# ADVANCED MATERIALS

## A Key Enabler for Zero-Carbon Emission Commercial Flight

FLY ZERO

AEROSPACE TECHNOLOGY INSTITUTE

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# ABOUT FLYZERO

Led by the Aerospace Technology Institute and backed by the UK Government, FlyZero began in early 2021 as an intensive research project investigating zero-carbon emission commercial flight. This independent study has brought together experts from across the UK to assess the design challenges, manufacturing demands, operational requirements and market opportunity of potential zero-carbon emission aircraft concepts.

FlyZero has concluded that green liquid hydrogen is the most viable zero-carbon emission fuel with the potential to scale to larger aircraft utilising fuel cell, gas turbine and hybrid systems. This has guided the focus, conclusions and recommendations of the project.

This report forms part of a suite of FlyZero outputs which will help shape the future of global aviation with the intention of gearing up the UK to stand at the forefront of sustainable flight in design, manufacture, technology and skills for years to come.

To discover more and download the FlyZero reports, visit **ati.org.uk**

# ACKNOWLEDGEMENTS

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# EXECUTIVE SUMMARY

Materials scientists and engineers are critical to the FlyZero mission, providing the fundamental research, development and qualification of advanced materials that will enable the transition to zero-carbon emission commercial flight. The development of materials is an area of strength for the UK and the FlyZero project has used this capability to commission a number of in-depth reports to assess key areas of materials technology. These reports cover both new areas for aerospace, such as high temperature superconducting materials and next generation semiconductors, as well as the evolution of existing areas, such as magnetic materials and carbon fibre reinforced polymer technology. This report makes three key strategic recommendations:

## Establishment of New, UK-Based, Hydrogen Materials Test Facilities

There are currently no UK facilities capable of conducting mechanical tests in hydrogen environments, across a range of temperatures, at the scale required. New, UK-based, materials test facilities will be needed to requalify existing materials and coatings, and to qualify new ones. New test standards will also be needed to meet the specific requirements of commercial aerospace.

## Funding of Research and Development in the UK for Materials in Hydrogen Environments

Hydrogen, the smallest atom, can diffuse rapidly into most engineering materials often causing a significant negative impact on their mechanical properties. Greater research emphasis on the interaction of hydrogen will be needed before advanced materials, developed specifically for use in hydrogen containing environments, can be developed. The UK could generate its own datasets for existing and new materials, enabling wider innovation in the supply chain.

## Putting Sustainability and Responsible Value Chains at the Centre of Decision Making

Sustainability is a global priority, and the aerospace industry is likely to be subject to increasing regulatory pressure to ensure that its products are recyclable, feature low embedded carbon materials and use energy efficient, low waste processing and production technologies. It is vital that the materials used in aerospace are responsibly sourced, limiting environmental impacts, minimising greenhouse gas emissions, respecting human rights and supporting local communities. Companies need to ensure sustainability and environmental & social lifecycle requirements are being set and adhered to throughout their supply chains.

This report also highlights ten core materials challenges that exist across several aircraft systems (referred to on the FlyZero project as 'technology bricks') which are considered to be critical enablers for hydrogen powered aircraft. Solutions to the challenges discussed in this report are yet to be qualified for use in aerospace. The adoption of hydrogen as the preferred zero-carbon emission aviation fuel has the most significant impact from a materials perspective. Additionally, whilst some of the challenges are specific to hydrogen powered commercial flight (e.g. lightweighting of liquid hydrogen tanks) others are equally transferable to kerosene and Sustainable Aviation Fuel (SAF) (e.g. reducing costs for the qualification of new composites).

| *Technology Brick* | *Core Materials Challenges* |
|---|---|
| *Hydrogen Fuel System and Tanks* | *Lightweighting of liquid hydrogen tanks* |
| | *Development of solid-state storage of hydrogen* |
| *Hydrogen Gas Turbines* | *Requalification of existing materials for use in hydrogen gas turbines* |
| | *Coatings optimised for hydrogen combustion* |
| *Fuel Cells and Batteries* | *Novel battery chemistry development* |
| *Power Electronics, Machines and Devices* | *Enhanced magnetic materials for megawatt-class machines* |
| | *Replacement of silicon semiconductors* |
| | *Harnessing superconductivity* |
| *Aerodynamic Structures* | *Multifunctional composites* |
| | *Reducing costs for the qualification of new composites* |

*Image © ATI*

# INTRODUCTION

## Materials science is a key enabler for zero-carbon emission commercial flight, providing the alloys, ceramics, polymers and composites with which to realise engineering solutions. This report aims to highlight the main areas of challenge and opportunity for the UK's materials science community.

This report highlights ten core materials challenges for research, development and innovation in materials which have been identified throughout the course of the FlyZero project through a combination of workshops and in-depth Materials Technology Position Papers[1] commissioned by the project from leading UK subject matter experts. These position papers are available via download from **www.ati.org.uk**. If acted upon, these core materials challenges represent a significant opportunity for the UK to lead on materials innovation for zero-carbon emission commercial flight. Beyond the core challenges additional opportunities for each technology brick have also been identified.

| *Core Materials Challenges* | | *Section of this report* |
|---|---|---|
| *1* | *Lightweighting of liquid hydrogen tanks* | 1.1 |
| *2* | *Development of solid-state storage of hydrogen* | 1.2 |
| *3* | *Requalification of existing materials for use in hydrogen gas turbines* | 2.1 |
| *4* | *Coatings optimised for hydrogen combustion* | 2.2 |
| *5* | *Novel battery chemistry development* | 3.1 |
| *6* | *Enhanced magnetic materials for megawatt-class machines* | 4.1 |
| *7* | *Replacement of silicon semiconductors* | 4.2 |
| *8* | *Harnessing superconductivity* | 4.3 |
| *9* | *Multifunctional composites* | 5.1 |
| *10* | *Reducing costs for the qualification of new composites* | 5.2 |

The ATI FlyZero project has identified liquid hydrogen as the zero-carbon emission fuel with the greatest potential to scale to large (regional to midsize) commercial aircraft **[1]**. Liquid hydrogen provides a significant materials technology challenge, see *"Hydrogen Fuel System and Tanks"* (**Section 1**) and *"Hydrogen Gas Turbines"* (**Section 2**). The further electrification of flight provides opportunities for *"Fuel Cells and Batteries"* (**Section 3**) and *"Power Electronics Machines and Devices"* (**Section 4**). The continued evolution of composites and their utilisation in newly developed *"Aerodynamic Structures"* (**Section 5**) is key to enabling zero-carbon emission commercial flight.

