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MULTI-SCALE SAFETY AND RISK ANALYSIS OF SODIUM-ION BATTERIES

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ID#705

DOE OE Energy Storage Peer Review & Annual Meeting, 2026

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PROJECT OVERVIEW

- Goal: Assessing and determining failure mechanisms of commercial sodium-ion (NIB) chemistries for application in grid energy storage. This FY focuses on NFM/HC.
- Current Practice: Single cell abuse testing utilizing a variety of thermal, mechanical, and electrical initiation methods.
- Why Sandia: The Battery Abuse Testing Laboratory at Sandia has decades of experience in abuse testing lithium secondary and primary chemistries. Our expertise and facilities are perfectly suited to assess NIB safety, hazards, and diagnostics.
- Innovation: We are using materials scale safety analysis in addition to single cell abuse testing to determine high fidelity mechanistic failure pathways for NIB.
- Duration: FY25-FY26
- Impact: Relevant stakeholders include Standards Development Organizations, Power Utility Companies, Investors, Developers, and Emergency Services. This work will generate valuable data to determine if current thermal runaway mitigation strategies for Li-ion are adequate for NIBs.
- Vertical/Investment Area: Safety & Reliability
- Alignment/Supports strategic pathway: Stabilize and optimize grid services

PROJECT DETAILS

- Problem
- Approach (Methods)
- Results
- Conclusion & Impact
- Future Direction/Next steps

PROBLEM: THE SAFETY OF NEW CHEMISTRIES IS CRITICAL

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

CATL

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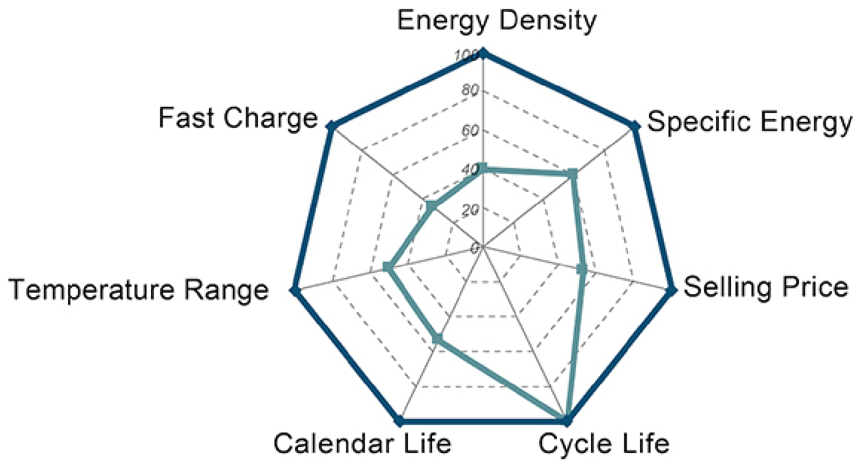
CATL and HyperStrong Sign the World's Largest Sodium-Ion Energy Storage Cooperation Agreement

2026-05-06

Modern Lithium Ion:

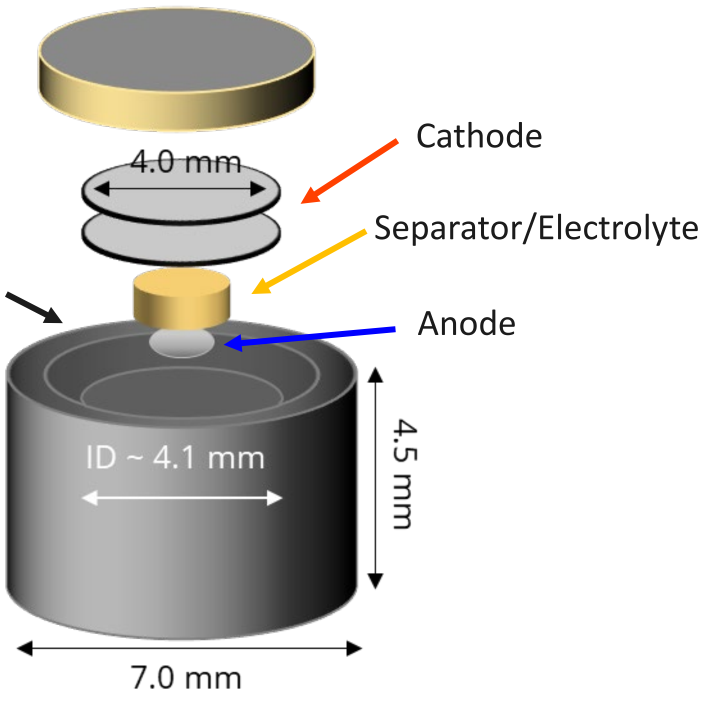


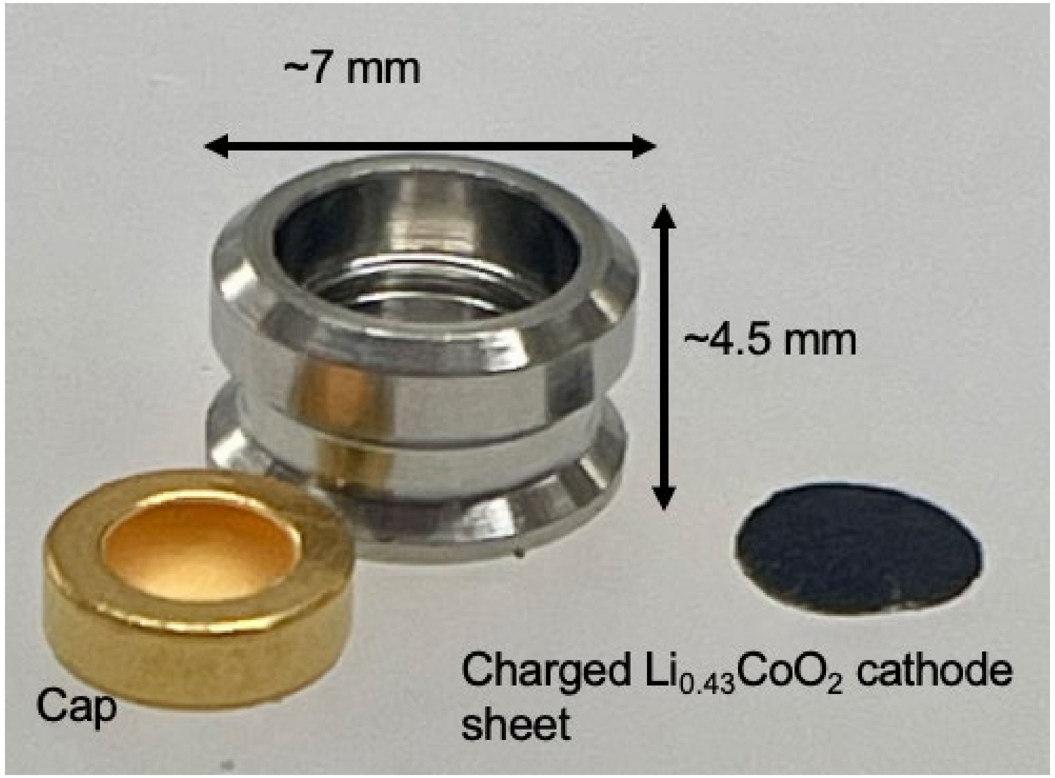
https://www.jcesr.org/research/

The safety of sodium-ion is still not well understood

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

APPROACH: CALORIMETRY OFFERS MECHANISTIC INTERPRETATION OF SINGLE CELL ABUSE



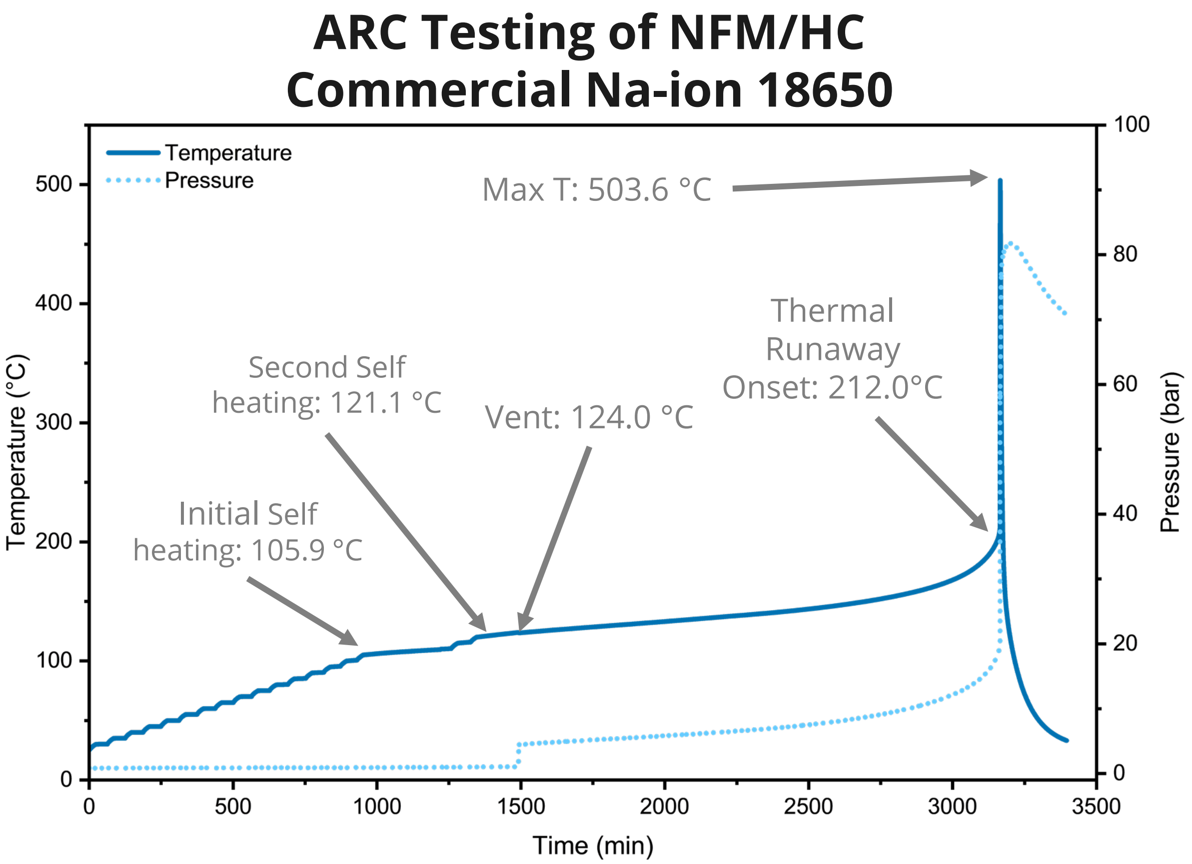


Material ratios are carefully balanced

Only ~10mg of material required

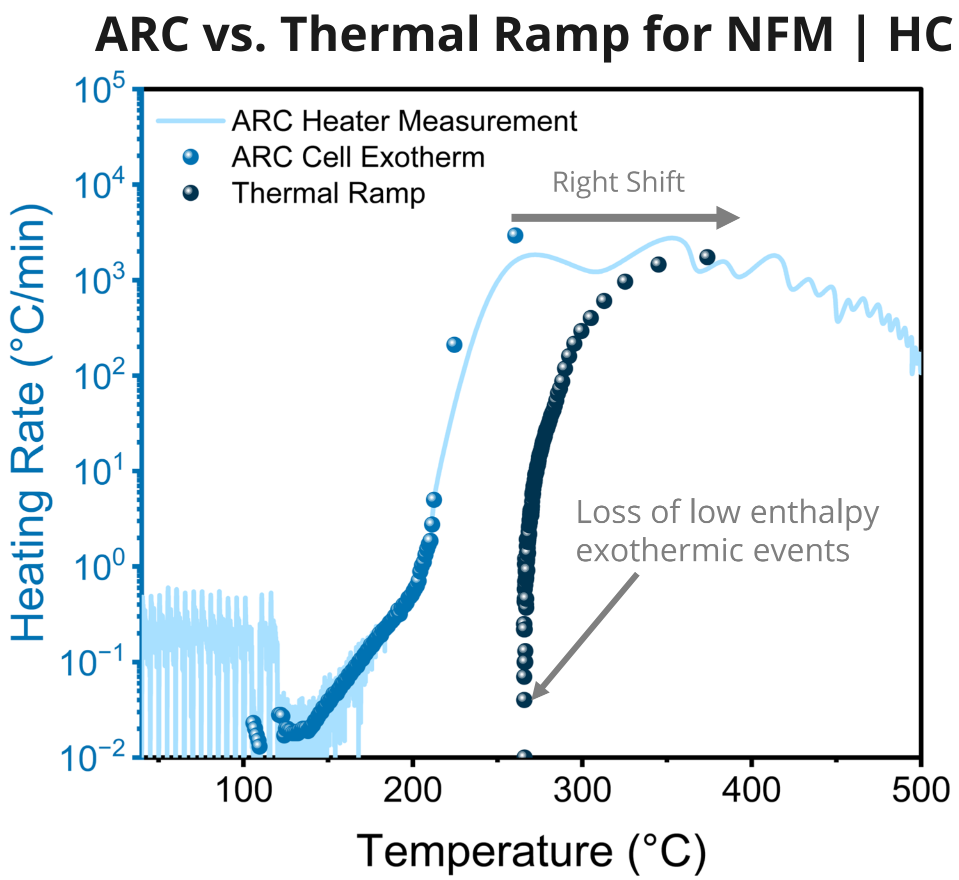
Johnson, N. et al. (2023) *ACS Applied Materials and Interfaces* ***15****(49)*, 57134-57143

