ACADEMIC PROGRAMME RESEARCH FINDINGS AND RECOMMENDATIONS

FZO-ACA-REP-0056

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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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FlyZero contributing companies: *Airbus, Belcan, Capgemini, easyJet, Eaton, GE Aviation, GKN Aerospace, High Value Manufacturing Catapult (MTC), Mott MacDonald, NATS, Reaction Engines, Rolls-Royce, Spirit AeroSystems.*

Department for
Business, Energy
& Industrial Strategy

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EXECUTIVE SUMMARY

The FlyZero programme included a ringfenced £1m budget for academic research to support the project team addressing some of the most challenging questions and to strengthen the depth of research capacity.

The level of engagement from the research community has been extremely supportive, mirroring the level of commitment to the project from collaborating firms and contracted staff.

Thirty-two research projects were commissioned ranging in value from £15k to £150k, covering a variety of technical, commercial, sustainability and innovation areas of specific interest to the programme. Due to the short project timeframe, all research groups have had to respond quickly to requests in order to deliver robust evidence in a timely manner to support the wider project team and influence core project decisions. Project durations varied from 2 to 9 months. Despite the modest budget, this felt proportionate alongside our internal capability, and internal capacity to manage off-load activities. FlyZero has drawn on a significant amount of research expertise across a wide number of the UK's leading academic institutions in a range of relevant disciplines.

All research activities have not only created value for the programme but also it has been very clear that FlyZero has channelled a lot of value into academia. By effectively acting as a proxy OEM, supplying technical requirements and working closely with the research groups, academic researchers have learnt a lot about the impact of their work at the systems and aircraft level, thus they can better define priority future research activities, as shown by the quote below. These lessons and the future research priorities included in this report will be discussed with EPSRC and the UK-ARC, and will be made available to UK academia.

"The Cranfield team is very pleased that you feel our work has added value to the FlyZero research. It has certainly been a challenge to deliver on so many topics and within a relatively narrow timeframe. But we learnt a lot in the process too. Not only technically, but also how to pull together internal diverse resources more effectively to deliver as a team at the highest level.

"So thanks again for presenting us with a 'challenge', and we certainly hope to work with you and your team in the future again."

Prof Vassilios Pachidis

Head, Centre for Propulsion Engineering

Director, Rolls-Royce UTC, Cranfield University

The list of contracted research institutions is as follows:

1) Strathclyde University
2) Leeds University
3) Nottingham University
4) Loughborough University
5) Cardiff University
6) Bristol University
7) National Composites Centre (NCC) and Bath University
8) Satellite Applications Catapult
9) Advanced Manufacturing Research Centre (AMRC)
10) TWI and Cambridge University
11) Cranfield University
12) National Physical Lab
13) Southampton University
14) Oxford University
15) Central St. Martins
16) Warwick Manufacturing Group

Figure 1 – Research map (Source: FlyZero).

Sustainability

- Impact of water and other emissions (University of Leeds)
- Design to decommissioning (University of Strathclyde)

Propulsion

- Combustion analysis (Loughborough, Cardiff and Cambridge Universities)
- Aircraft and propulsion noise studies (University of Southampton)
- Electric motor design (Nottingham University)
- Hydrogen tank design – composites/multi-material (National Composites Centre)
- Hydrogen tank manufacture – metallics (AMRC)
- Peri-dynamics (University of Strathclyde)
- Propulsion system design (Cranfield University)
- Hydrogen tank design (Cranfield University)
- Performance analysis (University of Oxford)
- Cryogenic fuel system, gas turbine and thermal management (Cranfield University)
- Batteries, power electronics and high voltage systems (Warwick Manufacturing Group and Nottingham University)

Industrial

- Materials: Semiconductors for high voltage applications (Nottingham University)
- Materials: Superconductors for cryogenic powertrains (University of Strathclyde)
- Materials: Material based hydrogen storage (University of Bath)
- Materials: Carbon fibre for liquid hydrogen (University of Bath)
- Materials: Next generation materials for increased battery power density (Qdot)
- Materials: Novel composites and composite structures for next generation aircraft (Avalon)
- Materials: Alloy compatibility with hydrogen (-253°C – 1200°C) (Reaction Engines)
- Materials: Magnetic materials for electrification (Nottingham University)
- Materials: Magnetic materials for electrification (National Physical Laboratory)
- Space & cryogenics capability mapping (Satellite Applications Catapult)

