Is Sodium the New Lithium? How Table Salt Might Save the Energy Storage Industry

November 7, 2024

A Presentation of the Energy Storage Technology Advancement Partnership (ESTAP)

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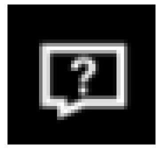
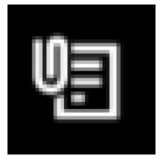
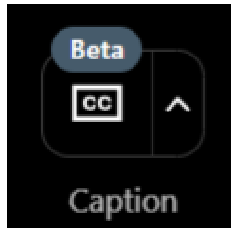
Submit questions and comments via the Questions panel 

Speaker bios available in the "Materials" section 

Automated **captions** are available 

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20 CleanEnergy States Alliance

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IPA Illinois Power Agency

Governor's Energy Office (Maine)

State of New Hampshire Department of Energy

Massachusetts Clean Energy Center

Maryland Energy Administration

EGLE Michigan Department of Environment, Great Lakes, and Energy

BPU New Jersey Board of Public Utilities

New Jersey's Clean Energy Program – njcleanenergy.com

New Mexico EMNRD Energy, Minerals and Natural Resources Department

New York State NYSERDA

mn Commerce Department

SMUD Powering forward. Together.

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Oregon Department of Energy

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OPC-DC Office of the People's Counsel – Advocacy | Education | Protection

Energy Storage Technology Advancement Partnership (ESTAP)

Conducted under contract with Sandia National Laboratories, with funding from US DOE Office of Electricity.

- Facilitate public/private partnerships to support joint federal/state energy storage demonstration project deployment
- Support state energy storage efforts with technical, policy and program assistance
- Disseminate information to stakeholders through webinars, reports, case studies and conference presentations

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Thank You!

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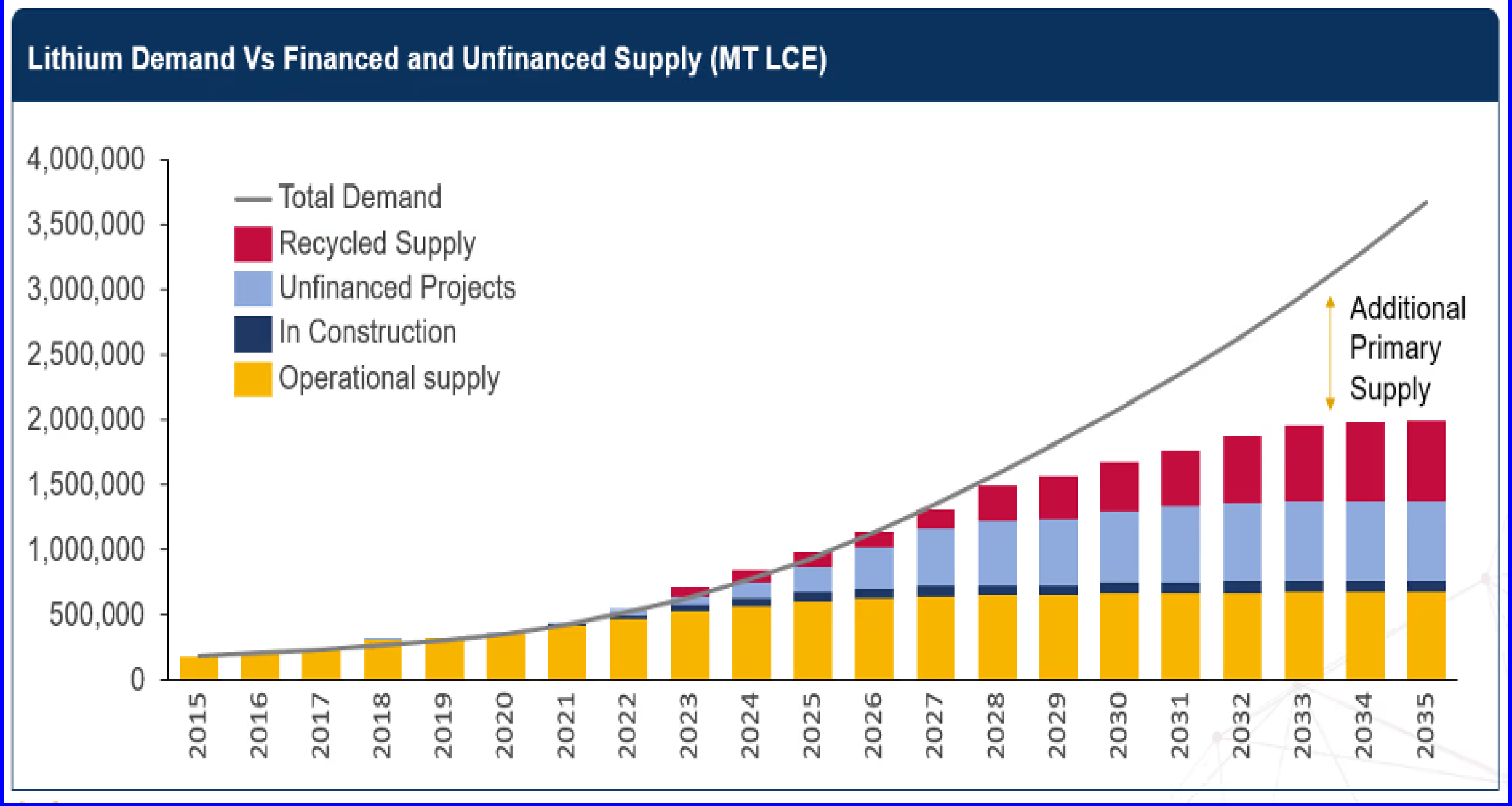
Decarbonization Needs Diversification!

IMRE GYUK, CHIEF SCIENTIST
ENERGY STORAGE RESEARCH, DOE-OE

11-07-24

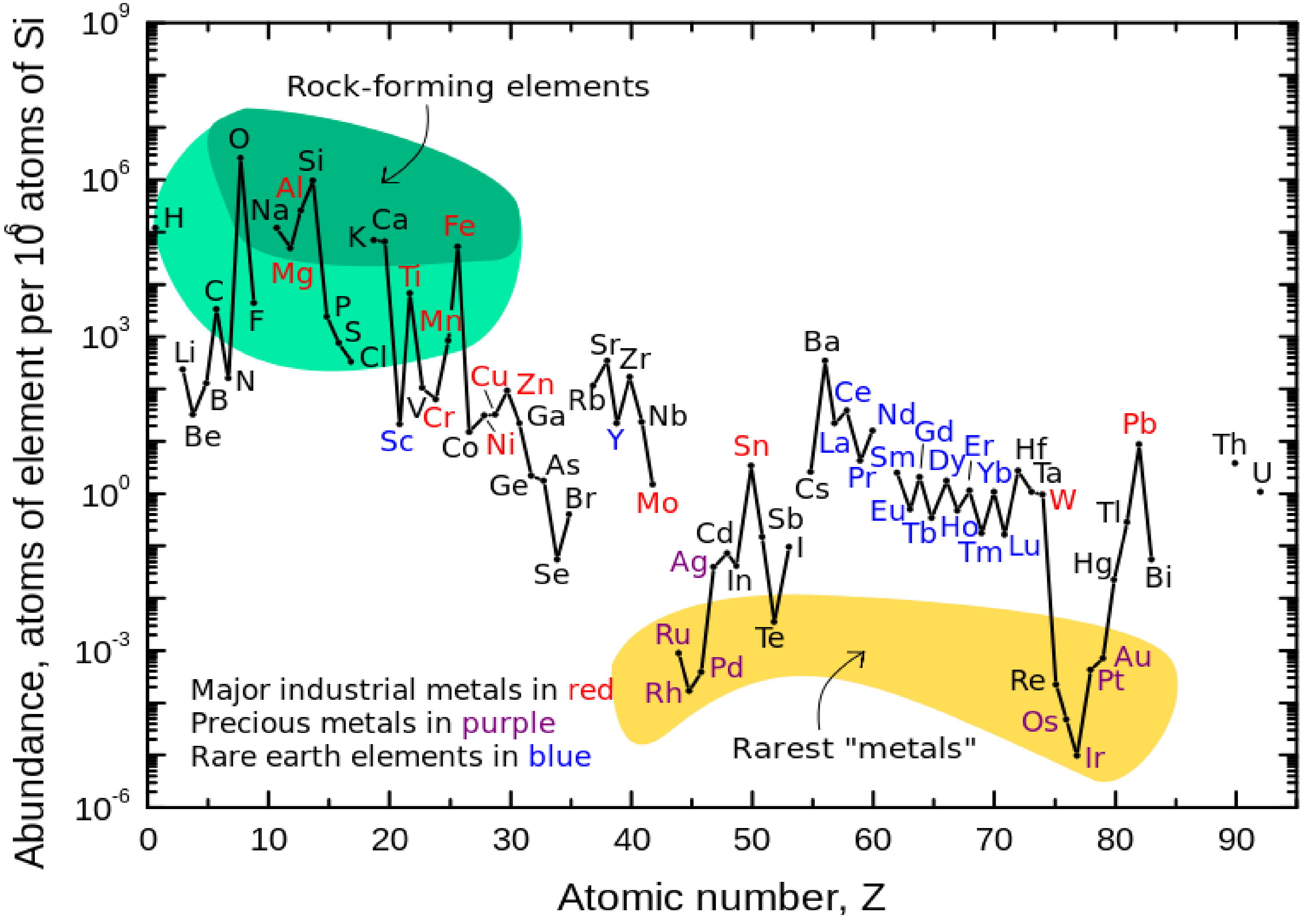
While Li is excellent for
Short Duration Applications
< 4 hours,
Li is not expedient for
Medium and Long Duration
Energy Storage.

Furthermore, available Lithium
will be needed for
Vehicle Electrification.
EVs require
the high Energy Density of Li.



By 2029 Denand will outstrip Supply!

We are looking for Batteries
using Earth-abundant,
Domestically available,
Inexpensive Materials,
while showing
Performance Characteristics
Similar to Li-ion

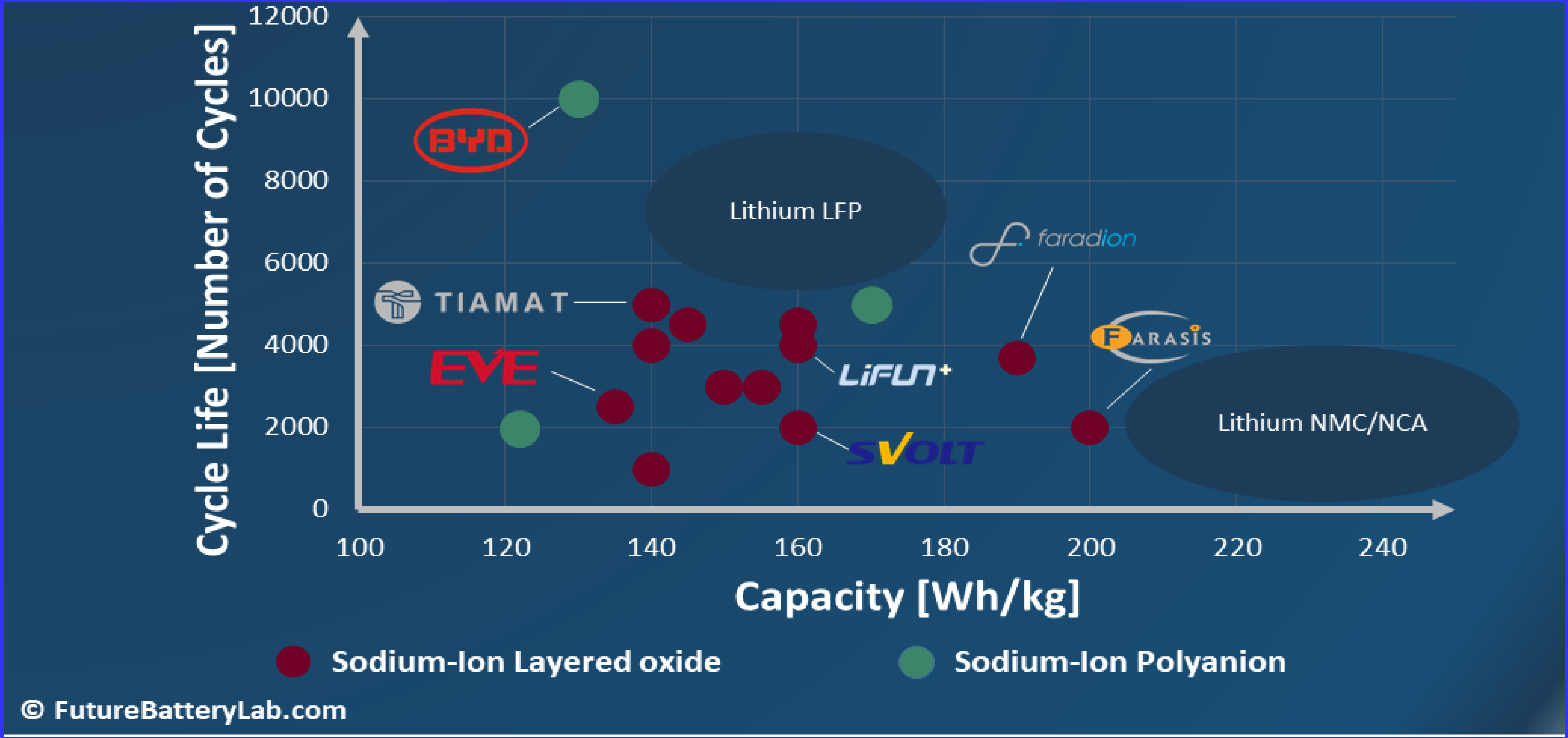


We want low Cost !

Li Carbonate: $20.000 /ton

Na Carbonate: $332 /ton

There are 135 Billion tons of minable Sodium Carbonate available in the Green River Basin of Wyoming



CYCLE LIFE vs CAPACITY for COMMERCIAL Na-ion BATTERIES

GIGAFACTORIES

US: Natron

China: CATL, BYD

India: Reliance (Faradion)

Sweden: Altris

JAC EV powered by 25kWh Na-ion Battery – 250 km/charge

"BYD begins construction of 30GWh sodium-ion battery plant in China"

BYD, Na-ion, 30 kW / 100kWh

Na-ion Batteries lag Li-ion
with respect to performance,
but they are
competitive on price and
can be sourced domestically.
They will find their market
when Li becomes scarce.

Sodium Batteries – Liquid Sodium and Sodium Ion Batteries.

Ramesh Koripella, Ph.D.

CESA webinar presentation, Nov 07, 2024.

Sandia National Laboratories

This material is based upon work supported by the U.S. Department of Energy, Office of Electricity (OE), Energy Storage Division.

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Sodium ion batteries

- There is a lot of excitement about Na-ion batteries.
  - They are made with earth abundant materials that are lower in cost and safe.
  - No significant thermal runaway problems.
  - They can be shipped in zero charge state. - much safer during shipping.
- There are many different types of sodium batteries – low temperature, high temperature, different chemistries.
  - What are the differences?
  - How do they compare with Li-ion batteries?
  - What is the current state of commercialization?

Outline

- Types of Sodium (Na) batteries
  - High temperature molten Na ion battery types
  - Low temperature Na ion batteries analogous to Li- ion batteries.
- Battery chemistries
- Pros and Cons, typical issues
- Current development status

Information presented here is gathered mostly from the literature articles, publicly available information from conference presentations with some insights based on our discussions with SNL battery experts.

Types of Na ion batteries

Types of Na ion batteries

1. **High temperature** molten Na battery
2. **Low temperature** Na ion battery, analogous to Li ion battery.

1. **Molten Na batteries** (high temperature batteries – few are commercial, few at R&D stage)
   - i. Na-S (Sodium – Sulphur) batteries – Commercial
   - ii. Na-Metal halide (ZEBRA) molten salt batteries – Commercial
   - iii. Intermediate and Low temperature molten Na batteries– still in R&D

2. **Na-ion batteries** (low temperature analogues to Li ion batteries) – early commercial to precommercial stage. Different types based on differences in the choice of anodes and cathodes:
   - i. Layered Oxide
   - ii. Polyanion
   - iii. Prussian Blue Analogs

Moten Sodium Batteries - Sodium-Sulphur Batteries

- **Na-S batteries:** One of the oldest battery chemistries, developed in 1960's.
- Anode is molten sodium (MP: 98 °C) , Cathode is molten sulphur (MP: 118 °C). Electrolyte is solid Beta alumina ceramic tube. It uses low cost raw materials, but operating temperatures are high.
- Discharge: $xS + 2Na = Na_2S_x$ ($3 \le x \le 5$), cell V_{oc}~2.08 V at >300°C

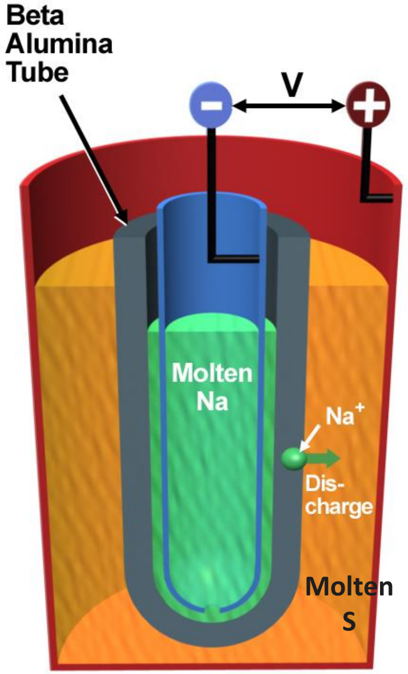
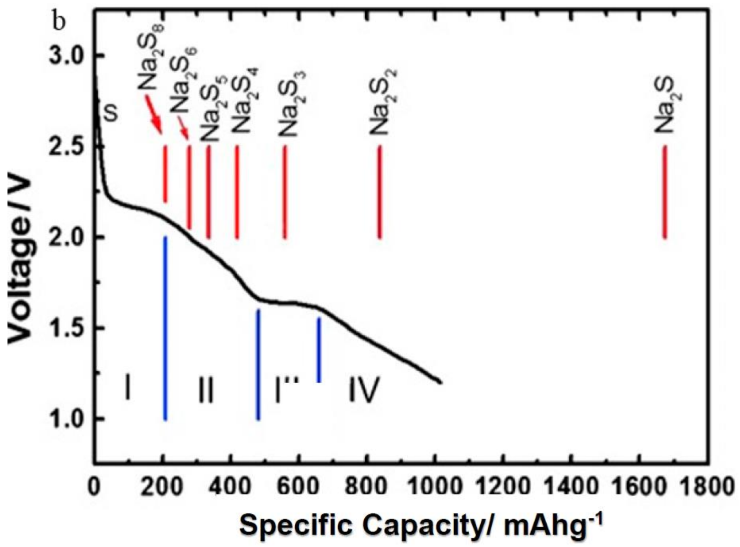
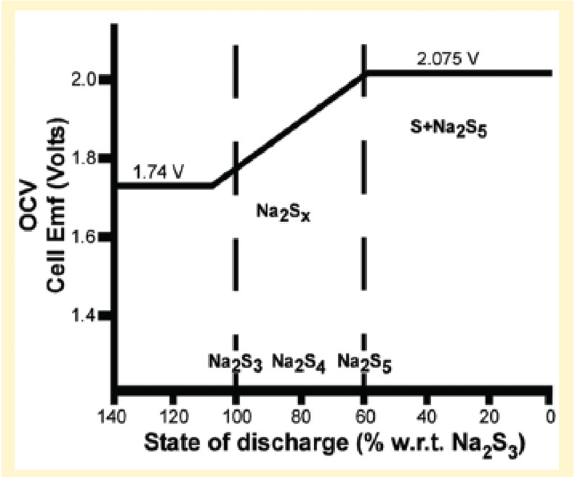


Illustration of a tubular molten Na-S battery configuration using a β″-alumina solid electrolyte (BASE).



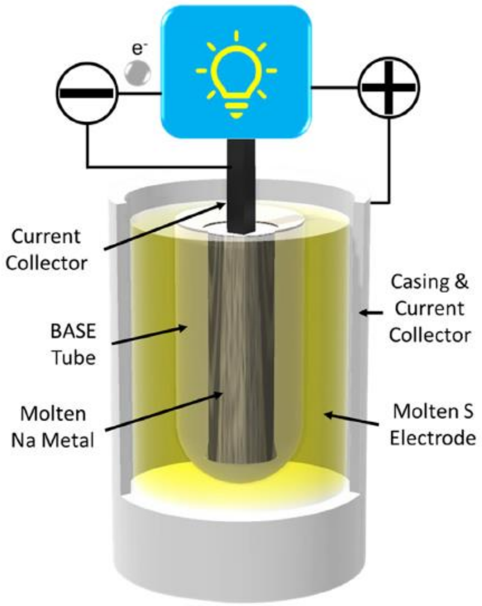


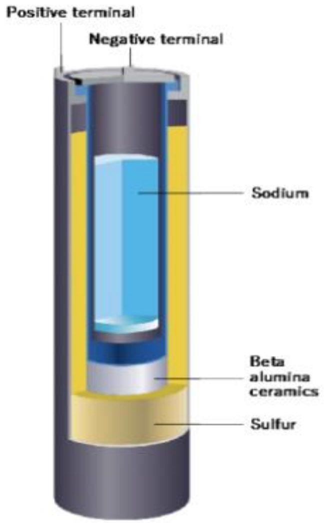
<u>Developed in 1960s at Ford Motor Company.</u>

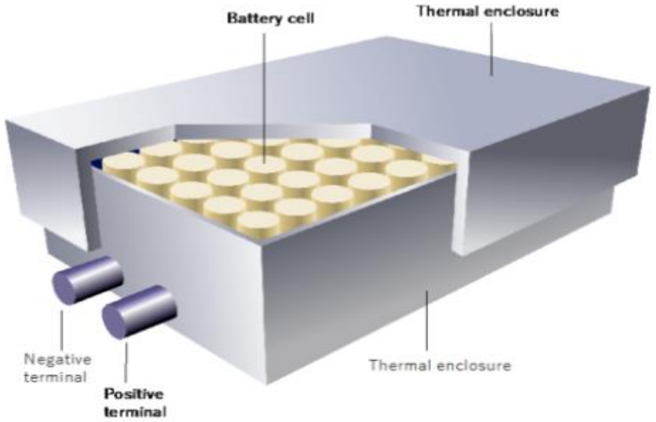
- **Typically fabricated in tubular form for ease of handling molten liquid metals. Difficulty with seals for planar configuration.**
- **High temperature operation (>300C), needed for good ionic conductivity, but raises safety concerns.**
- **Theoretical specific capacity of Na-S is very high 1672 mAh/g, but due to the 1.74V discharge limitation, it drops to 557 mAh/g**

Commercial Sodium-Sulphur Batteries (NGK)

- **Originally developed by Ford Motor Co in 1960's**
- **Commercialized by NGK for stationary power. 700MW/4.9GWh deployed mostly in Japan.**







Issues:

- High temperature (**300-350 °C**) **operation**. Thermal management is important, approximately **15%** daily **thermal loss** is normal. Need external heaters for start up. Targeted for 6-8 hr storage duration, energy density ~ 115 Wh/Kg, >5000 Cycle life, ~75% RTE and 15 yrs life.
- **Safety issues:** Handling two molten liquid electrodes Na (MP: 98 °C) and Sulphur (MP: 118 °C) separated by a Beta alumina solid electrolyte (BASE). Any cracks or failures in the ceramic Beta alumina electrolyte can cause short circuits by mixing the liquid Na and S, creating violent reactions and explosions.
- Metallic Na is combustible if exposed to moisture. **Cells are hermetically sealed, surrounded by sand in an insulated box**.
- **After one major safety incident, several design and operational improvements were made** with BMS controls with a good track record.

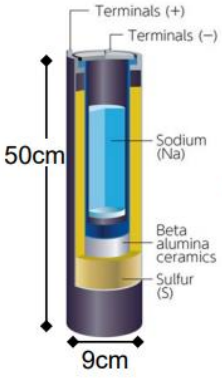
BASF- NGK collaborative efforts on Na-S batteries

NAS® Battery system design

NEW PRODCUT RELEASE 2024

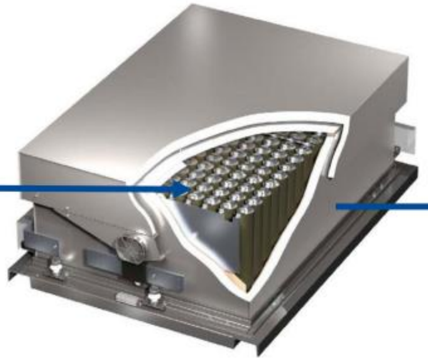
- Significantly improved heat management system
- Superior capacity degradation rates over lifetime

Battery cell



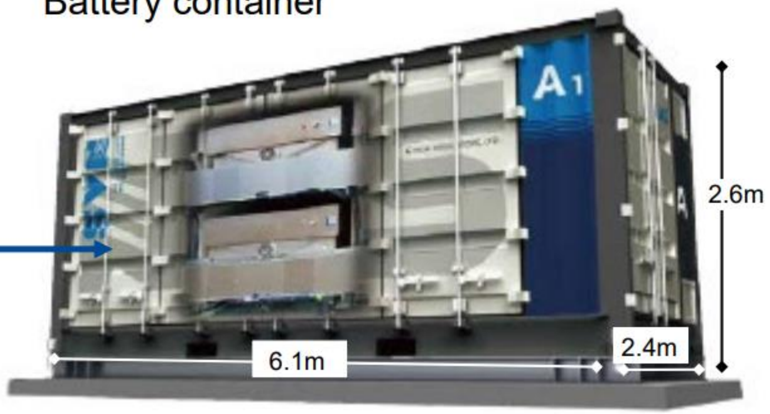
X 192

Battery module



X 6

Battery container



- 1.2kWh / 5.3kg
- ~2V
- C-rate 1/6 (0.17)
- T-range: 290°C – 360°C
- Life time: 7300 cycles or 20 years

- 40kW / 245kWh

- 20 feet container / 21 ton
- 250kW / 1.45MWh

4

BASF
We create chemistry

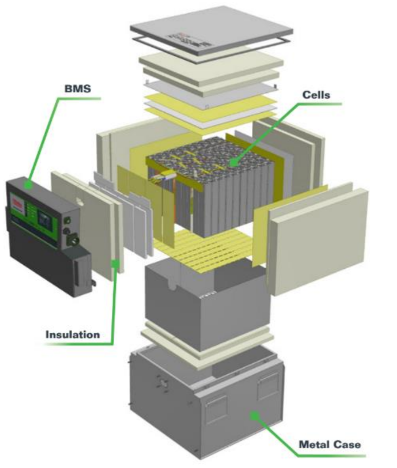
Several safety features were introduced. Successfully completed the UL 9540a, container level thermal runaway tests.

Source: BASF presentation at NattBatt - Na, Zn batteries conference in Houston, 2023.

Sodium Metal Chloride Batteries also known as ZEBRA batteries.

