Concerns with the Effects of Environmental Conditions on Mine Utility Vehicle and Rubber-tired Mantrip Lithium-ion Batteries

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Mining Diesel Emissions Council (MDEC)
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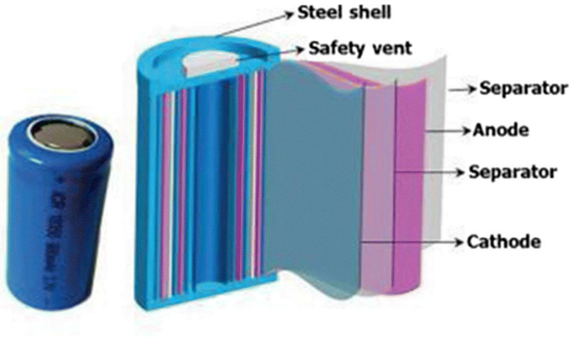
Ontario, Canada

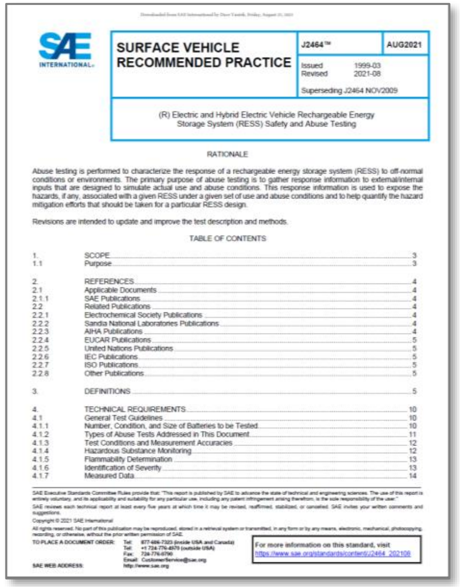
Presentation topics

LIB background



LIB environment concerns

LIB environment test standards



SURFACE VEHICLE RECOMMENDED PRACTICE

J2464™ AUG2021

Issued 1999-03
Revised 2021-08

Superseding J2464 NOV2009

(R) Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing

RATIONALE

Abuse testing is performed to characterize the response of a rechargeable energy storage system (RESS) to off-normal conditions or environments. The primary purpose of abuse testing is to gather response information to external/internal inputs that are designed to simulate actual use and abuse conditions. This response information is used to expose the hazards, if any, associated with a given RESS under a given set of use and abuse conditions and to help quantify the hazard mitigation efforts that should be taken for a particular RESS design.

Revisions are intended to update and improve the test description and methods.

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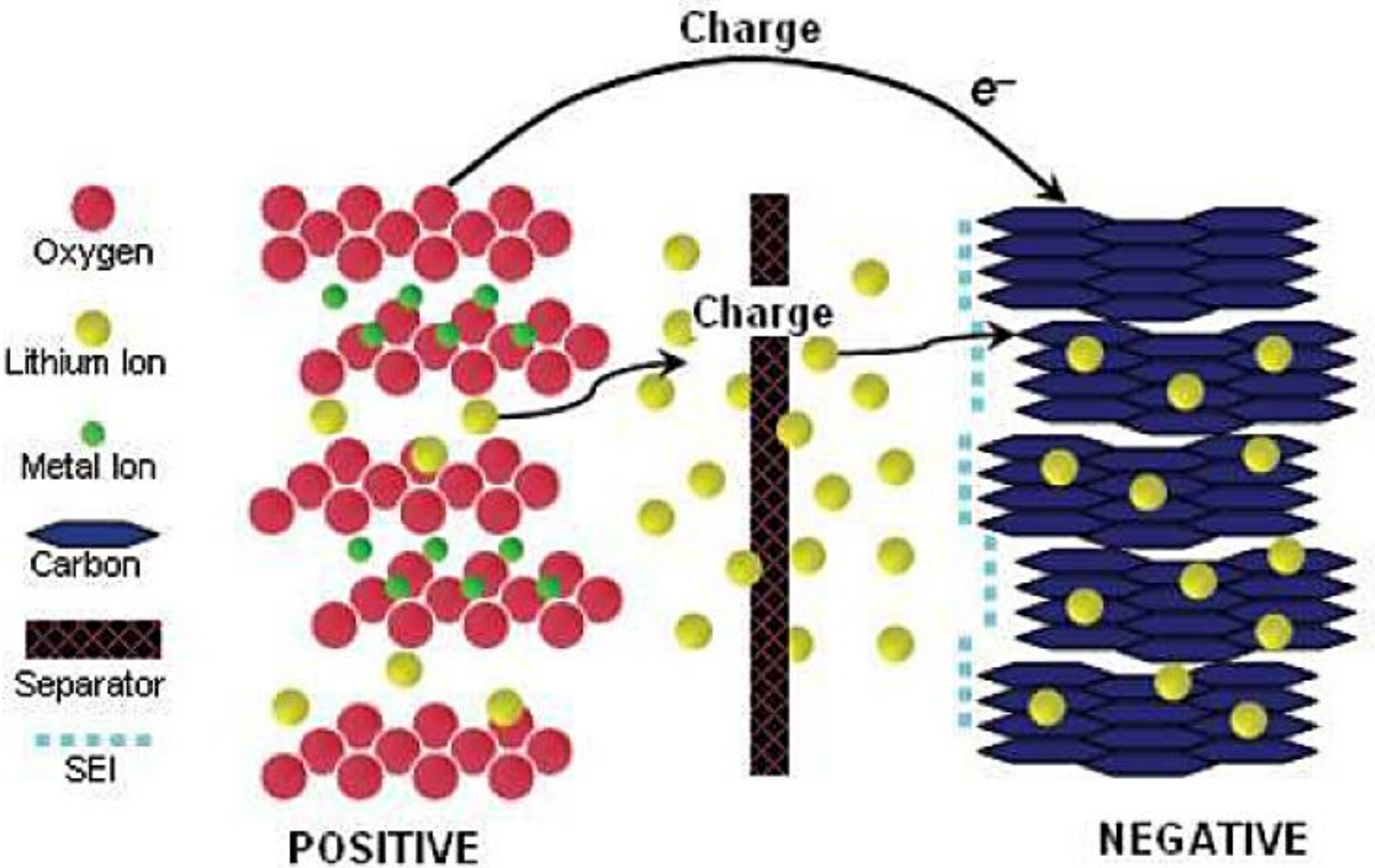
For more information on this standard, visit https://www.sae.org/standards/content/J2464_202108

NIOSH mine utility Vehicle & rubber-tired Mantrip LIB project

A lithium-ion battery (LIB) consists of positive and negative electrodes in an electrolyte separated by a porous polymer layer