Airframe

- Wing icing drivers (University of Nottingham)
- Sustainable cabin technology (Cranfield University)
- Sustainable cabin design (Central St. Martins, University of London)
- High lift and movables design (Cranfield University)
- Wing morphing and MDO (University of Bristol)
- Waste heat utilisation for aerodynamic performance (TWI)

Academic Innovation

- Innovation management (University of Southampton)

01. RECOMMENDATIONS

Below are the strategic recommendations derived from the FlyZero research programme necessary to ensure the UK remains in a competitive position for zero carbon aviation.

- EPSRC and UKRIs aerospace technical specialists should review the research findings and further research priorities identified from the FlyZero research programme and use these to inform future research and development funding specifically to take forward the technology roadmaps arising from the project.
- There remain many fundamental questions in materials and systems design when using hydrogen as a fuel. The UK requires a dedicated hydrogen research and development facility for materials and systems which should be open and designed to collaboratively engage with industry and academia. This should support cryogenic and gaseous hydrogen development to service the aerospace industry together with other sectors including automotive, marine, space and energy.
- We recommend a group be established to develop a strategy, coordinate and accelerate sustainability knowledge in aviation. This would deliver a more integrated academic and industry approach in order to answer questions needed to inform design, policy and market decisions, and would require involvement from the ATI, NERC and EPSRC. More funding for climate research related to aviation would also be required to support over a five year period.
- Project FlyZero has acted as a cross-industry proxy aircraft prime OEM (original equipment manufacturer), procuring research priorities for a future high growth industry. Government should consider whether other sectors could benefit from this model in order to accelerate innovation by improving pull through of academic research and knowledge transfer.
- UK academic research institutions do not have the same standard research terms across the UK. It would be useful to look again at whether a better solution for multi-institution research agreements can be found to enable the rapid deployment of research contracts to assist accelerating UK innovation.

02. RESEARCH FINDINGS AND FUTURE RESEARCH

The following 32 research summaries, one for each of the academic research packages, details concisely the main research findings that have fed into the FlyZero engineering integration and trades programme during 2021.

In a small number of cases specialist industrial firms were used to complement the academic research programme. Based on this initial research and with these leading UK research groups, in many cases now familiar with the impact of their research at the system and aircraft level, our combined teams have defined priority future research to accelerate towards zero carbon aviation.

This report provides the research overview. For the complete and more detailed research outputs, these have been incorporated within FlyZero's specialist research papers. Each academic institution also has the right to publish their research and use it for further research and teaching purposes, subject to some approvals.

Finally, one of the significant outputs for the FlyZero project are a series of technology roadmaps. The research programme detailed in this report has fed into these roadmaps which are available separately as project outputs.

Listed below is a snapshot of research findings detailed throughout the report.

- The interactions of emissions at altitude are complex which translates to modelling uncertainties. There is a need for further scientific research with verification using experimental and flight measurements.
- Regulation offers an opportunity to stipulate more extensive requirements for end-of-life recycling which are limited today in aviation.
- Green hydrogen is the recommended fuel for FlyZero with ammonia considered as an alternative but unable to meet NO_x emission requirements.
- Support from government and institutions to promote the development and adoption of hydrogen, higher investment and appropriate research programs would help the UK overcome the barriers to adoption. Coordination from an institute such as ATI is critical to ensure that models, codes, experiments, validations, designs, know-how and further expertise are gathered, agreed and shared with industry.
- The study concluded that FlyZero's three proposed concept aircraft studied have the potential to be competitive regarding future noise regulations.

