Group1.ai

3.7V K-ion Battery Enabled by Potassium Prussian White (KPW)

From Invention to Commercialization

Leigang Xue (leigang@group1.ai)

Chief Product Officer and Co-Founder, **Group1 inc**

International Battery Materials Association

Austin, Texas

03/06/2023

"Powering Batteries Beyond Lithium…Building on the Best of Lithium"

The world's 1st engineered materials company focused on enabling Potassium-ion batteries.

- Founded: Q3 2021
- Began operations Q1 2022
- HQ: Austin, TX

Dr. Goodenough Inventions over 4 decades Enabled Sustainable Battery Materials

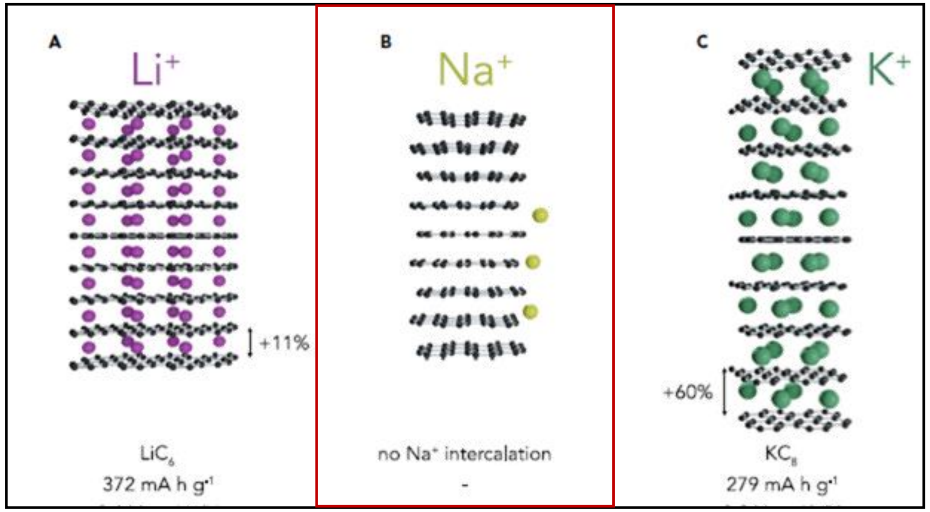
G1

$LiCoO_2$	$LiMn_2O_4$	$LiFePO_4$	$Na_2MnFe(CN)_6$	$K_2MnFe(CN)_6$
1980	1984	1997	2013	2016

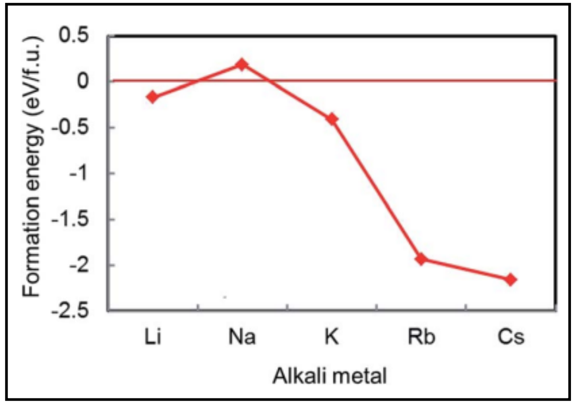
LIB invention → Co/Ni-free → Li-free (beyond-Li)

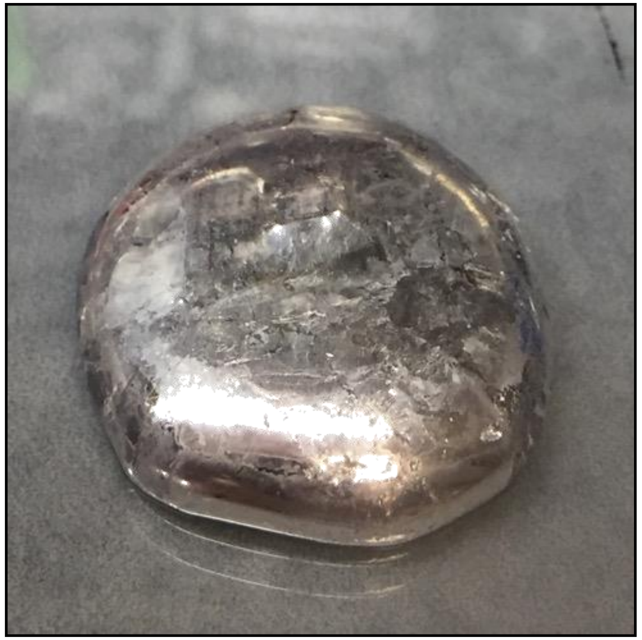
Commercialization of these materials needed to meet US goals for electrification

Discovery of $K_2MnFe(CN)_6$: Dendrite free liquid Na-K alloy anode



- Na does not form graphite intercalated compound
- $Na_2MnFe(CN)_6$ does not work with graphite
- **Liquid Na-K alloy to the rescue**





Liquid Na-K alloy

Liquid Na-K alloy in porous membrane

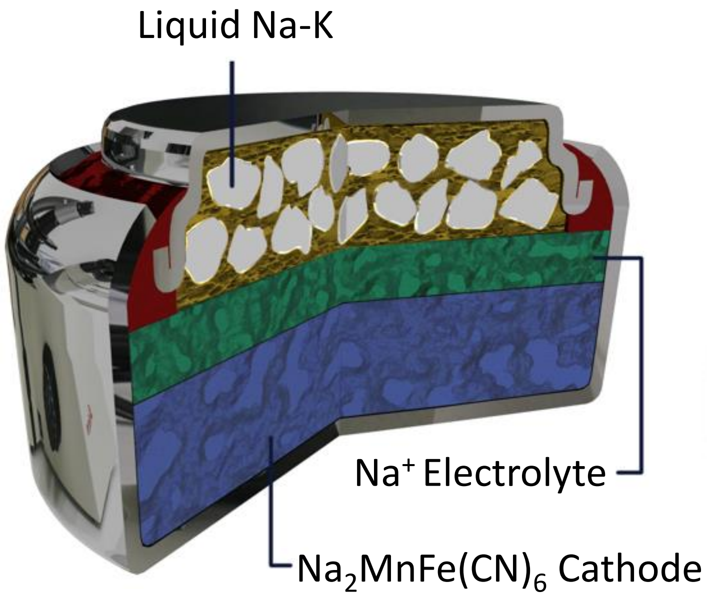
Adv Mater. 2016;28(43):9608-9612
https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.201602633

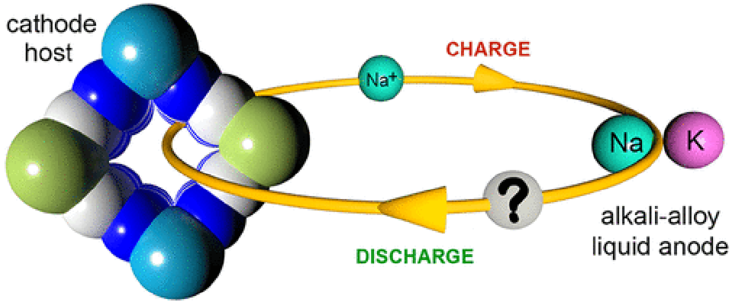
Outlook on K-Ion Batteries, Chem 6, 2442–2460, 2020
https://www.sciencedirect.com/science/article/pii/S2451929420304228

J. Am. Chem. Soc. 2017, 139, 6, 2164–2167
https://pubs.acs.org/doi/10.1021/jacs.6b12598

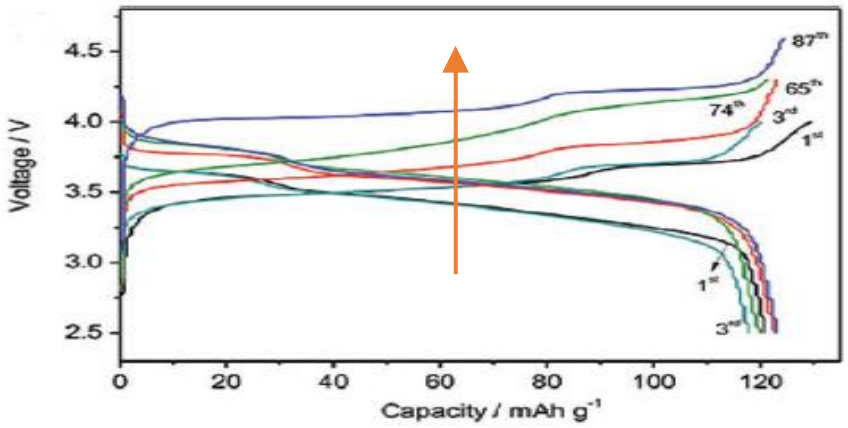
Why is sodium-intercalated graphite unstable?
https://pubs.rsc.org/en/content/articlelanding/2017/ra/c7ra06777a#:~:text=It%20is%20generally%20considered%20that,AM)%20ion%20and%20C%20atoms.