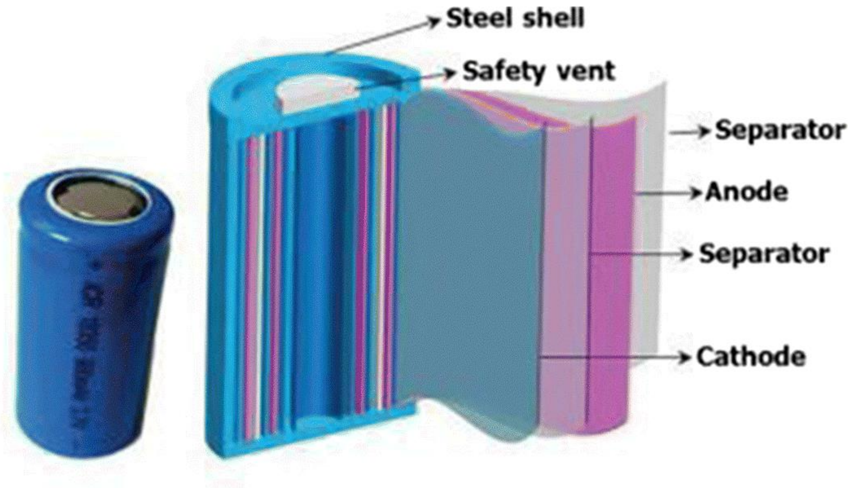
- During charging, lithium ions flow from the cathode to the anode through the separator
- While discharging, lithium ions flow from the anode to the cathode through the separator



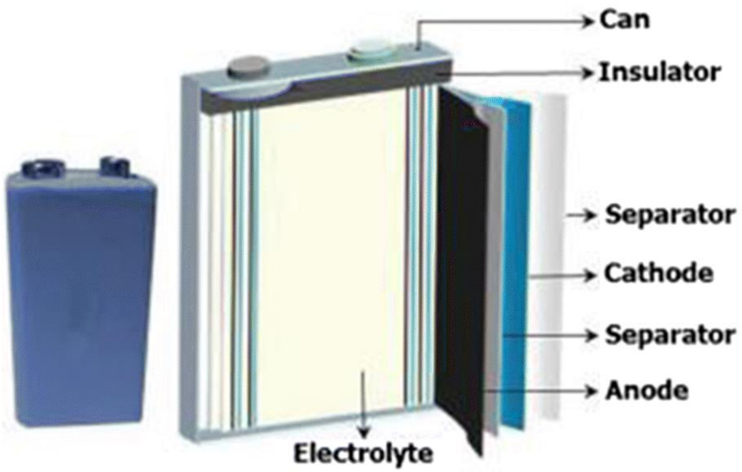
cathode anode

Three types of LIB cell form factors used in EV applications: cylindrical, prismatic, and pouch

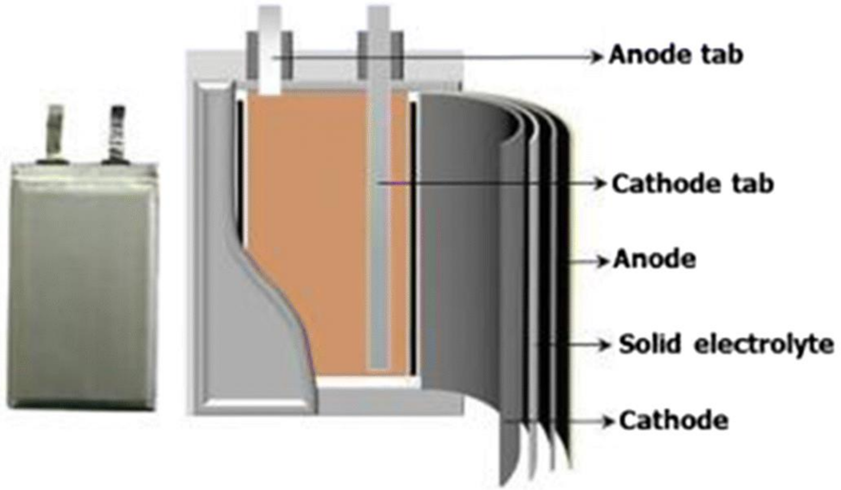
cylindrical



prismatic



pouch



Liang, Y., et al. [2019]. A review of rechargeable batteries for portable electronic devices. *InfoMat*, *1*(1), 6-32. https://doi.org/10.1002/inf2.12000.

Multiple cells are combined into modules, and multiple modules are combined into packs that power equipment

cylindrical
18650
cell

module w/
multiple
18650 cells

pack w/
multiple
modules

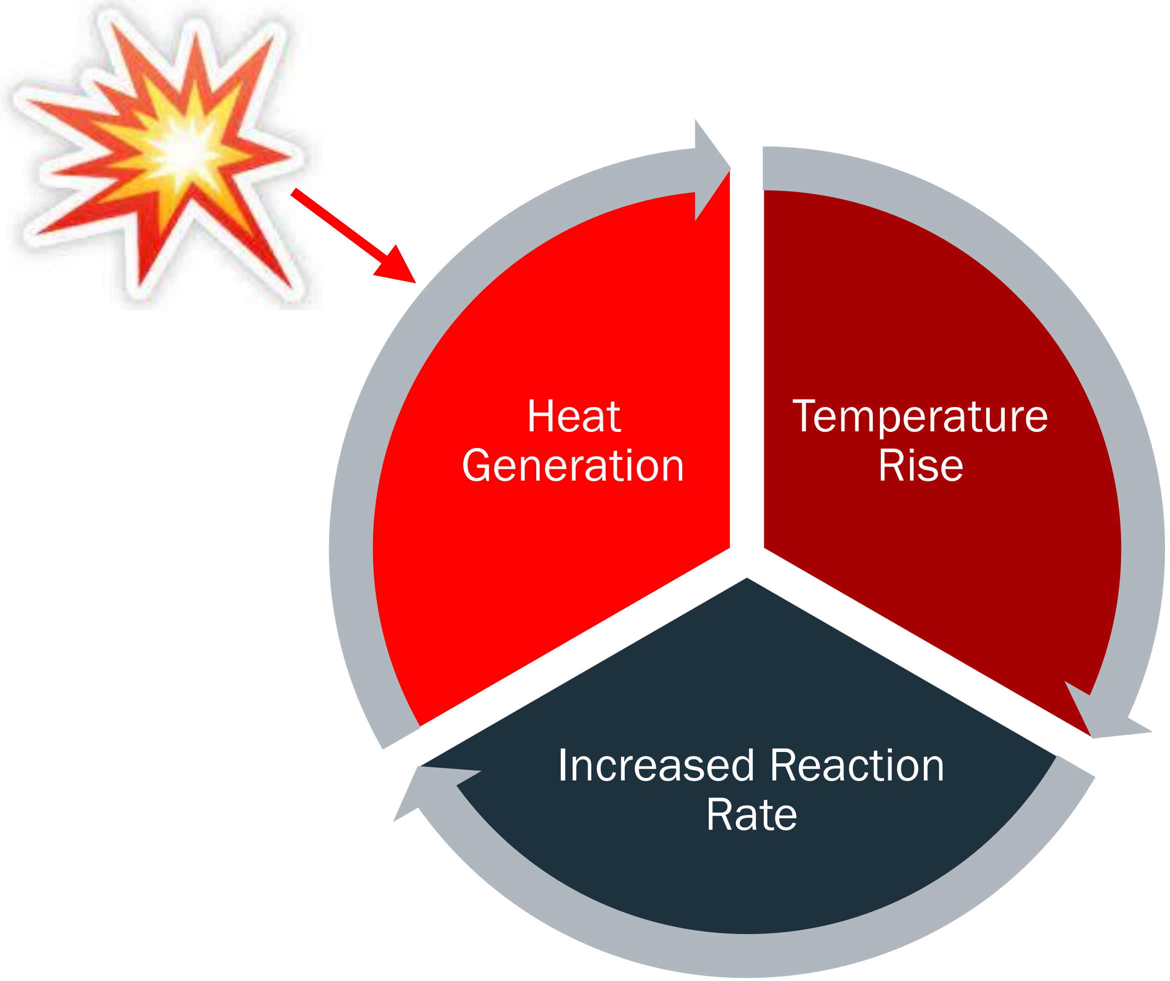
LIB-powered equipment

Multiple LIB chemistries are available, and each has advantages and disadvantages

