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SAFETY EVALUATION OF EMERGING CHEMISTRIES

A Multi-Scale Approach to Solid-State and Na-ion

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Sandia National Laboratories

2026 Safety and Reliability Forum, Albuquerque, NM

U.S. DEPARTMENT of ENERGY

NNSA National Nuclear Security Administration

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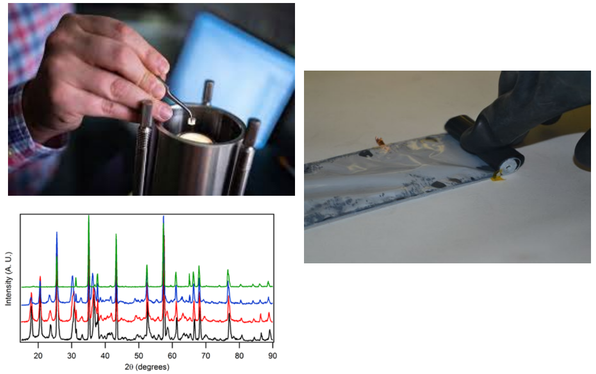
SANDIA ADDRESSES ALL ASPECTS OF BATTERY SAFETY AND RELIABILITY

Materials R&D

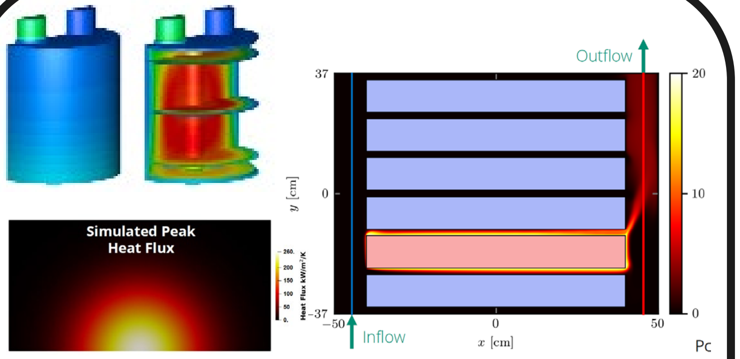


Thermal stability
Gas evolution
Degradation
Mfg. Defect Evaluation

Cell and Module Testing

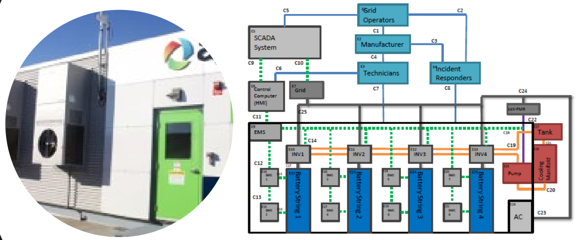
Aging
Diagnostics
Abuse testing
Thermal propagation

Simulations and Modeling



Multi-scale models
Fire dynamic simulations
Predictive simulations
Machine Learning

System Level Design and Analysis



Hazard analysis methods
Predictive maintenance
Power electronics

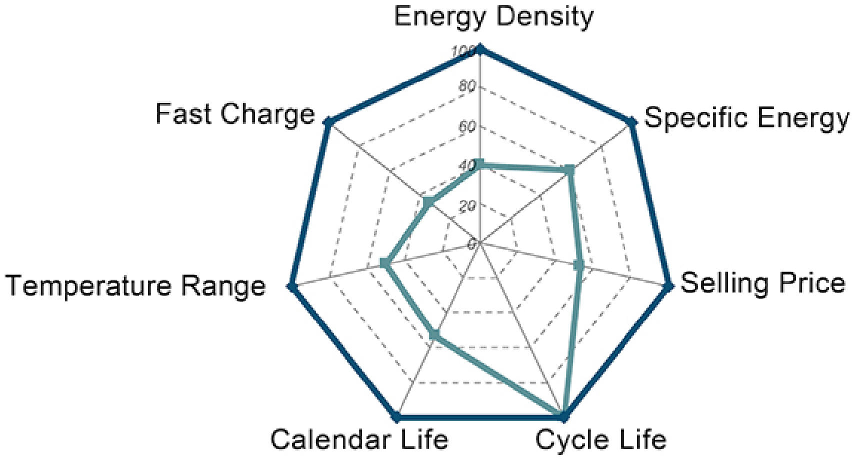
Outreach, Codes, and Standards

ES safety working group
IEEE BMS standard
EPRI ESS data guidelines

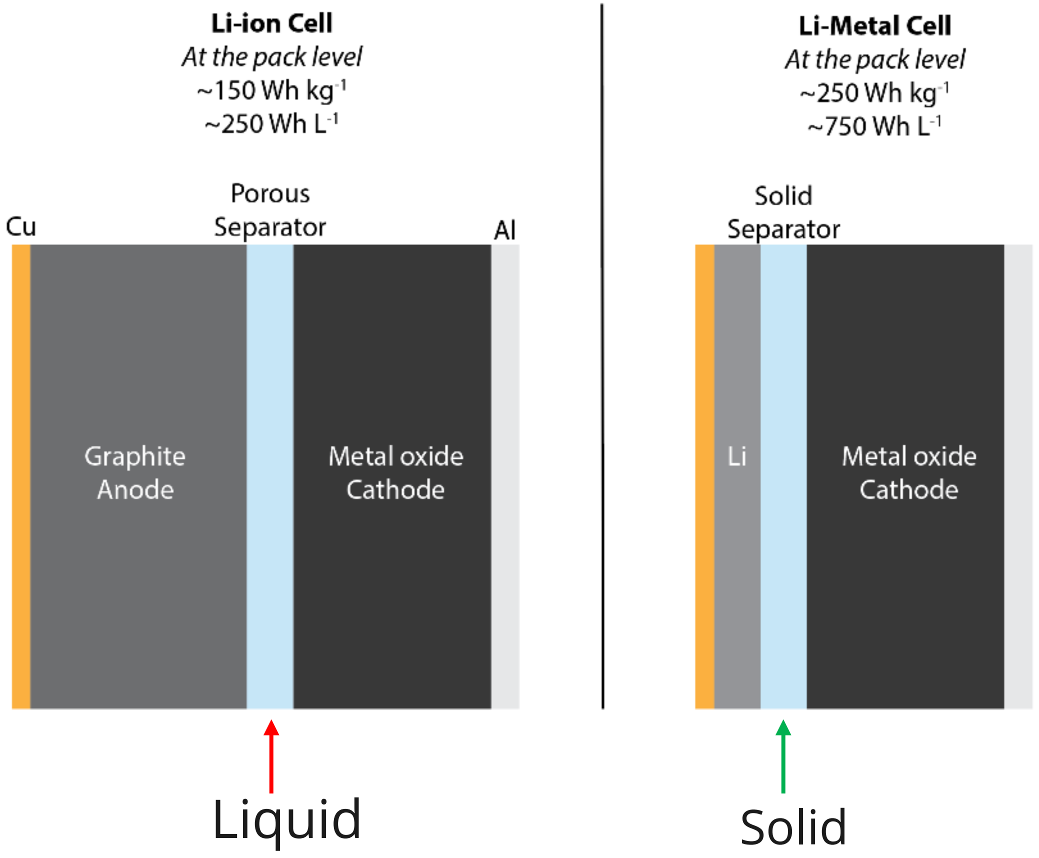
NEW BATTERY TECHNOLOGIES NEED THREE PRIMARY METRICS

1. High energy or power density
2. Safety
3. Cost effectiveness ($/kWh)

Modern Lithium Ion:



https://www.jcesr.org/research/



Albertus, P., et al. (2018). *Nature Energy* **3**(1), 16-21.

THERMAL EVENTS DRAW MEDIA ATTENTION…

Bloomberg

Hyperdrive

Explosions Threatening Lithium-Ion's Edge in a Battery Race

By Brian Eckhouse and Mark Chediak
April 23, 2019, 4:58 PM MDT *Updated on April 24, 2019, 8:24 AM MDT*

- Battery exploded at plant in Arizona; two others were shut
- Arizona utility regulator calls for 'thorough investigation'

LISTEN TO ARTICLE
▶ 4:52

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Another lithium-ion battery has exploded, this time at an energy-storage complex in the U.S.

At least 21 fires had already occurred at battery projects in South Korea, according to BloombergNEF. But this latest one, erupting on Friday at a facility owned by a Pinnacle West Capital Corp. utility in Surprise, Arizona, marked the first time it has happened in America since batteries took off globally.

https://www.bloomberg.com/news/articles/2019-04-23/explosions-are-threatening-lithium-ion-s-edge-in-a-battery-race

Greentech Media

APS and Fluence Investigating Explosion at Arizona Energy Storage Facility

The stakes are high for the energy storage sector after an explosion with an unknown cause left several firefighters injured.

KARL-ERIK STROMSTA | APRIL 22, 2019

Earlier this year APS announced plans to build 850 megawatts of battery storage by 2025.

Fluence has dispatched a team of experts to help utility Arizona Public Service determine what caused an explosion at one of its grid-scale battery facilities. The explosion on Friday reportedly left four firefighters injured, including three who were sent to a burn center.

Firefighters responded to a call on April 19 after smoke was seen rising from APS' McMicken Energy Storage facility, one of two identical 2-megawatt/2-megawatt-hour grid-scale batteries the utility installed in 2017 in Phoenix's growing West Valley region.

According to local press reports, the firefighters were inspecting the facility's lithium-ion batteries when they were hit with an explosion. Several of the firefighters received chemical burns, the local fire department told the *Arizona Republic*.

https://www.greentechmedia.com/articles/read/aps-and-fluence-investigating-explosion-at-arizona-energy-storage-facility

Korea Times

Frequent fire raising concerns over safety of solar energy

A fire engulfs an energy storage system at a cement plant in Jecheon, North Chungcheong Province, Monday. / Courtesy of North Chungcheong Province Fire Service Headquarters

By Nam Hyun-woo

A series of fires in energy storage systems (ESSs) has been raising safety concerns, according to industry analysts, Tuesday.

With ESSs essential for optimizing energy efficiency, further accidents may compromise the feasibility of renewable power and hamper the government's bid to expand the use of cleaner energies.

According to the Ministry of Trade, Industry and Energy, it recommended individuals, companies and other organizations to stop using 584 uninspected ESSs across the country.