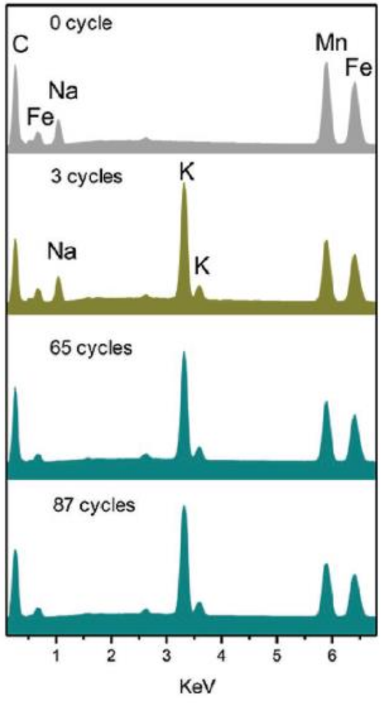
Liquid Na-K is effective reservoir of K^+ as anode for $MnFe(CN)_6$





J. Am. Chem. Soc. 2018, 140, 9, 3292–3298
https://pubs.acs.org/doi/10.1021/jacs.7b12267

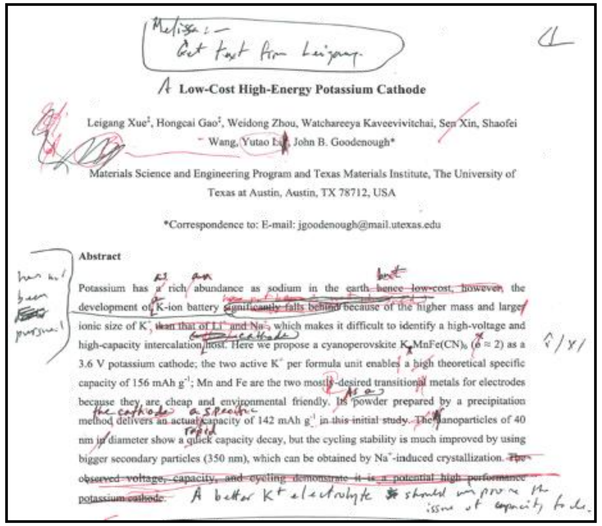




During charge, $Na_2MnFe(CN)6$ lose Na^+ and transforms to $MnFe(CN)_6$
During discharge, $MnFe(CN)_6$ only accept K^+ and transforms to $K_2MnFe(CN)_6$ because of it is thermodynamically more stable than $Na_2MnFe(CN)_6$

Adv Mater. 2016;28(43):9608-9612
https://onlinelibrary.wiley.com/doi/abs/10.1002/adma.201602633

$K_2MnFe(CN)_6$: discovery of a new class of K-ion Cathode



A Low-Cost High-Energy Potassium Cathode

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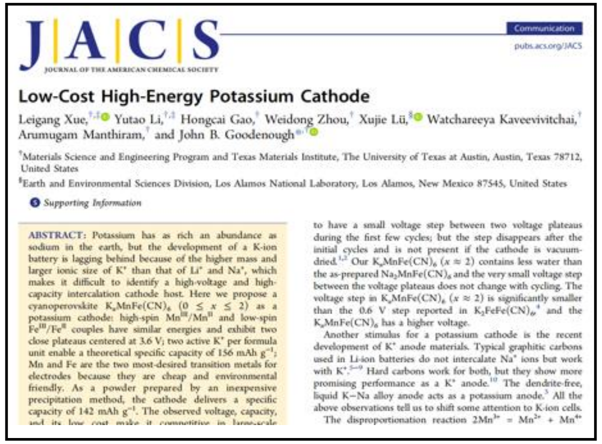
Abstract

Potassium has a rich abundance as sodium in the earth hence low-cost, however, the development of K-ion battery significantly falls behind because of the higher mass and larger ionic size of K^+ than that of Li^+ and Na^+, which makes it difficult to identify a high-voltage and high-capacity intercalation host. Here we propose a cyanoperovskite $K_xMnFe(CN)_6$ ($\delta \approx 2$) as a 3.6 V potassium cathode; the two active K^+ per formula unit enables a high theoretical specific capacity of 156 mAh g^{-1}; Mn and Fe are the two mostly-desired transitional metals for electrodes because they are cheap and environmental friendly. Its powder prepared by a precipitation method delivers an actual capacity of 142 mAh g^{-1} in this initial study. The nanoparticles of 40 nm in diameter show a quick capacity decay, but the cycling stability is much improved by using bigger secondary particles (350 nm), which can be obtained by Na^+-induced crystallization. The observed voltage, capacity, and cycling demonstrate it is a potential high performance potassium cathode.



JACS
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY
Communication
pubs.acs.org/JACS

Low-Cost High-Energy Potassium Cathode

Leigang Xue,[†,‡] Yutao Li,[†,‡] Hongcai Gao,[†] Weidong Zhou,[†] Xujie Lü,[§] Watchareeya Kaveevivitchai,[†] Arumugam Manthiram,[†] and John B. Goodenough[*,†]

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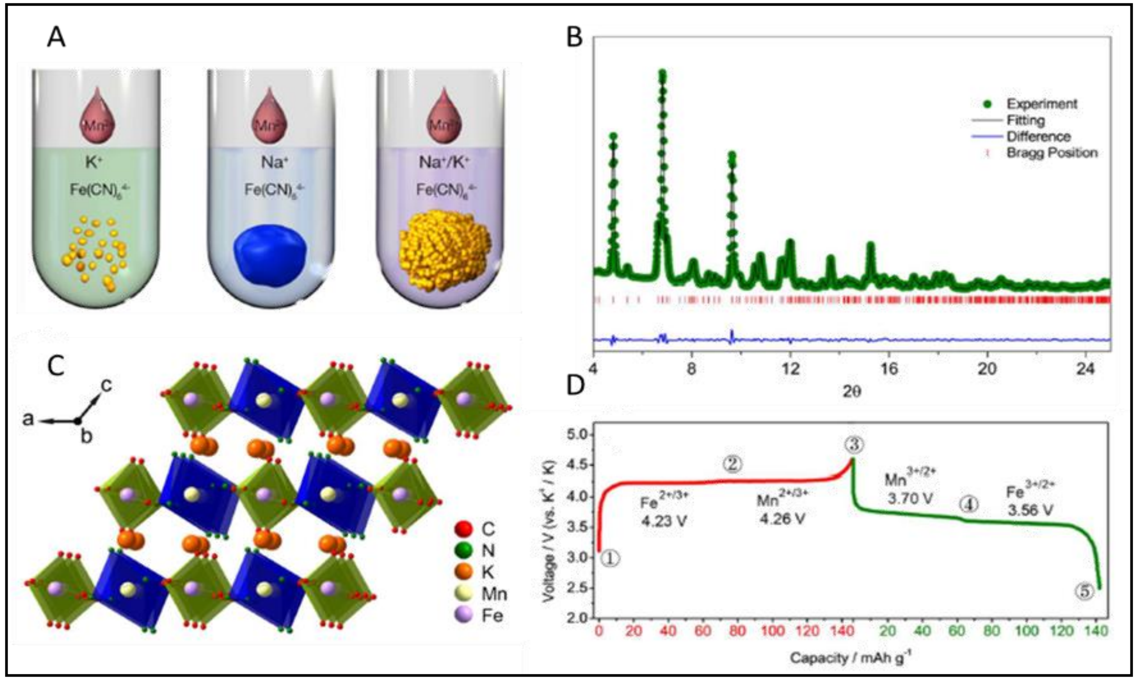
Supporting Information

