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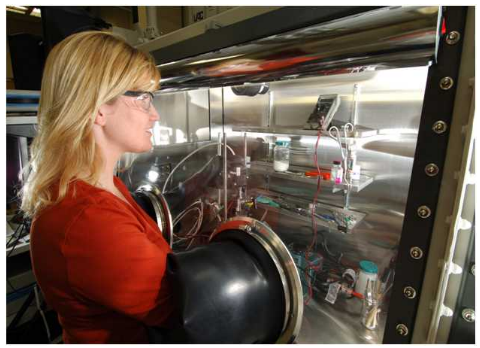
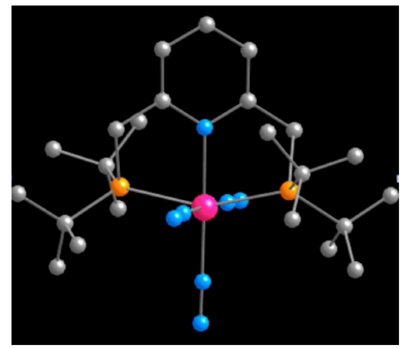
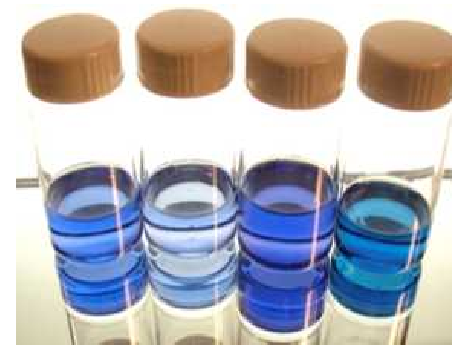

Advanced Power Sources R&D

Power Source Technology Group

Nick Hudak
Chris Apblett
Department Manager: Tom Wunsch

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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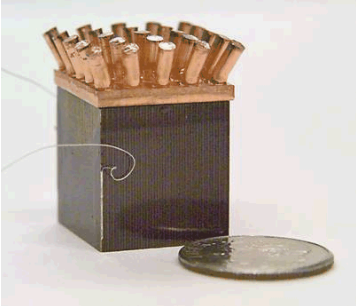
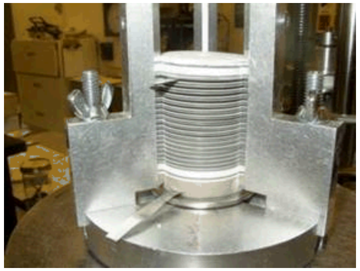
Program Areas

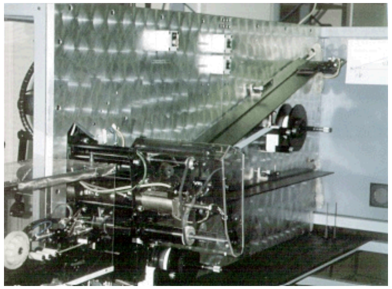
- DOE/National Nuclear Security Administration
  - Reserve battery technology for weapon system power
  - Primary battery technology for flight test (telemetry) power
- DOE/Office of Electricity Delivery & Energy Reliability
  - Materials, applied R&D, systems, characterization & testing, analysis
  - Batteries for grid-scale energy storage
- DOE/Office of Vehicle Technologies
  - Battery safety research and abuse testing
  - Materials R&D: Inactive materials (separator, electrolyte)
- LDRD (internal investments)
  - Modeling and characterization
  - Novel energy storage concepts and materials
  - Degradation mechanisms

PSTG Capabilities

- Thermal battery and Li-ion cell prototyping facilities; small lot manufacturing of high-reliability thermal batteries
- Design and development of a wide variety of batteries, capacitors, and thermoelectric power supplies
- Unique battery abuse testing facilities; tester design and support for battery performance characterization and product acceptance
- Development of advanced electricity storage and power engineering technologies for electric supply
- High-fidelity modeling and simulation
- Fundamental electrochemical studies and development of improved battery materials
- More than 20 scientists and engineers, many with decades of experience in power source engineering



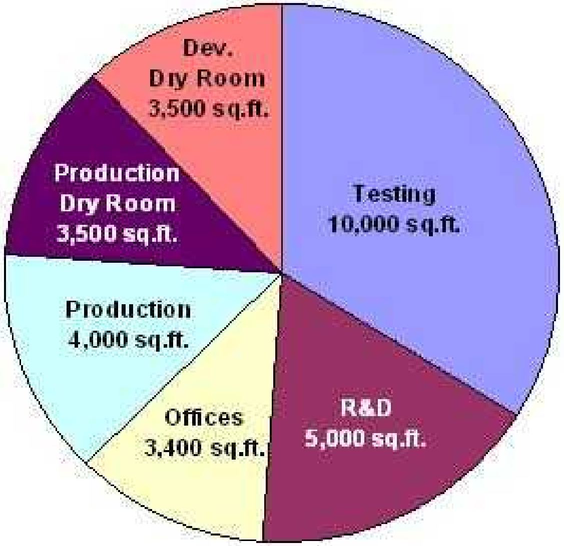




PSTG Research, Development, Test and Production Facilities

Two distinct work environments:

- **Building 894**
  - Three Dry Rooms
    - Production
    - Development
    - Research, cell prototyping
  - Chemistry Labs
  - Battery/Cell performance testing
  - Production
    - Header assembly
    - Battery assembly
    - Inspection (leak and x-ray)
  - Machine Shop
  - Records Room
  - Offices
- **Building 905**
  - Battery Abuse Testing Laboratory



Building 894

29,400 sq.ft.