- Sodium metal chloride batteries also known as sodium metal halide batteries or ZEBRA batteries: Anode is molten Na, Cathode is molten sodium tetrachloroaluminate ($NaAlCl_4$) salt mixed with $NiCl_2$ (and some times $FeCl_2$), electrolyte is modified Beta alumina ceramic.   Low cost raw materials, high temperate operation.
- Discharge: $NiCl_2 + 2Na = Ni + 2NaCl$, cell V~2.58 V at 250°C
- Currently being developed and commercialized by SoNick® systems, based in Switzerland. (*Similar Na metal chloride battery system was developed earlier by GE for locomotive applications and abandoned*)
- For the ZEBRA system, power density is ~166 Wh/kg.   Na-$NaCl_2$ operates at a lower temperature and slightly safter compared to Na-S batteries, but the higher cost of Ni is a challenge.

SMC Battery Modules



Module Contents

FZSONICK ENERGY BACKUP

Other molten Sodium batteries – Adena Power

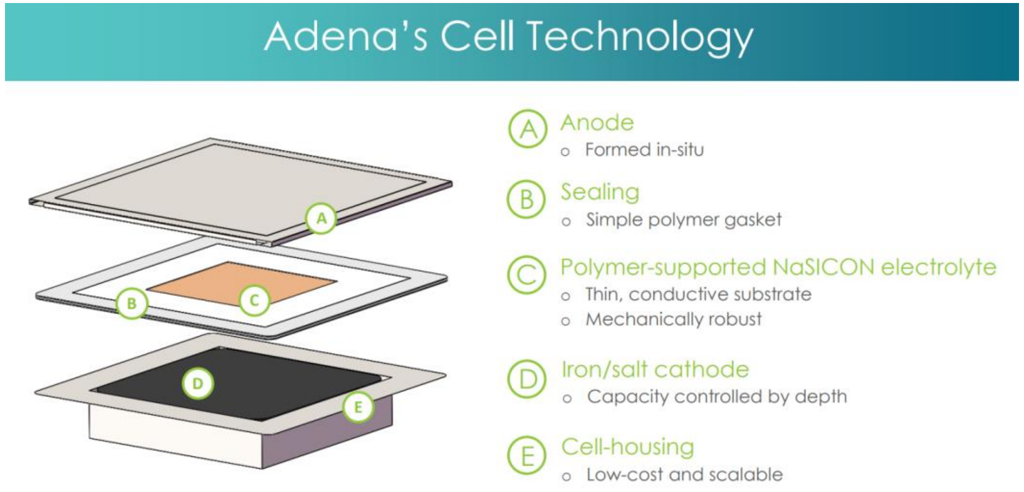
ADENA POWER

Sodium Solid Electrolyte batteries for stationary energy storage

Demonstrations with utility partners to support C&I buying decision

DUKE ENERGY. 15 kWh system demonstration

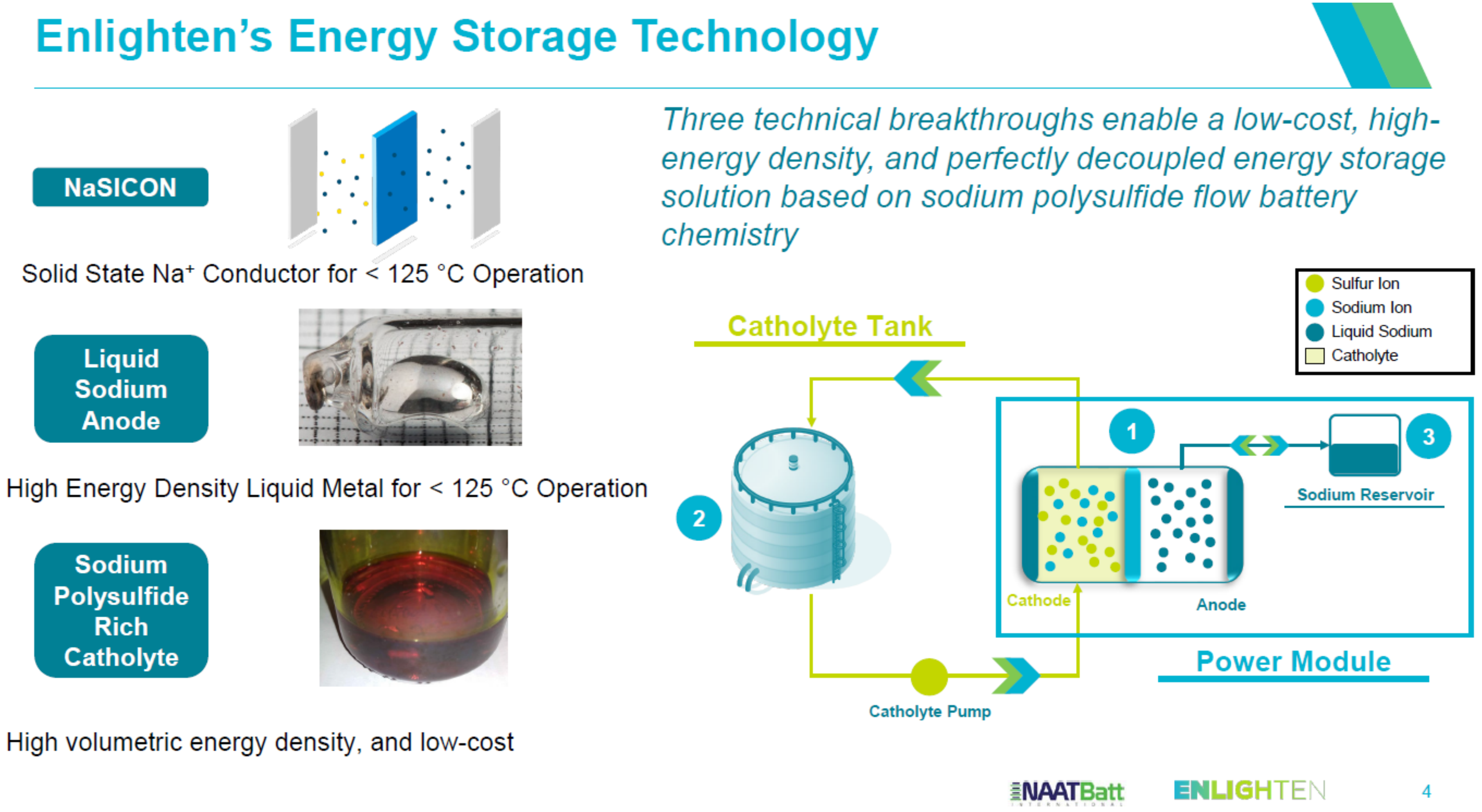
incubatenergy labs



- It utilizes **NaSICON** a slightly lower temperature (~125-150°C) electrolyte.
- High temperature plastic seals can be used.
- **Precommercial stage.**

https://adenapower.com/

Sodium-polysulphide flow Battery



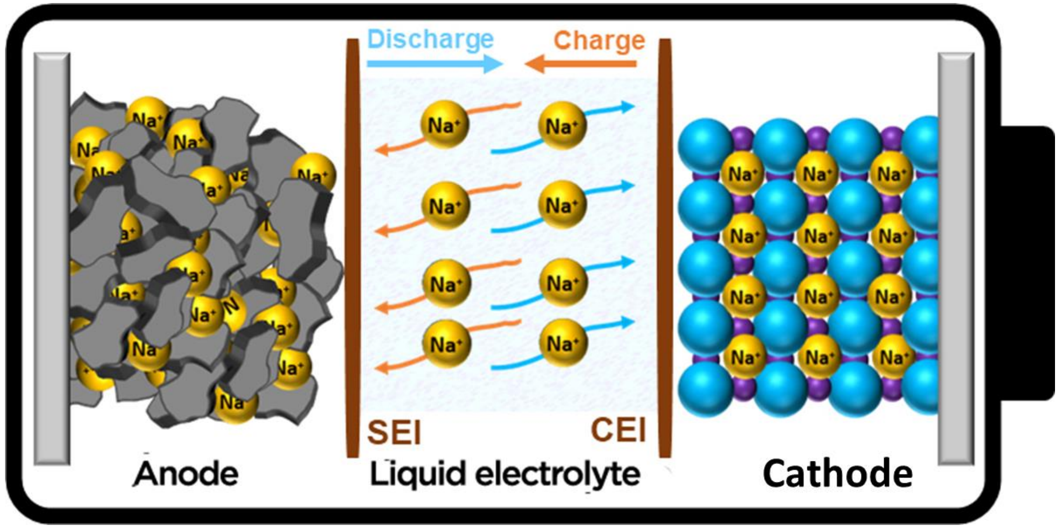
R&D stage.

From Enlighten's presentation at NATTBatt 2023, Houston.

Switching gears to low temperature Na-ion batteries.

Na-ion batteries

Na-ion batteries (SIB) are very similar to Li-ion batteries (LIB).



Na ions shuttle between the anode and cathode during charge and discharge very similar to Li ion battery.
Cathodes: Na based material of different types
Anodes: Hard Carbon, intercalation oxides, conversion & alloying
Electrolyte: mostly organic, few aqueous electrolytes
Separator: Polymer membrane very similar to Li ion battery
Current collectors: Al on both sides

- During charging Na ions move from the cathode to anode and the reverse process occurs during discharge.
- In Li ion batteries, Li ions shuttle between graphite anode and layered perovskite type cathode during charge and discharge. Graphite anodes (also Si anodes) used in Li-ion batteries are not a good choice for Na ion batteries.
- Through R&D efforts, suitable stable anode and cathode materials were developed for Na ion batteries and some versions are being commercialized.
- Several Chinese companies such as HiNa, CATL and Farasis announced mass production plans for commercialization. In the Europe, Faradion, Northvolt, Tiamat and in the US, Natron Energy have also announced commercialization plans.

Figure Source: https://cicenergigune.com/en/blog/sodium-ion-batteries-sustainable-lowcost-energy-storage-technology

Sodium ion Battery Performance Comparison

	Lead acid	NiMH	Na-Ion	LFP	NMC
Energy density (Wh/Kg)	30-50	60-120	70-160	90-160	200-250
Nominal Voltage (V)	2	1.25	3.1-3.2	3.2	3.6
Cycle life (80% retention)	200-300	300-1000	>1000	5000	1000-2000
Self discharge [month]	5-10%	15-20%	5%	2-3%	0.5-2.5%
Est. Cost ($/kWh)	50-100	250	50-80	60-95	90-110
Operating Temp. range (°C)	-20C to 70C	-40C to 50C	-40C to 80C	-20C to 60C	-20C to 60C

- Performance of Na ion batteries are comparable to LFP batteries, their biggest competition.
- Even though Na is much less expensive than Li, the difference are only in the cathode materials and in the current collectors of both batteries, rest of the materials and processing costs would be similar. May be 10-20% cost advantage.

Source: 2024 DOE-OE peer review presentations, open literature

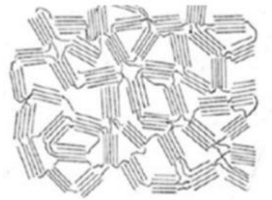
Na-ion battery types and material choices

- There are different varieties of Na ion batteries depending on the choice of materials used for the anode, cathode and the electrolyte. Voltage output, performance, cycle life and cost depend on the materials choice.

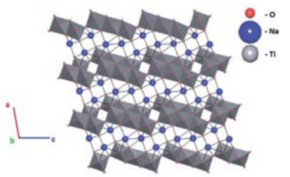
- **Anode materials:** 3 types - Hard Carbon, Ti based intercalation oxides, conversion & alloying anodes.

  - **Hard Carbon** – current standard anode. **Pros:** decent specific capacity (~300 mAh/g), voltage and rate performance. **Cons:** limited capacity, initial irreversible capacity loss, Na plating.
  - **Ti based intercalation oxides:** TiO_2, $Na_2Ti_3O_7$ etc. **Pros:** low working potential (0.3V for $Na_2Ti_3O_7$). **Cons:** low electronic conductivity and Na diffusion kinetics, low capacity.
  - **Conversion and alloying:** Sn, Pb, P, Sb etc. **Pros:** High capacity (>500 mAh/g). **Cons:** large volume change, low electronic conductivity.

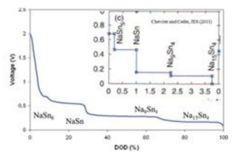
    [Sodium is known to electrochemically and reversibly alloy with several group IV and V elements including phosphorus (P), germanium (Ge), tin (Sn), antimony (Sb), lead (Pb), and bismuth (Bi). Alloying materials store Na through a series of reactions involving bond breaking and forming, leading to the formation of the various alloy phases (NaxM, where M = P, Ge, Sn, Sb, Pb, or Bi).] (**UNIGRID**)



TiO_2, $Na_2Ti_3O_7$, etc.



Sn, Pb, P, Sb, etc.



Na-ion battery types and material choices

Cathode materials: different types such as; Layered oxides, Polyanionic, Prussian blue analogs.

- **Layered oxides**: Na_xMO_2 (***Faradion***), capacity ~ 190 mAh/g
- **Polyanionic:** NASICON, NaFP, NVP, NVPF (***Tiamat***), capacity ~ 117 mAh/g
- **Prussian Blue**: $Na_xMFe(CN)_6$ and other variations (***Natron Energy, CATL*** -Prussian white). capacity ~ 165 mAh/g

Electrolytes: mostly organic solvents, Na-salts.

- Organic solvent: Ethylene carbonate (EC), propylene carbonate (PC)
- Na-salts: $NaClO_4$ salts, $NaPF_6$ salts, and other R&D efforts
- Aqueous Electrolytes: Natron uses aqueous electrolyte, results in lower cell voltage compared to organic electrolyte systems. Ex: $NaNO_3$, $NaClO_4$ with other additives.

Current Collectors: Al metal is used at both cathode and anode (Lower cost, less inventory). *(For Li-ion batteries, Cu at the anode and Al at the cathode are used.)*

Source: Christopher Johnson (Argonne National Labs), NattBatt Na & Zn Conf 2003, Houston

Na - ion Battery Types Schematic

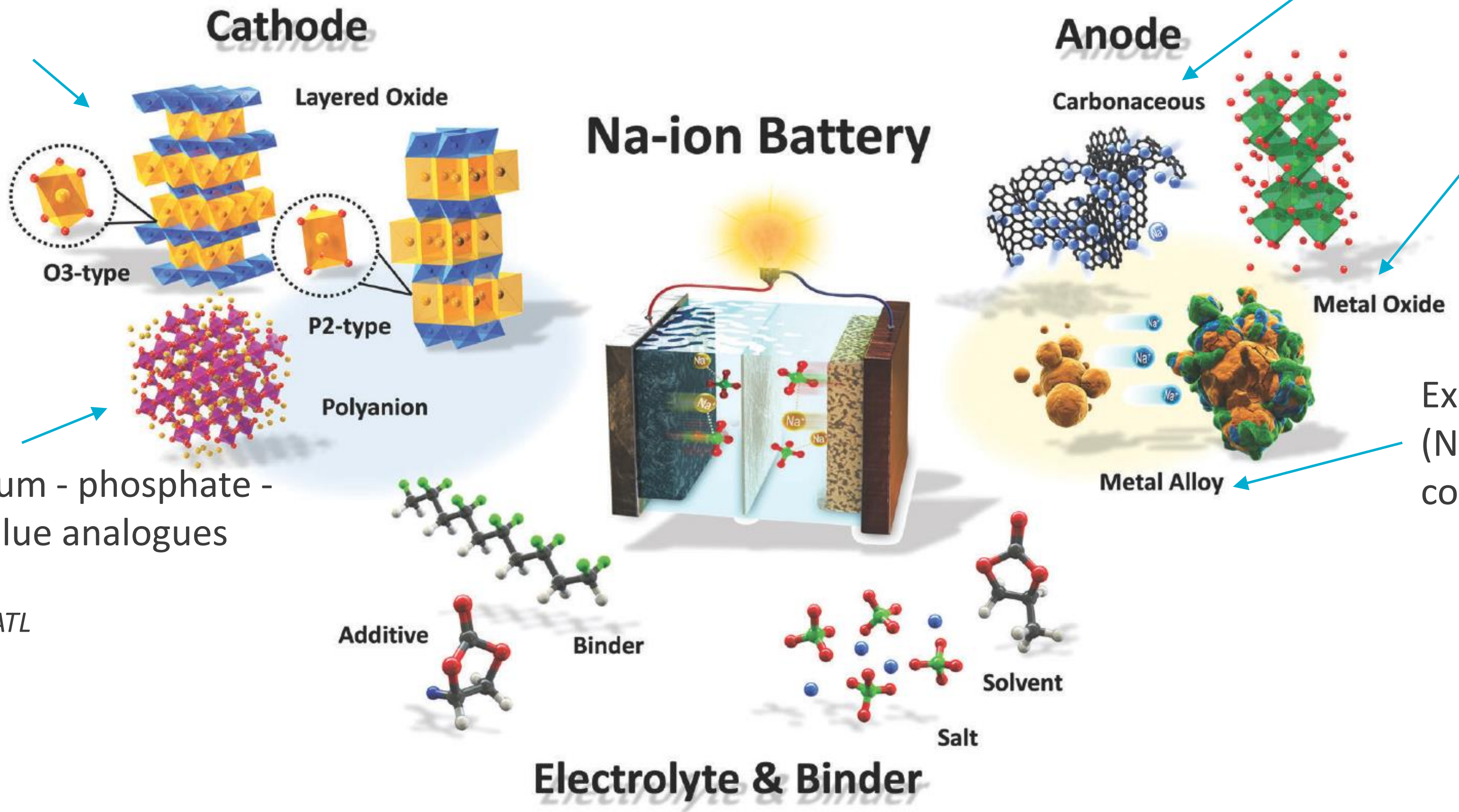
Ex: Transition metal oxide of type P3, P2 or O3. $Na_{0.76}Mn_{0.5}Ni_{0.3}Fe_{0.1}Mg_{0.1}O_2$ (Intercalation of Na)

Faradion, NorthVolt

Ex: Hard Carbon (Intercalation of Na)

Faradion

Ex: $Na_2Ti_3O_7$ or $NaTiO_2$ (Intercalation of Na)



Ex: Pb, P, Sn, Ge, etc. (Na alloying with metals or conversion reaction, FeS_2)

Unigrid

Ex: sodium - vanadium - phosphate - fluoride. Prussian blue analogues ($Na_2MnFe(CN)_6$).

Natron Energy, CATL

Ex: typically non-aqueous electrolytes with $NaClO_4$ and $NaPF_6$ salts dissolved in EC, PC, DMC, DEC. Few aqueous types.

Source: https://doi.org/10.1039/C6CS00776G, Chem.Soc.Rev., 2017, 46, 3529-3614.

Comparison of few Na ion batteries under development

	Faradion	Tiamat	HiNa Battery	Natron Energy
Anode	Hard Carbon	Hard Carbon	Hard Carbon	Prussian Blue
Cathode	Layered Oxide ($Na_xNi_{1-x-y-2}Mg_xMn_yTi_zO_2$)	Polyanionic ($Na_3V_2(PO_4)_2F_3$)	Layered Oxide ($Na_wCu_xFe_yMn_zO_2$)	Prussian Blue
Electrolyte	Organic Liquid	Organic Liquid	Organic Liquid	Aqueous Liquid
Voltage (V)	3.0 -3.15	~3.7	~3.2	~1.56
Cycles	1000-3000	4000	> 4500	35000
est. Energy density (Wh/Kg)	130-190	90-160	140-155	70

- Natron uses aqueous electrolyte, demonstrated long cycle life, but energy density is low.
- Other developers uses organic electrolyte with high energy density but cycle life is low.

Source: https://cicenergigune.com/en/blog/achievements-challenges-sodium-ion-battery-materials, Montse Galceran, CIC energiGUNE.

Sodium-ion batteries summary

- Compared to Li ion batteries, Na ion batteries are lower in cost, and uses earth abundant materials.
  - No Lithium, Cobalt and very low or no Nickel.
  - Utilizes Aluminum current collectors on both sides.
  - Main differences between the two are in cathode materials and current collectors.
  - Manufacturing processes are similar. Approx. 10-20% cost advantage over Li-ion batteries.
- Lower energy density than NMC batteries, but performance is comparable to LFP, their main competition.
- Offers better low temperature performance compared to Li ion batteries.
- They can be charged and discharged faster than Li ion batteries.
- Na ion batteries can be stored and transported in zero voltage. Safe for transportation. Li ion batteries should be stored at some minimum charge.
- The Na ions are larger than the Li ions and causes more stresses in the anodes and cathodes during intercalation leading to structural failures during charge/discharge cycles. Prussian Blue analogues have 3D structures with large channels for Na ion diffusion offering good cycle life.
- Main challenges are; increasing the cycle life, increasing the energy density and scaling up for high volume manufacturing.

Thank you for your attention

Questions?

Acknowledgements

This material is based upon work supported by the U.S. Department of Energy, Office of Electricity (OE), Energy Storage Division.

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Exceptional service in the national interest

MULTI-SCALE SAFETY EVALUATION OF COMMERCIAL SODIUM-ION CELLS AND MATERIALS

Alex M. Bates

Sandia National Laboratories

ESTAP Webinar, Sodium-Ion Batteries

November 5, 2024

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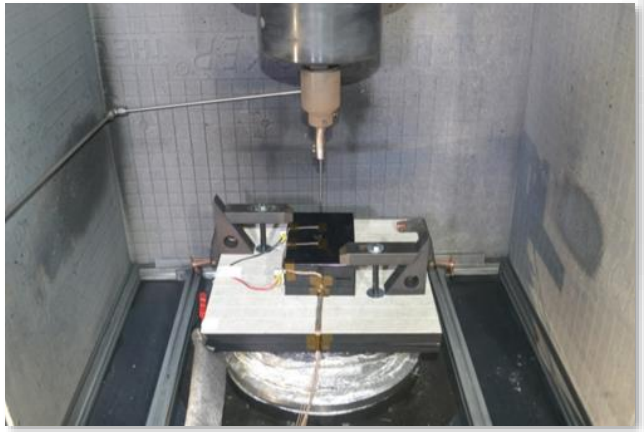
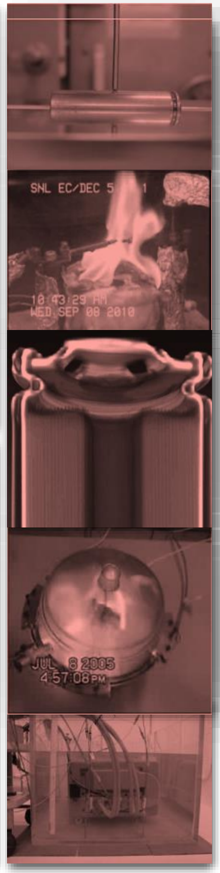
Sandia National Laboratories – Capabilities and Infrastructure

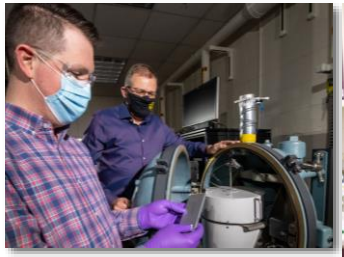
Cell and Module Testing (<1kWh)
Battery Abuse Testing Laboratory (BATLab)

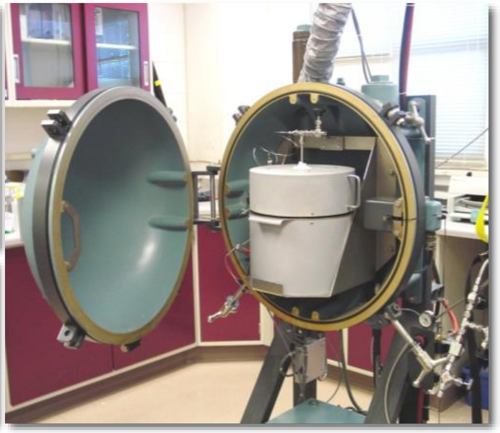




Battery Pack/System Testing
Thermal Test Complex (TTC) and Burnsite (<100kWh)



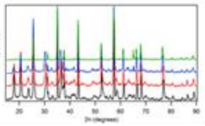

Battery Calorimetry (multi-scale)





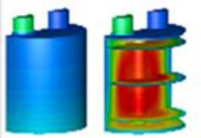
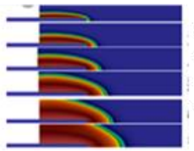

BATLab Destructive Testing – Demonstration Reel

Exploring All Aspects of Battery Safety and Reliability

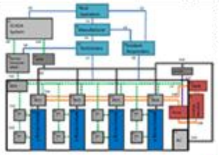



Materials R&D
- Thermal stability and aging impact on battery components
- Vent gas composition
- Solid state battery safety
- Aqueous battery gas evolution


Cell and Module Testing
- High precision cell cycling and degradation
- Electrical, thermal, mechanical abuse testing
- Failure propagation testing on batteries/systems
- Diagnostics during and post battery failure

Simulations and Modeling
- Multi-scale models for understanding thermal runaway and failure propagation
- Fire Dynamic Simulations to predict the size, scope, and consequences of battery fires

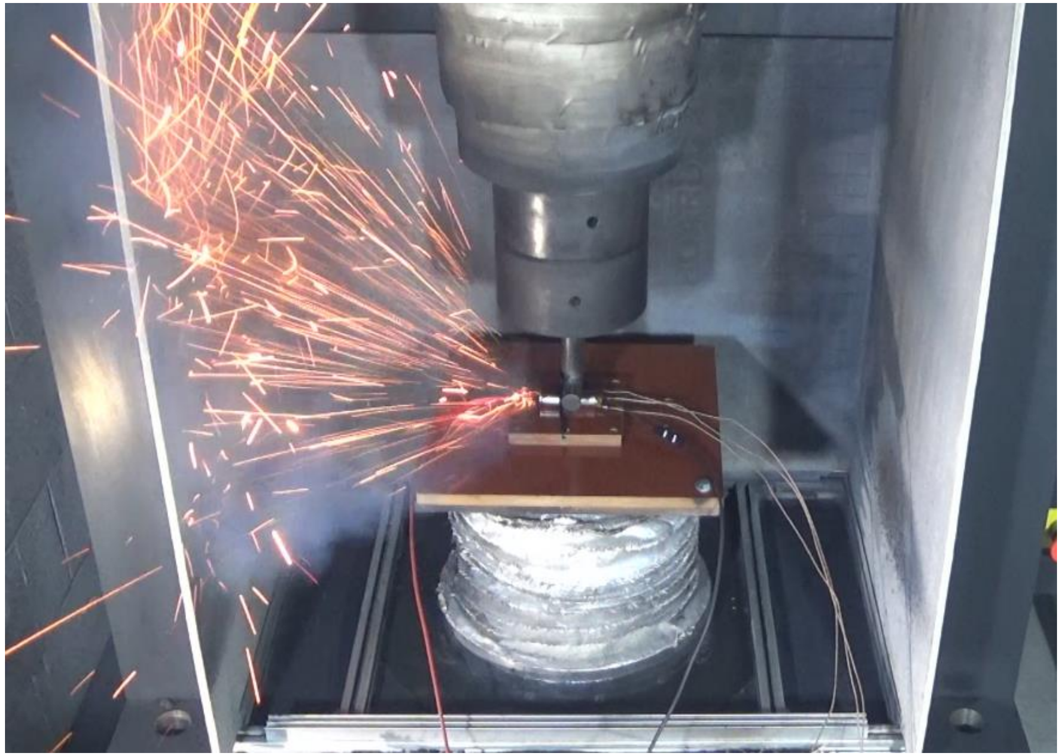



System Level Design and Analysis
- Hazard analysis methods to avoid fire and explosion
- Predictive maintenance
- Improved control using power electronics

Outreach, Codes, and Standards
- USABC Abuse Testing Manual (2022)
- Energy storage safety working group
- IEEE battery management system standard
- EPRI energy storage data submission guidelines

Motivation for Na-ion Safety Testing

Rechargeable, room temperature operation Na-ion technology has quickly transitioned to commercial availability with the promise of similar to Li-ion performance characteristics and fabrication requirements, and lower materials cost.



