Report of Chief Science Officer

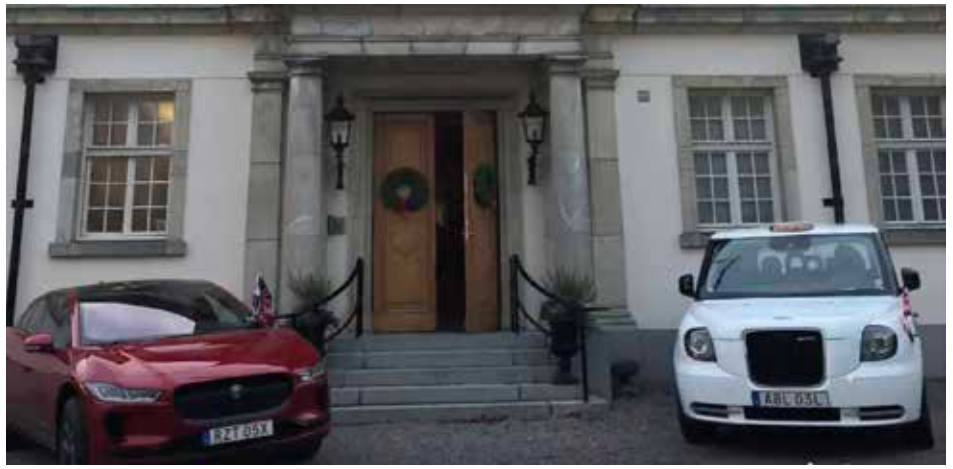
Trends for the Future of High Energy Density Battery Technology

M. Stanley Whittingham

Binghamton University (SUNY)

Peterbilt Trucks

Bermuda Rental Car



UK Ambassador Residence, Stockholm

The Progress of Li-Ion Intercalation Battery Science

Cathode Trends:

- High **Ni NMC** will dominate for EVs
  - Trend to move higher Ni than 622
- Challenges
  - 1st cycle loss
  - Meatballs vs separate crystals (Dahn)
  - Status of Battery 500
  - Protocols