Grid-Scale Energy Storage
Office of Electricity Program Area

Sandia National Laboratories

Long term research ↔ Applied Research ↔ Battery and Field Testing

Long term research

Goal: Seek breakthroughs in materials, components and cell designs for next generation technologies.

- ❑ Novel electrodes, materials, and membranes;
- ❑ New electrolyte and new redox chemistry;
- ❑ **Next gen. redox flow batteries;**
- ❑ Next gen. low cost Na batteries;
- ❑ State-of-the-art diagnostic/characterization.

Applied Research

Goal: Improve key technologies for mid term applications in power management and other specialized applications.

- ❑ **Advanced lead-carbon batteries;**
- ❑ Low cost Li-ion batteries;
- ❑ Long life redox flow batteries;
- ❑ Electrochemical modeling

Battery and Field Testing

Goal: Test and validate grid relevant performance of components and systems:

- ❑ **Components and systems;**
- ❑ Protocols and standards;
- ❑ Performance and cost;
- ❑ Grid viability and scalability;
- ❑ Non-electrochemical options

3-10 year	2-3 year	1-3 year

- Universities, National Labs
- National Labs, Universities, & Industry
- Industry, National Laboratories

Cross-cutting activities:

Analysis, Modeling, and Integration

- ❑ Impact of renewable and storage on grid;
- ❑ Storage needs for different applications;
- ❑ System analysis and storage options;
- ❑ Cost and performance of different technologies;

Battery Abuse Testing
Office of Vehicle Technologies Program Area

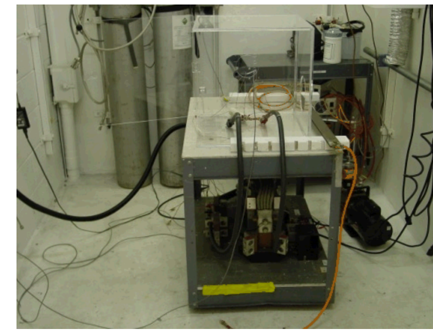
Sandia National Laboratories

Full range of material, cell, module and pack level thermal characterization, electrical, and mechanical abuse testing.

Over Discharge

Over Temperature

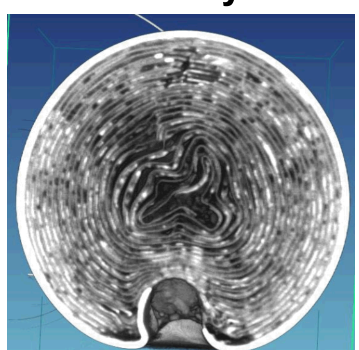
Overcharge



Short circuit

Cell Prototyping

CT X-ray

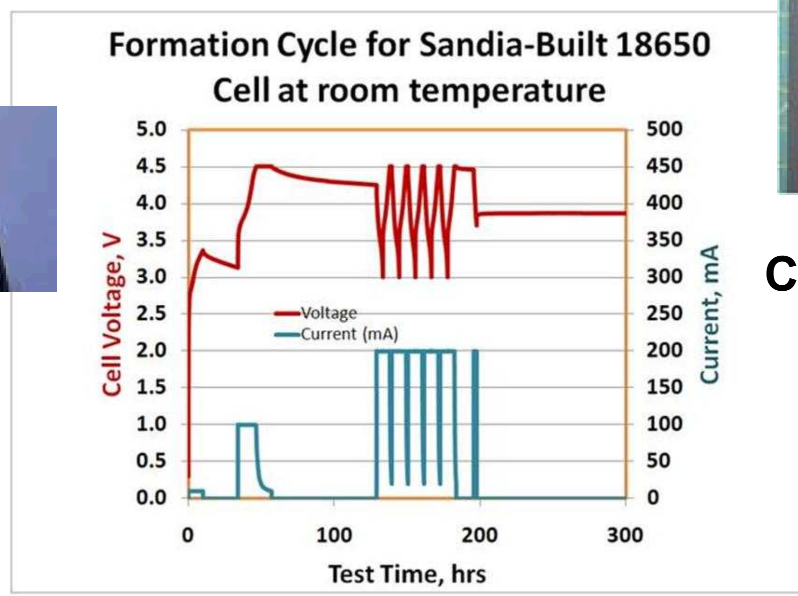


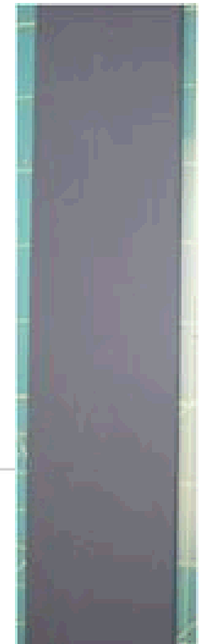
Thermal Stability (Accelerating Rate Calorimetry)

Crush

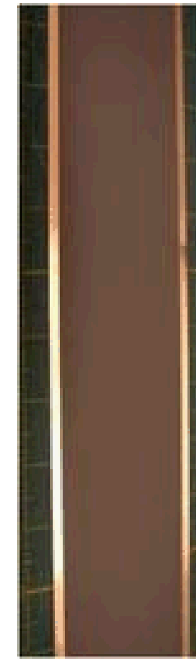
SNL-Built, Rechargeable 18650 Cells with SNL Coated Electrodes

- Coated both anode and cathodes with in-house facility
- Anode is Conoco Phillips carbon
- High voltage cathodes:
  - $LiNi_{0.4}Mn_{0.3}Co_{0.3}O_2$ (4.3 -4.5 V)
  - $LiMn_{1.5}Ni_{0.5}O_4$ (>4.8 V)
- Fabrication of 18650 cells and testing
- Thermal abuse facility
  - ARC run on 18650 cell