[1] *See Appendix A for full list of the Materials Technology Papers commissioned as part of the FlyZero project.*

# 01.
# HYDROGEN FUEL SYSTEMS AND TANKS

**The accommodation of large liquid hydrogen tanks and the associated cryogenic fuel distribution system represents the biggest change to conventional aircraft architecture associated with a liquid hydrogen powered aircraft. Materials challenges associated with these systems are significant with the effect of hydrogen a key factor that needs to be considered in addition to cryogenic temperatures.**

## 01.1
## CORE MATERIALS CHALLENGE: LIGHTWEIGHTING OF LIQUID HYDROGEN TANKS

The reduction in weight of liquid hydrogen tanks is seen as a key driver for liquid hydrogen powered aircraft [2], however, materials selection is a complex issue. There are several materials technologies that could be used singly or in combination to meet the requirements.

*Box 1:*
*Mechanical Testing at Cryogenic Temperatures*

*Mechanical property allowables of materials at cryogenic temperatures are yet to be established. The effect of hydrogen at cryogenic temperatures is thought to be less than at higher temperatures but also needs to be considered. Cooling of test pieces can be achieved by a number of methods. However, an emphasis is needed on increasing the rate at which mechanical tests can be carried out.*

Existing alloys based on aluminium offer a route to qualification on shorter timescales with a route to lightweighting achieved through the use of low-density aluminium-lithium alloys or new alloys designed for this specific purpose.

Carbon-fibre reinforced plastic composites offer a reduction in weight compared to aluminium alloys and have been used extensively for high pressure hydrogen storage tanks. However, there is a propensity for existing grades to suffer microcracking when cycling between ambient and cryogenic temperatures. For liquid hydrogen tanks to become a reality, new resin formulas will need to be developed and composite systems designed to resist microcracking. The assumption is that any composite tank would require an inner liner/coating to prevent the escape of hydrogen.

Further lightweighting through the use of metal matrix composites, as well as multi-material hybrid solutions (for instance carbon fibre overwrap of metallic tanks) are of significant interest and require further investigation.

Irrespective of the material of construction, any material selected will need to be qualified (**Box 1** and **Box 2**) and fundamental understanding of the materials behaviour will be needed to inform lifing model predictions and guide the requirement for monitoring and inspection. Failure mechanisms related to fatigue and crack growth are of significant interest. Materials down-selection prior to full qualification in a representative hydrogen environment may be accelerated by proxy testing, for example pre-soaking of coupons in hydrogen and/or testing in a non-hydrogen cryogenic environment may be appropriate.

Readers interested in more information can refer to the following Materials Technology Position Papers commissioned by FlyZero:

| | |
|---|---|
| *Carbon Fibre Composites for Liquid Hydrogen Powered Aerospace* | *FZ_RB_0007* |
| *Alloy Compatibility in Hydrogen* | *FZ_RB_0013* |
| *Coating and Insulation for Liquid Hydrogen Powered Aerospace* | *FZ_RB_0017* |

*Figure 1 – The FlyZero midsize concept aircraft with hydrogen tanks highlighted in green (source © ATI).*

# UK Capability Snapshot in Materials for Liquid Hydrogen Tanks

The UK is home to at least two major aerospace companies developing liquid hydrogen for aerospace, both with significant materials capability. Airbus is developing solutions to liquid hydrogen powered commercial flight with its ZEROe demonstrator. Its site in Bristol is its main location for fuel systems design globally. GKN Aerospace is leading the ground-breaking H2GEAR project, a UK collaboration to develop a liquid hydrogen propulsion system for sub-regional aircraft, which could then be scaled up to larger aircraft. The UK has strong research capability in composite materials and manufacture of composites components. The UK capability for new aluminium alloy development is hampered by the lack of UK based companies in this area. However, TISICS (based in Farnborough) are investigating the use of aluminium alloy metal matrix composite tanks for hydrogen storage.

| *Universities* | *Industry* | *Research Technology Organisations* |
|---|---|---|
| • *University of Bath (Professor Richard Butler, Professor Tim Mays)*[2]<br>• *Cranfield University* | • *Airbus UK*<br>• *British Cryogenics Council*<br>• *GKN Aerospace*<br>• *HSE*<br>• *Reaction Engines*[3]<br>• *TISICS* | • *National Composites Centre (NCC)* |

*Table 1 – Examples of UK organisations with capability relevant to the materials challenges associated with liquid hydrogen tanks, gathered through engagement over the course of FlyZero, between March 2021 and January 2022.*

[2] *Authors of the FlyZero "Carbon Fibre Composites for Liquid Hydrogen Powered Aerospace" FZ_RB_0007*
[3] *Author of "Alloy Compatibility in Hydrogen" FZ_RB_0013*

# 01.2
# CORE MATERIALS CHALLENGE: DEVELOPMENT OF SOLID-STATE STORAGE OF HYDROGEN

Work carried out within the FlyZero project assessed the suitability of a range of materials groups for the storage of hydrogen in the solid-state. There is great potential for these materials to capture hydrogen that has leaked or boiled-off. However, even for the best performing sorbents and hydrides the hydrogen gravimetric capacities are only 15% of the total system mass and a solid-state based system is, therefore, unlikely to compete with liquid hydrogen as a primary fuel carrier. The relative merits of each material group have been summarised in **Table 2** against the following scoring criteria: temperature and pressure of operation and gravimetric and volumetric efficiency.

