Batteries for Aviation: Technology trajectories - what is the future?

Global Urban Air Summit

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Electrification Research at WMG

Internationally recognised expertise and facilities in energy research. Strong and practical focus, industry-facing expertise, bridging the TRL spectrum. Thought leadership, helping shape the UK government agenda.

Projects across many sectors:

Covers all aspects of Electrification:

Batteries:
Materials, Cell/Module/Pack level characterisation and testing, Cell instrumentation, Module and pack design, Scale-up, analysis & manufacture, Safety / Abuse Testing, Protocols and Standards, Recycling. Able to go from base chemistry through to pack assembly. Forensics.

eMachines:
Materials in manufacture, Design / topologies, Test techniques, Scale-up.

Power electronics:
System design for wide bandgap materials, Power converters, inverters, voltage stabilities, fast /wireless charging, grid balancing, Microgrids.

Modelling and control:
Cell modelling, Vehicle / energy flow modelling, Control algorithm development, Hardware/Software in the Loop, and functional safety.

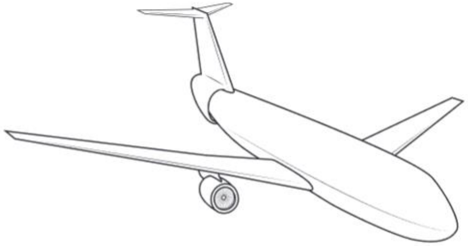
Vehicle Systems:
Propulsion system design and integration, Full vehicle prototype capability, System optimisation, System electrical architectures.

What does Aerospace demand? Is it different to other sectors?

- The same attributes are important across sectors, but with different priorities,
- This means that sub-systems, such as batteries, may not be optimised for aerospace as yet.

Automotive	Cost	Mass	Volume	Life	Safety
Static / Grid	Cost	Mass	Volume	Life	Safety
Marine	Cost	Mass	Volume	Life	Safety
Aerospace	Cost	Mass	Volume	Life	Safety
Consumer	Cost	Mass	Volume	Life	Safety

Power and Energy Requirements for Aerospace

Category	Urban Air Transport (new market)	Sub-regional small commercial air transport (new)	Midsize commercial air transport (existing market)	Large air transport (existing market)
				
Power requirement	150-200kW	2MW propulsive	22MW propulsive	60MW propulsive
Energy requirement	1C	0.2C	0.4C	0.2C
Non-propulsive energy requirement	5-10 kWh	0.1-0.3 MWh	1-6 MWh	8-30 MWh
Number of passengers	1-5	9-20	120-200	240-500
Range	30 miles + limited divert	300 miles + divert	800 miles + divert	3000 miles + divert
All-up weight	30C	3C	2C	0.5C
Recharge/refuel time				

Source: ATI Insight_07 – Electrical Power Systems

The **C-rate** is a measure of the **rate** at which a battery is being discharged. It is **defined** as the discharge current divided by the theoretical current draw under which the battery would deliver its nominal rated capacity in one hour. A 1C discharge **rate** would deliver the battery's rated capacity in 1 hour.

ENERGY CELLS

- State of the art Li-Ion 280 Wh/kg, 480 Wh/l
  - 1390T battery, 100m^3
- Lithium Sulfur (ultimate) 500Wh/kg
  - 780T battery (similar volume)

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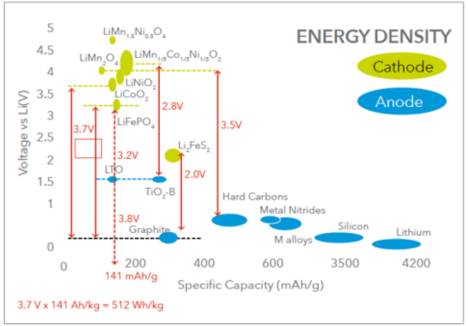
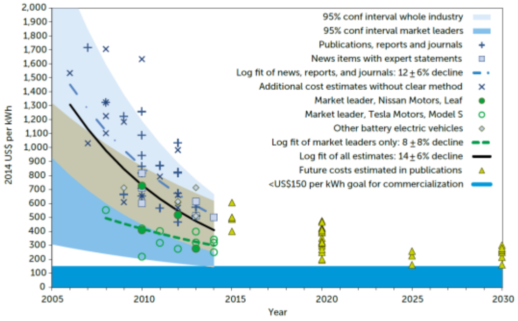
POWER CELLS

- State of the art Li-Ion 5kW/kg, 11kW/l
  - 1T battery, 2m^3
- 50C rating – research aiming 200C
  - 250kg, 1m^3 ?

Automotive Battery Status?