ABSTRACT: Potassium has as rich an abundance as sodium in the earth, but the development of a K-ion battery is lagging behind because of the higher mass and larger ionic size of K^+ than that of Li^+ and Na^+, which makes it difficult to identify a high-voltage and high-capacity intercalation cathode host. Here we propose a cyanoperovskite $K_xMnFe(CN)_6$ ($0 \le x \le 2$) as a potassium cathode: high-spin Mn^{III}/Mn^{II} and low-spin Fe^{III}/Fe^{II} couples have similar energies and exhibit two close plateaus centered at 3.6 V; two active K^+ per formula unit enable a theoretical specific capacity of 156 mAh g^{-1}; Mn and Fe are the two most-desired transition metals for electrodes because they are cheap and environmental friendly. As a powder prepared by an inexpensive precipitation method, the cathode delivers a specific capacity of 142 mAh g^{-1}. The observed voltage, capacity,

to have a small voltage step between two voltage plateaus during the first few cycles; but the step disappears after the initial cycles and is not present if the cathode is vacuum-dried.[1,2] Our $K_xMnFe(CN)_6$ ($x \approx 2$) contains less water than the as-prepared $Na_2MnFe(CN)_6$ and the very small voltage step between the voltage plateaus does not change with cycling. The voltage step in $K_xMnFe(CN)_6$ ($x \approx 2$) is significantly smaller than the 0.6 V step reported in $K_2FeFe(CN)_6$,[4] and the $K_xMnFe(CN)_6$ has a higher voltage.

Another stimulus for a potassium cathode is the recent development of K^+ anode materials. Typical graphitic carbons used in Li-ion batteries do not intercalate Na^+ ions but work with K^+.[5−9] Hard carbons work for both, but they show more promising performance as a K^+ anode.[10] The dendrite-free, liquid K−Na alloy anode acts as a potassium anode.[3] All the above observations tell us to shift some attention to K-ion cells. The disproportionation reaction $2Mn^{3+} = Mn^{2+} + Mn^{4+}$

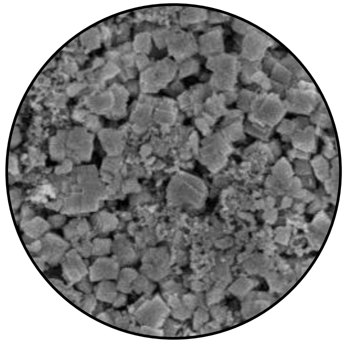


	Voltage	Specific capacity	Energy density
$Na_2MnFe(CN)_6$	3.4	171	581
$K_2MnFe(CN)_6$	4.0	156	624
$LiFePO_4$	3.4	170	578

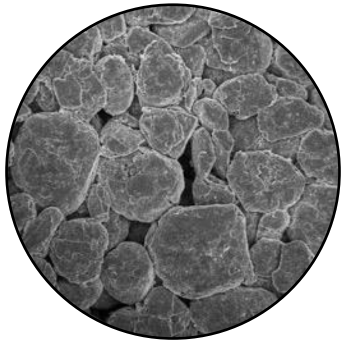
J. Am. Chem. Soc. 2017, 139, 6, 2164–2167
https://pubs.acs.org/doi/10.1021/jacs.6b12598

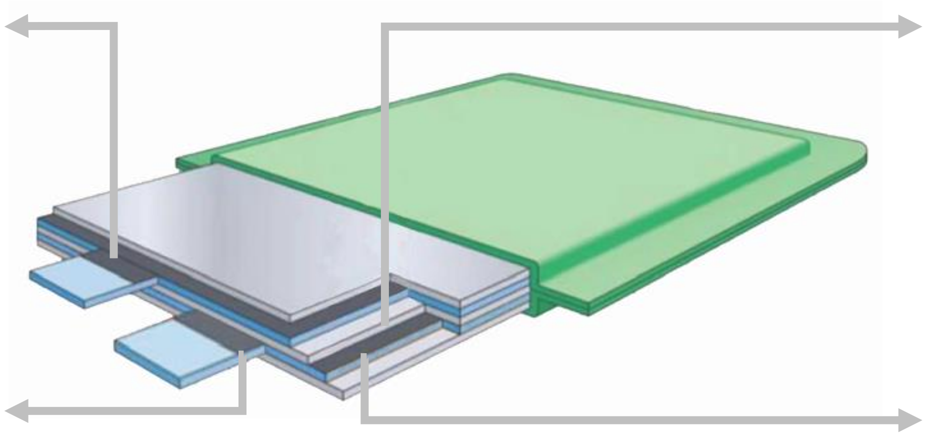
KIB is building on best of LIB technology.. Some challenges of KIB remain to be resolved

Cathode, $K_2MnFe(CN)_6$
- Purity
- Defects
- Particle size, BET
- PSD
- Specific capacity
- ICE
- Conductivity

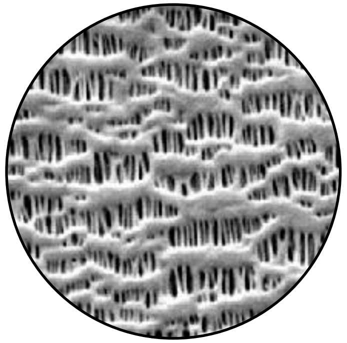


Anode, Graphite
- Drop-in
- Specific capacity
- ICE





Separator, Al_2O_3/PE/PP
- Drop-in

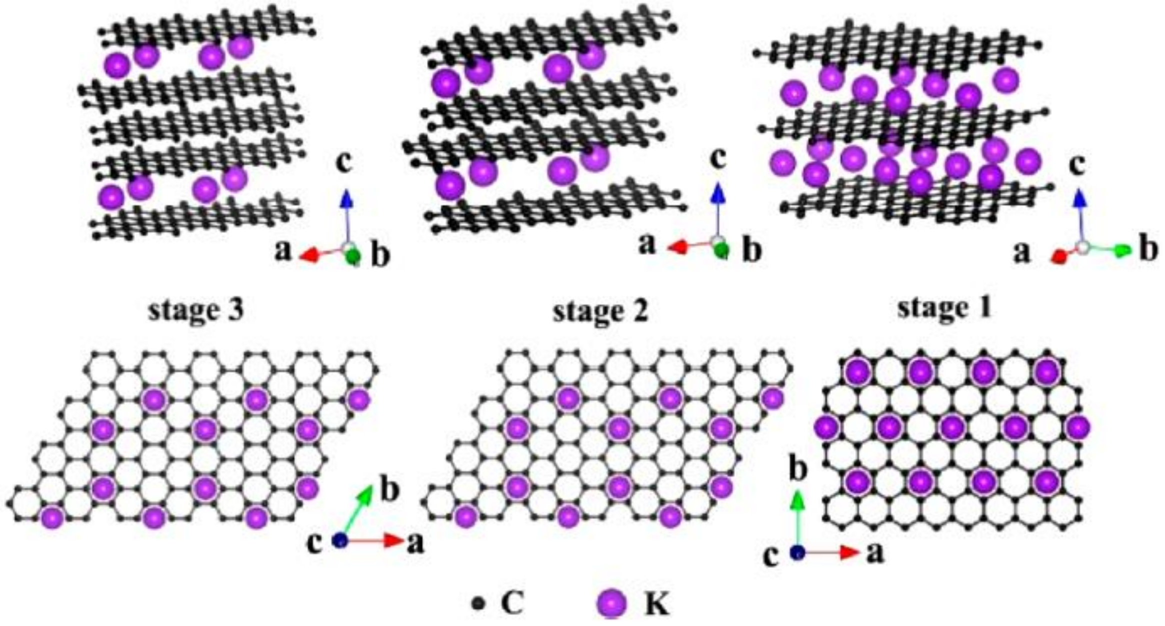


Electrolyte, Organic-based
- Salts: KPF6, KFSI…
- Solvents: carbonates or phosphates… (nonflammable)
- Additives to manage ICE
- Electrolyte formulations to enable performance cycling beyond LFP