Novel systems, which utilise Kubas binding of hydrogen (e.g. Kubas Manganese Hydride-1/KMH-1) have very high volumetric capacity which could allow for a combined liquid/solid hydrogen system that allows for the volumetric limit of liquid hydrogen systems to be exceeded at the expense of gravimetric capacity.

| *Meterial Type* | *Presure [bar]* | *Temp. [K]* | *Gravimetric [wt.%]* | *Volumetric* $[gH_2L^{-1}]$ |
|---|---|---|---|---|
| *Sorbents* | 2 | 3 | 1 | 2 |
| *Interstitial hydrides* | 1 | 1 | 3 | 1 |
| *Binary ionic hydrides* | 1 | 2 | 2 | 2 |
| *Complex hydrides* | 1 | 2 | 2 | 2 |
| *Chemical hydrides* | 1 | 2 | 1 | 2 |
| *Reactive hydrides* | 1 | 3 | 2 | 1 |
| *Novel systems* | 2 | 1 | 1 | 1 |

*Table 2 – Potential material types for solid state hydrogen storage. Where the capability against each metric has been scored as (1) Good, (2) Average or (3) Poor.*

Readers interested in more information can refer to the following Materials Technology Position Paper commissioned by FlyZero:

| | |
|---|---|
| *Material Based Hydrogen Storage for Aerospace* | *FZ_RB_0011* |

# UK Capability Snapshot in Material Based Hydrogen Storage

With new materials frequently being discovered this is an active area of research, however, commercial aerospace represents a new avenue for the research community. A supply chain does not currently exist for the manufacture of these materials on an industrial scale.

| *Universities* |
|---|
| • *University of Bath (Professor Tim Mays)*[4]<br>• *University of Birmingham*<br>• *University of Bristol*<br>• *Lancaster University*<br>• *University of Manchester*<br>• *University of Nottingham* |

*Table 3 – Examples of UK organisations with capability relevant to the materials challenges associated with material-based hydrogen storage, gathered through engagement over the course of FlyZero, between March 2021 and January 2022.*

*[4] Authors of FlyZero Report "Material Based Hydrogen Storage for Aerospace" FZ_RB_0011*

*Image © ATI*

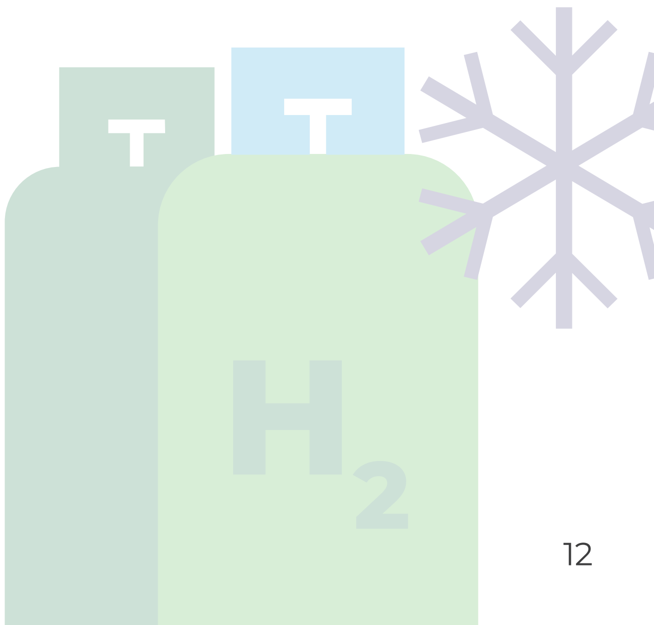
# 01.3
# ADDITIONAL OPPORTUNITIES FOR HYDROGEN FUEL SYSTEMS AND TANKS

Beyond the core challenges the following are also considered to be of significant importance:

- **Advanced insulation systems:** Required to have low thermal conductivity, low emissivity and low density. For vacuum insulated tanks, multi-layer insulation (MLI) systems, comprising alternating layers of BoPET (biaxially-oriented polyethylene terephthalate, better known as Mylar®) and polyester, offers thermal radiation performance in the high-vacuum gap. For single wall tanks, or around complex geometries where maintaining a vacuum is not practicable, MLI is not suitable and closed-cell, polyisocyanurate, spray-on foam insulation is the incumbent technology. The development of flexible aerogel products and their use as spacer layers for advanced MLI's could offer significant performance improvements. For additional information see the Materials Technology Position Paper "Coating and Insulation for Liquid Hydrogen Powered Aerospace" FZ_RB_0017.

| | |
|---|---|
| *Coating and Insulation for Liquid Hydrogen Powered Aerospace* | *FZ_RB_0017* |

- **Cryogenic sealing technology:** Capable of repeated thermal cycling from ambient to -253°C.
- **The use of coatings to prevent hydrogen diffusion.** Metallic, polymer or ceramic coatings all have potential utilisation.
- **Lightweighting of fuel distribution system:** The initial FlyZero design has utilised stainless steel grade 316L, with which has relatively low thermal conductivity and high stiffness. Future improvements should focus on weight reduction.



# 02. HYDROGEN GAS TURBINES

**The adoption of hydrogen as the preferred zero-carbon emission aviation fuel has potentially significant impacts on materials and coatings selection for the hot section of a hydrogen burning gas turbine. The expectation will be that current materials and coatings, which have been optimised for kerosene combustion, will be suitable. However, this will need to be assessed with requalification and new solutions developed if required.**

## 02.1 CORE MATERIALS CHALLENGE: REQUALIFICATION OF EXISTING MATERIALS FOR USE IN HYDROGEN GAS TURBINES

Nickel-based superalloys provide the main materials of construction of the hot section, which includes the combustor and turbine, of aerospace gas turbines. The level of exposure to hydrogen is yet to be established and for some components may only occur in a fault scenario. However, superalloys exhibit a wide range of responses to hydrogen exposure which can be dependent not only chemical composition but also the heat treatment used during manufacture. The sensitivity of existing nickel-based materials may require new alloys that are resistant to hydrogen to be developed in particular for uncoated components. It may also make the selection of other high temperature alloys or ceramic matrix composites more attractive.

