Summary of 2017 NASA Workshop on Assessment of Advanced Battery Technologies for Aerospace Applications

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Key Objectives of the workshop:

• Assess the battery needs for future aerospace missions
• Assess the state of battery technology and projected technology advances
• Assess the need for additional investments for future aerospace missions.

Participants:

• 109 participants, 85 non-NASA
• Leaders from DOE, DOE labs (ANL, PNNL, ORNL), Aerospace companies (Boeing, Airbus, Bell Helicopters, GE, P&W, Honeywell), Automotive companies (GM, Chrysler), Battery manufacturers (cell and pack manufacturers), academia, small businesses (many funded by venture capitalists)

Sessions:

• First day – 19 short (~20 min) overview presentations
• Second day morning – 3 breakout sessions – (1) requirements, (2) chemistry and materials, (3) packing and integration

Primary focus was on batteries for Electrified Aircraft Applications
What is Included in This Presentation

- Findings from the workshop

- Additional facts gathered from multiple sources after the workshop
  - System analysis
  - Recent reviews of battery technology
State-of-the-art: Li-Ion Battery

**SOA:**
- Cell: 250 Wh/kg
- Pack: 150 – 170 Wh/kg

**Potential:**
- Cell: 300 Wh/kg
- Pack: ~200 Wh/kg
Notional Battery Requirements for Different Classes of Aircraft

**Current capability, 150 – 170 Wh/kg**

- 2-3 passenger, CTOL, 200 miles, all electric
- 2 – 3 passenger, VTOL, 40-50 miles, all electric
- 6 – 10 passenger, CTOL, 300 – 600 miles, all electric

**Pack level**

- 250 Wh/kg
- ~400 Wh/kg
- ~600 Wh/kg
- ~1000 Wh/kg

1. 2-3 passenger, CTOL, 200 miles, all electric
2. 4 – 10 passenger, VTOL, 60 – 200 miles, all electric
3. 50 – 70 passenger, CTOL, > 300 miles, all electric
4. 737 type hybrid electric aircraft with at least 900 mile range, CTOL

**Cell level**

- Pack level
- Current capability
- 300 Wh/kg
- 400 - 500 Wh/kg
- > 750 Wh/kg

- Pack level
- 250 Wh/kg
- ~400 Wh/kg
- ~600 Wh/kg
- ~1000 Wh/kg

- Notional Battery Requirements for Different Classes of Aircraft
- Extended range for everything in Box 1
- Extended range for everything in Box 2
- Extended range for everything in Box 3

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Other Requirements in Addition to High Specific Energy

- Specific power (1 kW/kg for most applications, although some applications might require 2-3 kW/kg)
- Cycle life (1000 - 2000 ??)
- Discharge rate (C rating)
- Speed of charging
- Calendar life

System analysis required to identify detailed requirements
Beyond Li-Ion

Maximum cell:
~300 Wh/kg

Maximum cell:
~600 – 700 Wh/kg?

Maximum cell:
~900 – 1000 Wh/kg?

Beyond Li-Ion
**Li Metal With Liquid Electrolyte and Conventional cathode**

**Conventional Li-Ion**
- Claims of 400 – 450 Wh/kg at cell level by startup companies
- Probably low cycle and long-term life (no publicly available data)
- Optimistic claim for commercial introduction in electric vehicles in 2020 (?????) – might need serious interest from a major manufacturer
- Focus of DOE BAT-500 program

**Li Metal**
- Except for Li metal anode, everything else very similar to SOA Li-ion battery

**300 Wh/kg achievable at pack level**

ANL study
Progress to date:
- 300 – 400 Wh/kg achieved at cell level, low cycle life
- 250 Wh/kg at pack level, low cycle life
- 180 Wh/kg at cell level with high cycle life

Challenges:
- Limited cycle life (< 300 cycles)
- High self discharge rate
- Reactions not well understood

Maximum achievable specific energy at pack level is < 500 Wh/kg
Li – Air Battery

- Limited cycle life
- Complex mechanical system for introduction of oxygen
- Maximum achievable specific energy at pack level no better than Li metal with liquid electrolyte and conventional cathode

ANL study
Solid State Lithium Metal Battery

Current Status:
- Significant world-wide interest (Strong belief that solid state is the future) - Eliminates safety challenges associated with liquids, provides better packing and stack designs
- Significant progress made in development of solid ceramic electrolytes with high ionic conductivity
- Solid state battery with solid state polymer electrolyte – 250 Wh/kg at cell level, potential for 400 Wh/kg at cell level (required 180°C operating temperature)

Challenges:
- Interfacial instability and lack of understanding of various interfacial phenomena
- Mechanical stability
- Low cycle life contributed by interfacial and mechanical instability
- Commercially scalable process for manufacturing of thin films
- Development of full cell

