MATERIALS FOR ELECTRICAL ENERGY STORAGE

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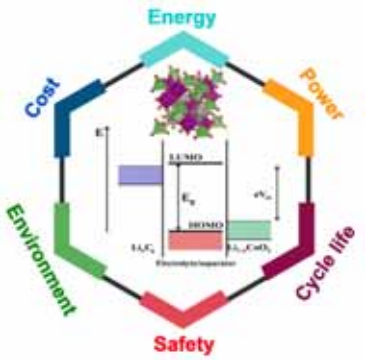
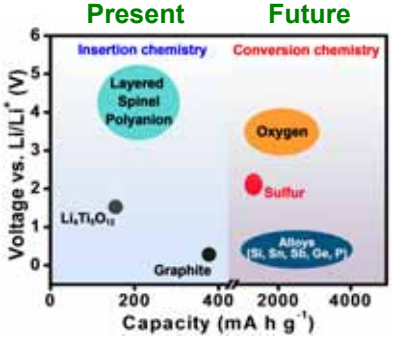
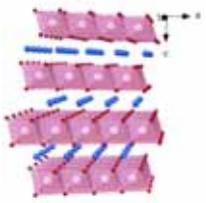
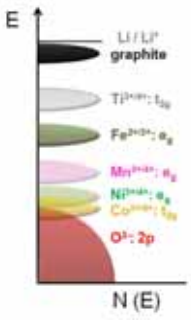
USE-INSPIRED BASIC SCIENCE RESEARCH WITH ENGINEERING TARGETS









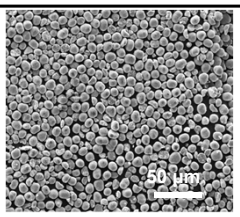
- Renewable energy is the solution to address the world's energy and environmental challenges
- Storage is the bottleneck to utilize efficiently and economically the intermittent renewable energy
- We are engaged in the development of energy-dense, long-life, safe batteries at an affordable cost
  - cobalt-free lithium-ion and sodium-ion batteries; lithium-sulfur and sodium-sulfur batteries
  - all-solid-state lithium and sodium batteries; solid-electrolyte redox flow batteries

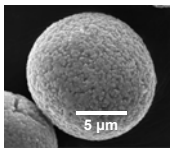
A. Manthiram, *ACS Central Science* **3**, 1063 (2017); A. Manthiram, *Nature Communications* **11**, 1550 (2020)

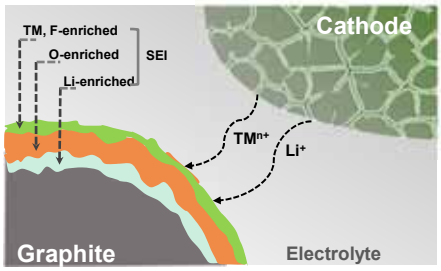
2

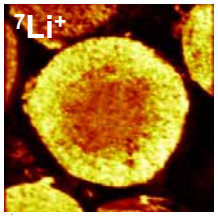
SYNTHESIS INNOVATION AND ADVANCED CHARACTERIZATION

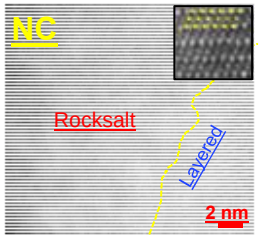
- Controlled synthesis with practically relevant characteristics
  - scale-up: 10 kg per batch, incorporation of hard to dope ions
- Pouch full cell fabrication with lithium-ion, sodium-ion, Li-S
- In-situ and ex-situ XRD, SEM, TEM, XPS, TOF-SIMS, *etc*.
  - before and after extended full pouch cell cycling
- In-depth electrochemical characterization of pouch full cells

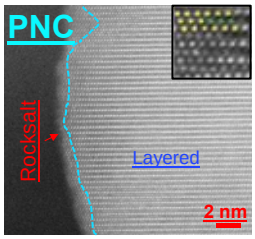












W. Li, X. Liu, H. Celio, P. Smith, A. Dolocan, M. Chi, and A. Manthiram, *Advanced Energy Materials* **8**, 1703154:1-11 (2018)
Q. Xie and A. Manthiram, *Chemistry of Materials* **32**, 7413–7424 (2020)
H. Yaghoobnejad Asl and A. Manthiram, *Science* **369**, 140 (2020)