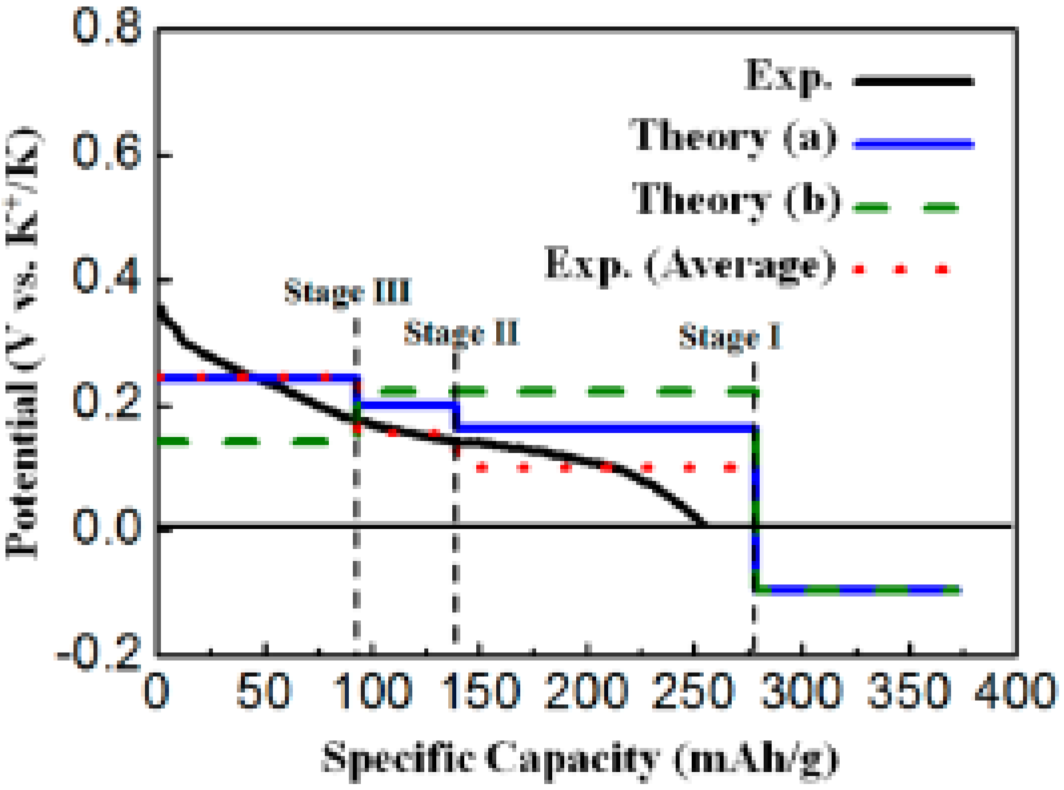
Graphite performs well as K^+ anode with specific capacity of 279 mAh/g and long cycle life

G1

	A-C Alloy	Intercalation Voltage (V)	Theoretical Spec. Cap.
Li+	LiC6	0.10	372
Na+	N/A	N/A	0
K+	KC8	0.15	279

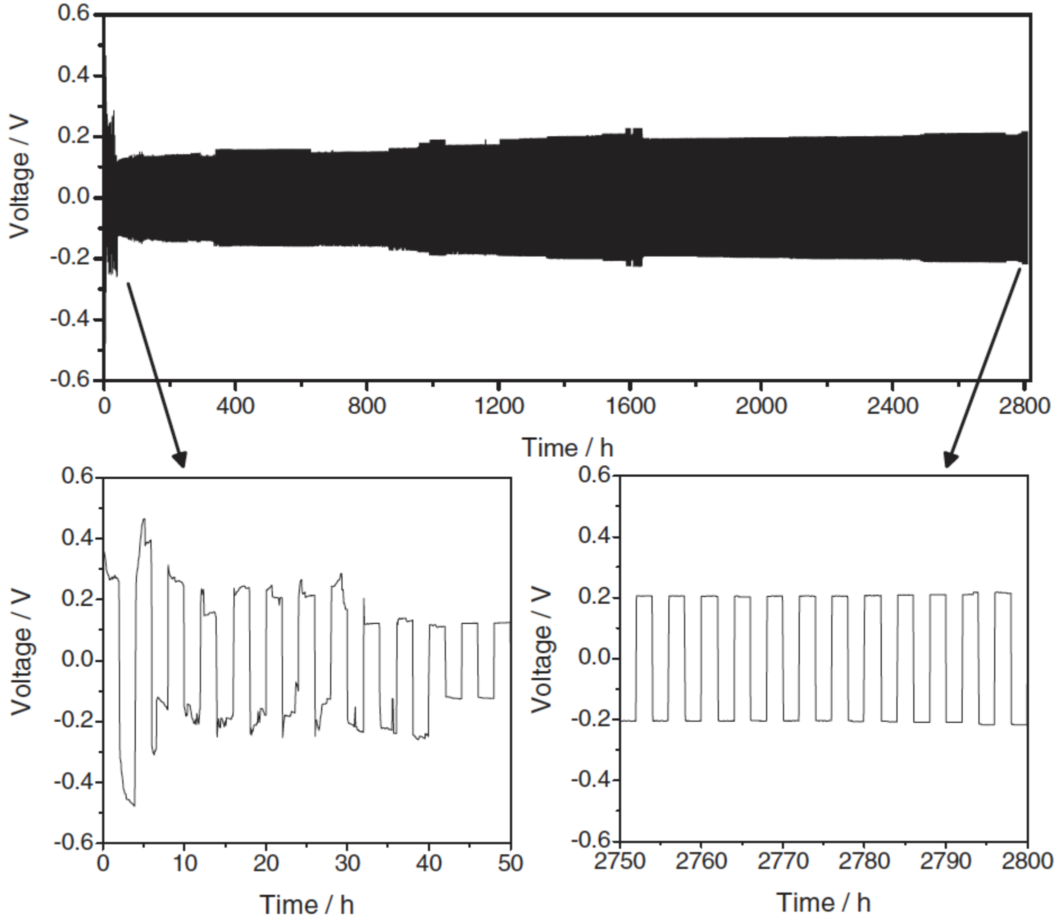


Carbon Electrodes for K-Ion Batteries
https://pubs.acs.org/doi/10.1021/jacs.5b06809

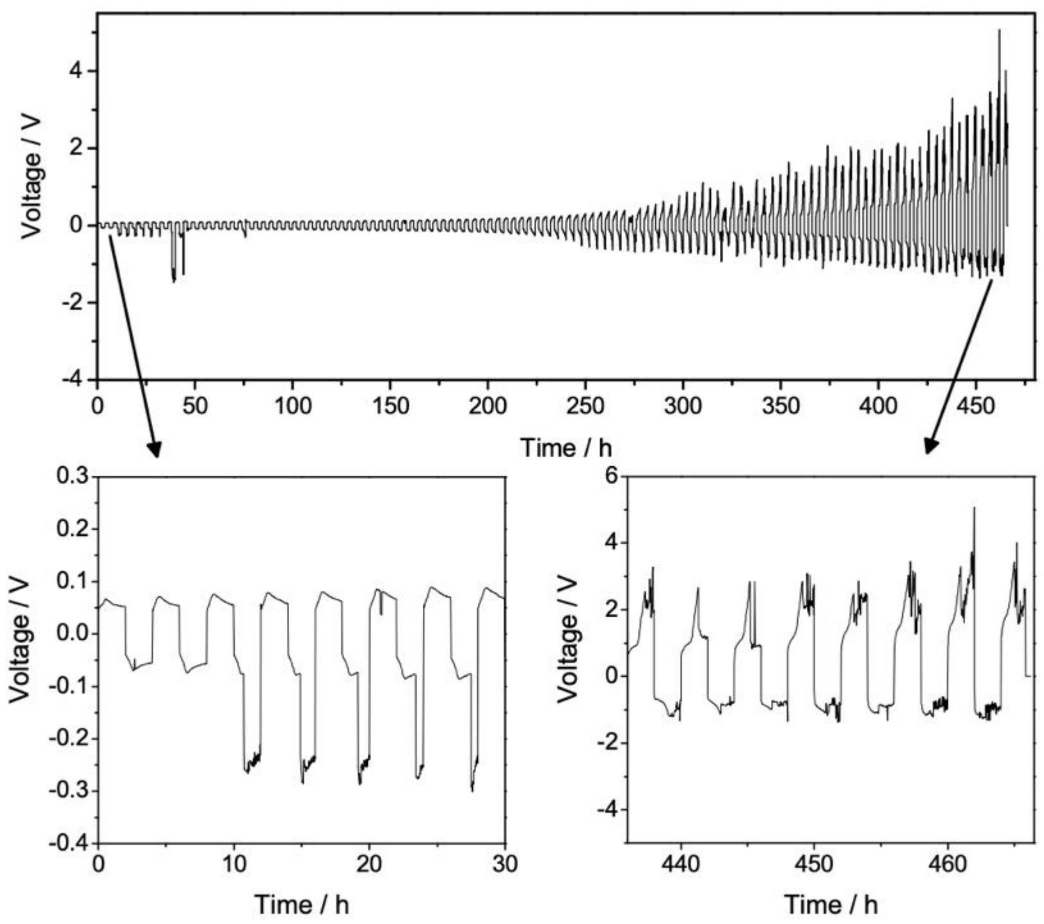


Potassium Ion Batteries with Graphitic Materials
https://pubs.acs.org/doi/10.1021/acs.nanolett.5b03667

