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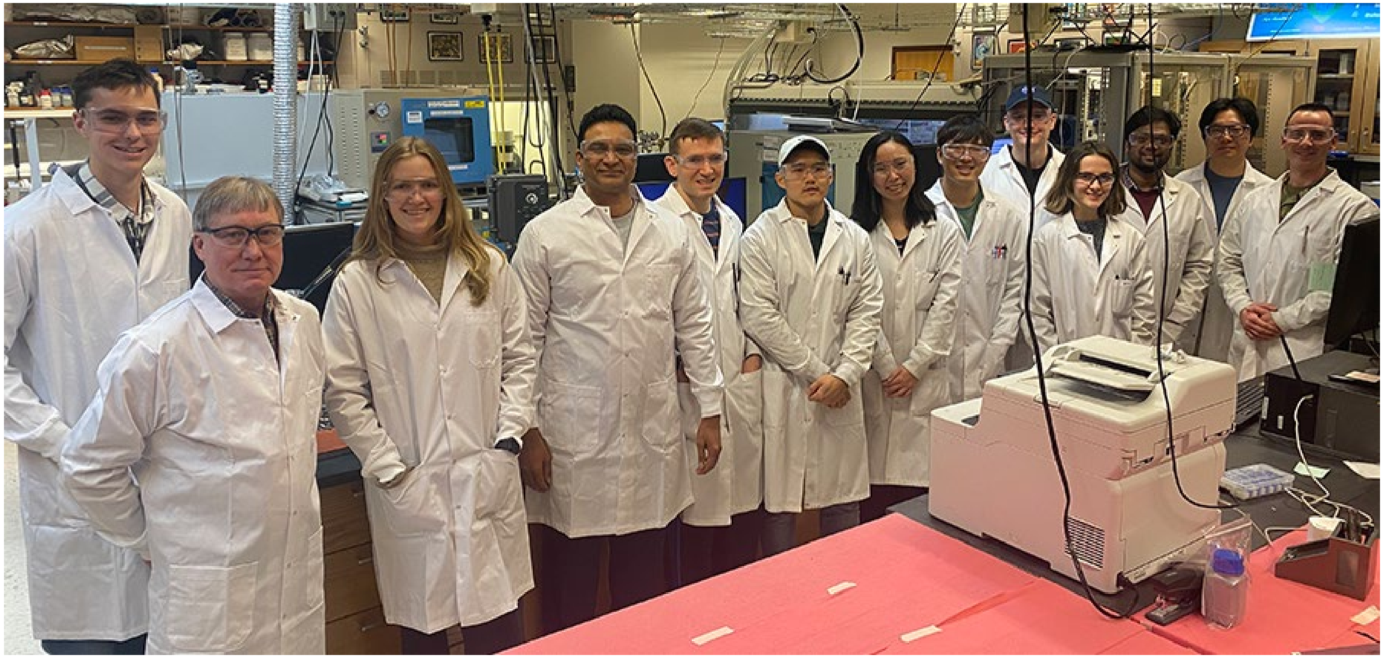
P²SAC
Purdue Process Safety & Assurance Center

Are the Lithium-ion Batteries Unsafe?

Vilas G. Pol

Professor of Chemical Engineering



Acknowledgement: While this presentation utilizes AI-generated visuals from platforms like Perplexity, ChatGPT, and Gemini for enhanced clarity, all underlying scientific concepts and frameworks remain the original intellectual property of the presenter and have been verified for technical accuracy.

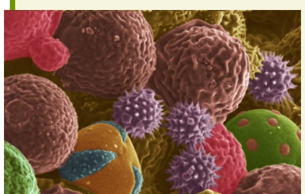
Prof. Vilas G. Pol

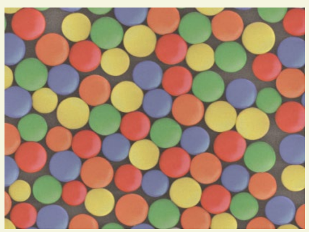
PURDUE ENGINEERING
CHEMICAL ENGINEERING

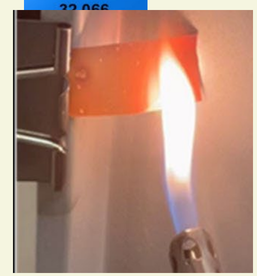
ViPER
Vilas Pol Energy Research

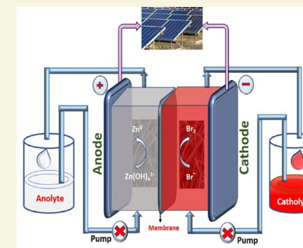
Research Areas

Lithium-ion	Sodium ion	Potassium ion	Li-S/Solid state	Flow
3 Li Lithium 6.941	23 Na SODIUM 11	19 K Potassium 39.0983	16 S	30 Zn Zinc 65.37









300+ Publications; 65 H index, 200+ invited talks
27 issued US patents (10+ pending), 40+ awards

Li-ionBattery Research Challenges

- **Cost**

  Current projected cost (25 kW battery) ~ $1000

  - Target cost (25 kW battery) ~ $500

- **Safety**

  Inherently safe batteries needed

  Overcharge protection circuitry expensive

- **Life**

  Current technology ~ 5 to 10 years

  - Target ~ 15 years

- **Low Temperature Performan**

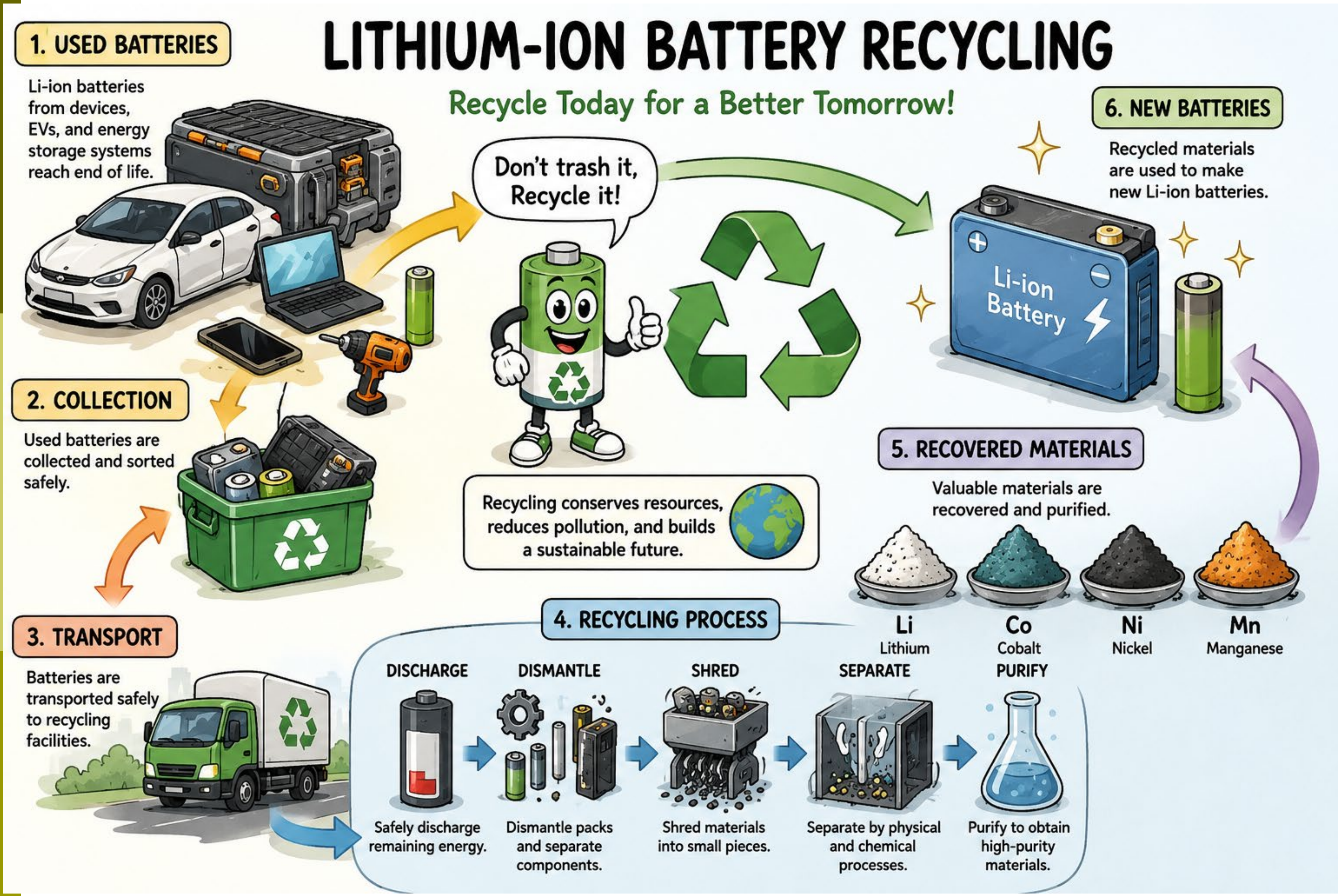
  Current technology ~ Sluggish < 0 ºC

  - Target ~ -30 ºC (cold cranking)

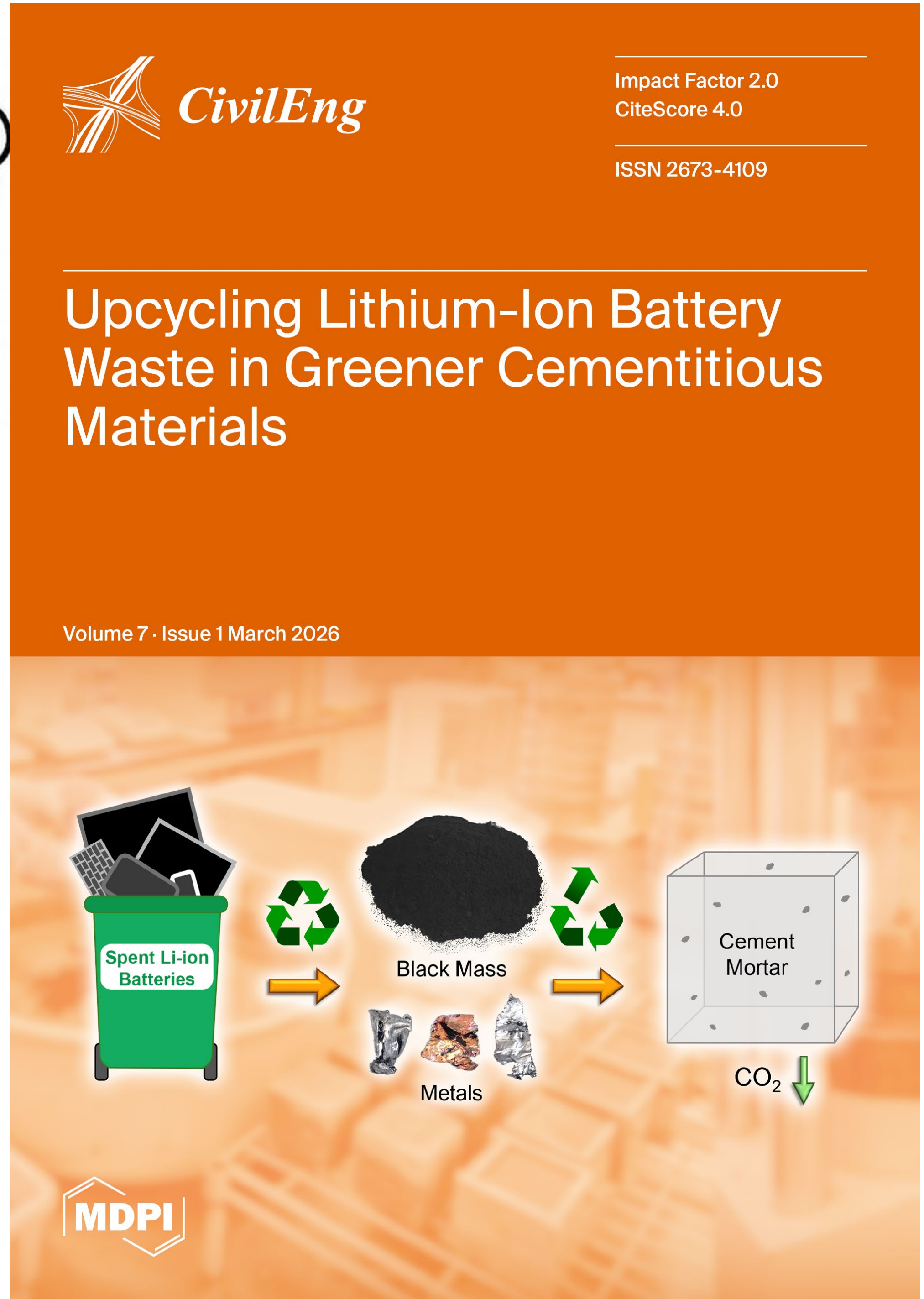
John B. Goodenough *et al.*, *Chemistry of Materials* **(2010)** *22*, 587


25 BILLION BATTERIES.
8.3 BILLION PEOPLE.
ONE BIG RECYCLING QUESTION.
~25 BILLION BATTERIES
HOW DO WE RECYCLE ALL OF THIS?
BIG NUMBERS. BIGGER CHALLENGE.
BETTER SOLUTIONS.