Chemical Name	Advantages	Disadvantages
Lithium nickel manganese cobalt oxide (NMC) Lithium nickel cobalt aluminium oxide (NCA)	High energy density (W-h/L), High voltage (~3.7 V)	Shortest lifespan, Lower thermal stability
Lithium iron Phosphate (LFP)	Long lifespan, durability, good thermal stability, raw material availability	Lower specific energy (W-h/kg), reduced low T performance
Lithium titanate/ titanium oxide (LTO)	Long lifespan, faster charging, good thermal stability	Lower energy density (W-h/L), lower voltage (~2.4 V), cost

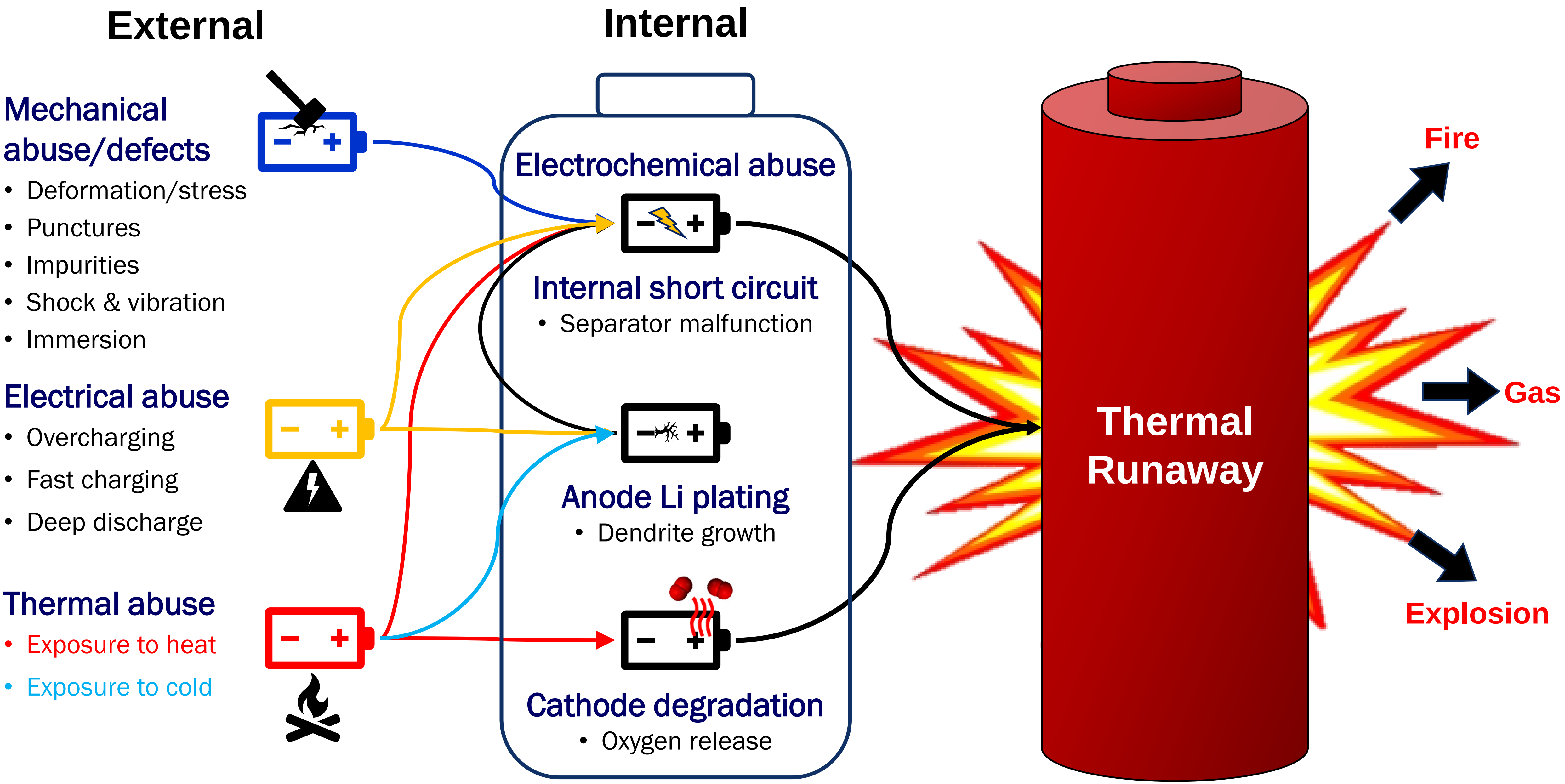
One serious concern with LIBs is thermal runaway (TR)—a chemical reaction that can lead to fires, explosions, & harmful gas emission

initiation event



- The chemical rxn generates oxygen
- Gas generation increases pressure
- Pressure buildup can cause an explosion and release of gas

Thermal runaway can be initiated by external or internal factors



The mining environment presents severe conditions for LIBs during normal operation