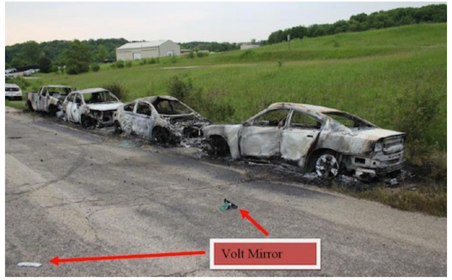
https://www.koreatimes.co.kr/www/tech/2024/07/129_260560.html

… BUT, BATTERY FIRES ARE NOT NEW

2006
Sony/Dell Laptops

2010
UPS Cargo Plane

2011
DOT/NHTSA Facility

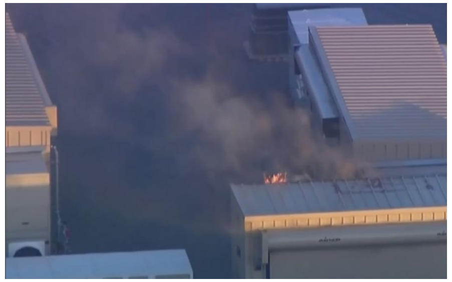


2013
Boeing Dreamliner

2019
ESS Arizona

2022
Electric Vehicle (Tesla)

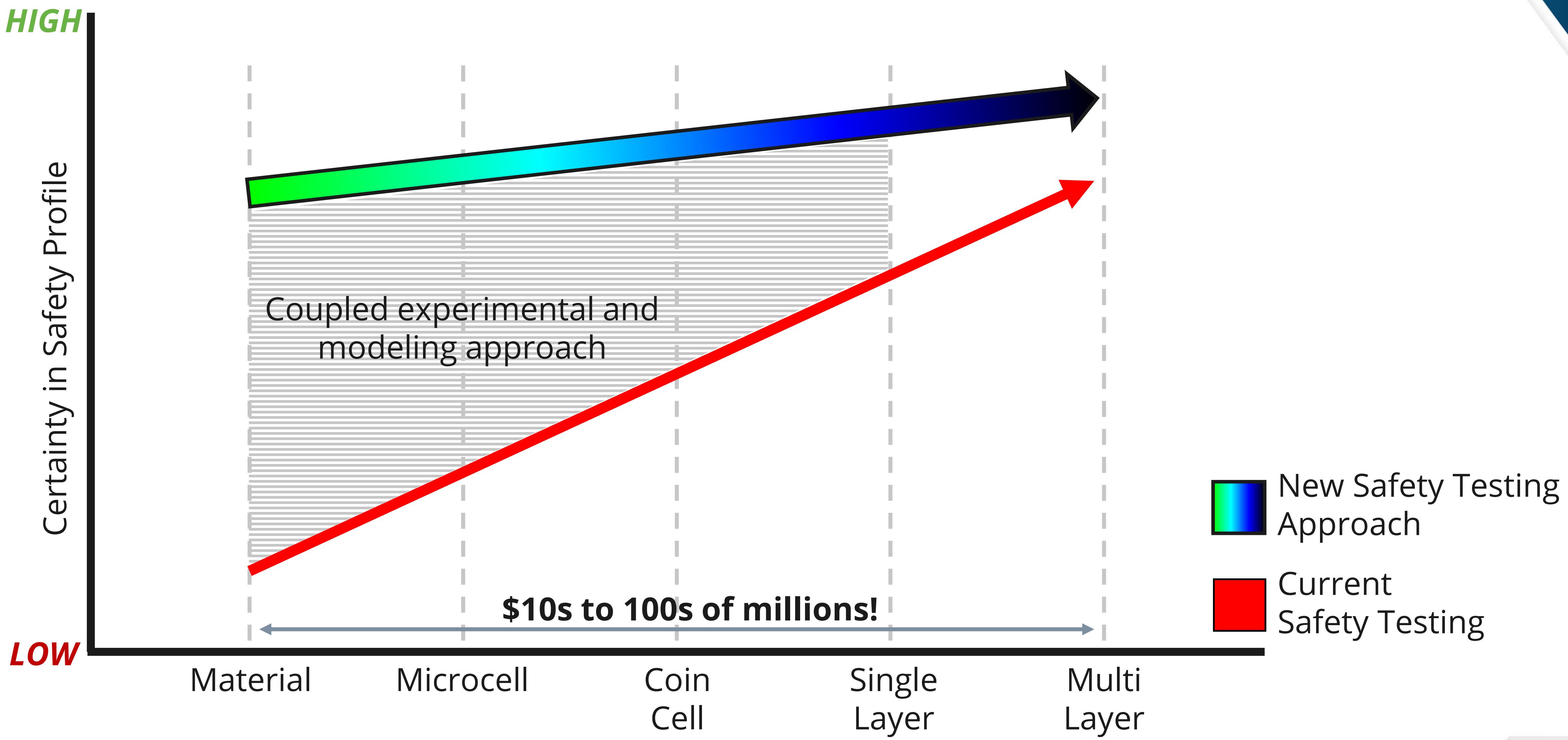
2023
Battery Storage Facility



2024
Manufacturing Facility

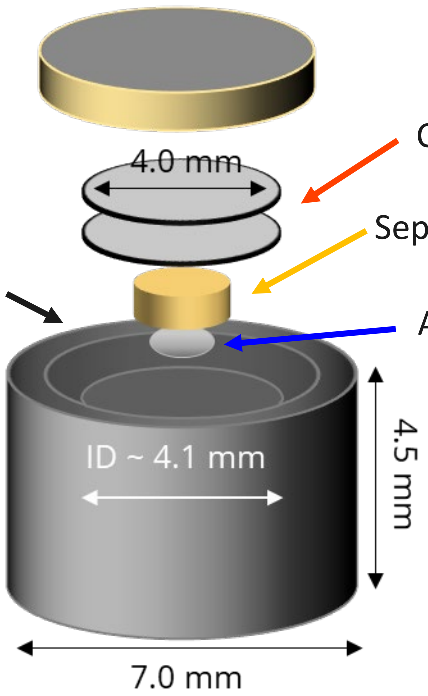
Each incident has provided valuable lessons, leading to advancements in battery technology, improved safety standards, and better risk management practices.

PREDICTIVE SAFETY ASSESSMENT IS CRITICAL FOR NEW MATERIALS



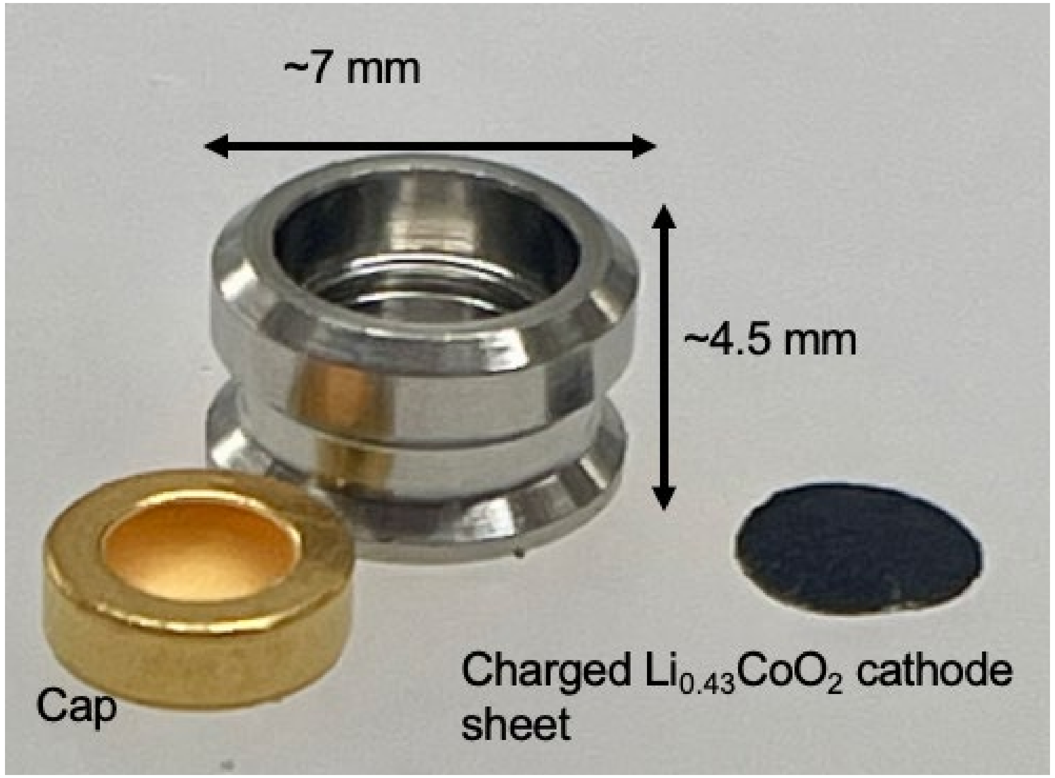
Bates, A.M. et al. (2024) *ECS Interfaces. 33(69).* https://doi.org/10.1149/2.F10243IF