- A number of new early TRL electric motor concepts together with incremental innovations such as light-weighting through manufacturing process development offers a large range of opportunity to improve motor performance by up to 200% over the current state-of-the-art.
- Composites and hybrid material systems offer significant scope for hydrogen tank systems design. Further work is needed to better understand material properties and efficacy at cryogenic temperatures and with hydrogen - repulsion, embrittlement or permeation. Thermal shock is predicted as a challenge area which may be mitigated by slow purging, but this needs to be better understood.
- Although gas turbines burning hydrogen deliver a greater aircraft range than fuel cells, fuels cells could be incorporated to power auxiliaries and be fuelled from boil off from the main hydrogen storage tanks.
- Through adoption of materials innovation, superconducting propulsion powertrains above 20MW can be developed without significantly increasing the voltage level. The zero-resistivity feature ensures the overall high efficiency of the powertrain reducing the fuel usage and the size of fuel tanks.
- Unique visual design language should be developed for hydrogen powered aircraft to enhance the passenger experience.
- To reduce the effect of wing icing, a dry wing (without fuel storage) lends itself to a thinner aerofoil thickness to chord ratio, and combined with other technologies such as morphing wing, the area available with where icing can occur is significantly reduced.
- Sustainability provides a valuable hook to aid recruitment whilst agile working practices were successful in delivering the project. Further development of organisational design would offer further value going forwards.

02.1 SUSTAINABILITY

02.1.1 IMPACT OF WATER AND OTHER EMISSIONS

FlyZero commissioned University of Leeds for a detailed understanding of the impact of water emissions arising from new FlyZero concepts for a range of fuels/energy sources for propulsion, including hydrogen, Fuel Cells (hydrogen), Battery-electric and ammonia.

Specifically, an assessment on the impact of water emissions and other emissions resulting from the fuels/energy sources and evaluated their effect on global warming, formation of contrails and potential formation of cirrus clouds and warming effects of these. The assessment included the impact of different flight envelopes and altitudes in relation to the tropopause. The nature and form of the water (temperature, humidity and mixing ratio) was considered. Other emissions considered were H_2, NH_3 leakages NO_x and particulates.

Research Findings

Modelling work included the use of atmospheric, chemical transport and climate models. The output from these was very useful to understand the non-CO_2 impacts from aviation and how these may change by the deployment of liquid hydrogen as a fuel. The specific work involved assessments of the impact of water emissions leading to the formation of contrails as well as impact from emissions of oxides of nitrogen.

The research findings confirmed that the use of hydrogen fuel will generate 2.6 times the amount of water emissions whether from Fuel Cells or Gas Turbine propulsion units. This will lead to the formation of condensation trails (contrails) in ice super-saturated regions (ISSRs) of the atmosphere. However, studies indicate that contrails from water emissions will dissipate more quickly and initial analysis indicates that these will have lower optical density due to the absence of soot particles, meaning that the overall impact from contrails may be less. There is high potential for navigational contrail avoidance (altitude or route change) to provide a rapid reduction in the overall radiative forcing. Significant research is still needed to confidently predict ISSR locations.

Increased water emissions will also lead to the direct impact of water vapour emissions in the stratosphere when aircraft fly above the tropopause. This has some impact, around 2% of ERF for current aviation. Further research taking into account flight altitudes is recommended to inform design decisions.

Given that Fuel Cells will not produce any NO_x emissions and that ultra-lean burn technology for hydrogen combustion in a Gas Turbine suggest that NO_x emissions will be between 50% to 70% compared to typical kerosene fuelled engines, the overall climate impact from NO_x emissions will likely be less.

Further Research

There are a number of areas where further research will be valuable, including:

- Improving and extending existing models.
- Contrail formation and the balance between their cooling and warming effects. These should be done for different propulsion systems including hydrogen burning gas turbines and fuel cells. The comparison with contrails formed from current technologies using kerosene and/or various sustainable aviation fuels also needs to be understood.
- Impact of increased water vapour into the stratosphere requires further scientific understanding.
- Understanding uncertainties associated with aerosol/cloud interactions, saturation of NO_x emissions as well as the impact from hydrogen as a greenhouse gas.
- The interactions of emissions at altitude are complex and this translates to uncertainties which need to be better understood through scientific research followed by verification using experimental and flight measurements. This work will be essential to inform technology development and selection in order to minimise the overall climate impacts from aviation for future generation of aircraft.

