia.org/wiki/Asiana_Airlines_Flight_991
- **UPS Flight 1307**
  https://www.ntsb.gov/investigations/AccidentReports/Reports/AAR0707.pdf
  http://www.aviation-accidents.net/ups-mcdonnell-douglas-dc8-71f-n-748up-flight-ups1307/
  https://www.skybrary.aero/index.php/DC87,_Philadelphia_USA,_2006
- **Flight MH370 and the Lithium Battery Theory**
  https://aircargoworld.com/allposts/flight-mh370-and-the-lithium-battery-theory-9754/
  https://sputniknews.com/asia/201811121069744479-mh370-batteries-crash/
  https://www.express.co.uk/news/world/612389/MH370-lithium-mobile-phone-batteries-missing-Boeing-777-crash
- **Union Pacific train**
  http://trn.trains.com/news/news-wire/2017/04/28-lithium-ion-batteries-cause-fire-and-explosion-aboard-up-train
- **Fire Deals New Setback to Navy's Heralded Mini-Sub**
  http://the.honoluluadvertiser.com/article/2008/Dec/14/ln/hawaii812140366.html
- **Russia Submersible Fire was in Battery Compartment**
  https://www.bbc.com/news/world-europe-48865332
  https://www.theguardian.com/world/2019/jul/23/russia-submersible-fire-faulty-battery-may-be-cause-reports

Li-ion batteries are widely utilized by the U.S. Army and DoD, but—**when confined on a plane, ship, train or other vehicle during transportation**—they are **inherently unsafe** (i.e., DG - Dangerous Goods)[1,2]:

- **Hazardous Materials: Enhanced Safety Provisions for Lithium Batteries Transported by Aircraft (FAA Reauthorization Act of 2018)**
  https://www.federalregister.gov/documents/2019/03/06/2019-03812/hazardous-materials-enhanced-safety-provisions-for-lithium-batteries-transported-by-aircraft-faa
- **IATA: Lithium Batteries**
  https://www.iata.org/whatwedo/cargo/dgr/Pages/lithium-batteries.aspx
- https://batteryuniversity.com/learn/article/bu_704a_shipping_lithium_based_batteries_by_air
- https://www.concordia.ca/content/dam/concordia/services/safety/docs/EHS-DOC-147_LithiumBatteries.pdf

Challenges include the (a) potential to "**energetically disassemble**" or result in **very hot fires** (e.g., > 650°C or 1200°F), (b) the **inability of Halon and other fire suppression methods to adequately stop Li-ion battery fires** (see insets) and (c) venting of **flammable (H_2)** and **poisonous gases (CO, HF and other)**[3-8] which are particularly hazardous in an enclosed environment such as a plane. In Feb 2019, the **U.S. Department of Transportation (DOT)** prohibited the transportation of Li-ion batteries as cargo on passenger aircraft, required that the batteries for carry-on not exceed 100 Wh... and also required that **all batteries must be shipped at ≤ 30% state-of-charge (SoC)** (**Fig. 1**):

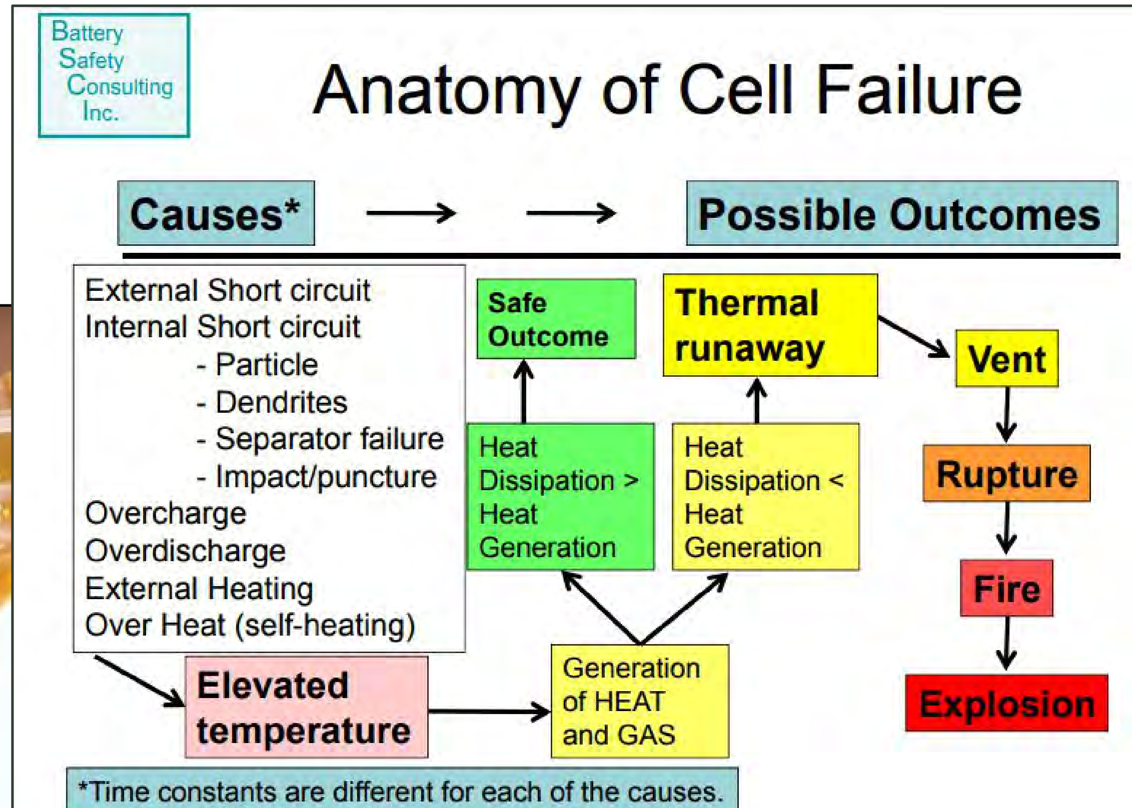
https://www.youtube.com/watch?v=OCMRTRSdIYc

Battery SoC — Safety

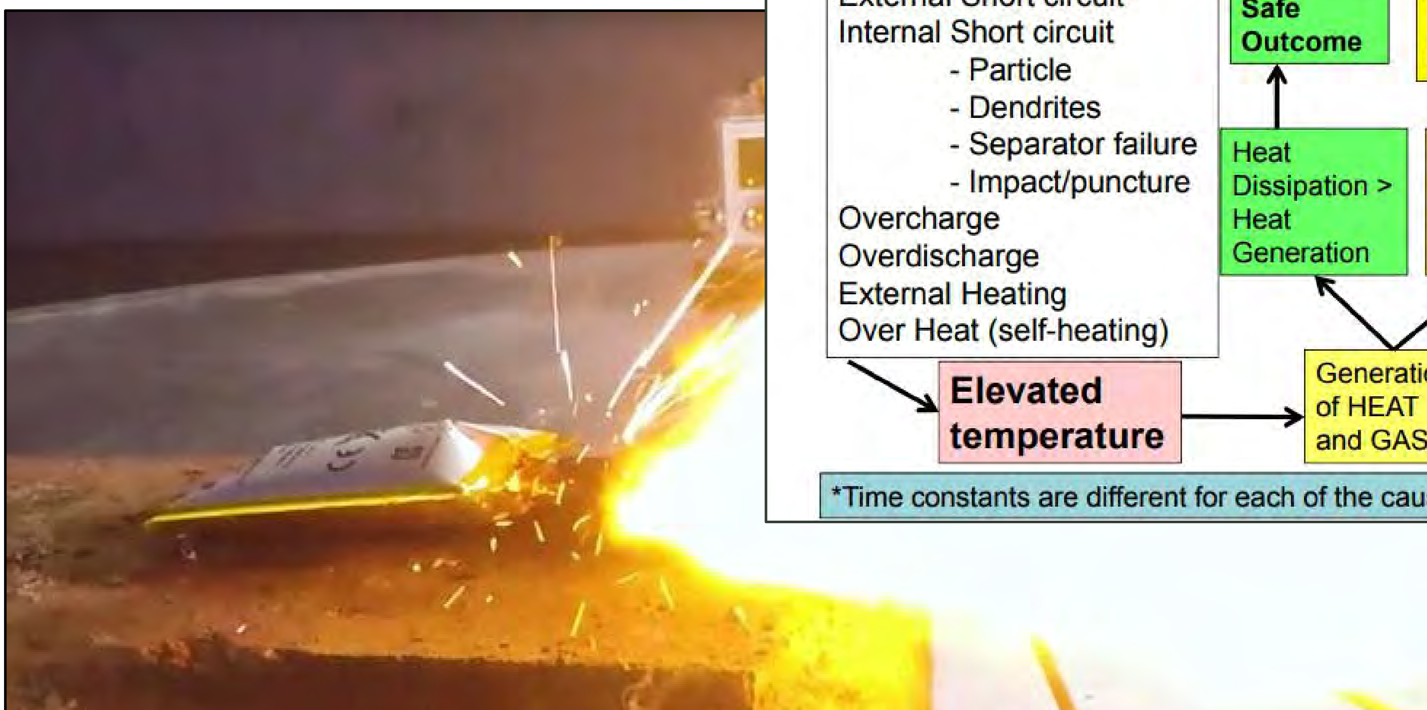
Li-Ion Batteries—Safety

Li-ion batteries can—and do—catch fire/explode…

The reasons why this occurs are fairly well understood:

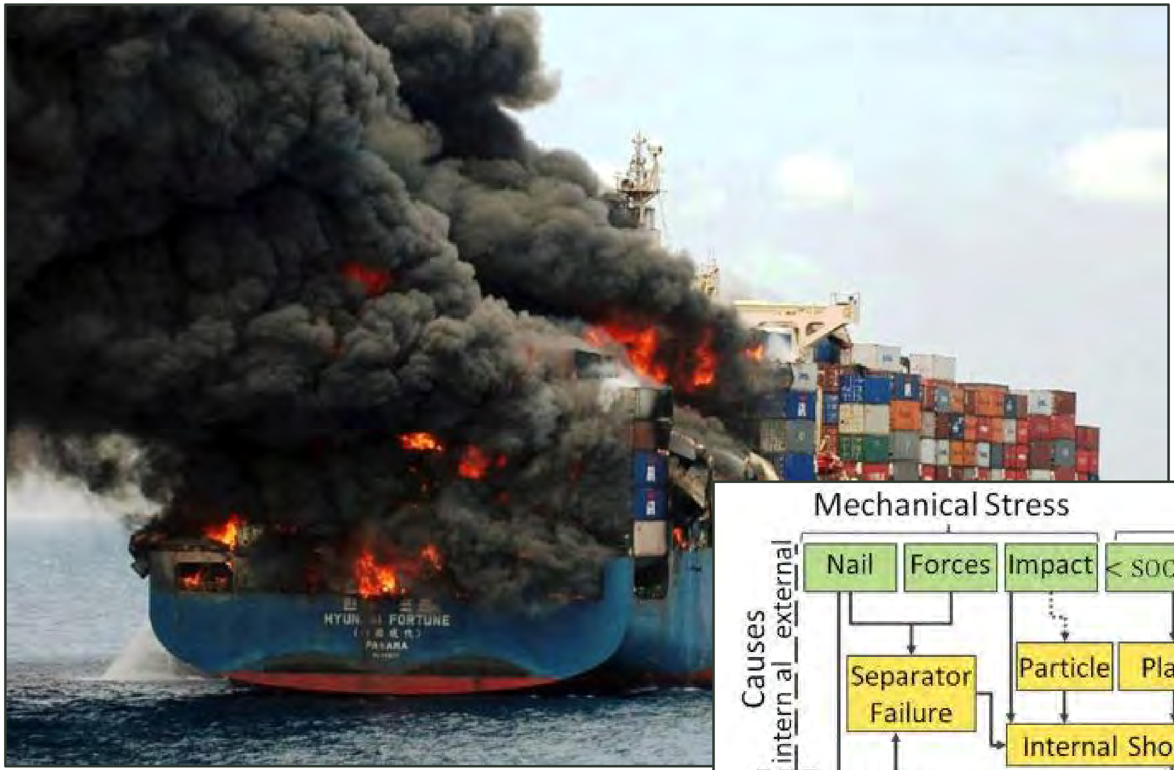


https://www.electricgaadi.com/learn-about-ev/safety-standards-of-ev

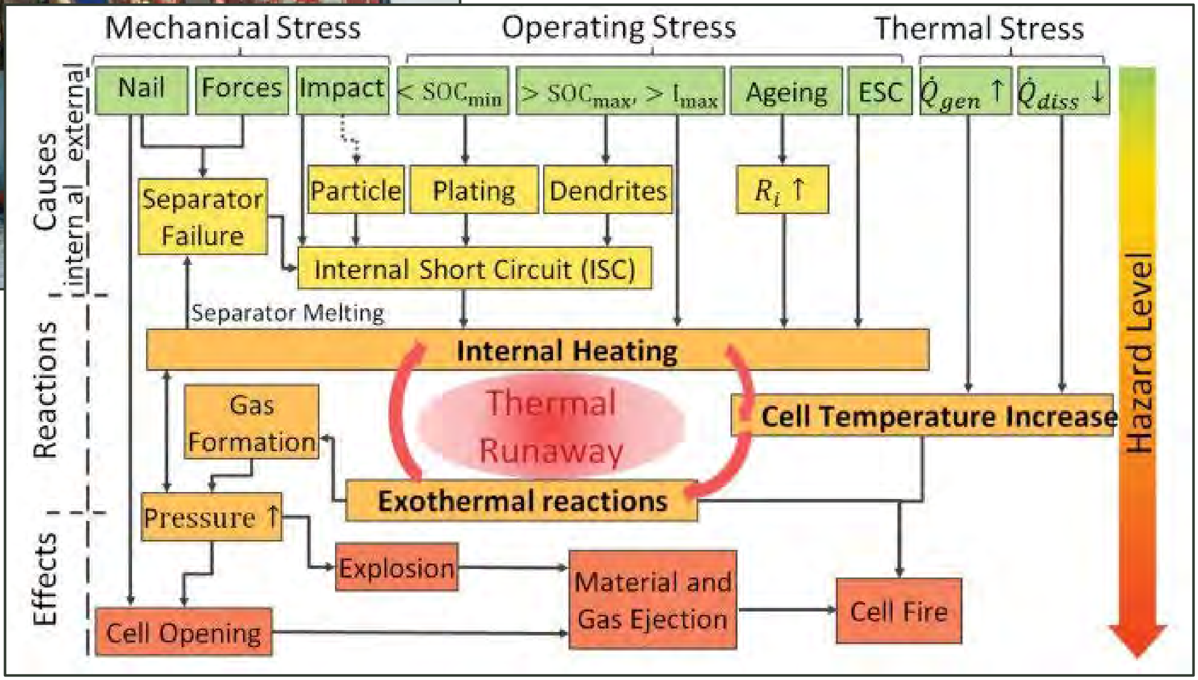


https://electronics360.globalspec.com/article/7868/video-learn-why-lithium-ion-batteries-explode