Development of KIB requires robust half cells - choosing the right reference electrode: K vs. Na-K alloy

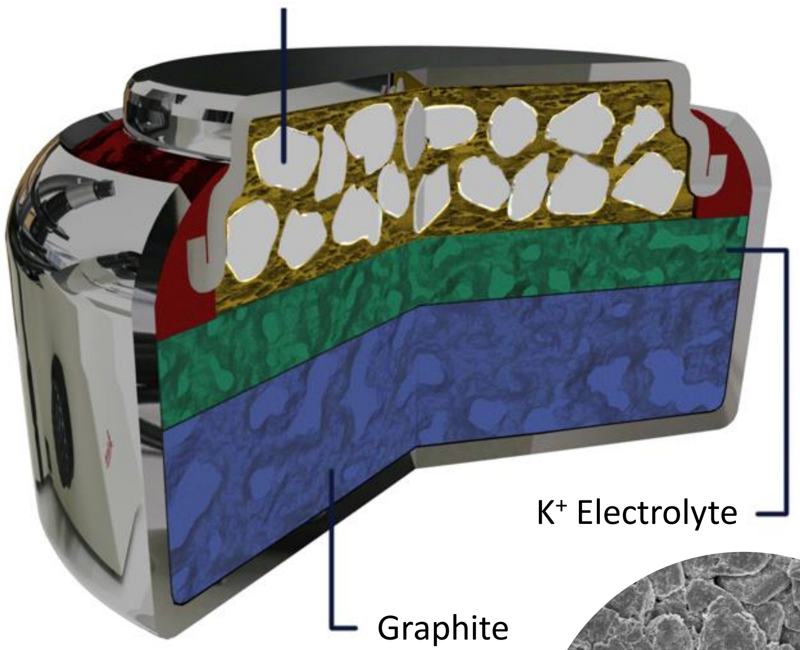


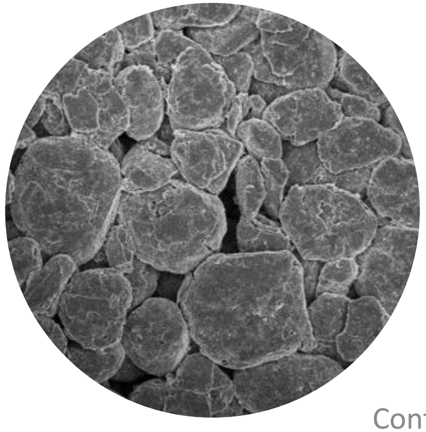
Liquid NaK-NaK symmetric cell

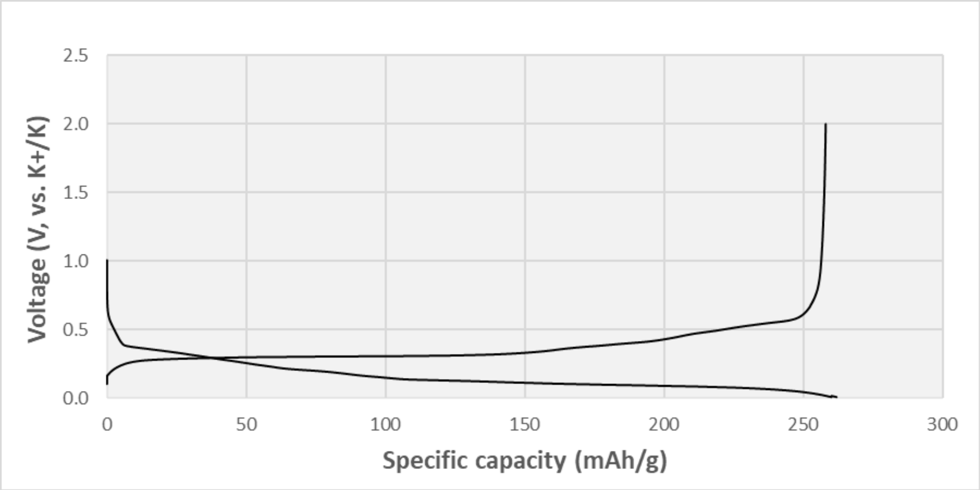


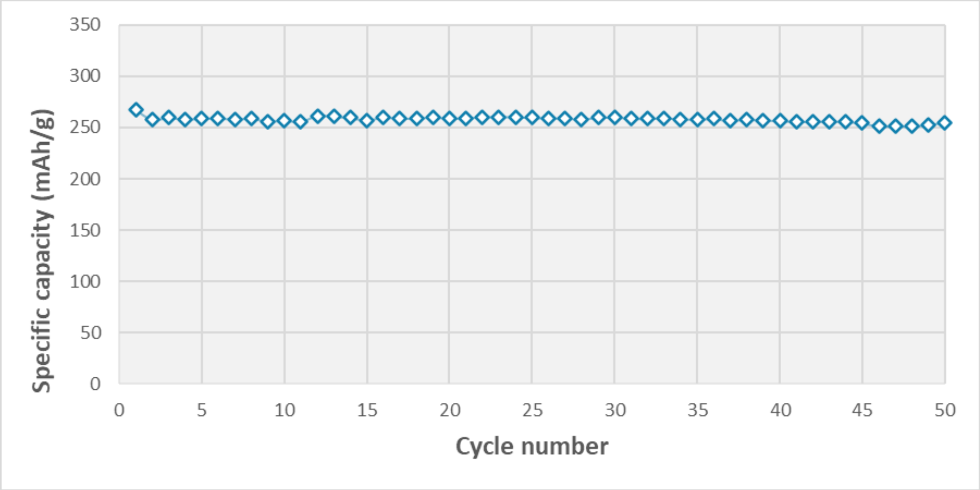
K-K symmetric cell

Graphite anode half cell data









Contact – leigang@group1.ai

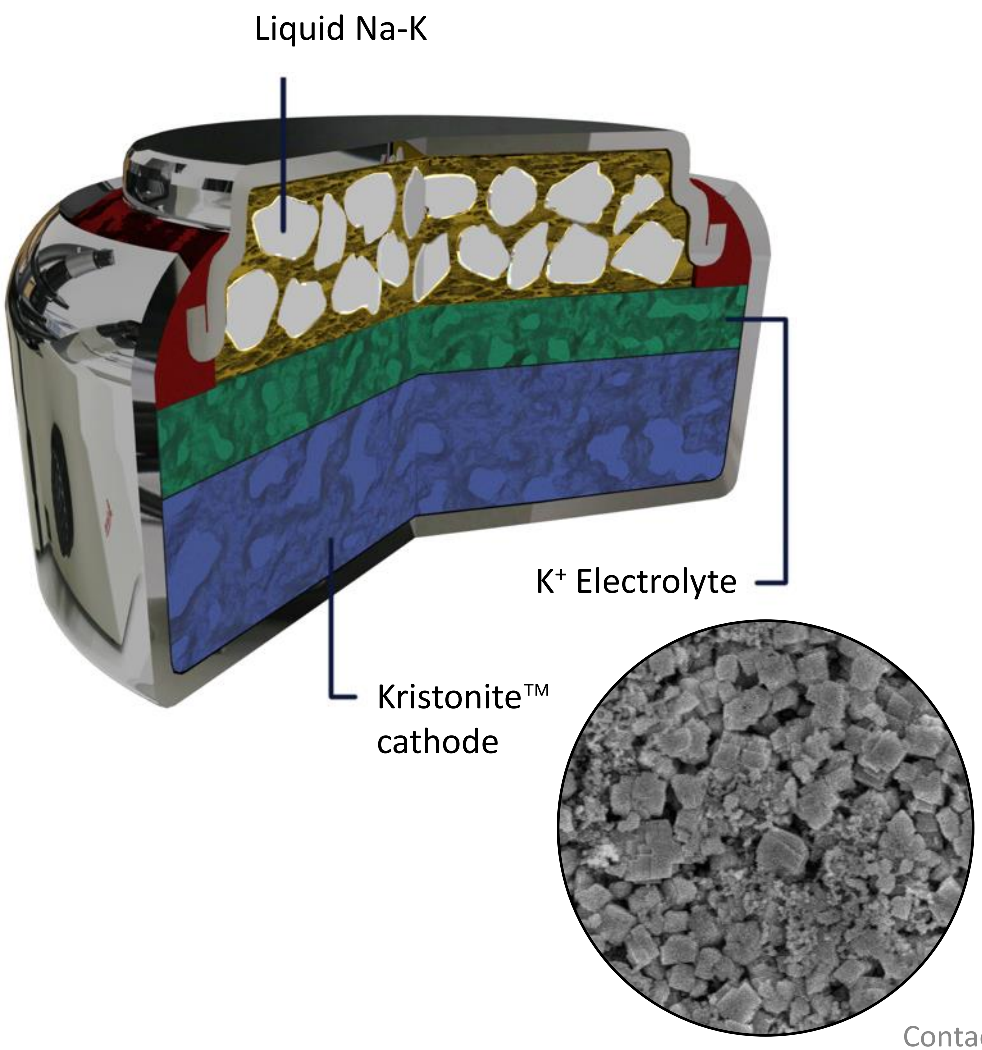