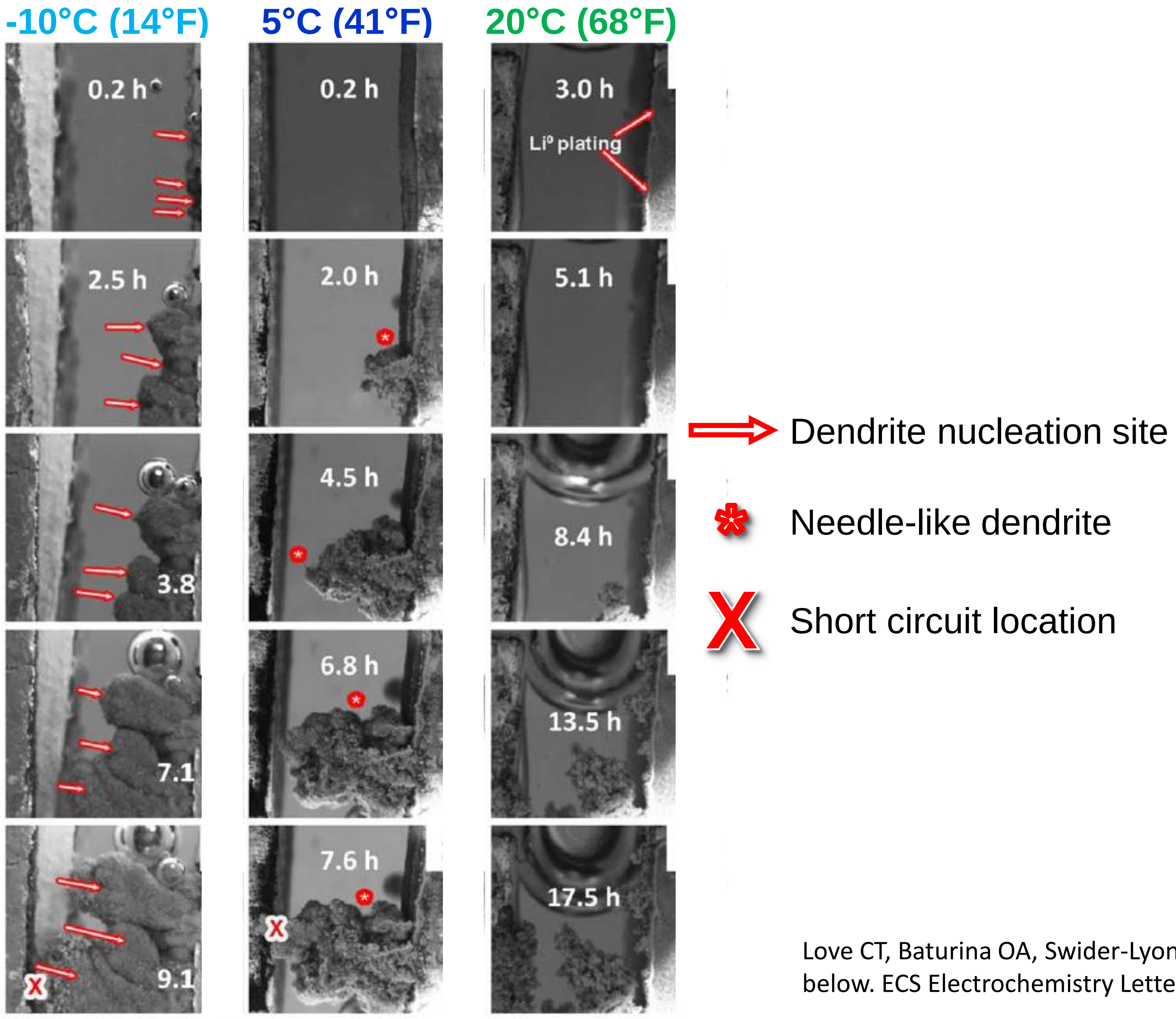
- Thermal
  - Wide temperature range
  - High humidity
  - Transition from cold to hot with high humidity
  - Fires

"normal", non-catastrophic conditions

- Mechanical
  - Mechanical shock & vibration
  - Dust
  - Dripping water
  - Roof falls, crushing
  - Inundations, flooding

"normal", non-catastrophic conditions

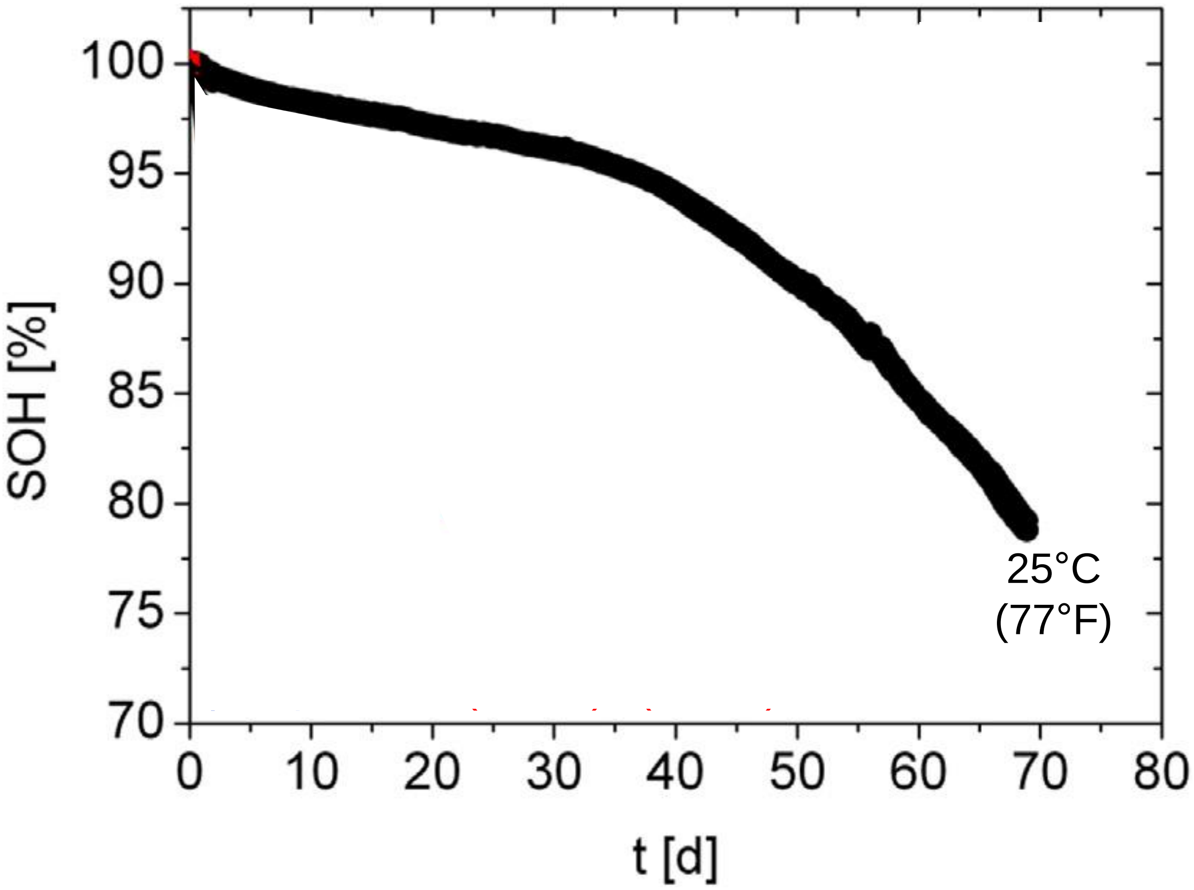
Dendrite growth occurs during charging (and regenerative braking); could pierce the separator and cause internal short circuits



- Dendrite shape depends on temperature
  - -10°C (14°F), rounded
  - 5°C (41°F), jagged and needle-like
  - 20°C (68°F), needle-like
- Dendrite shape depends on current
  - Low current, rounded
  - High current, needle-like
- Dendrite growth rate is higher at lower temperatures

Love CT, Baturina OA, Swider-Lyons KE [2015]. Observation of lithium dendrites at ambient temperature and below. ECS Electrochemistry Letters, 4 (2) A24-A27. https://iopscience.iop.org/article/10.1149/2.0041502eel

LIB ageing mechanisms and end of life depend on temperature



- SOH vs temperature studied by cycling 18650 cells at various temperatures
  - Discharge/charge rate of 1 C
  - Constant T from -20°C (-4°F) to 70°C (158°F)
- End of life at 80% SOH
- Longest life at 25°C (°F)