Perplexity



ChatGPT: Chat - Generative Pre-trained Transformer


CivilEng

Impact Factor 2.0
CiteScore 4.0

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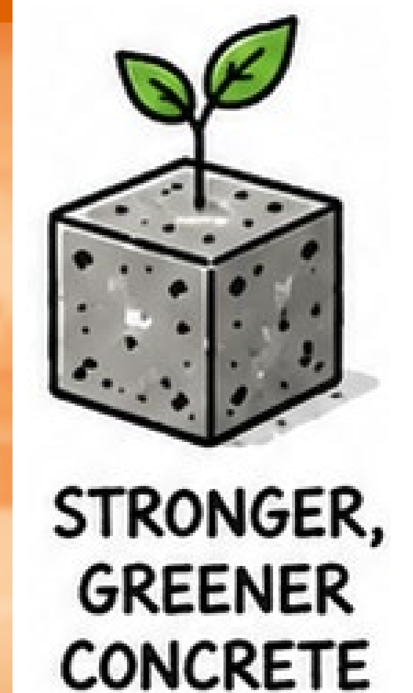
Upcycling Lithium-Ion Battery Waste in Greener Cementitious Materials

Volume 7 · Issue 1 March 2026



CivilEng

MDPI

Article

A Pilot Study on Upcycling of Lithium-Ion Battery Waste in Greener Cementitious Construction Material

Gaurav Chobe [1], Ishaan Davariya [2], Dheeraj Waghmare [1], Shivam Sharma [1], Akanshu Sharma [1,*], Amit H. Varma [1] and Vilas G. Pol [2]

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Abstract

Lithium-ion batteries (LIBs) are essential for electric vehicles, consumer electronics, and grid storage, but their rapidly increasing demand is paralleled by growing waste volumes. Current disposal methods remain costly, complex, energy-intensive, and environmentally unsustainable. This pilot study investigates a scalable, low-impact disposal method by incorporating LIB waste into concrete, evaluating both the structural and environmental effects of LIB waste on concrete performance. Several cement–mortar cube specimens were cast and tested under compression using the cement–mortar mix with varying battery waste components, such as black mass and varied metals. All mortar mixes maintained an identical water-to-cement ratio. The compressive strength of the cubes was measured

Discarded Battery Materials to replacing sand in the concrete

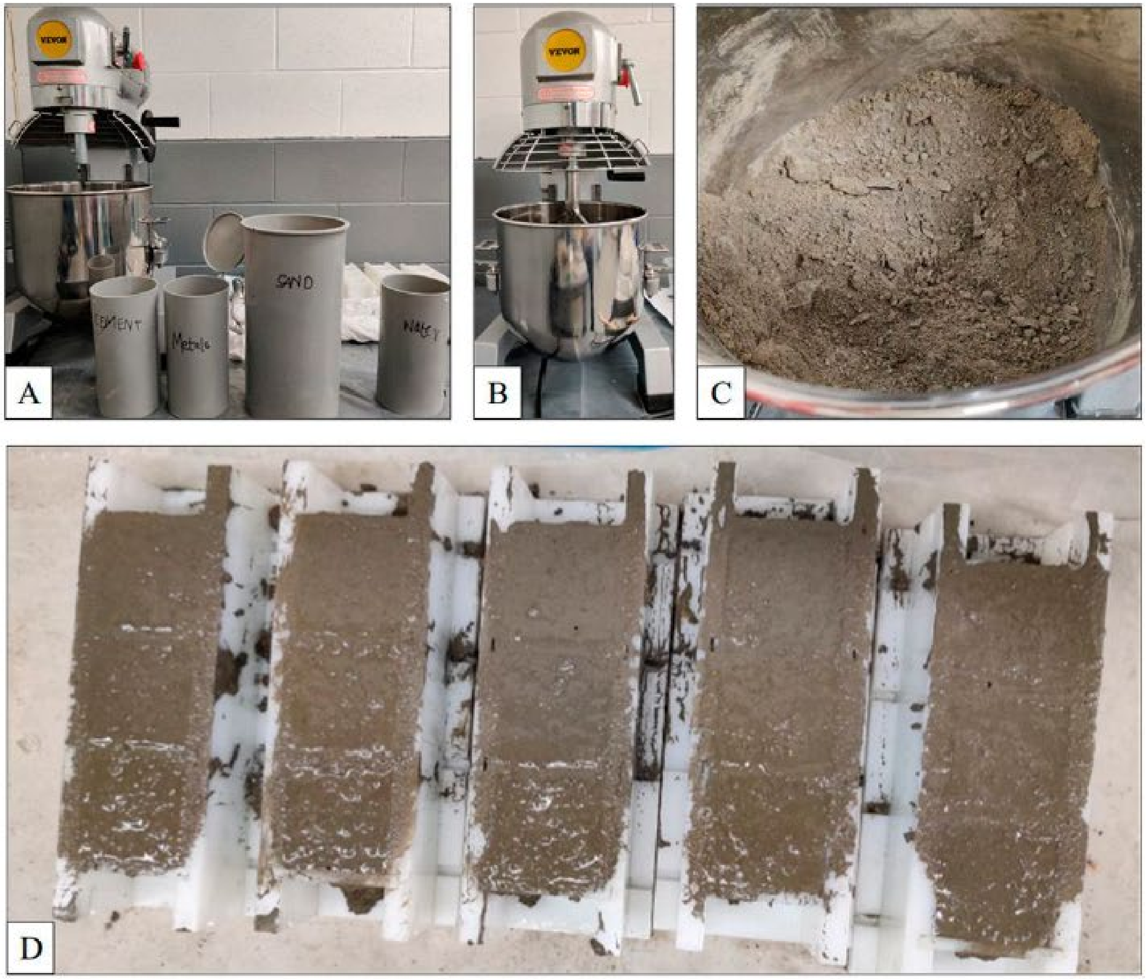


Figure 5. Process of preparing mortar cubes with varied metals: (**A**) Water, cement, sand, metal mass. (**B**) Mixing process. (**C**) Final mix. (**D**) The 50 mm mortar cubes.

Compressive strength

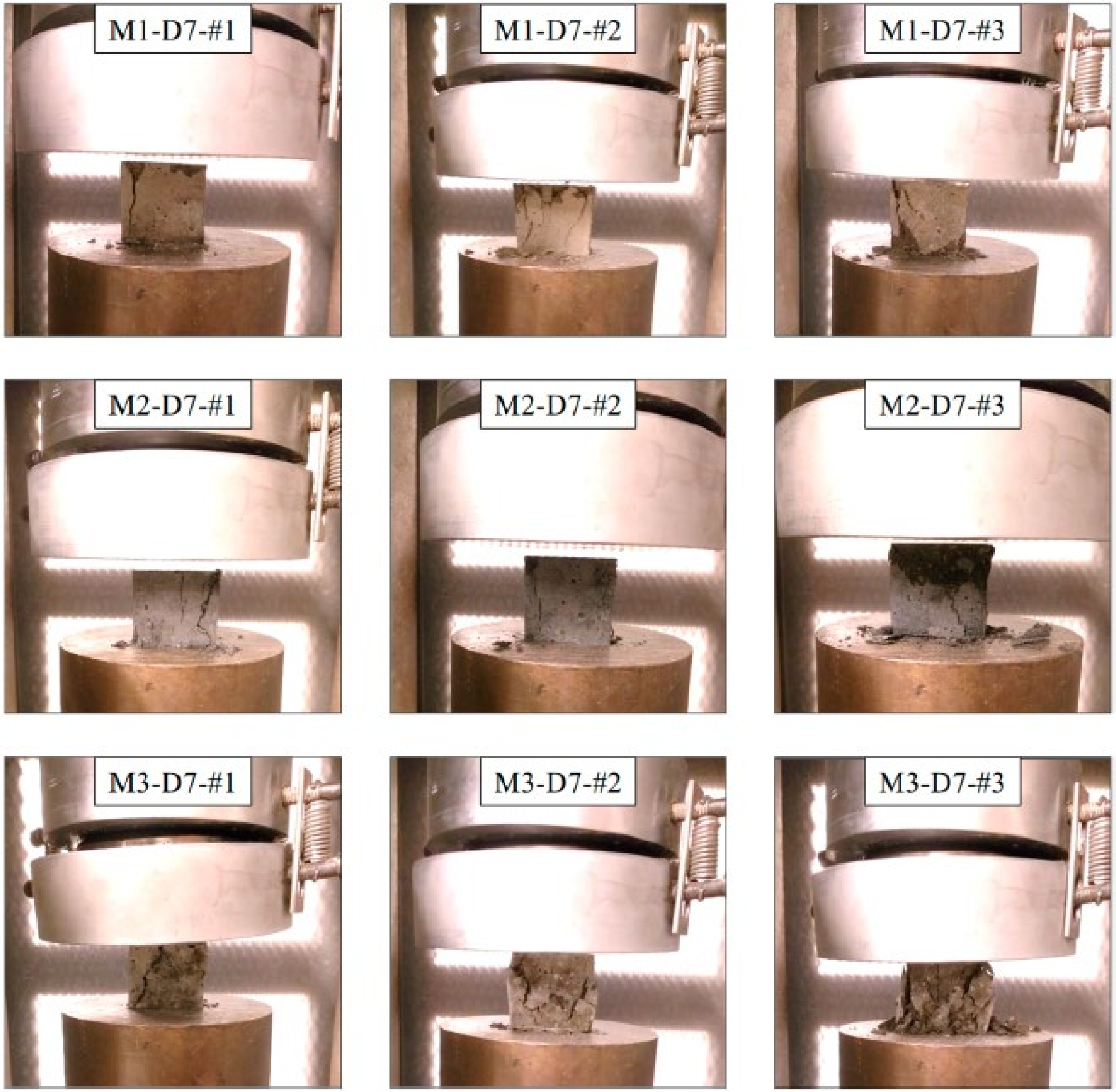


Figure 7. Overview of the failure modes of different mortar mix cubes on 7th day.

Mix	Contents
M1	Water, Cement, Sand
M2	Water, Cement, Sand, Black Mass
M3	Water, Cement, Sand, Varied Metals

Mix ID	Compressive Strength (MPa)	Embodied Carbon (kg CO_2e)	Avoided Emissions (kg CO_2e)	Net Embodied Carbon (kg CO_2e)	Strength-to-Net Embodied Carbon Ratio (MPa/kg CO_2e)
Mix A	52	350	0	350	0.149
Mix B	34	350	300	50	0.680
Mix C	23	350	187.5	162.5	0.142