- Currently settled on Li-Ion family of chemistries:
  - Can be tailored for high power or high energy – not both.
  - Volumetric density increasing - 700+ Wh/l
  - Gravimetric density 280 Wh/Kg.
- No consensus on cell format:
  - Pouch – Highest power/energy density at cell level, but need more structure. Cooling can be an issue for high power.
  - Cylindrical – highly developed, standard sizes, mechanically self supporting, but relatively heavy.
  - Prismatic – Non standard, can be good for volume utilisation.
- Cost is critical in Automotive:
  - Battery is most expensive part of vehicle.
  - Pack cost fallen $1000/kWh to <250kWh in 8 years.
- Thermal management is required for safety:
  - Most chemistries have thermal runaway potential.
  - This is managed with battery management system and physical enclosures.
  - Step out of vehicle and retire to safe distance in the unlikely event of an incident.

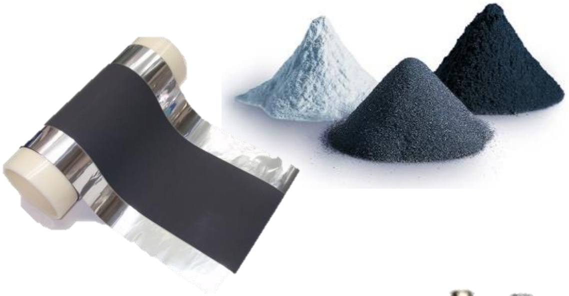




Aerospace needs developments at material, cell, module and pack level

Material

- Development of higher power materials (driven by charging times)
- Development of higher energy density materials (driven by pack weight)
- Emerging chemistries (solid state) driven by safety and energy density



Cell

- Format and form factor (pouch, cylindrical or prismatic)
- Durability with pressure cycling
- Availability in ‘low’ volume at high quality
- Cell quality & traceability
- Balanced power & energy density (kW/kg , kWh/kg) to meet mission profile

Pack

- Lightweighting – minimise cell to pack mass ratio
- BMS – cell / system monitoring , diagnostics and failure prevention
- Creepage and Clearance (for higher voltages > 800V)
- SAFETY – standards development, functional safety concepts, pack system development & validation
- Distributed modules / battery concepts for system redundancy, package flexibility & thermal propagation mitigation.
- Thermal management – to optimise usable energy & charging power versus life

Promising Chemistry for Aerospace

Type	Advantages	Disadvantages
$LiFePO_4$ Cathode Lithium Iron Phosphate	• **Inherently safe; tolerant to abuse** • Acceptable thermal stability • High current rating • Long cycle life	• Lower energy density due to low operating voltage and capacity (about 14% less than $LiCoO_2$ battery)
LTO Anode Lithium Titanate	• Withstands fast charge/discharge rates • **Inherently safe** • Long cycle life	• Lower energy density compared to • graphitic anodes • Cost
Li-S Lithium Sulphur	• High theoretical gravimetric energy density • Sulphur is a low cost, abundant material • **Improved safety**	• Poor volumetric energy density • Issues with power density and discharge rate • Issues with cycle life stability
Solid State Batteries	• Solid electrolyte and separator components; no concerns over 'leakage' • **Improved safety** due to lack of liquid electrolyte • High operating voltages increase potential energy density • Lighter and more space efficient; less need for cooling	• Poor conductivity • High volume manufacturing at acceptable cost

No Silver bullet

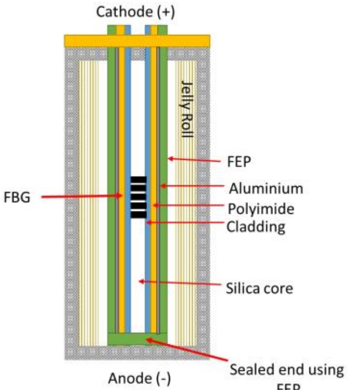
Smart Cells – Initially R&D tool or Product for Aerospace

Fibre Optics -Internal Temperature Measurement & more

- Gives active material temperature rather than case temperature
- Allows operation closer to maximum safe limits
- Senses early onset failure

Reference electrode

- Allows anode and cathode voltage to be measured independently
- Provides insight on failure modes such as lithium plating, dendrite formation
- Allows higher power operation by operating up to (but still within) safe limits



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Smart Cell research

- Embedded sensing, internal diagnostics & coms over power line with its own power switching capability.
- WMG Unique capability to manufacture cells into packs with imbedded instrumentation.

If you know what is happening inside the cell you can operate it up to limits safely and extend existing chemistry capability

Battery Mass

- **Only about half of a battery is active chemistry.**
- A battery pack includes:
  - **Enclosure** – to contain and protect the cells and also manage thermal events.
  - **Internal brackets** – to support modules/cells.
  - **Battery management system** – to monitor and manage the cells/modules to ensure safe operation and battery life.
  - **Contactors** – To isolate/connect battery from HV distribution during normal operation.
  - **Cooling / Heating system** – to keep the cells at optimum temperature.
  - **Bus bars / Electrical distribution** – to connect the cells/modules electrically.
  - **Service Disconnect** – to manually isolate battery.
  - As well as the **cells / modules** themselves.
- Taking mass out of the battery is not all about greater energy density in the cells
  - Pack energy density about half that of cells alone.