Waldmann T, Wilka M, Kasper M, Fleischhammer M, and Wohlfahrt-Mehrens M [2014]. Temperature dependent ageing mechanisms in lithium-ion batteries - a post-mortem study. Journal of Power Sources 262, 129-135. https://doi.org/10.1016/j.jpowsour.2014.03.112

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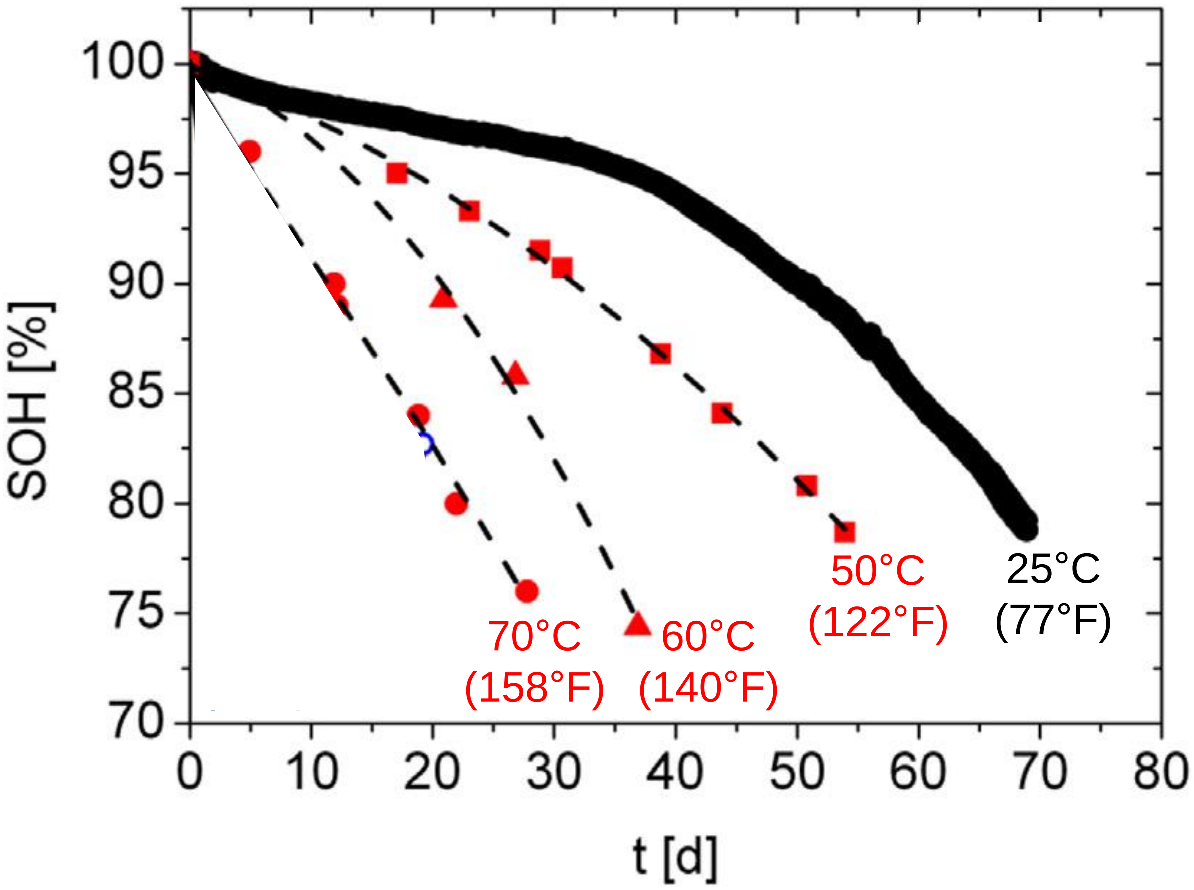

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- Life decreased above or below 25°C (77F)

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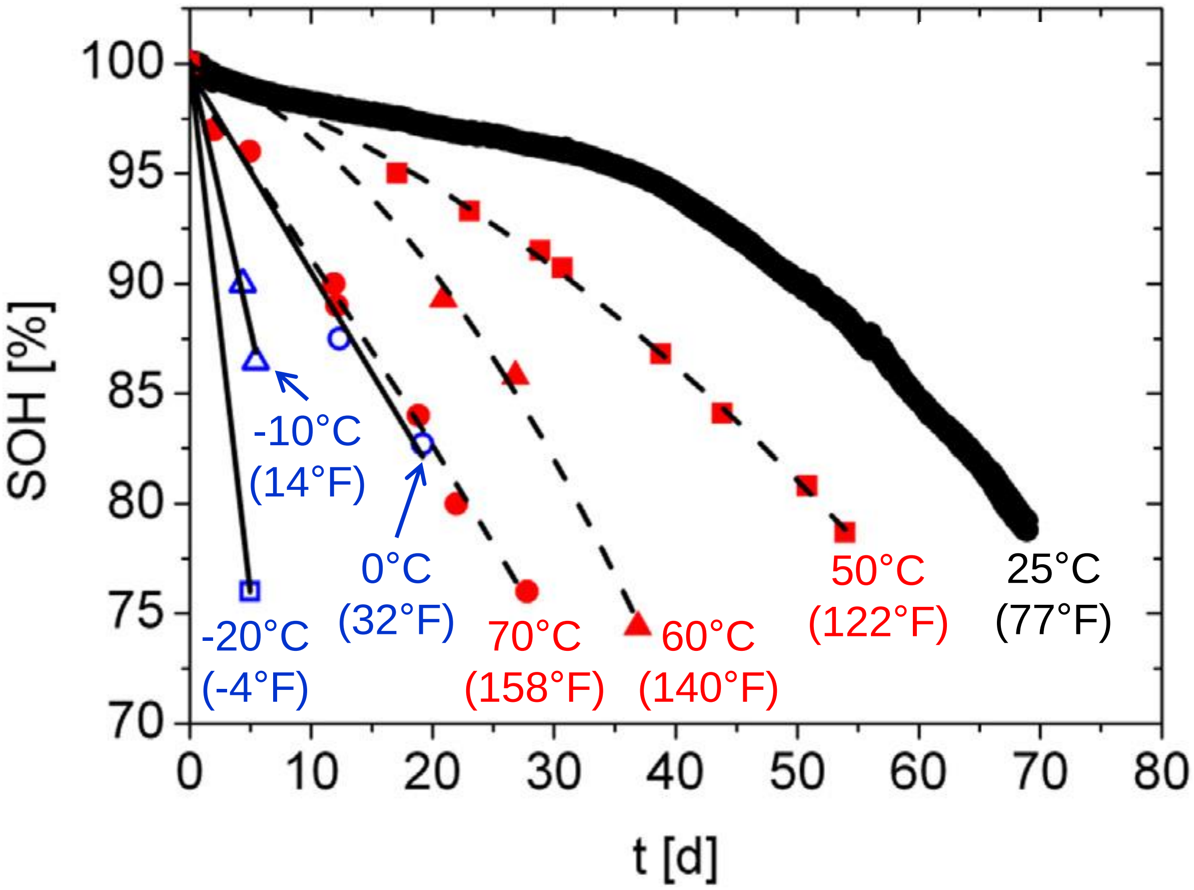