02.1.2 DESIGN TO DECOMMISIONING

This project was established with Strathclyde University to learn lessons from end-of life (EOL) decommissioning, including the maintenance, repair and overhaul (MRO) perspective which influences design. The objectives are to highlight areas where:

- Design changes could make aircraft more circular
- Development of new materials and recycling processes for improved circularity

The definition of more circular is to maintain the value of materials and products in the economy for longer, in terms of economic value and embodied energy. This may include repairability, lifetime extension, re-use, recyclability, reducing toxic materials and hazardous waste.

Research Findings

Strathclyde university conducted interviews with stakeholders including asset owners, MROs, decommissioning organisations and recyclers. Areas of questioning were included challenges with aircraft at the maintenance and end-of-life (EoL) stages, the economic challenges, responsibilities and regulations, and their opinion on emerging technologies. The research questions focused on the following areas:

- Financial investment from aircraft OEMs to support:
  - MROs developing their skillset in keeping with new aircraft design.
  - Research and development of EoL strategies for complex materials.
- Aerospace sector expansion to accommodate composite material and battery processing at EoL within the UK.
- Develop reuse and recycling methods for all materials, in a cost-effective way, to progress EoL strategies, including designing components for easier disassembly and separation.
  - Increase reuse of aluminium aircraft fuselage rather than recycling.
- Standardize the type of composites used by manufacturers and, where possible, restrict the variety of composite types on an aircraft.
- Open source data from OEMs to facilitate material identification and processing.
- Expand battery recycling business within the UK to prevent export.
  - New domestic market for anode, cathode and graphite recovery and processing through hydrometallurgical processes.
- Design batteries in a modular way to enable greater EoL solutions.

There was a general view among participants that as circular economy principles become more embedded within business models across other broad sectors, such as automotive and renewables, they will become more embedded in aerospace. Participants acknowledged there needs to be a mindset shift in aerospace not yet seen, whereby companies should want to fulfil sustainability targets, rather than needing to fulfil the minimum required through legislation. As it stands, the industry in general is slow to change – the particularly high competition within aerospace has meant that being environmentally sustainable and “green” isn’t currently viable, hence the reliance on other industries kick-starting this. One suggestion made was to reuse existing fuselage with retro fit of modern technologies, such as, battery electric or hydrogen electric. One participant mentioned how aircraft could last a lot longer than they currently do, however what is seen as the commercial value of a plane inhibits this. It could be possible that the move to net zero in aerospace will allow for life extension programmes, as seen in the wind energy sector. One way in which this shift could be encouraged would be through charges for crushing, recycling and landfill.

Other participants suggested that, if aircraft were designed more simply with easy disassembly in mind, there would be increased value at the decommissioning stage through reduced labour time and increased volume in separated materials for processing, as well as the environmental benefit of being able to rework individual materials. As it stands, manufacturing does not seem to consider maintenance and disassembly of entire aircraft or components, resulting in breakages and lost revenue.

From a regulatory perspective, the focus is very much focused on the safety of an aircraft rather than EoL. Through life emissions are currently considered under some regulatory bodies in line with Net Zero targets for the sector, and some participants suggested the responsibilities of regulatory bodies should be expanded to incorporate more environmental aspects if mandated from governments. Similarly, it was raised by some participants that there is no industry-wide standard on recording recycling rate, either by weight, by volume or otherwise. It was therefore suggested that a standard be implemented to ensure companies are releasing comparable data rather than data which worked best for them depending on what material they were dealing with.

It is important to note that none of the participants stated they would like to see composites removed from aerospace, and they understand the reasons for the increased use of the materials from a safety and weight-saving perspective. However, almost all discussed the challenges faced with handling these materials through life and at EoL. One participant suggested there should be more readily available training for MROs and dismantlers who are used to working with majority aluminium fuselages but are now faced with a shift towards majority composite.

It was highlighted that investment into EoL treatment for composites would be more beneficial than investing in research to design new materials to replace composites, as this would only lead to the same EoL material processing issues. It was also noted that if some form of standardisation of composites across the sector occurred then this could promote the development of new recycling process routes.