Li-Ion Batteries—Safety

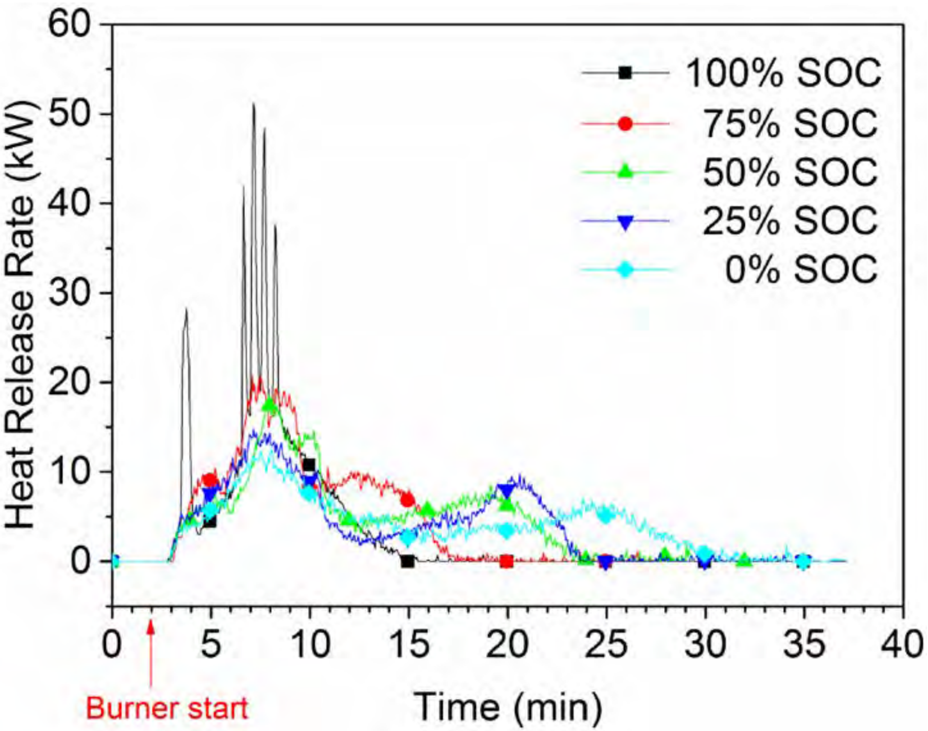


https://www.upsbatterycenter.com/blog/marine-battery-fire-suppression/



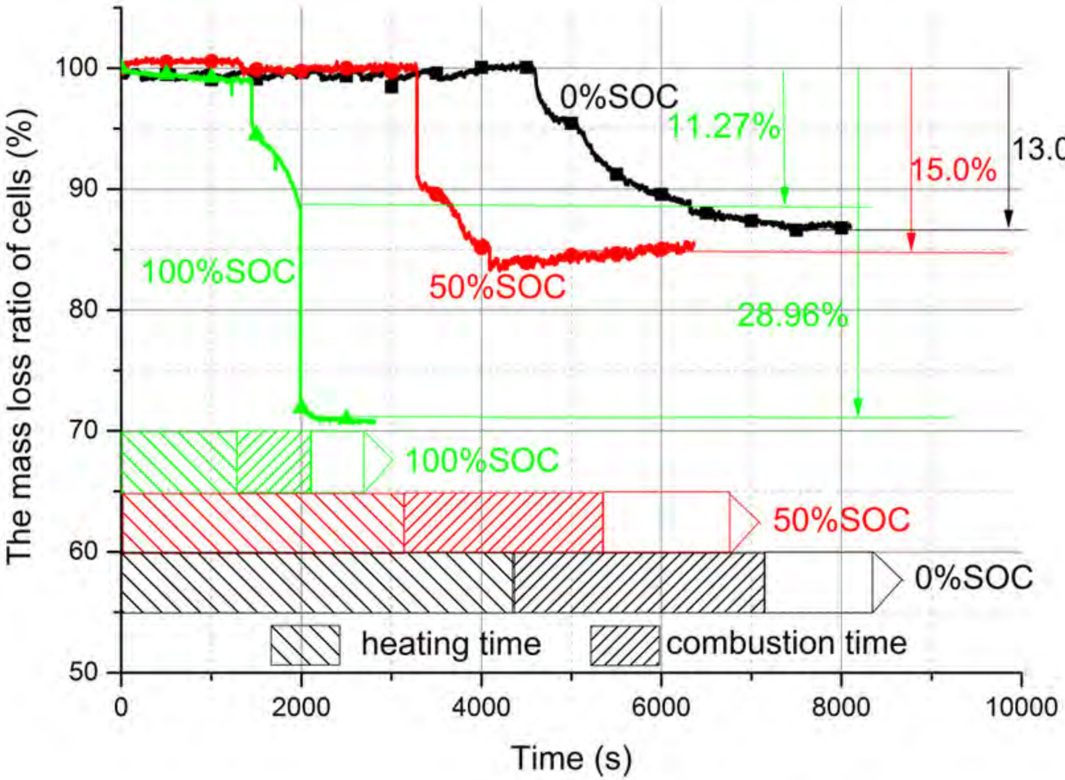
https://www.scitecheuropa.eu/calorimeters-battery-safety/95275/

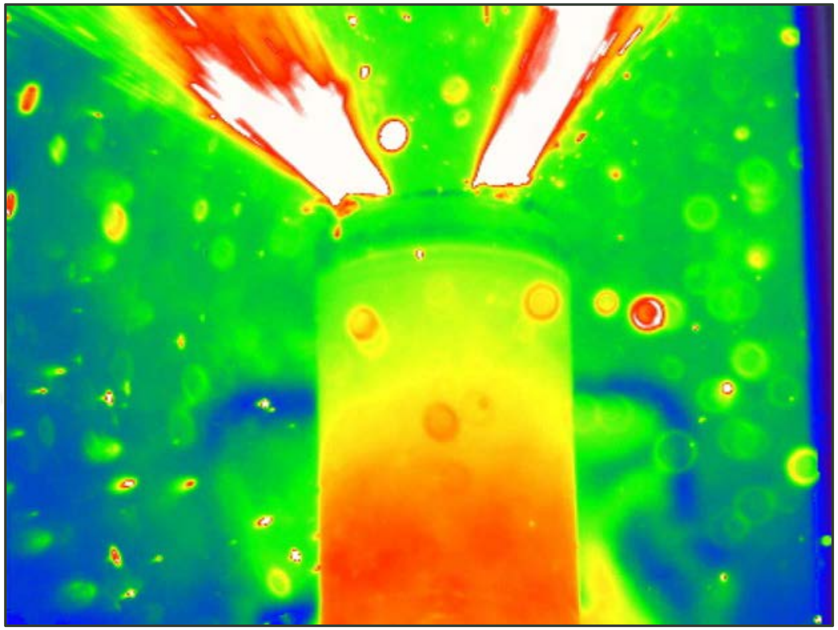
Li-Ion Batteries—Safety



F. Larsson, P. Andersson and B.-E. Mellander, *Batteries* **2016**, *2*, 9.
Lithium-Ion Battery Aspects on Fires in Electrified Vehicles on the Basis of Experimental Abuse Tests.

Li-Ion Batteries—Safety





Exploding 18650 in SLO-MO 120 FPS

https://www.youtube.com/watch?v=mZ9vIy2dYDU

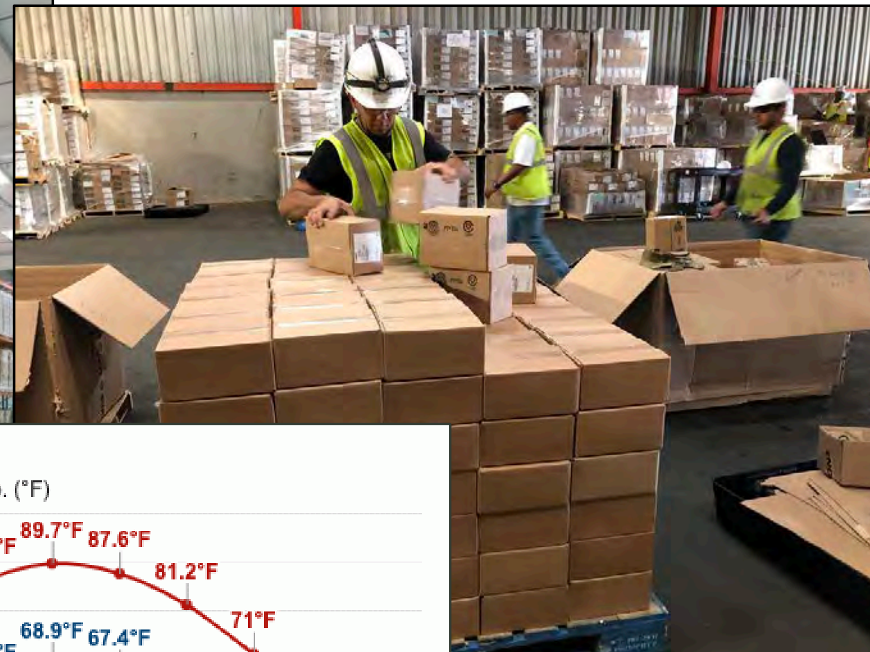
https://spectrum.ieee.org/energywise/consumer-electronics/portable-devices/first-xray-views-into-overheating-lithiumion-batteries

P. Huang, Q. Wang, K. Li, P. Ping and J. Sun, *Sci. Rep.* **2015**, *5*, 7788.
The Combustion Behavior of Large Scale Lithium Titanate Battery.

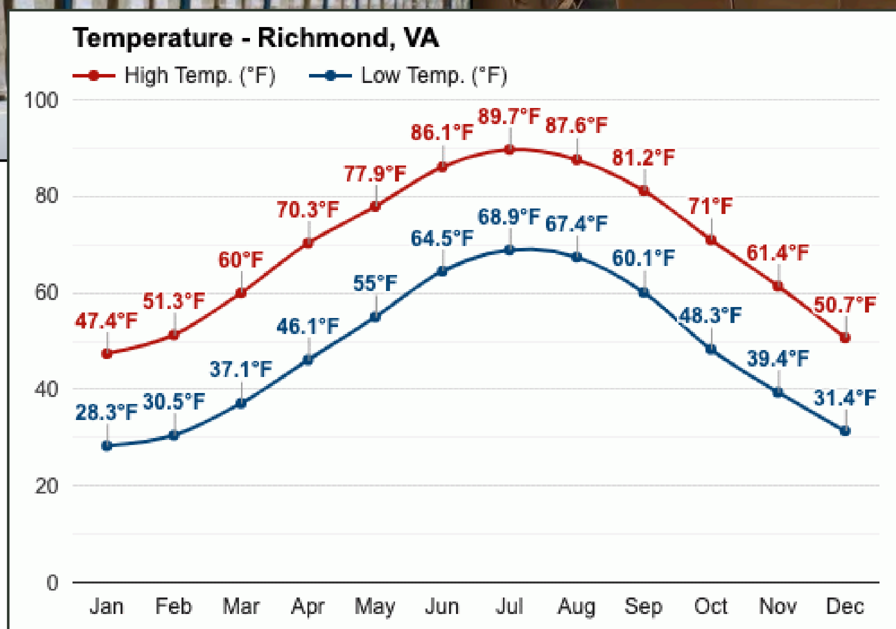
Battery Shipping/Storage

Li-Ion Batteries—DLA Storage/Shipping

https://www.aecom.com/projects/defense-logistics-agency-dla-physical-distribution-warehouse-services/