K^+ offers unique ability to formulate electrolyte due to its mobility and conductivity

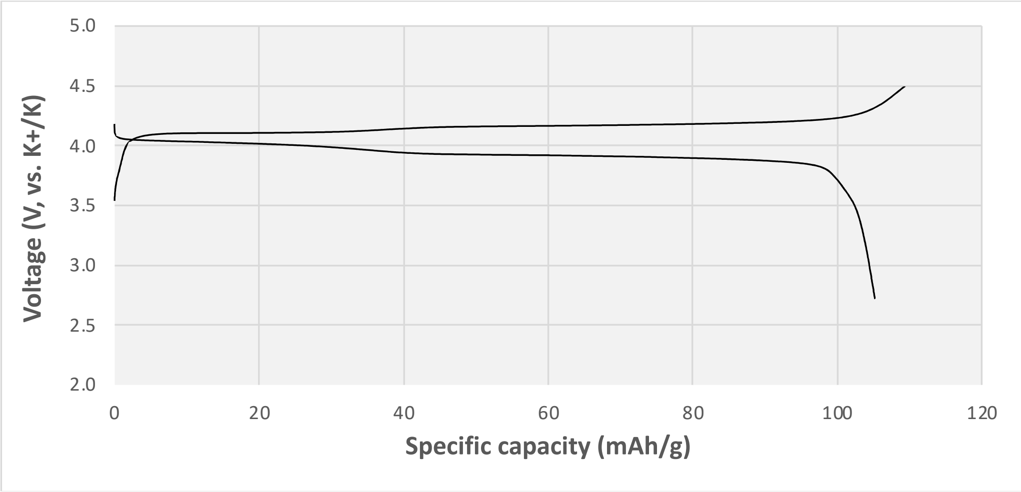
Radius	K^+	Na^+	Li^+
Ion radius			
Stokes radius (H_2O)			
Stokes radius (PC)			

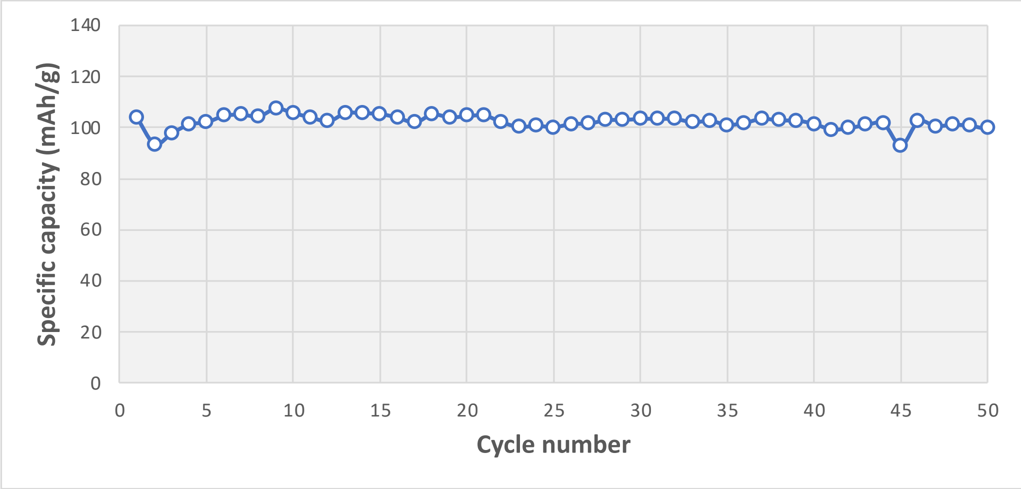
Conductivity	K^+	Na^+	Li^+
1M APF6 in EC/DEC	10.7	9.7	9.3
0.8M AFSI in PC	6.55	6.38	4.38
2M AFSI in TEP	3.1	2.2	1.3

Adv.Mater.2021, 33, 2003741
Electrolytes and Interphases in Potassium Ion Batteries
https://onlinelibrary.wiley.com/doi/full/10.1002/adma.202003741