RESULTS: ARC TESTING OF NFM SODIUM-ION 18650



- 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

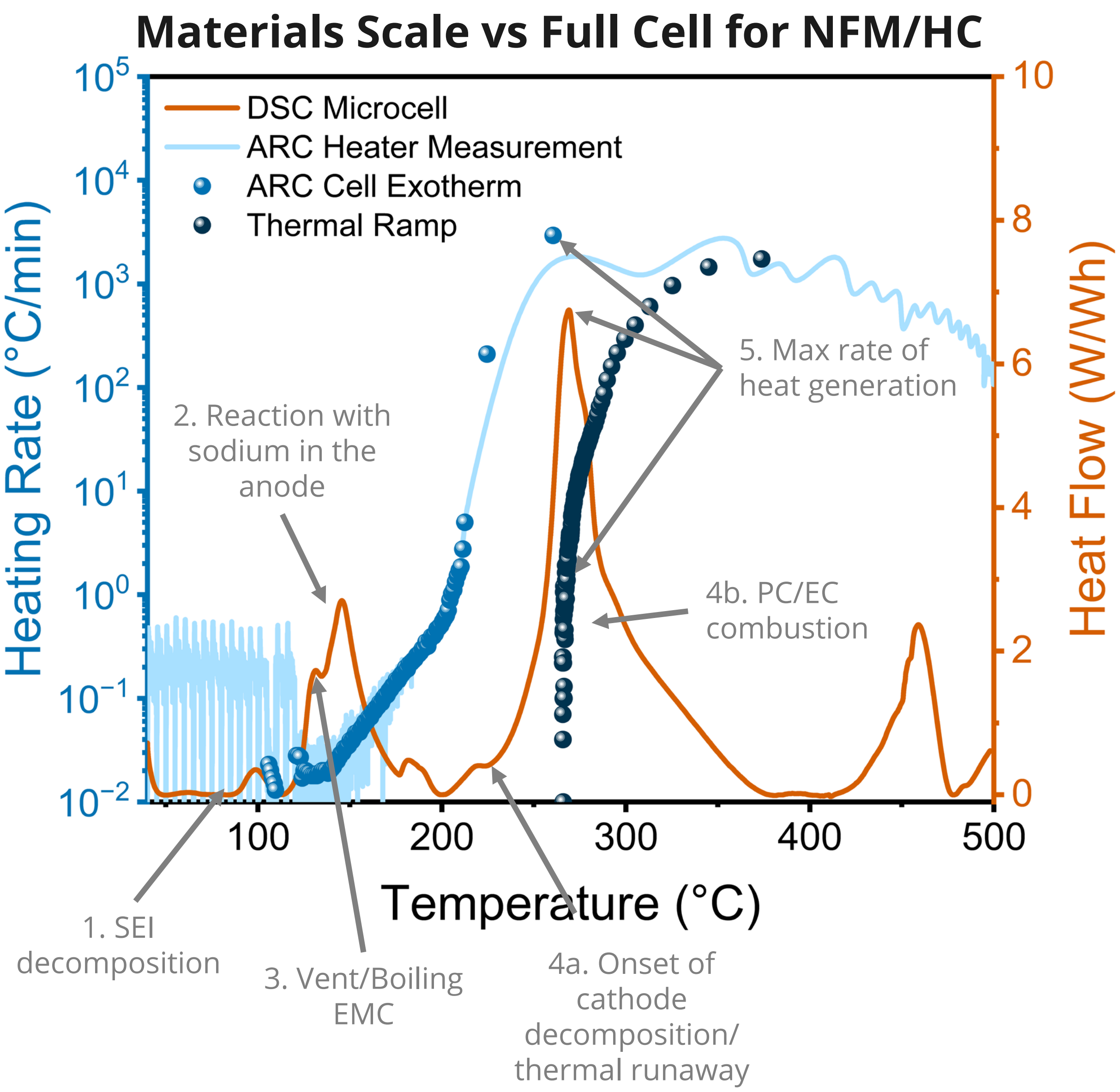
RESULTS: COMPARING ADIABATIC ARC TO NONADIABATIC THERMAL RAMP



- The introduction of non-adiabatic conditions introduce clear discrepancies to thermal runaway behavior
  - Events shift to higher temperatures
- Thermal Ramp testing has allowed heat dissipation
- Heater cartridges keep heating independently of cell exothermic activity
  - Lose resolution on small exothermic events