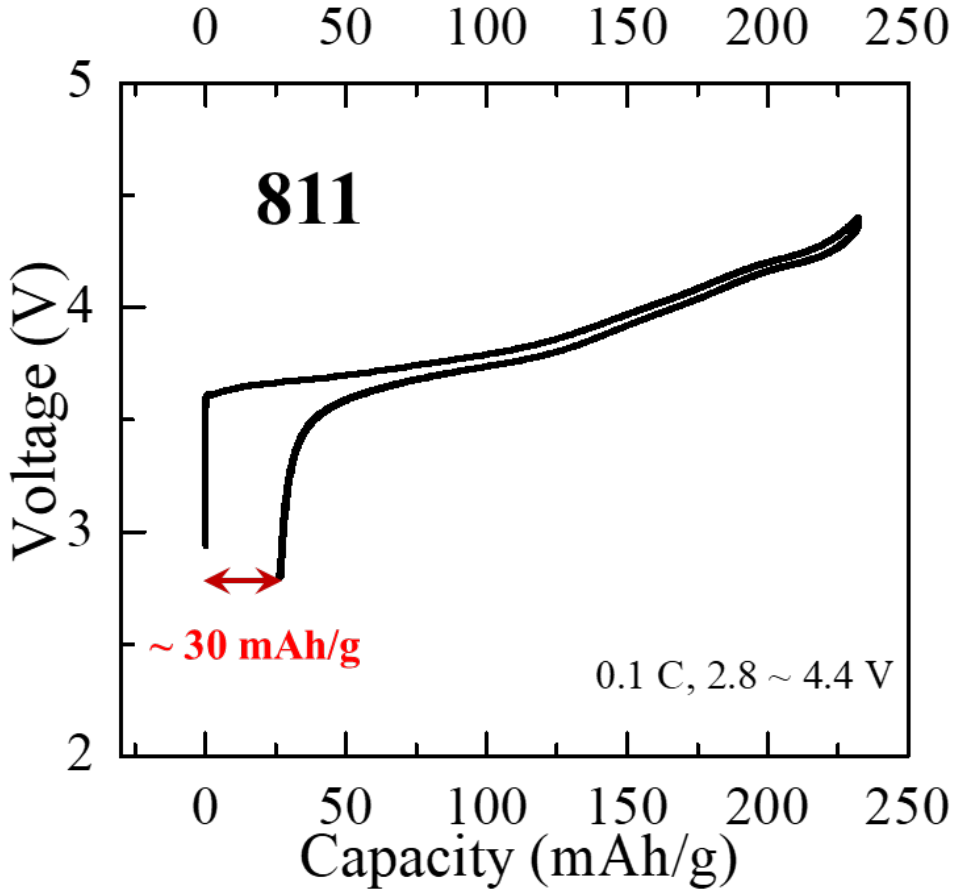
Consortia Arising around the world

- Science
- Manufacturing

The 1st Cycle Loss of High Ni NMCA Intercalation Batteries

Today ~ 12% capacity loss on 1st cycle

- If eliminated allows:
  - 400-500 Wh/kg cells
  - 1000 Wh/l



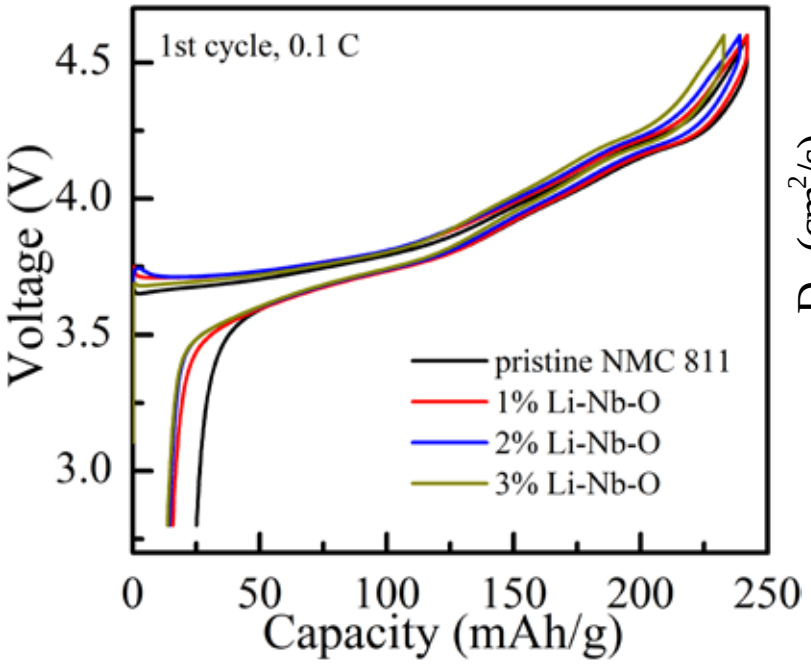
How to get even Higher Energy Density: Use all the Material!

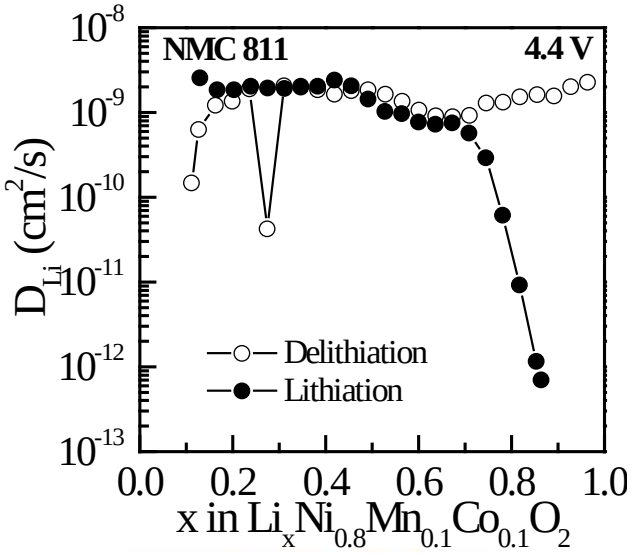
Today ~ 12% capacity loss on 1st cycle

- If eliminated allows 400-500 Wh/kg cells?