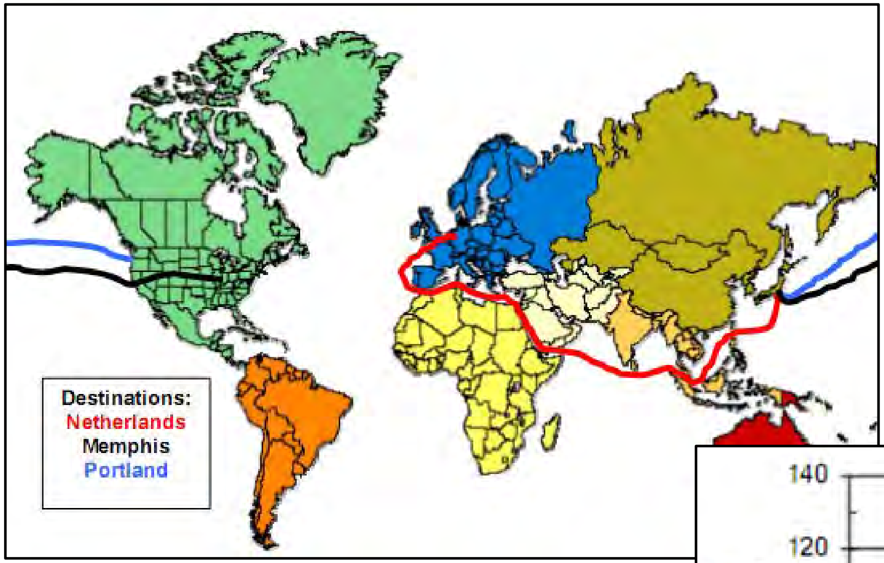


https://www.flickr.com/photos/dlamil/40154818352/

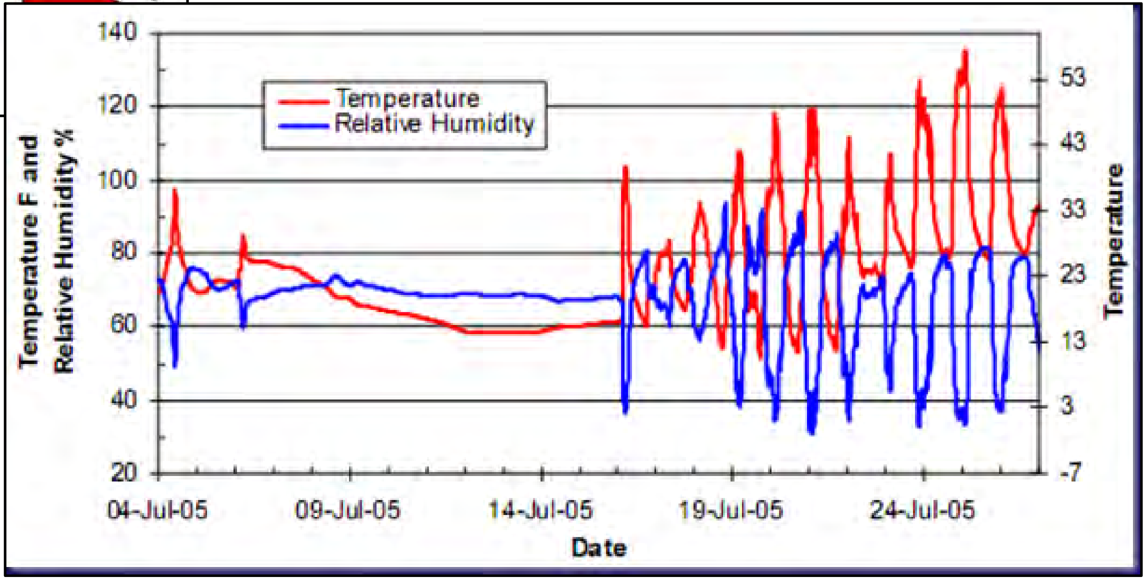


https://www.weather-us.com/en/virginia-usa/richmond-climate

Li-Ion Batteries—Storage/Shipping



Ocean Container Temperature and Humidity Study



Hottest shipment 135ºF (57ºC) – Japan to Memphis (USA)

https://interdry.wordpress.com/2012/01/27/ocean-container-temperature-and-humidity-study-2/

Li-Ion Batteries—Storage/Shipping

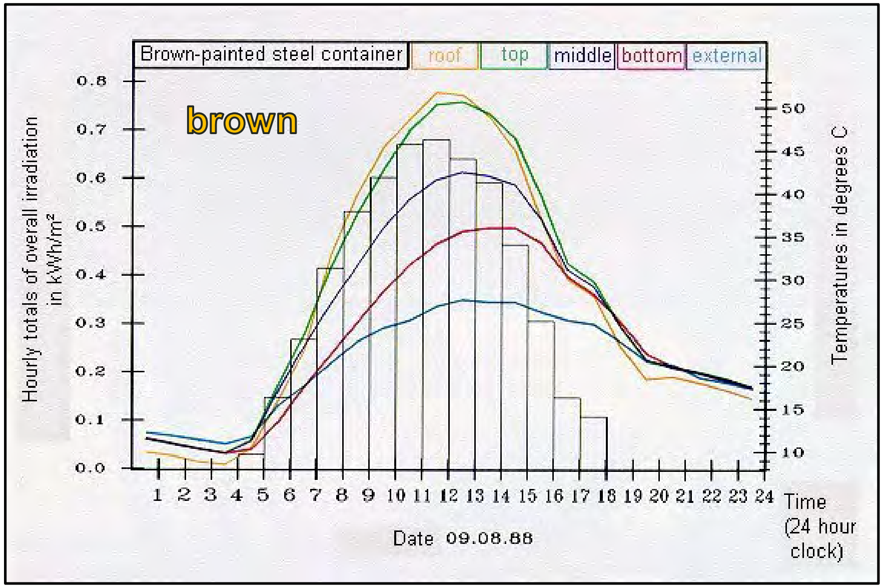
Sea Containers WA Container Temperature Case Study

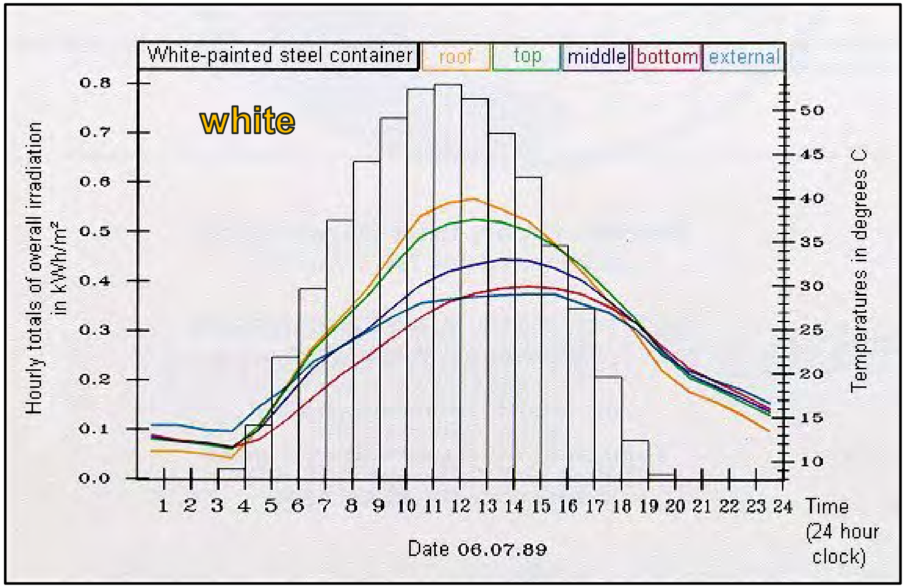
https://www.youtube.com/watch?v=B5fUGo3OQZY

Reflective Roof Paint on Shipping Container - Part 2

https://www.youtube.com/watch?v=S3vULXwurYI

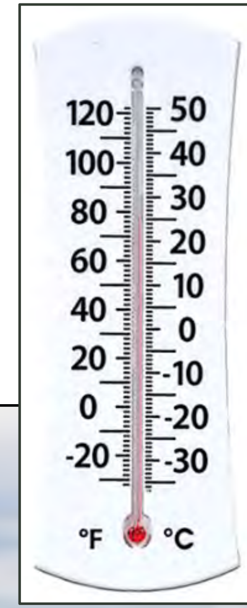
http://integratedequipmentsales.com/40-foot-high-cube-containers/