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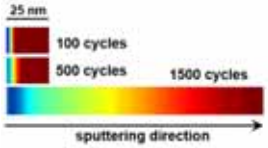
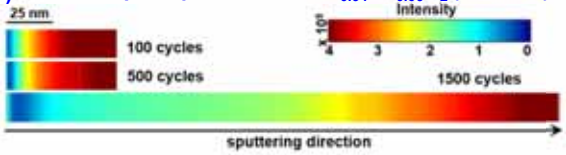
GRAPHITE-ELECTROLYTE INTERPHASE EVOLUTION WITH TOF-SIMS

Depth Profile of C_5^- fragment (representing bulk graphite)

Graphite paired with $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ (NMC 811)

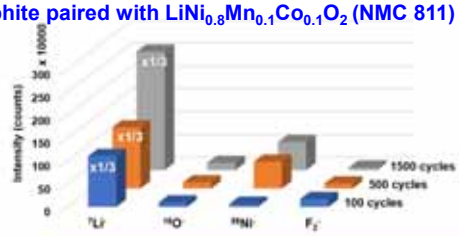


Graphite paired with $LiNi_{0.94}Co_{0.06}O_2$ (NC 9406)

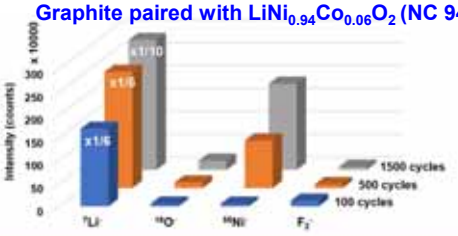


- AEI thickness can be estimated by probing C_5^- (representing graphite) with sputtering
- AEI on graphite paired with NC 9406 is much thicker than that paired with NMC 811

Graphite paired with $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ (NMC 811)



Graphite paired with $LiNi_{0.94}Co_{0.06}O_2$ (NC 9406)

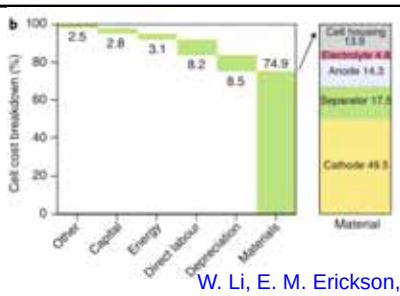


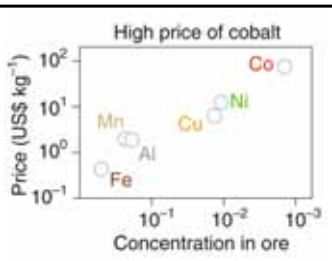
- Continuous accumulation of transition-metal ions & trapping of active Li on graphite surface
- NC 9406 exhibits more severe transition-metal dissolution & leads to Li trapping on graphite

J. Li and A. Manthiram, *Advanced Energy Materials* **9**, 1902731 (2019)

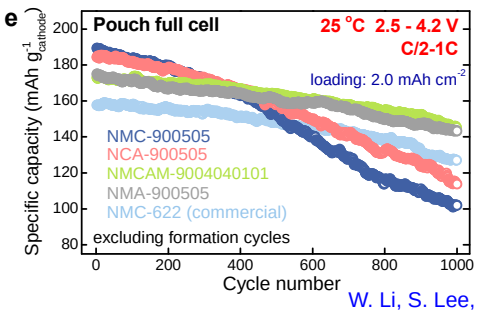
4

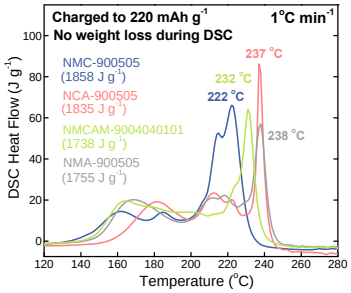
COBALT-FREE CATHODE: HIGH NICKEL $LiNi_{0.9}Mn_{0.05}Al_{0.05}O_2$ (NMA-900505)