DSC "MICROCELLS" OFFER PREDICTIVE SAFETY DATA



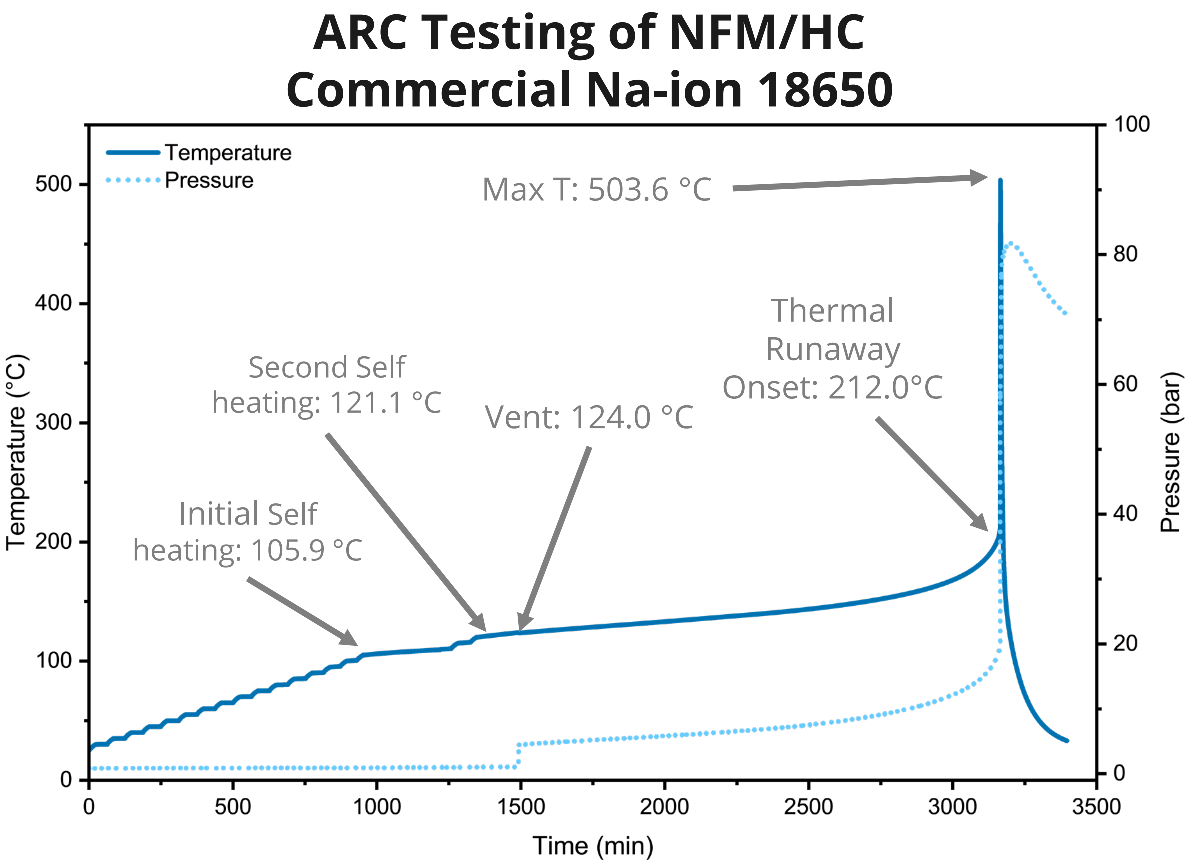
Material ratios are carefully balanced

Only ~10mg of material required



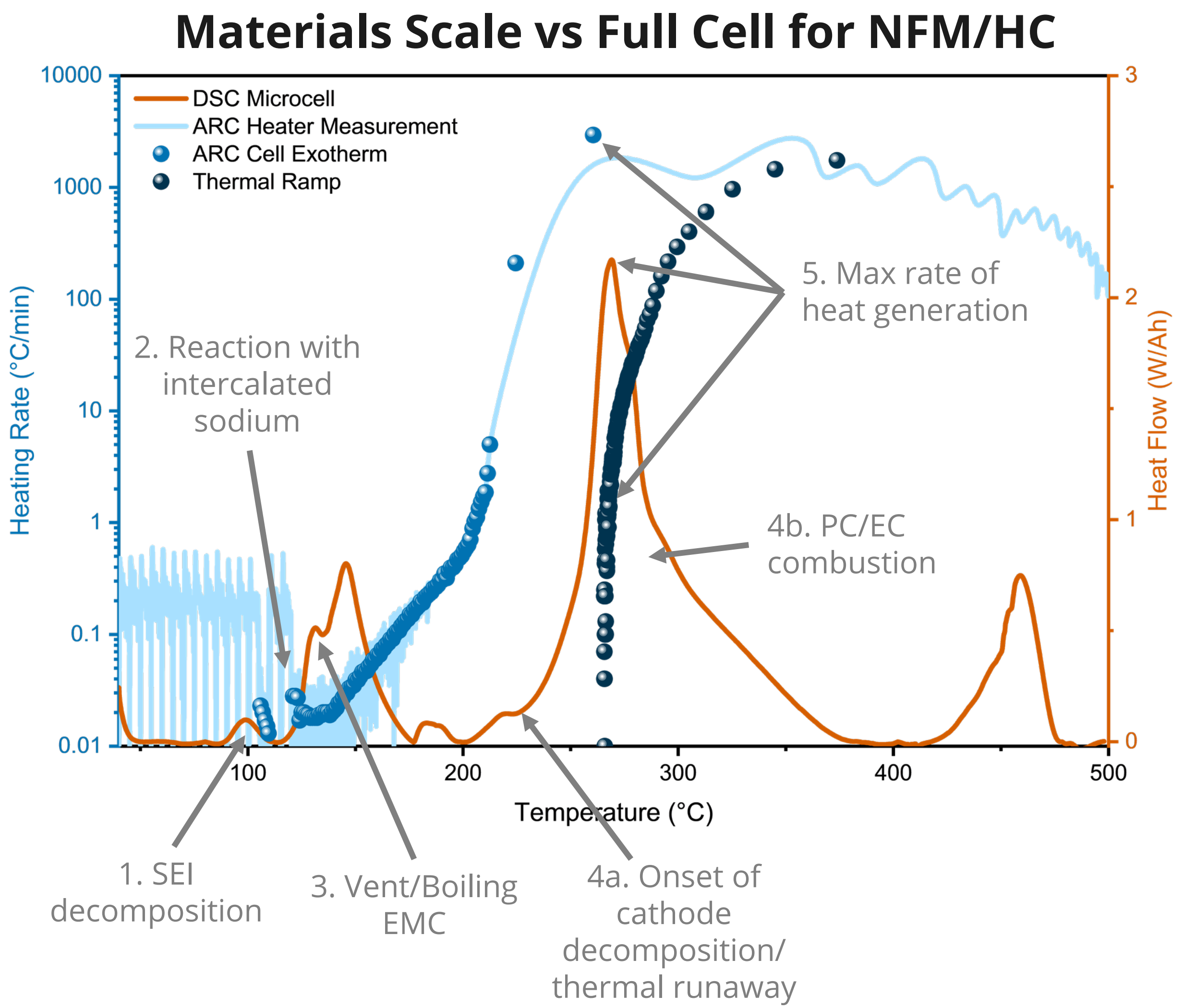
Johnson, N. et al. (2023) *ACS Applied Materials and Interfaces* ***15****(49)*, 57134-57143

ARC TESTING OF NFM SODIUM-ION CELLS



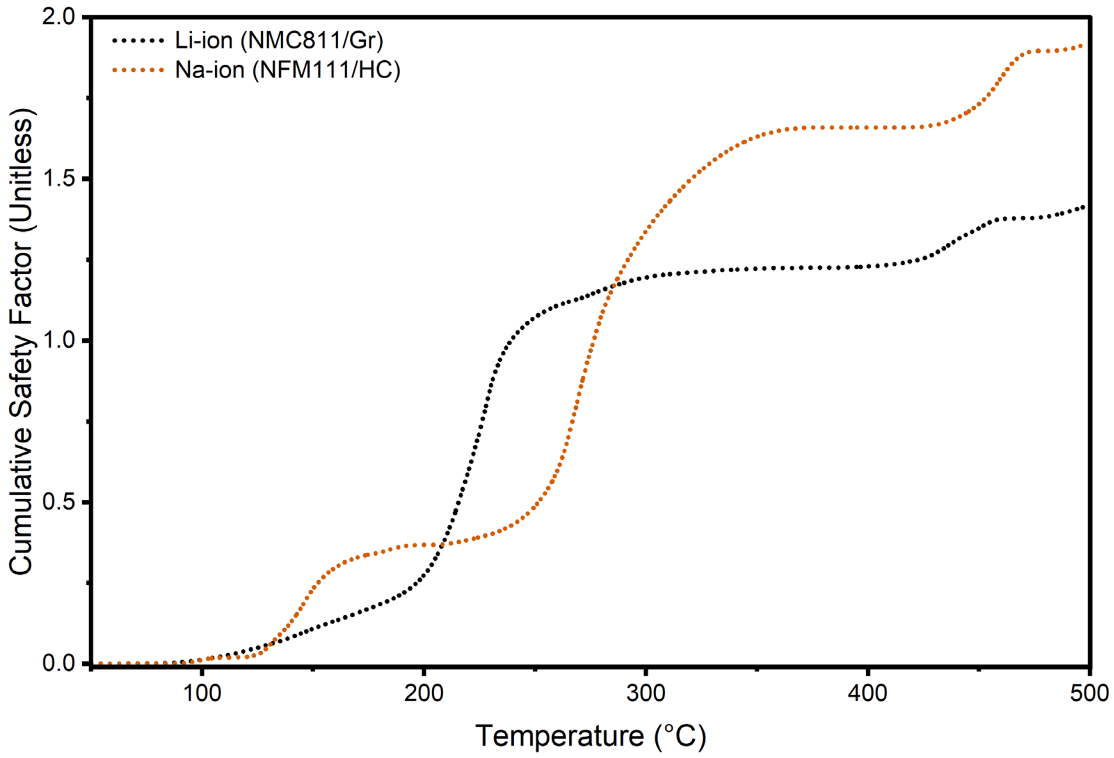
- ARC demonstrates behavior of cell under adiabatic conditions
  - Does not factor in impacts of heat dissipation
- Provides information on heating rates, temperatures, and gas generation particularly during the onset of thermal runaway
  - Loses accuracy at higher temperatures
  - Extrapolation of a mechanistic interpretation is challenging without supplementary data