Na-ion crush test performed at SNL.

Motivation for Na-ion Safety Testing

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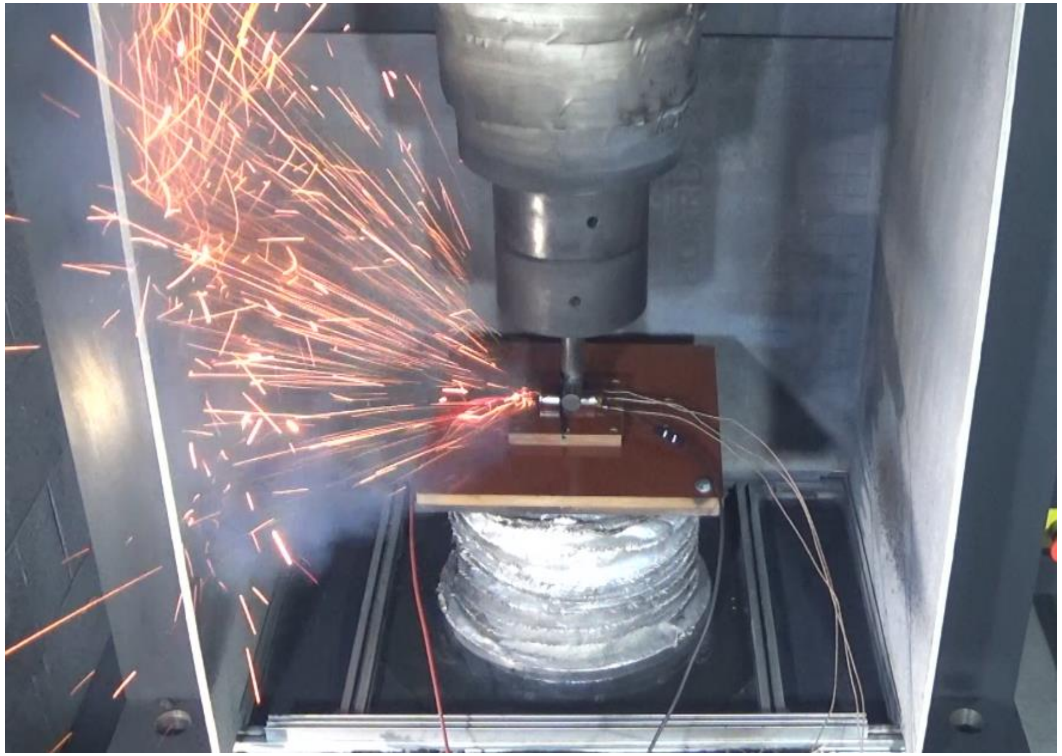
Safety often advertised.

Still largely unknown!



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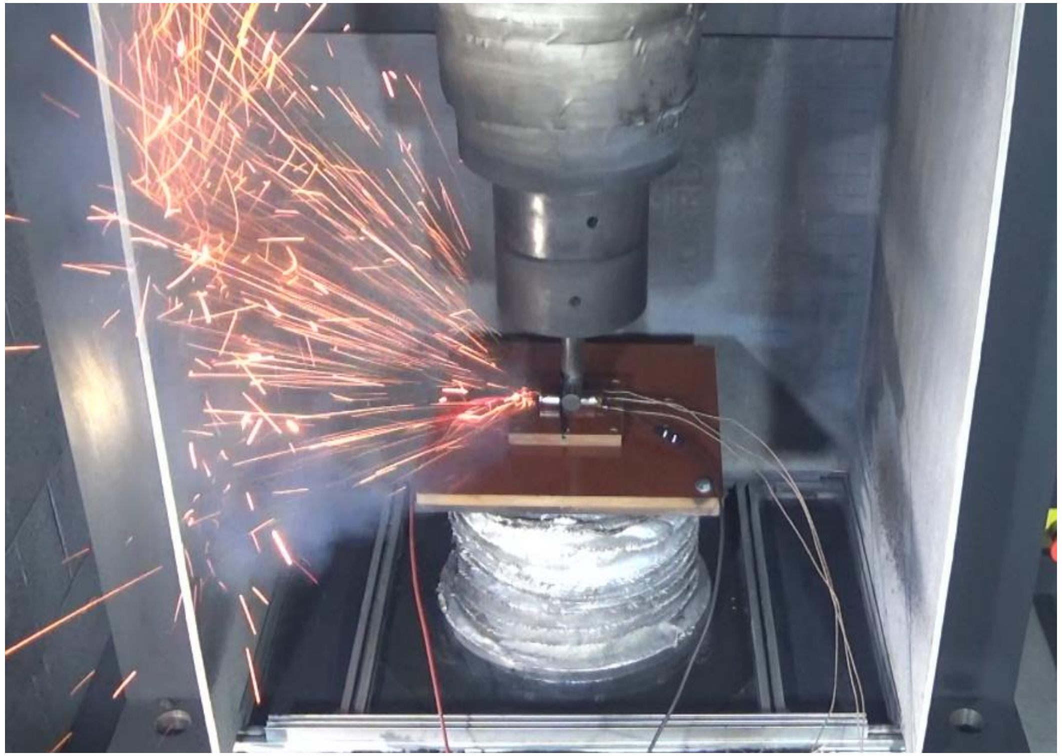
This Presentation:

1. Destructive Testing Comparison of:
   - 1.5 Ah Na-ion 18650 cell
   - 1.5 Ah Li-ion (NMC) 18650 cell
2. Introduction to Materials Scale Analysis



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Na-ion Grid Installations

https://cnevpost.com/2024/05/13/china-1st-large-sodium-battery-energy-storage-station-operation/

https://www.yicaiglobal.com/news/worlds-largest-sodium-ion-battery-project-starts-operation-in-china

- Operational May 11, 2024
- 10 MWh
- Nanning, Guangxi, China
- China Southern Power Grid

- Second Phase
- 100 MWh

18650 DESTRUCTIVE TESTING

Na-ion Material Composition

Na-ion 18650 cells purchased commercially

Specification	Value	Notes
Rated Capacity	1.5 Ah	123 Wh/kg (including case)
Experimental Capacity	1.43 Ah	1.5 to 4.1 V, C/5 rate, C/20 taper charge
Cathode	$Na_{2.5}Ni_1Mn_1Fe_1O_2$	ICP-MS
Anode	Hard Carbon	XRD
Electrolyte – Salt	$NaPF_6$	Assumed based on ICP-MS
Electrolyte – Solvent	46% PC, 21% EC, 14% EMC, 13% DMC	Area% from GCMS

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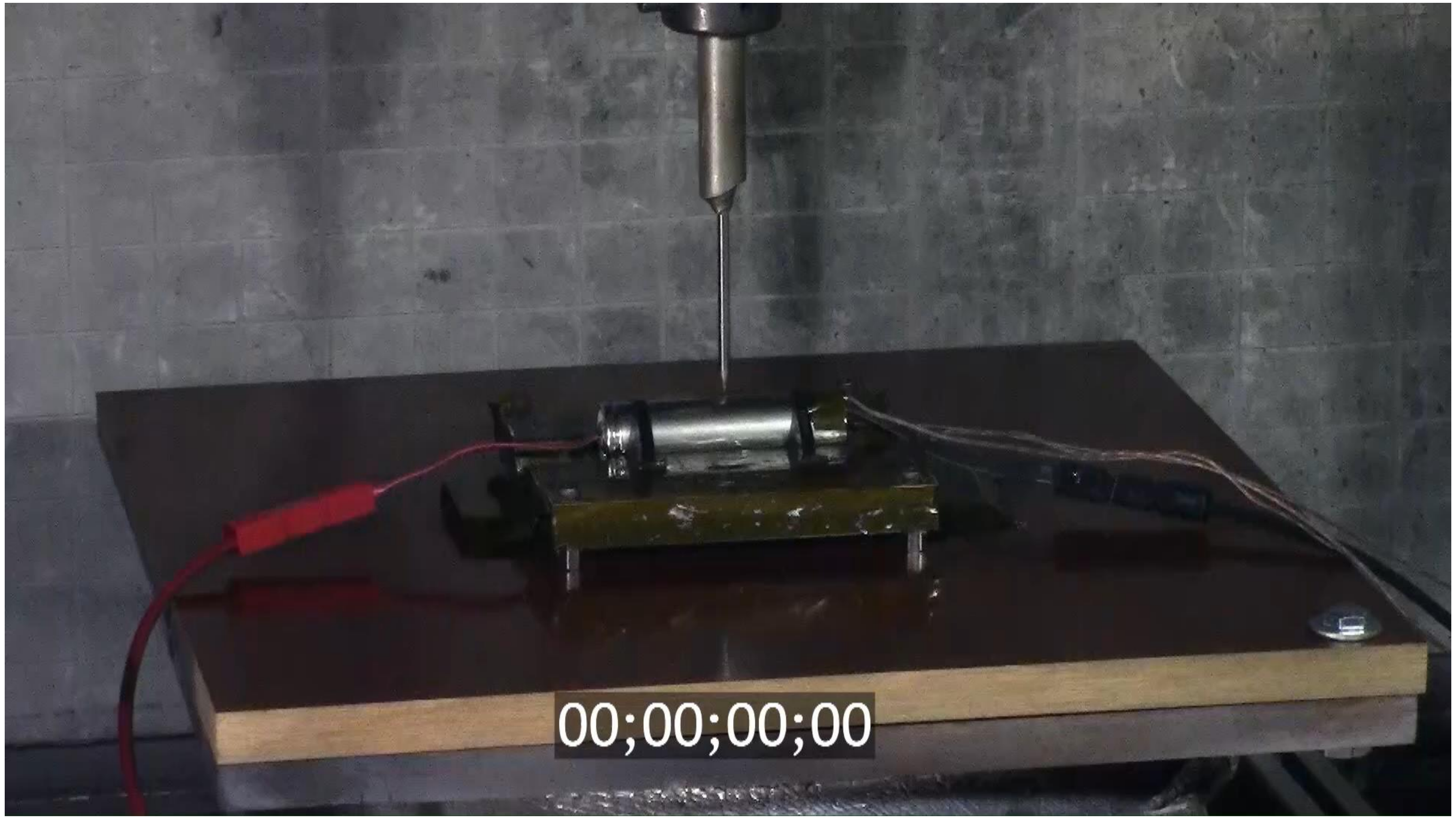
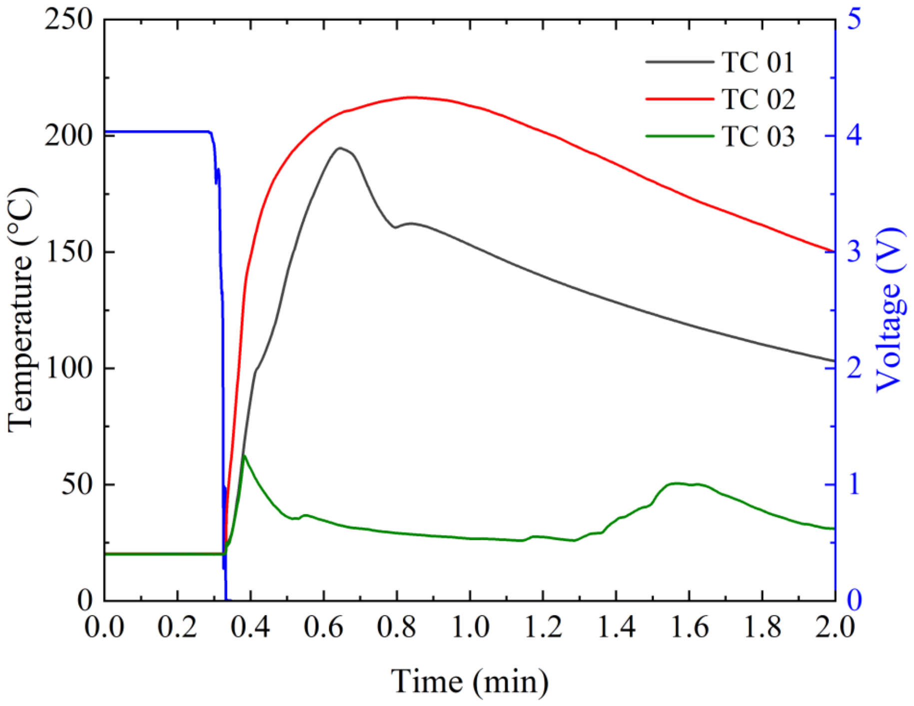
Company	Cathode	Anode	Electrolyte
Natron Energy (US)	Prussian Blue Analog	Prussian Blue Analog	Aqueous
Novasis (US)	Prussian Blue Analog	Hard Carbon	Organic
Faradion (UK)	Layered Oxide	Hard Carbon	Organic
CATL (China)	Prussian Blue Analog	Hard Carbon	Organic
TIAMAT (France)	NVPF	Hard Carbon	Organic
Rechargion (India)	Olivine	Hard Carbon	Organic

Nail Penetration, Na-ion Cell
Close-up Video



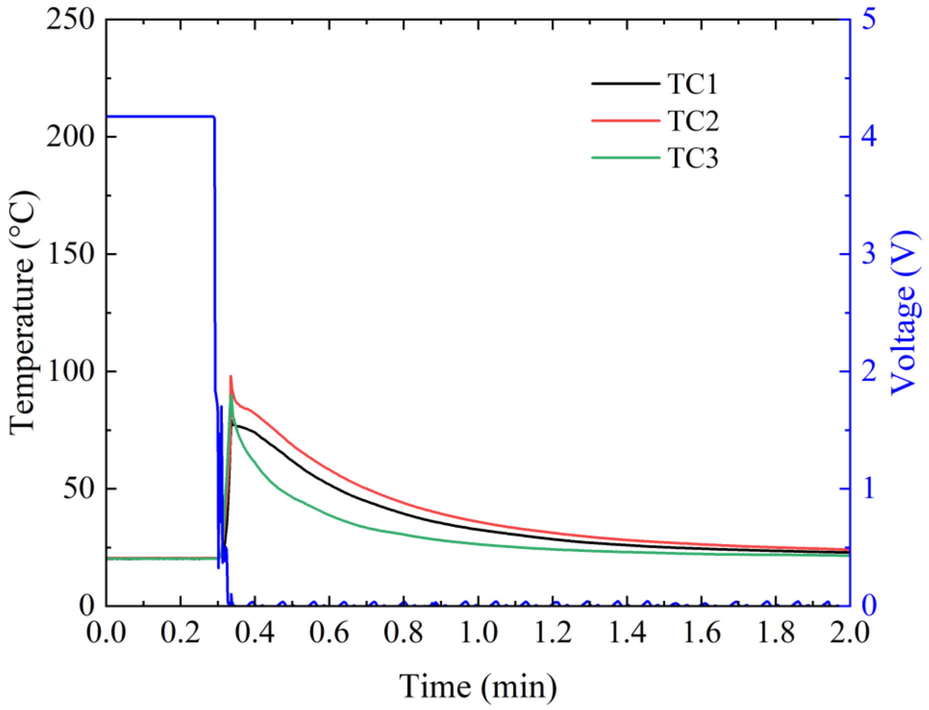
Nail Penetration – Horizontal Orientation
100% SOC, 3 mm sharp nail, 2 mm/s

Na-ion



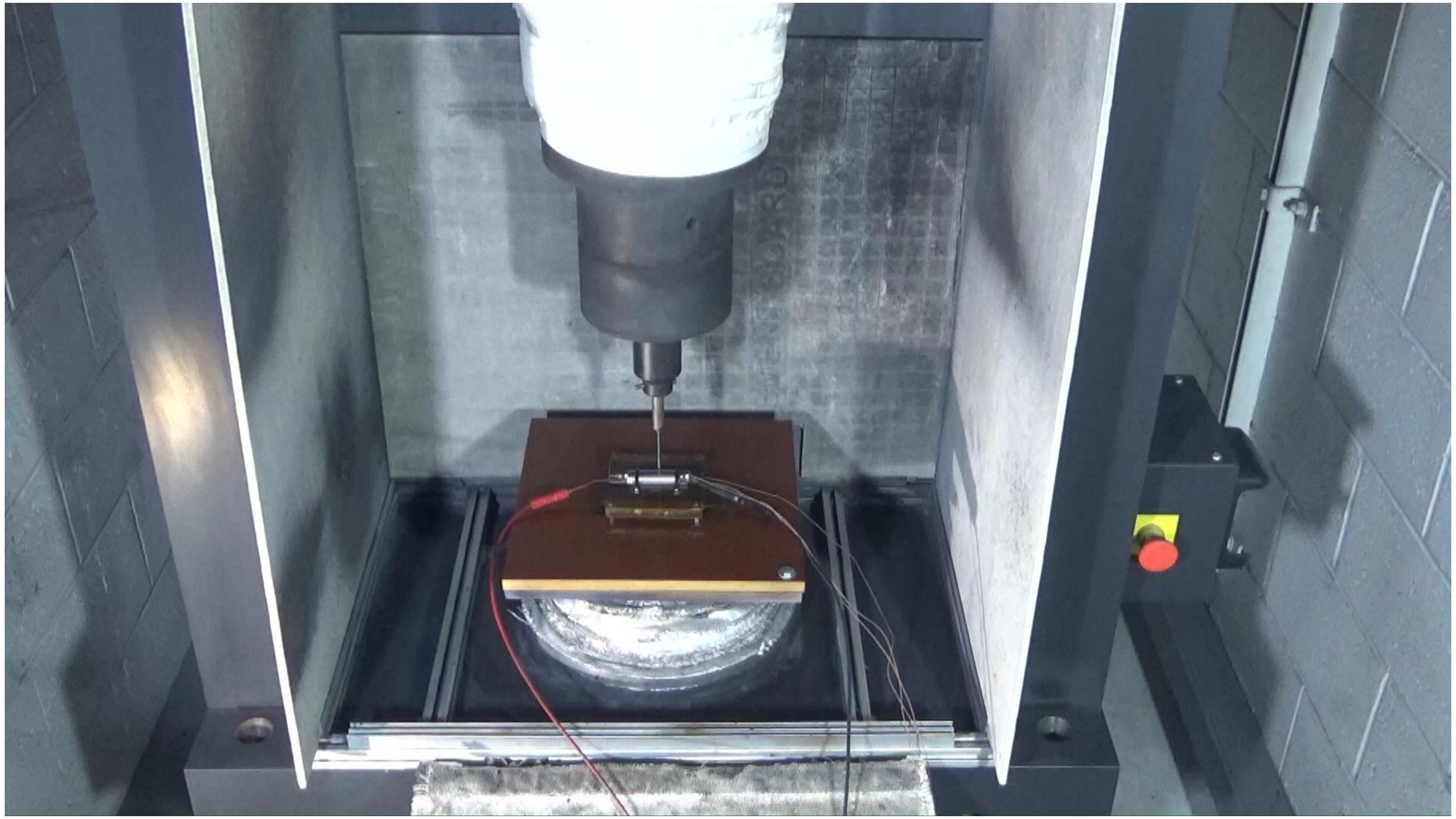
- Max temperature: 216.5 °C
- Nail penetration depth at voltage drop: 1.86 mm
- Venting, smoke, sparks, violent pressure release

Li-ion

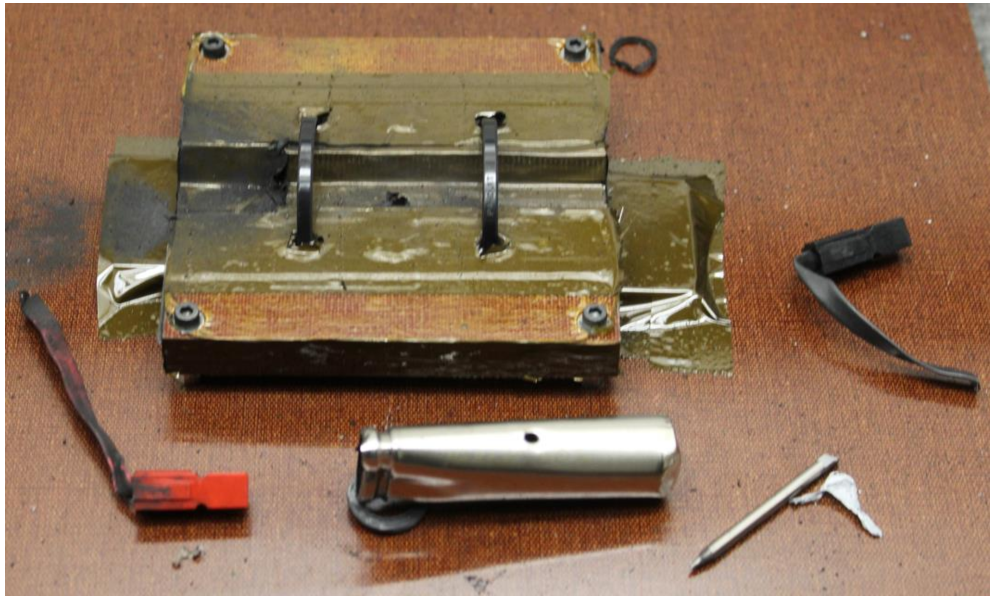


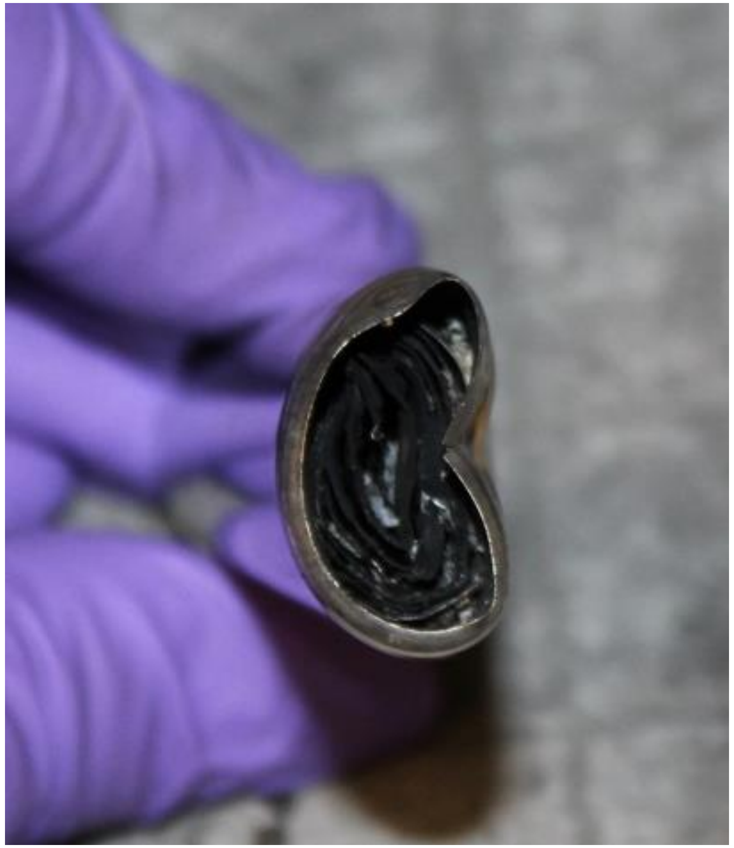
- Max temp: 98.1 °C
- Nail penetration depth at voltage drop: 1.84 mm
- No observable features