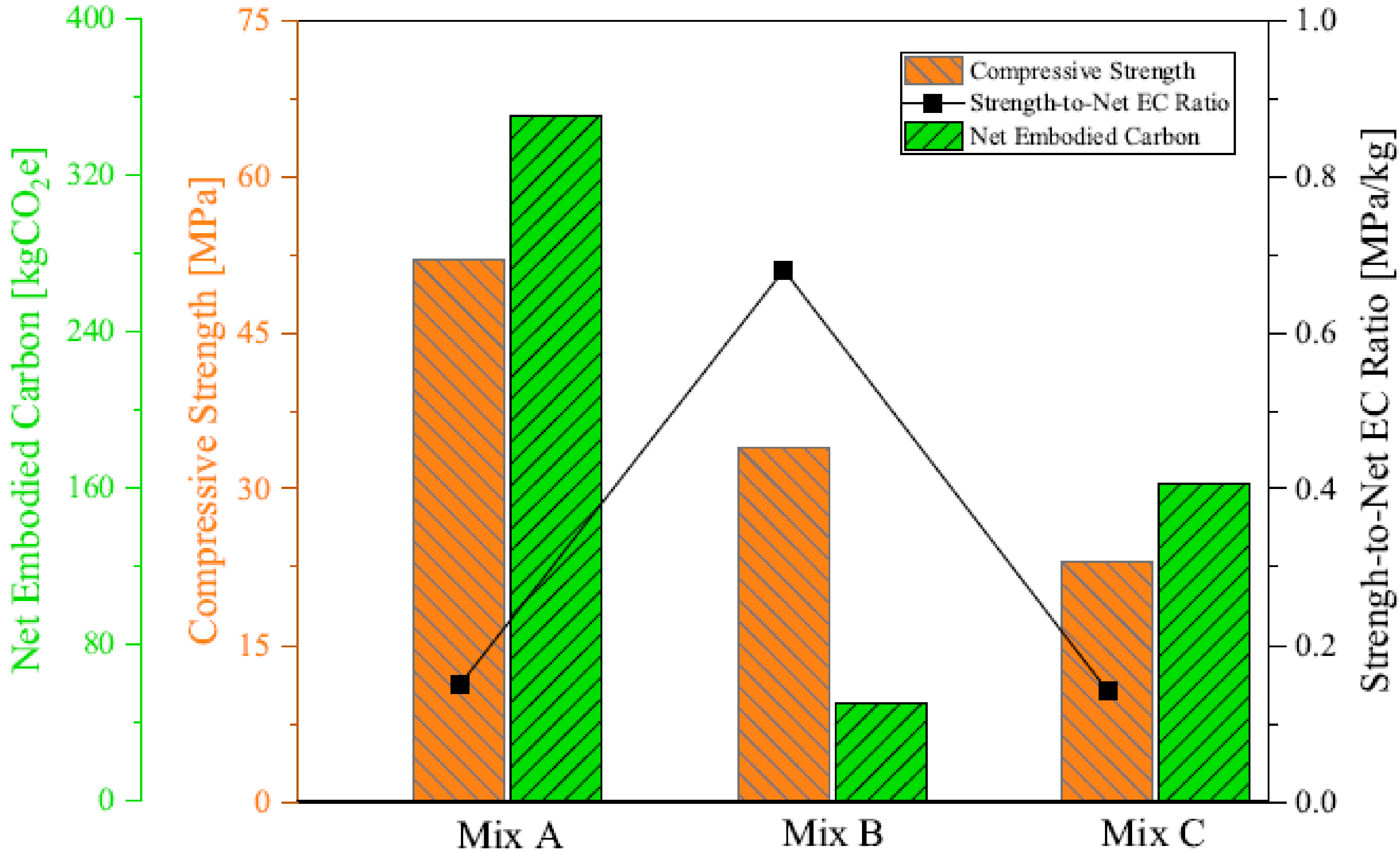
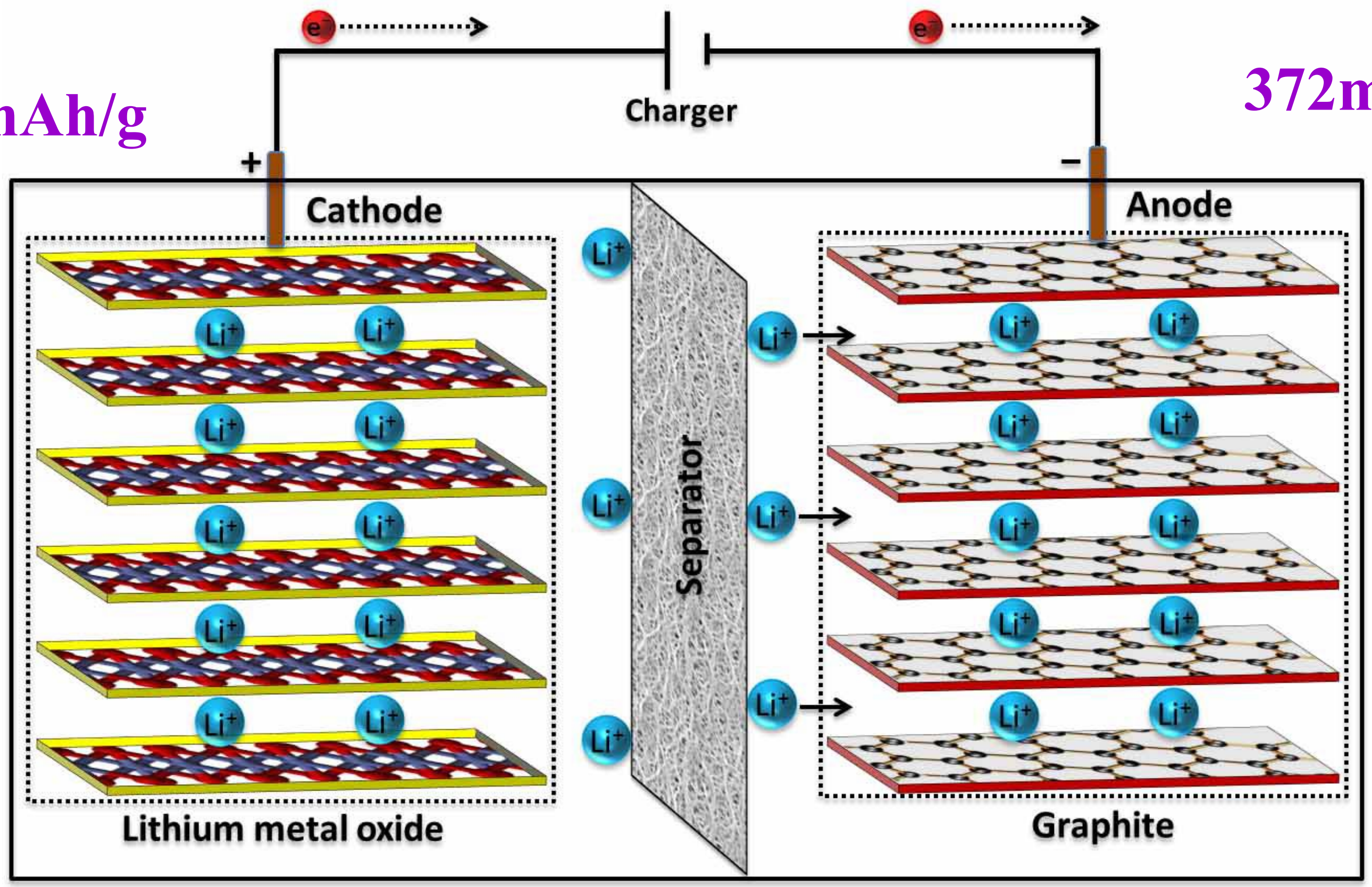


Figure 12. Comparative values of compressive strength, net EC, and strength-to-net EC ratio.

How Li-ion Batteries Work?

200 mAh/g

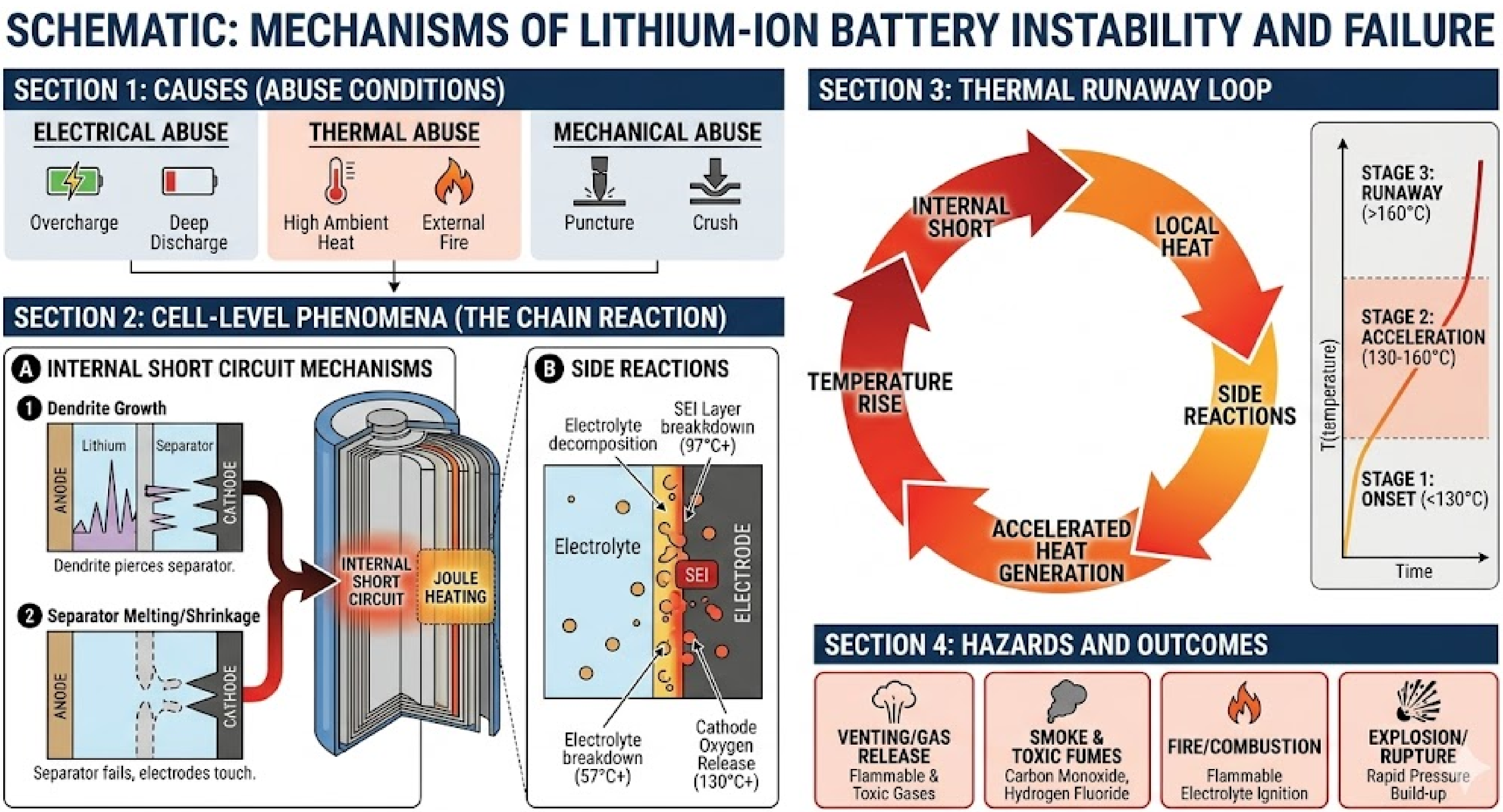
372mAh/g



LiC_6

- ✓ **Process reversibility should be 100% to have longer cycle life**
- ✓ **Requires high-capacity electrode materials**

Lithium-Ion Battery Safety Concerns



Google Gemini (twins)

What happens to solvents and salt in batteries during thermal runaway?

$C_3H_4O_3$ (EC) + $(C_2H_5O)_2CO$ (DEC) + $LiFF_6$ salt

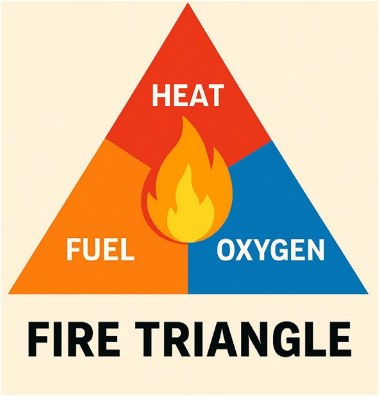
	$2CH_2OCO_2Li_2 \rightarrow Li_2CO_3 + C_2H_4\uparrow + CO_2\uparrow + \frac{1}{2}O_2$	**(1)**
	$2Li + CH_2OCOOCH_2 \rightarrow Li_2CO_3 + C_2H_4\uparrow$	(2)
	$2Li + C_2H_5OCOOC_2H_5 \rightarrow Li_2CO_3 + C_2H_4\uparrow + C_2H_6\uparrow$	(3)

70-120 °C

$LiPF_6 + H_2O \rightarrow LiF + HF\uparrow + POF_3$	**(4)**
$C_2H_5OCOOC_2H_5 + PF_5 \rightarrow C_2H_5OCOOPF_4 + HF\uparrow + C_2H_4\uparrow$	(5)
$C_2H_5OCOOC_2H_5 + PF_5 \rightarrow C_2H_5OCOOPF_4 + C_2H_5F\uparrow$	(6)
$C_2H_5OCOOPF_4 \rightarrow HF\uparrow + C_2H_4\uparrow + CO_2\uparrow + POF_3$	(7)
$C_2H_5OCOOPF_4 + HF \rightarrow PF_4OH + CO_2\uparrow + C_2H_5F\uparrow$	(8)

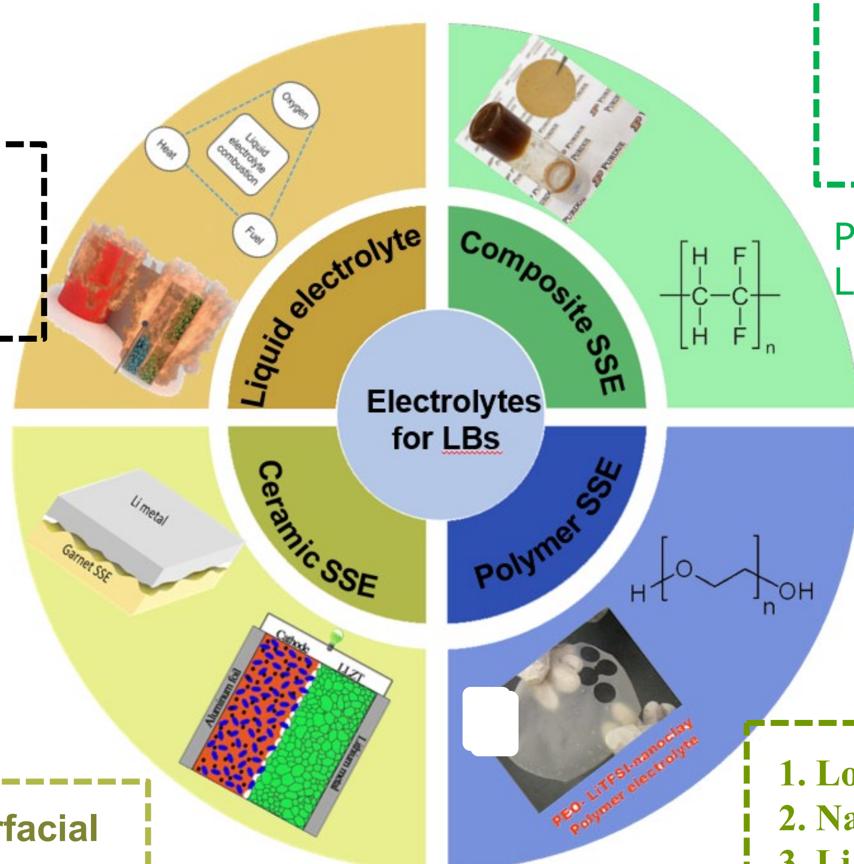
>120 °C

Cathode decomposes
e.g., $LiCoO_2$ at 150 °C, $LiNi_xCo_yMn_zO_2$ at 210°C, $LiMn_2O_4$ at 265 °C, and $LiFePO_4$ at 310°C.