MECHANISTIC INTERPRETATION OF THERMAL ABUSE TESTING USING DSC MICROCELLS



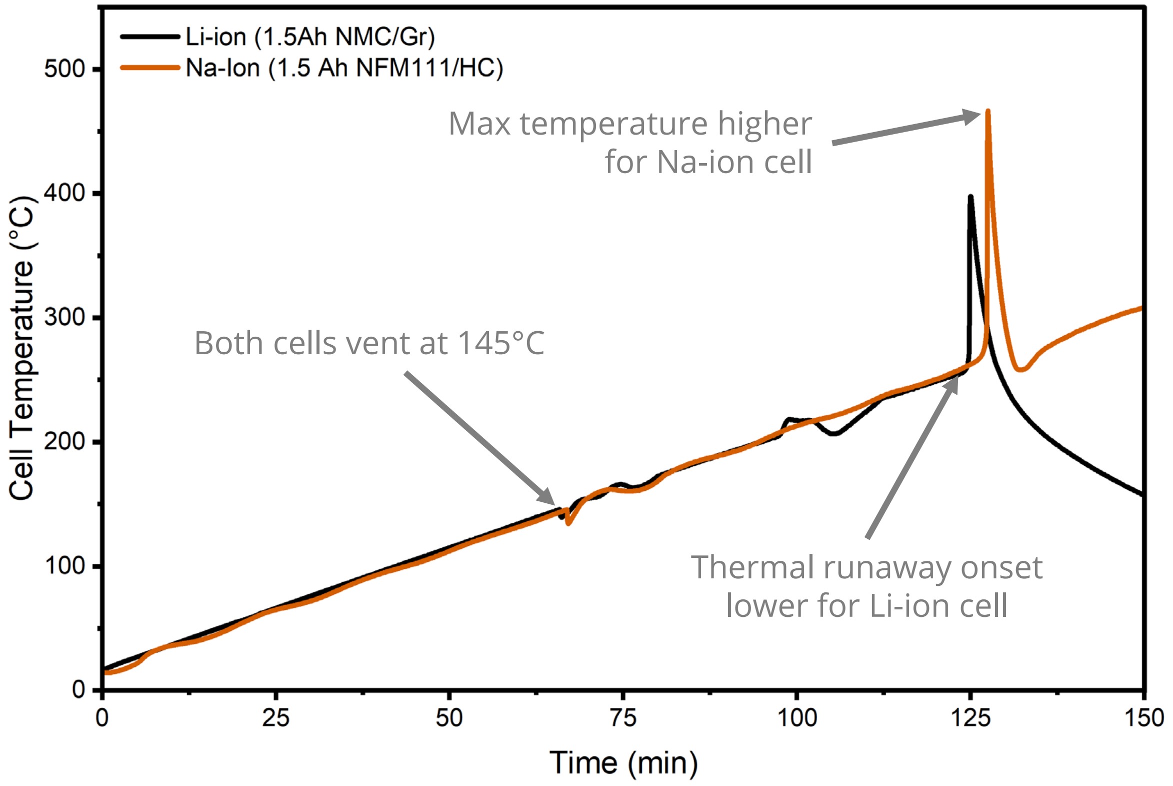
- ARC and DSC show close agreement
  1. *Initial self-heating from SEI decomposition and reaction with DMC*
  2. *Second self-heating from reaction of intercalated sodium with EMC*
  3. *EMC boiling matches ARC venting temperature*
  4. *Thermal runaway onset caused by NFM decomposition and PC/EC combustion*
  5. *Max heating rate matches maximum heat flow*
- Thermal ramp enters thermal runaway at maximum heat flow
  - Heat accumulation outweighs heat dissipation

LI-ION AND NA-ION HAVE SIMILAR THERMOCHEMICAL PROFILES



- NFM and NMC chemistries have similar self-heating onset temperatures of ~80°C
- NMC has continuous heat generation while NFM briefly stops
- Onset to thermal runaway is lower for NMC
- Similar rates of heat generation
- Both show heat generation >400°C after the separator pyrolyzes

THERMAL RAMP COMPARISON

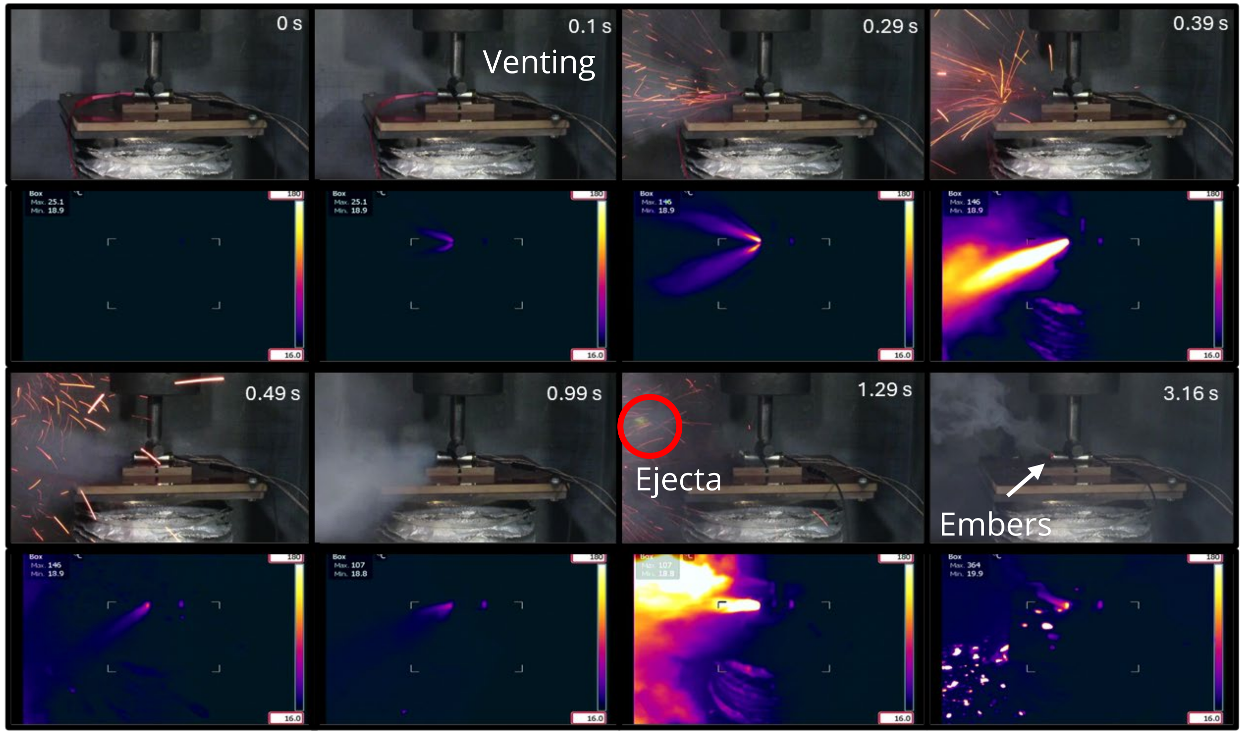


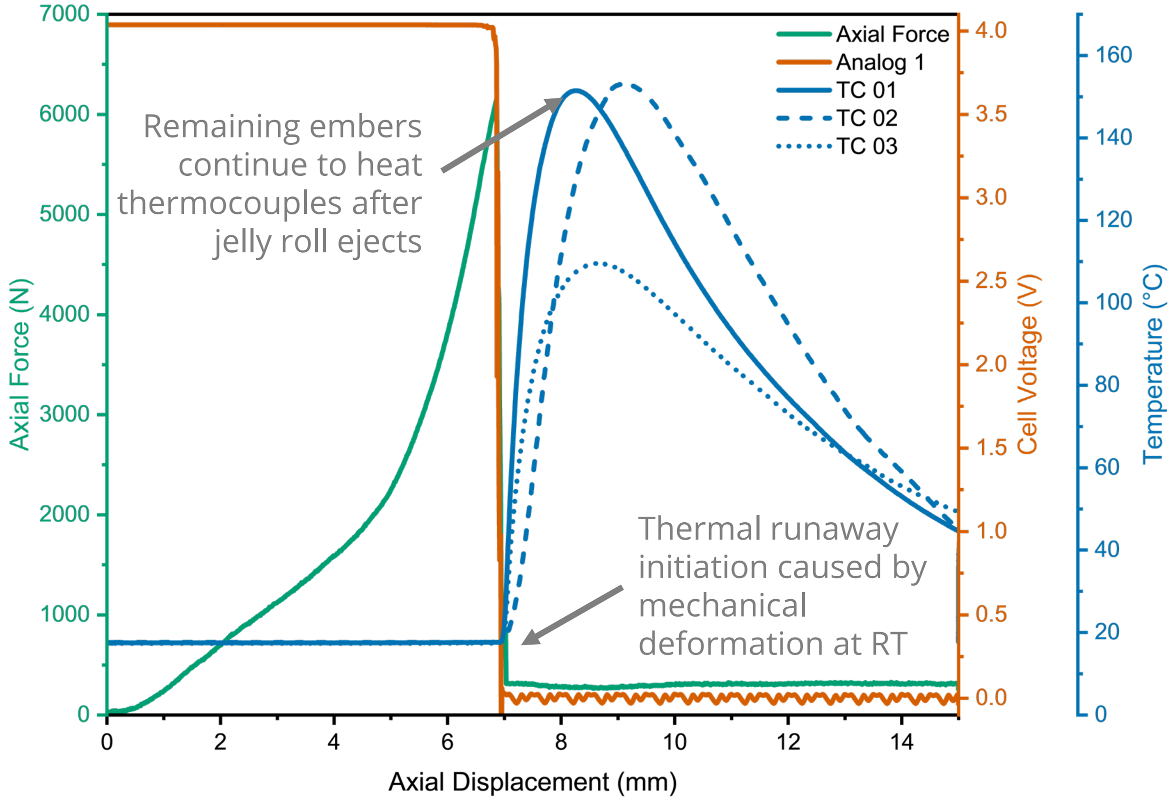
- Venting temperature is the same for both chemistries
- NMC goes into thermal runaway earlier
- NFM has higher temperature rise
- Consistent with DSC prediction

WHAT ABOUT NON-THERMAL INITIATION METHODS?

- DSC, ARC, and Thermal Ramp all have thermal initiation methods
- More difficult to translate to mechanical and electrical initiations