Nail Penetration, Na-ion Cell
Wide-angle Video

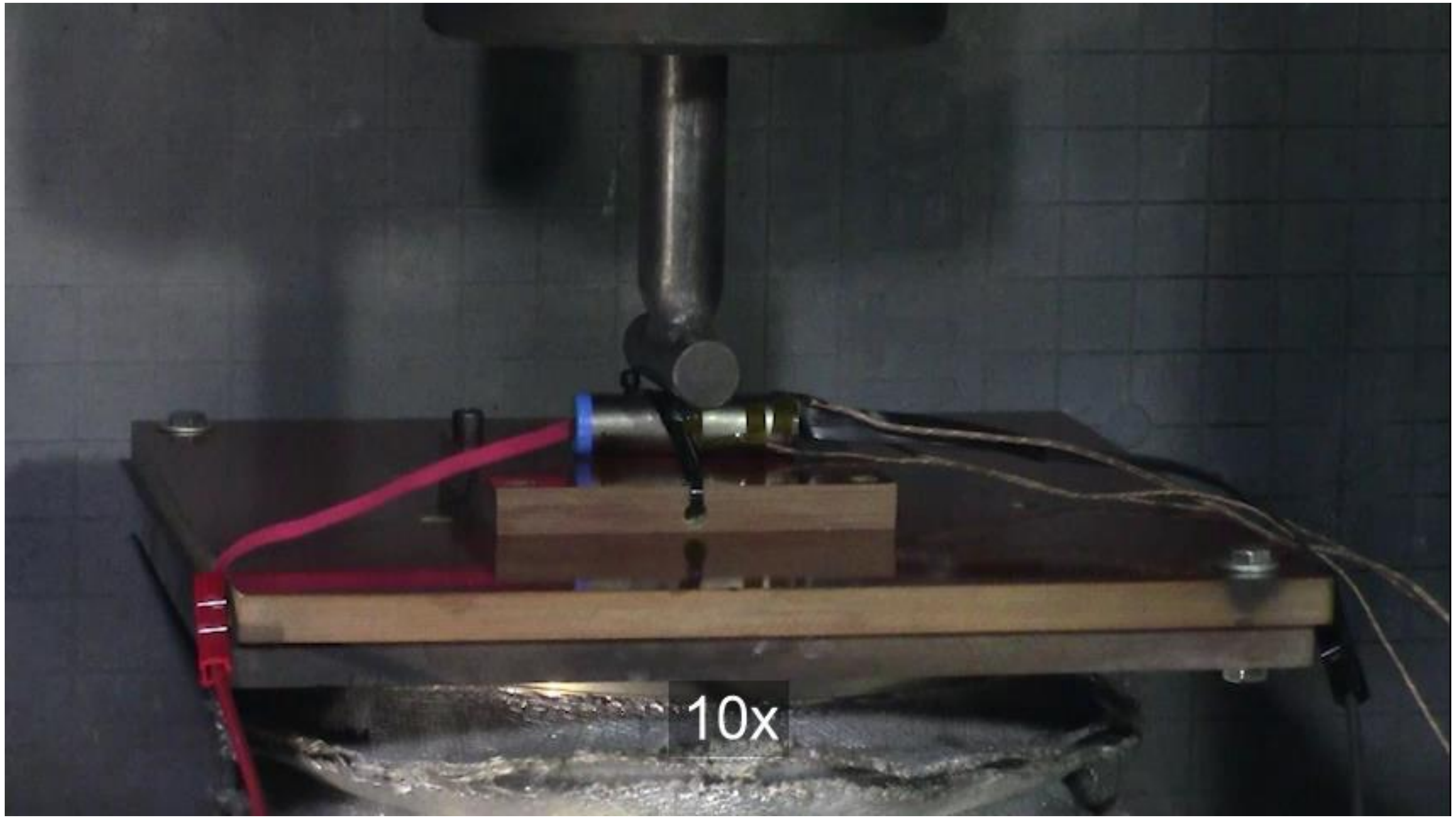


Nail Penetration, Na-ion Cell Post-test Images



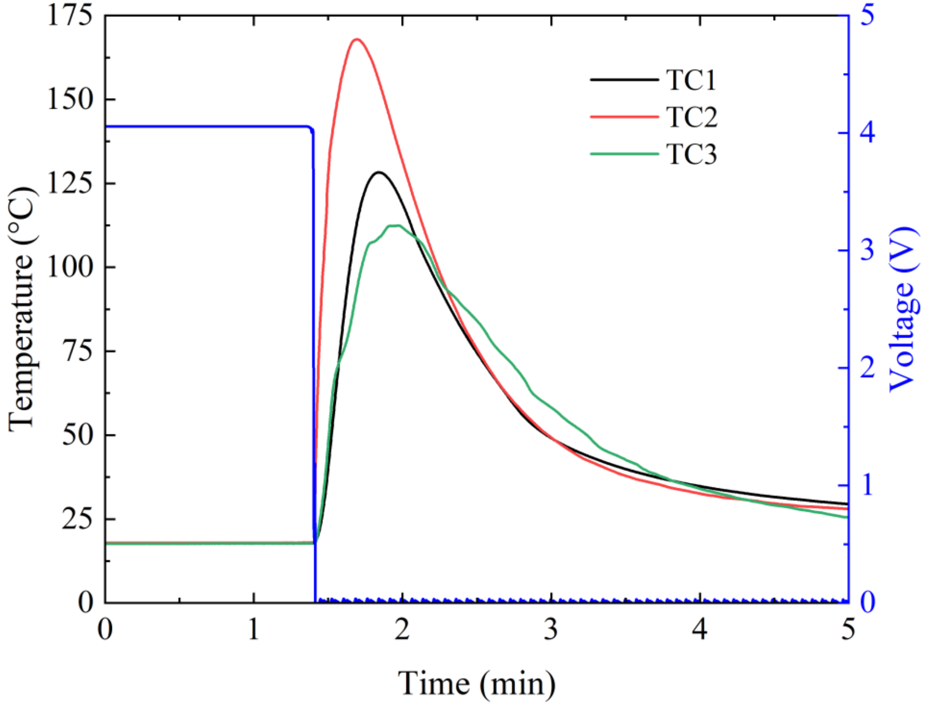


Mechanical Crush, Na-ion Cell



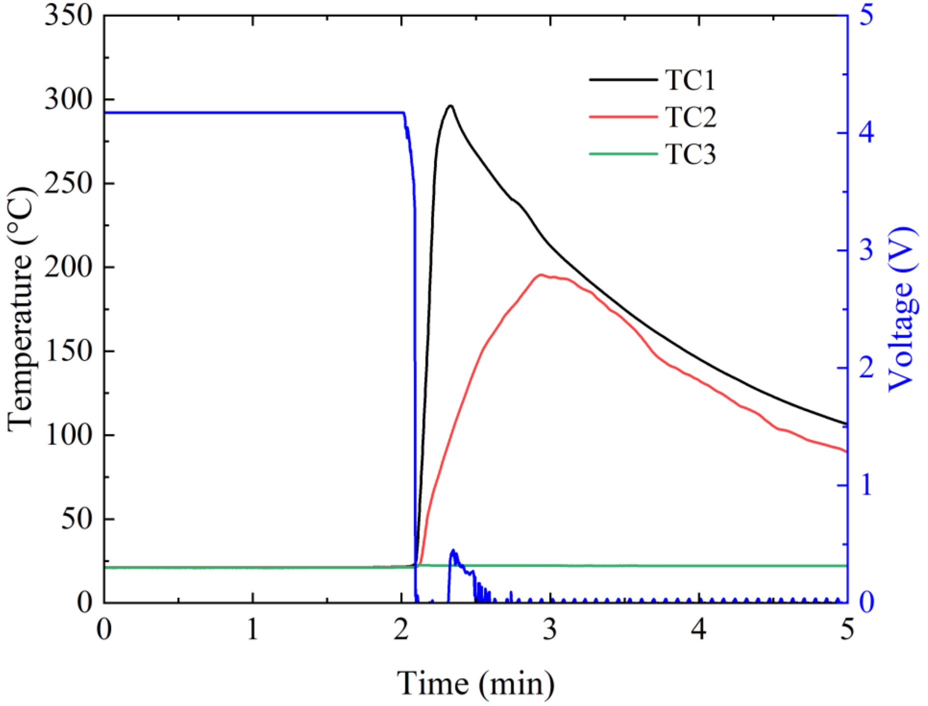
Mechanical Crush
100% SOC, Hammer Implement, 0.1 mm/s

Na-ion



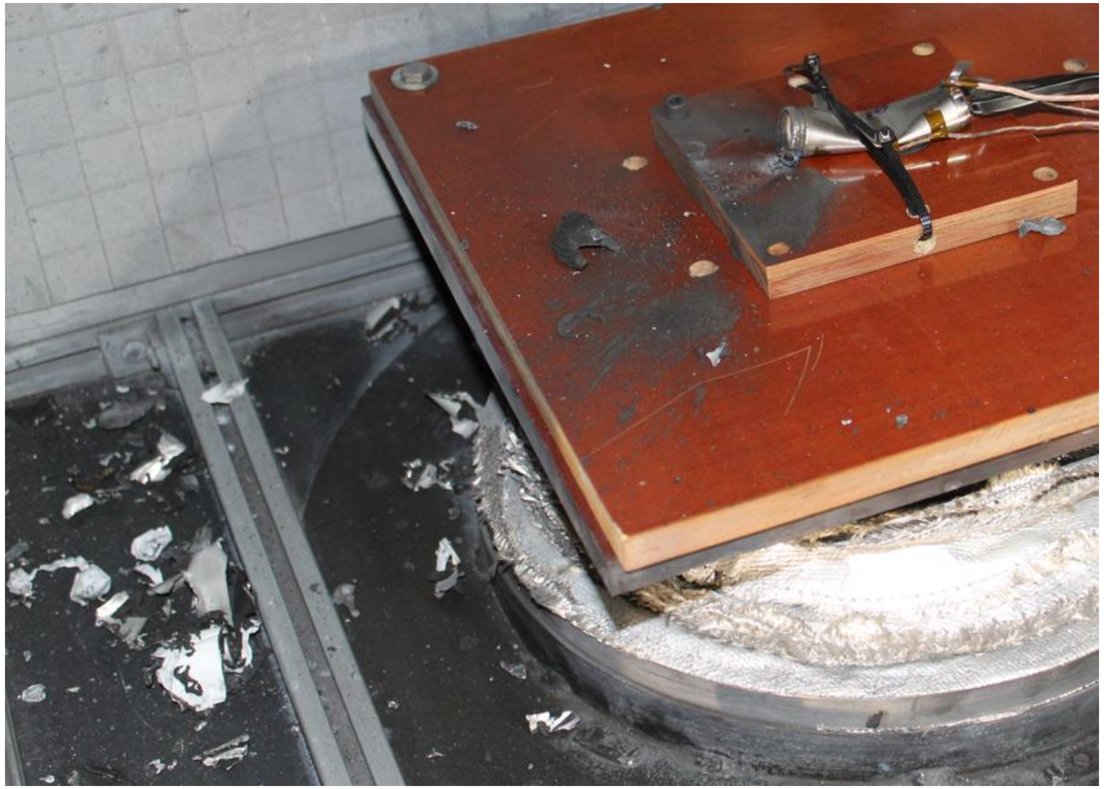
- Max temp: 167.9 °C
- Crush depth at voltage drop: 6.46 mm
- Vent, smoke, sparks, lid pop, flame

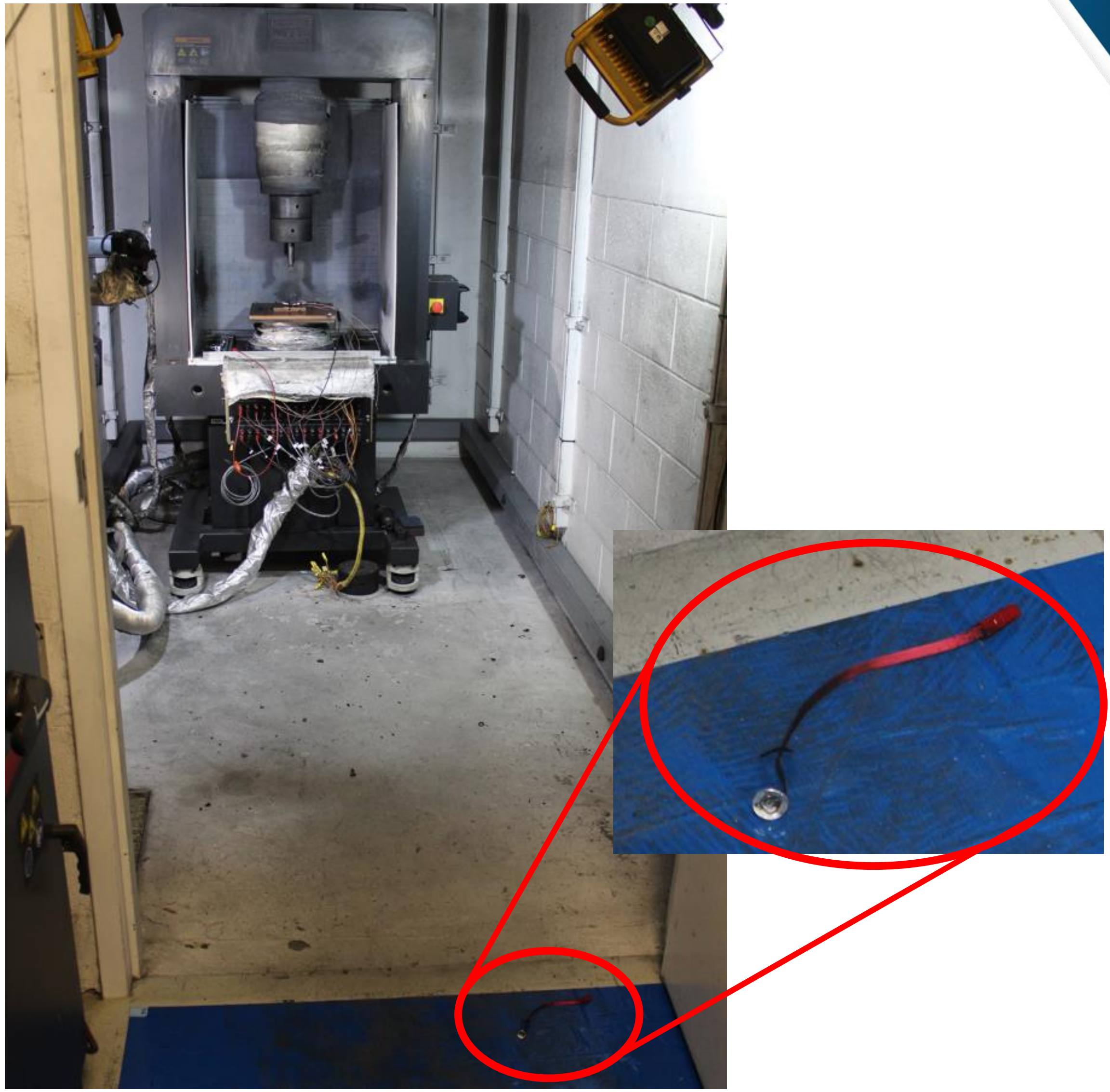
Li-ion



- Max temp: 296.3 °C
- Crush depth at voltage drop: 9.61 mm
- Vent, smoke, sparks, lid pop

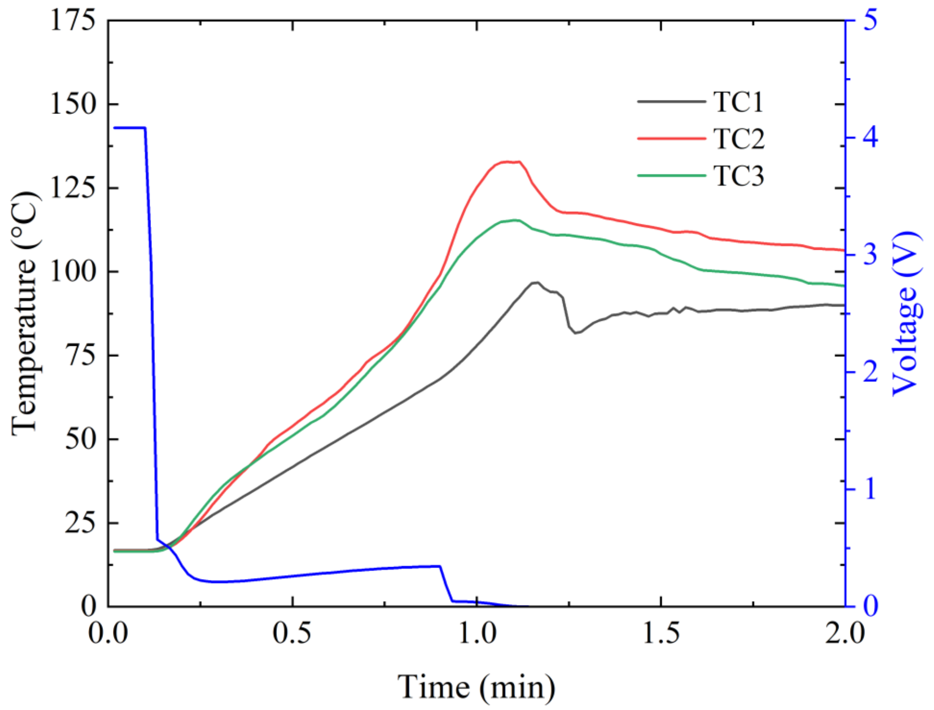
Mechanical Crush, Na-ion Cell Post-test Images





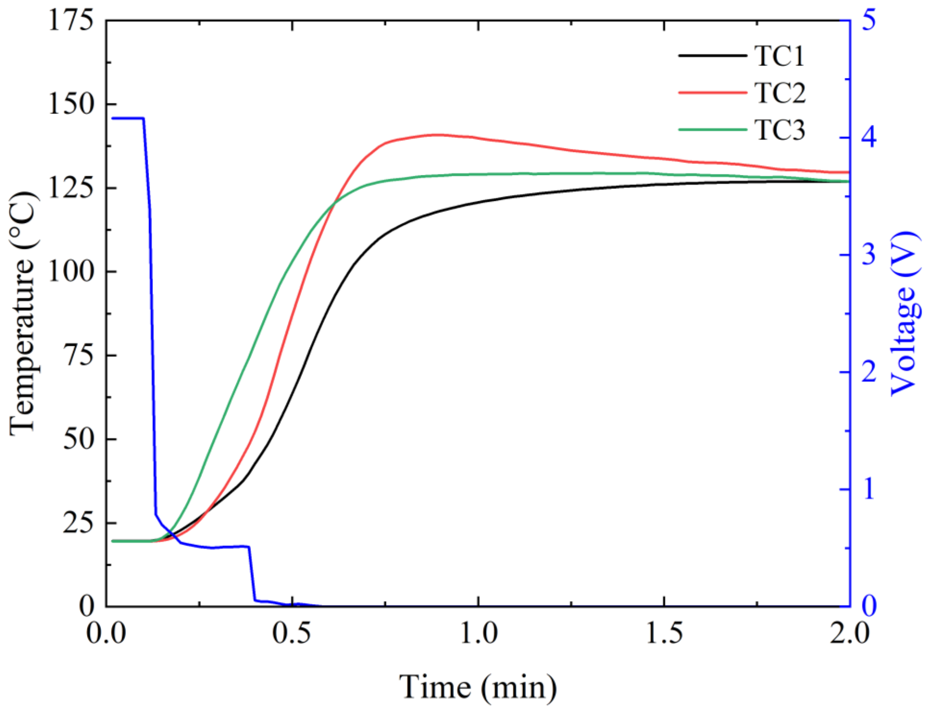
External Short Circuit
100% SOC, 10 mΩ resistor

Na-ion



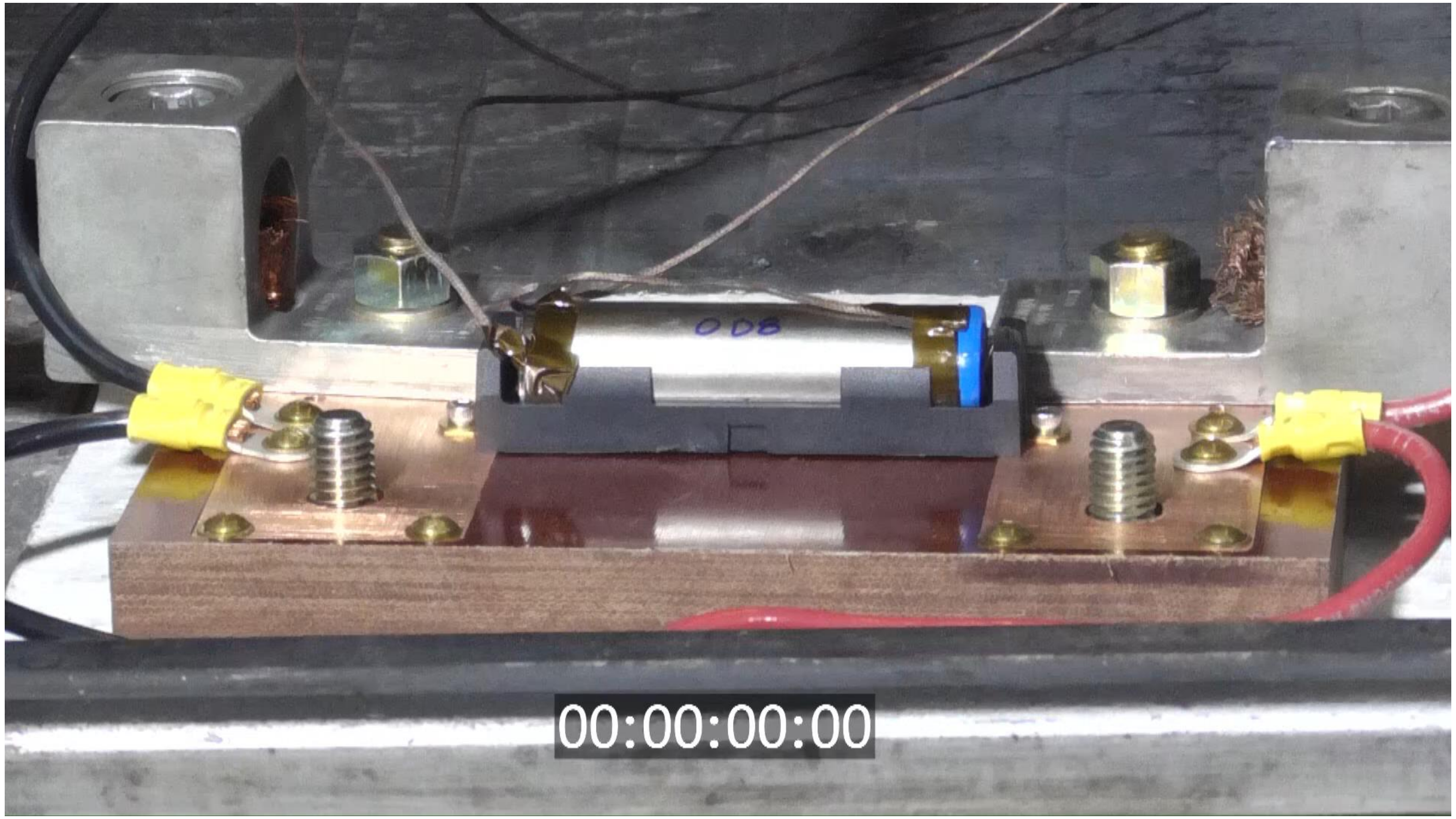
- Max temp: 132.8 °C
- Smoke, vent, electrolyte leak, swelling
- Discharge 159% more capacity than Li-ion

Li-ion

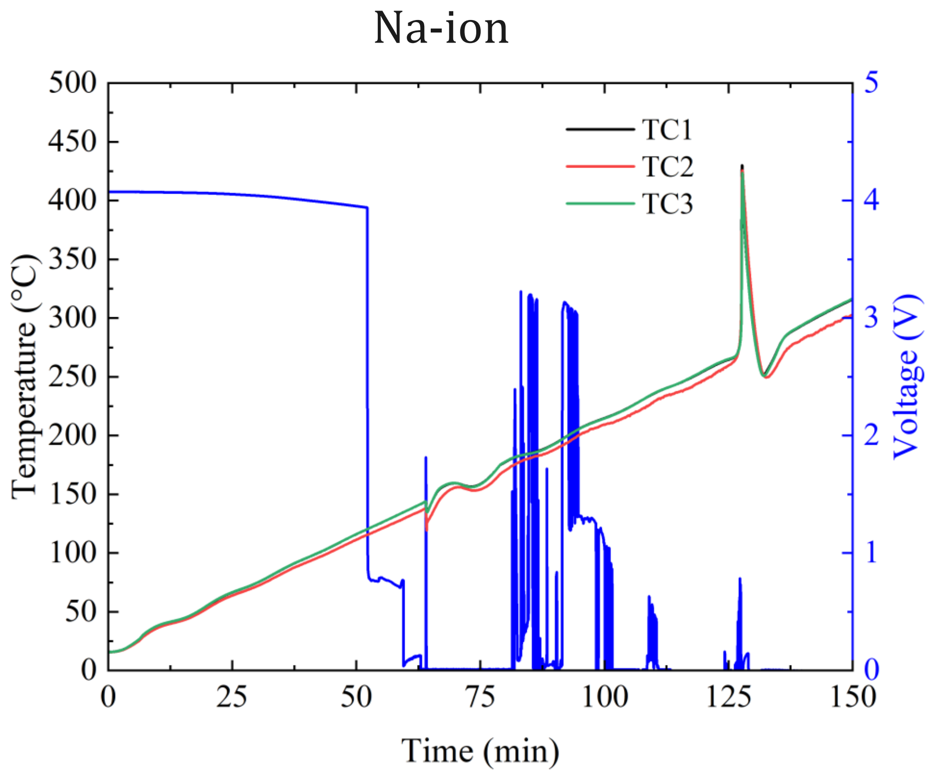


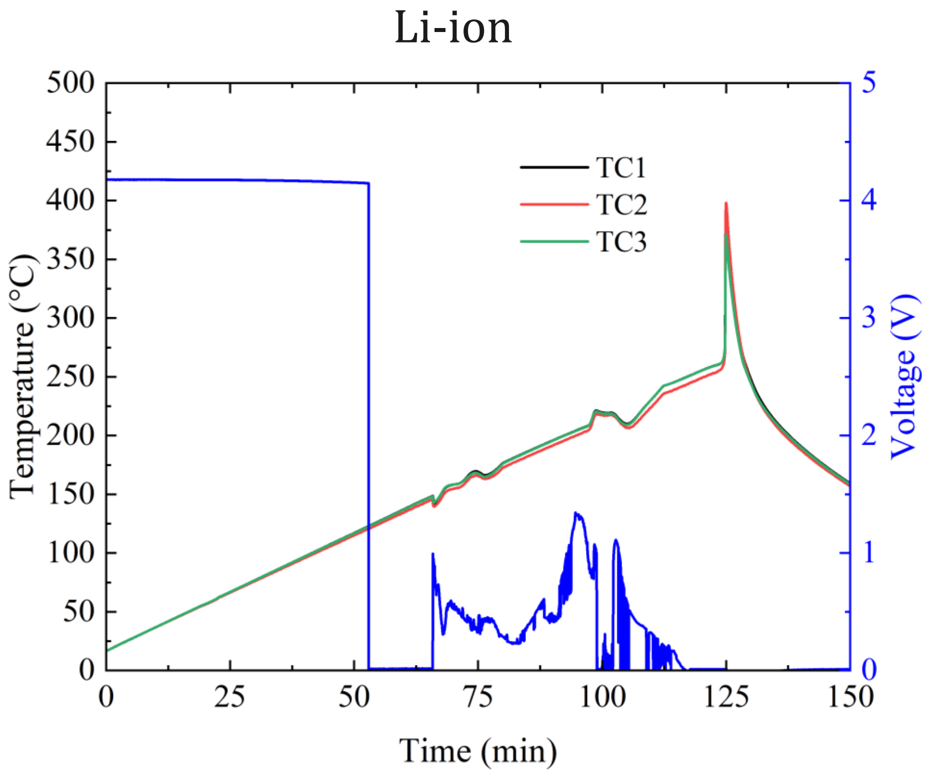
- Max temp: 140.8 °C
- Swelling

External Short Circuit, Na-ion



Thermal Ramp
100% SOC, 2 °C/min, 500 °C or Failure



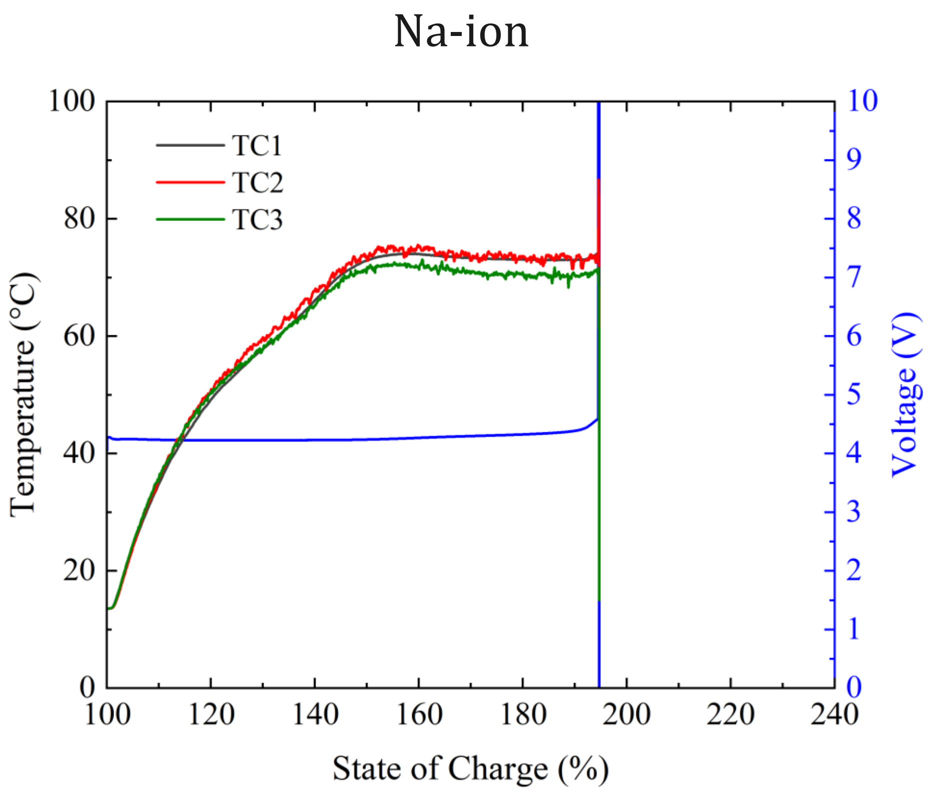


- Max temp: 430.1 °C
- Voltage drop: 120.4 °C
- Vent: 143.9 °C
- Thermal runaway (>10 °C/min): 271.1 °C
- Vent, electrolyte leak