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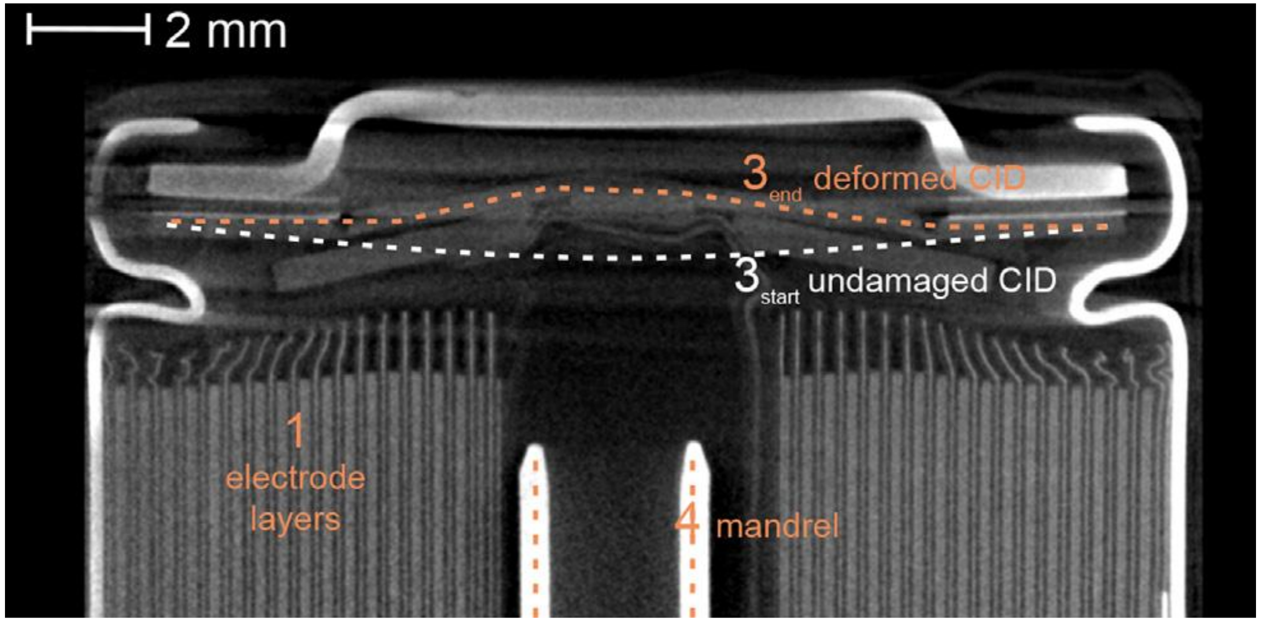
- End of life at 80% SOH
- Longest life at 25 °C (°F)
- Life decreased above or below 25 °C (77 °F)
- Shortest life for colder T
- Ageing mechanisms depend on T
  - T < 25 °C (77 °F): Li plating on anodes and loss of cyclable Li
  - T > 25 °C (77 °F): cathode degradation and solid electrolyte interphase growth

Waldmann T, Wilka M, Kasper M, Fleischhammer M, and Wohlfahrt-Mehrens M [2014]. Temperature dependent ageing mechanisms in lithium-ion batteries - a post-mortem study. Journal of Power Sources 262, 129-135. https://doi.org/10.1016/j.jpowsour.2014.03.112

Mechanical shock and vibration could cause failures and internal short circuits

- Mechanical shock along the longitudinal axis of 18650 cells caused
  - Damage to “center pins”
  - Deformation of the current interrupt device
  - Shorting between center pins and separator
- Sine sweep vibration caused
  - Loose center pins
  - Damaged separators
  - Internal short circuit



Brand MJ, Schuster SF, Bach T, Fleder E, Stelz M, Glaser S, Müller J, Sextl G, Jossen A [2015]. Effects of vibrations and shocks on lithium-ion cells. Journal of Power Sources 288 (2015) 62-69. https://doi.org/10.1016/j.jpowsour.2015.04.107.

Flooding of a LIB with mine water could lead to internal short circuiting and thermal runaway

- After Hurricane Ian hit in September 2022, golf carts caught fire on two separate occasions
  - October 16, 2022
  - November 18, 2022
- 71 of 72 golf carts destroyed
- Conductive saltwater entering battery case caused shorting

Bickel MH [2022]. Golf carts burst into flames at Sanibel's The Dunes Golf & Tennis Club. Fort Myers News-Press. Oct. 17, 2022. https://www.news-press.com/story/weather/hurricane/2022/10/17/hurricane-ian-sanibel-florida-golf-courses-golf-carts-catch-fire/10521170002/

Bickel MH [2022]. Golf carts on Sanibel Island engulfed in flames for second time since Hurricane Ian. Fort Myers News-Press. Nov. 19, 2022. https://www.news-press.com/story/news/local/sanibel/2022/11/19/sanibel-golf-carts-fire-dunes-2nd-time-ian-lithium-batteries/10731316002/

Numerous standards exist that are related to environmental testing of LIBs and/or equipment that uses LIBs

- Standards consider various environmental hazards
  - Temperature
  - Thermal shock
  - Humidity
  - Immersion
  - Drop
  - Mechanical shock
  - Vibration
    - Sine sweep or random

Applicable ANSI, CSA, IEC, and ISO Standards

Standard	Title/Description
ANSI/NEMA C18	Safety Standards for primary, secondary and lithium Batteries
CSA M424.4-2022	Self-Propelled, Electrically Driven, Non-Rail-Bound Mobile Machines For Use In Non-Gassy Underground Mines
IEC 60068	Basic climatic and mechanical robustness testing procedure for component
IEC 62133-2:2017	Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications - Part 2: Li systems
IEC 62619	Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries, for use in industrial applications
IEC 62660-2	Secondary Lithium-ion Cells for the Propulsion of Electrical Road Vehicles Reliability and Abuse Testing
IEC TR 62131-1	Environmental conditions - Vibration and shock of electrotechnical equipment - Part 1: Process for validation of dynamic data
ISO 6469-1	Electrically propelled road vehicles — Safety specifications — Part 1: Rechargeable energy storage system (RESS)
ISO 16750	Road vehicles — Environmental conditions and testing for electrical and electronic equipment

Applicable SAE, UL, and UN Standards

Standard	Title/Description
SAE J2380	Vibration Testing of Electric Vehicle Batteries
SAE J2464	Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing
SAE J2929	Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems Utilizing Lithium-based Rechargeable Cells
SAE J3060	Automotive and Heavy Duty Storage Battery Vibration
UL 1642	Standards for Lithium Batteries
UL 1973	ANSI/CAN/UL Batteries for Use in Stationary and Motive Auxiliary Power Applications
UL 2054	Standard for Household and Commercial Batteries
UL 2271	ANSI/CAN/UL/ULC Standard for Batteries for Use In Light Electric Vehicle (LEV) Applications
UL 2580	Batteries for Use In Electric Vehicles
UL 9540	Energy Storage System (ESS) Requirements
UL 60086-4	Standard For Safety For Primary Batteries - Part 4: Safety Of Lithium Batteries
UN 38.3:2015	Recommendations on the Transport of Dangerous Goods - Manual of Tests and Criteria - Sect. 38.3 Li Batteries
UN ECE Reg.100	Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric powertrain