Crush Test of NFM/HC Commercial 18650

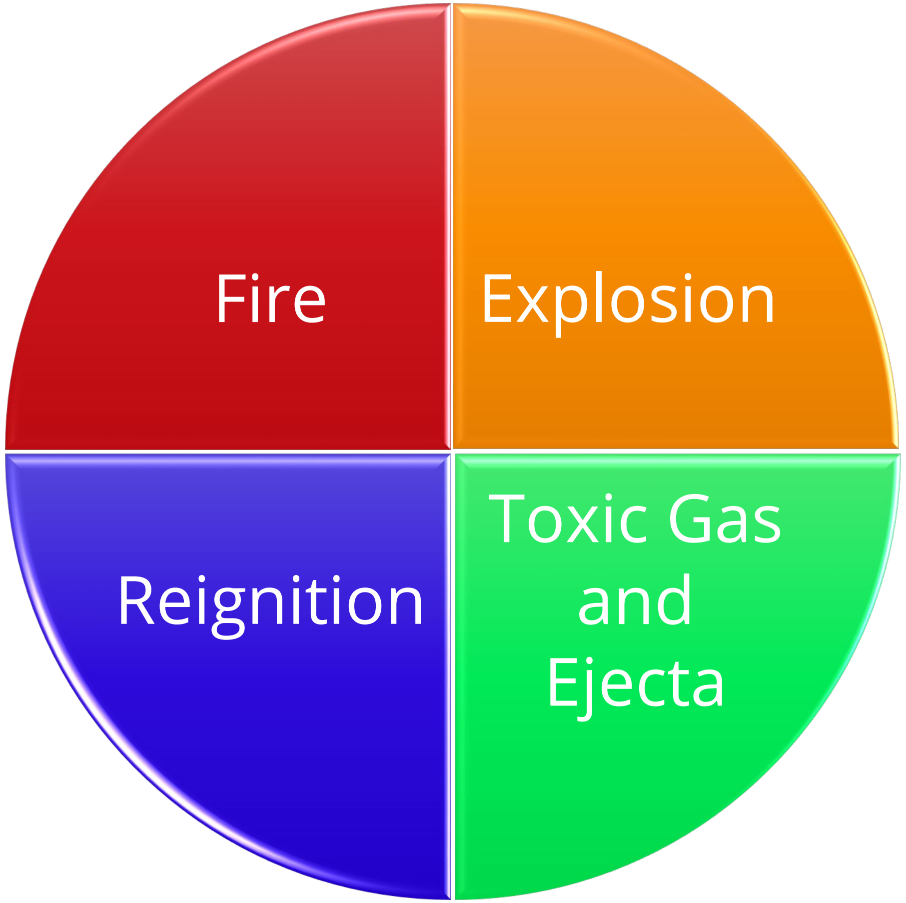


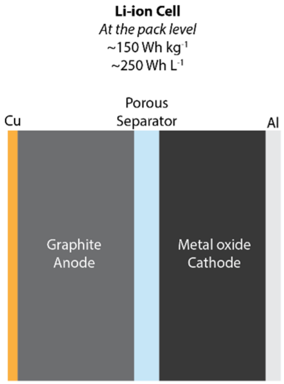


SUMMARY OF NMC AND NFM ABUSE TESTING RESULTS

Destructive method	Cell Type	Max Temperature (°C)	Thermal Runaway Onset	Observable response
Nail Penetration	Na-ion	216.5	1.91 mm	Vent, smoke, sparks, significant pressure release
	Li-ion	98.1	1.88 mm	No observable effect
Crush	Na-ion	167.9	6.67 mm	Vent, smoke, sparks, lid pop
	Li-ion	296.3	9.71 mm	Vent, smoke, sparks, lid pop
External Short Circuit	Na-ion	132.8	N/A	Vent, smoke, electrolyte leak, swelling
	Li-ion	140.8	N/A	Swelling
Thermal Ramp	Na-ion	443.1	271.1 °C	Vent, Electrolyte leak
	Li-ion	398.1	263.7°C	Vent, Electrolyte leak

A COMPREHENSIVE SAFETY PROFILE



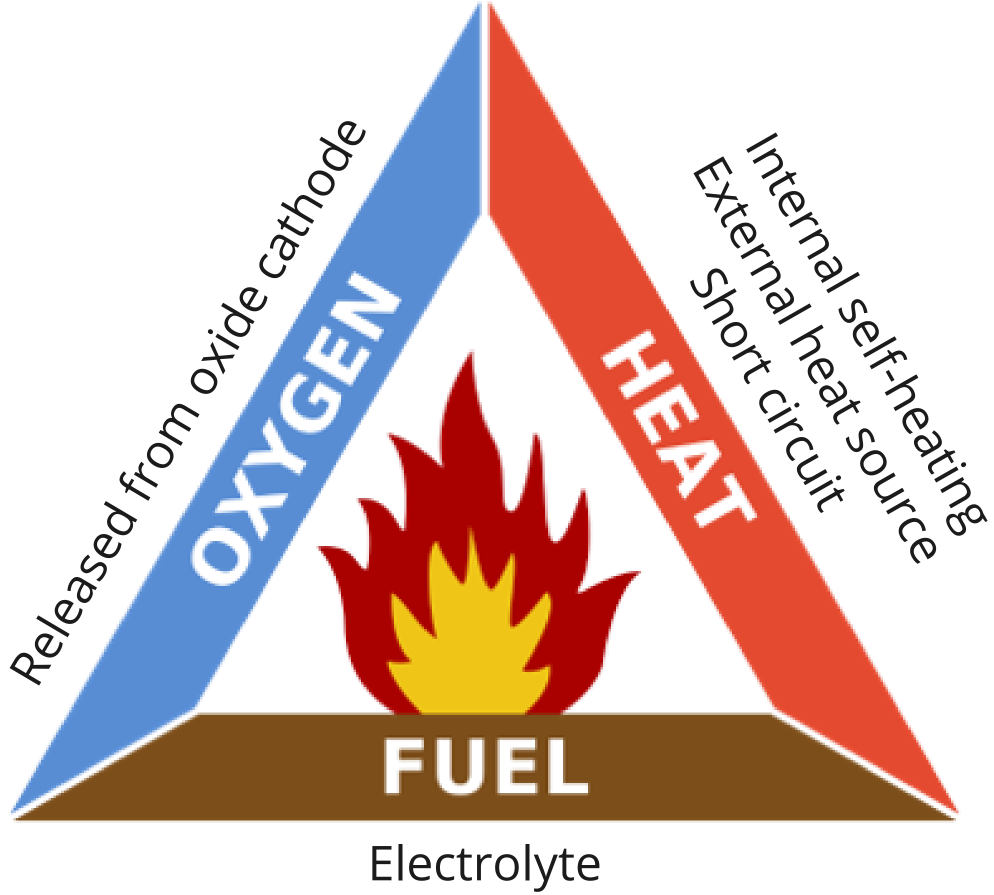


Albertus, P., et al. (2018). *Nature Energy* **3**(1), 16-21.

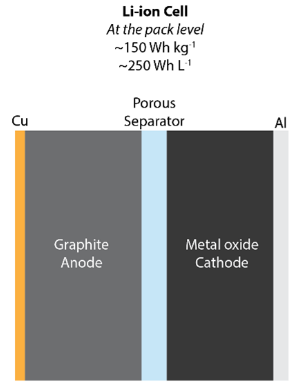
https://www.usfa.fema.gov/a-z/lithium-ion-batteries/risks-and-response-strategies/

ASSESSING THE FLAMMABILITY HAZARD OF LI-ION AND NA-ION

Fire



Electrolyte Combustion Fire



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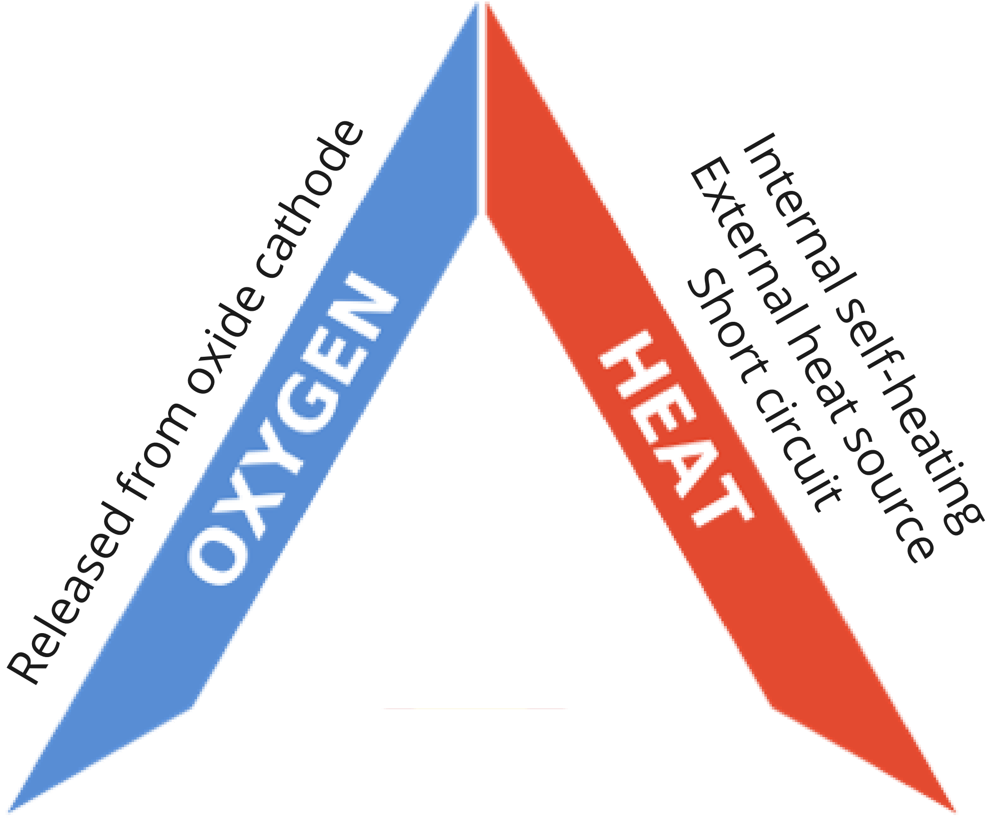
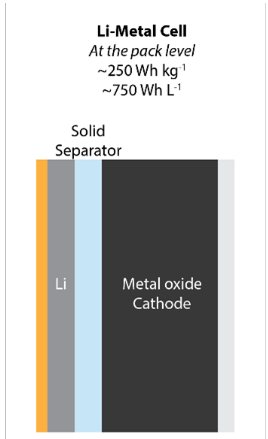
https://www.usfa.fema.gov/a-z/lithium-ion-batteries/risks-and-response-strategies/

https://www.nps.gov/articles/wildlandfire-facts-fuel-heat-oxygen.htm

SOLID-STATE REMOVES FLAMMABLE ELECTROLYTE…



Non-flammable Electrolyte



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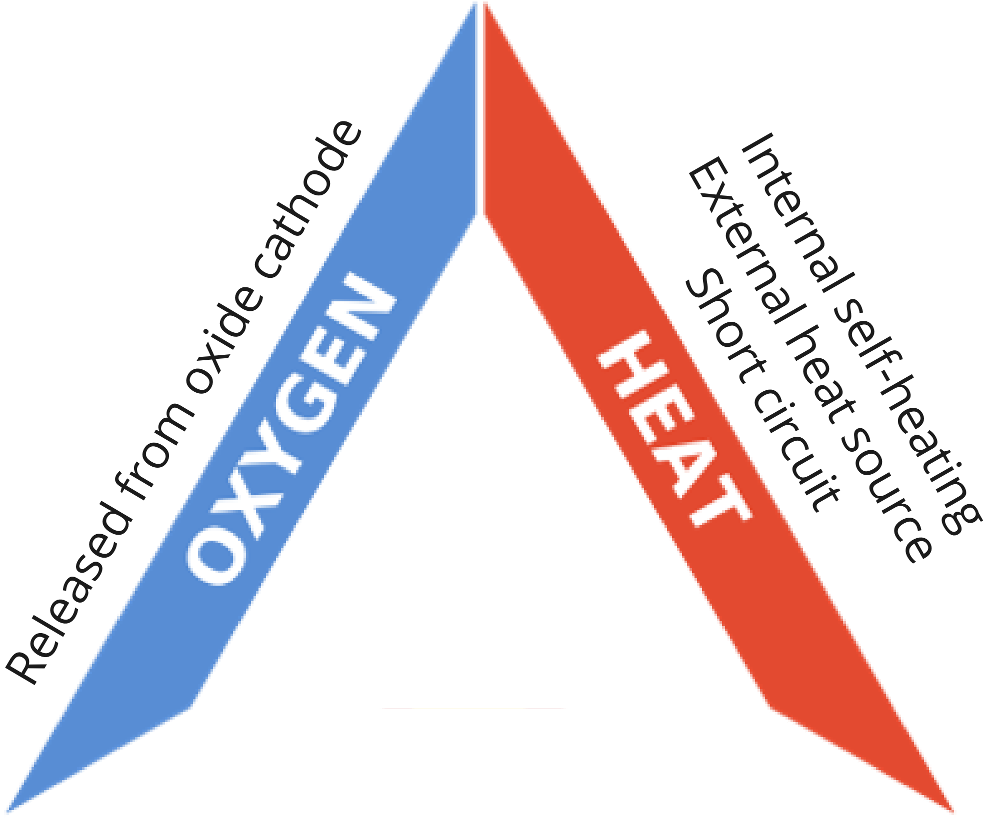
https://www.usfa.fema.gov/a-z/lithium-ion-batteries/risks-and-response-strategies/