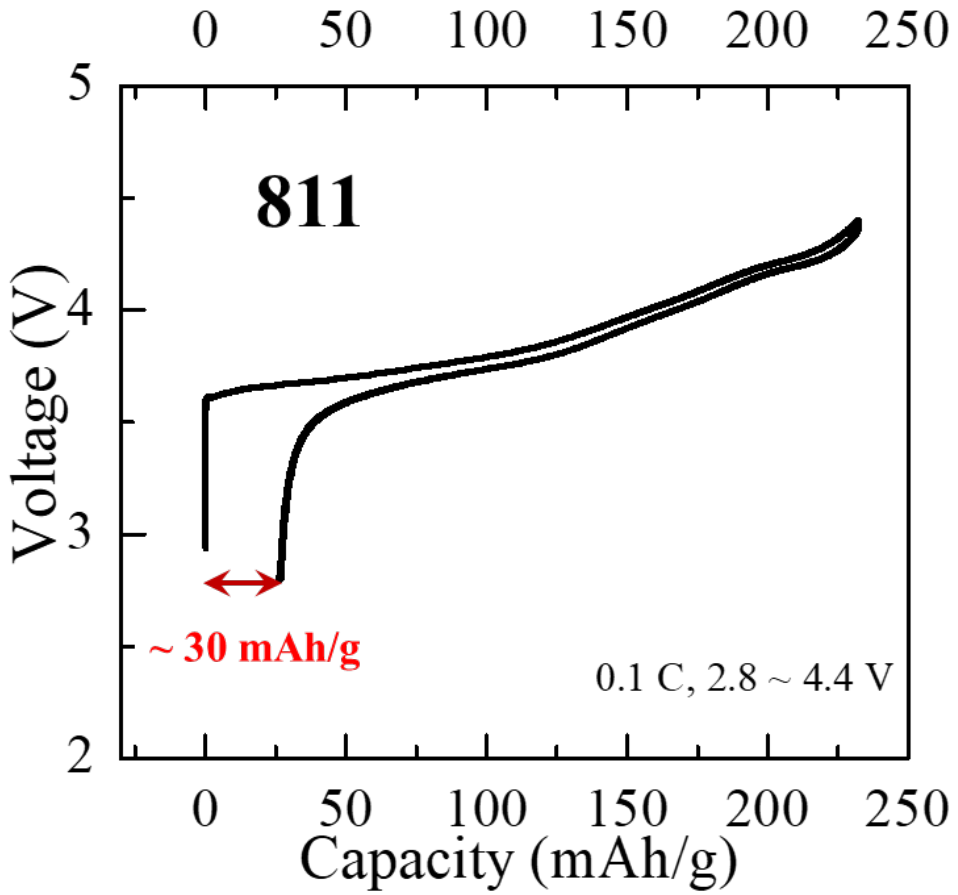
What are the possible causes of loss?

- Slow Li^+ in-diffusion
  - Coatings and Substitution





Xin et al ACS Appl Mtls Interf., 11, 34889,



ACS Energy

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http://pubs.acs.org/journal/aelccp

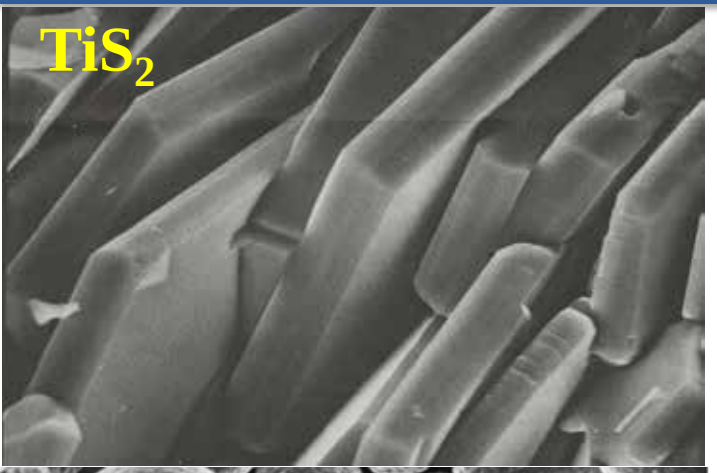
VIEWPOI

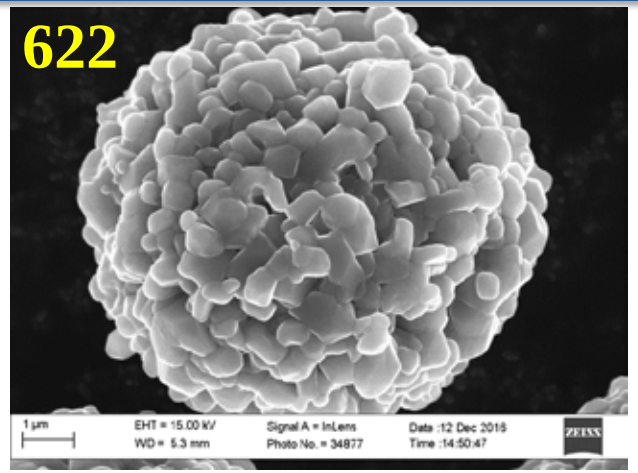
What Limits the Capacity of Layered Oxide Cathodes in Lithium Batteries?