*Box 2:*
*Materials Testing in Hydrogen Environments*

*Testing in hydrogen environments at a range of temperatures will be needed to qualify materials for service. Although testing samples pre-exposed to hydrogen (but tested conventionally) may offer some initial insight, ultimately, testing in a representative environment will be required.*

Once the appropriate level of hydrogen exposure is established for each component, it will be necessary to reassess existing materials in the new environment (**Box 2**). New stress allowables will need to be generated or else knock-down factors applied to account for the presence of hydrogen.

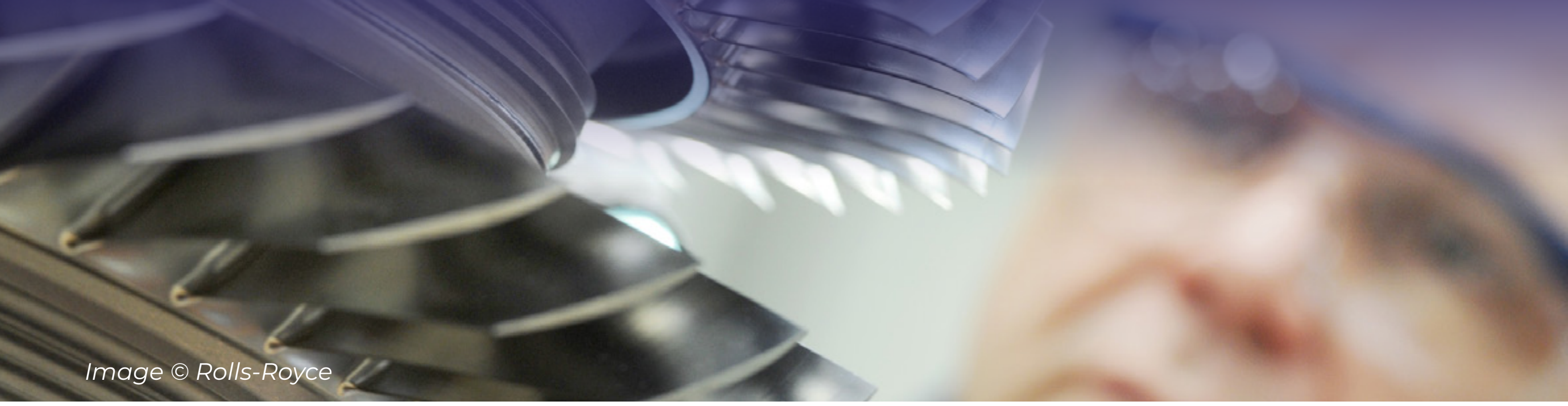


*Image © Rolls-Royce*

Readers interested in more information can refer to the following Materials Technology Position Paper commissioned by FlyZero:

| | |
|---|---|
| *Alloy Compatibility in Hydrogen* | *FZ_RB_0013* |

## UK Capability Snapshot in Nickel-based Superalloys

The UK network of Rolls-Royce University Technology Centres have a long history of nickel-based superalloy development and would be well placed to understand the potential impact of hydrogen on these materials and mitigate against it.

| *Universities* | *Industry* |
|---|---|
| • *Imperial College London*<br>• *University of Birmingham*<br>• *University of Cambridge*<br>• *Swansea University*<br>• *University of Oxford* | • *Rolls- Royce* |

*Table 4 – UK organisations with capability relevant to the materials challenges associated with nickel-based superalloys, gathered through engagement over the course of FlyZero, between March 2021 and January 2022.*

# 02.2 CORE MATERIALS CHALLENGE: COATINGS OPTIMISED FOR HYDROGEN COMBUSTION

Modern gas turbines utilise an array of coatings to protect the underlying material from the effects of corrosion and oxidation, to improve performance and increase the time between maintenance repair and overhaul. In common with nickel-based superalloys, these coatings have been optimised over several decades for the combustion of kerosene.

The environment these coatings will find themselves in will be altered in a hydrogen burning gas turbine. The effect of hydrogen as well as increased levels of water vapour (more than 250% compared to kerosene combustion) will need to be understood. All existing coatings (including environmental barrier coatings, thermal barrier coatings, wear coatings and abradable coatings etc.) may need to be requalified and new coating systems developed.

Readers interested in more information can refer to the following Materials Technology Position Paper commissioned by FlyZero:

| | |
|---|---|
| *Coating and Insulation for Liquid Hydrogen Powered Aerospace* | *FZ_RB_0017* |

## UK Capability Snapshot in Gas Turbine Coatings

The UK's surface engineering experts are connected via the Institute of Materials, Minerals and Mining (IOM3) Surface Division and the Thermal Spraying and Surface Engineering Association (TSSEA) which have good links with industry. There are a number of coatings providers based in the UK, some of whom are global players in surface engineering technologies, equipment, and coating consumables, as well as providing coating services. By combining the efforts of centres of excellence in materials, surface engineering, corrosion and interfaces, the UK has the potential expertise to lead the world on coatings for liquid hydrogen gas turbine coatings.

| *Universities* | *Industry* | *Research Technology Organisations* |
|---|---|---|
| • *Cranfield University*<br>• *University of Manchester*<br>• *Nottingham University* | • *Rolls- Royce* | • *TWI*[5] |

*Table 5 – Examples of UK organisations with capability relevant to the materials challenges associated with gas turbine coatings, gathered through engagement over the course of FlyZero, between March 2021 and January 2022.*

[5] *Author of "Coating and Insulation for Liquid Hydrogen Powered Aerospace" FZ_RB_0017*

# 02.3 ADDITIONAL OPPORTUNITIES FOR HYDROGEN GAS TURBINES

Beyond the core challenges the following are also considered to be of significant importance:

- **Heat exchangers:** Will require testing and qualification of alloys for high temperature hydrogen applications at temperatures ranging from -253˚C to 500˚C and pressures ranging from ambient to 100bar. For increased performance, tube wall thicknesses will need to be reduced to the extent that the mechanical properties of the bulk material may no longer be representative. Improvements in the understanding of micromechanical properties and the development of tools to measure mechanical properties at the microscale are required.
- **Reducing engine weight:** To realise the full potential of a hydrogen powered aircraft reduction in engine weight through advanced materials technology is critical.