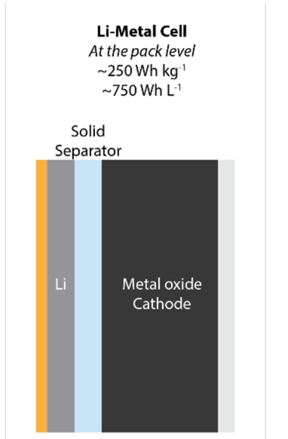
https://www.nps.gov/articles/wildlandfire-facts-fuel-heat-oxygen.htm

… BUT, POTENTIAL NEW FIRE RISK IN SOLID STATE BATTERIES



Metal Anode

Metal Fire



Albertus, P., et al. (2018). *Nature Energy* **3**(1), 16-21.

https://www.usfa.fema.gov/a-z/lithium-ion-batteries/risks-and-response-strategies/

https://www.nps.gov/articles/wildlandfire-facts-fuel-heat-oxygen.htm

SAFETY NEEDS TO BE VIEWED HOLISTICALLY

- Battery safety is complex and multifaceted
- Inherent risk with energy storage
- Mitigation of risk is necessary to maintain public support
- How much risk are we willing to tolerate?
- Do new technologies present new hazards?

https://www.usfa.fema.gov/a-z/lithium-ion-batteries/risks-and-response-strategies/

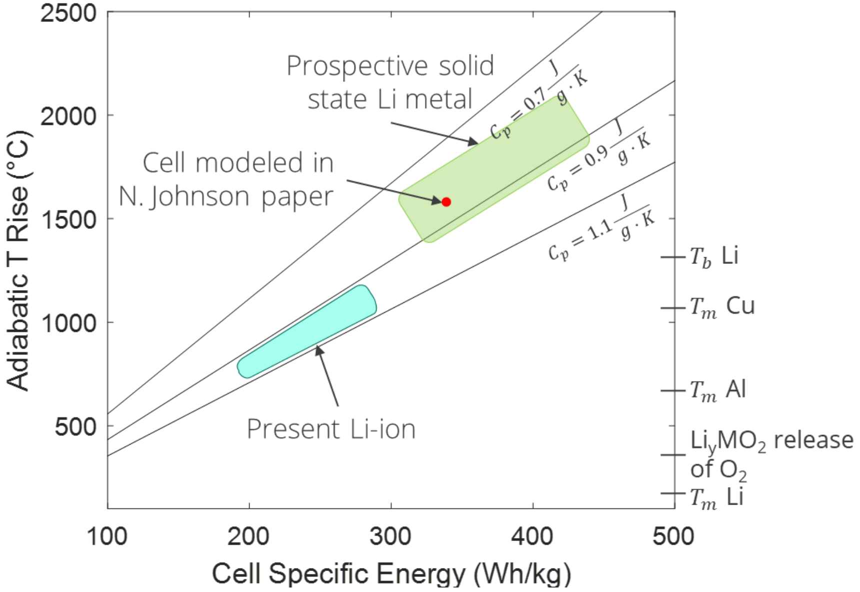
https://www.nps.gov/articles/wildlandfire-facts-fuel-heat-oxygen.htm

EMERGING RISKS OF SOLID-STATE BATTERIES

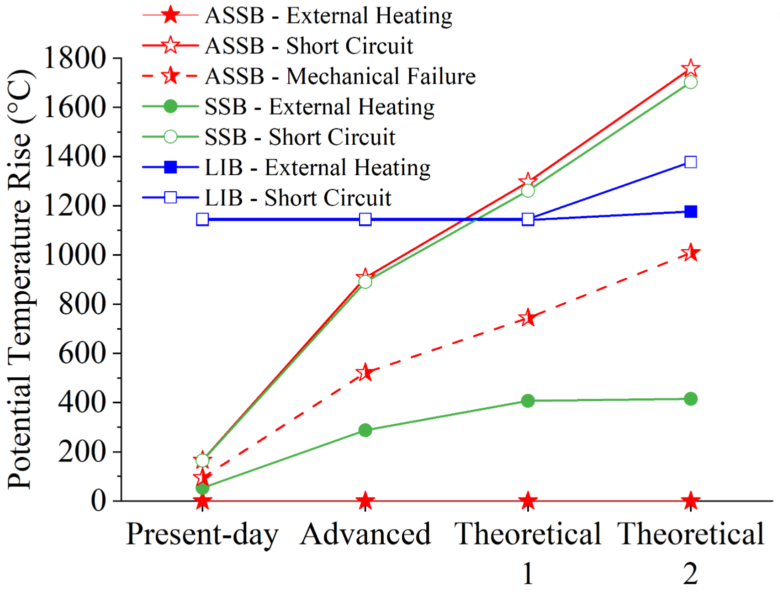
Emerging Potential Safety Risks

- Highly reactive metal anode
- High temperature failure
- Unwanted side reactions based on separator choice
- Poor stress tolerance leading to gaseous byproduct reactions

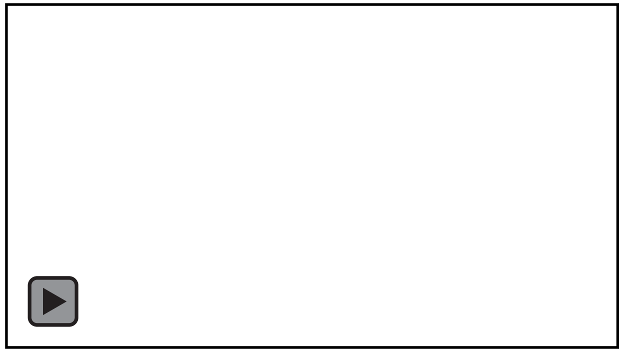
Ge, S. et al. (20234). *ACS Energy Lett.* **9**(12), 5747-5755.



Johnson, N. and P. Albertus (2022). *Journal of The Electrochemical Society* **169**(6), 060546.



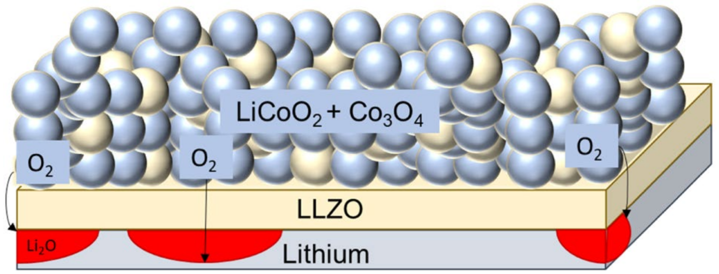
Bates, A. M., et al. (2022). Joule **6**(4), 742-755.



Kim, T. et al. (2022). *Chemistry of Materials* **34**(20), 9159.

ANODE-CATHODE INTERACTIONS ARE A SAFETY RISK FOR SOLID-STATE BATTERIES

Oxygen Evolution from Cathode



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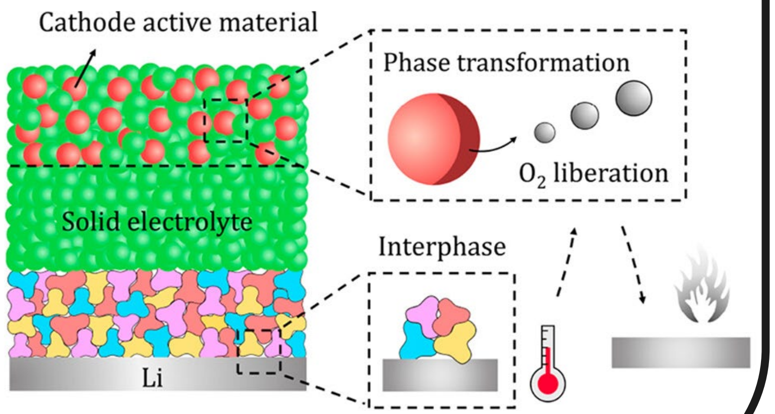
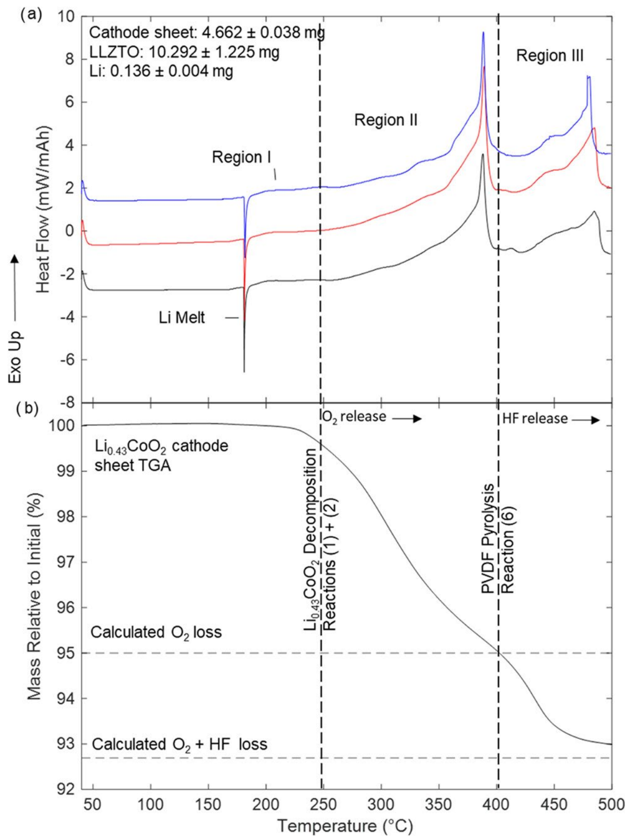