Purdue's Advanced Solid-state Battery Technology

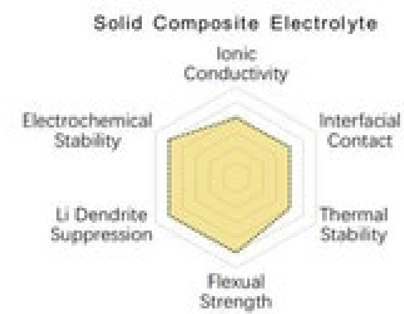
1. Flammable
2. Leak
3. Li dendrite



Purdue Innovation

1. High ionic conductivity
2. Wide voltage window
3. Thermal Safe
4. Li Dendrite free

Polyvinylidene fluoride **(PVDF)**
$Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$ **(LLZTO)**



1. High interfacial resistance
2. Li dendrite

1. Low ionic conductivity
2. Narrow voltage window
3. Li dendrite

Poly(ethylene oxide) (PEO)

Purdue's Generation I

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Room-temperature, high-voltage solid-state lithium battery with composite solid polymer electrolyte with *in-situ* thermal safety study ✔

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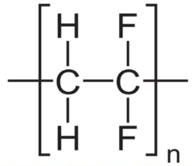
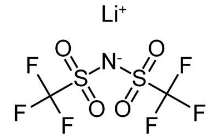
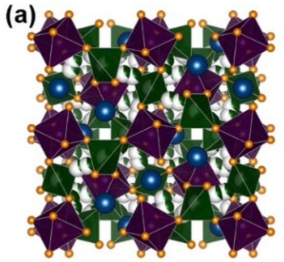
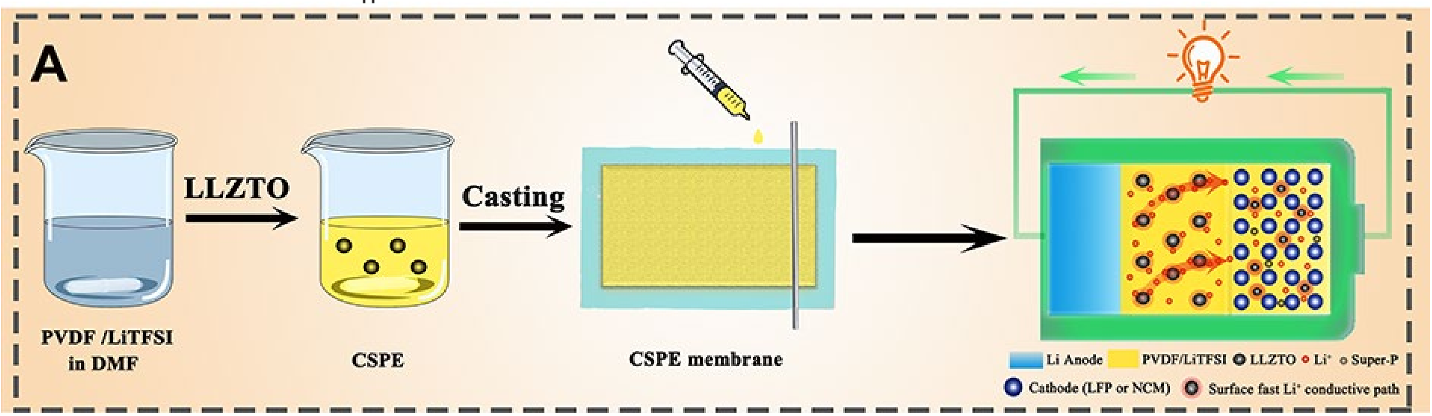
Scalable Fabrication of SS Composite Electrolyte

PVDF – Polymer Matrix; LiTFSI – Li salt; LLZTO – ceramic nanoparticles



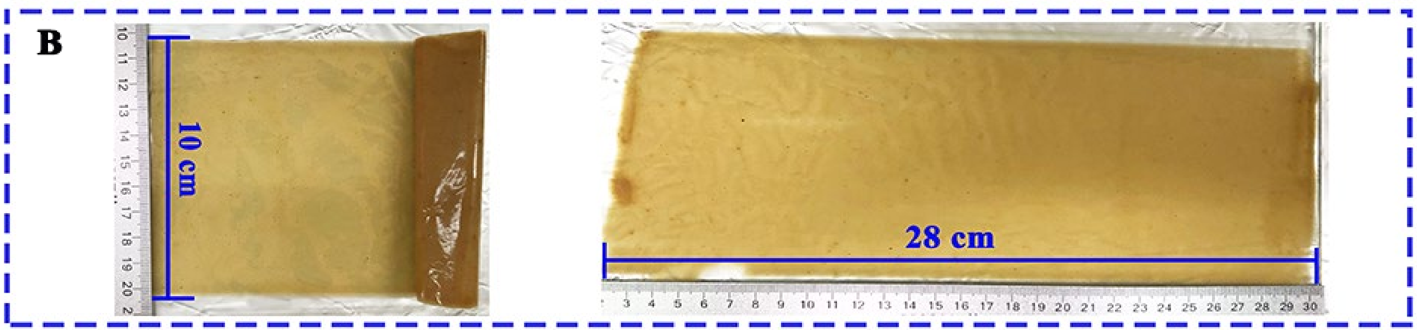






The synthesis of composite solid polymer electrolyte

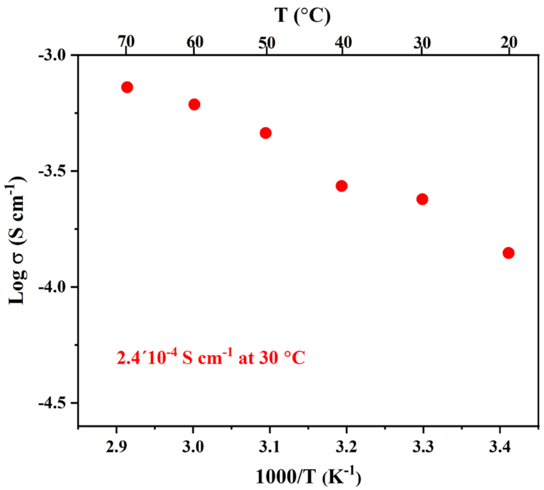
- ✓ **Facile synthesis**
- ✓ **Operation at room temperature**

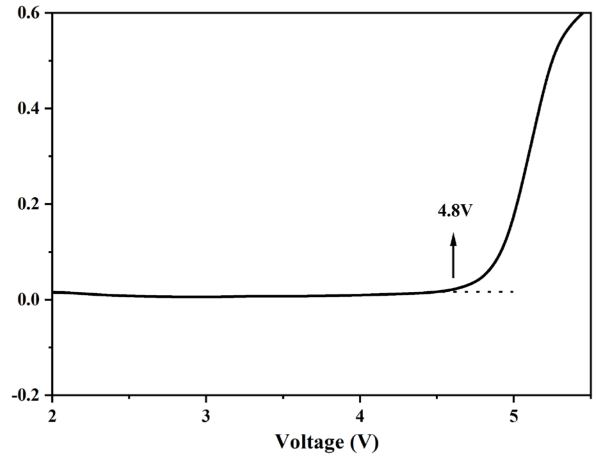


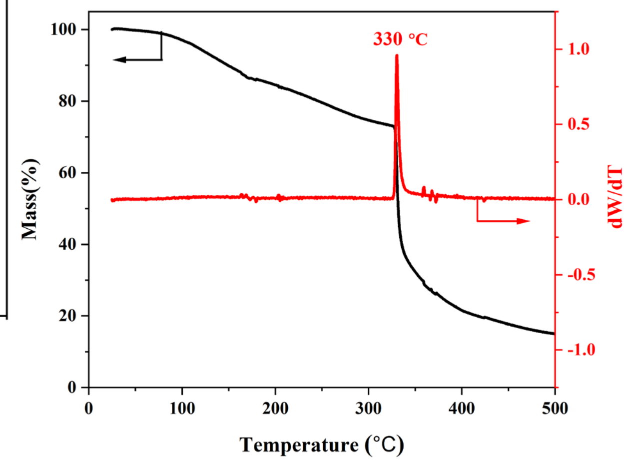
Pictures of as-prepared composite solid polymer electrolyte

- ✓ **Flexible**
- ✓ **Free standing**
- ✓ **Scalable**

Ionic Conductivity, Voltage Window, Thermal Stability







- ✓ High room-temperature ionic conductivity (2.4×10^{-4} S cm^{-1})
- ✓ Wide voltage window (~ 4.8 V)
- ✓ Excellent thermal stability (~ 330 °C)

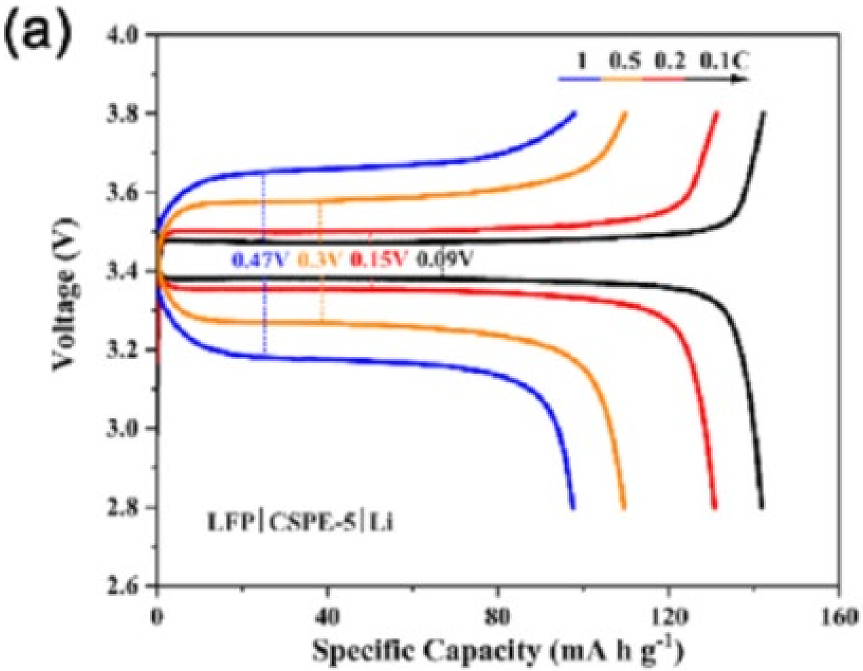
Purdue's Composite solid polymer electrolyte