Kristonite™ (KPW) cathode half cell data

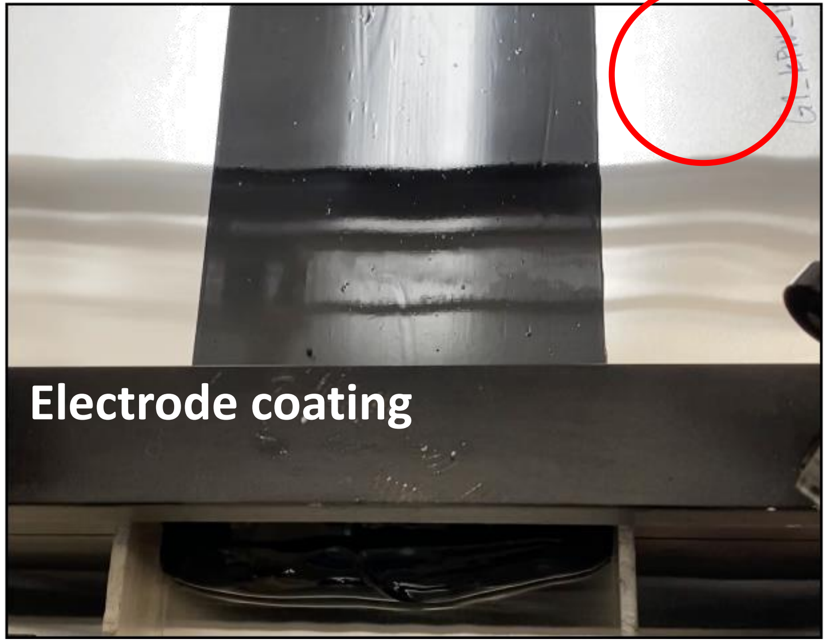




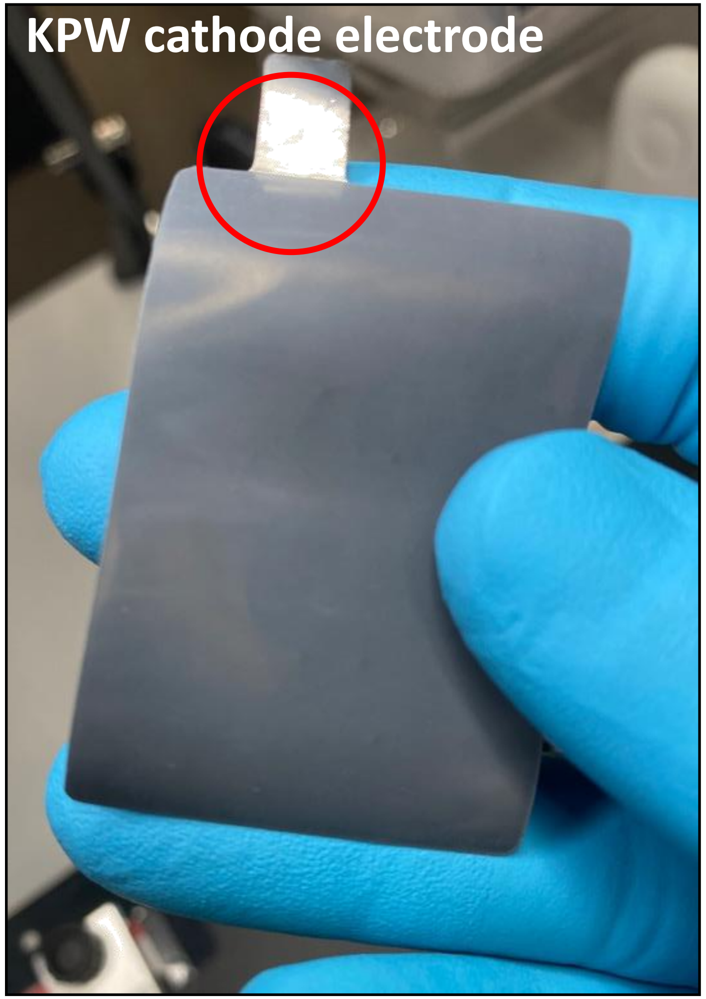


Building first in the world KIB (Kristonite™/G) pouch cell

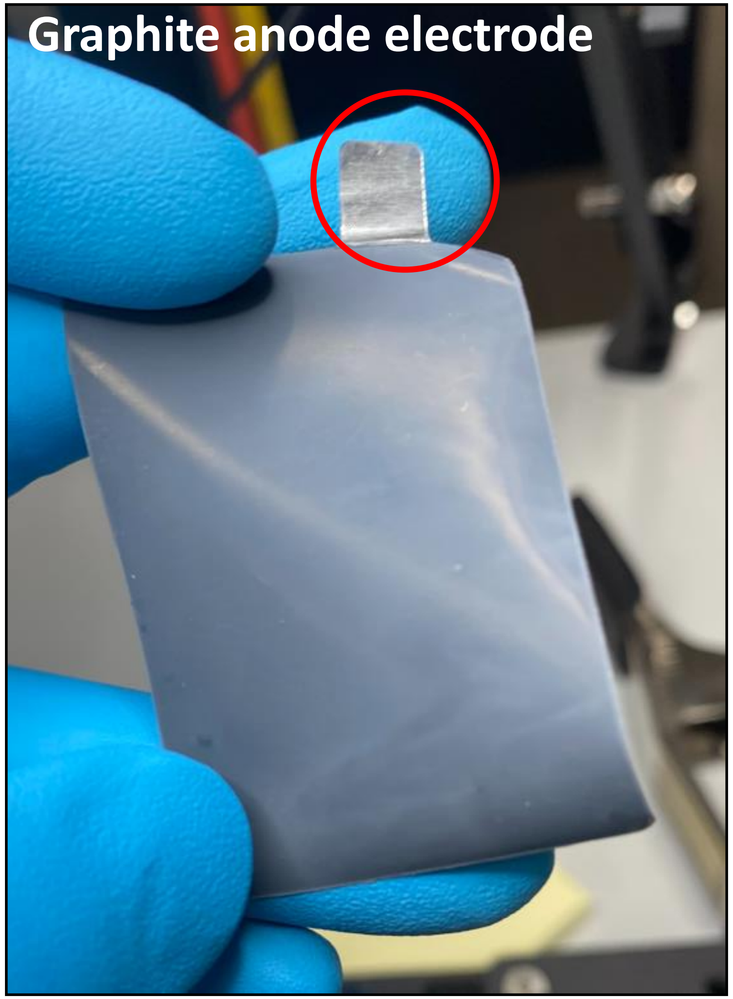
Kg-scale material synthesis



Electrode coating



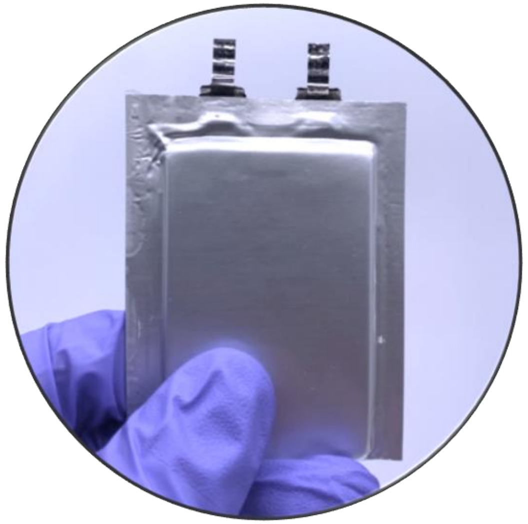
KPW cathode electrode

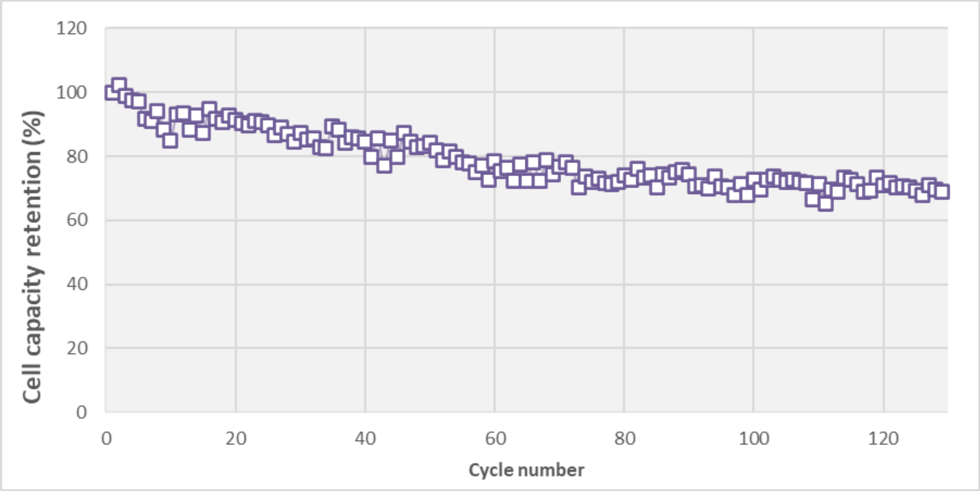


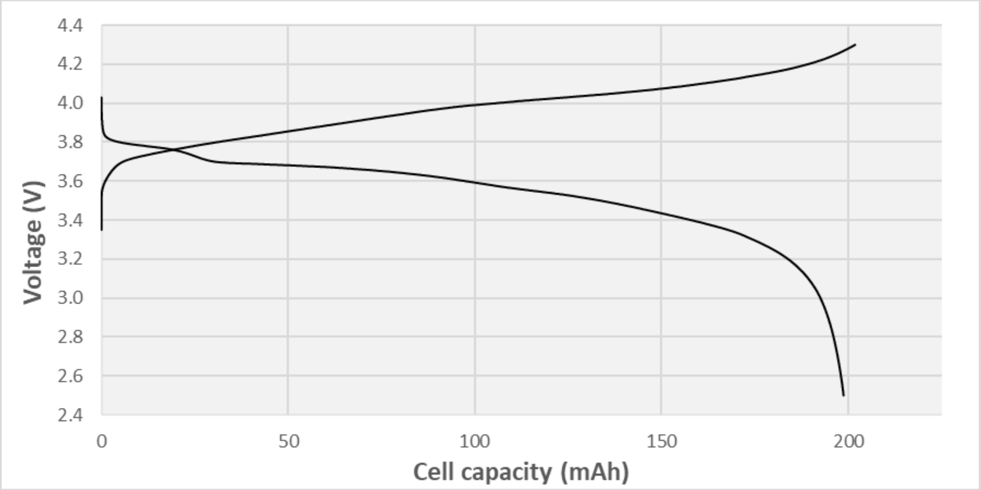
Graphite anode electrode

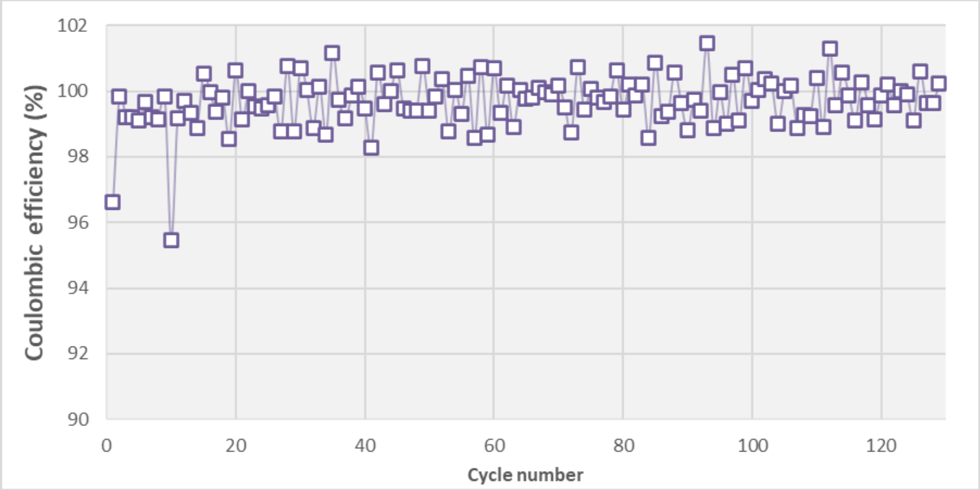
The world-first 200mAh KIB (Kristonite™/G) pouch cell

The world-first KIB pouch
- **3.6V**
- **200mAh, multistack**
- **Co/Ni/Li/Cu/O-free**
- **Drop-in with graphite**
- **Nonflammable electrolyte**