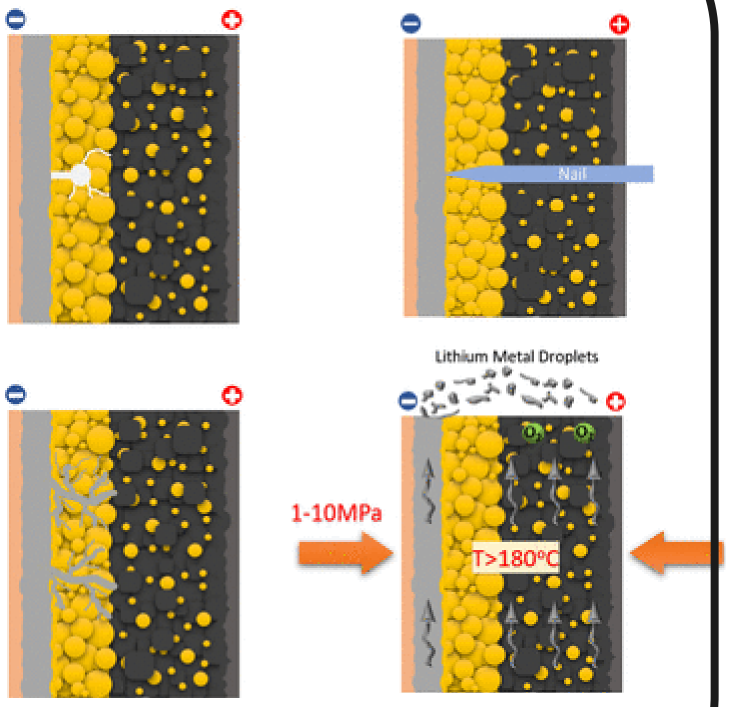
Vishnugoppi, B. et al. (2023). *ACS Energy Lett.* **8**(1), 398-407.

Gas Evolution From Inactives



Johnson, N. et al. (2023). *ACS Appl. Mater. Interfaces* **15**(49), 57134-57143.

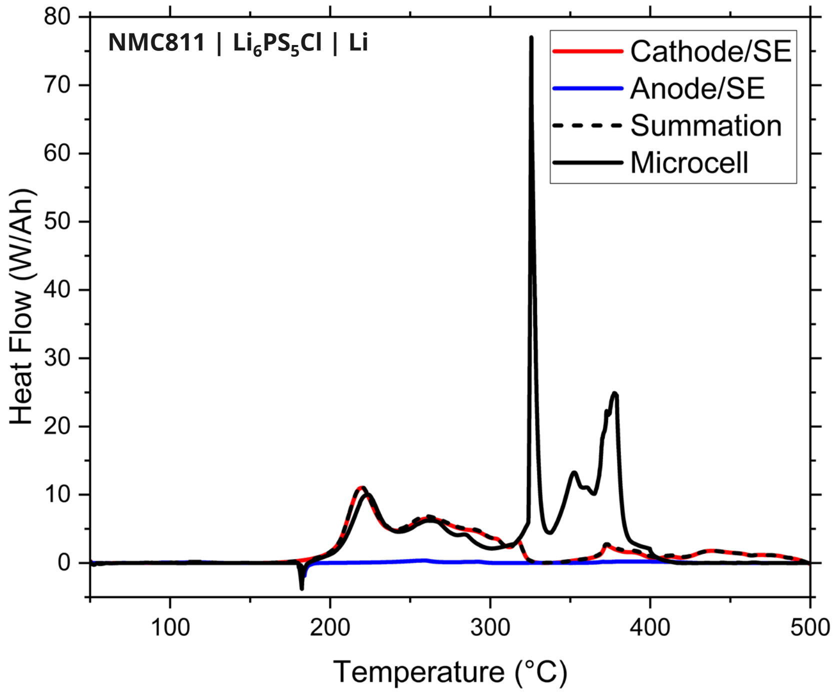
Gas Driven Lithium Fires



Ge, S. et al. (20234). *ACS Energy Lett.* **9**(12), 5747-5755.

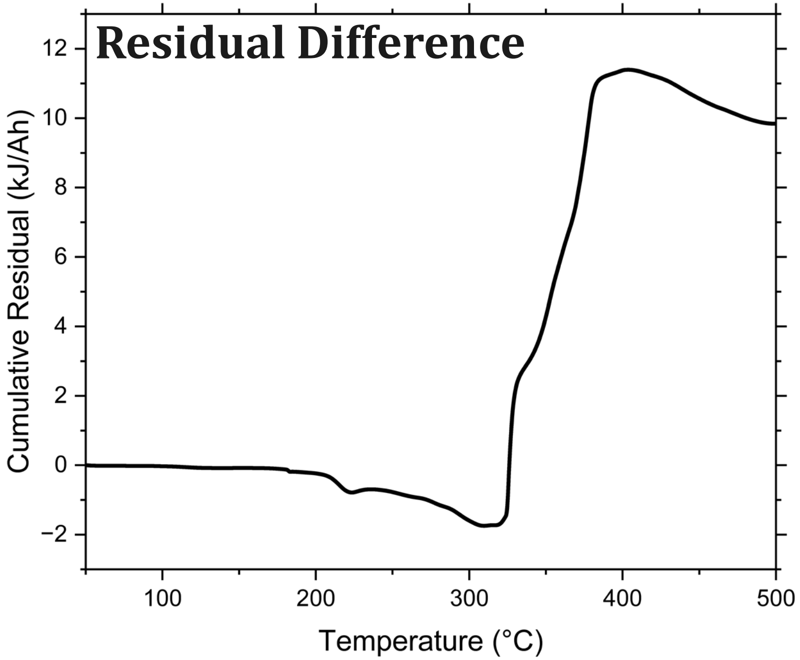
WHAT ARE THE DOMINANT HEAT SOURCES IN SOLID-STATE?

Summation vs. Microcell



Interpretation from individual electrodes:

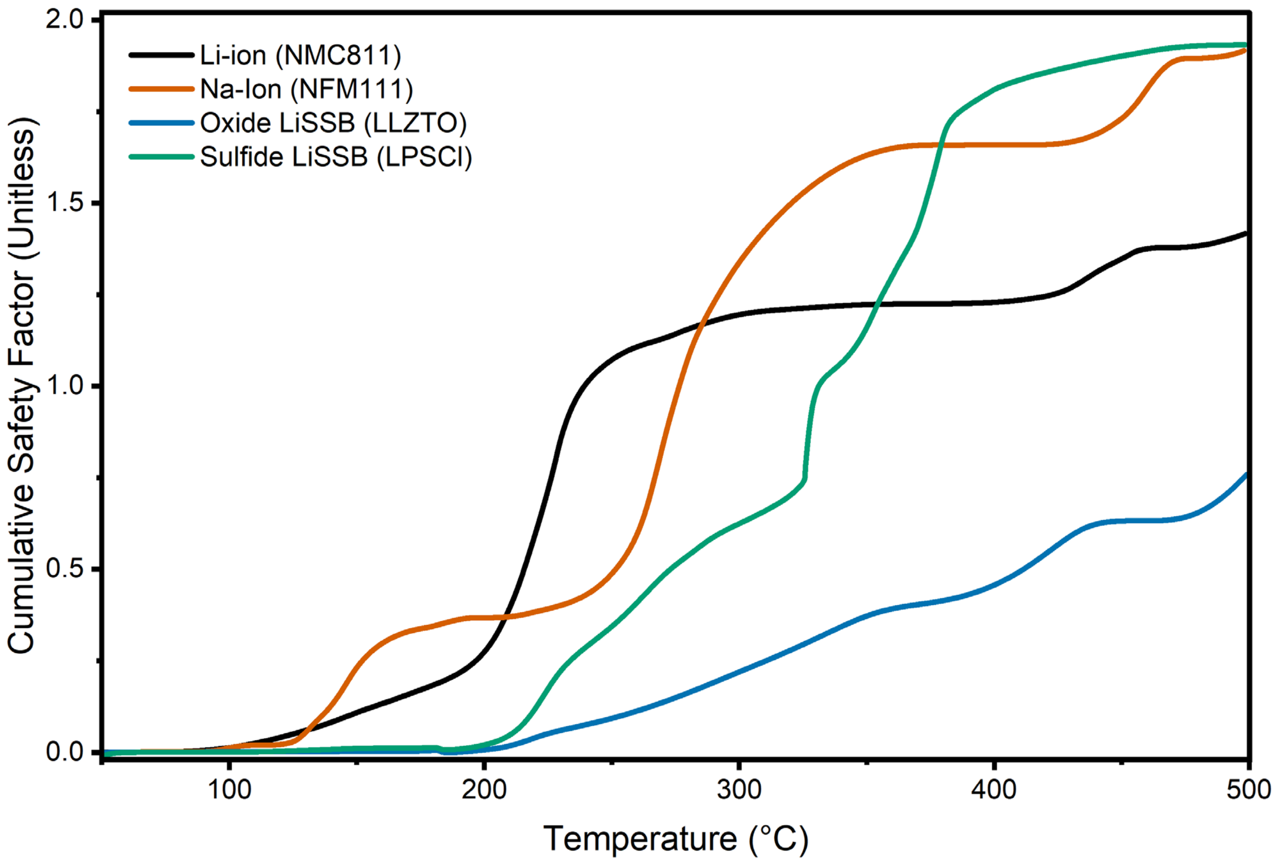
- Anode and SE are mostly stable in contact
- ~~Appears overall safer than Li-ion and Na-ion~~
  - Better onset, ~~less heat, slower rate of heat release~~



What's Missed:

- Gaseous byproduct reactions add >10 kJ/Ah at 300°C
- Sulfide no longer appears definitively safer than Li-ion