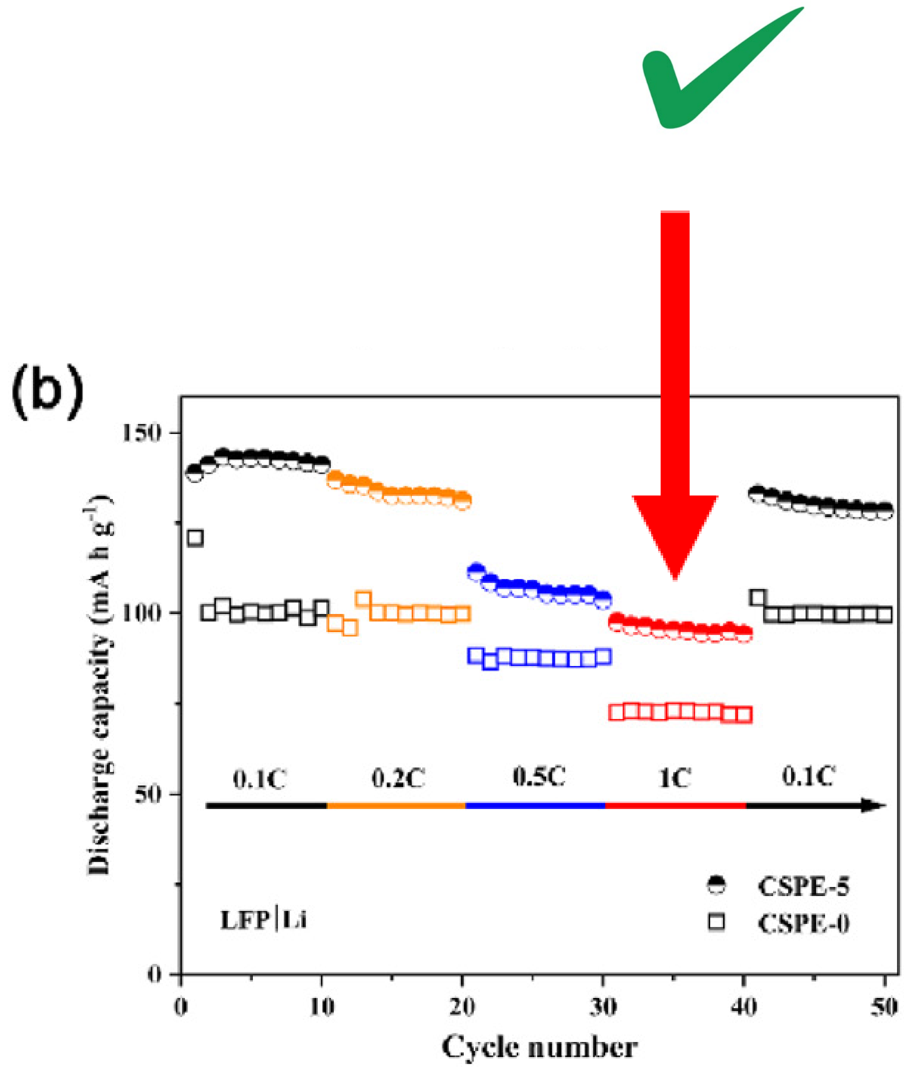
VS

- ✗ Low room-temperature ionic conductivity (10^{-7} -10^{-5} S cm^{-1})
- ✗ Narrow voltage window (~ 3.8 V)
- ✗ Inferior thermal stability (~ 230 °C)

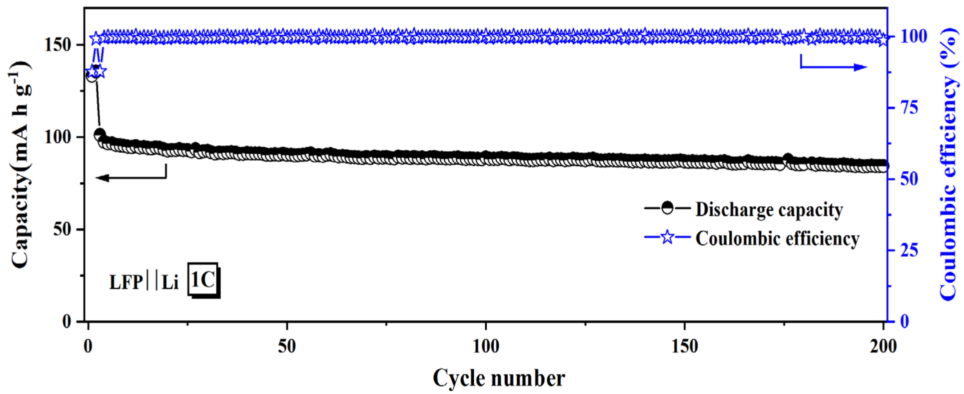
Typical PEO-based polymer electrolyte

Rate studies



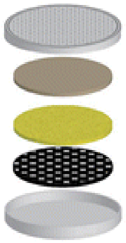


Electrochemical Performance of Solid-state Full Cell

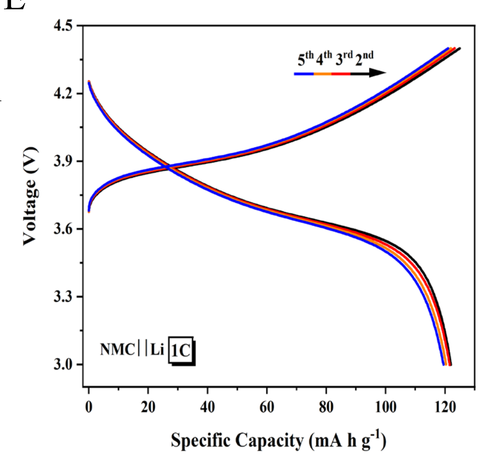


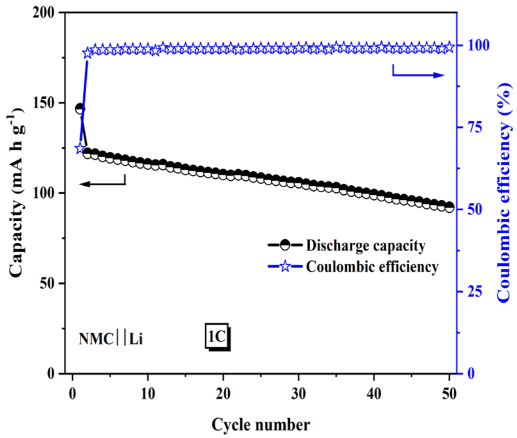
$LiFePO_4$

2.8 ~ 3.8 V



Room Temperature



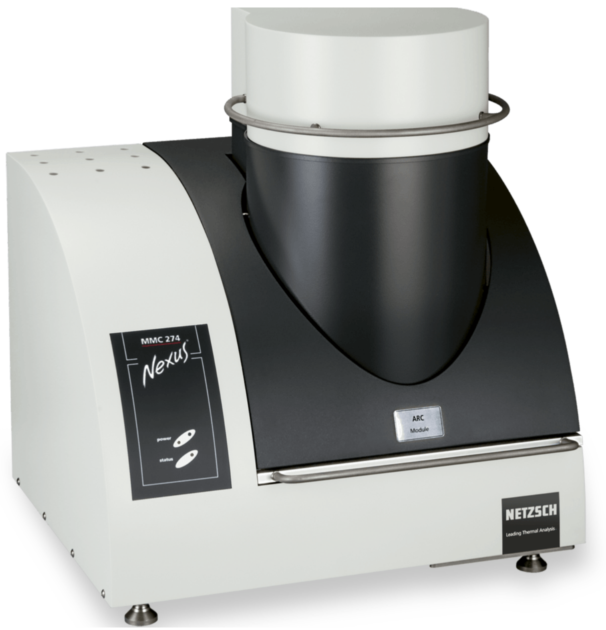


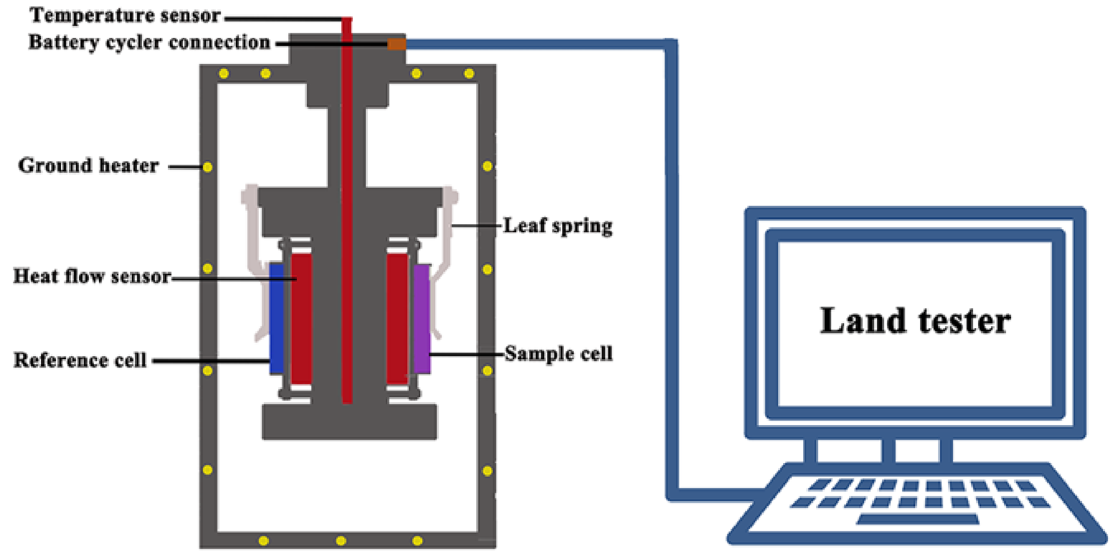
$LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$

3 ~ 4.4 V

- ✓ Purdue's Gen I composite solid polymer electrolyte does work with various cathodes

Schematic of multiple module calorimeter

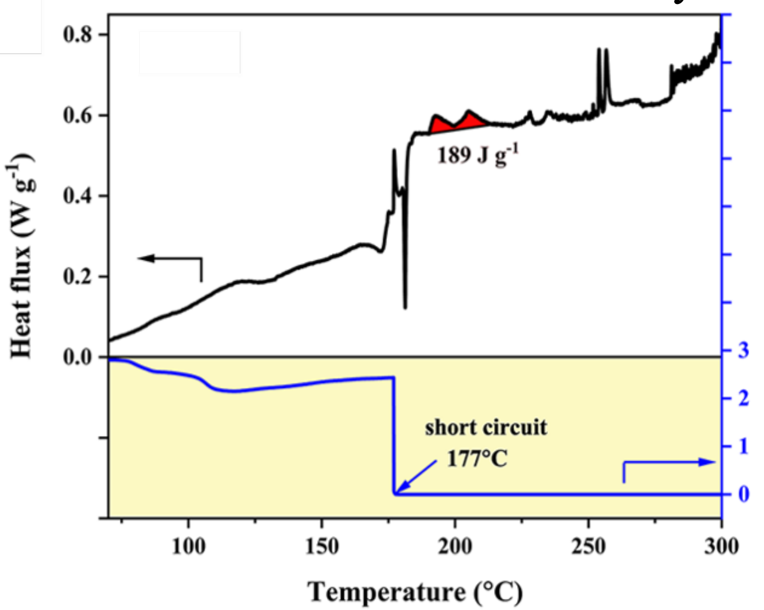




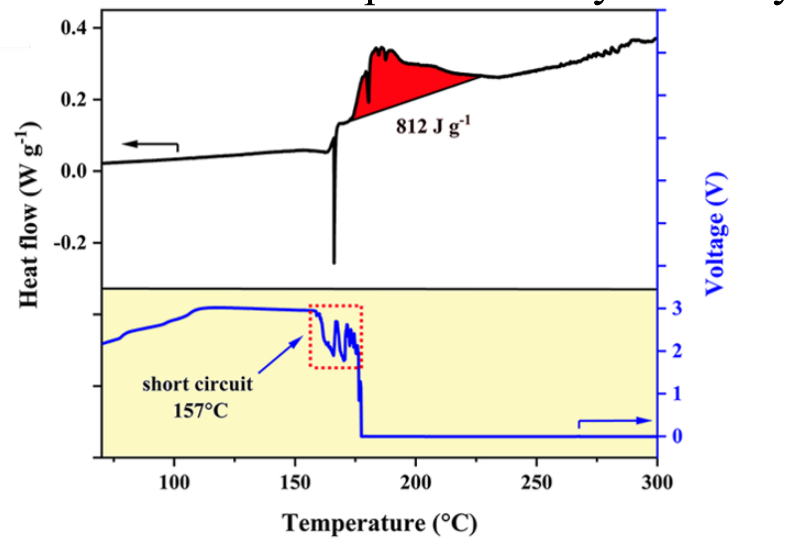
- Different from DSC and ARC
- **MMC** can **in-situ** investigate the thermal behavior of an **entire coin cell** instead of individual components