*Image © ATI*

# 03. FUEL CELLS AND BATTERIES

**Proton Exchange Membrane fuel cells have potential as primary power for sub-regional and regional aircraft and as an auxiliary power unit on all aircraft sizes. Batteries have potential as primary power for sub-regional aircraft and can provide additional auxiliary power. Much of the research emphasis in both areas is heavily influenced by the automotive sector which has different requirements to aerospace. Although no core materials challenge has been selected for fuel cells, interesting areas for research are identified in Section 3.2.**

## 03.1 CORE MATERIALS CHALLENGE: NOVEL BATTERY CHEMISTRY DEVELOPMENT

The primary limiting factor in battery cells is the gravimetric energy density. Batteries have potential for primary power for sub-regional aircraft, but the gravimetric energy density is significantly lower than that required for a battery-electric regional aircraft with current cell chemistries. However, batteries can be used as part of a hybrid system with a fuel cell or gas turbine, providing peak power to enable take-off.

For significantly improved battery powertrain performance two battery chemistry combinations have been identified as being of significant interest in the near term. Through a novel, quantitative down selection methodology carried out as part of the FlyZero project lithium-sulphur and lithium-ion (with novel anode materials for improved performance) were found to offer the highest promise. Over longer timeframes magnesium-sulphur battery chemistry offers additional capability.

To develop these chemistries from their current performance to meet the minimum outputs for regional aircraft, materials challenges in manufacturing and chemistry will need to be overcome. The primary opportunities and areas of UK expertise are in solid-state electrolyte processing, developing advanced electrode coatings to prevent early cell degradation and in developing the standards to ensure the materials, cells and processes meet the needs of a burgeoning industry.

Additionally, standardisation of cell material testing and reporting methodologies to allow improved comparison of chemistries for application is required.

Readers interested in more information can refer to the following Materials Technology Position Paper commissioned by FlyZero:

| | |
|---|---|
| *Assessment of Present and Future Battery Materials for Aerospace* | *FZ_RB_0008* |

## UK Capability Snapshot in Fuel Cells and Batteries

The Faraday Institute has been instrumental in supporting UK battery research since its establishment in 2017, however, no parallel organisation currently exists to support the research and development of fuel cells. The UK has world leading industrial capability in catalyst coated membranes and membrane electrode assemblies for Proton Exchange Membrane Fuel Cells through Johnson Matthey who currently develop and manufacture these for the automotive sector.

| *Universities* | *Industry* |
|---|---|
| • *Birmingham University*<br>• *Imperial College*<br>• *University of St Andrews*<br>• *UCL*<br>• *University of Warwick / Warwick Manufacturing Group* | • *Johnson Matthey*<br>• *QinetiQ* |

*Table 6 – Examples of UK organisations with capability relevant to the materials challenges associated with fuel cells and batteries for aerospace, gathered through engagement over the course of FlyZero, between March 2021 and January 2022.*

# 03.2 ADDITIONAL OPPORTUNITIES FOR FUEL CELLS AND BATTERIES

Beyond the core challenges the following are also considered to be of significant importance:

- **Corrosion resistant coatings for metallic bipolar plates (PEM fuel cells).**
- **Lightweight bipolar and end plates (PEM fuel cells):** Made of composite or lightweight alloys.
- **Membrane development (PEM fuel cells):** Including high-protonic conduction, non-fluorinated, high temperature operation, and resistance to impurities.
- **Increased platinum loading and shape control for catalysts (PEM fuel cells):** A great deal of research has gone into reducing catalyst loading through improved particle shape control. This work could be utilised to maximise performance in aerospace applications where high loading of platinum is required.
- **Replacement of cobalt in lithium-ion batteries.**
- **Battery recycling:** Li-ion battery recycling in UK is currently limited and does not include lithium, though cobalt and nickel are recovered.

# 04. POWER ELECTRONICS, MACHINES AND DEVICES

**The electrification of aerospace continues at pace with electric motors for aircraft propulsion of particular interest. Materials challenges come from the requirement for higher gravimetric power density and increased efficiency. Where these new requirements render existing materials obsolete there is need for new ones to be researched, developed and qualified.**

## 04.1 CORE MATERIALS CHALLENGE: ENHANCED MAGNETIC MATERIALS FOR MEGAWATT-CLASS MACHINES

*Box 3:*
*Responsible Sourcing of Cobalt*

*The production of cobalt, a key component in superalloys and batteries, will need to increase by 500% in 2050 compared to 2018 levels [3].*
*The Democratic Republic of the Congo (DRC) is the world's largest supplier of cobalt [4]. The expected increase in demand, without the benefit of good regulation could lead to an increase in environmental impact and negative social impacts.*

Permanent magnet motors offer the greatest potential for high power density and are inherently more efficient than other currently available options. As the flux-sources and key magnetic circuit flux paths, hard and soft magnetic materials respectively play a crucial role in the design and performance of these machines.

Hard magnetic materials in the automotive sector are based on neodymium-iron-boride, however, samarium-cobalt permanent magnets have the advantage of greater thermal stability despite having a lower power density. Promising new alloys such as iron-nitride ($Fe_{16}N_2$) and samarium-iron-nitride offer superior energy density but are not yet commercially available.

Cobalt-iron alloys are the preferred soft magnetic material for high power density motors. However, while externally applied stress is known to impact the magnetic properties of these alloys, there is little published research to date.

Sustainability, both environmental and social, and security of supply are of particular relevance to magnetic materials. For example, cobalt has been identified from a sustainability perspective (**Box 3**) and rare earth hard magnetic materials could be subject to supply chain issues **[5]**. The UK has the potential to become a leader in recycling of these materials with several organisations already developing solutions.