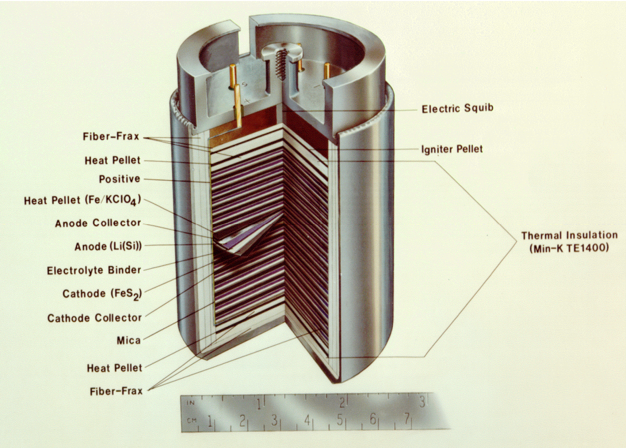


Cathode

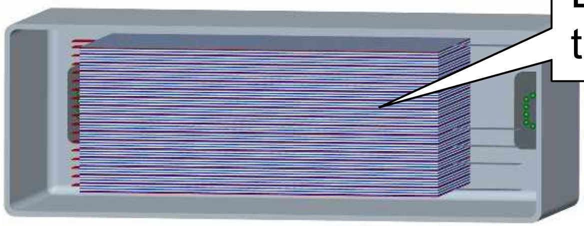


CP Anode

Advanced Thermal Battery Technology



Traditional Design



Each layer will be much thinner than traditional devices

Based on thin film coating technology, enabled by new binder technology

Much more volume efficient

- **Improved Electrical Performance**
- **More Robust**
- **Lower Cost**
- **Enhanced Safety**
- **Enable New Form Factors**
- **Design for Commercial Manufacture**
- **Enable Commercial Applications**

Advanced Thermal Battery Architecture Project
Thin Film Thermal Battery (TFTB) Prototypes

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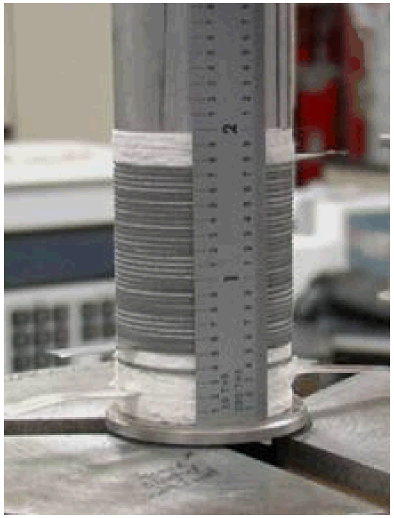
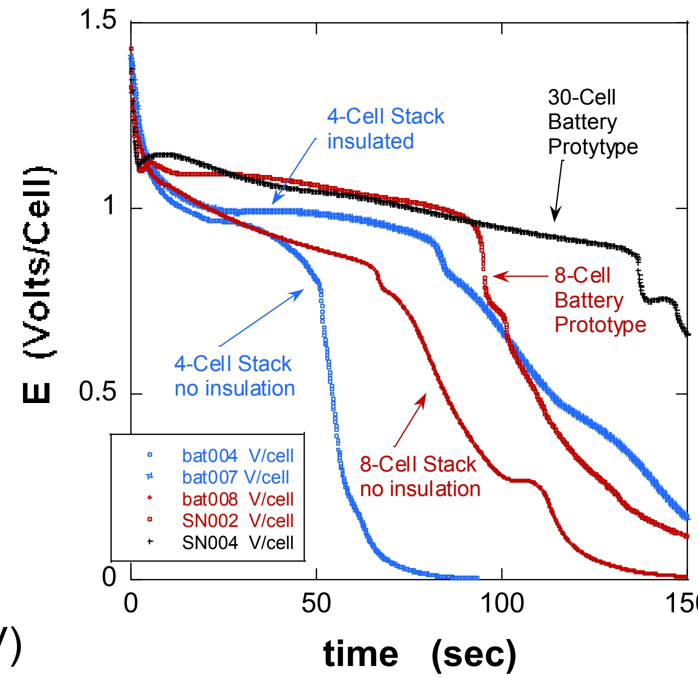


8-cell stack
1.25 inch electrode diameter



- Five TFTB prototypes fabricated and tested (1-10V, 4-36V)
- 2X improvement in energy density using pellet heat source (82% of stack)
- No gas pressure, no electrolyte leakage, no short circuits
- Pulse Power below requirements (~ 0.3X)

Provisional patent application filed 12/09

36-Volt Prototype

NNSA-Funded Ambient Temperature Lithium Battery Development

Sandia National Laboratories

Significant lithium battery work started at SNL in the 1970's

- Li/SO_2 fielded in multiple applications
- Li/SO_2 continues to be used in JTA TM applications today
- Li/MnO_2 used in CMS applications