Thermal Safety Performance

Purdue's solid-state battery



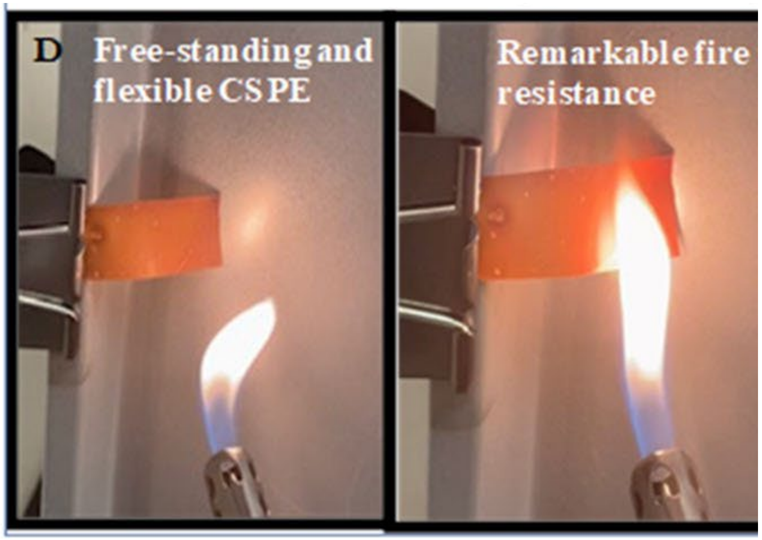
Traditional liquid electrolyte battery



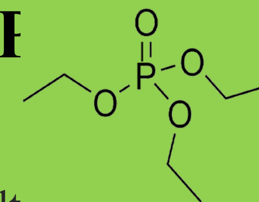
Thermal stable window: ✓ up to 177 °C *VS* × up to 157 °C

Heat generation: ✓ 189 J g^{-1} *VS* × 812 J g^{-1}

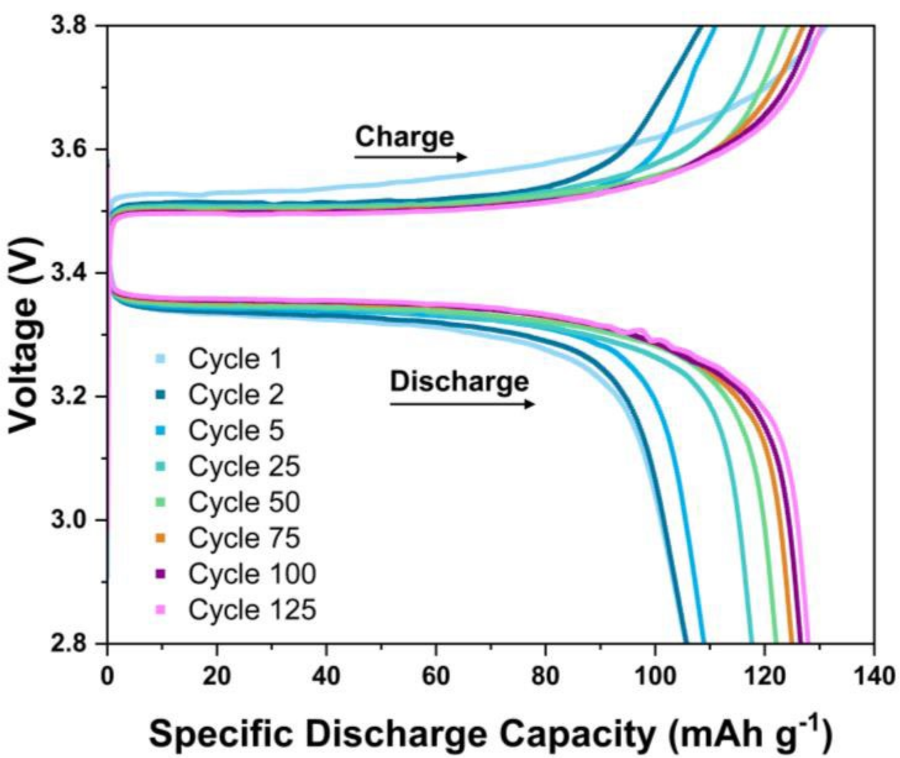
Purdue's Generation II:



Triethyl Phosphate (TEI



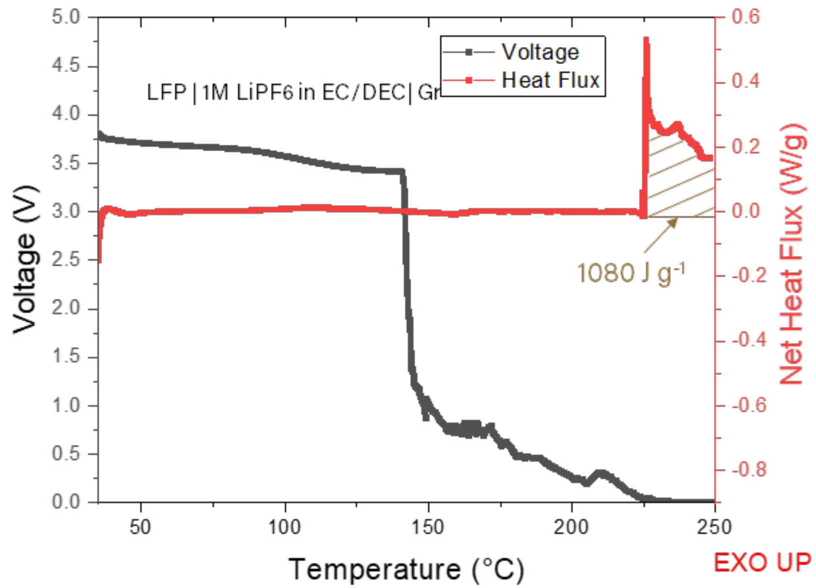
- Green and nontoxic liquid
- Excellent solubility with lithium salts and polymer
- Excellent oxidative stability



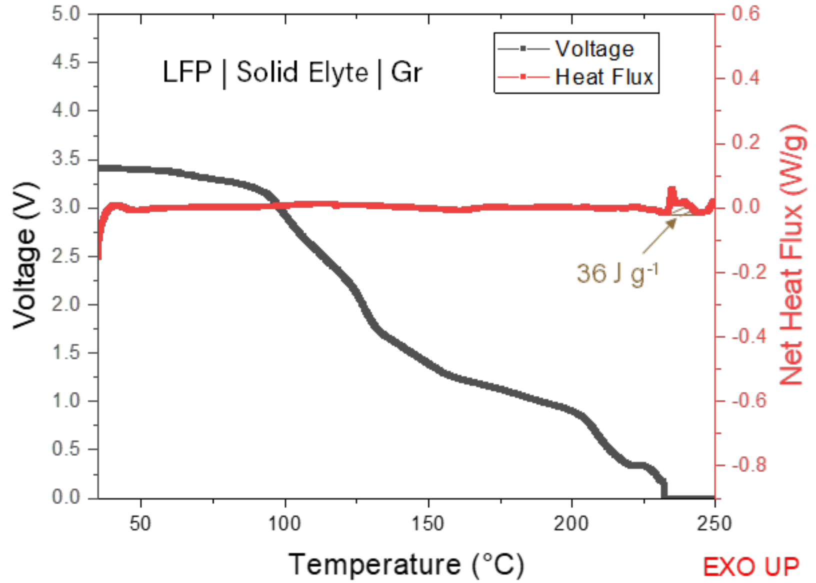
$$PO\bullet + H\bullet \rightarrow HPO$$
$$PO\bullet + OH\bullet \rightarrow HPO_2$$
$$HPO + H\bullet \rightarrow H_2 + PO\bullet$$
$$OH\bullet + H_2 + PO\bullet\ r\!\rightarrow H_2O + HPO$$
$$HPO_2\bullet + H\bullet \rightarrow H_2O + PO$$
$$HPO_2\bullet + H\bullet \rightarrow H_2 + PO_2$$
$$HPO_2\bullet + OH\bullet \rightarrow H_2O + PO_2$$

Exothermic heat measurements - MMC

Conventional



Quasi-solid state



Does it really make battery safer?

Ballistic Testing of 100% SOC Multilayer Pouch Cell

- Collaborative ballistic testing courtesy of Cornerstone Research Group (CRG) in Ohio
- **Cell configuration**:
  - 120 mAh; 5-layer pouch
  - LFP Full Cell | fire retarding electrolyte | Li anode
- **Testing Protocol**
  - Precycled and fully charged
  - Shot with 7.62x39mm round (cartridge size of AK-47)
  - Visual/IR monitoring for smoke, flame, or temperature increase

Bullet Type	Velocity (m/s)	Energy (J)	Time of Impact (s)	Temperature Increase from impact to 10s
8.0 g FMJ	738.0 m/s	2,179 J	2.20 s	None detected by IR

Abuse testing with functionality

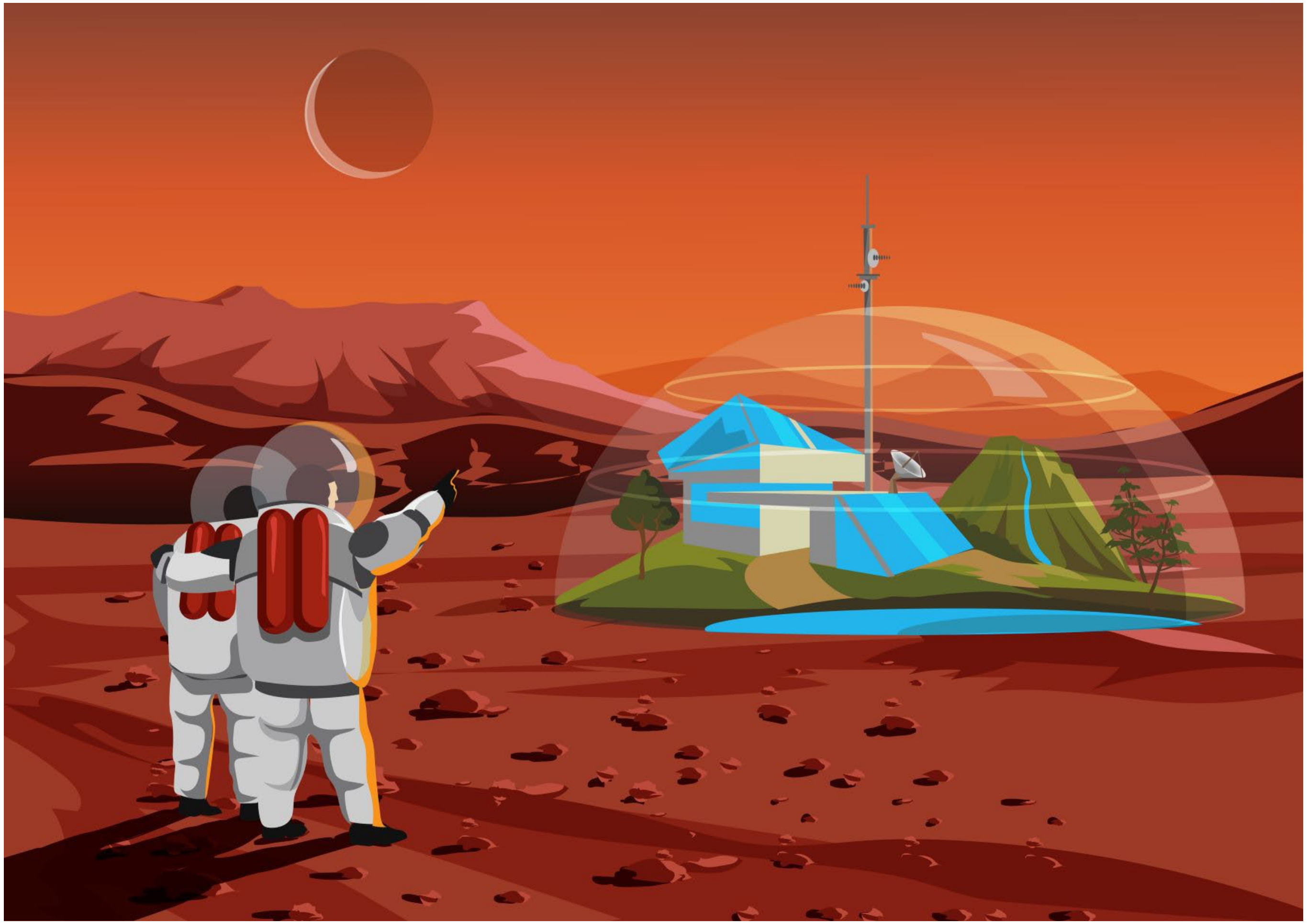
Original | Bending | Cutting | Punching

- Apart from various abuse tests still functional

Why are we NOT going on Mars (Yet)?