- Max temp: 398.1 °C
- Voltage drop: 122.2
- Vent: 148.4 °C
- Thermal runaway (>10 °C/min): 269.1 °C
- Vent, electrolyte leak

Thermal Ramp, Na-ion

Overcharge
1C to 250% SOC, Hold for 15 minutes or Failure

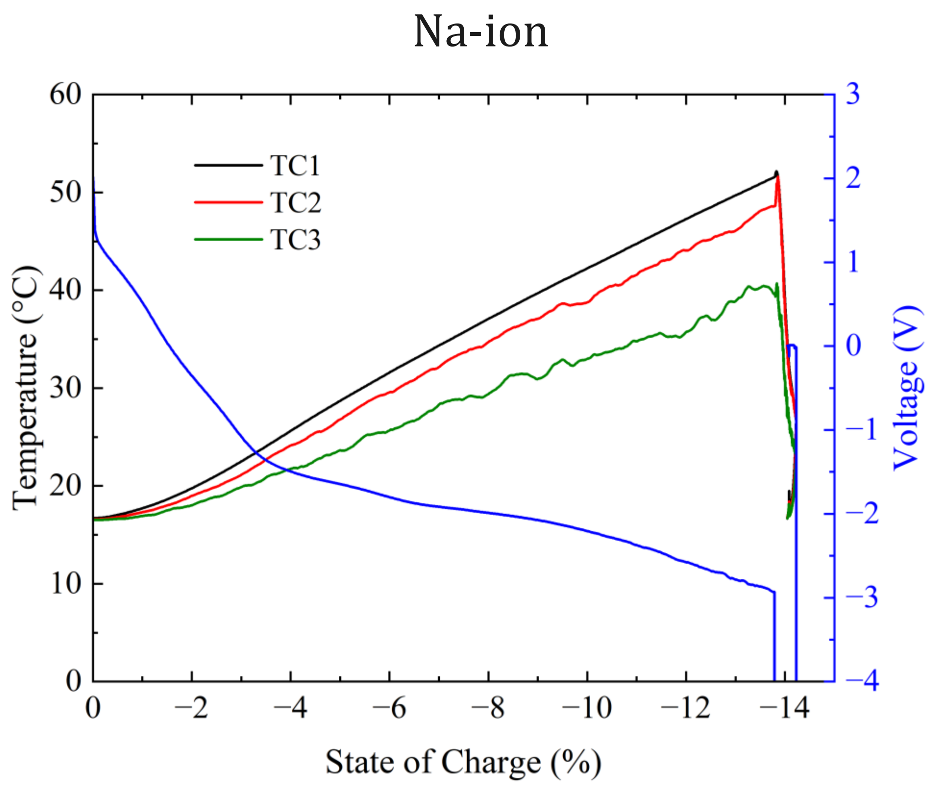


- Max temp: 75.4 °C
- Compliance voltage: 194.5% SOC
- No observable event

Post Overcharge Crush

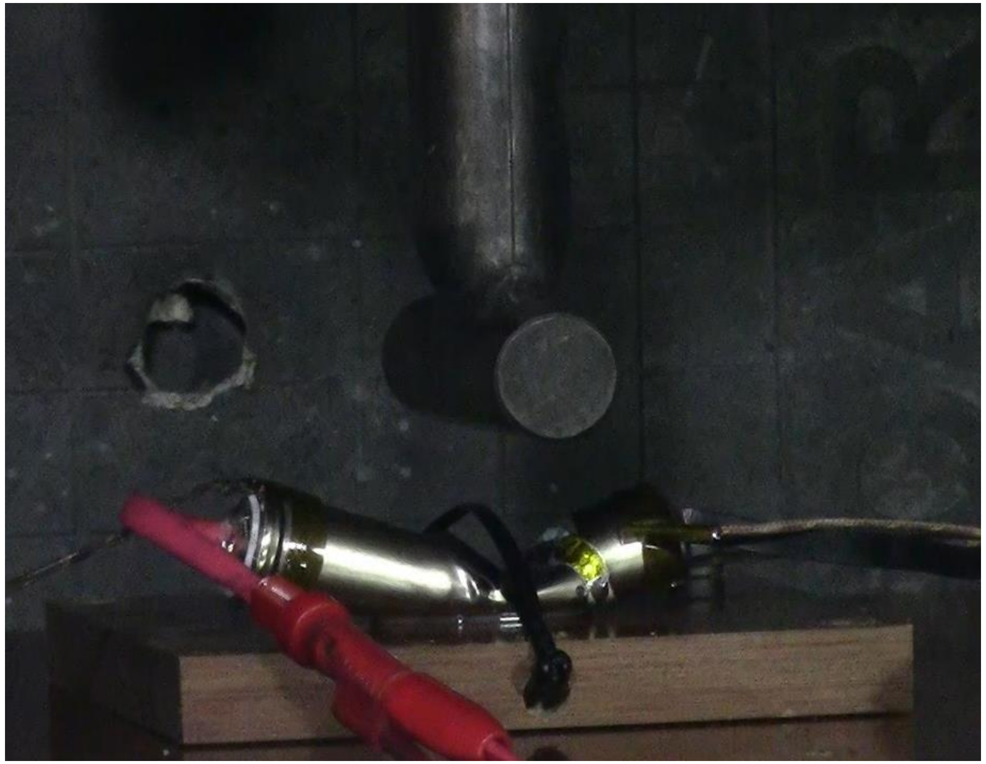
Cell had no voltage but, energy remained.

Overdischarge
1C to -150% SOC, Hold for 15 minutes or Failure



- Max temp: 52.1 °C @-13.8% SOC
- Voltage polarization: -13.8% SOC
- Realistic practical discharge capacity: 0.023 Ah
- No observable event

Post Overdischarge Crush



Liquid electrolyte leakage.
IR camera showed no signs of heating.

Comparison Summary

Destructive method	Cell Type	Max Temperature (°C)	Thermal Runaway Onset	Observable response
Nail Penetration	Na-ion	216.5	1.91 mm	Vent, smoke, sparks, violent 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	430.1	271.1 °C	Vent, LE leak
	Li-ion	398.1	269.1 °C	Vent, LE leak

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Key Takeaway

- ***Na-ion cells have a propensity for destructive failure under mechanical abuse***

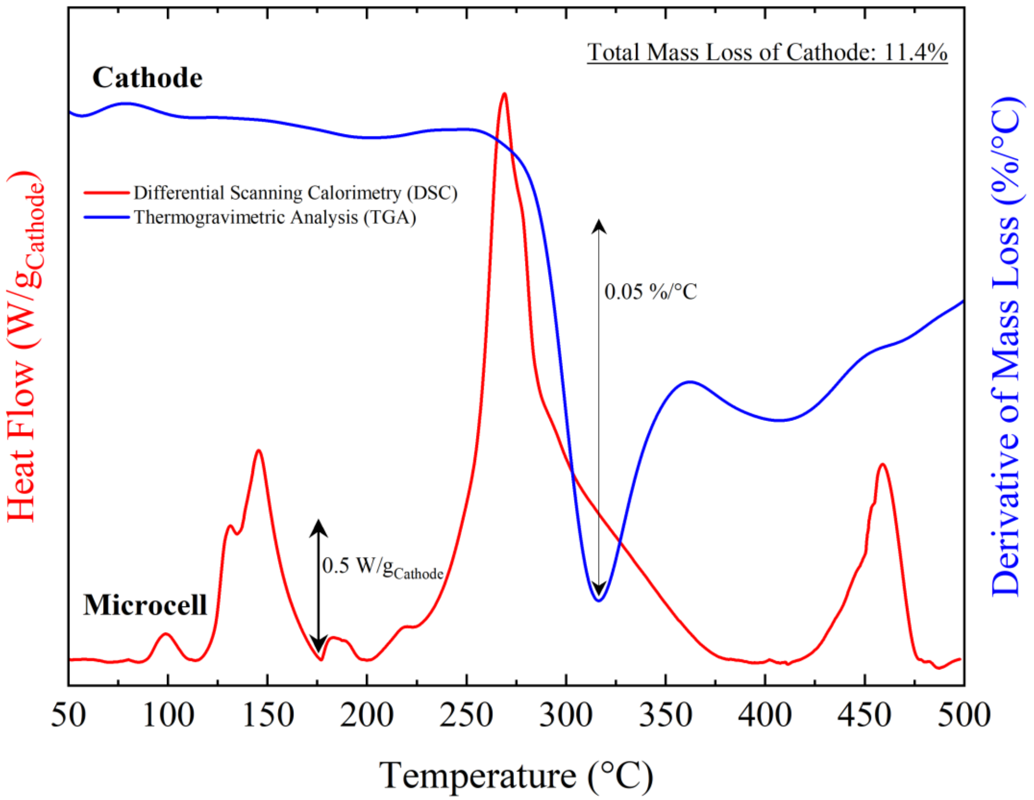
MATERIALS SCALE TESTING

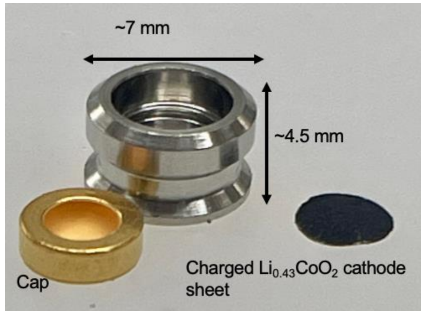
Case Study– Ford Ecostar
Sufficient Safety Research is Necessary Before Commercialization

- 1965 – Ford developed sodium-sulfur technology
- 1993 – ~100 prototype Ecostars began production
  - Sodium-sulfur battery
    - 332 V architecture
    - 600 °F internal temperature
  - $250,000 /car (hand built, non-production battery)
- 1993 to 1996 – Two vehicles caught fire while charging
- 1997 – Ford ends sodium-sulfur research

Kevin Smith, (1994), "Tested: 1994 Ford Ecostar Cargo Van Makes a Case for EVs", *Car and Driver.*

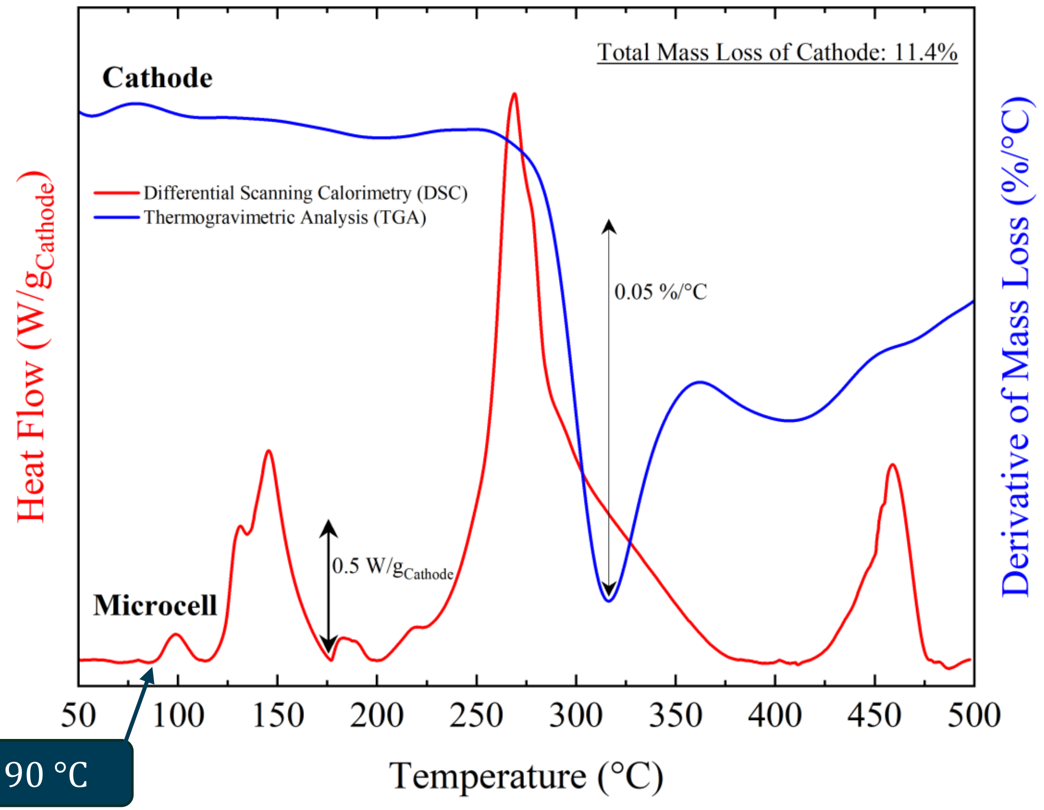
Methods to Uncover Reaction Pathways



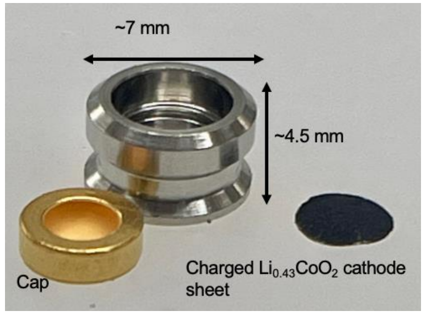


- *Based on these results, we have an understanding of what chemicals are resident to the system.*
- *We can begin to formulate hypothesis on reaction pathways.*

Methods to Uncover Reaction Pathways



Boiling point DMC: 90 °C



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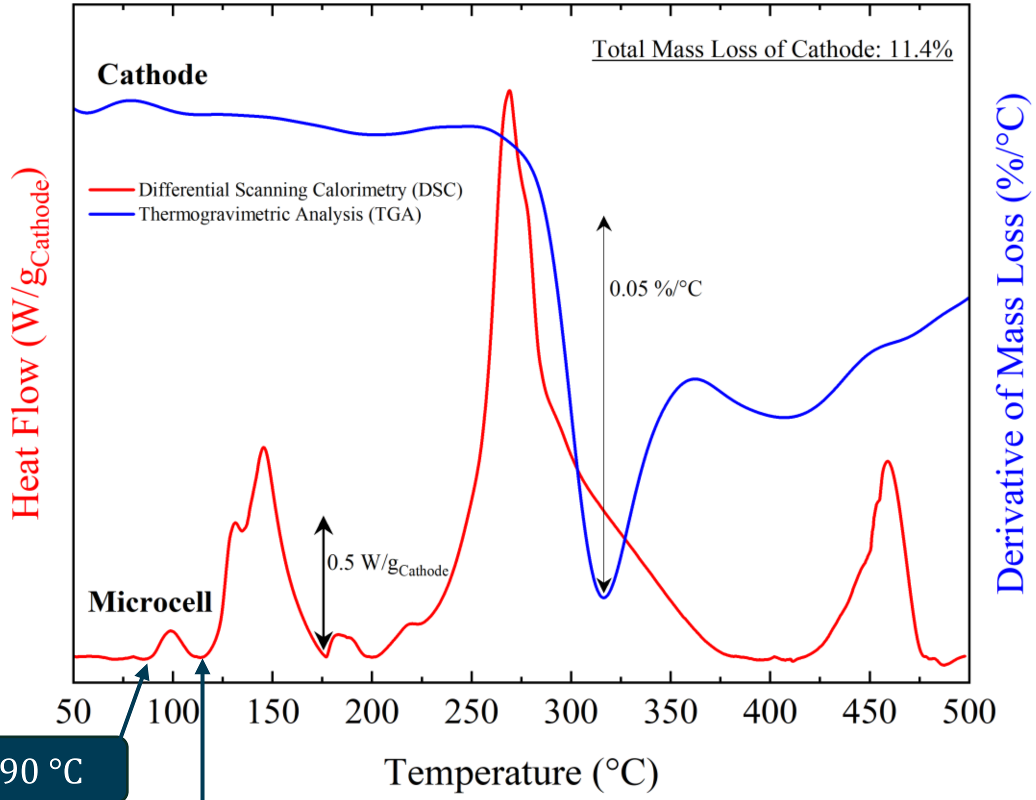
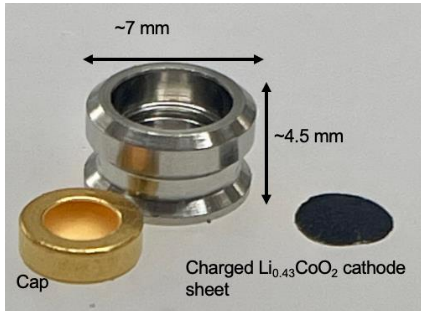


Boiling point DMC: 90 °C

Boiling point EMC: 107 °C



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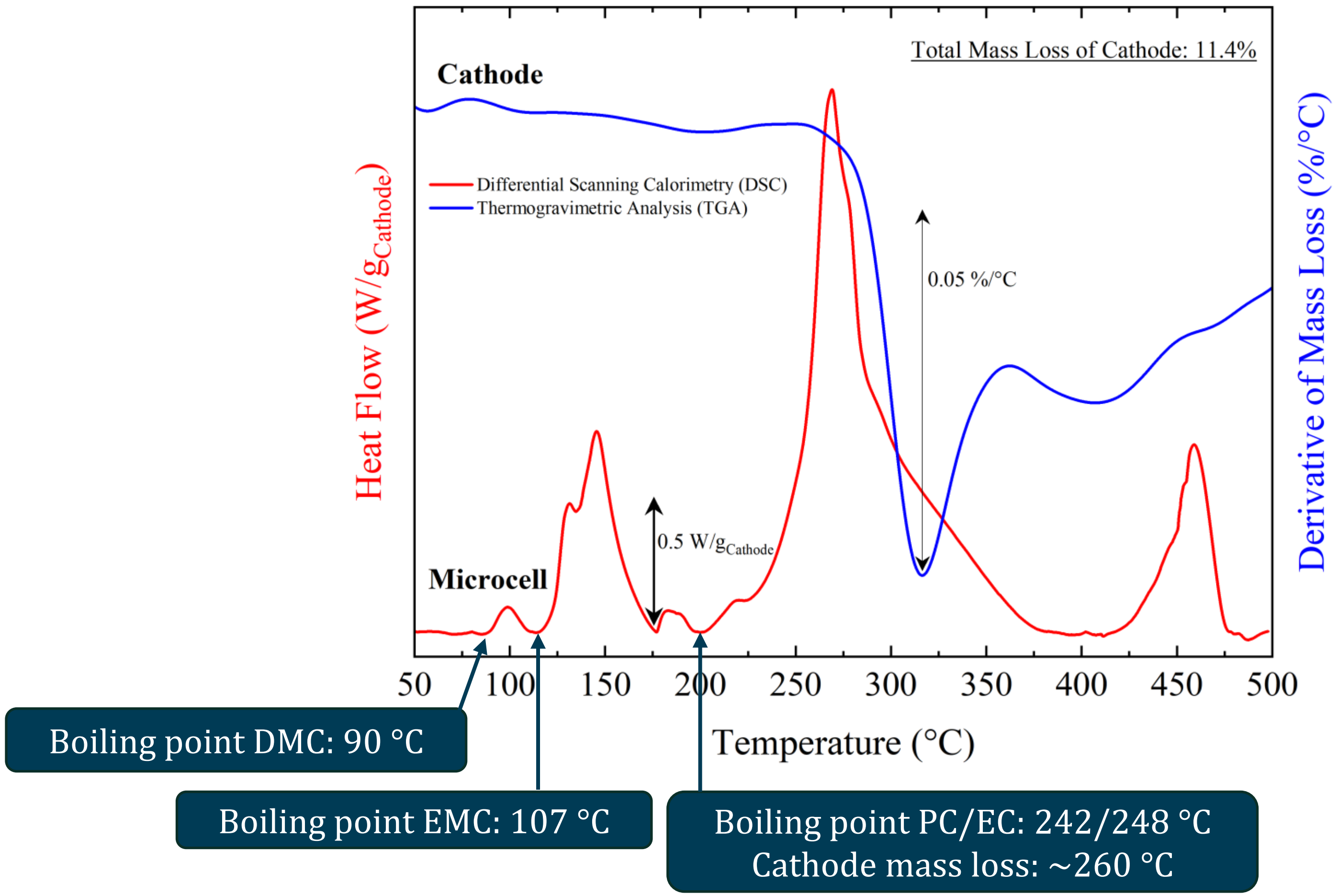

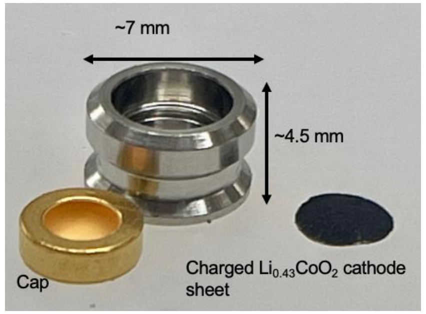

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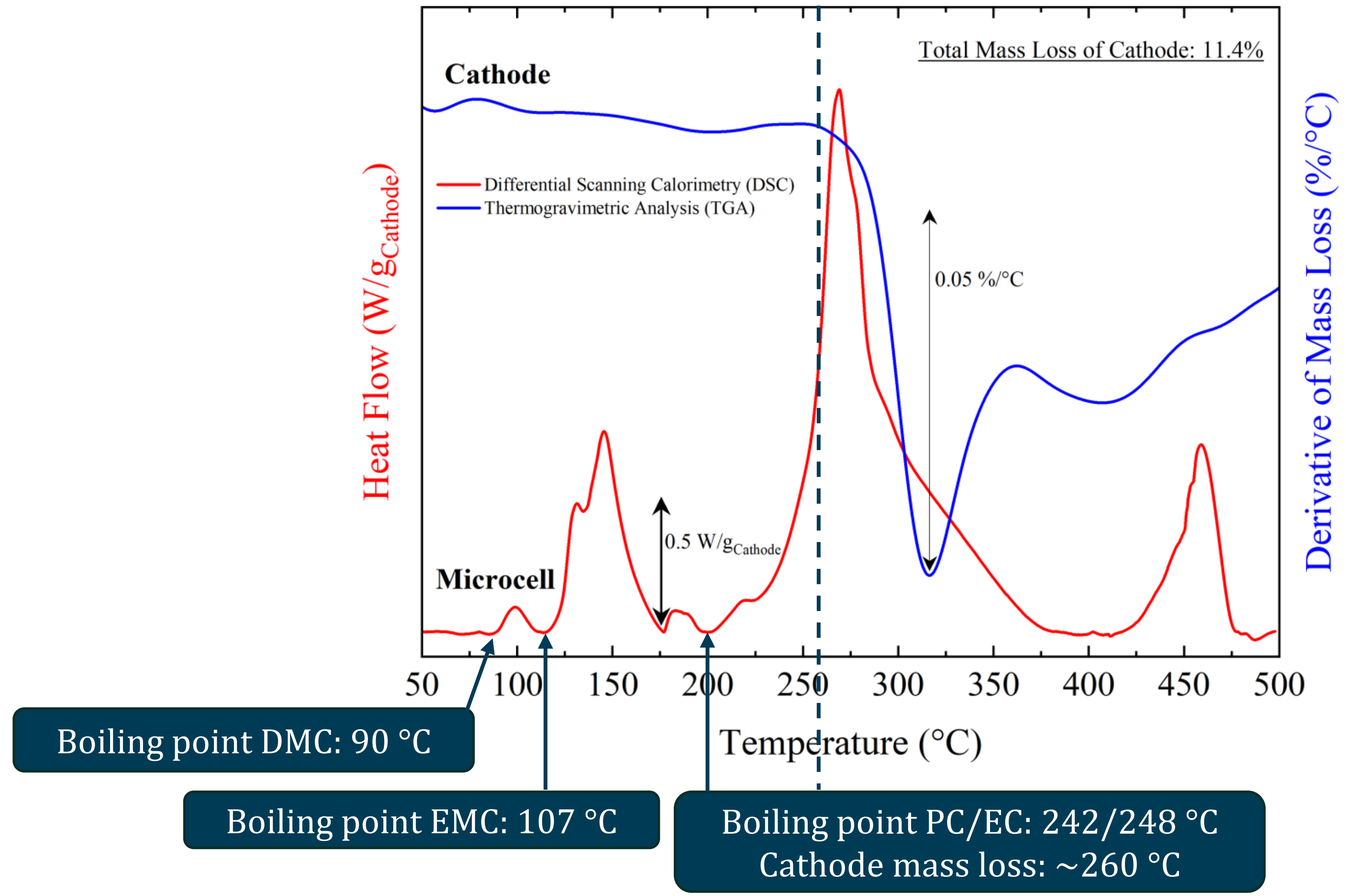