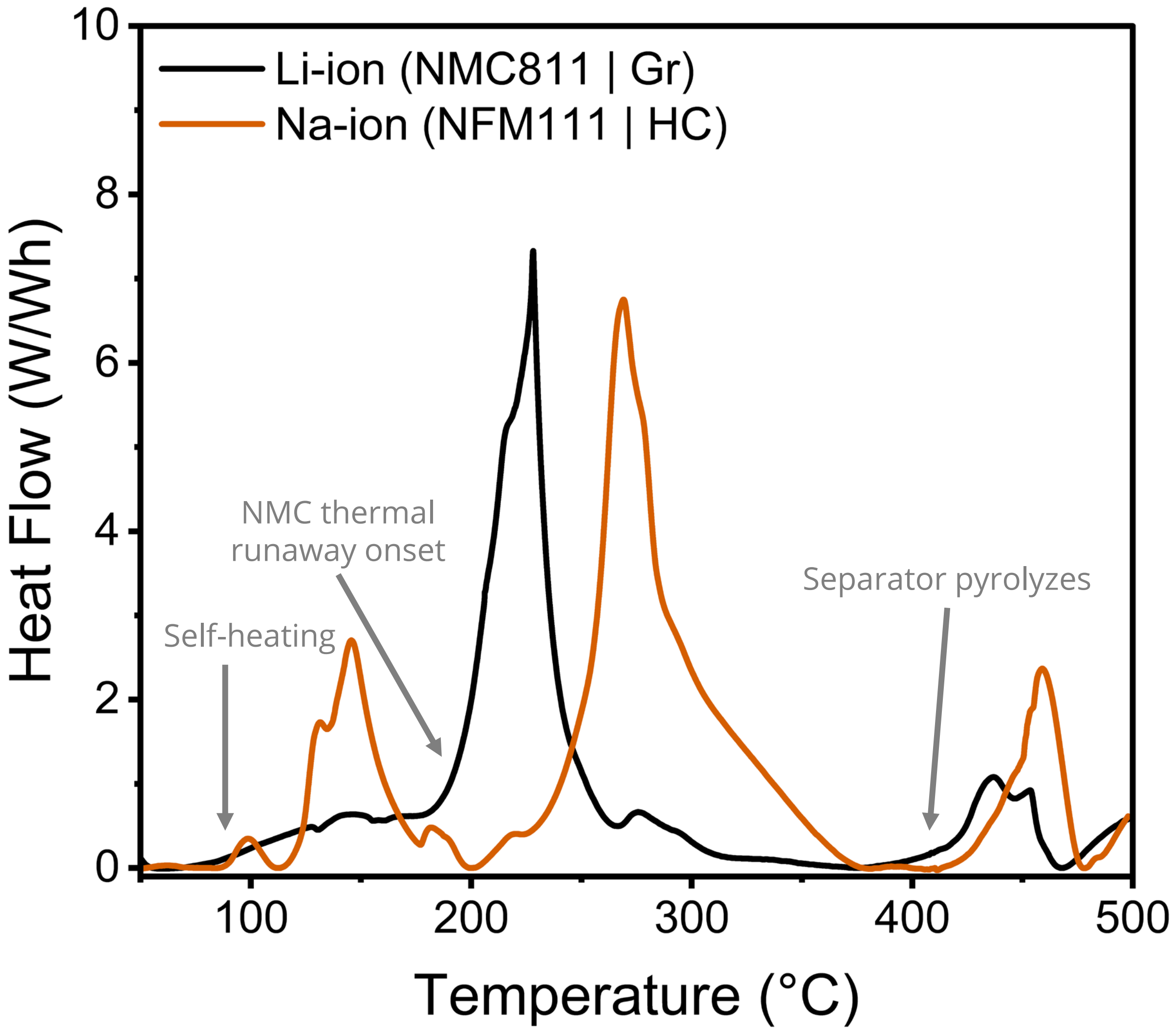
	Self-Heating Onset (°C)	Venting Temperature (°C)	Thermal Runaway Onset (°C)	Max Temperature (°C)	Max Heating Rate (°C/ min)
ARC	105.9 / 121.1	124.0	212.0	503.6	2941.0
Thermal Ramp	265.8	147.5	276.7	441.1	1741.7