Cold

Energy



Water

Food

NANO · MICRO small
www.small-journal.com

Enabling Extreme Low-Temperature (≤ −100 °C) Battery Cycling with Niobium Tungsten Oxides Electrode and Tailored Electrolytes

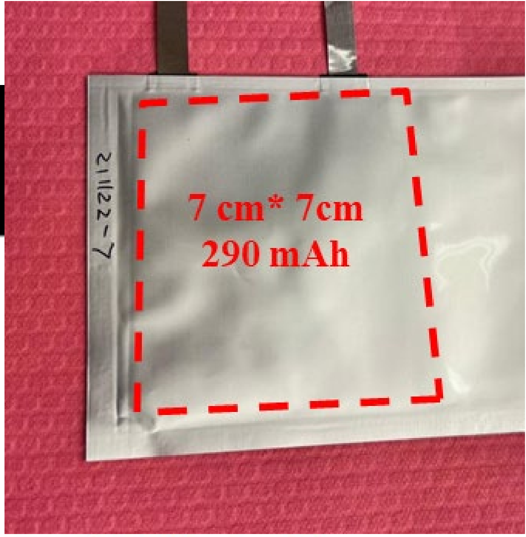
Soohwan Kim, Yizhi Zhang, Haiyan Wang, Thomas E. Adams, and Vilas G. Pol**

The degradation of current Li-ion batteries (LIBs) hinders their use in electronic devices, electric vehicles, and other applications at low temperatures, particularly in extreme environments like the polar regions and outer space. This study presents a pseudocapacitive-type niobium tungsten oxides (NbWO) electrode material combined with tailored electrolytes, enabling extreme low-temperature battery cycling for the first time. The synthesized NbWO material exhibits analogous structural properties to previous studies. Its homogenous atom distribution can further facilitate Li^+ diffusion, while its pseudocapacitive Li^+ storage mechanism enables faster Li^+ reactions. Notably, the NbWO electrode material exhibits remarkable battery performance even at −60 and −100 °C, showcasing capacities of ≈90 and ≈75 mAh g^{-1}, respectively. The electrolytes, which have demonstrated favorable Li^+ transport attributes at low temperatures in the earlier investigations, now enable extreme low-temperature battery operations, a feat not achievable with either NbWO or the electrolytes independently. Moreover, the outcomes extend to −120 °C and encompass a pouch-type cell configuration at −100 °C, albeit with reduced performance. This study highlights the potential of NbWO for developing batteries for their use in extremely frigid environments.

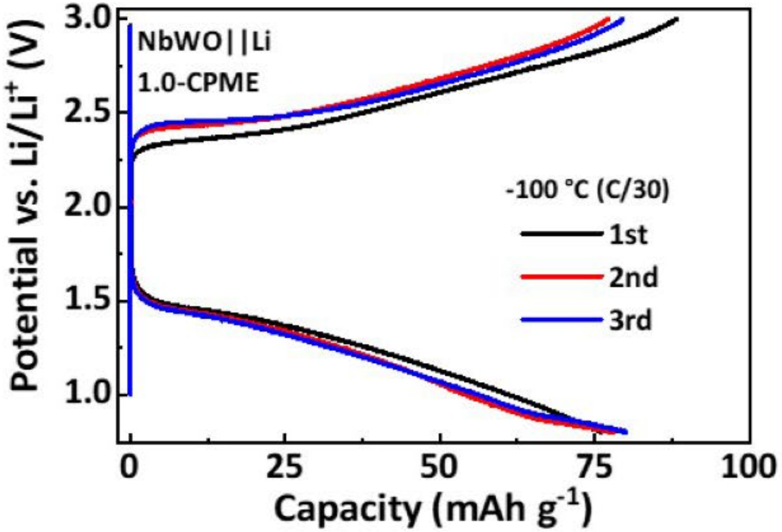
1. Introduction

Research on low-temperature Li-ion batteries (LIBs) has gained increasing attention in recent years due to the rising demand for energy storage in cold regions.[1,2] Nevertheless, the severe performance degradation of current LIBs at low temperatures has impeded their cold climate applications in electronic devices, electric vehicles, drones, and other applications.[1,2] This is particularly significant for defense and advanced exploration missions that necessitate specialized equipment in extremely frigid environments such as the polar regions of the Earth and outer space.[3–5] In these environments, batteries are often subjected to temperatures well below freezing, which can cause severe performance degradation and even failure. While secondary/external heating systems are currently being utilized to operate the batteries, these systems add significant weight, cost, and energy requirements.[5,6] Therefore, it is essential to develop batteries that can operate themselves and ef-

-100 °C Tests (NbWO||Li)



-100 °C (C/30) test (0.8-3.0V)



~75 mAh g^{-1} @ -100 °C

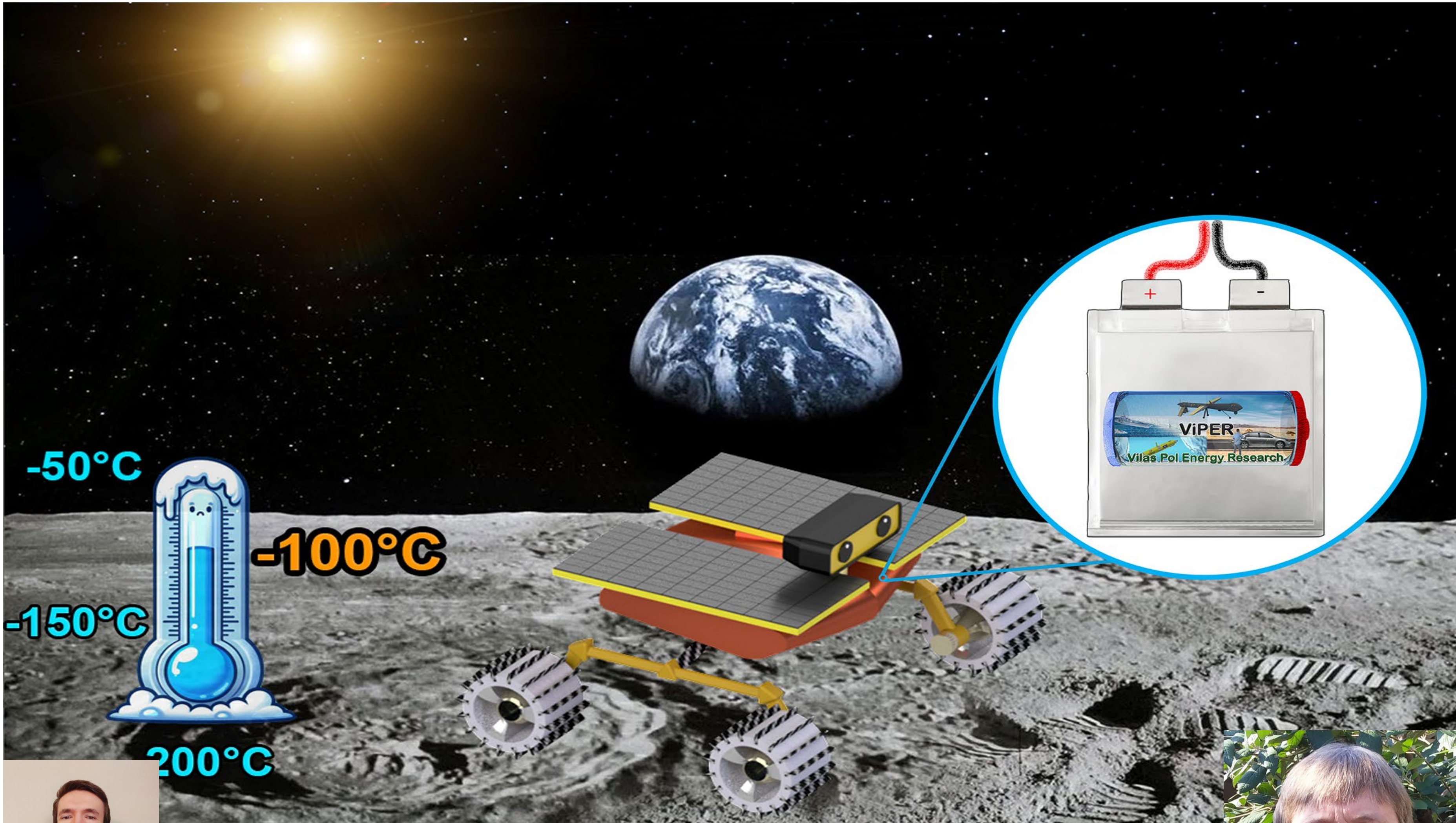
-100 °C tests with 1.0-CPME

- 1.0-CPME
  → Good low-temperature performance (graphite anode)
  → Charge-discharge ability at -100 °C with a small capacity and extremely slow current rate
- Finally, NbWO with 1.0-CPME achieved >75 mAh g^{-1} at C/30.
  → Much improved extreme low-temperature battery performance

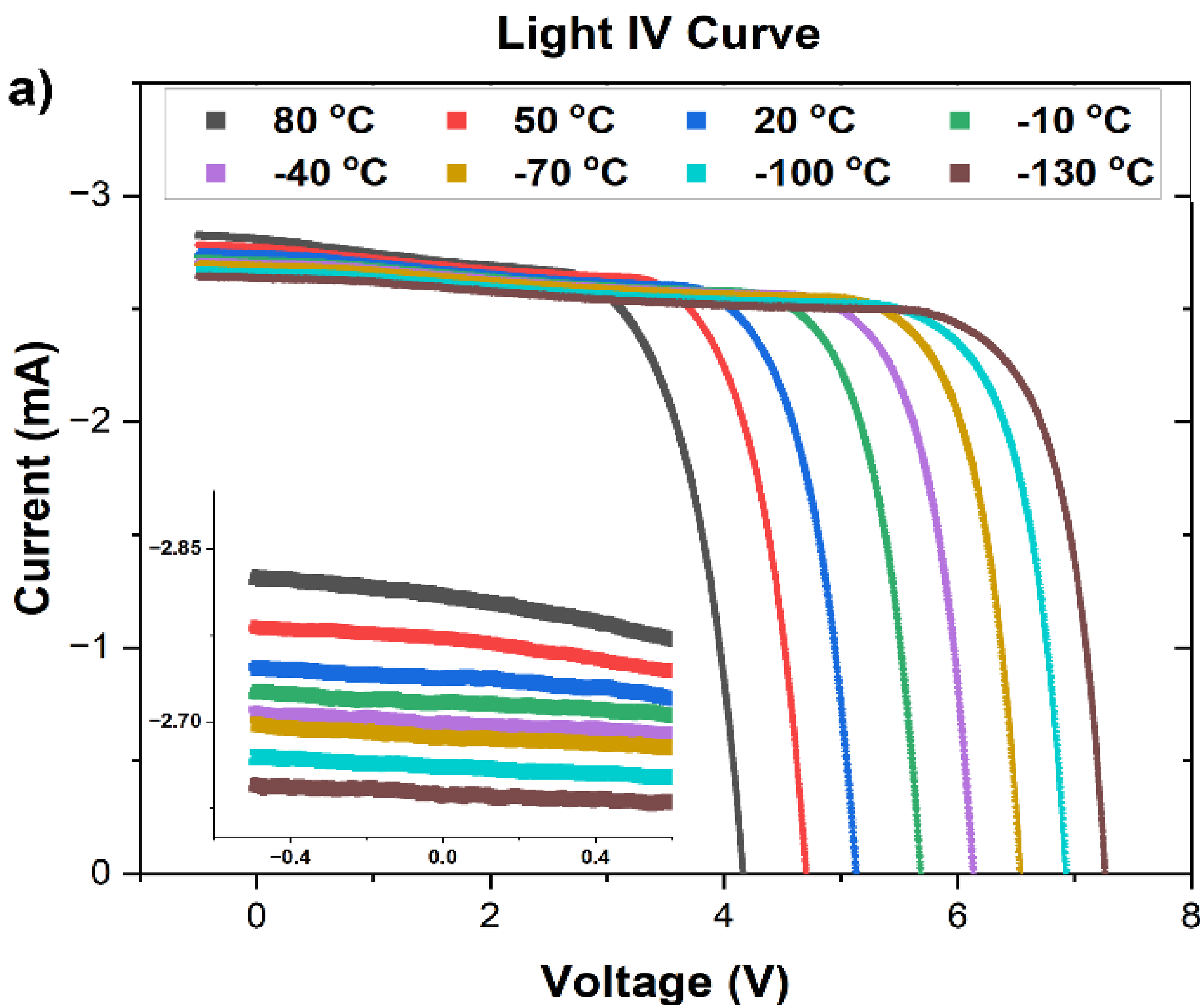
1.0-CPME electrolyte (1M LiFSI in CPME)

CPME: cyclopentyl methyl ether (-140 °C)