Applicable MIL standards and other guidelines/recommendations

Standard/guide	Title/Description
BATSO 01[1]	Manual for Evaluation of Energy Systems for Light Electric Vehicle (LEV) - Secondary Lithium Batteries
GMG07-EM-2022	Recommended Practices for Battery Electric Vehicles in Underground Mining
MIL-STD-810G	Environmental Engineering Considerations and Laboratory Tests
SMC-S-016[2]	Test Requirements for Launch, Upper-Stage, and Space Vehicles
SAND99-0497	Sandia National Laboratories Electrochemical Storage System Abuse Test Procedure Manual
SAND2005-3123	FreedomCAR Electrical Energy Storage System Abuse Test Manual for Electric and Hybrid Electric Vehicle Applications
USABC 1996[3]	Electric Vehicle Battery Test Procedures Manual

1 - Battery Safety Organization is a cooperation between ExtraEnergy EV, Industrial Technology Research Institute, TÜV Rheinland Taiwan Ltd., and UL

2 - United States Air Force Space and Missile Systems Center

3 - Developed by USABC and DOE National Laboratories personnel based on the experience and methods developed at Argonne National Laboratory (ANL), Idaho National Engineering Laboratory (INEL), and Sandia National Laboratories (SNL)

See "Survey on standards for batteries and system integration with them" at https://batterystandards.info/standard

Vibration tests vary widely across standards and are not typically based on actual operating data from real-world machine use

Example of Sine Sweep Test

IEC 62133-2:2017
Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications – Part 2: Lithium systems

Logarithmic frequency sweep (same number of cycles for each frequency); 15 min per cycle per axis (3 hr total)

F_L (Hz)	F_u (Hz)	Amplitude	Axes	#Cycles
7	17.62	1 g (5.1 mm - 0.8 mm)	X, Y, Z	12 each axis
17.62	49.84	0.8 mm (1 g - 8 g)		
49.84	200	8 g (0.8 mm - 0.05 mm)		

- One frequency at any instant of time
- Excites structural resonances when frequencies match
- Not representative of real-world vibration

Example of Random Vibration Test

IEC 62660-2: 2018
Secondary lithium-ion cells for the propulsion of electric road vehicles – Part 2: Reliability and abuse testing

Rnd vibr at RMS accel of 27.8 m/s^2 (2.83 g); 8 hr per axis (24 hr total)

F (Hz)	PSD ($(m/s^2)^2/Hz$)	PSD (g^2/Hz)	Axes
10	20	0.21	X, Y, Z
55	6.5	0.068	
180	0.25	0.0026	
300	0.25	0.0026	
360	0.14	0.0015	
1000	0.14	0.0015	
2000	0.14	0.0015	

- Numerous frequencies present at any instant of time
- More representative of real-world vibration

Most standards do not go low enough in frequency to capture low frequency vehicle suspension vibration modes!

Mechanical shock tests from standards are often much higher and much shorter duration than shocks during equipment operation

IEC 62133-2:2017
Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications – Part 2: Lithium systems

1/2-sine shock			
Pk Accel.	**Duration**	**Axes**	**# Shocks**
150 g	6 ms	X, Y, Z	3 per positive & negative direction per axis (18 total)

IEC 62660-2: 2018
Secondary lithium-ion cells for the propulsion of electric road vehicles – Part 2: Reliability and abuse testing

1/2-sine shock			
Pk Accel.	**Duration**	**Axes**	**# Shocks**
51 g	6 ms	Axis of max acceleration on vehicle or all six if max direction is unknown	10 per test direction

- Directions specified for shock testing varies across standards, some specify only vertical direction shocks
- In mining, lower level shocks may occur frequently due to poor travel way conditions and bumping into the rib or other equipment

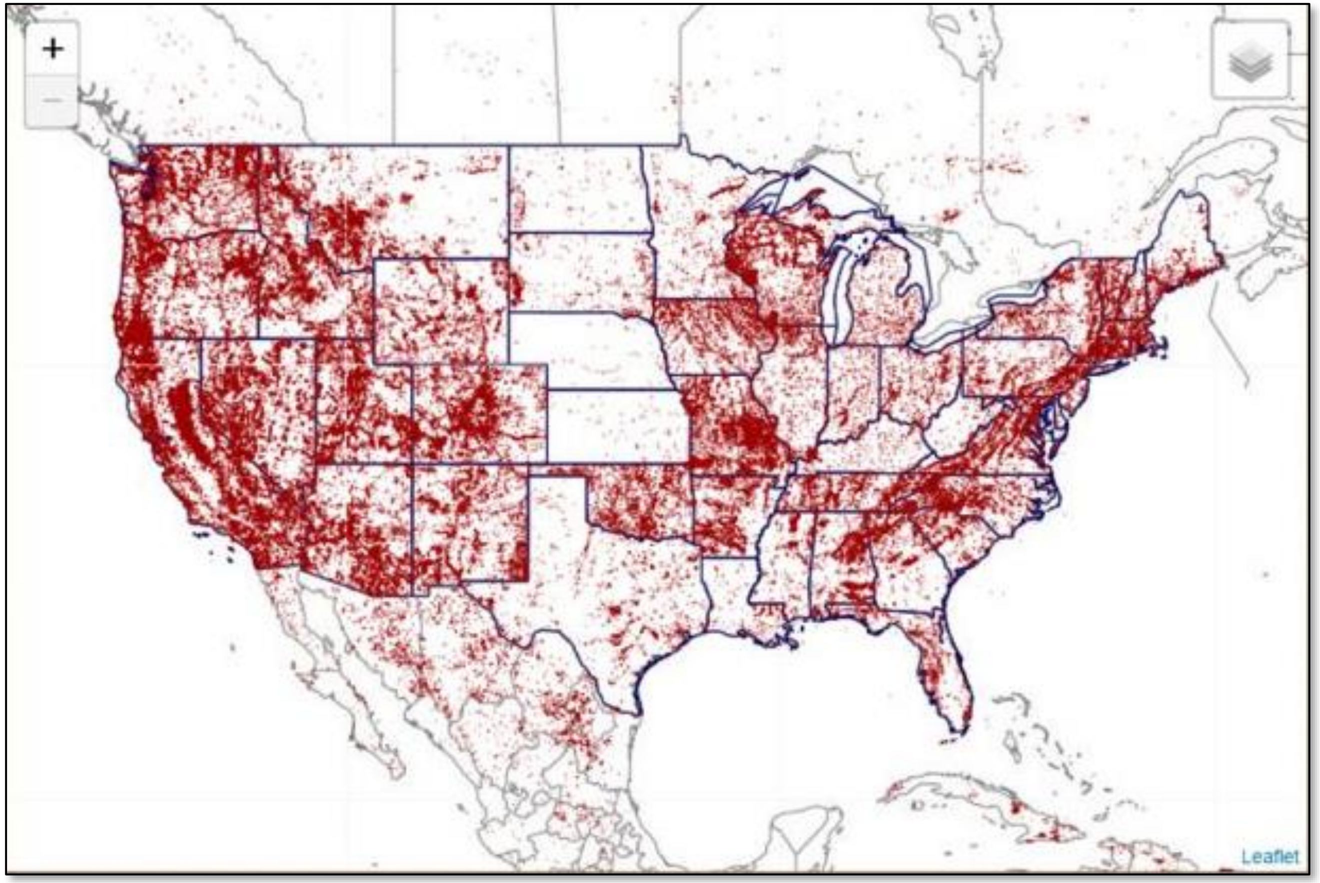
NIOSH is starting a new project: *Environmental Susceptibility of Mine Utility Vehicle (MUV) and Rubber-Tired Mantrip (RTM) LIBs*