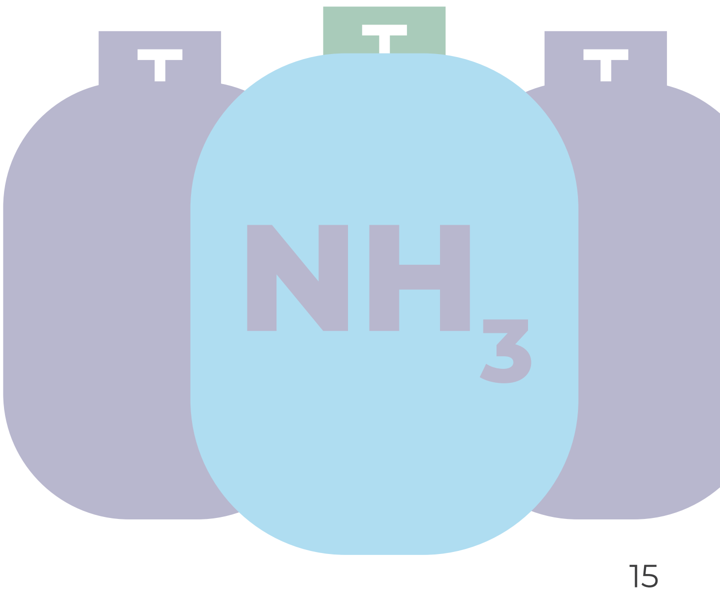
In line with participants believing OEMs should hold greater responsibility for EoL material processing, participants outlined a number of suggestions. Firstly, there was an opinion raised that OEMs should help manage waste materials and offer solutions by making it cheaper and more environmentally friendly to maintain existing parts rather than selling new, although it was acknowledged that this may require incentivisation to make this shift. A second suggestion was for a “tax” to be placed on the OEM for every commercial unit they sell. The money raised should be used to fund research into developing solutions for EoL material processing, as well as establishing hangers worldwide which are capable of fully decommissioning new design aircraft. These would be fully equipped to process all materials including carbon fibre, separating it from resins and contaminants.

The outputs from this work package have been used to inform the Lifecycle Impact roadmap, which is a separate document available via the ATI with document reference FZO-STY-POS-0034 **[1]**.

02.2 PROPULSION

02.2.1 COMBUSTION ANALYSIS

The project commissioned feasibility studies in the combustion area, specifically hydrogen and ammonia as fuels in gas turbine architecture. The research conducted by the Universities of Loughborough, Cambridge and Cardiff explored the capabilities, risks and opportunities to inform our technology roadmap. The outputs from these work packages have been used to inform the Gas Turbine and Thrust Generation Roadmap, which is a separate document available via the ATI with document reference FZO-PPN-MAP-0022 **[2]**.



Here below is the scope of work:

Research Tasks	Motivation	Questions to be answered
NO_x implications of ammonia/H_2 in the fuel mix	May be obviated by concept decisions over the next month	Predict the effects of various H_2/ NH_3 mixes vs kerosene.
Fuel/Air mixing strategy (e.g. multiple injectors design) for NO_x	H_2 has extremely high diffusivity and low density	Make initial proposals for rapid mixers
Combustion instability (Rumble)	Compressible fuel may make the thermo-acoustics worse.	What is the difference with H_2?
Flashback limits of fuel at top condition (autoignition?) - pressure dependency?	Crucial to fuel injector design	Literature search and simulation
Pre-mixing and combustion of H_2/ammonia mix	Mixing quality may be an issue. Very different properties between the two. Could they burn in separate locations? Opportunities of modulating splits?	Literature search and simulation
NO_x in cruise	Current legislation focusses on the LTO cycle rather than what happens at altitude.	Regulate current standard or increase stringency?
Inter turbine reheat	Theoretical cycle benefit. Challenge to control size and complexity in a vitiated environment.	What is the real SFC advantage and how big/feasible is the second combustor?
Aerodynamic challenges of Gaseous fuelling system	Hot gaseous fuel has high volumetric flow rate and intrusive pipework. RRCa problems with external aerodynamics and pre-ignition	Simulation and definition of experimental programme
Water injection during T/O and climb for NO_x, SFC and/ or turbine life (Wet Low Emissions, WLE)	Fuel cell exhaust re-use. May need a novel solution if liquid water is used due to phase differences.	Literature search and simulation
Cooling and combustion near wall effects with new fuel	H_2 quench distance change effects. Seek opinion from experts first.	Literature search and simulation
Safety - Explosive ignition through turbine system?	Pre-work required to assess the risk.	Literature search and simulation
Design for increased "hot loss" due to combustion at higher velocities	Potential efficiency penalty if not controlled or designed for.	Literature search and simulation

Table 1 – Scope of work.