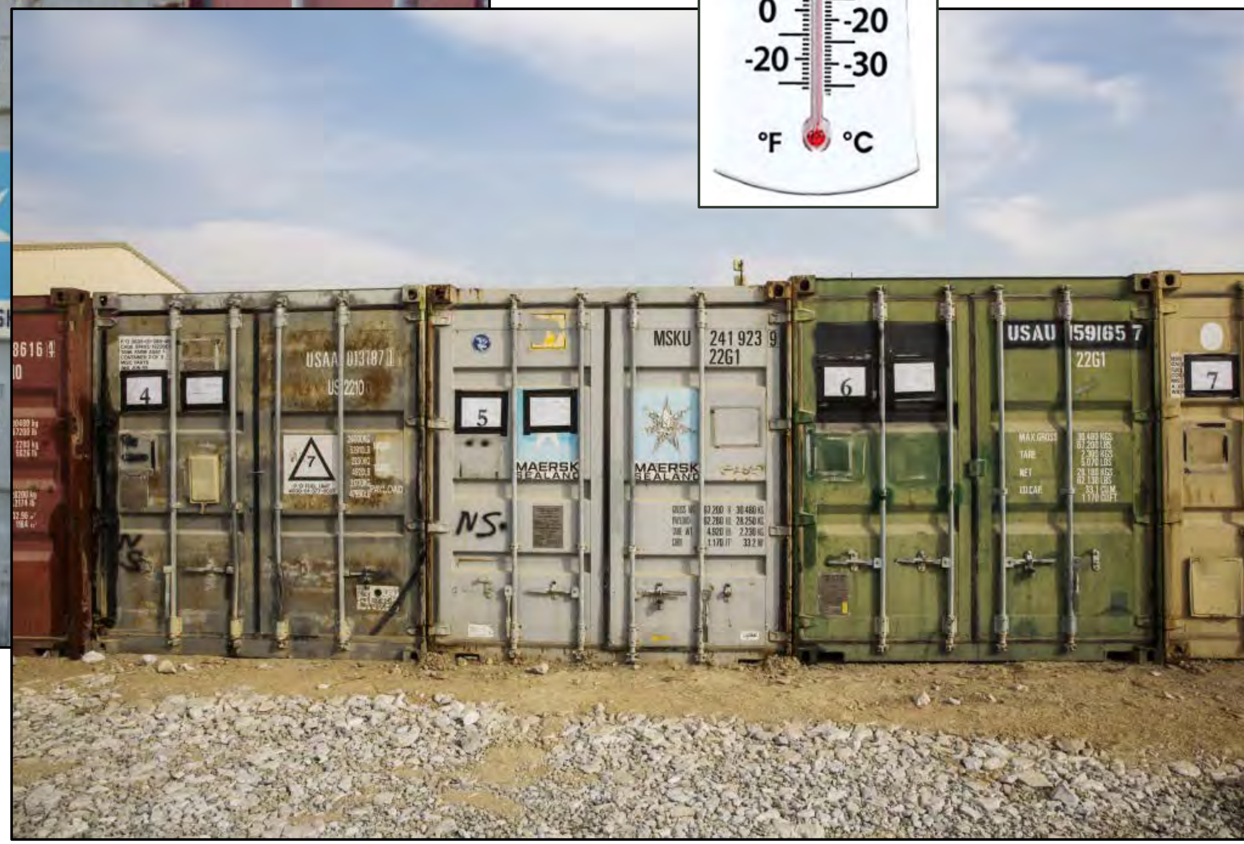


https://www.tis-gdv.de/tis_e/containe/klima/klima.htm/

Li-Ion Batteries—Storage/Shipping



https://www.stripes.com/news/army-counts-containers-in-kuwait-1.25659



https://www.pbs.org/newshour/world/photo-essay-remnants-trillion-dollar-war-afghanistan

Battery SoC — Calendar Aging

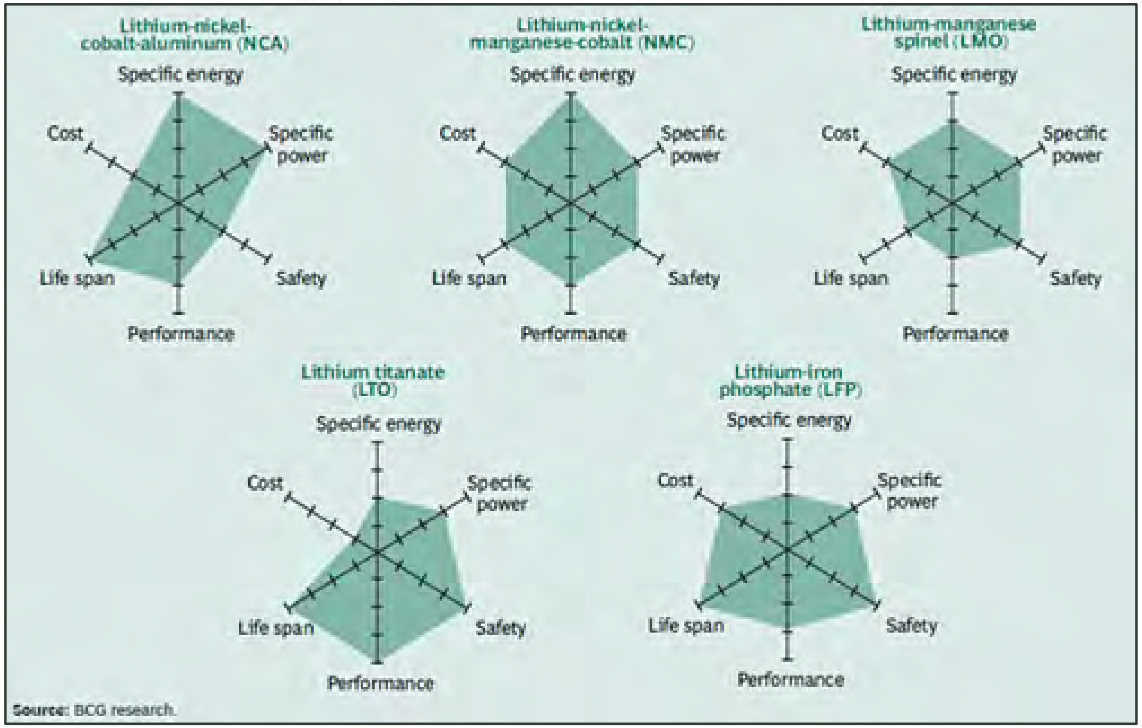
APPROVED FOR PUBLIC RELEASE

Li-Ion Batteries—Calendar Aging

Lithium Battery Technologies

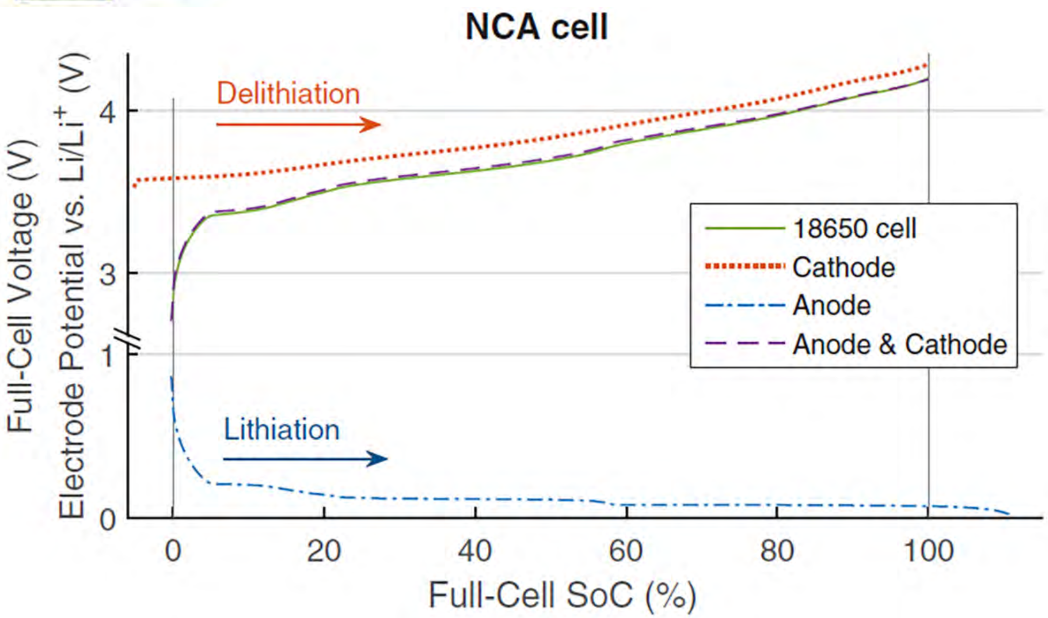
Chemical Name	Material	Abbreviation	Applications
Lithium cobalt oxide	$LiCoO_2$	LCO	Cell phones, laptops, cameras
Lithium manganese oxide	$LiMn_2O_4$	LMO	Power tools, EVs, medical, hobbyist
Lithium iron phosphate	$LiFePO_4$	LFP	Power tools, EVs, medical, hobbyist
Lithium nickel manganese cobalt oxide	$LiNiMnCo0_2$	NMC	Power tools, EVs, medical, hobbyist
Lithium nickel cobalt aluminum oxide	$LiNiCoAlO_2$	NCA	EVs, grid storage
Lithium titanate	$Li_4Ti_5O_{12}$	LTO	EVs, grid storage

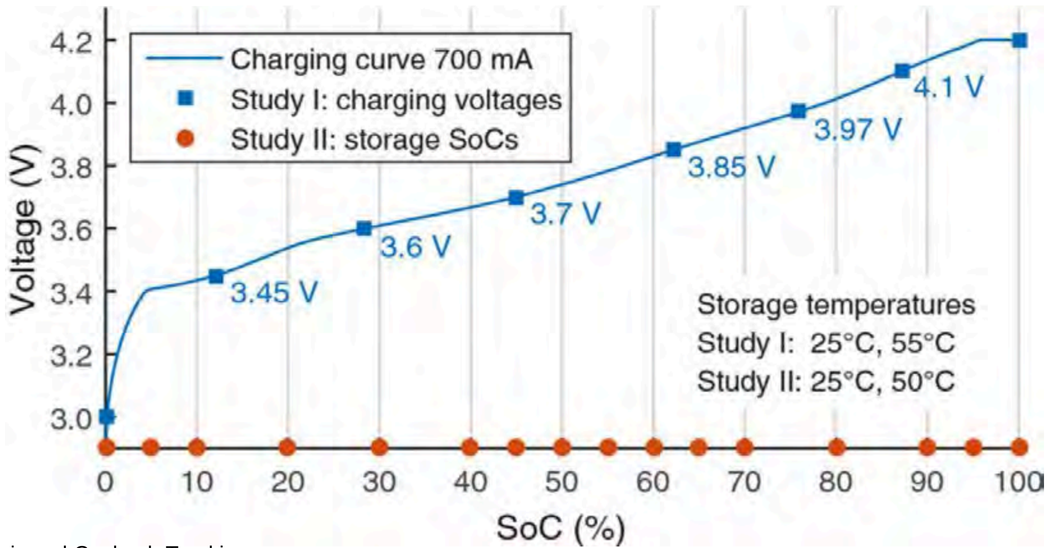
Source: batteryuniversity.com



https://batteryuniversity.com/learn/archive/is_li_ion_the_solution_for_the_electric_vehicle