Readers interested in more information can refer to the following Materials Technology Position Paper commissioned by FlyZero:

| | |
|---|---|
| *Magnetic Materials for the Electrification of Aerospace* | *FZ_RB_0005* |

## UK Capability Snapshot in Magnetic Materials

The UK has university researchers and industry engaged in both hard and soft magnet materials development, including innovative recycling technologies. For example, Less Common Metals (based in Ellesmere Port) is a world leader in the manufacture, recycling and supply of rare earth hard magnetic materials.

| *Universities* | *Industry* | *Research Technology Organisations* |
|---|---|---|
| • *University of Birmingham*<br>• *University of Cambridge*<br>• *Cardiff University*<br>• *University of Nottingham (Professor Chris Gerada)*[6] | • *Less Common Metals*<br>• *UK Magnetics Society* | • *National Physical Laboratory (NPL)*[6] |

*Table 7 – Examples of UK organisations with capability relevant to the materials challenges associated with magnetic materials, gathered through engagement over the course of FlyZero, between March 2021 and January 2022.*

[6] *Joint author of "Magnetic materials for the Electrification of Aerospace", FZ_RB_0005*

# 04.2
# CORE MATERIALS CHALLENGE: REPLACEMENTS FOR SILICON SEMICONDUCTORS

**Current semiconductor device technology is silicon based. Although silicon is a mature technology it has significant performance limitations which prevent its use in high voltage (>1kW) electrical power systems and electric drivetrain technologies.**

The maximum operating temperature, switching speed, current and voltage rating of silicon device technology and the energy losses associated with silicon based electric powertrain result in relatively bulky, heavy, and inefficient electric drivetrains which require the incorporation of complex cooling systems.

Alternatives to silicon, specifically wide bandgap and ultra-wide bandgap materials have a number of superior properties which have the potential to achieve performance improvements in terms of efficiency, simplicity, volume, and weight. Silicon Carbide (SiC) and Gallium Nitride (GaN) are high performance wide bandgap semiconductor technologies which have the highest technology and manufacturing readiness level and are already used in certain lower voltage and lower power applications. SiC material and device technology has the most promising potential for high voltage, high power aerospace electrical power systems, including electric powertrains. GaN technology is better suited for systems with very high operating frequencies. Ultra-wide bandgap semiconductors such as gallium oxide and diamond have theoretical potential but are still in the early research stage of exploration and concept demonstration.

Readers interested in more information can refer to the following Materials Technology Position Paper commissioned by FlyZero:

| | |
|---|---|
| *Post-Silicon Power Semiconductors* | *FZ_RB_0006* |

## UK Capability Snapshot in Novel Semiconductors

The UK has a significant capability in power semiconductor science, engineering, and manufacturing. It consists of a pool of academic and independent research institutions, start-ups, small-medium and larger enterprises, and corporations with strong UK research and development sites. It also includes multiple silicon foundries which, with appropriate investment, have the potential to produce alternatives to silicon semiconductors devices.

| *Universities* | *Industry* | *Research Technology Organisations* |
|---|---|---|
| • *University of Cambridge*<br>• *University of Nottingham (Professor Patrick Wheeler, Dr Neophytos Lophitis )*[7]<br>• *University of Warwick*<br>• *Swansea University* | • *Clas-SiC*<br>• *Dynex Semiconductor*<br>• *Nexperia* | • *Compound Semiconductor Applications Catapult* |

*Table 8 – Examples of UK organisations with capability relevant to the materials challenges associated with novel semiconductor technology, gathered through engagement over the course of FlyZero, between March 2021 and January 2022.*

# 04.3 CORE MATERIALS CHALLENGE: HARNESSING SUPERCONDUCTIVITY

There are numerous technical challenges to achieving a light and efficient electrical powertrain at the limited voltage levels for contemporary aircraft. For any powertrain above the 10 MW level, there comes a point where conventional powertrains, even with forced cryogenic cooling and novel semiconductors, cannot meet the efficiency requirements without significantly increasing the voltage level.

Materials such as the rare-earth barium copper oxides (ReBCO) and $MgB_2$ which are superconducting at the temperature of liquid hydrogen (-253°C) enable superconducting powertrain components including superconducting machines, superconducting power network cables, and superconducting busbars. Superconducting materials have shown great potential in carrying a current with minimal energy dissipation at voltage levels below 1 kV. Superconducting propulsion powertrains above 20 MW can therefore be developed without significantly increasing the voltage level.

[7] *Authors of the Semiconductors for "Post-Silicon Power Semiconductors" FZ_RB_0006*

Readers interested in more information can refer to the following Materials Technology Position Paper commissioned by FlyZero:

| | |
|---|---|
| *Superconductors for Aerospace* | *FZ_RB_0004* |

## UK Capability Snapshot in Applied Superconductivity

The uptake of cryogenic and superconducting powertrains can benefit from UKAEA's STEP fusion program [6]. With the two industries utilising the same supply chains for superconducting magnets, high current leads and joints, cryogenic supporting components, and superconducting cables. The UK has some emerging industrial capability in superconductivity. As an example, Epoch Wires, based in Cambridge, can manufacture $MgB_2$ second generation high temperature superconducting wires over 30km in length.

| *Universities* | *Industry* |
|---|---|
| • *University of Bath*<br>• *University of Cambridge*<br>• *Durham University*<br>• *University of Oxford*<br>• *University of Southampton*<br>• *University of Strathclyde (Professor Weijia Yuan, Dr Min Zhang)*[8] | • *Epoch Wires*<br>• *Oxford Instruments*<br>• *Siemens Healthineers Magnet Technology, Oxford*<br>• *Tokamak Energy*<br>• *UK Atomic Energy Authority (UKAEA)* |

*Table 9 – Examples of UK organisations with capability relevant to the materials challenges associated with high temperature superconducting materials, gathered through engagement over the course of FlyZero, between March 2021 and January 2022.*

[8] *Authors of the FlyZero Report "Superconductors for Aerospace" FZ_RB_0004*

# 04.4 ADDITIONAL OPPORTUNITIES FOR POWER ELECTRONICS, MACHINES AND DEVICES

Beyond the core challenges the following are also considered to be of significant importance:

- **Electrical insulation:** Often the operating temperatures of motors are governed by the insulation on the magnet wires. Higher operating temperatures allow for greater current, more efficient thermal management, improving the power density. By adding thin nickel plating and nanofillers to the polyimide matrix, magnet wire rated to 280°C can be achieved. To improve the insulation temperature further, ceramic coatings provide extremely high temperature tolerance (500°C).
- **Magnet wire conductivity:** Copper-coated aluminium wire combines the benefits of copper's high conductivity with aluminium's low mass-density to achieve a hybrid solution with improved power densities.
- **Power electronics cooling:** Utilising novel high thermal conducting materials.
- **Component miniaturisation:** Power electronics systems for multi-MW platforms, passive components like capacitors and inductors contribute greatly to the overall weight of a system. Novel material and design technologies for next generation passive filtering components can facilitate a substantial increase of the overall power density and efficiency of power electronics systems.