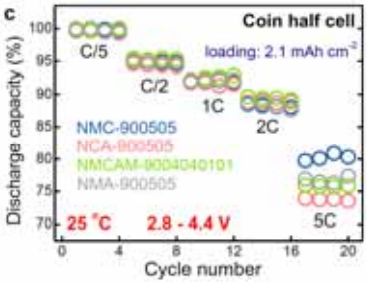




W. Li, E. M. Erickson, and A. Manthiram, *Nature Energy* **5**, 26 (2020)







W. Li, S. Lee, and A. Manthiram, *Advanced Materials* **2002718** (2020)

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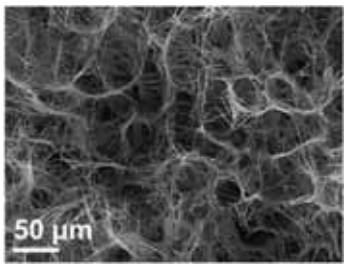
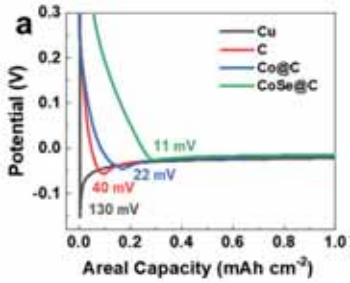
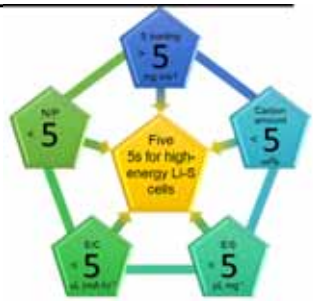
LITHIUM-SULFUR BATTERIES WITH STABILIZED LITHIUM METAL







- Sulfur is abundant and inexpensive, but met with challenges for lithium deposition and cycle life
- Can we develop a better understanding of the dynamics of lithium deposition?
- Can we engineer a uniform SEI layer *in situ* or a 3D framework with favorable properties?
- What role do the crossed over species play on the dynamics of lithium deposition?

J. He and Manthiram, *Advanced Energy Materials* 2002654 (2020)
A. Bhargav, J. He, A. Gupta, and A. Manthiram, *Joule* **4**, 285-291 (2020)
A. Manthiram, Y.-Z. Fu, S.-H. Chung, C. Zu, & Y.-S. Su, *Chemical Reviews* **114,** 11751 (2014)