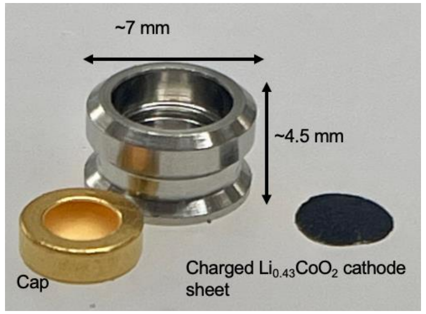

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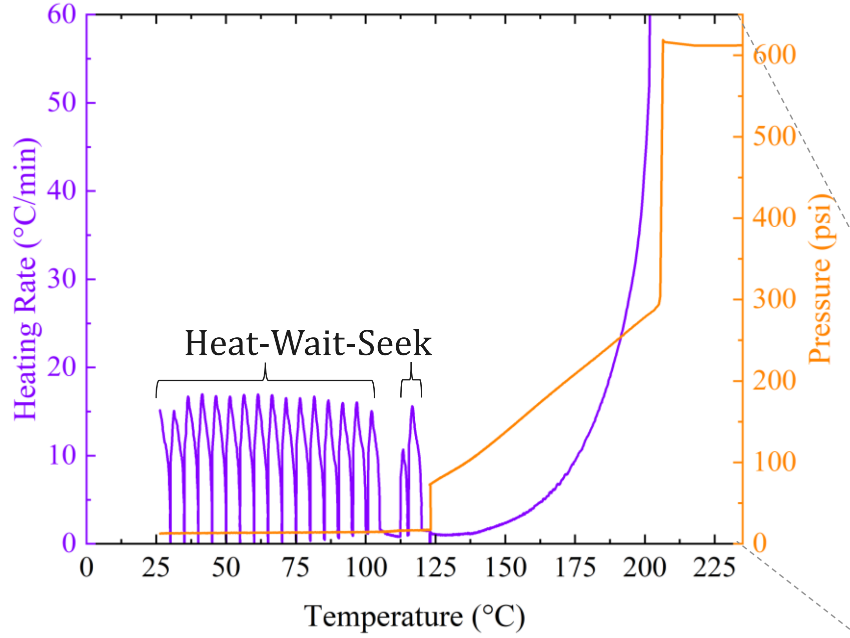
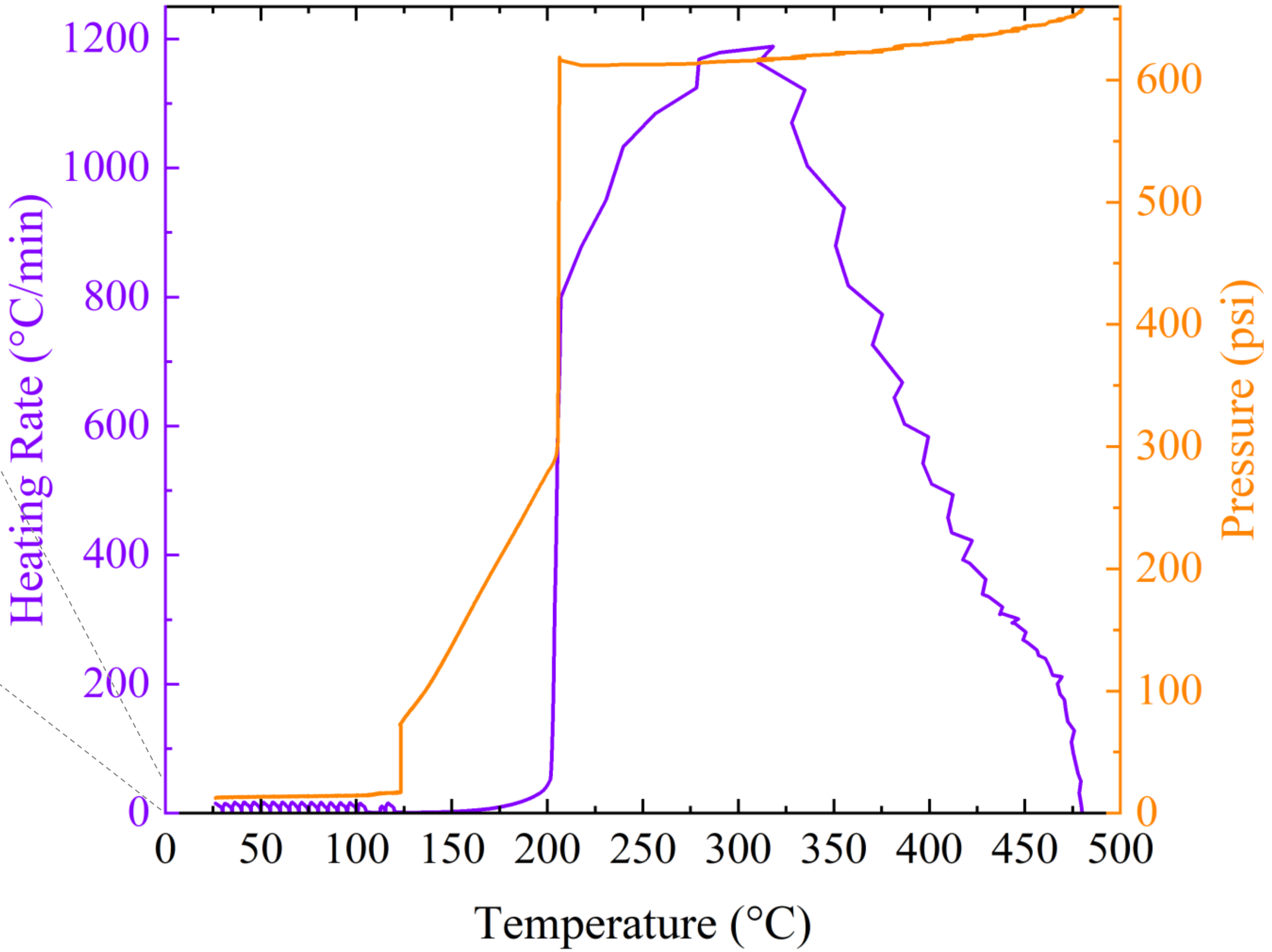
Accelerated Rate Calorimetry
Na-ion Cell





Condition	Temperature (°C)
First self-heating	105.1
Second self-heating	120.3
Vent	123.2
Thermal Runaway (>20 °C/min)	188.6
Pressure Ramp (>300 psi)	205.5
Maximum	480.1

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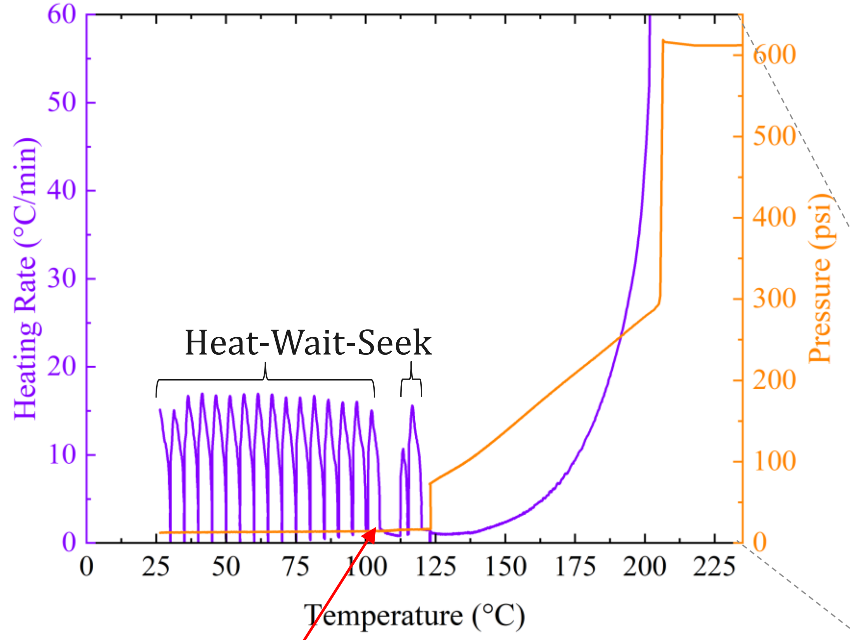

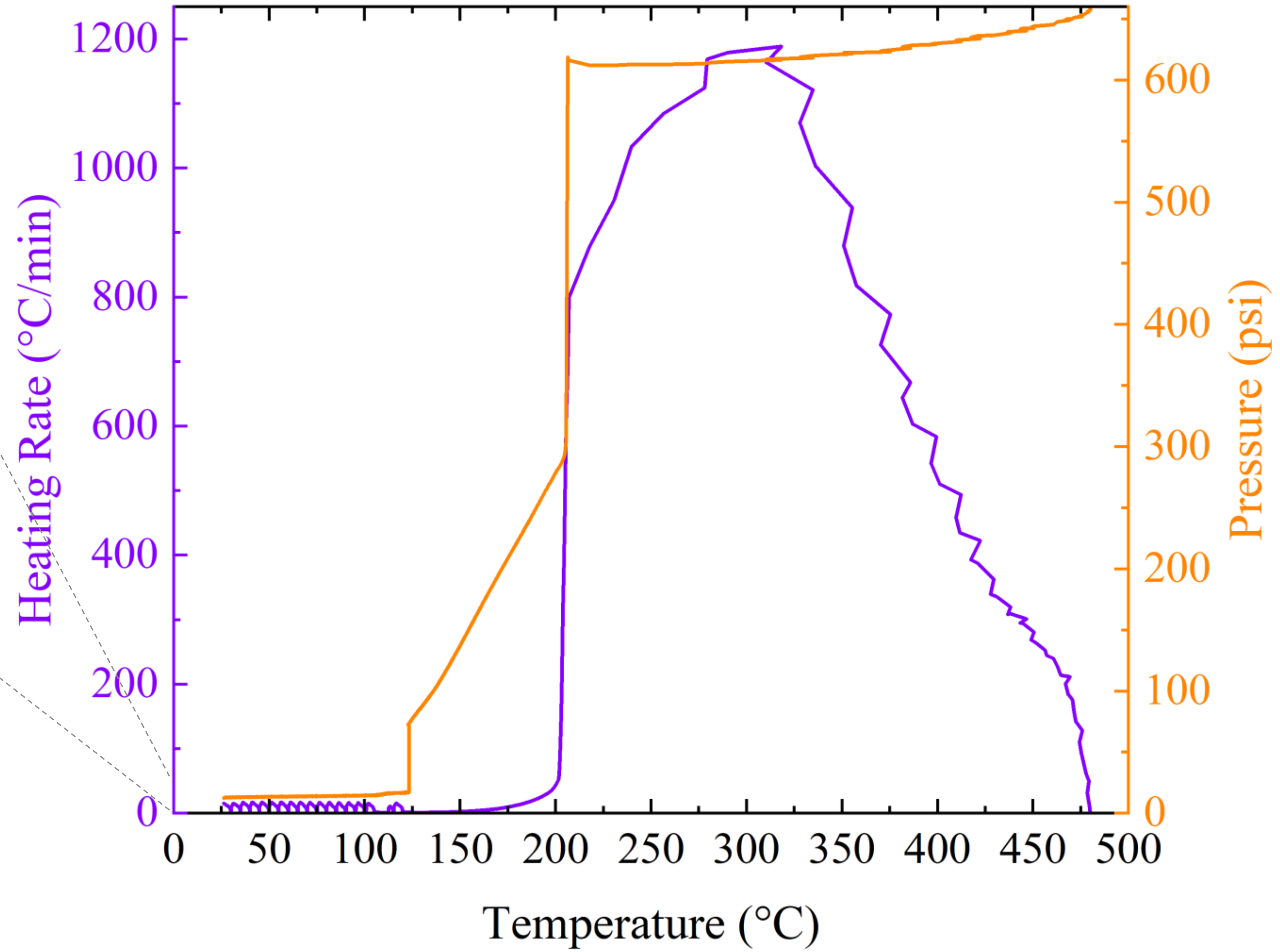

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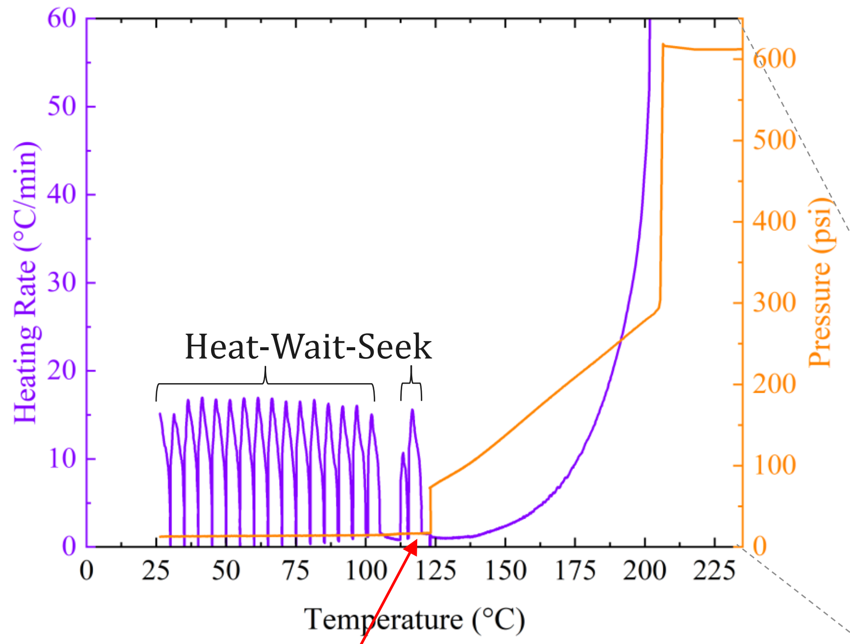

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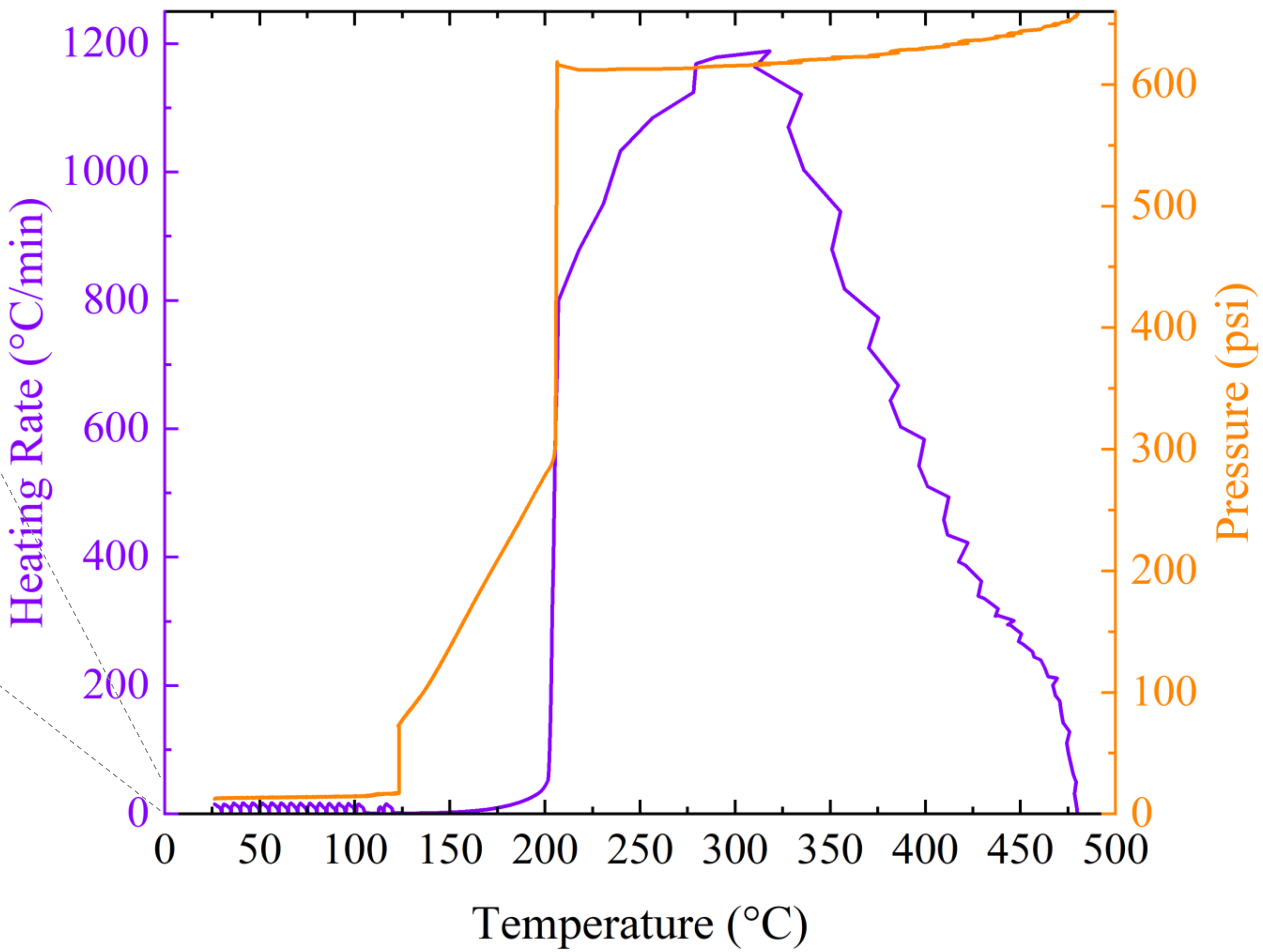

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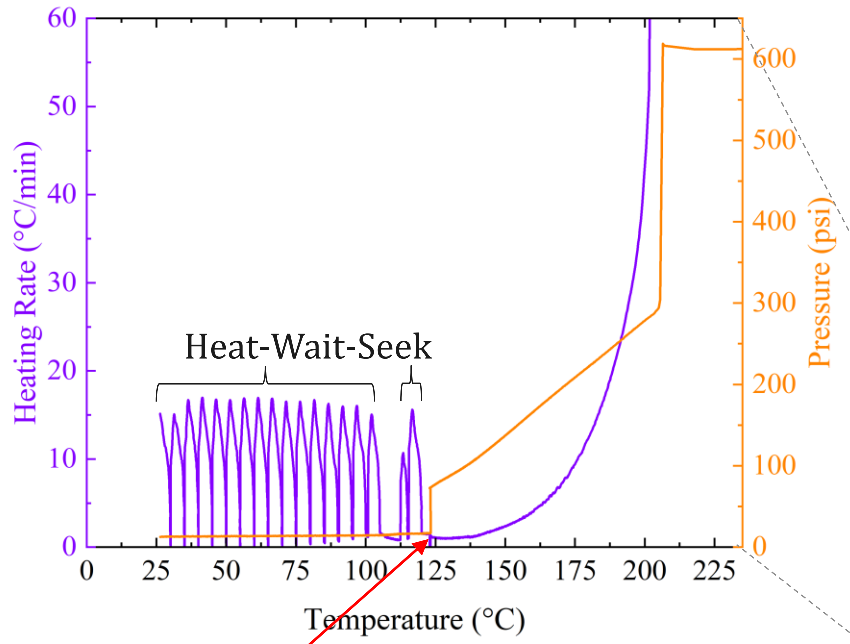

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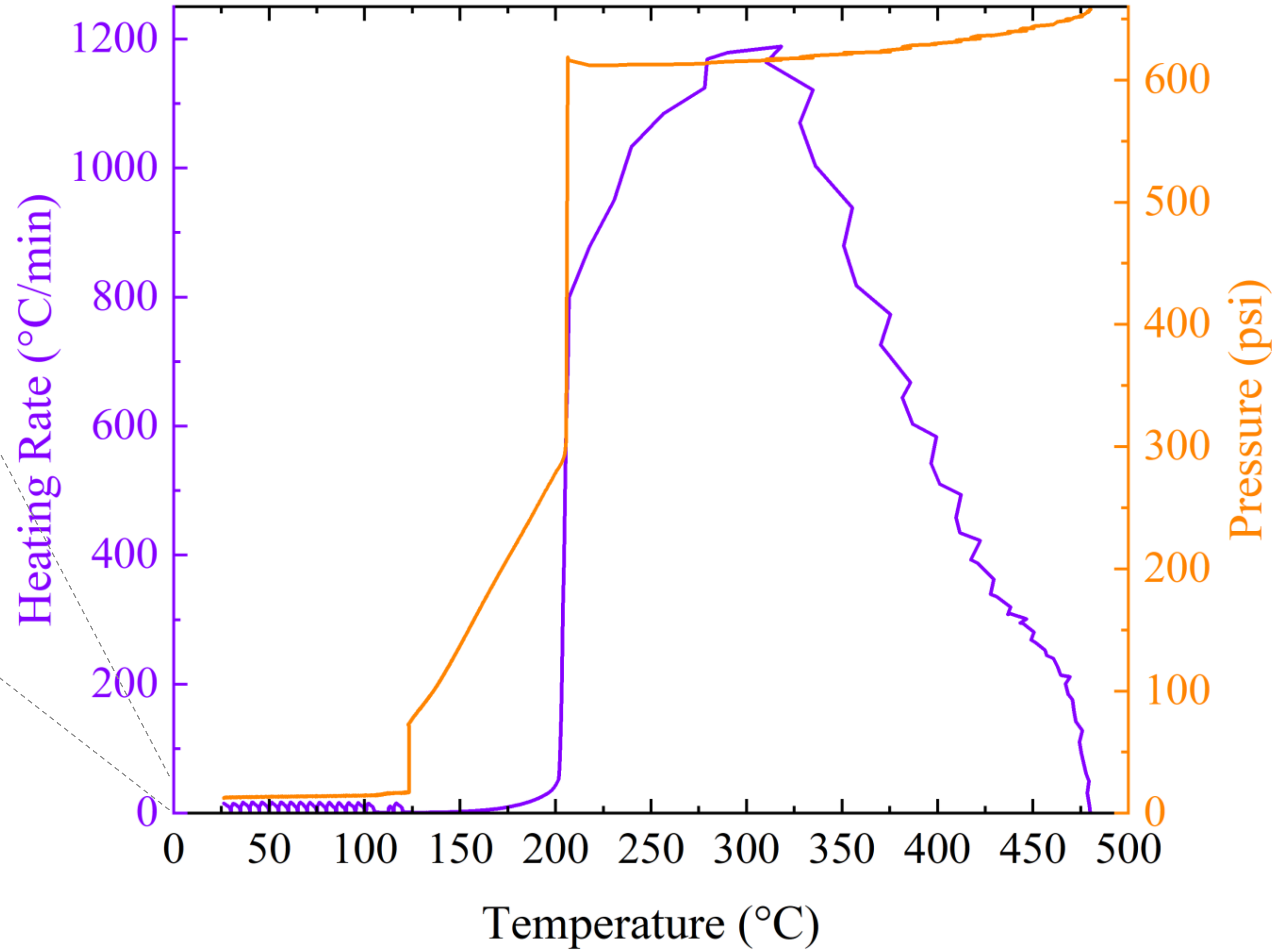

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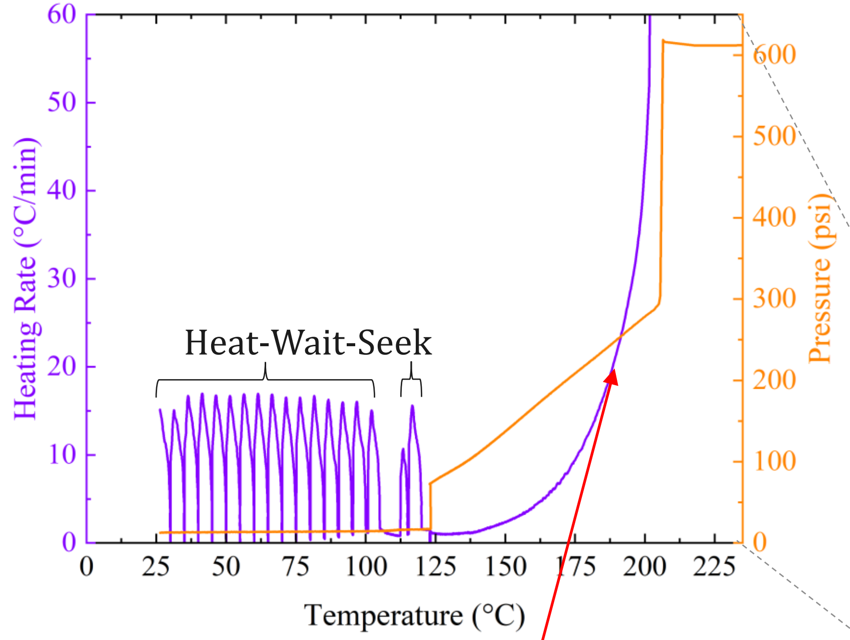

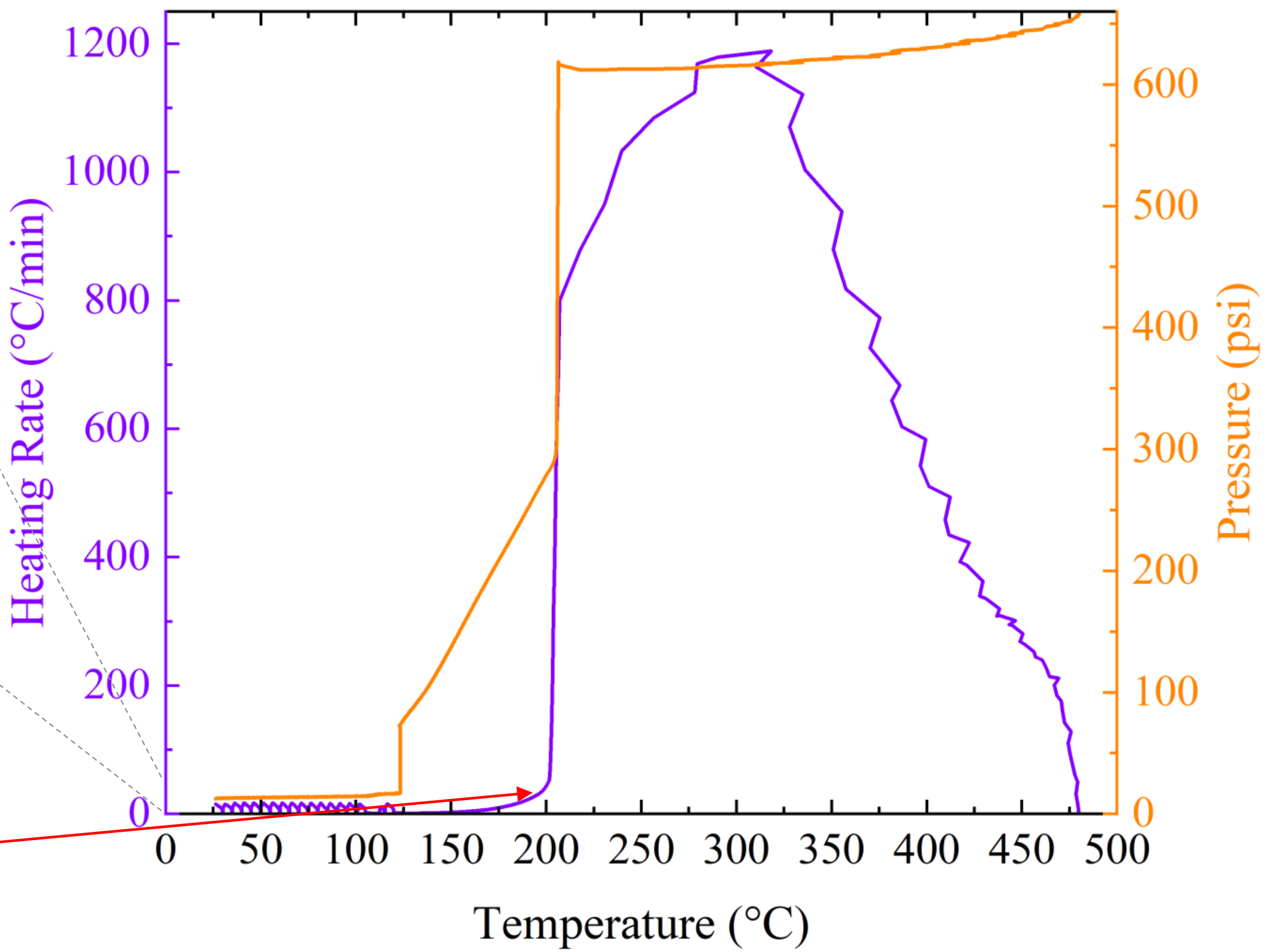

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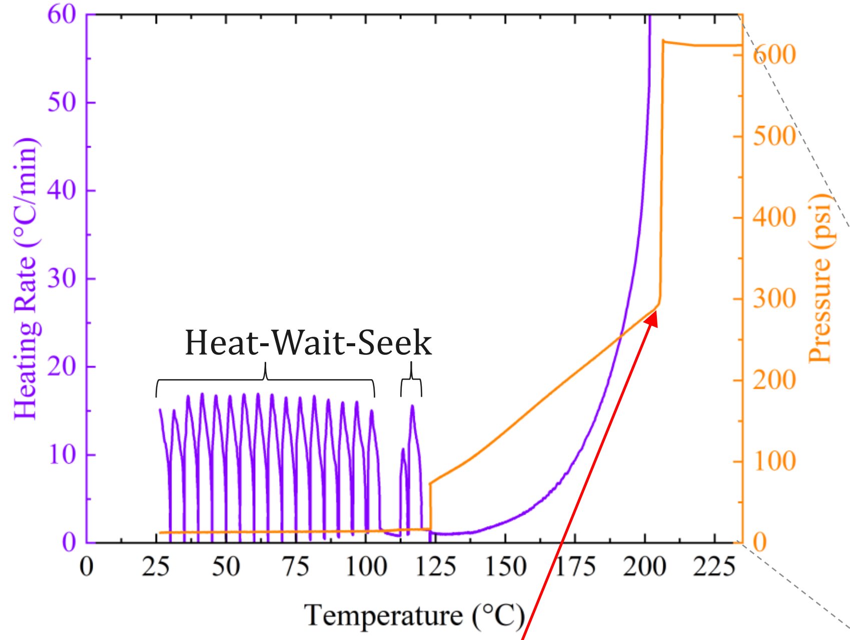

