Batteries at NASA – Today and Beyond

Undergraduate Seminar for Xavier University of New Orleans

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Abstract

NASA uses batteries for virtually all of its space missions. Batteries can be bulky and heavy, and some chemistries are more prone to safety issues than others. To meet NASA's needs for safe, lightweight, compact and reliable batteries, scientists and engineers at NASA develop advanced battery technologies that are suitable for space applications and that can satisfy these multiple objectives. Many times, these objectives compete with one another, as the demand for more and more energy in smaller packages dictates that we use higher energy chemistries that are also more energetic by nature. NASA partners with companies and universities, like Xavier University of Louisiana, to pool our collective knowledge and discover innovative technical solutions to these challenges. This talk will discuss a little about NASA's use of batteries and why NASA seeks more advanced chemistries. A short primer on battery chemistries and their chemical reactions is included. Finally, the talk will touch on how the work under the Solid High Energy Lithium Battery (SHELiB) grant to develop solid lithium-ion conducting electrolytes and solid-state batteries can contribute to NASA's mission.

Why is NASA Interested in Batteries?

- Batteries are an essential component of the power system of virtually all NASAs missions since we first ventured into space
- We have to carry all of our power generation and energy storage along on each individual mission (no electrical outlets in space)!
- Power generation for satellites and vehicles in Earth-orbits and other nearby solar system destinations is mainly from photovoltaics (solar arrays)
- Batteries provide energy storage, serve as a power source during eclipses, and can provide peaking power

General properties typically desired in batteries for NASA missions

- Safe
- Lightweight (high specific energy – energy per unit mass)
- Compact (high energy density – energy per unit volume)
- Can meet mission requirements reliably

Some Batteries used in Space

- Rechargeable battery chemistries (reversible chemical reaction)
  - Silver-Zinc (Ag-Zn)
  - Nickel-Cadmium (Ni-Cd)
  - Nickel-Metal Hydride (Ni MH)
  - Nickel-Hydrogen (Ni –H_2)
  - Lithium-ion
- Primary (non-rechargeable) batteries are also used in space
- An example of a reversible reaction in a zinc-chlorine battery:

$$Zn + Cl_2 \rightarrow ZnCl_2$$

Cell Voltage

- Theoretical voltage and capacity of a battery cell, and therefore the energy contained in it, are determined by the anode and the cathode materials.
- For the reaction above the standard cell potential is given by:

$$Zn \rightarrow Zn^{2+} + 2e \qquad 0.76\ V$$

$$Cl_2 \rightarrow 2Cl^{-} - 2e \qquad \underline{1.36\ V}$$

$$E° = \ 2.12\ V$$

- Source: Linden and Reddy, Handbook of Batteries, 3rd ed., McGraw-Hill, New York, 2002.

Cell Capacity

- For the reaction above the theoretical cell capacity is given by:

$$Zn \quad + \quad Cl_2 \quad \rightarrow \quad ZnCl_2$$

(0.82 Ah/g) (0.76 Ah/g)

1.22 g/Ah + 1.32 g/Ah = 2.54 g/Ah or 0.394 Ah/g

- Similar calculations can be done for any anode-cathode pairs

- Source: Linden and Reddy, Handbook of Batteries, 3rd ed., McGraw-Hill, New York, 2002.

Theoretical and Practical Values of Some Battery Chemistries

Chemistry	Anode	Cathode	Theoretical values				Practical values		
			V	g/Ah	Ah/kg	Specific Energy (Wh/kg)	Nominal Voltage (V)	Specific Energy (Wh/kg)	Energy Density (Wh/L)
Silver-Zinc	Zn	AgO	1.85	3.53	283	524	1.5	105	180
Nickel-Cadmium	Cd	Ni oxide	1.35	5.52	181	244	1.2	35	100
Nickel-Metal Hydride	MH*	Ni oxide	1.35	5.63	178	240	1.2	75	240
Nickel-Hydrogen	H_2	Ni oxide	1.5	3.46	289	434	1.2	55	60
Lithium-ion	Li_xC_6	Li (i-x) CoO_2	4.1	9.98	100	410	4.1	150	400

Many factors limit the ability to approach theoretical values – both electrochemically and practically

- Concentration gradients, conductivity, kinetics, side reactions, temperature, etc.
- Cans, containers tabbing, terminals, and safety features, etc. required to package the energy into cells

*Data based on 1.7% hydrogen storage by weight

- Source: Linden and Reddy, Handbook of Batteries, 3rd ed., McGraw-Hill, New York, 2002.