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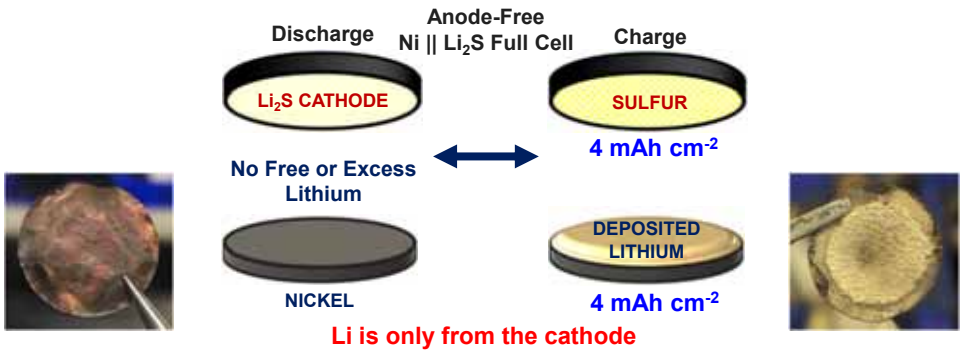
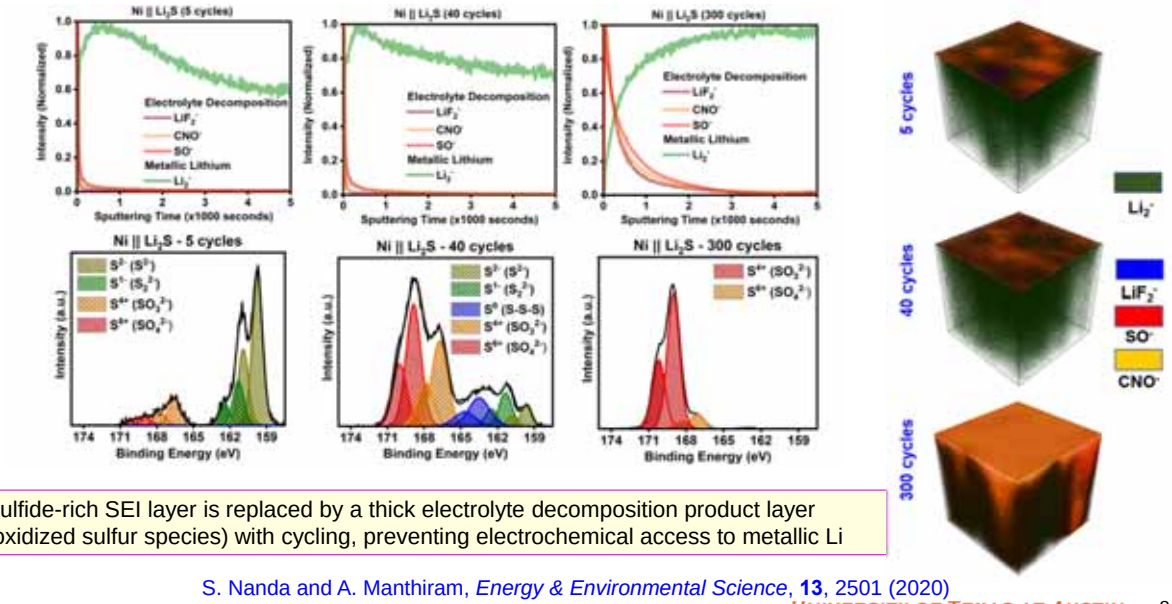
ANODE-FREE FULL CELL TO UNDERSTAND THE DYNAMICS



- Serves as an excellent template for evaluating the dynamics of lithium deposition
- Maximizes gravimetric and volumetric energy densities
- Eliminates self-discharge in assembled cells as they are in discharged state
- Obviates the technical challenges associated with thin lithium foils

S. Nanda, A. Gupta, and A. Manthiram. *Advanced Energy Materials* **8**, 1801556 (2018)

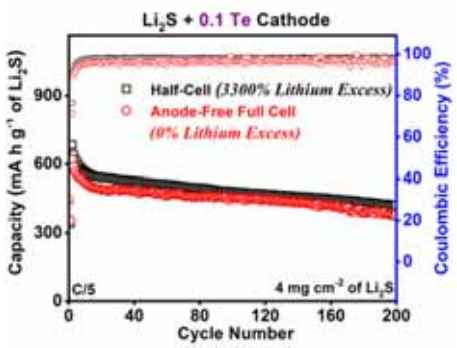
WHAT CAUSES LITHIUM-METAL DEGRADATION?

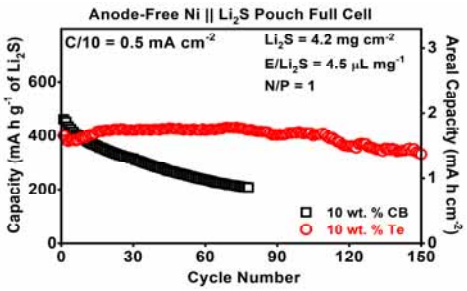


- Sulfide-rich SEI layer is replaced by a thick electrolyte decomposition product layer (oxidized sulfur species) with cycling, preventing electrochemical access to metallic Li

S. Nanda and A. Manthiram, *Energy & Environmental Science*, **13**, 2501 (2020)

HOW DO WE SUPPRESS LITHIUM-METAL DEGRADATION?