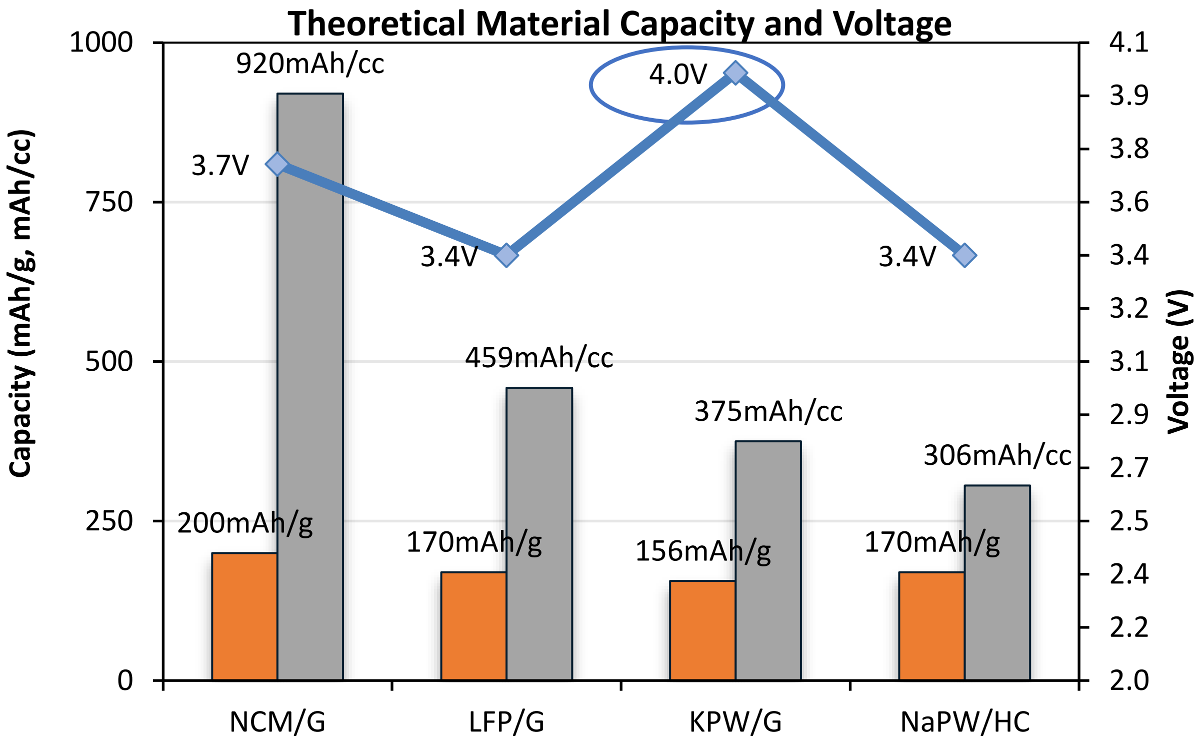


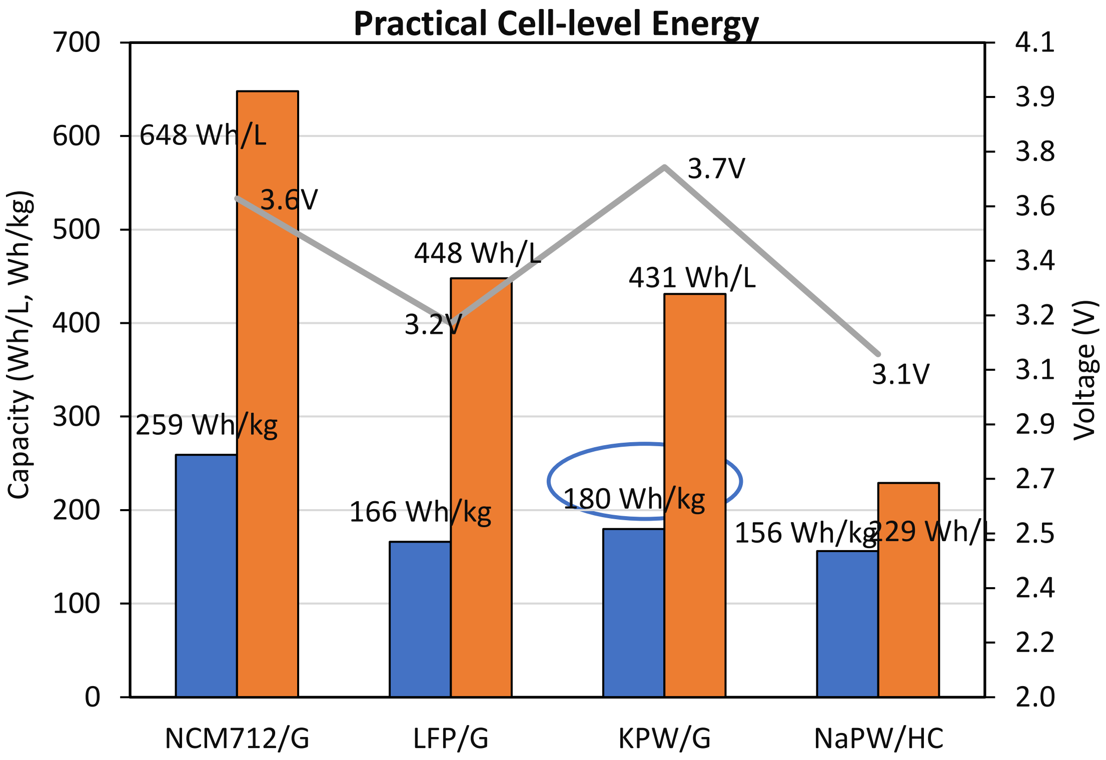






KIB well positioned for EV applications that use LFP cathode





LG Chem E66A (66Ah)

BYD Blade (202Ah)

CATL NiB (not commercial)

Our Team – We are Expanding!!

We are looking to expand the Group1 team to any collaborators, future staff customers etc that wish the make KIBs a reality!

Hiring: Cell R&D Scientist/Engineers, Process Development Engineers, Laboratory Technicians, etc

Partners: Technical Advisors, Industry and Supply-Chain Partners, Research Groups

Team: **Alex Girau, Yakov Kutsovsky, Leigang Xue**, Patrick Crowley, Cole Mough, Peyton Dowdle.

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