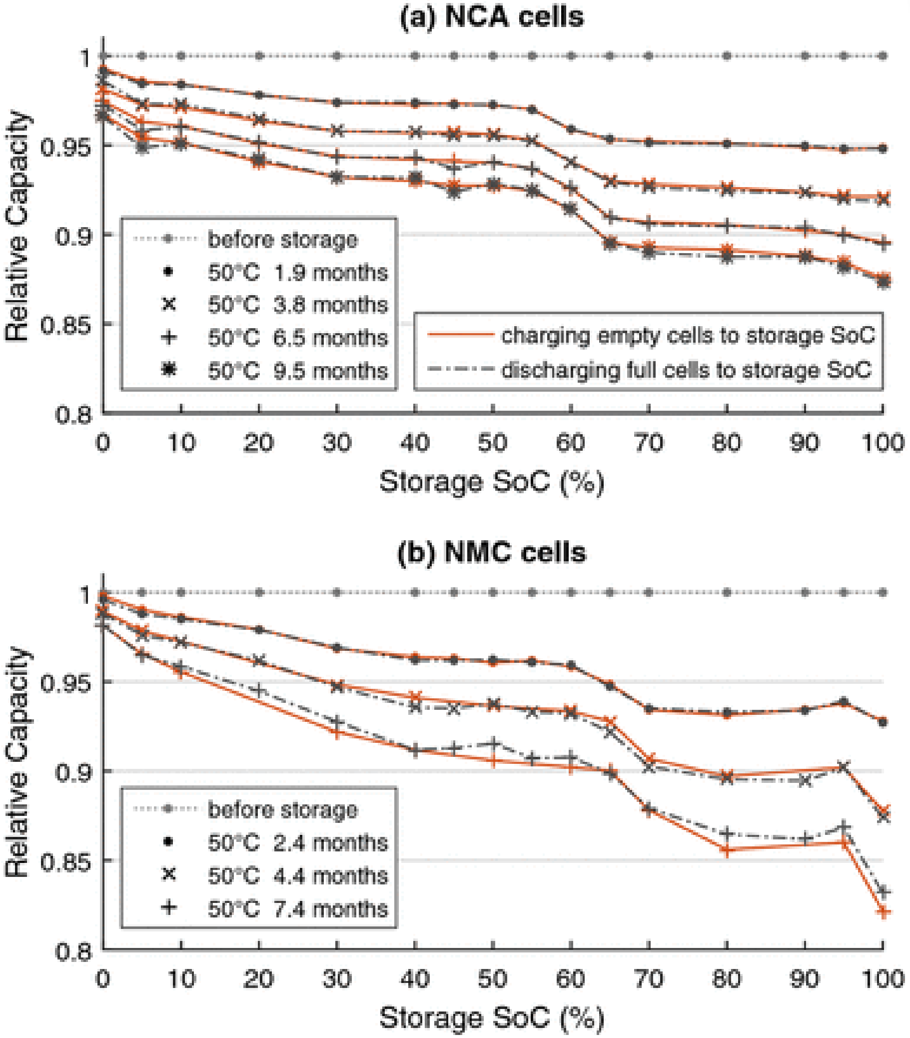
Li-Ion Batteries—Calendar Aging





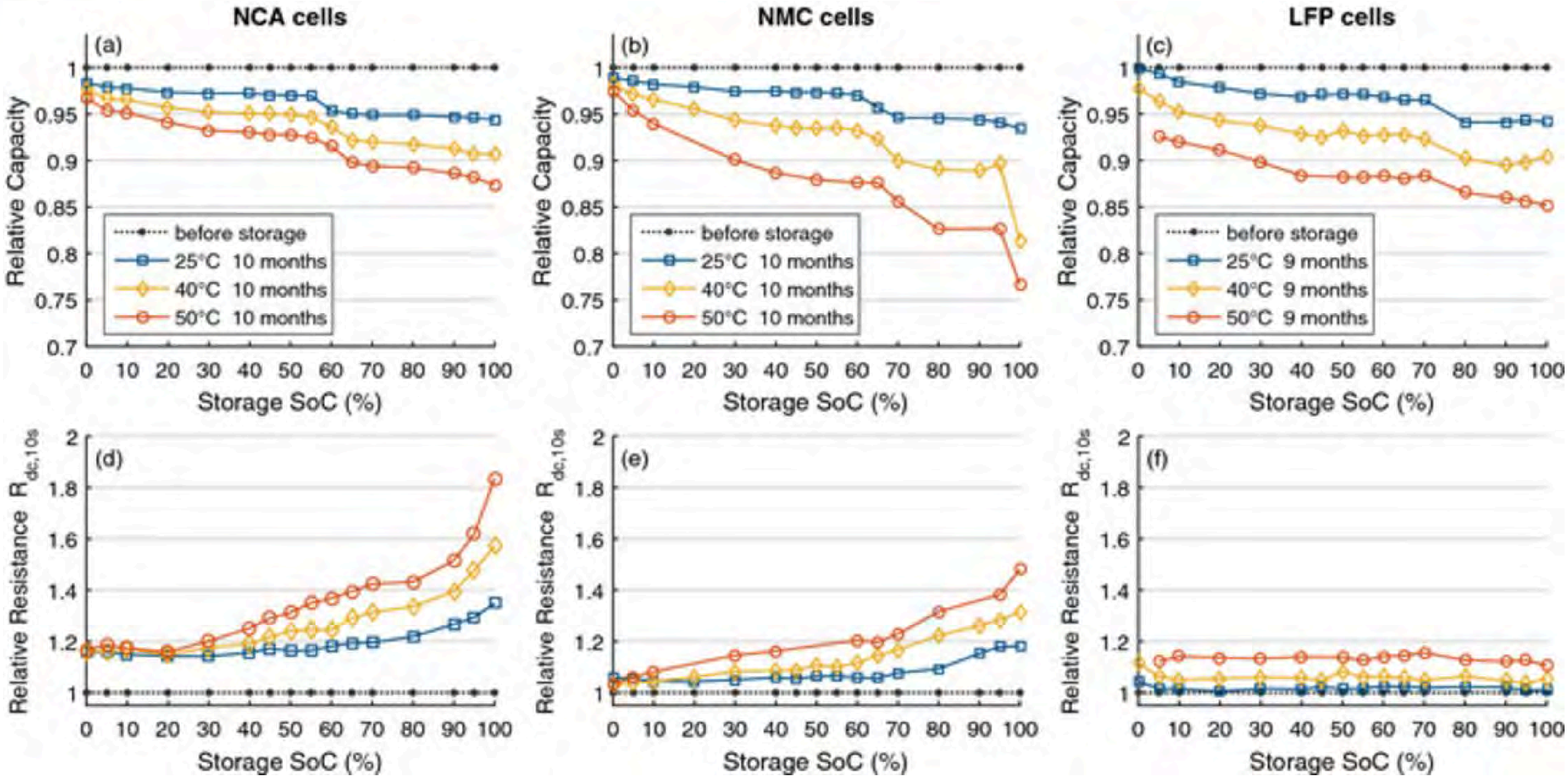
P. Keil and A. Jossen, *J. Electrochem. Soc.* **2017**, *164*, A6066.
Calendar Aging of NCA Lithium-Ion Batteries Investigated by Differential Voltage Analysis and Coulomb Tracking.