Research Findings - Loughborough University

Ammonia/hydrogen mixtures were considered, which concluded the addition of ammonia significantly increased NO_x emissions. Although NO_x reducing strategies were demonstrated, the use of ammonia is unlikely to meet future NO_x emissions legislation. Thermodynamics was used to determine the best method of delivering ammonia/hydrogen mixtures to the combustor and concluded the fuel must be delivered in the gaseous phase. The design rules provided for air-fuel mixing based on the injection of hydrogen jets in crossflow were analysed. This work demonstrated that the optimum hole diameter is sensitive to hole tolerancing, jet penetration and mixing through the flight cycle. Also assessed was the combustion system aerodynamics external to the flame tube, which showed that a conventional diffuser feed would significantly increase the NO_x for hydrogen jets in a cross flow system, hence a more optimised system architecture needs developing. Finally, due to the compressibility of hydrogen, the fuel system will be subject to various acoustic modes which can lead to unsteady fuel flow into the combustion system. Consequently, the fuel manifold needs to be considered as part of the thermacoustics of the combustion system.

Further Research

The work undertaken has indicated that the data available on hydrogen combustion at the temperatures and pressures representative of aerospace gas turbine applications is limited. Without this data there is a high risk of the hydrogen combustion system not meeting its operability requirements, leading to a worst-case scenario where any technology demonstration is significantly limited. The NCCAT development at Loughborough University is well placed to address these risks with its Intermediate Pressure and Temperature (x2) and Sub-atmospheric facilities which are primarily used for aerospace combustion technology development. However, these facilities will need to be upgraded to run on hydrogen, ideally covering a temperature range of the fuel being delivered to the combustion system for the proposed cycles (currently ~-70°C to >150°C.). Experimental and modelling work is required on the diffuser aerodynamics to provide a uniform feed of air to the hydrogen injectors and thereby ensure emissions targets are met whilst minimising pressure drop. Additionally, as the fuel system will now be compressible, work is required on how to acoustically decouple the hydrogen fuel system from the combustion system to minimise thermoacoustic instabilities. Finally, lab-scale experiments and modelling are required to provide design rules for flashback resistant ducts.

Research Findings - University of Cardiff

It is believed that the use of hydrogen in the short term is still restricted to combustion-based systems in the aerospace industry. The lack of a well-defined injection strategy for hydrogen (diffusive, partial or fully-premixed), the fast-reacting nature and highly diffusive characteristics of the molecule (that lead to highly unstable regimes such as flashback, autoignition and thermoacoustics), are still to be fully resolved.

Reaction kinetics (with "fair" models and designs that need further validation), and the potential risks associated to the use of hydrogen (high potential for leaks, wide flammability limits, likelihood of detonation, etc.) are the bases of this conclusion.

These development challenges when taken together with a lack of infrastructure, large costs of storing hydrogen over large periods of time, change of philosophy to design combustion systems for aerospace, and the low volumetric energy density of the hydrogen molecule, all point towards SAF being a quicker transition drop-in fuel.

With support from governments and institutions to promote the development and adoption of hydrogen, higher investment and appropriate research programs would help the UK and other economies to overcome these barriers.

A national effort is required to consolidate knowledge across UK institutions and companies, rather than the fragmented approach we have today, which would be unlikely to deliver the outcomes needed. Coordination from an institute such as ATI is critical to ensure that models, codes, experiments, validations, designs, know-how and further expertise are gathered, agreed and consolidated under the same umbrella to cut development times and deliver a system capable of high stability, low risk within a suitable commercial framework for the aerospace sector.