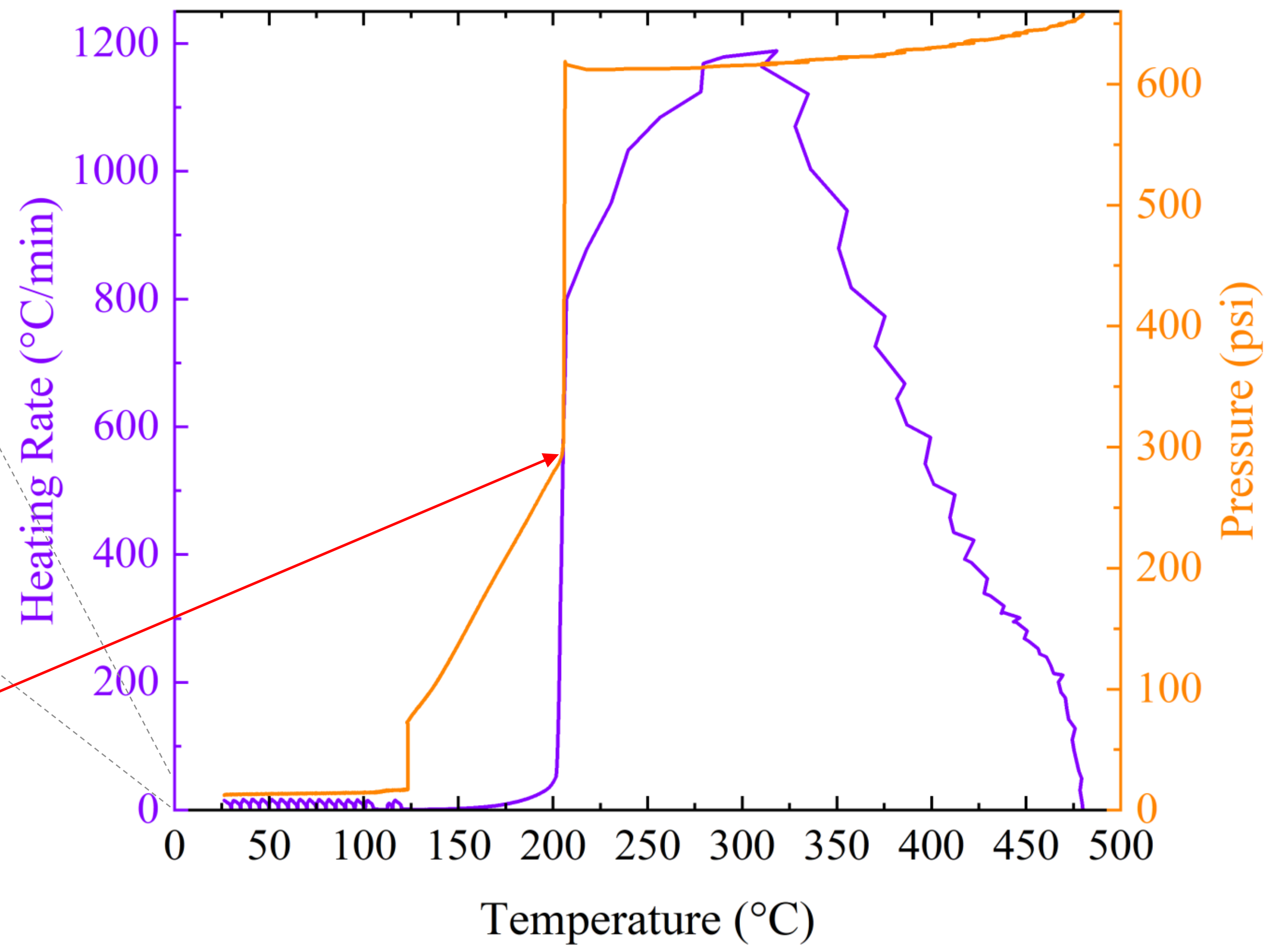

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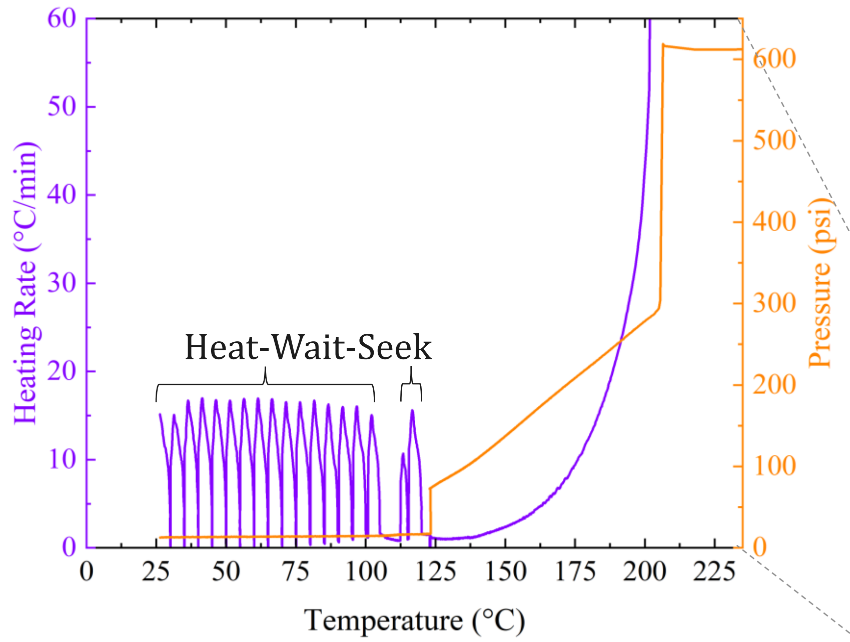

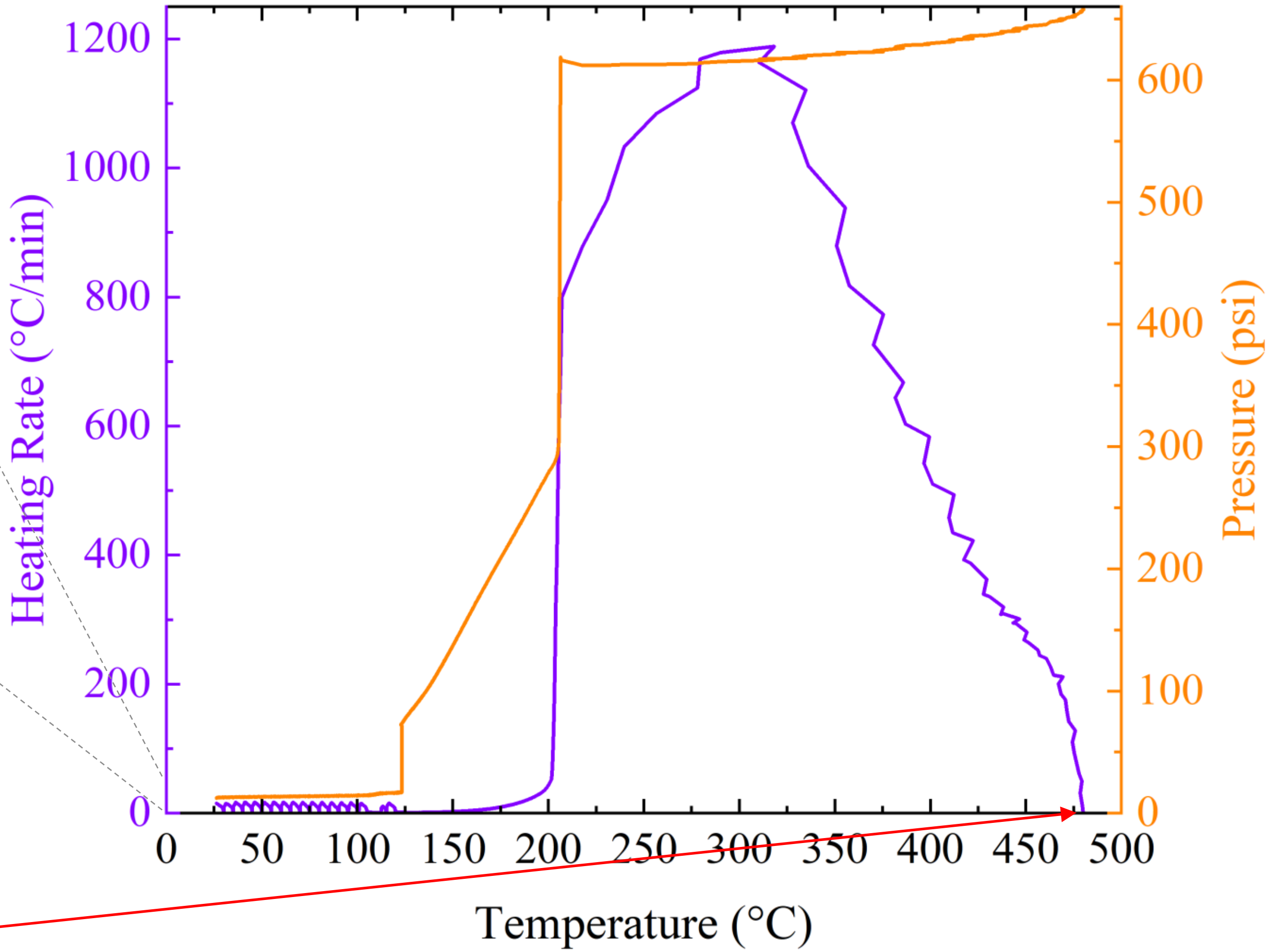

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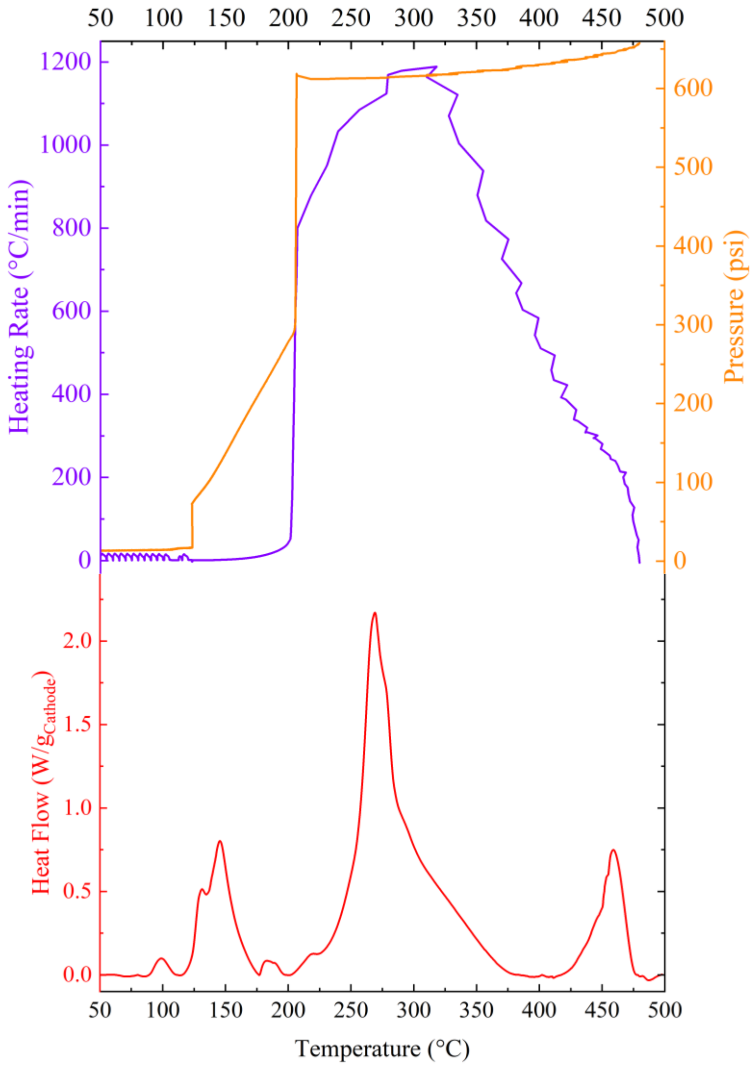
Comparison of DSC and ARC Data

18650 ARC Test

Microcell DSC Test
(4 mm diameter)



- Initial self-heating corresponds with small exothermic peak
- Return to heat-wait-seek mode in ARC corresponds with return to baseline in DSC
- Onset to high rate heating in ARC corresponds to onset to large exotherm in DSC
- At high temperature, reduction of heating rate in ARC has slowed corresponding with a high temperature exotherm in DSC

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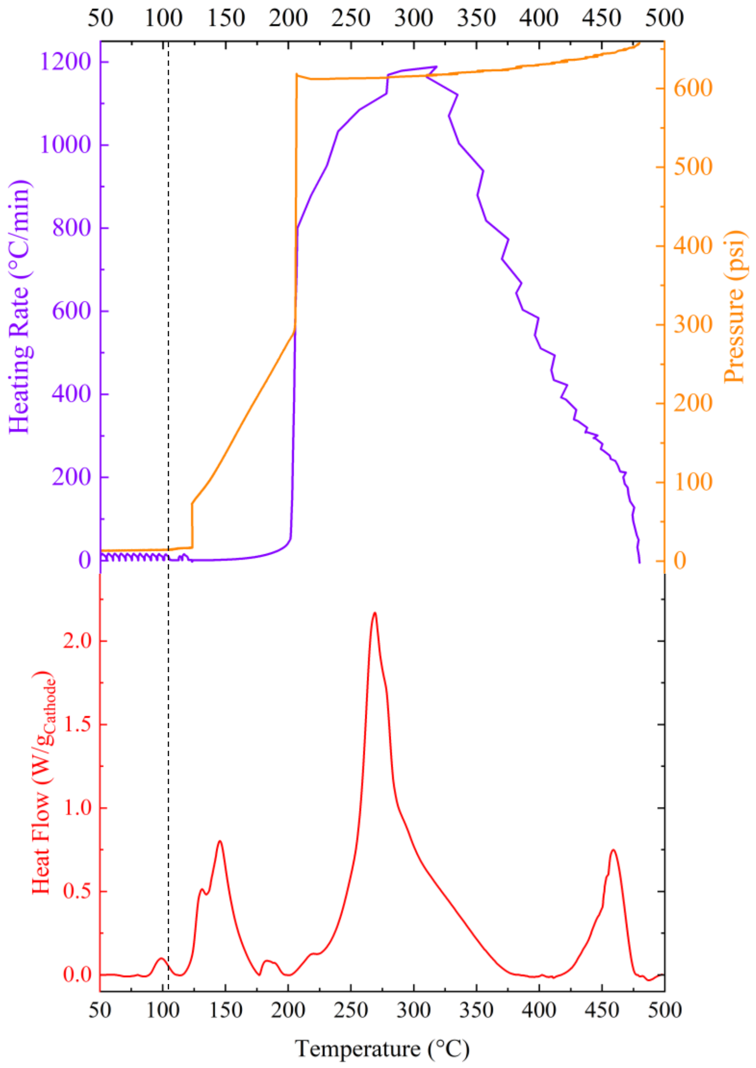

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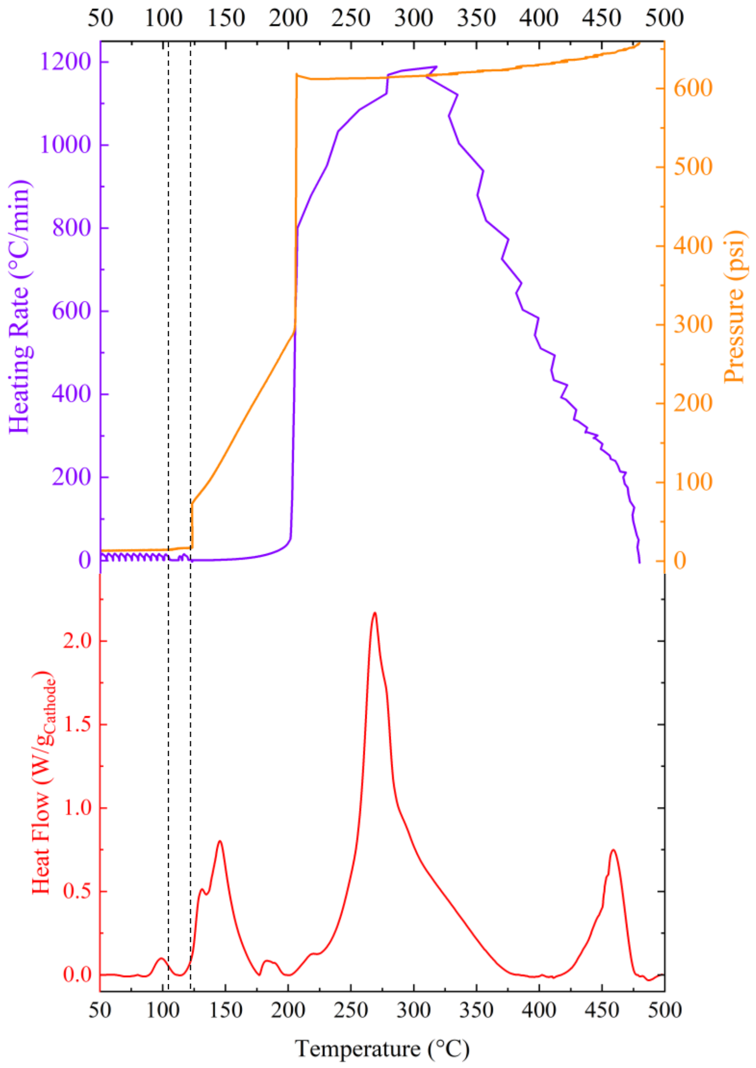

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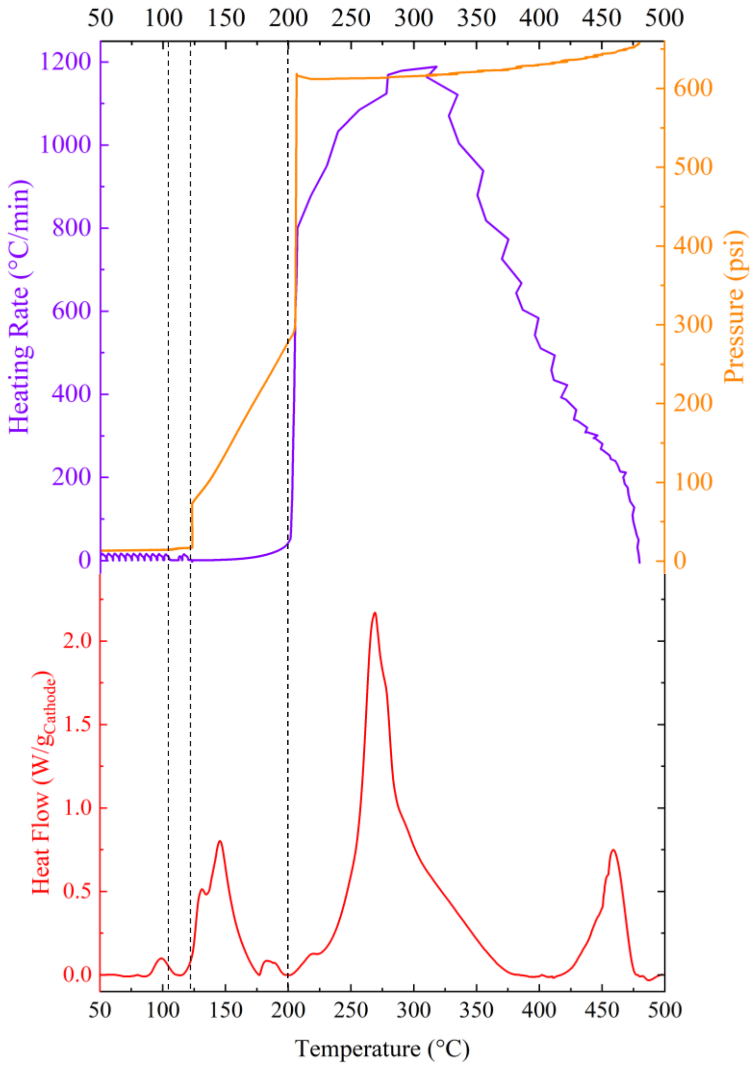

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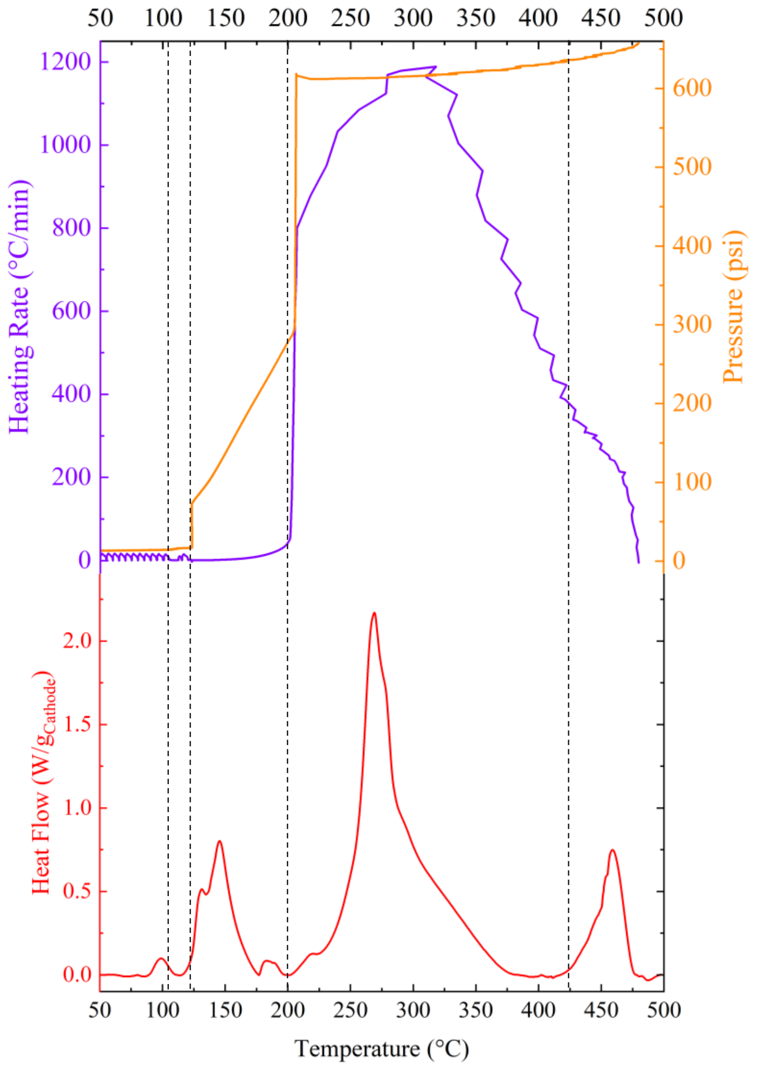

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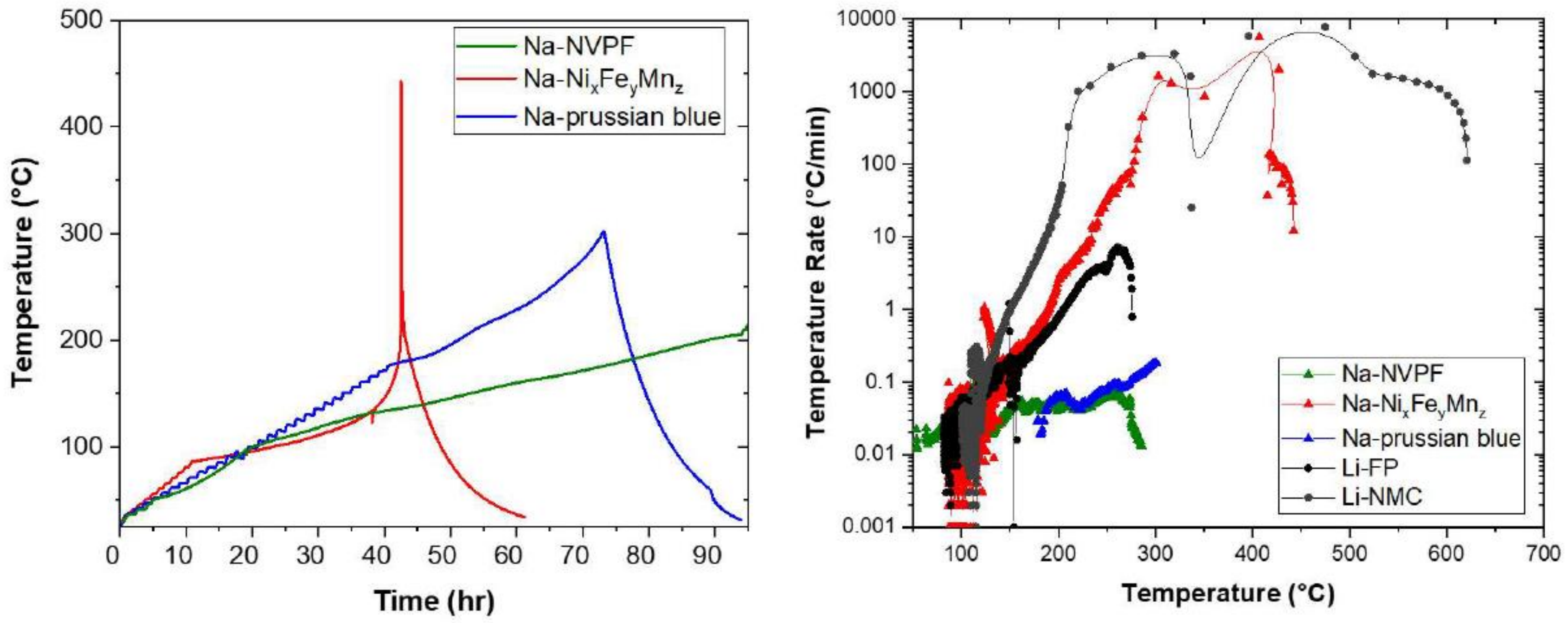
Findings At Other Institutions – ARC Results

- US Naval Research Laboratory as presented by Rachel Carter at the 2024 Energy Storage Safety and Reliability Forum, May 16, 2024
  - Red curves come from same manufacturer as SNL cells



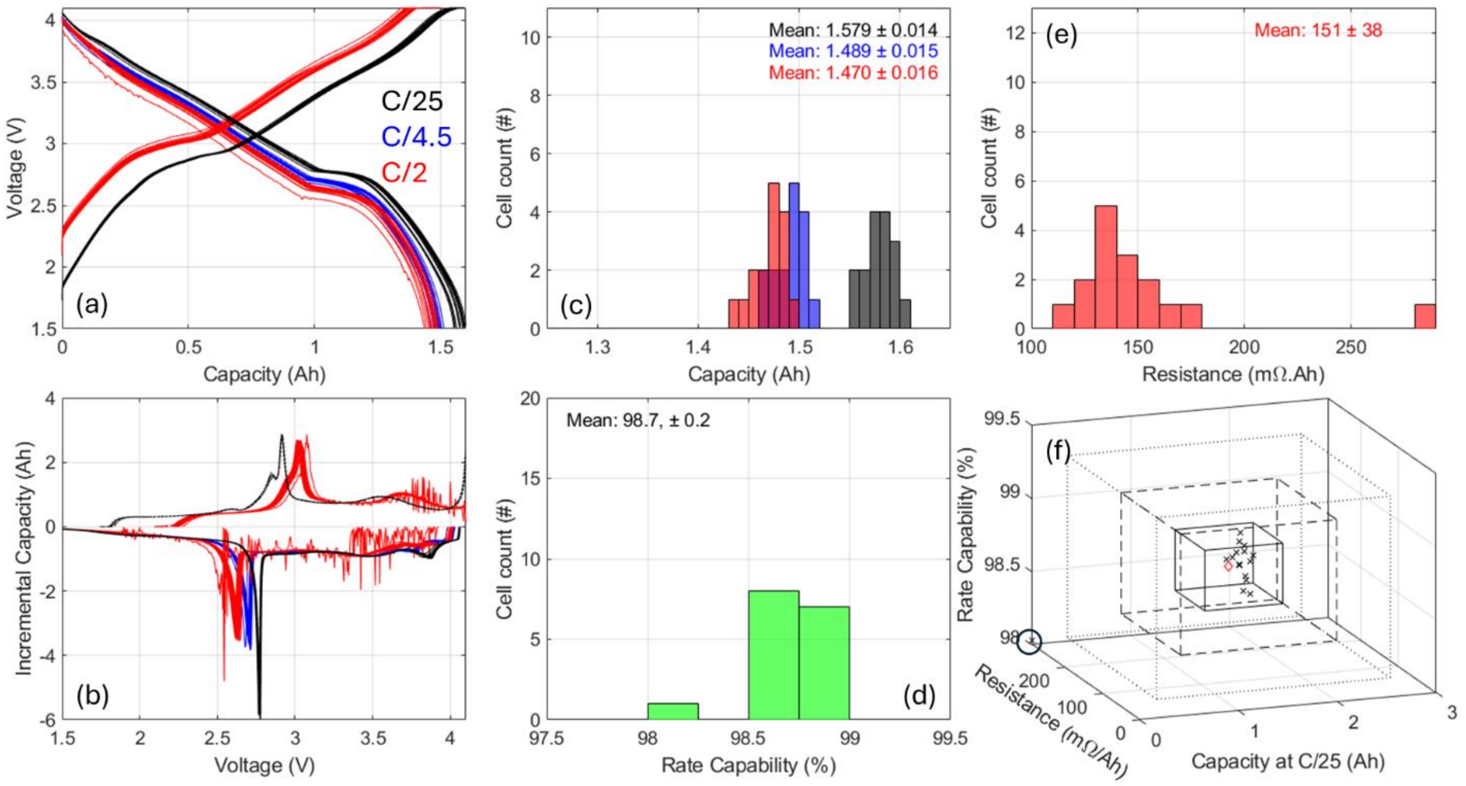
Na-NixFeyMnz exhibits similar thermal runaway to a much higher ED Li-NMC cell but the other Na cells exhibit less thermal event than Li-FP cells

13

Cycling Reliability and Degradation

- Reed Wittman, Alex Bates, Loraine Torres-Castro
    - *Sandia National Laboratories*
- Matthieu Dubarry
    - *University of Hawai'i at Manoa*
- David Anseán
    - *University of Oviedo, Spain*

Cell-to-Cell Variation



(a) Voltage vs. capacity curves at C/25, C/4.5, and C/2 for all the tested HKD cells with. (b) the associated incremental capacity curves, (c) their capacity distribution, (d and e) the rate capability and resistance distributions respectively, and (f) the summary of the cell to cell variations. The inner square represents a 1σ spread, the dashed square 2σ, and the dotted one 3σ.