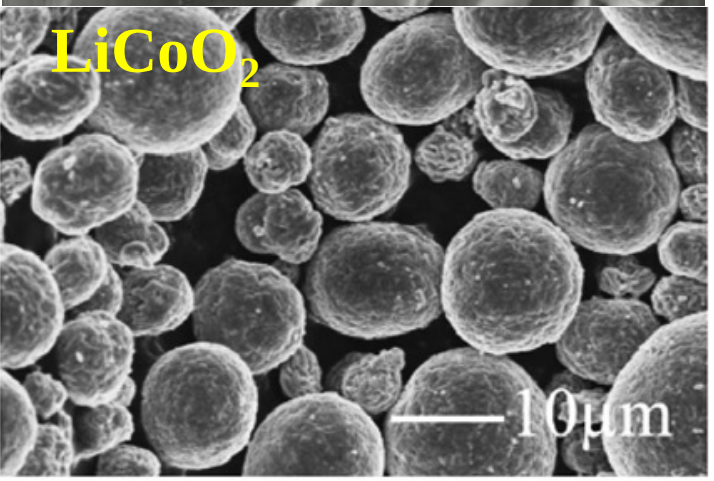
Transition metal dioxides, typified by $LiCoO_2$, have been and still are the dominant cathode in Li-ion

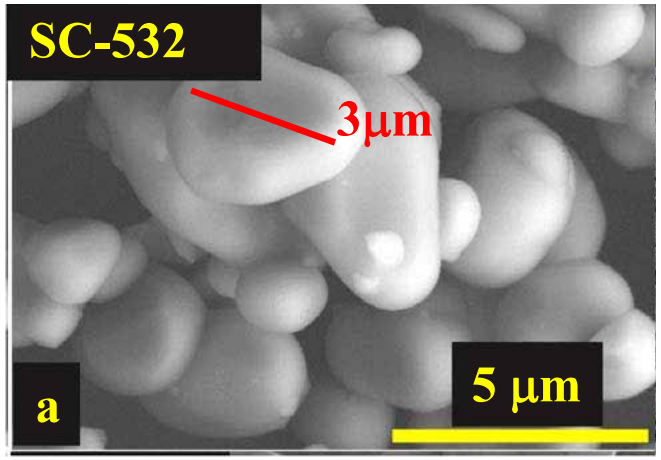
This Viewpoint discusses some of our recent work and the published literature to better understand this loss and to