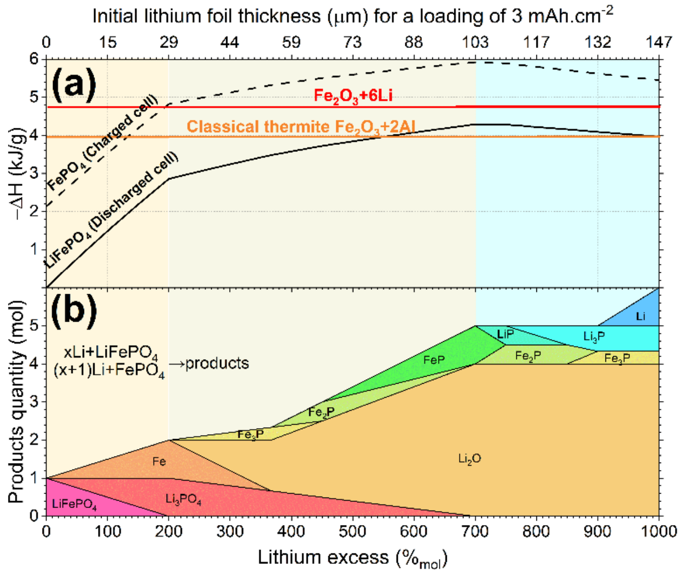
THERMAL COMPARISON OF SOLID-STATE TO LI-ION AND NA-ION



- Sulfide solid-electrolyte has total normalized energy release comparable to NFM
  - Sulfide is significantly higher absolute energy than NFM
- Both solid-state chemistries have onset to thermal runaway higher than Li-ion and Na-ion
  - Sulfide has onset to self-heating 83°C and thermal runaway at ~190°C
  - Oxide has onset to self-heating at 155°C and onset to thermal runaway at 190°C

THERMITE REACTIONS IGNITE FLAMES UNDER ARGON

Reaction Products



- Excess lithium (N:P ratio > 1) can engage in the thermite reaction with oxide cathodes
  - Extracts oxygen from cathode lattice
- Thermodynamically spontaneous at room temperature

No flammable electrolyte or gaseous oxygen required

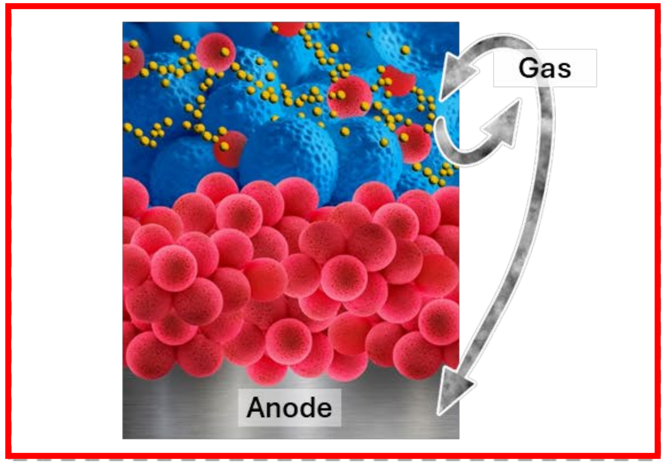
Bertrand, M., Johnson, N.B, Jin, L., Bates., A.M., Chartrand, P., Torres-Castro, L., Dollé, M. *Joule.* 2025, 9(5), https://doi.org/10.1016/j.joule.2025.101953

Mickael Dollé
Marc Bertrand
Université de Montréal

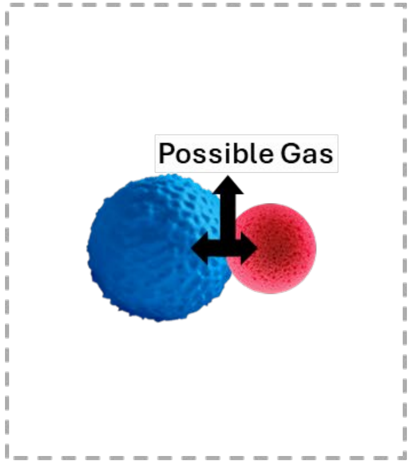
IDENTIFIED SOURCES OF FIRE IN SOLID-STATE BATTERIES

Cathode Active   Solid Electrolyte   Conductive Carbon

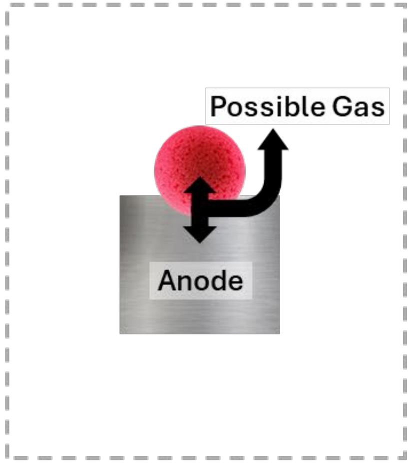
Gaseous Byproduct Reaction



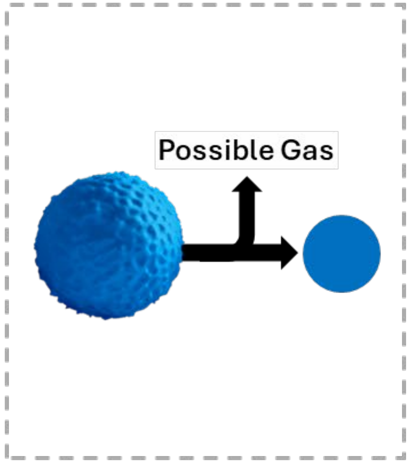
Cathode-Electrolyte



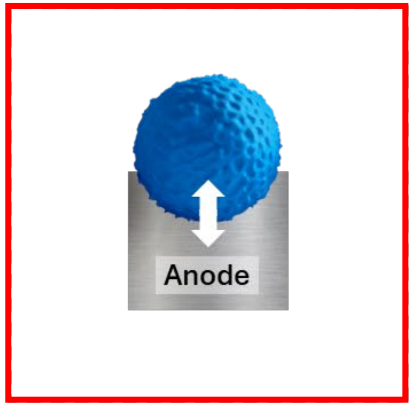
Anode-Electrolyte



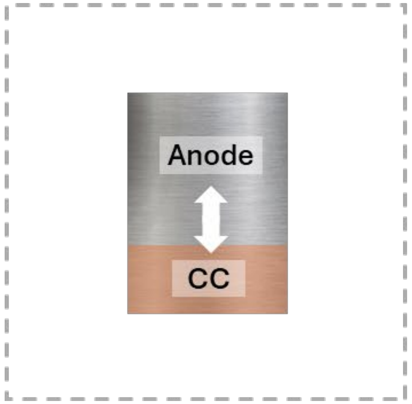
Thermal Decomposition



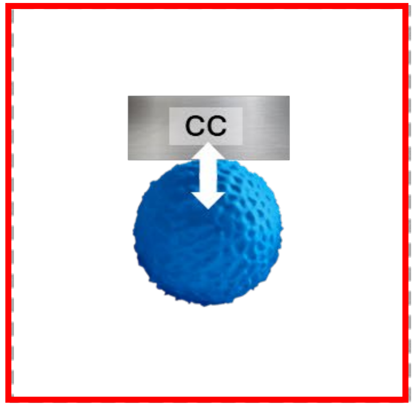
Anode-Cathode (Thermite/ISC)



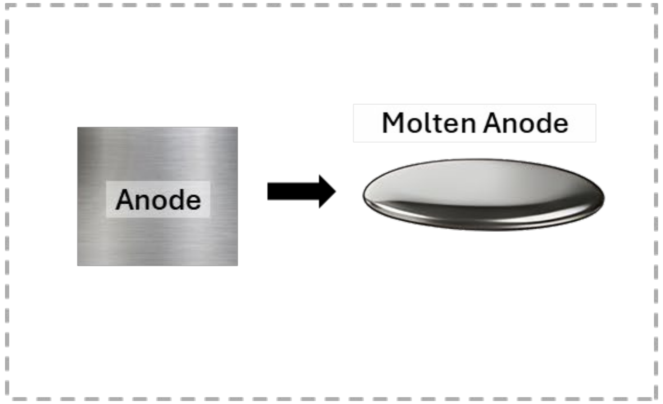
Anode-Current Collector (Alloy)



Cathode-Current Collector (Thermite)

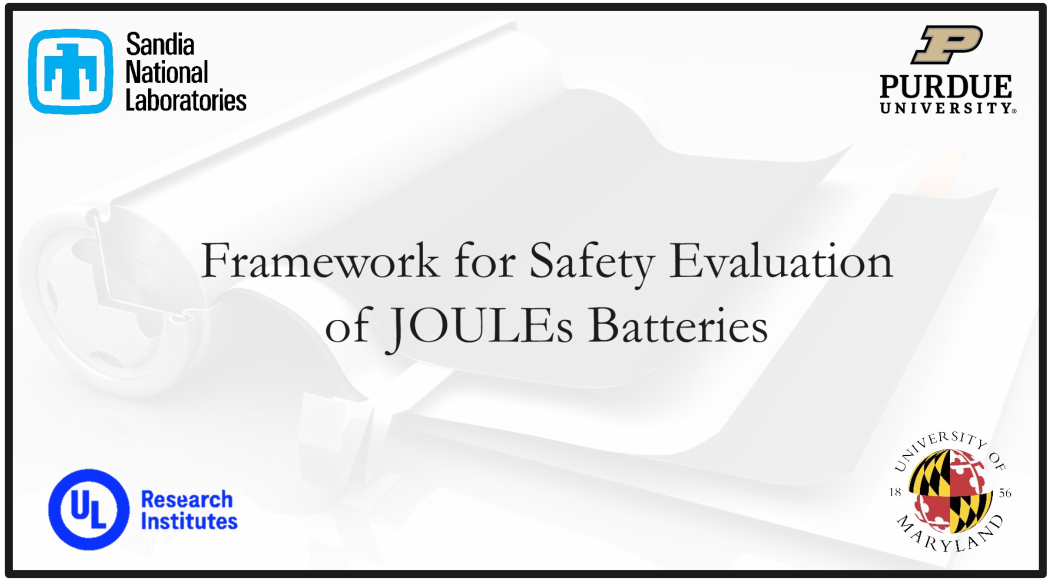


Phase Transition



KEY TAKEAWAYS

- NFM Na-ion safety is comparable to NMC Li-ion
- New chemistries have unique hazards
  - Need to be addressed individually
- New predictive safety methods are critical
  - Consider all possible material interactions
- DSC microcells offer valuable safety information early
- Safety issues will slow adoption of new technologies
  - Addressing safety early can avoid costly setbacks



Safety is complex and evolving. Critical assessments of hazards are necessary for safe deployment of next-generation chemistries.

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QUESTIONS?

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