The MUV/RTM LIB project consists of several tasks with the goal of preventing adverse LIB events caused by environmental conditions

1. Collect operating data to understand the environmental conditions
2. Develop a rigorous test procedure for LIBs used on MUVs and RTMs
3. Conduct laboratory testing on MUV/RTM LIB cells, modules, and packs
4. Design LIB installation methods to protect them from environmental effects

Field data collection is an essential element of understanding the complexities of the mine environment

- Goal is to collect data near MUV and RTM battery compartments at underground and surface mines in all commodities



Interactive map of mineral resources and mines across the United States.
https://www.americangeosciences.org/critical-issues/maps/mineral-resources-data-system-map-viewer

Our goal is to determine the environmental conditions for MUVs & RTMs with minimal interruption to cooperating mines

- Multiple shifts of data at each mine
- Measure shock, vibration, T, %RH, and speed during ordinary vehicle use
- Determine vehicle dynamic behavior using accelerometers at vehicle corners
- Process data to develop a database of max, min, average, range, etc.
- Use vibration data to determine vibration spectrum for durability testing

environmental data recorder

T/RH data logger

speedometer

data logger

rugged dacq w/ accelerometers

Field shock and vibration data will be used to develop an internal torture track in the NIOSH Experimental Mine

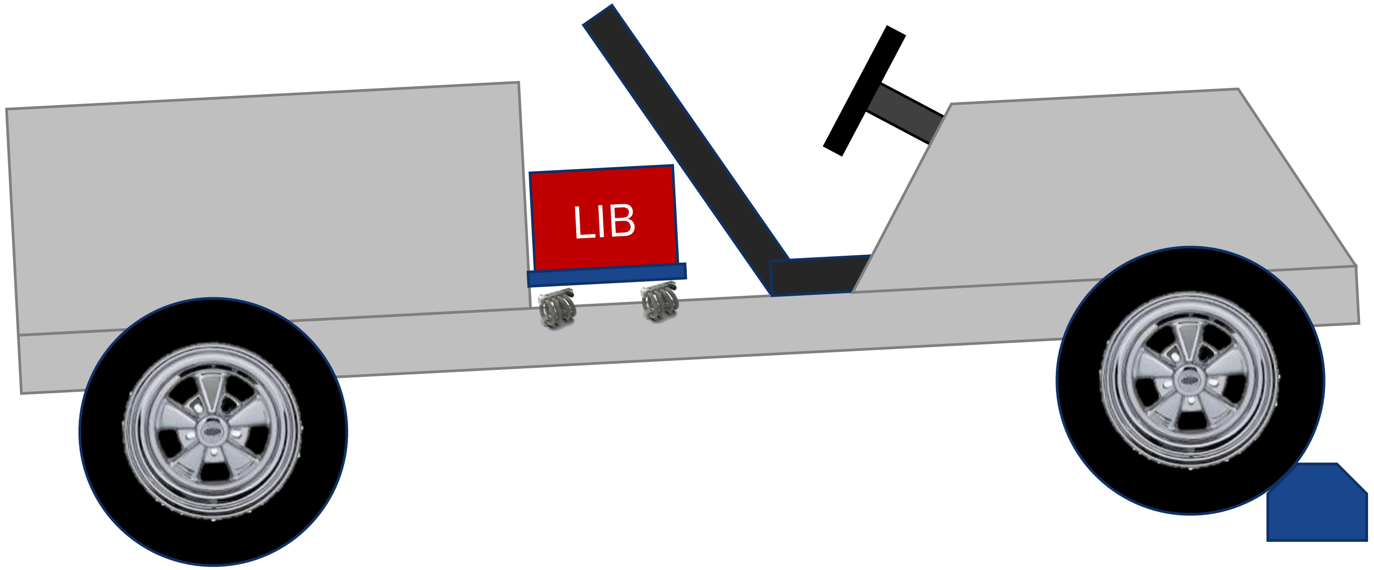
- Construct torture track using 2x4s, speed bumps, parking curbs, pea-sized gravel, 2B limestone, etc.
- Instrument NIOSH-owned MUVs
- Replicate field measurements
- Collect additional data with varying speed, terrain, mild collisions, etc.
- Prove out LIB installation methods

The field and in-house data will be used to develop a rigorous test procedure to evaluate reliability of LIBs

- Comprehensive tests including drop tests, mechanical shock and vibration at varying temperatures, and immersion in mine water are warranted
- Field shock/vibration data used for accelerated life testing
- We expect to have multiple parts to the test (example only)
  1. Drop test to represent pre-installation real-life mishandling
  2. Mechanical shock and vibration tests across ranges of temperature (-18°C to 38°C, 0°F to 100°F) and SOC (20% to 100%) at > 80 %RH
  3. Battery immersion test
     - Immerse battery in “mine water”, wait for a prescribed time after air bubbles stop
     - Remove battery from water and monitor (> 24 hours)
     - Go to #2

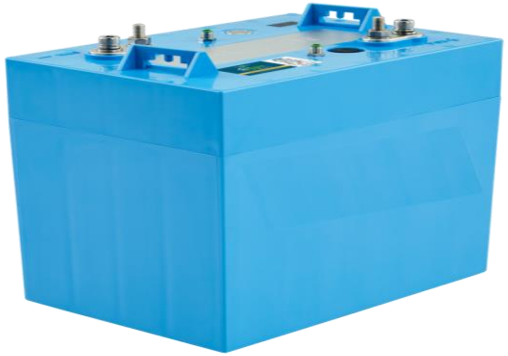
To reduce transmitted mechanical shock and vibration, we will design and test battery isolation systems

- Test MUVs/RTMs to determine suspension parameters
- Use simulation models to determine necessary vibration isolators
- Fabricate, install, and test to prove the isolation system achieves its objective
    - Instrumented NIOSH-owned MUV
    - Evaluate battery suspension
        - Calibrated test track at NIOSH
        - Field sites



The project will have multiple benefits to MUV and mantrip manufacturers, battery suppliers, and mines

- Knowledge of the operating conditions for MUVs/RTMs
- Improved LIB safety and durability
- Reduced risk of LIB thermal runaway



Questions?

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