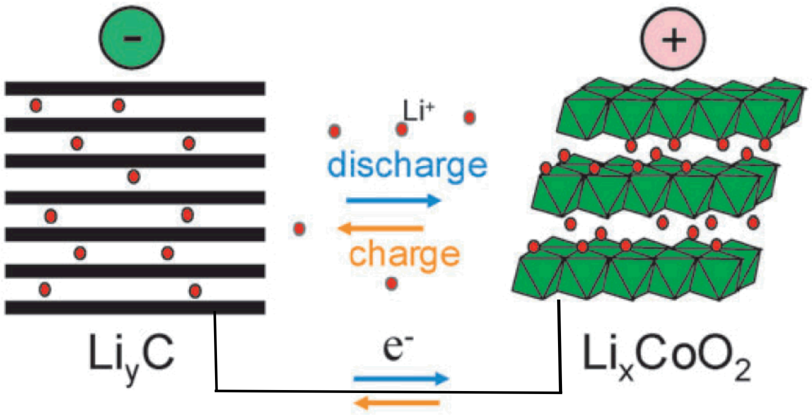
$Li/SOCl_2$ work started in late 1980's

- Needed to meet -55ºC requirements
- Sandia designed family of "D" cells
- Project terminated in late 1990's
- No funding to continue characterization of cells

LEP work started in 2000

- Changed direction to investigate use of commercial cells
- Used smaller cells to improve safety and reliability
- Project terminated in 2006
- No funding to continue characterization of cells
- One battery pack continued on real time test

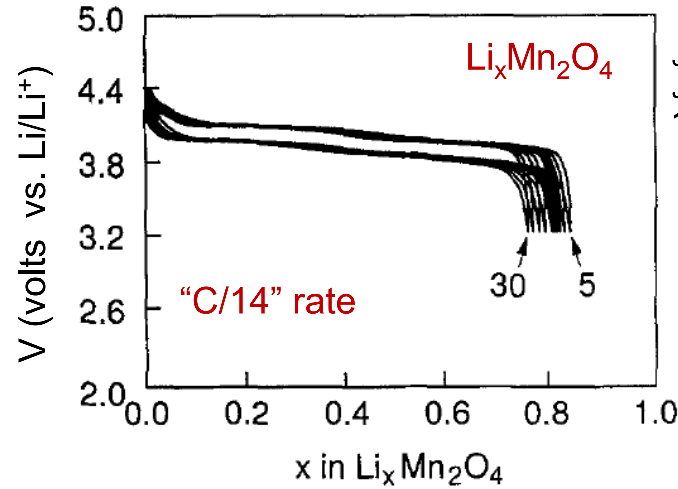
Portable Power: Lithium-ion Batteries



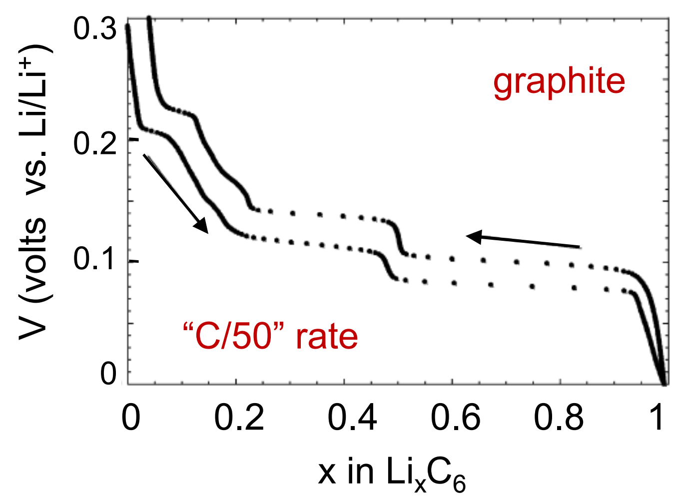
M. R. Palacín, *Chemical Society Reviews* **38**: 2565 (2009)

electrode	voltage (V)	capacity (mAh/g)
Li_xCoO_2	3.7	140
$Li_xMn_2O_4$	4	120
graphite Li_xC_6	0.1	370

Typical galvanostatic voltage profiles



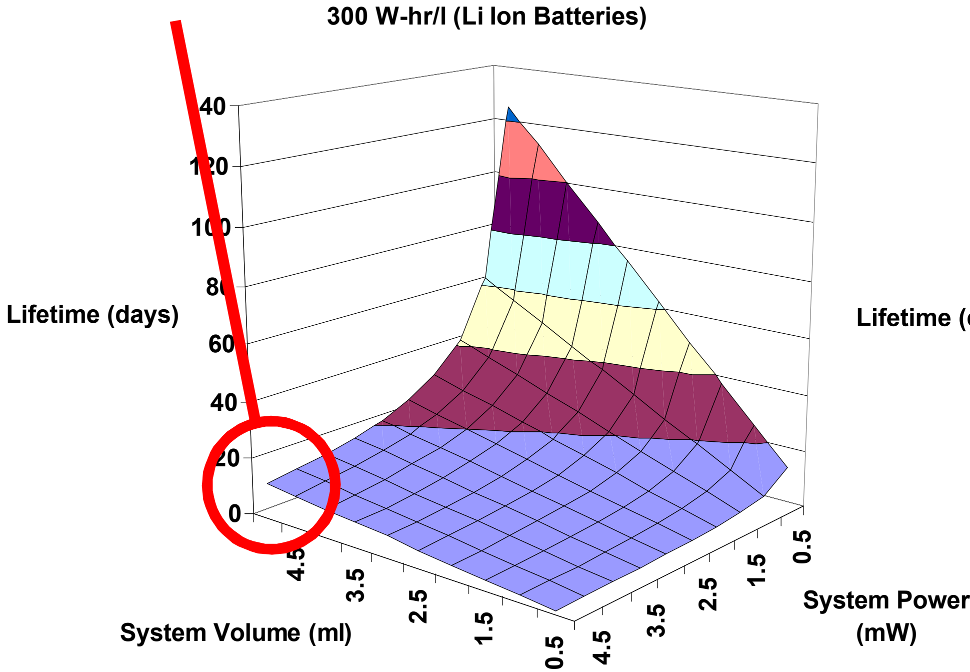
J. M. Tarascon et al., *J. Electrochemical Society* **138**: 2859 (1991)