Li-Ion Batteries—Calendar Aging



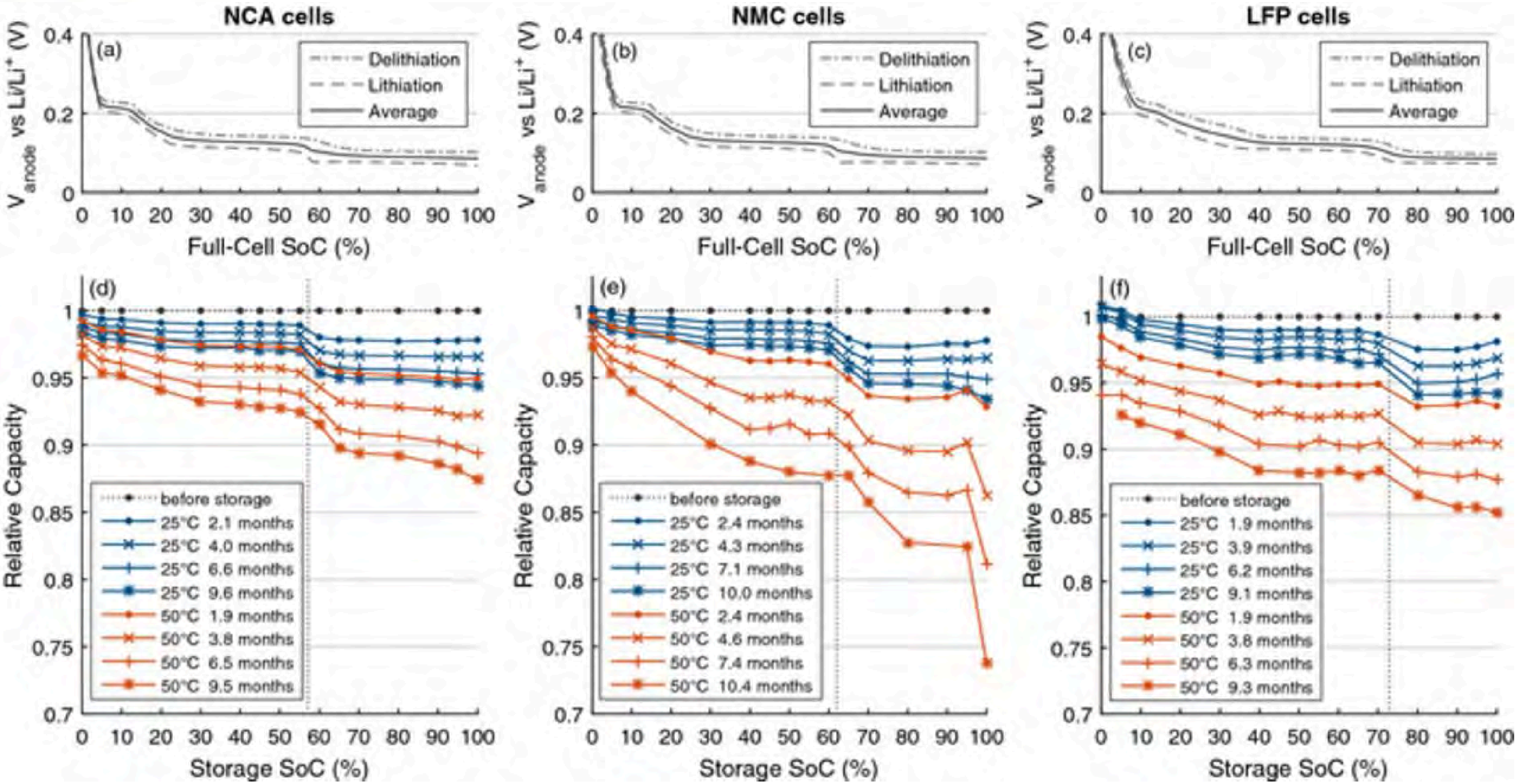
P. Keil, S. F. Schuster, J. Wilhelm, J. Travi, A. Hauser, R. C. Karl and A. Jossen, *J. Electrochem. Soc.* **2016**, *163*, A1872.
Calendar Aging of Lithium-Ion Batteries. I. Impact of the Graphite Anode on Capacity Fade.

Li-Ion Batteries—Calendar Aging



P. Keil, S. F. Schuster, J. Wilhelm, J. Travi, A. Hauser, R. C. Karl and A. Jossen, *J. Electrochem. Soc.* **2016**, *163*, A1872.
Calendar Aging of Lithium-Ion Batteries. I. Impact of the Graphite Anode on Capacity Fade.

Li-Ion Batteries—Calendar Aging



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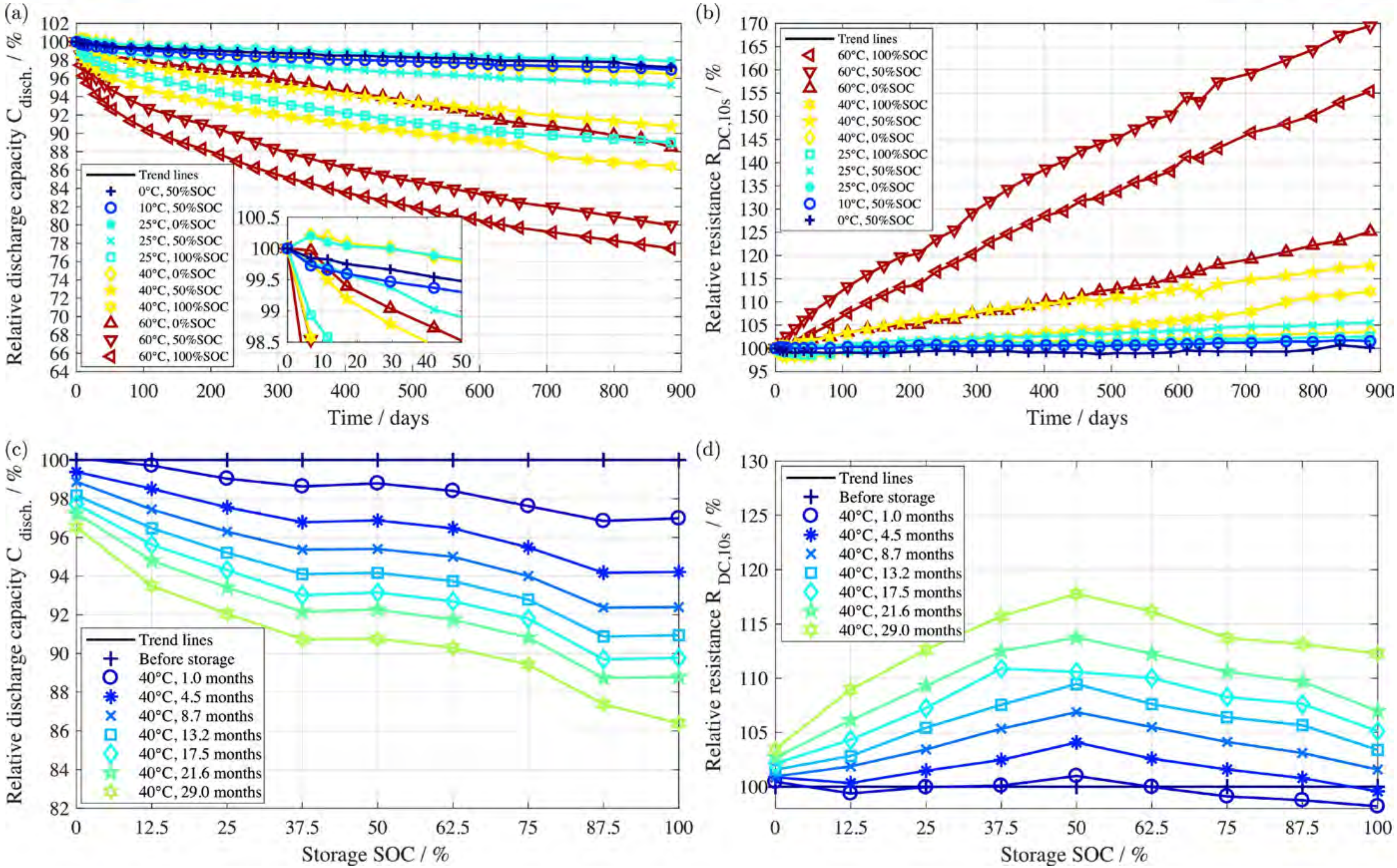
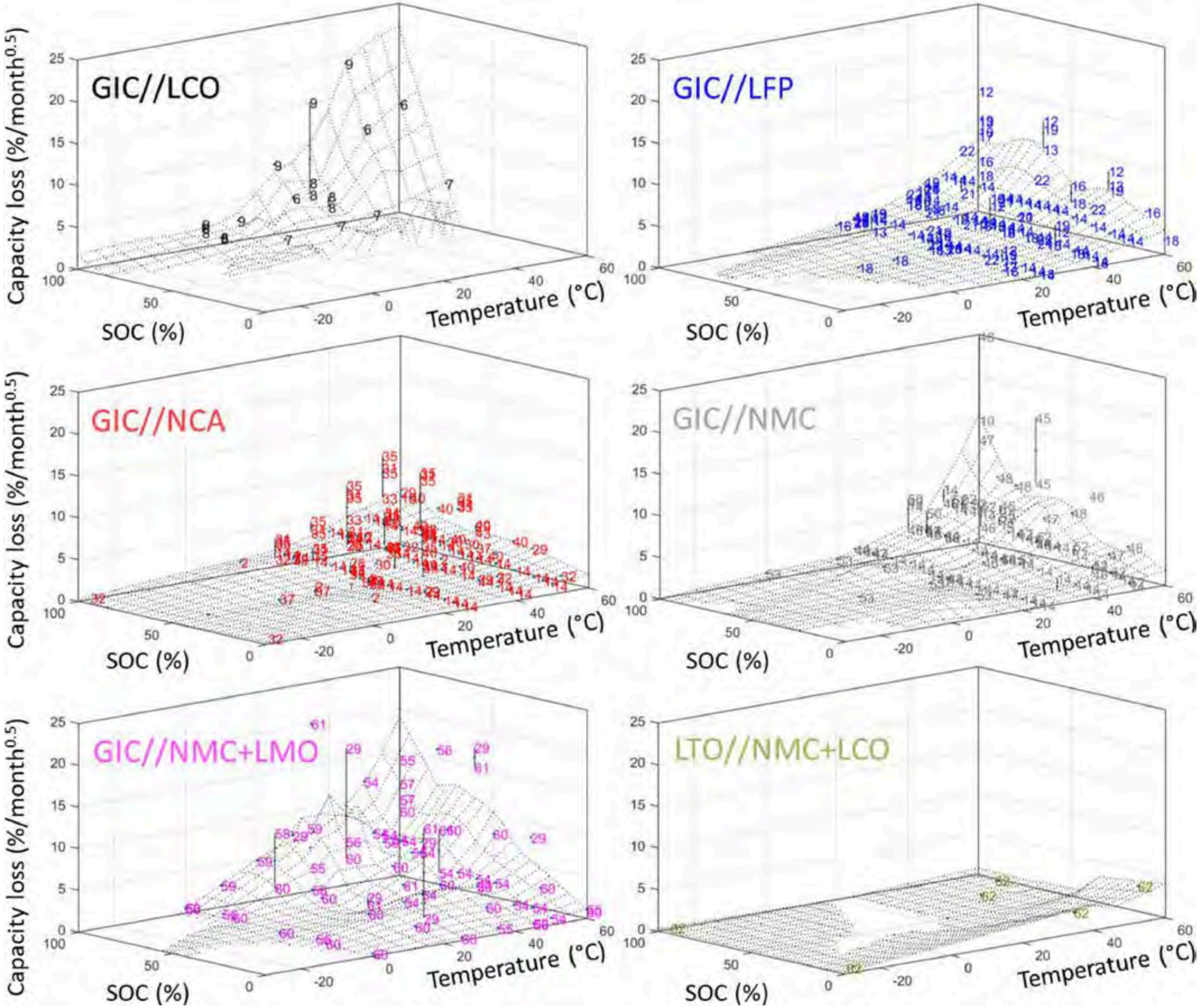