“Meatballs” or Separate Crystals for High Ni NMCA Intercalation Batteries



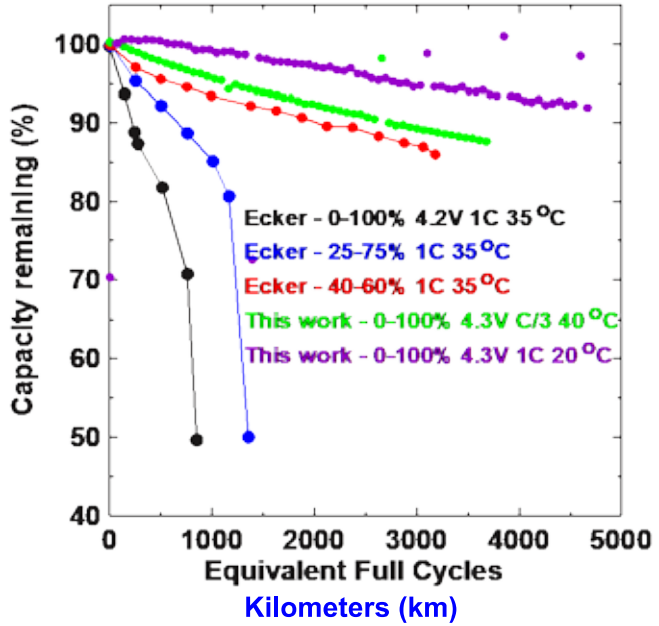


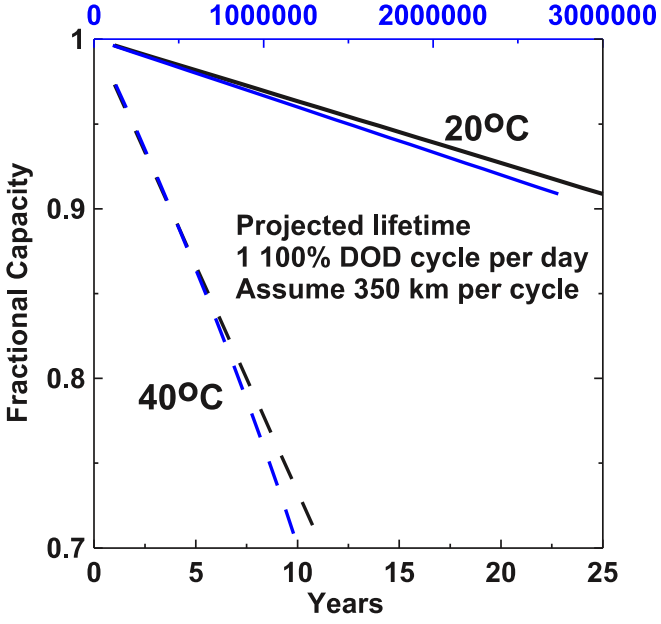




$LiCoO_2$ Nishi/SONY
20 mm particles
(Figure – Dahn 2007)

Electrolyte additives critical





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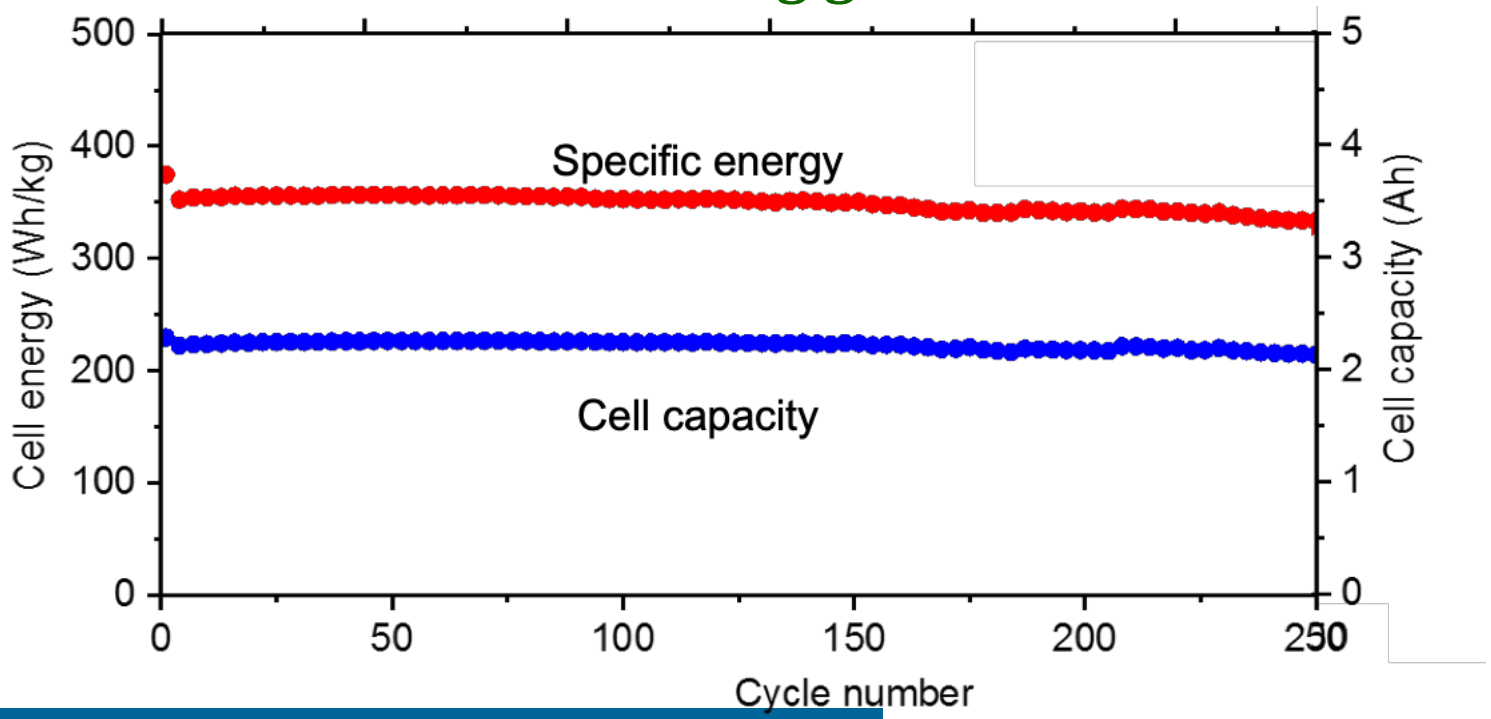
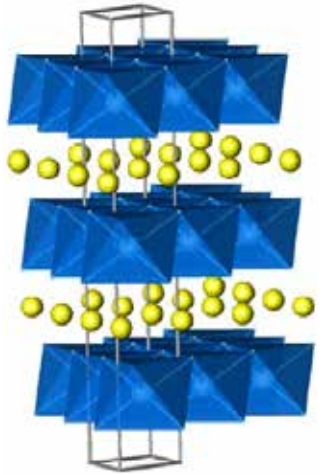
Battery500 Now Achieved >350 Wh/kg with NMC 622