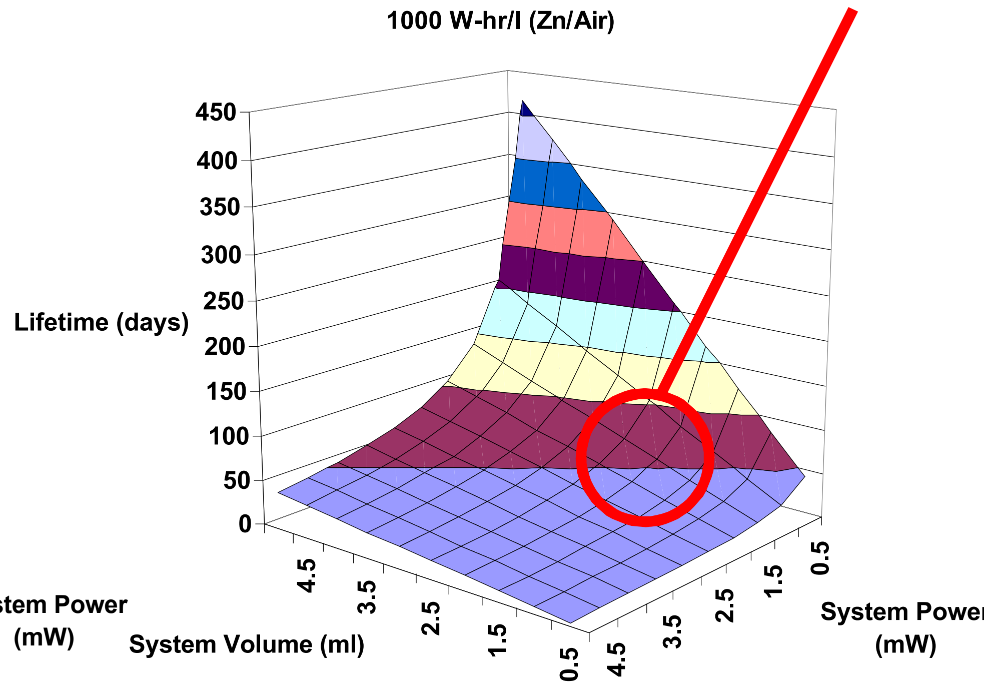
Y. Reynier et al., *J. Power Sources* **119-121**: 850 (2003)