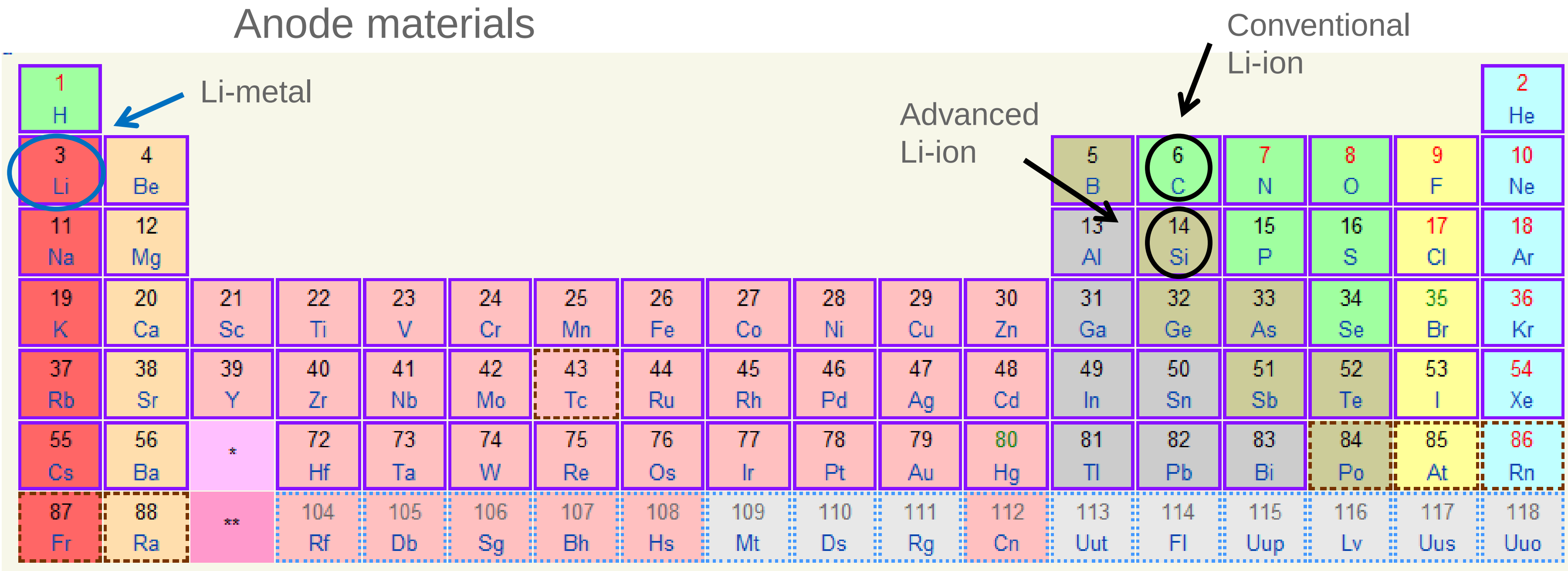
Why Li-ion chemistries?