Energy Harvesting and Storage at Extreme Temperatures



Silicon solar cell efficiency increases at lower temperature



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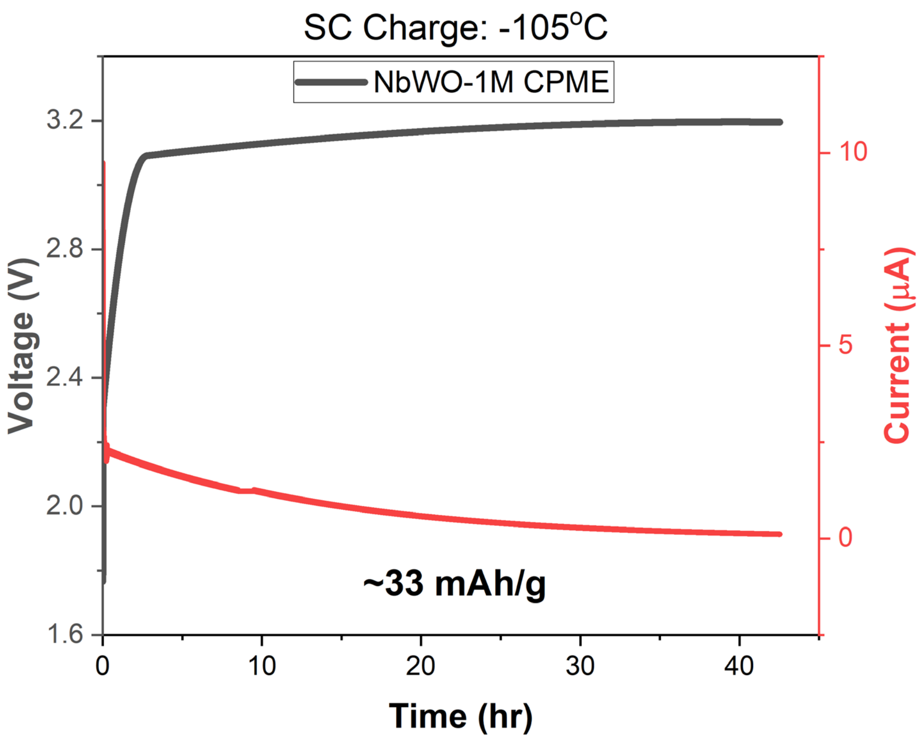
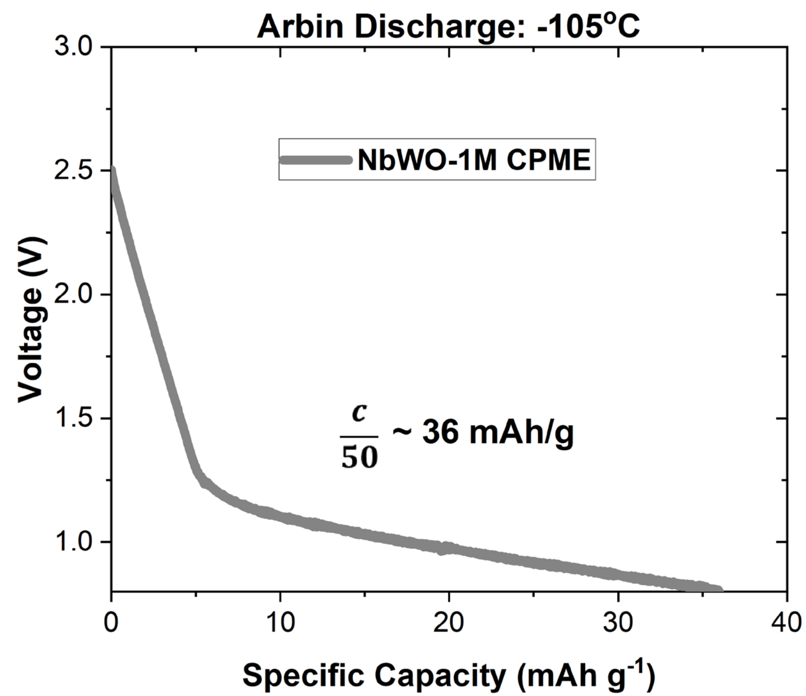
Efficient photovoltaics integrated with innovative Li-ion batteries for extreme (+ 80 °C to −105 °C) temperature operations

Ethan Adams[1], Alexander Camacho[1], Evan Mammana[1], Soohwan Kim[1], Thomas E. Adams[2] & Vilas G. Pol[1]

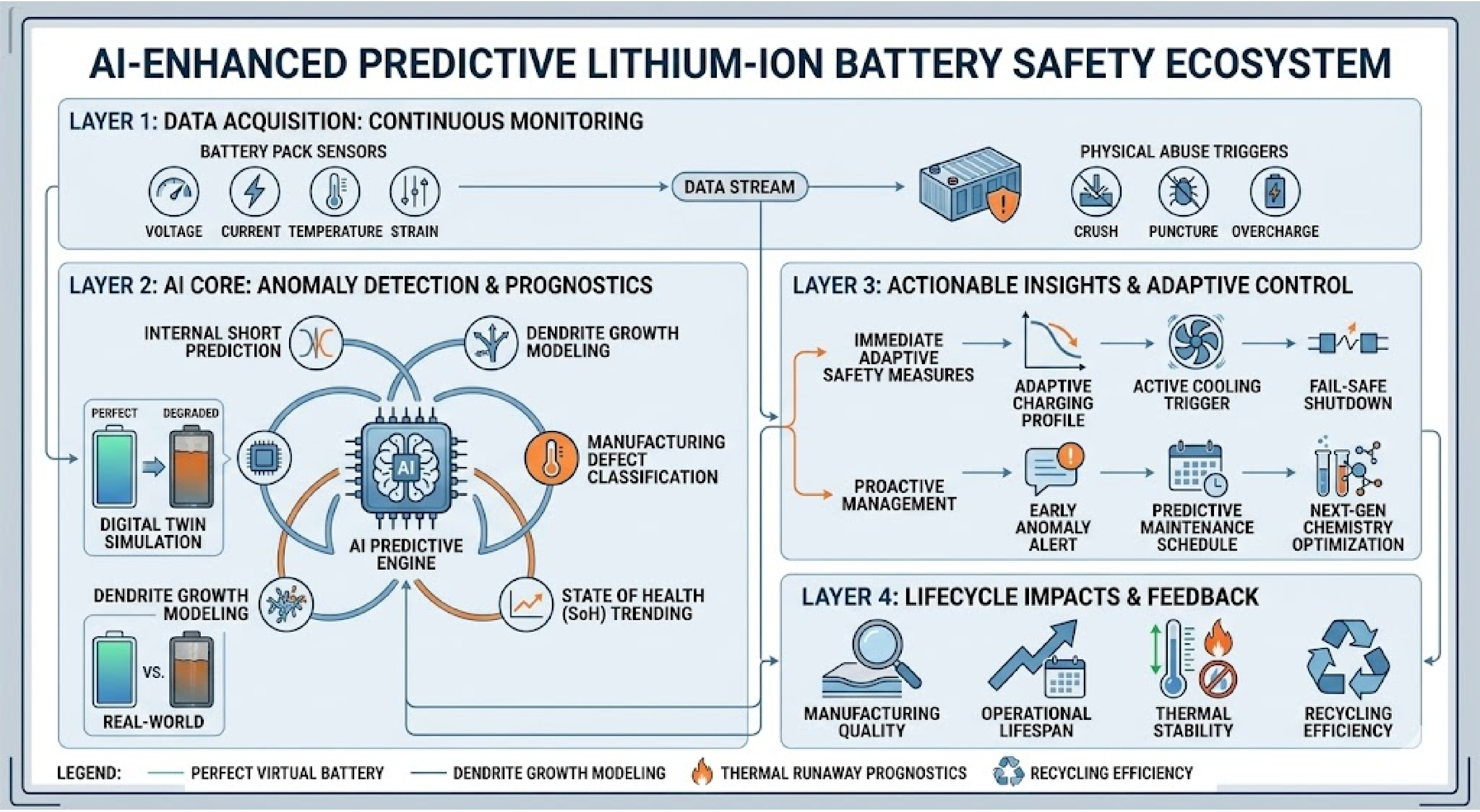
Promising charging and discharging at (-105 °C)





- Integrated batteries and **solar cells**
- Can operate at **extreme** temperatures ranging from -170°C to 300°C

How AI is going to help making lithium-ion batteries safer?



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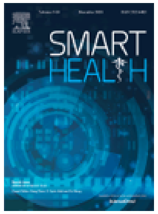

What Pivotal Role Could Artificial Intelligence Play in Advancing Li-ion Battery Safety?

Jayaganthan R [a]*, Vilas G Pol [b], Mangaiyarkarasi Padmanaban [a]*, Can Li [b]

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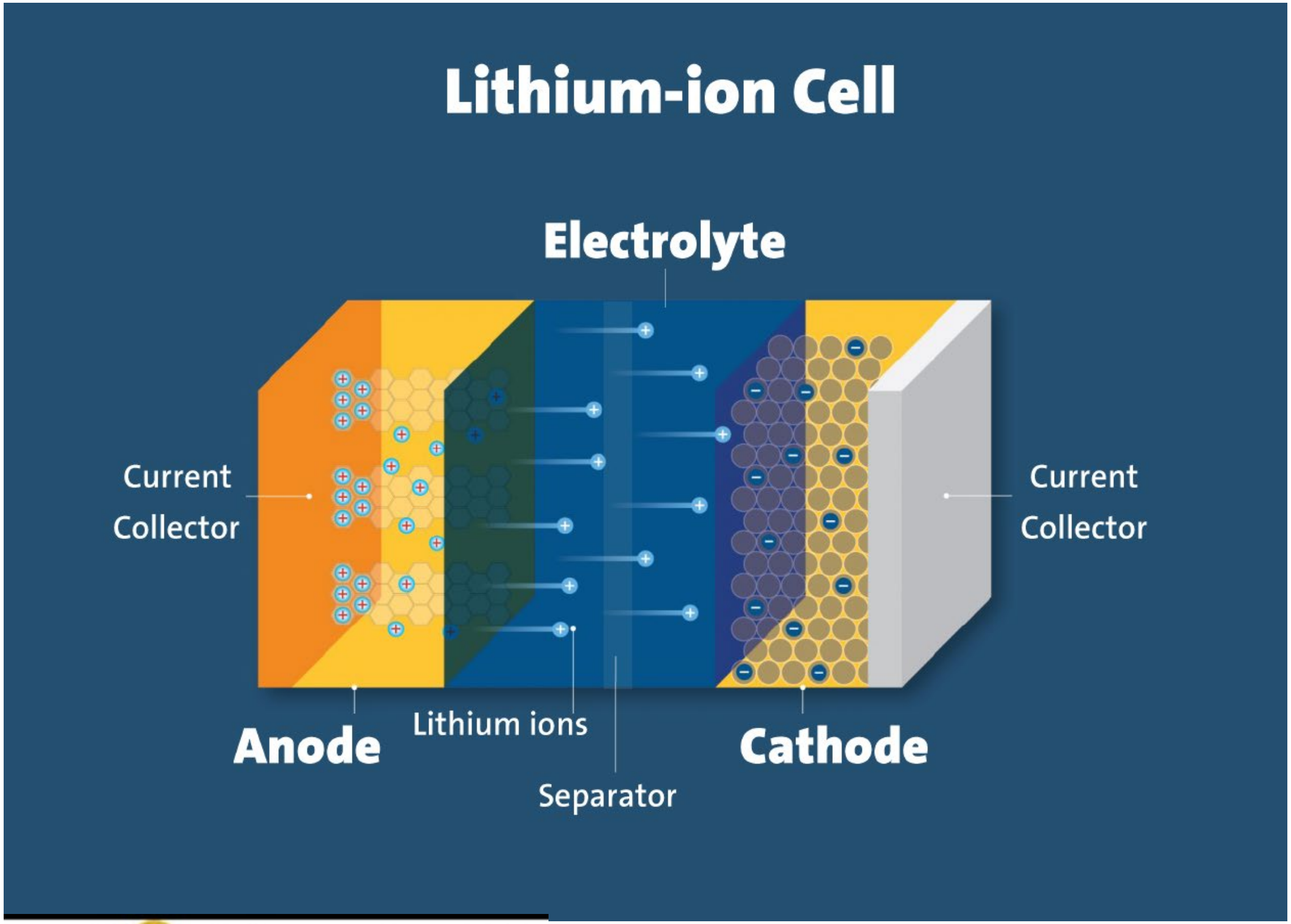
ABSTRACT

Lithium-ion batteries (LIBs) are important energy storage units in portable electronics and electric cars, but dendritic growth, thermal runaway, and rapid degradation issues still exist. Plentiful studies have been performed on the use of safer electrode/electrolytes combinations, separator advancement and improved reinforced safety layering, but these have been compromised with battery cost, energy density, and manufacturability. The preventative safety methods are also limited in capability. AI-based architecture can add a layer of security to LIBs by shifting from reactive supervision to proactive anticipation, prevention, and prescription by utilizing digital twin models and machine learning methods with a combination of measurements from multiple

Summary



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