RESULTS: MECHANISTIC INTERPRETATION OF THERMAL ABUSE TESTING USING DSC MICROCELLS



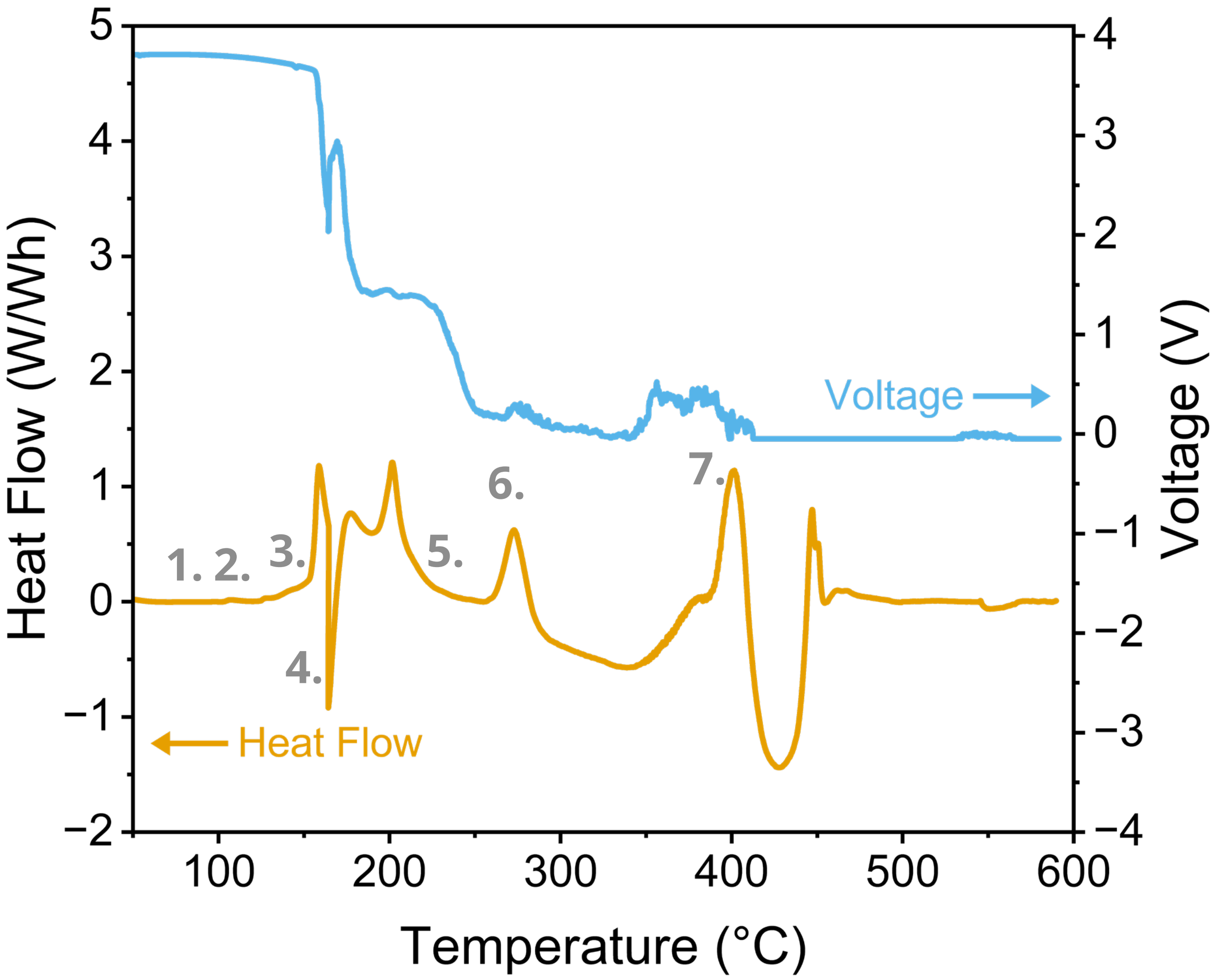
- ARC and DSC show close agreement
  1. *Initial self-heating from SEI decomposition and reaction with DMC*
  2. *Second self-heating from reaction of sodium in the anode with EMC*
  3. *EMC boiling matches ARC venting temperature*
  4. *Thermal runaway onset caused by NFM decomposition and PC/EC combustion*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

RESULTS: LI-ION AND NA-ION HAVE SIMILAR THERMOCHEMICAL PROFILES



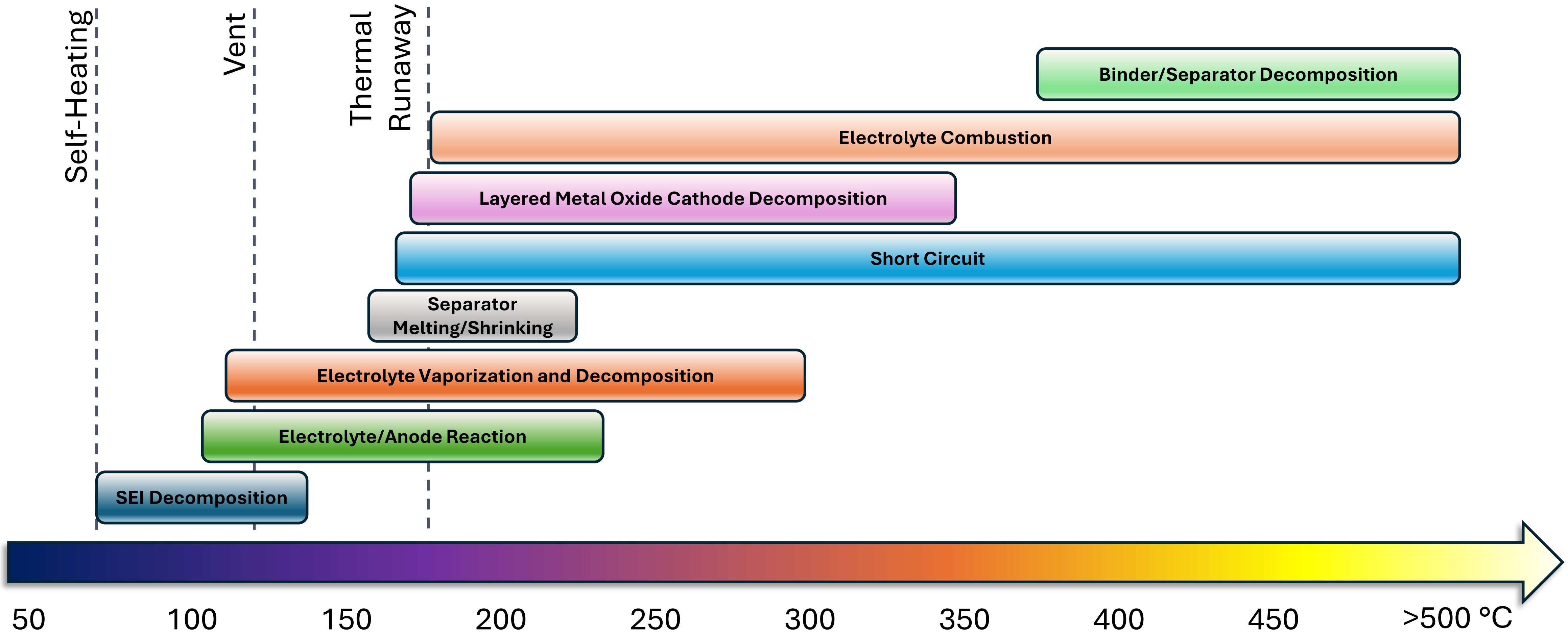
- NFM and NMC chemistries have similar self-heating onset temperatures of ~80°C
- NMC has continuous heat generation while NFM briefly stops
- Onset to thermal runaway is lower for NMC
- Similar rates of heat generation between NMC and NFM
- Heat generation >400°C after the separator pyrolyzes