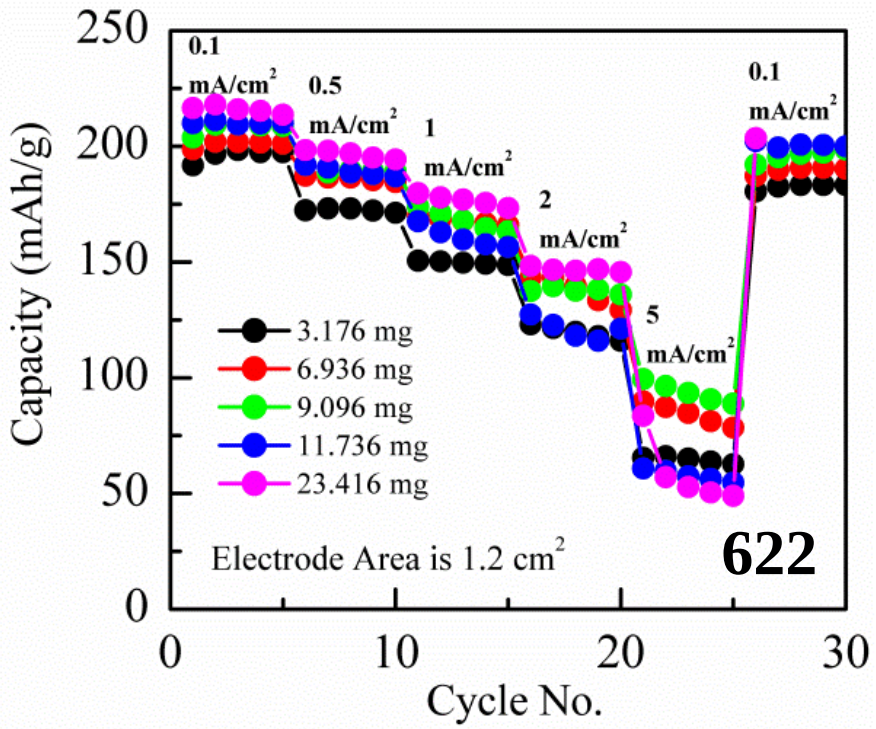
- **$LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ was 2019 baseline for the consortium**
  - X-ray characterization normal
  - Electrochemistry good
  - **Achieved 350 Wh/kg goal**