# 05. AERODYNAMIC STRUCTURES

**Three FlyZero concept aircraft have been developed to study the feasibility of zero-carbon emission commercial flight and provide a platform for technology exploration and learning. Following this the FlyZero team have separated the challenge on aerodynamic structures as follows:**

- Liquid hydrogen enabled e.g. a wing that does not contain fuel (known as a 'dry wing') and cryogenic boundary layer control.
- Non-specific to liquid hydrogen e.g. laminar flow aerodynamics, thermoplastic primary structure.

Advanced materials for weight saving, aerodynamic performance improvements and structural optimisation will be needed to reduce non-$CO_2$ emissions (i.e. NOX and water vapour), hydrogen fuel burn and operational costs whilst in service. In parallel, reduction in the cost of part manufacture is sought.

*Box 4:*
*Sustainable Composites*

*There are a range of potential future solutions to support sustainability goals (i.e. supply, recycling, reuse) for carbon fibre reinforced polymers, which include bio-based materials, recycling technologies and low energy manufacturing. Thermoplastics and vitrimers both have the potential to provide benefits in terms of recycling and repair.*

Carbon-fibre reinforced polymers in particular face a number of challenges around sustainability (**Box 4**). Bio-sourced materials as an alternative to hydrocarbon-based feedstocks are of significant interest. However, economic viability will not be possible until improvements in mechanical properties and their reproducibility are proven.

# 05.1
# CORE MATERIALS CHALLENGE: MULTIFUNCTIONAL COMPOSITES

Composites that fulfil a role in addition to that of aerostructure, known as multifunctional composites, are seen as a significant area of opportunity. The following areas have been identified as being of particular interest:

- Energy Storage including structural batteries and structural supercapacitors
- Lightning protection and anti-icing/de-icing
- Data transmission
- Heat management
- Structural health monitoring
- Radiotransparent structures

Nanomaterials, such as graphene, provide a route to develop multifunctional structures which can provide inbuilt sensing, de-icing and lightning strike protection. Modified carbon fibre composites also provide the potential for structural power units including integrated batteries and supercapacitors.

Readers interested in more information can refer to the following Materials Technology Position Paper commissioned by FlyZero:

| | |
|---|---|
| *Novel Composites and Composite Aerostructures* | *FZ_RB_0009* |

## UK Capability Snapshot in Multifunctional Composites

The UK has several universities, research technology organisations and companies with interests in multifunctional composites. For example, the Advanced Manufacturing Research Centre (AMRC) is a project partner of the EU Horizon 2020 MASTRO project (Intelligent bulk MAterials for Smart TRanspOrt industries) looking at a variety of novel composites concepts like self-sensing, self-de-icing, self-curing, self-healing and self-protection methodologies to increase consumer safety, component lifespan and performance while reducing maintenance and manufacturing costs.

| *Universities* | *Industry* | *Research Technology Organisations* |
|---|---|---|
| • *University of Bath*<br>• *Cranfield University*<br>• *Imperial College London*<br>• *Queen Mary University of London*<br>• *University of Manchester*<br>• *University of Nottingham*<br>• *University of Sheffield* | • *Haydale*<br>• *Technical Fibre Products* | • *National Physical Laboratory (NPL)*<br>• *Advanced Manufacturing Research Centre (AMRC)*<br>• *National Composites Centre (NCC)* |

*Table 10 – Examples of UK organisations with capability relevant to the materials challenges associated with multifunctional composites, gathered through engagement over the course of FlyZero, between March 2021 and January 2022.*

# 05.2 CORE MATERIALS CHALLENGE: REDUCING COSTS FOR THE QUALIFICATION OF NEW COMPOSITES

The costs associated with the qualification of new materials and manufacturing methods disincentivises innovation and the adoption of new design concepts into manufacturing such as non-standard lay-ups, fibre steering and hybrid processes such as overmoulding. A significant proportion of this cost is associated with material and component level testing. To reduce the testing burden virtual testing including simulation of digital twins to create 'virtual allowables' and greater reliance on element or subcomponent testing is needed. This would need to be supported by increased in-process monitoring, non-destructive testing and through life structural health monitoring.

Readers interested in more information can refer to the following Materials Technology Position Paper commissioned by FlyZero:

| | |
|---|---|
| *Novel Composites and Composite Aerostructures* | *FZ_RB_0009* |

## UK Capability Snapshot in Composite Qualification

The UK is home to several OEM manufacturers with interest in developing faster more efficient routes to qualification and well-established links to universities. For example, CerTest is a 5-year multidisciplinary project with £6.9m funding from the Engineering and Physical Sciences Research council (EPSRC) programme grant scheme. It is led by the University of Bristol, with partners at the University of Bath, University of Exeter and University of Southampton and industrial support from Airbus, BAE Systems, Rolls-Royce, GKN Aerospace, the Alan Turing Institute, CFMS and the National Composites Centre.