Lifetime and Size are Key for Low Power

5 ml system, 5mW draw, 10 days



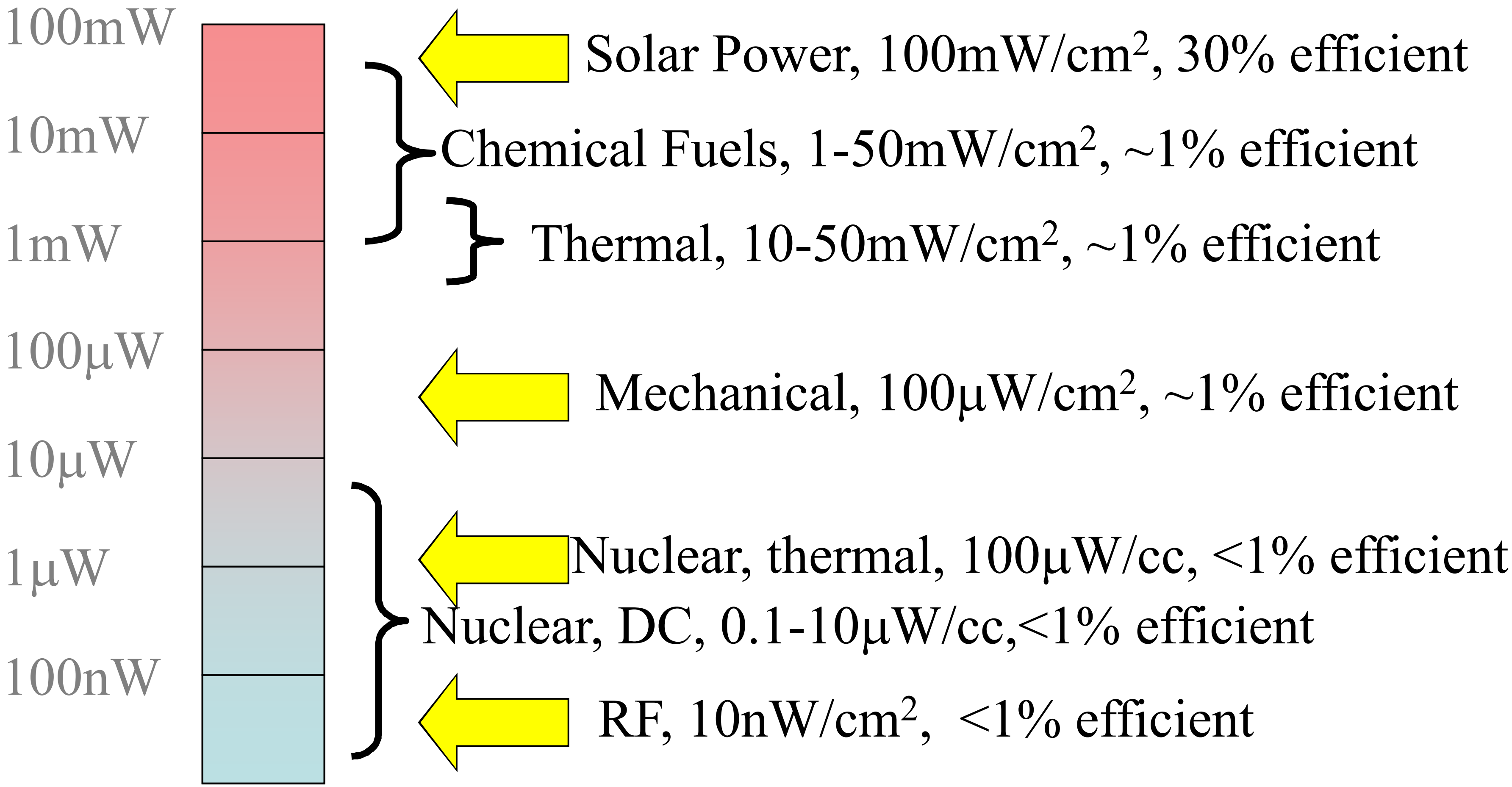
2 ml system, 1mW draw, 50 days



If we want to beat batteries with low power, we have to be small, and we have to last a long time

Lifetime constrained by size forces a consideration of harvesting technologies (battery chemical energy is a fixed quantity)

Environmental Scavenging: Summary



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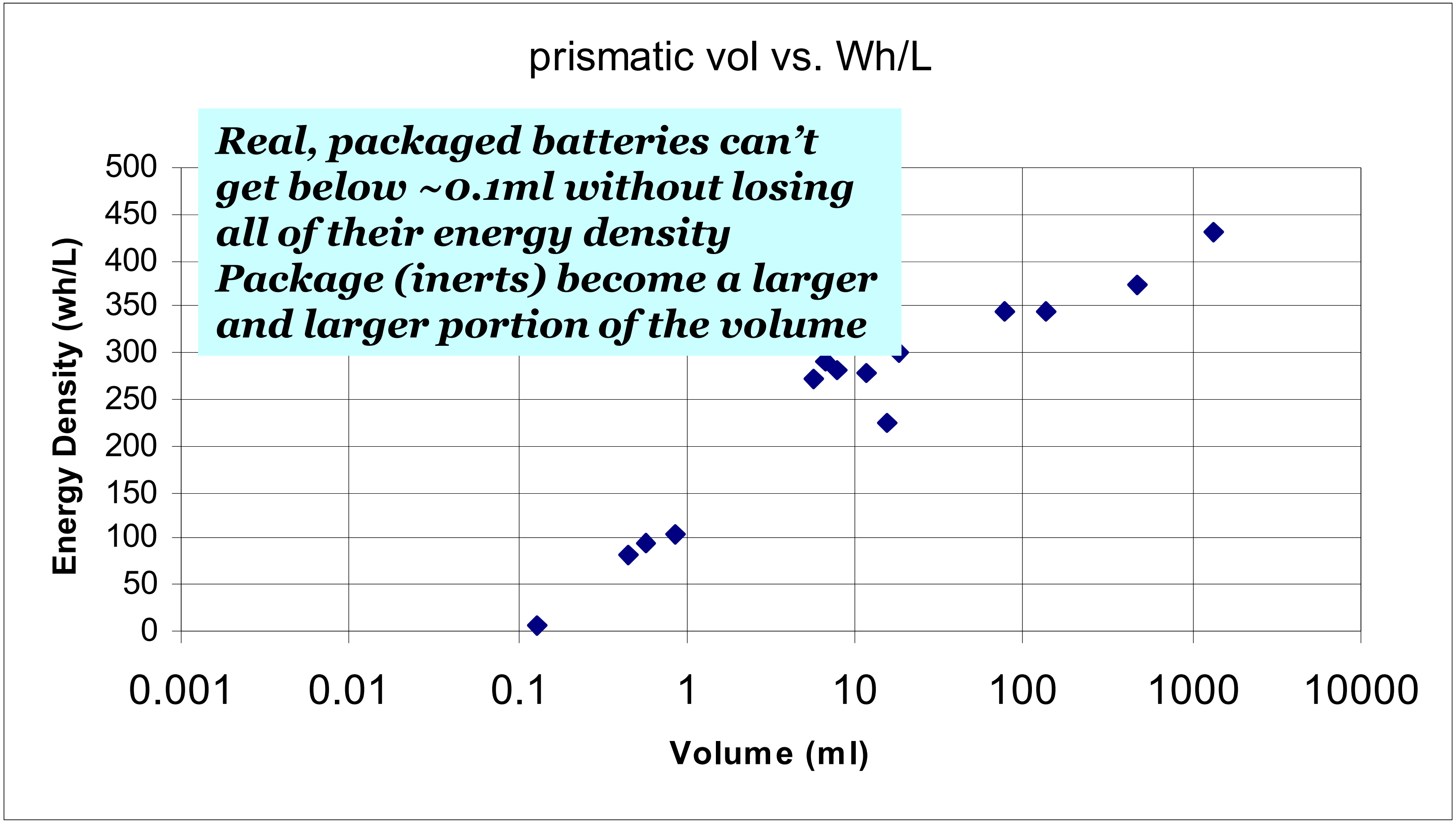
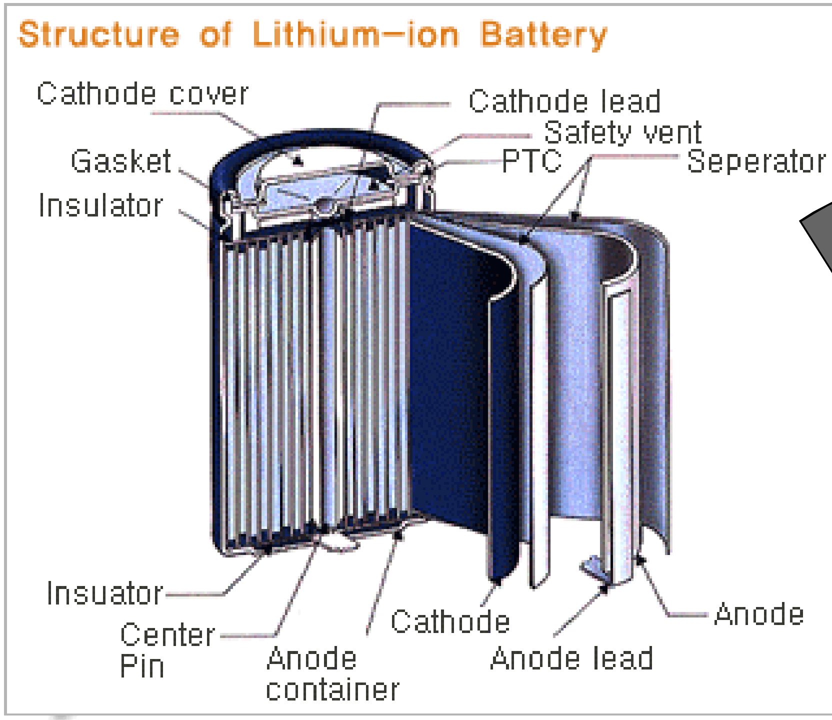
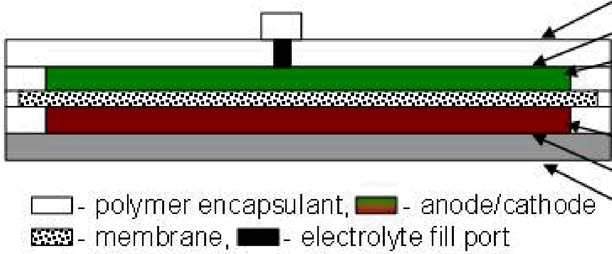
Energy Storage: Batteries