RESULTS: NOVEL COIN CELL CALORIMETRY FACTORS IN VENTING AND MONITORS CELL VOLTAGE

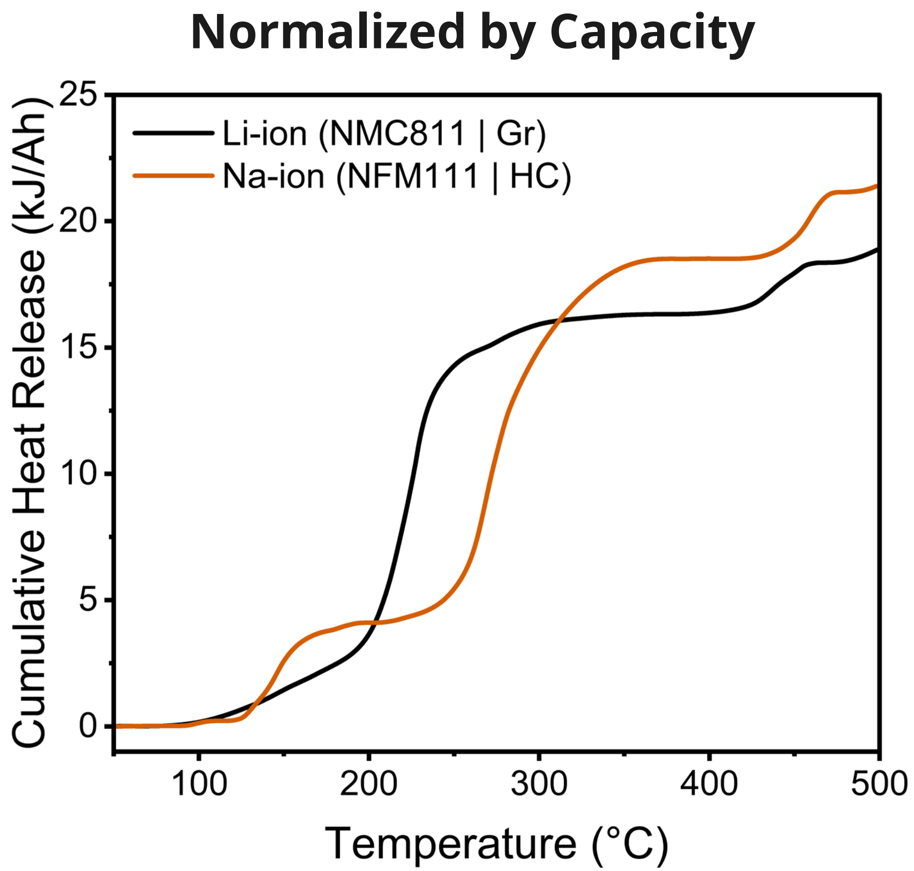


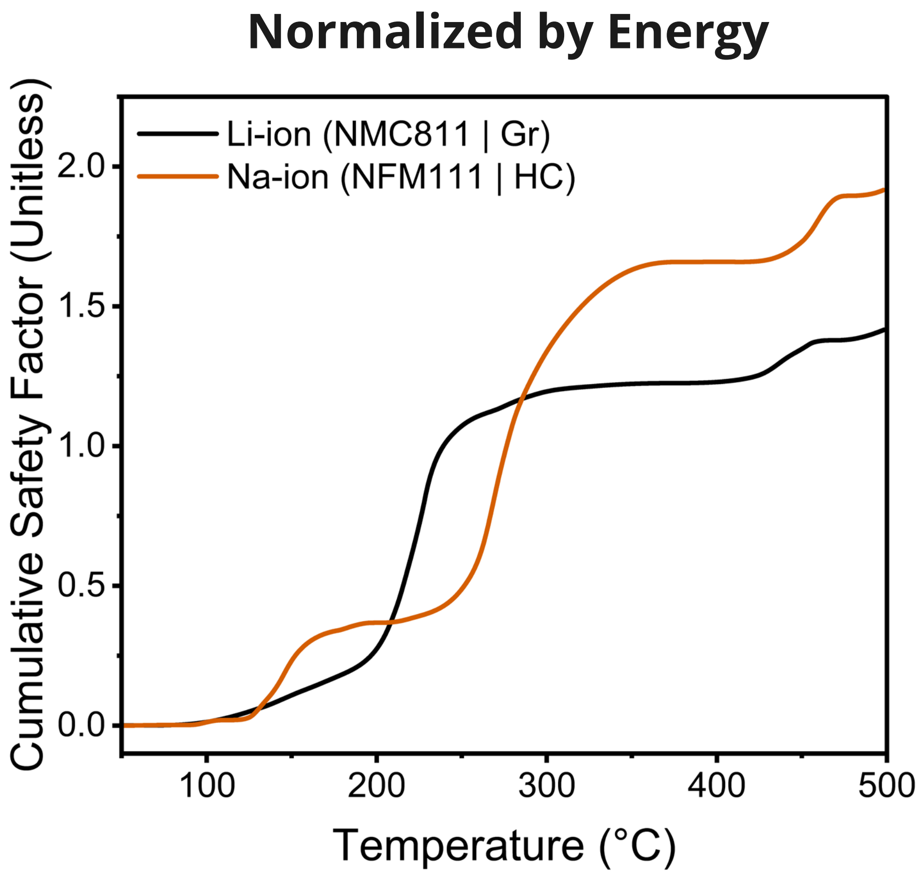
1. SEI decomposition begins ~80 °C
2. Slight self-heating begins 105 °C
3. Anode and electrolyte react 124 °C
4. Gasket and separator melt 160 °C
   - Sudden voltage drop and fluctuation with gas venting
5. Gas continues to vent endothermically
6. Cathode decomposition and oxygen release at 254 °C
   - Significant voltage drop
7. Separator and binder pyrolysis >400 °C
   - Complete loss of voltage