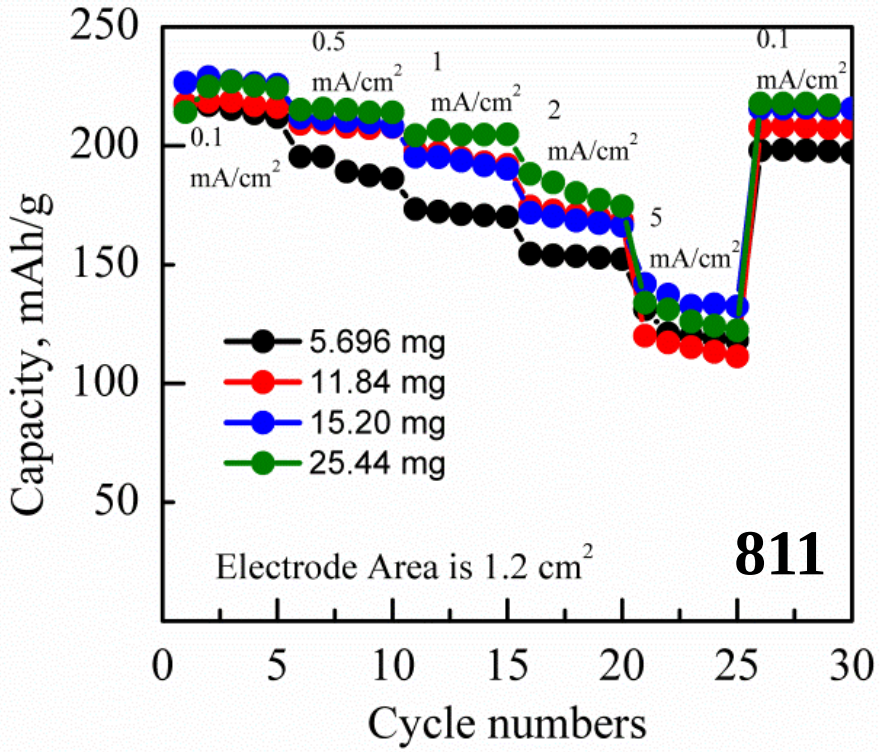




PNNL/INL Unpublished results

R,D&E Now Emphasizing NMC 811 over 622 as Tomorrow's Choice (How low can the Co go?)





- The cells cycled at different current densities, mA/cm^2, from 2.5 to 4.6 V
- 622 show dependency of loading on electrochemical performance at high rates
- 811 has better rate capability compared to 622, less thermally stable and more air sensitive

Protocols and Pathways for Future Intercalation Batteries

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Good Practices for Rechargeable Lithium Metal Batteries

Bingbin Wu,[1,=] Yang Yang,[1,=] Dianying Liu,[1] Chaojiang Niu,[1] Mark Gross,[1] Lorraine Seymour,[1,*] Hongkyung Lee,[1] Phung M. L. Le,[1,2] Thanh D. Vo,[1,2] Zhiqun Daniel Deng,[1] Eric J. Dufek,[3,*] M. Stanley Whittingham,[4,] Jun Liu,[1,**] and Jie Xiao[1,5,*,z]**

PERSPECTIVE
https://doi.org/10.1038/s41560-019-0338-x
nature energy

NATURE ENERGY | VOL 4 | MARCH 2019 | 180–186 |

Pathways for practical high-energy long-cycling lithium metal batteries

Jun Liu[1*], Zhenan Bao[2], Yi Cui[2], Eric J. Dufek[3], John B. Goodenough[4], Peter Khalifah[5], Qiuyan Li[1], Bor Yann Liaw[3], Ping Liu[6], Arumugam Manthiram[4], Y. Shirley Meng[6], Venkat R. Subramanian[1,7], Michael F. Toney[8], Vilayanur V. Viswanathan[1], M. Stanley Whittingham[9], Jie Xiao[1], Wu Xu[1], Jihui Yang[7], Xiao-Qing Yang[5] and Ji-Guang Zhang[1]

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BATTERY 500 CONSORTIUM

BINGHAMTON UNIVERSITY STATE UNIVERSITY OF NEW YORK

What are the battery systems of the future? – No change from 2019

- ü **Lithium intercalation systems will dominate for next 5-10 years**
  - ü NMCA likely to be dominant
  - ü $LiFePO_4$/$LiMnPO_4$ /$LiVOPO_4$ systems still have key markets
  - ü **Need safe and stable electrolytes**
- ü **Na cells (1-2 Na) may also be viable for fixed storage, but safety issues (mp 100°C)**
- X **Magnesium not a technical option**
  - X No evidence that Mg can transfer more than 1 electron/TM (=1/2 Mg); lower voltage than Li
  - X Mg readily grows dendrites
  - ü "Anything Mg can do, Li can do better"
- ü **Calcium more attractive than magnesium**
- ü **Lithium sulfur has the highest ED but is a real bear**
- X **Lithium air not viable technically and no ED incentive**
- ü **Zinc systems have renewed interest for low ED applications**