Significant Promise
Notional Progression of Battery Capability at Cell Level

Li Metal

- **300 - >500 Wh/kg**
  - Li metal, all solid state

- **400 – 500 Wh/kg**
  - Li metal anode, sulfur cathode, liquid or solid electrolyte
  - Li metal anode, advanced cathode (High Ni - NMC or sulfur), Liquid electrolyte
  - Li metal anode + high temperature polymer electrolyte

Li ion

- **300 Wh/kg**
  - Si anode, advanced cathode (e.g., High Ni), liquid electrolyte

SOA – 250 Wh/kg at cell level
Projected Advances in Battery Technology

Rate of increase in specific energy is typically on the order of 5 – 8% per year
Specific energy loss from cell to pack is typically 50 to 60%

Assuming 8% increase per year at cell level

Innovation required in:
- New chemistries and materials for cells
- Pack design and integration
Key Takeaways

- DOE, battery industry, academia, National Labs will drive to 300 Wh/kg at pack level (~400 Wh/kg at cell level) for automotive and industrial applications, but will not be focused on electric aircraft applications
  - 2022 – 2025 timeframe likely (optimistic ??)
  - Need to demonstrate applicability to aircraft through verification of performance, safety, and integration

- Beyond the 400 Wh/kg capability at cell level, aeronautics community can focus on developing batteries with 600 Wh/kg specific energy at cell level (400 – 500 Wh/kg at pack level), which is achievable and not impossible
  - Not current focus for DOE, battery industry, and national labs

- Specific energy on the order of > 700 Wh/kg at pack level is extremely difficult to achieve with the current knowledge, almost impossible at this time

- Need detailed system level analysis for different classes of aircraft and different missions

Aeronautics community lead is necessary to champion development of aircraft materials, cells and packs
**Potential Scenario for Electrified Aircraft**

### Cell level

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- 6 – 10 passenger, CTOL, 300 – 600 miles, all electric

### Pack level

- 300 Wh/kg
- **400 - 500 Wh/kg**

- 4 – 10 passenger, VTOL, 60 – 200 miles, all electric
- 30 passenger, CTOL, 300 miles, all electric
- 50-70 passenger, CTOL, 300 miles, hybrid electric
- Light utility helicopter, 100 miles, hybrid electric
- Extended range for everything in Box 1

- 50 – 70 passenger, CTOL, > 300 miles, all electric ??
- 100 -150 passenger, CTOL, 300 miles, hybrid electric ??
- VTOL - Multi-mission helicopter, hybrid electric, 100 miles ?
- Extended range for everything in Box 2

### Current capability, 300 Wh/kg

- 250 Wh/kg
- ~400 Wh/kg
- ~600 Wh/kg
- ~1000 Wh/kg
- > 750 Wh/kg

### Extended range for everything in Box 1

- Potentially achievable in 2022-25 timeframe with non-NASA investment
- Need validation for aircraft application

### Extended range for everything in Box 2

- Challenging, but achievable in 2030 timeframe, will need leadership from aeronautics community,

### Extremely challenging, may be impossible with current knowledge

- Extremely challenging, may be impossible with current knowledge

### Extended range for everything in Box 3

- 737 type hybrid electric aircraft with at least 900 mile range, CTOL
- Extended range for everything in Box 3

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Potential for Innovation in Packing and Integration

• Specific energy loss from cell to pack is typically on the order of 30 – 40 %, could be as high as 50% for some applications - opportunity to increase specific energy at pack level through innovation in packing and integration

• Potential concepts:
  – Lightweight container structure (e.g., cellular, lattice block)
  – Multifunctional structures with load carrying capability for packaging materials
  – Advanced thermal management techniques (e.g., phase change materials if cost is not a factor, high conductivity materials)
  – Integrated thermal management – system approach to cool battery packs
  – Polymer heat exchangers
  – Larger cells

• Innovation in battery health management – improved techniques/models (including move to software-based system) for state-of-charge and state-of-health estimation

Aeronautics community needs to lead innovation in packing and integration specific to aircraft applications
Non-Li Battery System to Watch

- Al – air
- Mg – air
- Zn-air
- Flow batteries

Schematic of Flow Battery
Role of Aeronautics Community in Battery Development

- Accelerate development of 300 Wh/kg battery pack (400 Wh/kg cell) for electrified aircraft application by
  - Developing innovative packing technologies
  - Studying safety of battery system and optimizing battery system for safety
  - Generating performance data under aircraft operating conditions and optimizing battery system for balancing performance and safety
  - Developing and validating battery performance and durability models

- Provide leadership for development of 400 – 500 Wh/kg battery pack (600 Wh/kg cell) system leveraging resources in Dept. of Energy, National Labs, battery industry, and academia

- Conduct system analysis to identify battery requirements for various classes of aircraft and various missions