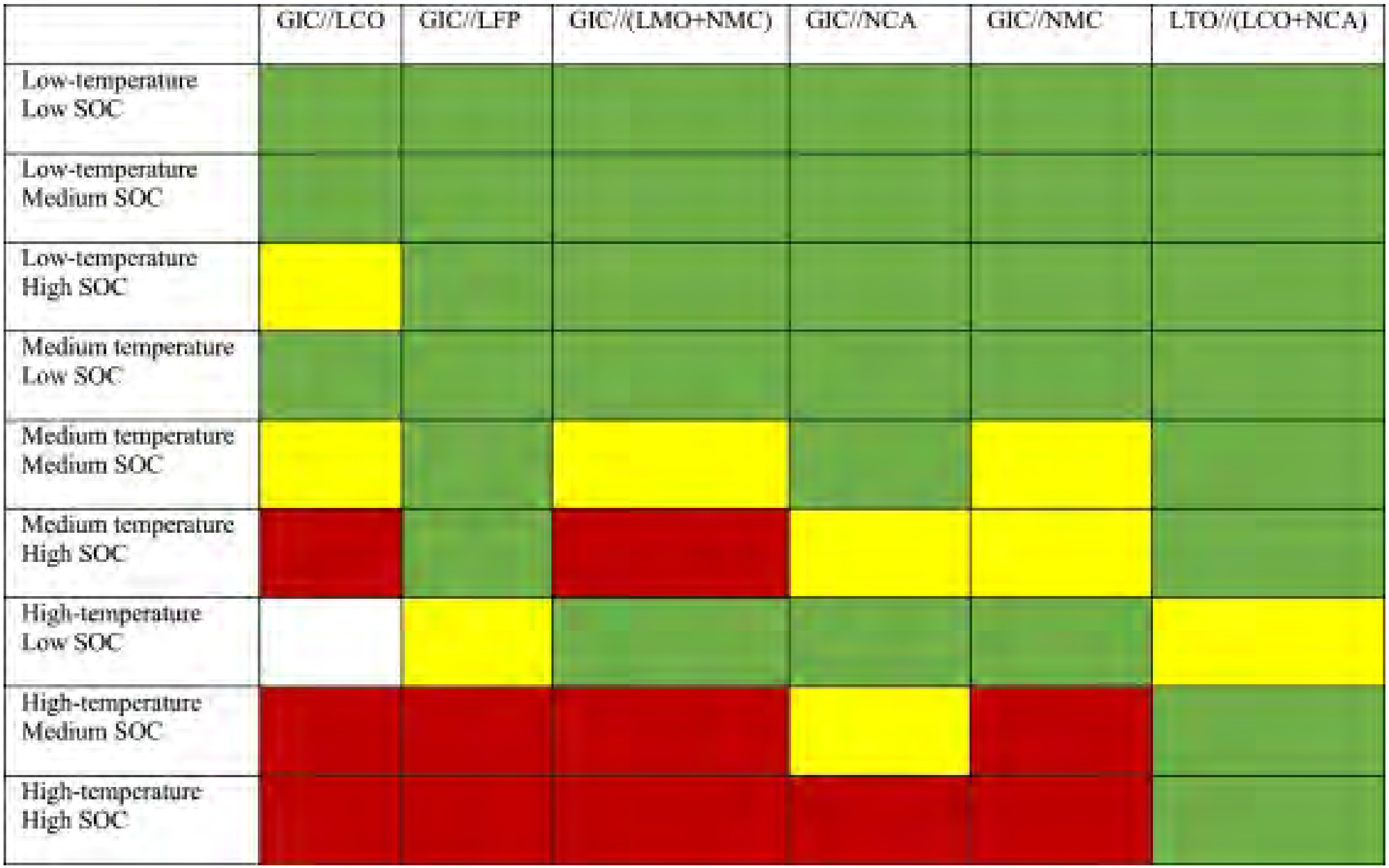
M. Naumann, M. Schimpe, P. Keil, H. C. Hesse and A. Jossen, *J. Energy Storage* **2018**, *17*, 153.
Analysis and Modeling of Calendar Aging of a Commercial $LiFePO_4$/Graphite Cell.

Li-Ion Batteries—Calendar Aging



M. Dubarry, Q. Nan and P. Brooker, *Curr. Op. Electrochem.* **2018**, *9*, 106.
Calendar Aging of Commercial Li-Ion Cells of Different Chemistries – A Review.

Li-Ion Batteries—Calendar Aging



M. Dubarry, Q. Nan and P. Brooker, *Curr. Op. Electrochem.* **2018**, *9*, 106.
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Li-Ion Batteries—Safety & Calendar Aging

The storage/shipping of Li-ion batteries at different SoC values has consequences…

https://www.dla.mil/News/Images/igphoto/2001690917/

https://www.stripes.com/news/logistics-personnel-prepare-to-move-all-materiel-out-of-iraq-1.153024

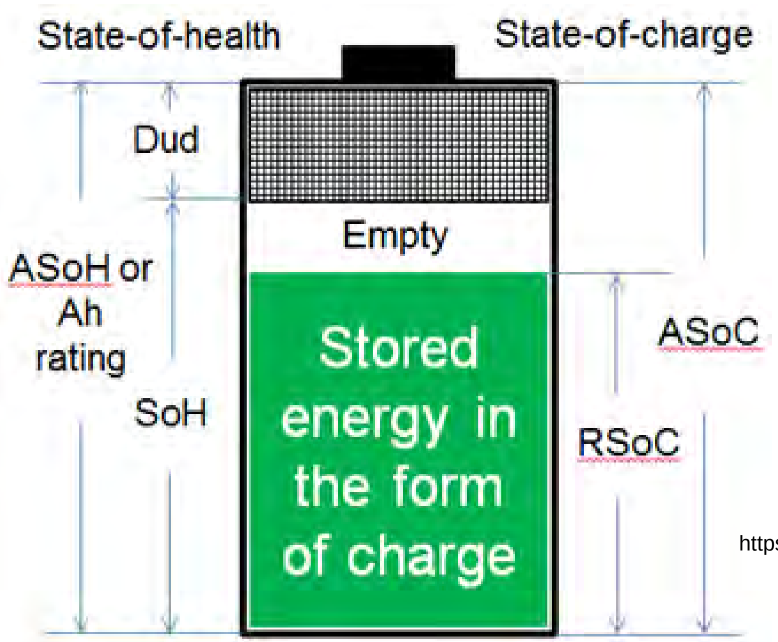
Li-Ion Batteries—Calendar Aging

The bottom line:

Storage of a new Li-ion battery at a high SoC, especially if done at higher temperatures, can result in significant degradation over time

Thus, a new 10 Ah BB-2590/U battery (right out of the box) may actually only be a 9 Ah battery (i.e., 10% capacity degradation) when fully charged (100% SoC)

Note that most Li-ion batteries are discarded when they reach an 80% State-of-Health (SoH) (i.e., 20% degradation)—perhaps sooner for military applications



https://batteryuniversity.com/learn/article/battery_definitions

Summary

LiPo batteries (with pouch cells inside) and cylindrical ("Li-ion") cells have the same… or nearly identical internal chemistry—it's the cell format which differs

Cylindrical cells have the highest energy density of any Li-ion cell format. Thus, replacing LiPo batteries with those assembled instead with cylindrical cells can result in a battery pack with a much higher capacity.

How batteries are stored (SoC, temperature) matters—it determines how safe the battery is and how much degradation occurs (even if not used)