Lots of opportunity to remove mass through optimised design with existing chemistry through good engineering.

Safety – Aerospace requires a different approach

- Safety is a whole system attribute and electrification brings different hazards that must be mitigated.
- Automotive approach does not work with Aerospace:
  - Single point of failure (e.g. single battery, HV distribution, e-motor).
  - Safe State = shut down (coast to side of road and exit vehicle).
- Safety standards for electrified aerospace are still evolving.
  - Approach will be at component level, system level and operational level – these will interact – **Multilevel approach needed.**
  - Example Battery Fire:
    - **Component:** Less reactive chemistry, physical enclosure.
    - **System:** Redundant battery systems, fire suppression.
    - **Operational**: Safe landing sites along route, time to land, procedures on ground.
- Electrification also brings benefits to offset risks, for example distributed (redundant) systems.

Risk Severity= Probability x Consequence
High, Medium, Low

Hazard Description	Multirotor	DEP Powered Lift	Powered Lift	Fixed Wing
Battery Thermal Runaway	High	High	High	High
Battery Energy Uncertainty	High	High	Medium	Medium
Common Mode Power Failure (Low-/High-Altitude)	High/High	High/Medium	Medium/Medium	Medium/ Medium
Fly-By-Wire System Failure	High	High*	Low**	Low
High-Level Autonomy Failure	High	High	High	High
Bird Strike	Medium	Medium	Medium	Medium

*Including Tilt-Lift vehicles **Except Tilt-Lift vehicles

Source: Report No. ICAT-2018-07 June 2018 MIT International Center for Air Transportation (ICAT)

And Don’t Forget – It is not ALL about the battery

- It is not all about getting more power or energy out of the battery but also about **needing less power or energy** to complete the mission.
- If you can make the aircraft 5% more efficient you need 5% less energy to do the job.
- Need to look at the whole system to understand where your losses are and where opportunities may be.
  - This is something aerospace is already very good at.
  - The cost to gain 5% overall efficiency may be lower than 5% bigger battery.
- Not just about propulsion also about efficient ancillaries:
  - Cabin heating / cooling.
  - Landing gear.
  - Flight surface control.
  - **Electrification can help here as well.**

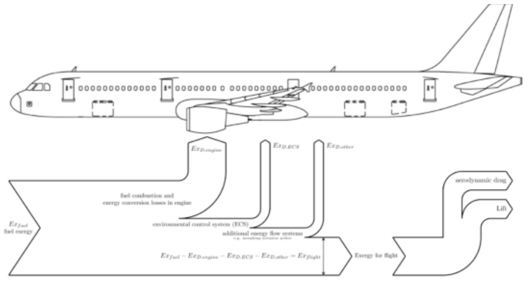

Fig. 12. Grassmann diagram for the exergy flow through an aircraft, highlighting irreversibility locations.

Progress in Aerospace Sciences 93 (2017) 73–94

However, remember the more optimised you are for a given mission profile the less flexible your product is.

Summary

- Batteries for other sectors not optimised for Aerospace:
  - Power capability okay, but gravimetric energy density needs improvement
  - Automotive safety approach cannot carry over to aerospace
- New Chemistries:
  - Can deliver thermal stability but at expense of energy/power currently.
  - No silver bullet and not an immediate solution.
- There is still lots you can improve whilst using existing chemistry:
  - Pack design to reduce weight. You are good at this!
  - **Instrumented / smart cells to deliver safety and improve performance.** Other sectors can't afford the costs, but can't afford not to do it.
  - Overall system efficiency gains through design. Again, aerospace is very good at this.
- Safety approach needs to be multilevel.
  - Cannot consider battery in isolation.

POWERING UP AEROSPACE

WMG
THE UNIVERSITY OF WARWICK

ON-AIRCRAFT ELECTRIFICATION

- Battery development and concept design
- Specialist battery V&V / safety testing
- System level architecture and optimisation
- Power electronics, electric machines
- Supporting supply chain development

CYBER SECURITY AND SOFTWARE

- Cyber security
- Connectivity and wireless communication
- Functional safety
- Control algorithm design and standards development

AIRSIDE

- Autonomous, electrified and connected ground vehicles
- Supporting infrastructure
- Green airports

CHARGING/POWER INFRASTRUCTURE

- Smart system infrastructure and optimisation
- Grid and load balancing
- Power electronics selection and design
- Energy storage and generation systems