RESULTS: NFM AND NMC HAVE SIMILAR THERMAL RUNAWAY PATHWAYS



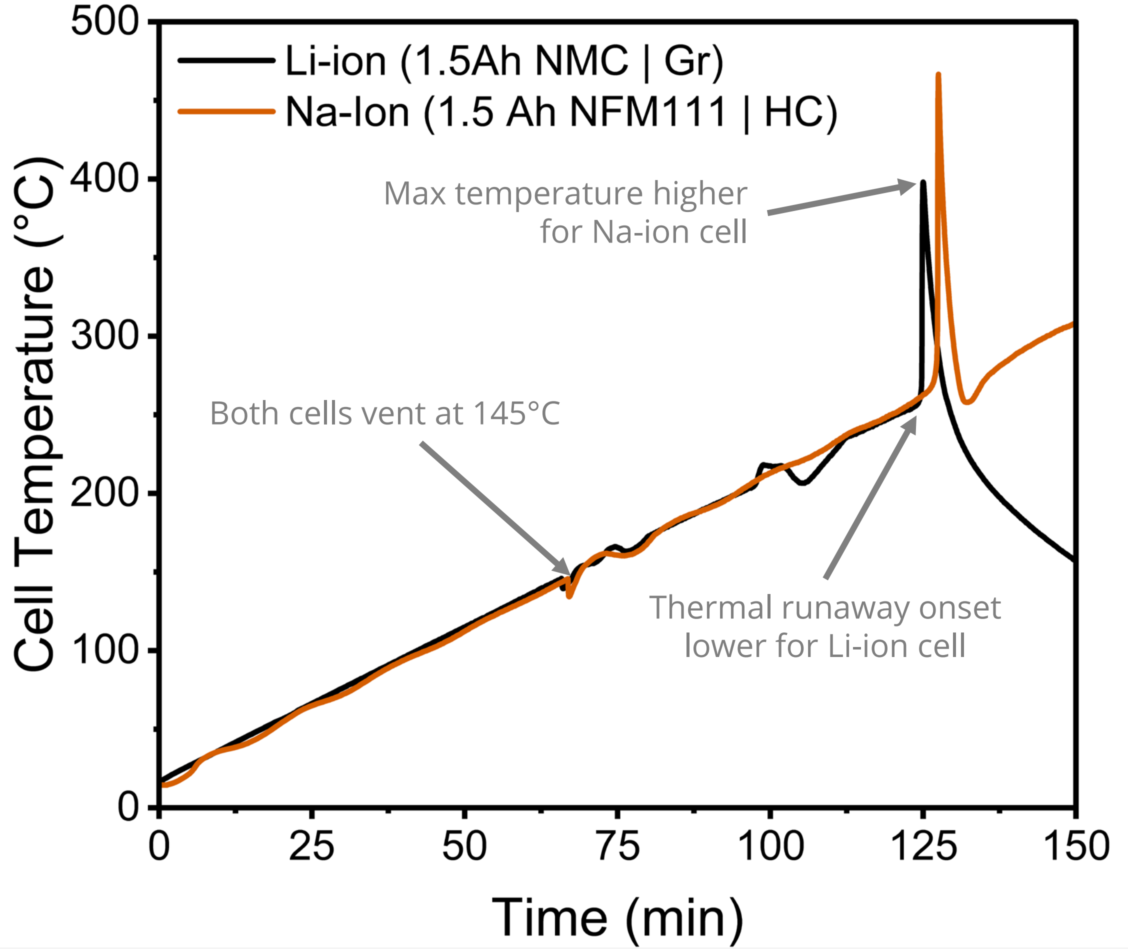
RESULTS: COMPARISON OF TOTAL HEAT RELEASE





- Energy release is similar between NMC and NFM on a per Ah basis
  - Would expect similar capacity cells to have similar failures
- Na-ion has significantly more heat release per unit of stored energy
  - Higher maximum temperature during failure