Data from Linden, Reddy, plot by E. Wang

Thinning Down Traditional Li-Ion Batteries





Encapsulant (DW SU-8, UV-curable epoxy) ✓
Current collector (DW gold nanoparticle ink) ✓
Anode (DW graphite/carbon) ✓
Separator (DW mesoporous SiO_2) ✓
Cathode (DW $LiFePO_4$) ✓
Current collector (DW gold nanoparticle ink) ✓
Substrate (polyimide ✓, paper, low T polymers ✓)

Chris Apblett, caapble@sandia.gov

Direct write enables 3D FSS, antennas, and microsystem interconnects

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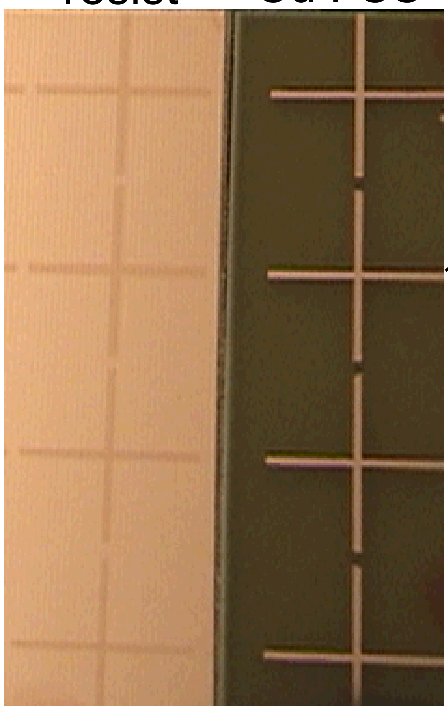
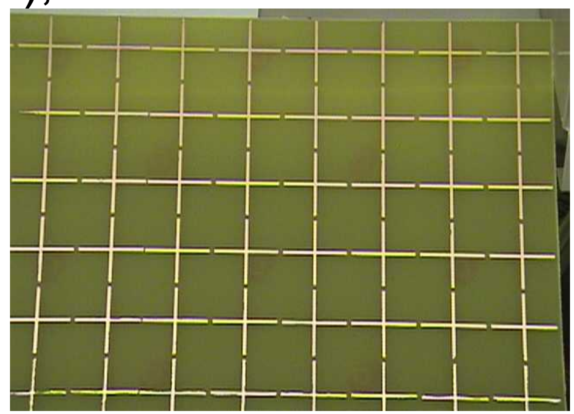
Aerosol jet on robotic x-y-z stage prints:
-etch resists on metallized polymer (subtractive), or
-silver ink on on polymers (additive),

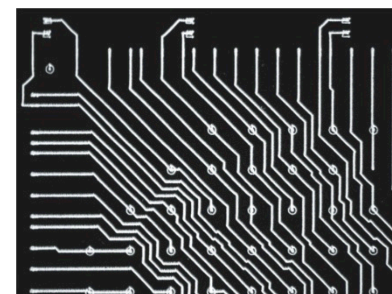
inkjetted resist | etched Cu FSS



2D FSS



25 μm silver lines processed at 150C: polymer-compatible



3D FSS

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$LiFePO_4$ Printed Battery Using Direct Write (DW) Technology