| *Universities* | *Industry* | *Research Technology Organisations* |
|---|---|---|
| • *CerTest (University of Bristol, University of Bath, University of Exeter and University of Southampton)*<br>• *The University of Manchester (National Composites Certification and Evaluation Facility, NCCEF)* | • *Airbus*<br>• *BAE Systems*<br>• *CFMS*<br>• *Composites Leadership Forum*<br>• *GKN Aerospace*<br>• *Rolls-Royce*<br>• *Spirit AeroSystems* | • *National Composites Centre (NCC)*<br>• *Advanced Manufacturing Research Centre (AMRC) Cymru* |

*Table 11 – Examples of UK organisations with capability relevant to the materials challenges associated with the qualification of composite materials, gathered through engagement over the course of FlyZero, between March 2021 and January 2022.*

# 05.3
# ADDITIONAL OPPORTUNITIES FOR AERODYNAMIC STRUCTURES

Beyond the core challenges the following are also considered to be of significant importance within composite manufacturing:

- **Improvements in CRFP resin systems:** Snap curing resins, two-part, low viscosity epoxies, powdered epoxies, bio-sourced resins, high temperature and fire-resistant resins, vitrimers and infusible thermoplastics.
- **Improvements in CRFP fibre technology:** Low energy processing of PAN (polyacrylonitrile) precursor and PAN replacement.
- **Improvements in CRFP toughness:** Improvements in the in-plane toughness of a composites using aligned but discontinuous fibres, thin plies to supress cracking and herringbone structures.
- **Lightweight Alloy Development:** Continued evolution of high strength, low density aluminium alloys.

# 06. KEY RECOMMENDATIONS

The following three key materials recommendations to enable zero-carbon emission commercial flight are made by this report.

## Establishment of New, UK-Based, Hydrogen Materials Test Facilities

There are currently no UK facilities capable of conducting mechanical tests in hydrogen environments at the scale required. New, UK-based, materials test facilities will be needed to requalify existing materials and coatings and qualify new ones. New test standards will also be needed to meet the specific requirements of commercial aerospace.

Mechanical testing will be needed across a range of temperatures and hydrogen concentrations. Solutions are needed regarding the time currently needed to reach cryogenic temperatures prior to testing and increasing the number of facilities that can handle hydrogen safely.

## Funding of Research and Development in the UK for Materials in Hydrogen Environments

Hydrogen, the smallest atom, can diffuse rapidly into most engineering materials often causing significant negative impact on their mechanical properties. Greater research emphasis on the interaction of hydrogen will be needed before advanced materials, developed specifically for use in hydrogen containing environments, can be developed. The UK could generate its own datasets for existing and new materials, enabling wider innovation in the supply chain.

The UK academic community can be grown by both redirection of existing researchers and organic growth through, as an example, doctoral training centres to produce the next generation of researchers for academia and industry.

## Putting Sustainability and Responsible Value Chains at the Centre of Decision Making

Sustainability is a global priority, and the aerospace industry is likely to be subject to increasing regulatory pressure to ensure that its products are recyclable, feature low embedded carbon materials and use energy efficient, low waste processing and production technologies. It is vital that the materials used in aerospace are responsibly sourced, limiting environmental impacts, minimising greenhouse gas emissions, respecting human rights and supporting local communities. Companies need to ensure sustainability and environmental & social lifecycle requirements are being set and adhered to throughout their supply chains.

A move to liquid hydrogen as the zero-carbon emission fuel to power future commercial aircraft, in particular those powered by a fuel cell and/or electric motors, will increase the use of alloys containing critical raw materials. This report has identified cobalt as being of particular concern, however, other elements such as lithium, the rare earth elements and platinum group metals often carry a degree of risk either geopolitically, around human rights or environmentally.

# 07. APPENDIX A – MATERIALS TECHNOLOGY POSITION PAPERS INDEX

These position papers are available via download from www.ati.org.uk.

| *FlyZero Report Reference* | *Title* | *Authors Organsation* |
|---|---|---|
| *FZ_RB_0004* | *Superconductors for Aerospace* | *University of Strathclyde* |
| *FZ_RB_0005* | *Magnetic Materials for the Electrification of Aerospace* | *University of Nottingham and NPL* |
| *FZ_RB_0006* | *Post-Silicon Power Semiconductors* | *University of Nottingham* |
| *FZ_RB_0007* | *Carbon Fibre Composites for Liquid Hydrogen Powered Aerospace* | *University of Bath* |
| *FZ_RB_0008* | *Assessment of Present and Future Battery Materials for Aerospace* | *Qdot Technology* |
| *FZ_RB_0009* | *Novel Composites and Composite Aerostructures* | *Avalon Consultancy Services* |
| *FZ_RB_0011* | *Material Based Hydrogen Storage for Aerospace* | *University of Bath* |
| *FZ_RB_0013* | *Alloy Compatibility in Hydrogen* | *Reaction Engines and TWI* |
| *FZ_RB_0017* | *Coatings and Insulation for Liquid Hydrogen Powered Aerospace* | *TWI* |

# 08. REFERENCES


*1 ATI FlyZero, "Realising Zero-Carbon Emisson Commerical Flight: Primary Energy Source Comparison and Selection," September 2021. [Online]. Available:* https://www.ati.org.uk/resources/publications/.

*2 Clean Sky 2, "Hydrogen-powered aviation: A fact-based study of hydrogen technology, economics, and climate impact by 2050," May 2020. [Online]. Available:* https://op.europa.eu/en/publication-detail/-/publication/55fe3eb1-cc8a-11ea-adf7-01aa75ed71a1/language-en.

*3 World Bank , "Climate-Smart Mining: Minerals for Climate Action," 2020. [Online]. Available:* https://www.worldbank.org/en/topic/extractiveindustries/brief/climate-smart-mining-minerals-for-climate-action.

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*5 Advanced Propulsion Centre UK, "Building a robust magnet supply chain," 2021. [Online]. Available:* https://www.apcuk.co.uk/building-a-robust-magnet-supply-chain-for-the-uk-report/.

*6 UK Atomic Energy Authority, [Online]. Available:* https://step.ukaea.uk/.

# ADVANCED MATERIALS

A Key Enabler for Zero-Carbon Emission Commercial Flight

FLY ZERO

AEROSPACE TECHNOLOGY INSTITUTE