RESULTS: THERMAL RAMP COMPARISON

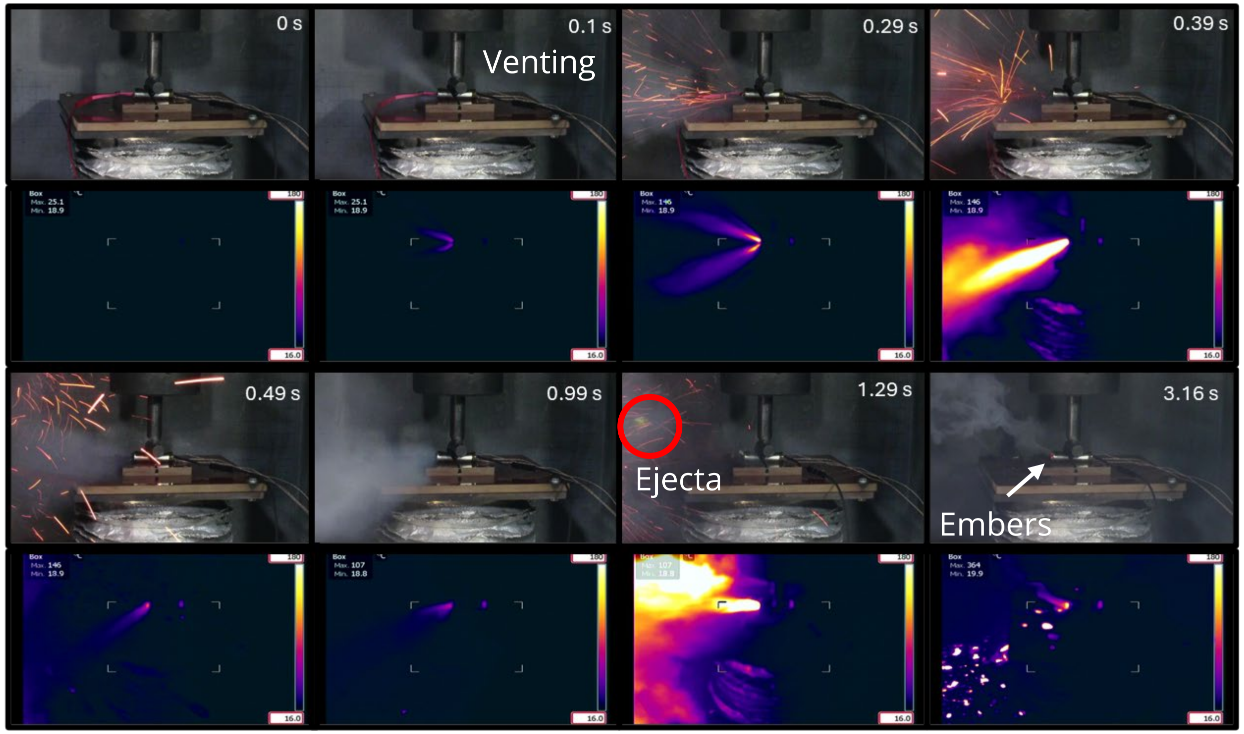


- Venting temperature is the same for both chemistries
- NMC goes into thermal runaway earlier
- NFM has higher temperature rise
- Consistent with DSC prediction

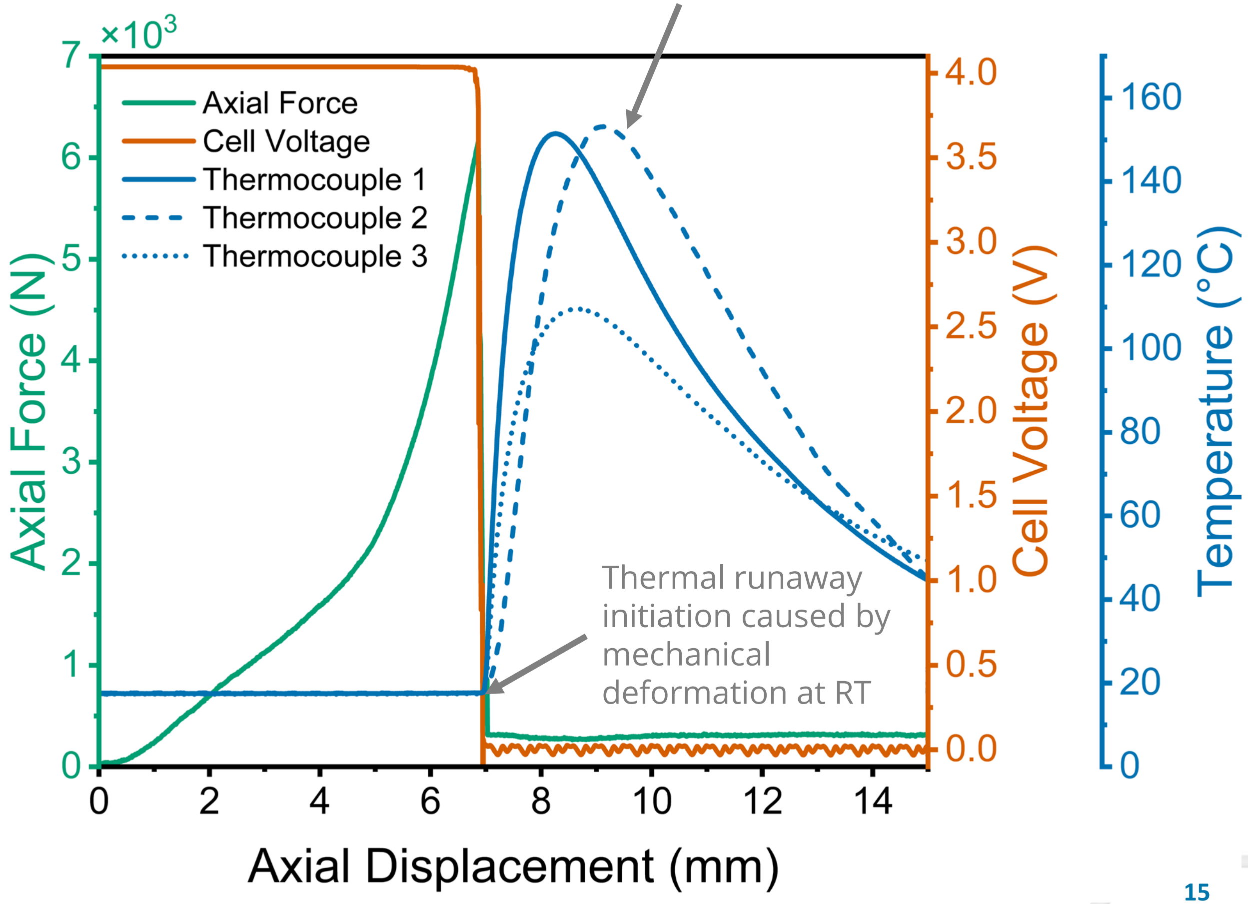
RESULTS: WHAT ABOUT NON-THERMAL INITIATION METHODS?

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

Crush Test of NFM/HC Commercial 18650



Remaining embers continue to heat thermocouples after jelly roll ejects



Thermal runaway initiation caused by mechanical deformation at RT

RESULTS: SUMMARY OF NMC AND NFM ABUSE TESTING RESULTS

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

CONCLUSIONS

- NFM may not be safer than NMC
  - NFM shows more energy release per kWh, and lower tolerance to mechanical abuse
- NFM follows similar thermal runaway pathway to NMC
  - Electrolyte reduction in the anode plays a strong role in onset to self-heating
  - Electrolyte reduction of the cathode seems to play a strong role in onset to thermal runaway
- Future Outlook: Tunability for Na-ion safety can be improved through electrolyte stability with electrodes

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