- Transition to Li-ion due to two factors –
  - Lower operating temperature (enabled 2003 MER exploration rovers to operate on Mars – 1st use of Li-ion batteries as a main power system at NASA!)
  - 2-3 times higher specific energy and energy density
- Heavier batteries limit the kinds of missions we can perform.
  - Batteries are typically 30% of mass of a space power system. Reducing that percentage means:
    - Lower launch mass and potential savings in launch vehicle cost
    - More mass allowances for payloads, fuel, station eeping or other essential vehicle functions.
  - Current space suit backpack containing the battery-powered life support system weighs ~150 lbs.
    - On Earth, astronaut would be carrying their own weight around with them.
    - Currently, astronauts perform space walks from ISS
    - For human missions to the Moon or Mars, we need to reduce this mass significantly to allow a reasonable amount of time for science to be performed (goal of 8 hrs for EVA)

Li metal has the greatest possible specific capacity

- Order-of-magnitude improvement over C
- Two-times greater than Si

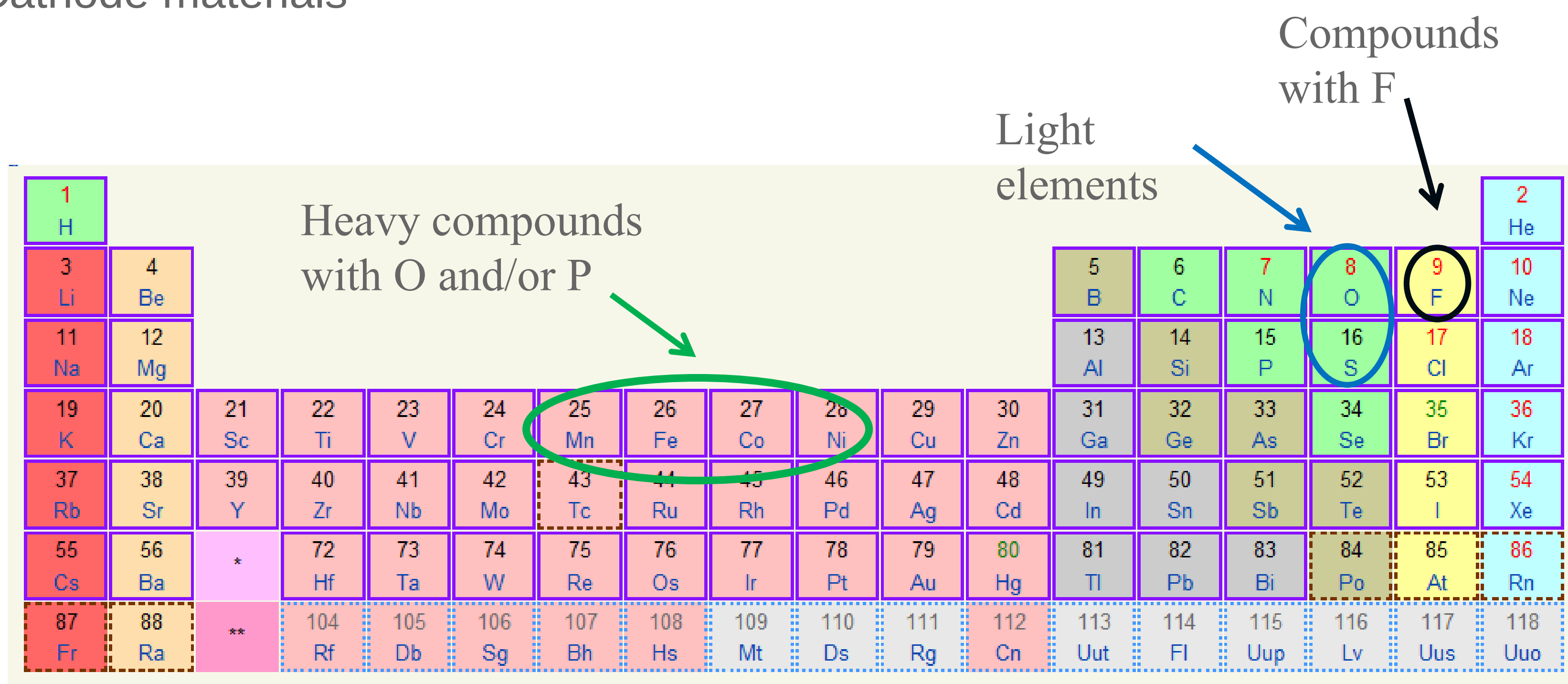
Anode materials



Anodes	Specific Capacity (mAh/g)
C (LiC_6)	334
Si practical ($Li_{15}Si_4$)	1857
Si theor. ($Li_{22}Si_5$)	2012
Li	**3860**