SNL Na-ion Safety Team


Alex M. Bates


Loraine Torres-Castro


Nathan Johnson

Acknowledgements

This material is based upon work supported by the U.S. Department of Energy, Office of Electricity (OE), Energy Storage Division.

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Questions?

Alex Bates

ambates@sandia.gov

https://www.linkedin.com/in/alex-bates/

Introduction

November 2024

Powered by Prussian Blue

Natron Energy

Who Is Natron Energy?

Sodium-ion Batteries Powered by Prussian Blue

Company:

- Founded in 2012 as a Stanford spin out
- 180+ employees
  - Headquarters - Santa Clara, CA.
  - Manufacturing Plant - Holland, MI
  - Future Gigafactory #1 – North Carolina, 2027

Products:

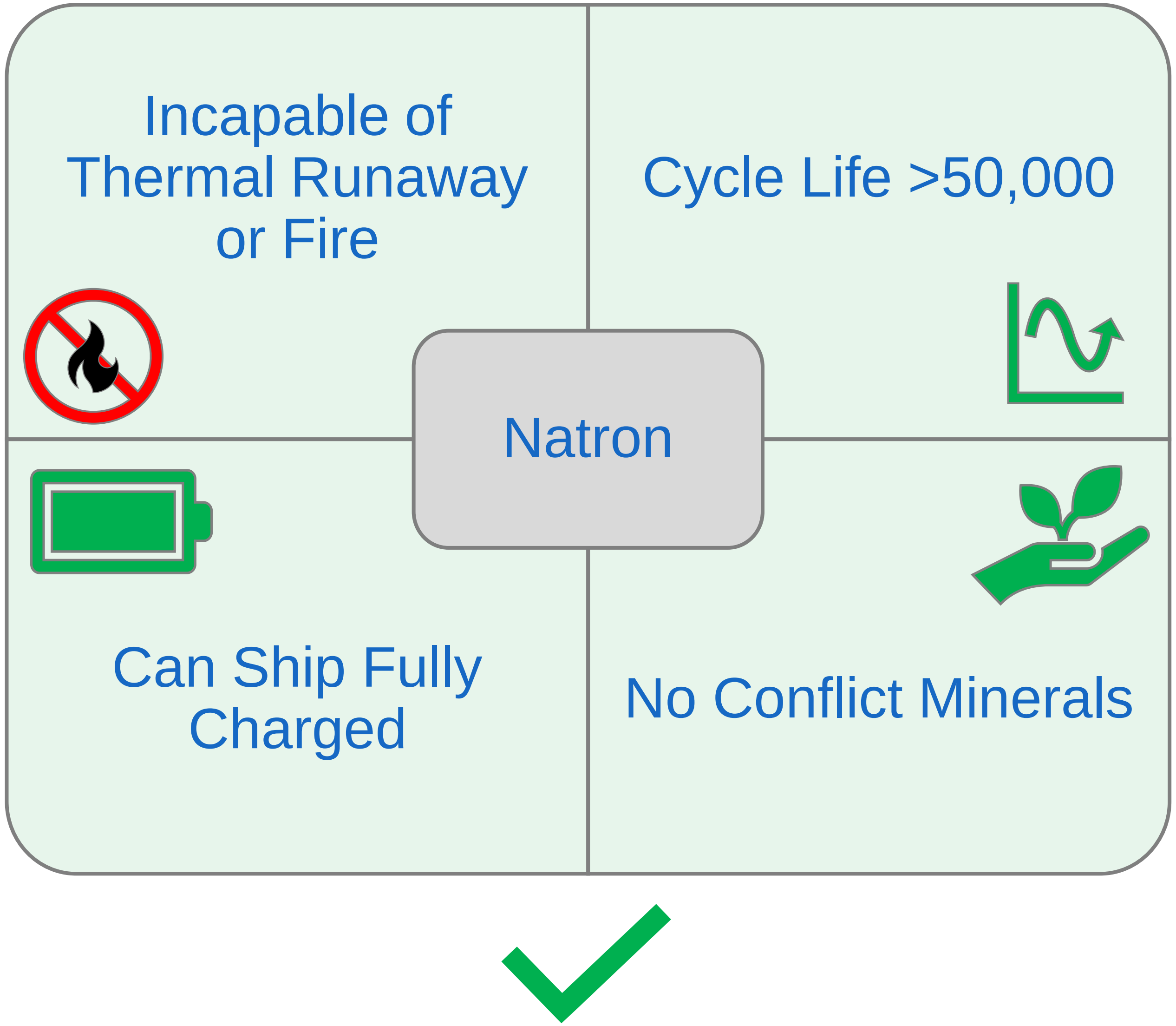
- High power, safe, sustainable batteries having no risk of thermal runaway or fire
- Based on new chemistry supported by more than 40 patents

Key Value Propositions

The Problems With Many Batteries

- Fire
- Human and Environmental Abuse in Materials Sourcing
- Hazardous Materials
- Ship with minimal charge
- Poison Gas Release
- Low Cycle Life

Prussian blue Sodium-ion breaks new ground in energy storage….



Sodium-ion Offers Wider Temperature Operating Range

- **Battery Operating Range -20 to 45℃ / -4 to 113℉**
  - *- 50℃ to + 50℃ is possible (Consult factory)*

-20℃

45℃

Safety

Prussian Blue Sodium-ion, The Safest Battery Ever Made!

- **No fire or explosion after puncture, pressure, heat, or electrical faults**
- **Natron is the only battery manufacturer to publish unredacted UL test report**

Nail penetration test

Natron | Li-ion

High speed projectile test

Natron | Li-ion

Click to view Natron's safety video on YouTube

Safe To Transport Fully Charged

Natron Energy

Safe for
Air Transport

- **Not considered hazardous goods**
- **Can be shipped installed in a battery cabinet**
- **Can be shipped by ground or air fully charged**

Hazardous warning labels not needed for Natron batteries!

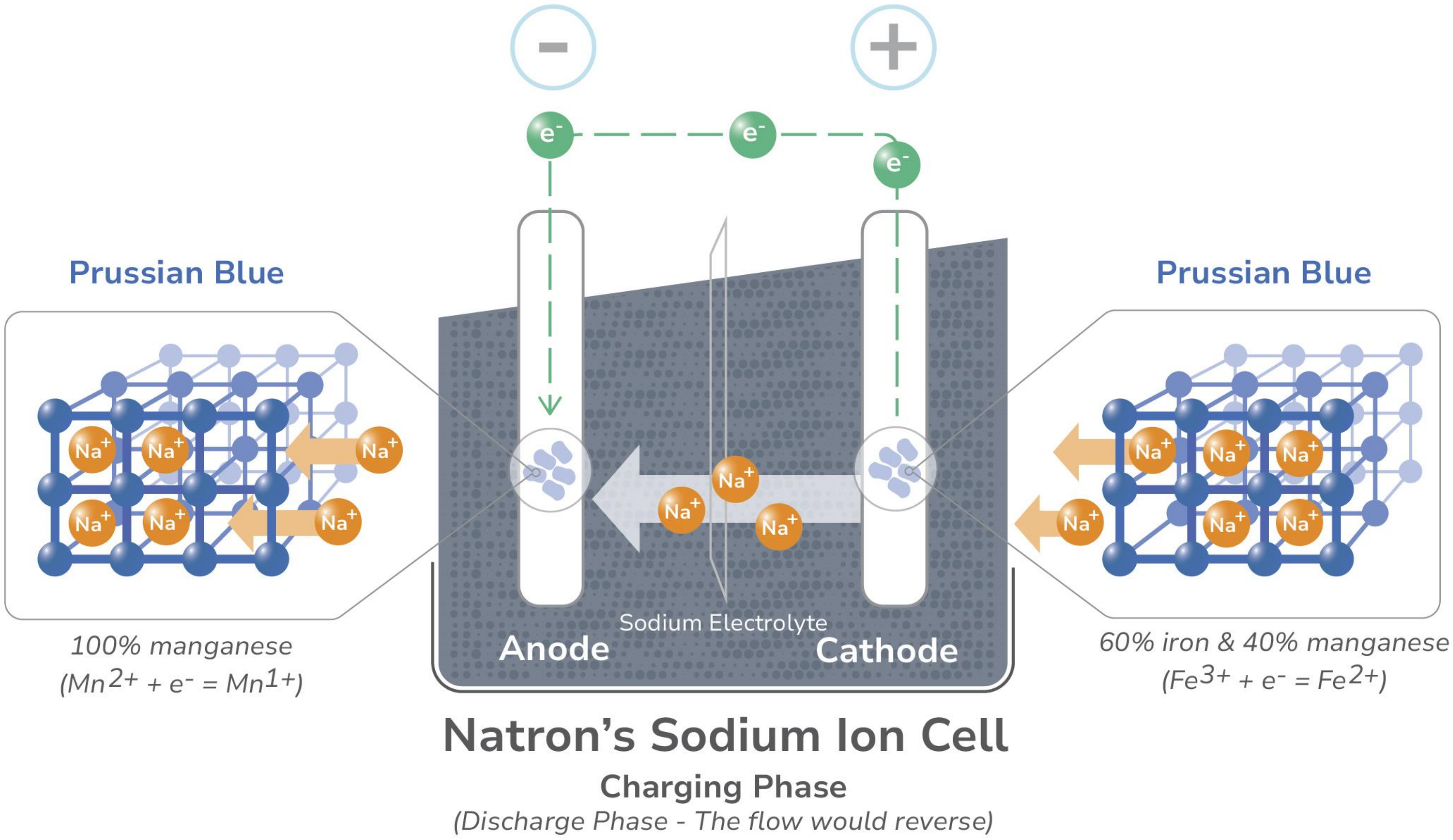
IATA

According to the International Air Transport Association, "…lithium-ion cells and batteries shipped by themselves must be shipped at a state of charge not exceeding 30% of their rated capacity. Lithium batteries are dangerous goods, and all of the regulatory requirements must be complied with…"

Natron Energy

Technology

Cell Chemistry Basics



Rapid Discharge/Charge Cycle

Natron Energy

Natron delivers more power, more often, and faster than any other chemistry

- Half the internal resistance of lead acid
- Significantly greater percentage of total energy delivered during rapid discharge than other battery chemistries
- 70% of rated energy is delivered during 2-minute discharge
- 33% of rated energy is delivered during 30 second discharge
- Extremely rapid recharge with no settling required, and no cooling required
    - 0-99% SOC in <15 minutes
    - 0-70% SOC during 16C recharge lasting 2.5 minutes
    - 70-99% SOC during constant voltage hold lasting 6 minutes

Natron Energy

Environmental, Social, and Governance

A Blue Battery for a Green Planet

Cleaner and more sustainable than the incumbents

Natron Energy

Natron eliminates the “blood” minerals

- No lithium, cobalt, nickel, copper, or zinc
- Check others’ SDS declarations!

Natron eliminates lead, a global public health crisis

- Uncontrolled emissions from lead smelting and recycling

Cobalt mining, Congo

Lead acid recycling, Indonesia

Supply Chain

Qualified for BABA and other Buy American Acts

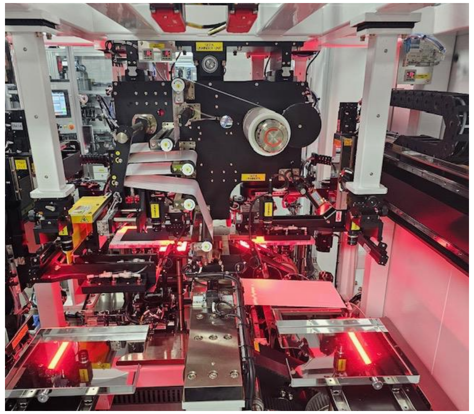
MADE IN USA

Michigan Production Facility

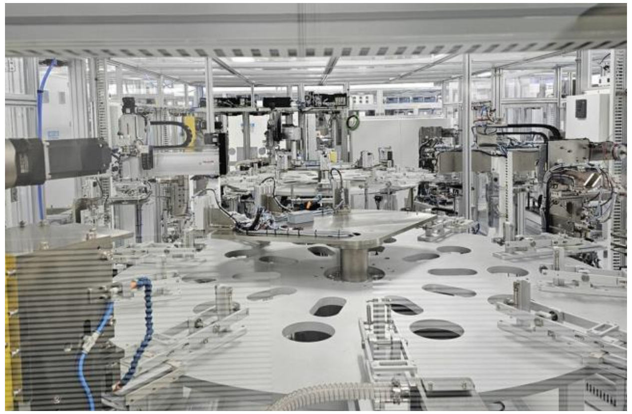
Holland, Michigan Production Facility Details

The Holland plant will allow us to establish markets and secure giga-scale demand before we build our first gigafactory.

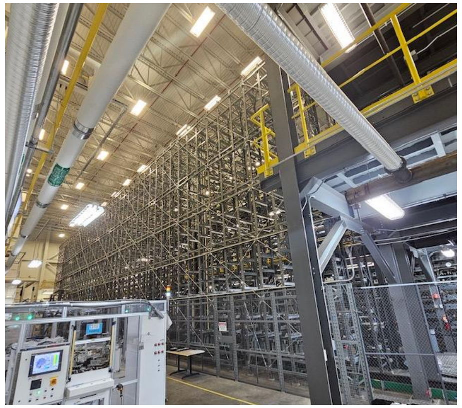
- **Plant has already proven the scalability of our process technology**
  - Materials: >1,000,000x scale-up complete
  - Current 500-ton/yr. capacity ready to scale to >10 kton
  - Electrodes: coating ~11.5km per shift
  - Cell assembly: first customer deliveries – December 2024
  - Giga-factory (NC) will leverage the Holland plant's performance to operate multiple parallel production lines



Automated Cell Stacking

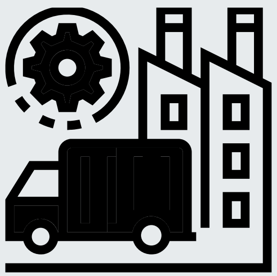


Tab Welding



Cell Testing Towers

No Supply Chain Constraints!



Secure Supply Chain

- **Natron does not depend on questionable supply chains**
- **Natron can source from multiple North American supply chains if ever needed**

These are not
an issue for Natron!

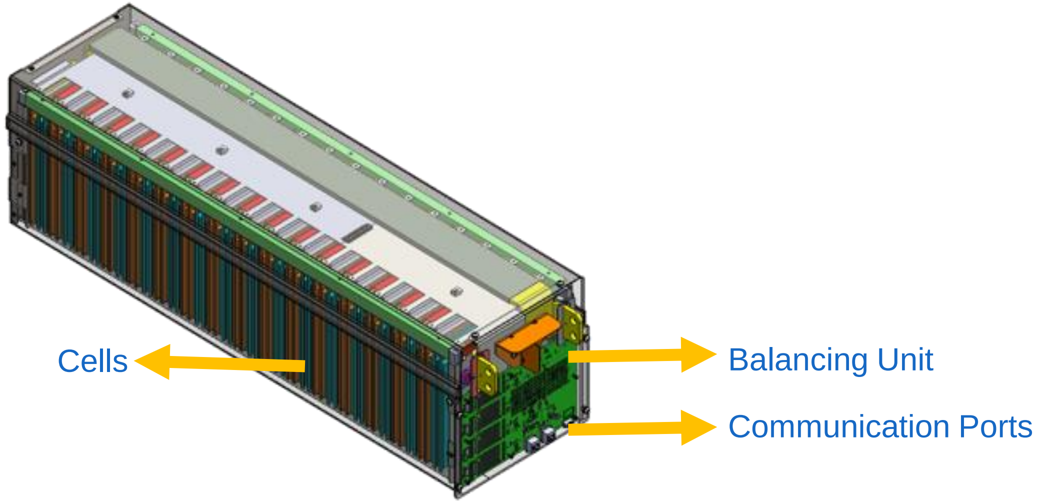
Geopolitical events

Delays at Ports

Products

BluePack™ 25kW, 48VDC Battery

- **Modular 25kW, 48VDC packs can be serialized for power systems from 96 to > 1,000VDC**
- **Operating Voltage range of 58 to 32 volts for max power/energy delivery**
- **800 Amp discharge & charge capable**
- **Class-leading charge and discharge**
  - **2-5 minute optimal discharge**
  - **Recharges in 10 minutes or less**

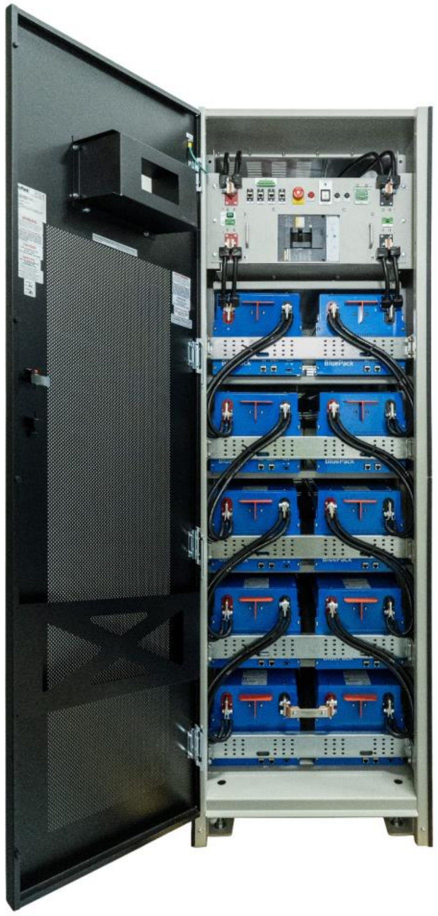


Watch it being tested here: https://www.youtube.com/watch?v=a3GURWZs_ec

BlueRackTM Battery Cabinets Shipping December 2024

- **Proof of Concept systems available now**
- **High Peak Power capacity eliminates need for N+1**
- **Higher power cabinets enable 2+ MVA UPS power blocks**
  - Fewer strings
  - Higher per cabinet standard power
  - Significantly higher Peak Power capacity
- **250 kW per cabinet nominal at a 2-minute discharge**
- **340 kW+ peak at <1 minute discharge rating**

- **Can be combined to make larger systems**
- **Other voltages available > 1,000 VDC**

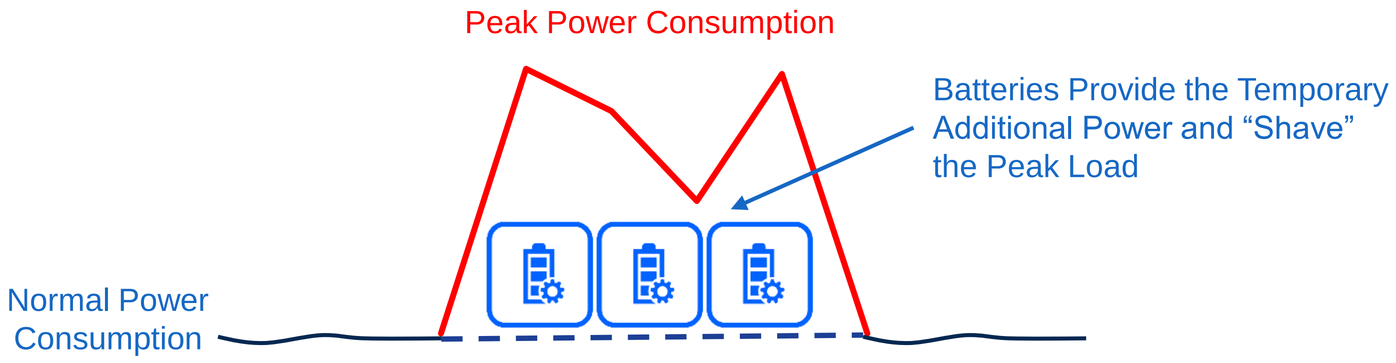


Applications And Use Cases

Uninterruptable Power Supplies

Natron Customer Demonstration Center

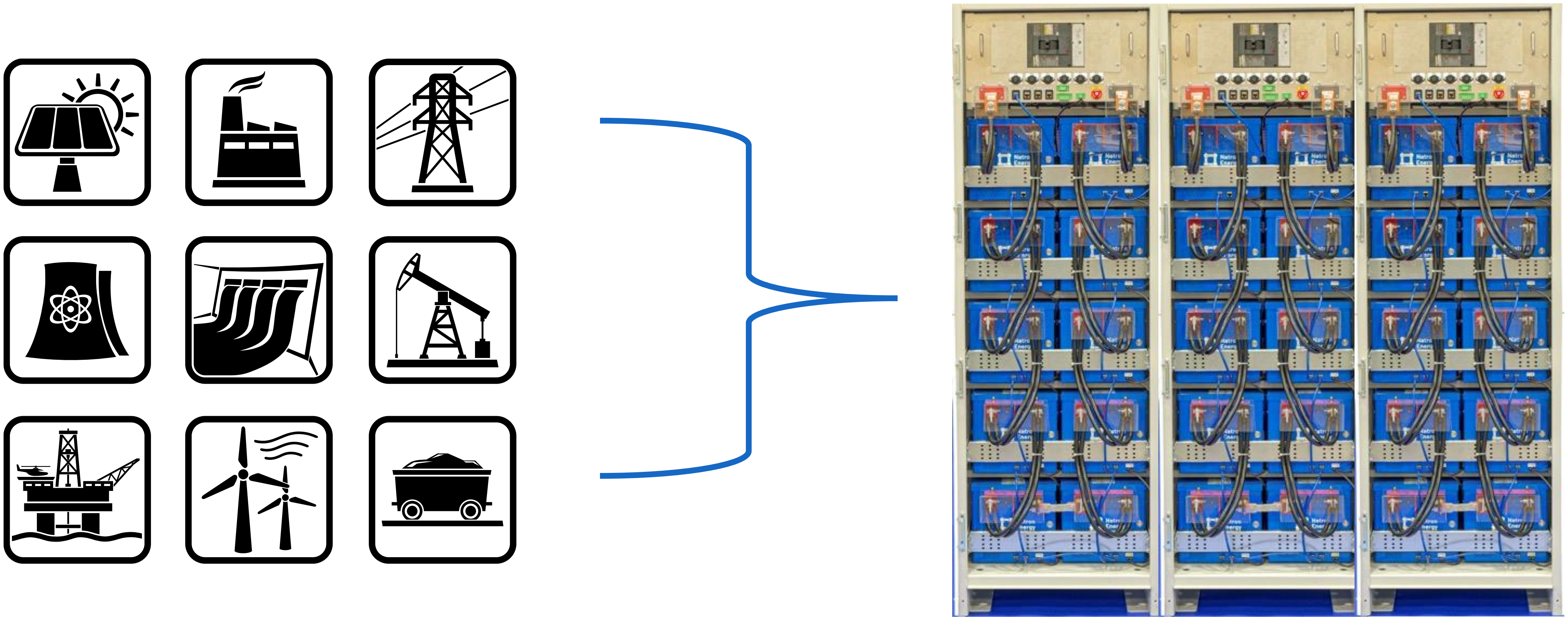
Decarbonization – Displacing GenSets



Example

- Batteries used as peak shaving for drill rig power system, displacing a generator
- Diesel fuel savings business model
- Hundreds of sites globally
- Tried other storage systems first - FAILED
- Managing peak loads from seconds to 15 minutes
- Natron solution requires no maintenance
- Cycle life very appealing – can be hundreds of partial discharges per day
- Best TCO & lowest OPEX battery system available

Micro-Grids & Grid Stabilization



Dark Start Applications

High Power for Engine & Turbine Starting systems

Other Sodium Chemistries / Batteries

Each with their own unique operating parameters

- **Faradion, UK, India – sodium-ceramic, safe, low peak power, long duration energy**
- **Horien, CH, former FZSoNick, high-temp SoNiCl long duration**
- **Tiamat, FR, – EV, cylindrical potential thermal runaway**
- **Northvolt, SW – energy storage, low cycle-count, low peak power**
- **China – CATL, BYD, HiNa – all EV-type, carbon anode, low peak power**
  - Potential thermal runaway

Natron Energy

Thank You

Powered by Prussian Blue