Tellurium addition to sulfur cathode
- forms polytellurosulfides ($Li_2Te_xS_y$) and deposits Li_2TeS_3 layer on lithium-metal anode
- suppresses electrolyte decomposition and helps retain good cycle life
- allows operation of practically relevant pouch cells with lean electrolyte

S. Nanda, A. Bhargav, and A. Manthiram, *Joule* **4**,1121 (2020)

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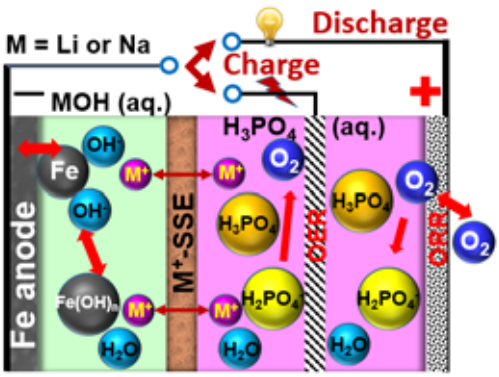
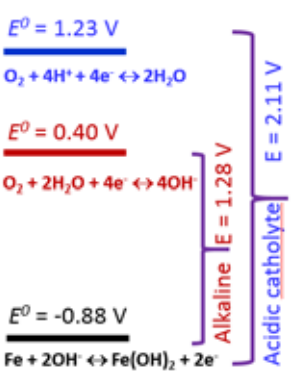
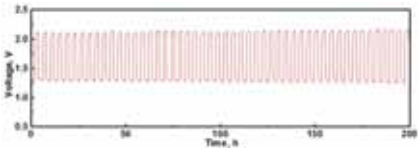
MEDIATOR-ION SOLID-ELECTROLYTE FLOW BATTERIES







- Solid electrolyte eliminates chemical crossover, suppresses dendrite (*e.g.*, zincate migration, carbonation by CO_2)
- Allows different media at the anode and cathode (aqueous vs. nonaqueous, acidic vs. basic, solid vs. liquid, *etc.*)

L. Li and A. Manthiram, *Advanced Energy Materials* **5**, 1502054 (2015)
X. Yu and A. Manthiram, *ACS Energy Letters* 2, 1050 (2017)

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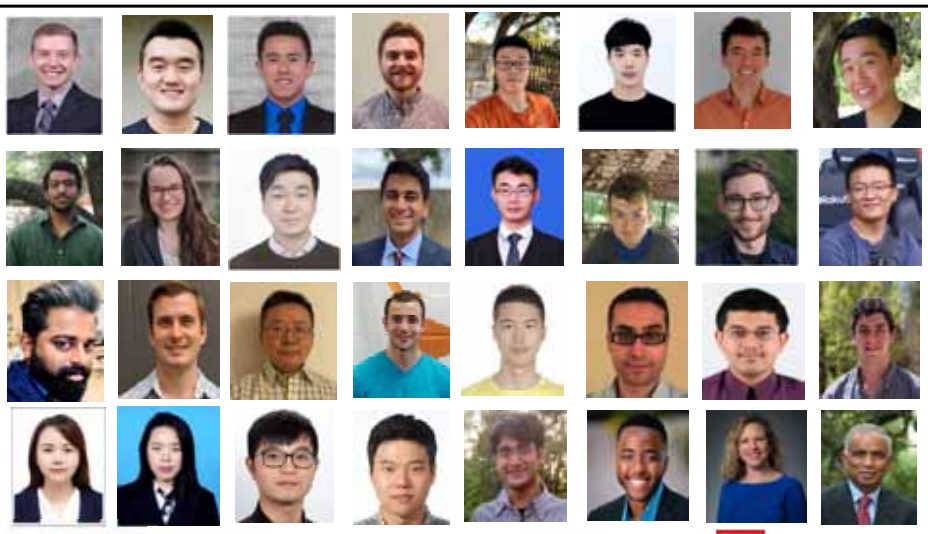
ACKNOWLEDGEMENTS



Large group
Interdisciplinary
Resources
Facilities
Community
Diversity
Training
Mentoring
Motivation
Passion

ENERGY BES
BATTERY 500 EERE-VTO
ENERGY EERE-VTO
NSF
NASA
EXXON Mobil
SAMSUNG SDI
TESLA
The Welch Foundation
energy institute