Chemistry dictates the theoretical limits of what advances can be achieved from certain materials

Cathode materials



Cathode	Specific Capacity (mAh/g)
$LiNMCO_2$	274
$LiMn_2O_4$	148
$LiFePO_4$	170
FeF_3	400
$LiFeO_xF_{2-x}$	400
S_8 (Li_2S)	1672
O_2 (Li_2O_2)	1675
O_2 (Li_2O)	3350

- Two-fold gain for fluorine compounds over LiNMC
- Six-fold gain for O and S

Significant breakthroughs are achievable!

NASA Drivers for Very High Specific Energy Batteries

Electric Aviation

- Green aviation – Less noise, lower emissions, high efficiency
- Hybrid / All-electric aircraft – Limited by mass of energy storage system
- Commercial aviation – Safe, reliable, lightweight on-board electric auxiliary power unit
- 500-750 Wh/kg

Extravehicular Activities (Spacesuit power)

Required to enable untethered EVA missions lasting 8 hours within strict mass and volume limitations.

- Astronaut life support
- Safety and reliability are critical
- Requires >400 Wh/kg
- 100 cycles

Landers and Rovers, Robotic missions, In-space habitats

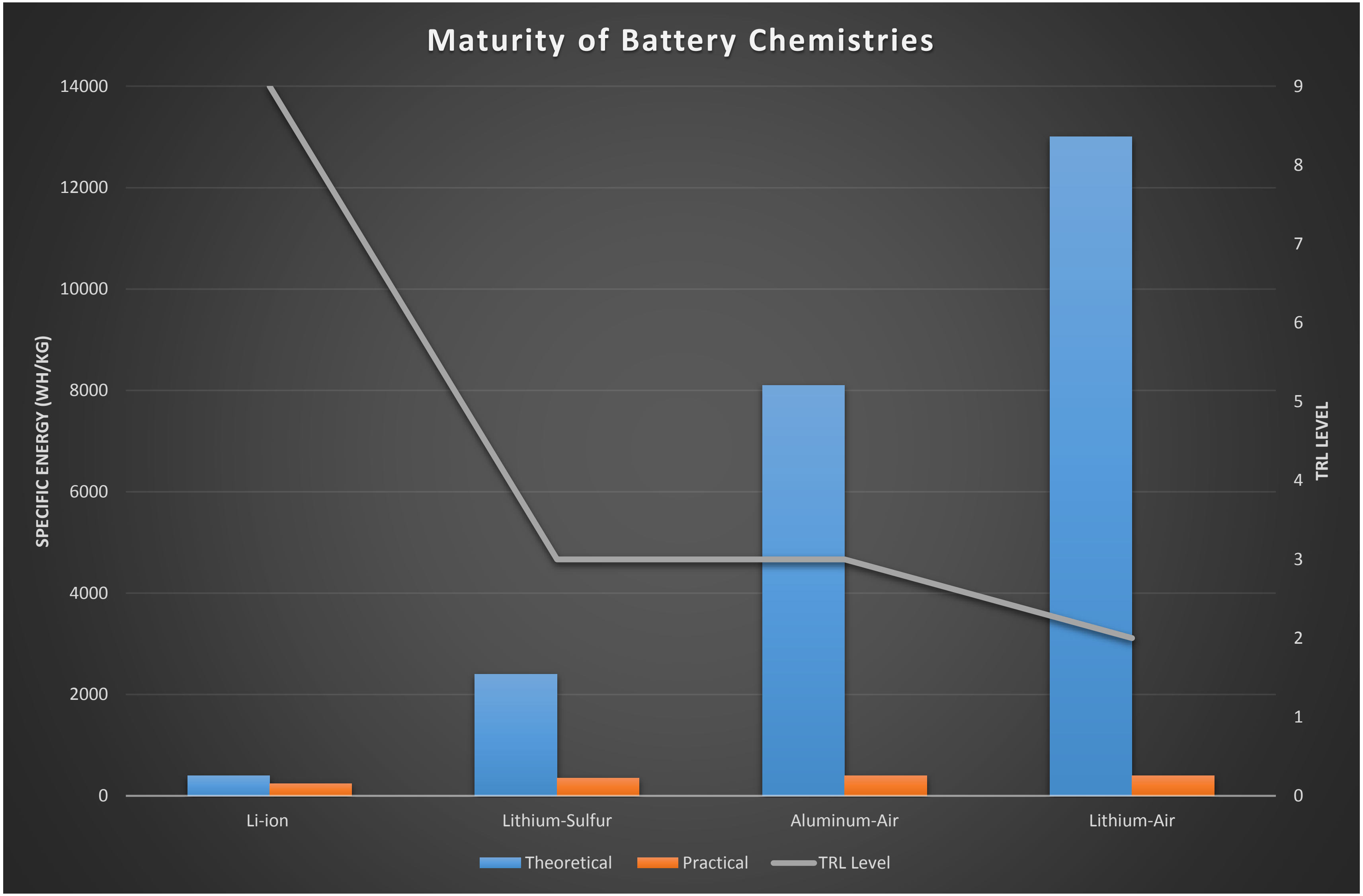
Batteries are expected to provide sufficient power for life support and communications systems, and tools including video and lighting.