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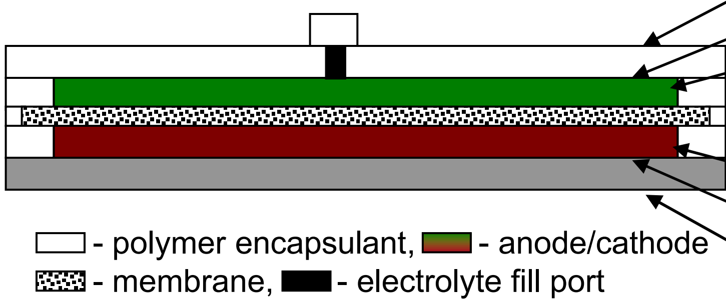
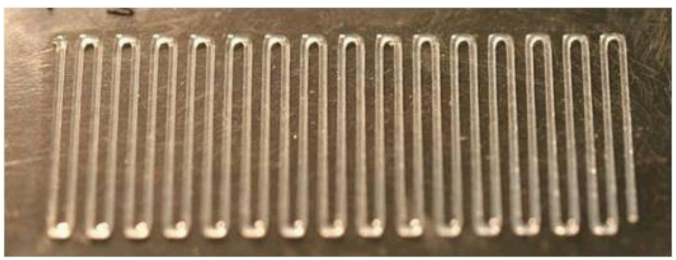
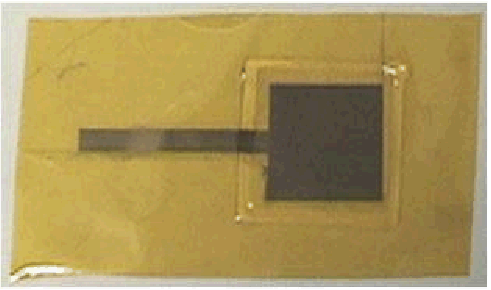


- Encapsulant (DW Resist, UV-curable epoxy)
- Current collector (DW gold nanoparticle ink)
- Anode (DW graphite/carbon)
- Separator (DW mesoporous SiO_2, Polymer)
- Cathode (DW $LiFePO_4$)
- Current collector (DW gold nanoparticle ink)
- Substrate (polyimide, paper, low T polymers)

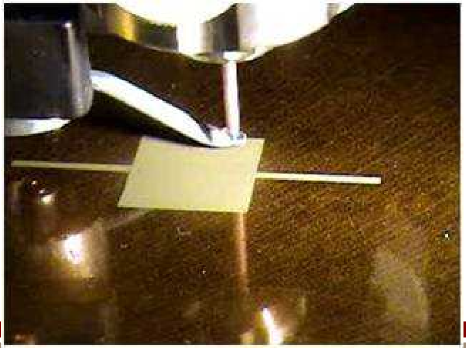


Direct written epoxy encapsulant

DW $LiFePO_4$ on current collector



DW cathode + encapsulant on Kapton



DW Gold on Kapton

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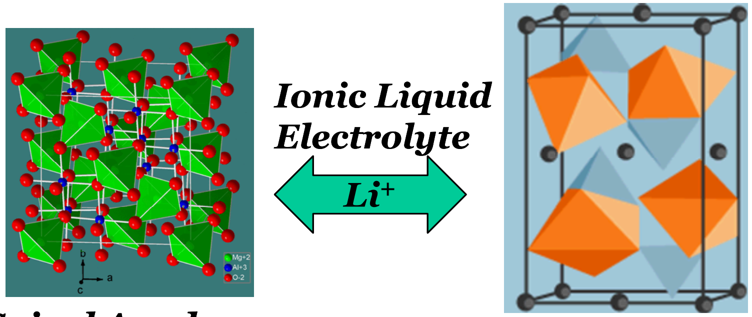
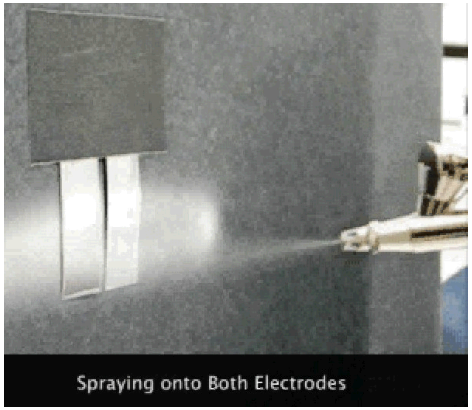
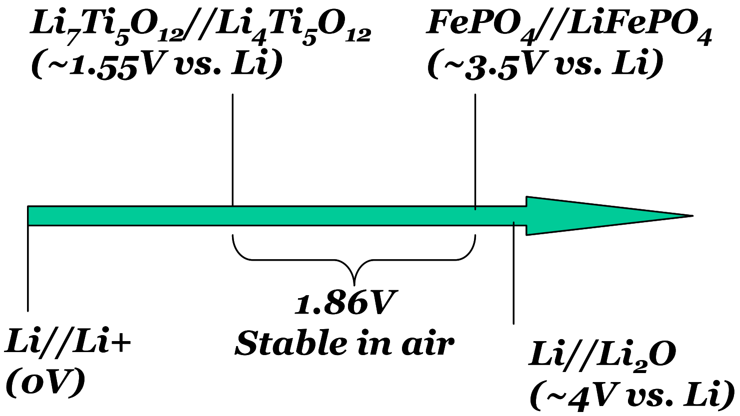
All Printed "Open Air" Cell



Spinel Anode
$Li_{4/3}Ti_{5/3}O_4$

Olivine Cathode
LiFePO4





- Allows printing in air
- Flexible anode/cathode allows bendable battery
- Good charge/discharge characteristics