- Requires > 500 Wh/kg
- >100 cycles

Requirements far exceed the capabilities of lithium-ion chemistries

➢ Progress in these areas requires advances in safe, very high energy batteries

Some Possibilities for Advanced Battery Chemistries



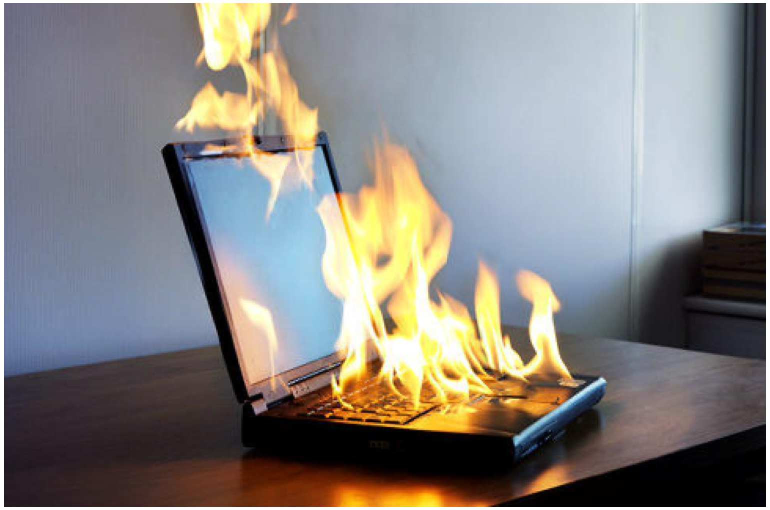
Trade-offs of Implementing Higher Energy Chemistries

- We enjoy the benefits of higher specific energy chemistries, but they are not inherently safe
- We manage cell safety on the battery level
  - Electronics – charge control, cell balancing
  - Mechanical means
- Batteries must be designed to mitigate against a catastrophic fault in one cell
  - Thermal runaway conditions
  - Short circuits
  - Open circuits

Japan Airlines 787 Battery – Exemplar Battery and Aftermath of Jan 2013 Fire Courtesy: NTSB

Benefits of Solid Electrolytes

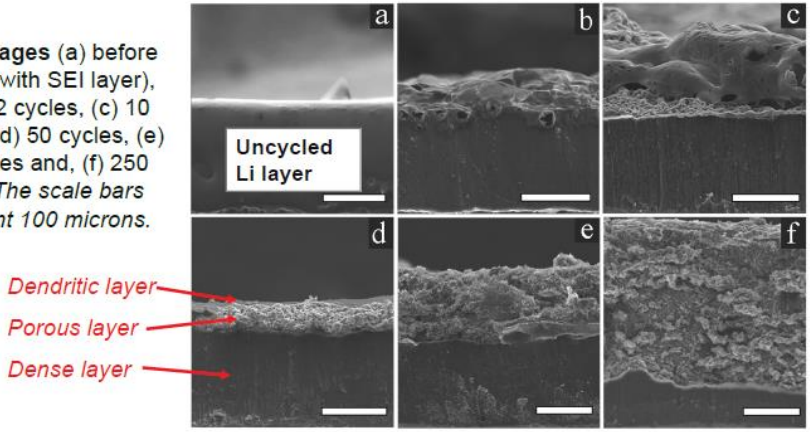
- Can improve inherent safety
  - Non-flammable
    - Replace flammable electrolytes
    - Suppress dendrite formation
      - Li plates unevenly
      - Can result in dendrite formation
      - Dendrite growth creates an internal short circuit hazard
    - Allow for a higher operational temperature limit



Courtesy: Sorensen/Getty

- Can potentially offer advantages over liquid systems for structural battery concepts
    - Multi-functional systems – energy storage and structural benefits

SEM images (a) before cycling (with SEI layer), and (b) 2 cycles, (c) 10 cycles, (d) 50 cycles, (e) 125 cycles and, (f) 250 cycles. *The scale bars represent 100 microns.*

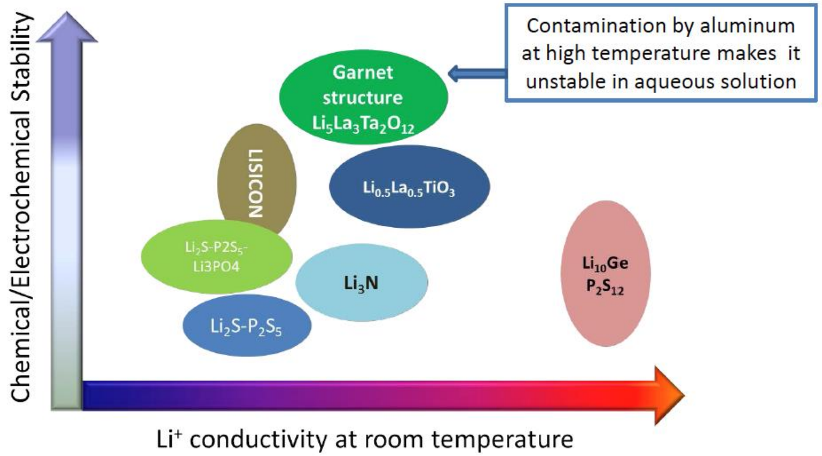


Courtesy: Argonne National Laboratory

Some qualities of a viable solid electrolyte for a Li-metal system

- Stable with Li
- Conducts Li ions
- Good conductivity at room temperature
- Low interfacial resistance (electrode-electrolyte)

Existing Solid Electrolytes



Garnet structure electrolytes are electrochemically stable with a larger window than commercial LISICON® membrane and are not sensitive to water as sulfides, so they are a promising separators for flow-through batteries using aqueous solutions.

The University of Texas at Austin

SHELiB Purpose – Ties to NASA

- SHeLiB is developing solid lithium-ion conducting electrolytes and solid state batteries in conjunction with NASA, the Army, Georgia Tech, and Auburn University.
- SEs have application to both Li-ion and Li-metal batteries and can improve inherent safety of the systems
- Xavier University is involving undergraduate student researchers in this important effort
- There will be many opportunities for technical exchanges among partnering institutions.
- Selected students will have an opportunity to intern at NASA through the grant
- We look forward to seeing the innovative solutions you develop!

Thanks for your attention!