Research Findings - University of Cambridge

Cambridge University supported the analysis and understanding of the capabilities of both hydrogen and ammonia as energy sources for gas turbine combustors, including how they differ in their fundamental behaviour from kerosene.

In addition to delivering conclusions on the relative behaviour of the fuels on properties such as flame temperature, NO_x production, autoignition and laminar flame speed, they have embodied their results in a MATLAB code H2ools, which is accessible and easy to interrogate, and the beginning of a standard database going forwards.

They proposed an improvement in how to compare the NO_x production when significantly different fuels are employed; conventional approaches, such as $EINO_x$, do not account for the different energy content of the fuel. They propose to use grams of NO_x versus cycle power, as this determines the NO_x against the usable energy delivered by the design solution.

In addition, they developed a novel approach to rapidly assess the design space of hydrogen fuel injection concepts; the initial assessment has been set-up to look at the propensity for autoignition. This approach is showing great promise and their results have been validated against detailed CFD simulations.

Future Work

H2ools has significant potential to become a de facto source of data for all people working on hydrogen gas turbines – thus ensuing consistency going forwards. Further development of this is required to allow for expanding the data to broader operating conditions and to include experimental data.

The preliminary design tool developed to assess autoignition would benefit from expansion to look at a broader range of phenomena, including NO_x production, and it should explore the combustion behaviour across the full range of engine operating conditions.

The work has highlighted the need to carry out experimental validation work at high pressure and temperatures as the chemical kinetics for hydrogen is unvalidated at these conditions, in terms of flame speed and ignition time. A suitable partner to carry out these experiments needs to be identified for the next phase of the programme.

Further, the impact of fluid mixing on phenomena such as ignition propensity and NO_x needs focussed experimental study. This is an area Cambridge are well placed to support, with the installation of additional infrastructure to safely manage the supply of hydrogen within their laboratories.

Postgraduate Skills

To develop the next generation of engineers equipped to work in the field of hydrogen combustion, additional focus is required for training in chemistry and its interaction with fluid dynamics for combustion application given the limited skills supply in the UK. The Centre for Doctoral Training in Future Propulsion and Power should cover the theory behind hydrogen chemistry and combustion and introduce the impact this has on gas turbine cycles. The project has demonstrated that much of the training on gas turbine engineering is based on hydrocarbon fuelled solutions, and hence many measures for comparing the performance of different concepts do not account for the impact of significant differences in the energy content of fuels or the difference that the products of combustion have on the gas turbine cycle design and efficiency.

02.2.2 AIRCRAFT AND PROPULSION NOISE STUDIES

Specialist noise support was sought from University of Southampton during FlyZero's preliminary design/scoping phase to influence the aircraft and propulsion system designs to deliver the noise targets and other associated targets like fuel burn, cost, etc.

This noise input initially allowed our concept matrix to diverge and then using a qualitative and quantitative assessment help converge the concepts phase to a narrower list of preferred candidate designs.

The noise understanding is developed further and as part of the overall package, an understanding for the regulations and their future aspirations was generated.

Two key outputs developed from this package are a technology roadmap necessary to deliver the preferred concepts and some working aircraft concepts that could be ready for 2030 entry into service.

- Noise study for regional/ single aisle aircraft in the 2030/35 timescale.
- General feasibility study of noise levels and targets.
  - Including gas turbines, internal combustion engines, fuel cells, batteries, propellers, fans, open rotors, hydrogen, ammonia fuels.
- Noise feasibility studies both qualitative and quantitative on a range of existing and novel aircraft/ propulsion concepts.

Research Findings

The aim of the work conducted by the Institute of Sound and Vibration Research (ISVR) at the University of Southampton was to provide specialist support during the initial scoping phase of FlyZero and influence potential concept designs to deliver noise targets alongside other performance targets.

The study provided an understanding of the regulations and an expert view of their projection into the future. As aircraft technology progressed, the ICAO noise regulations progress the drive for better efficiency, less emissions and less noise. As an example, the latest revision, Chapter 14, implemented in 2013 was approximately 7dB lower than its predecessor.

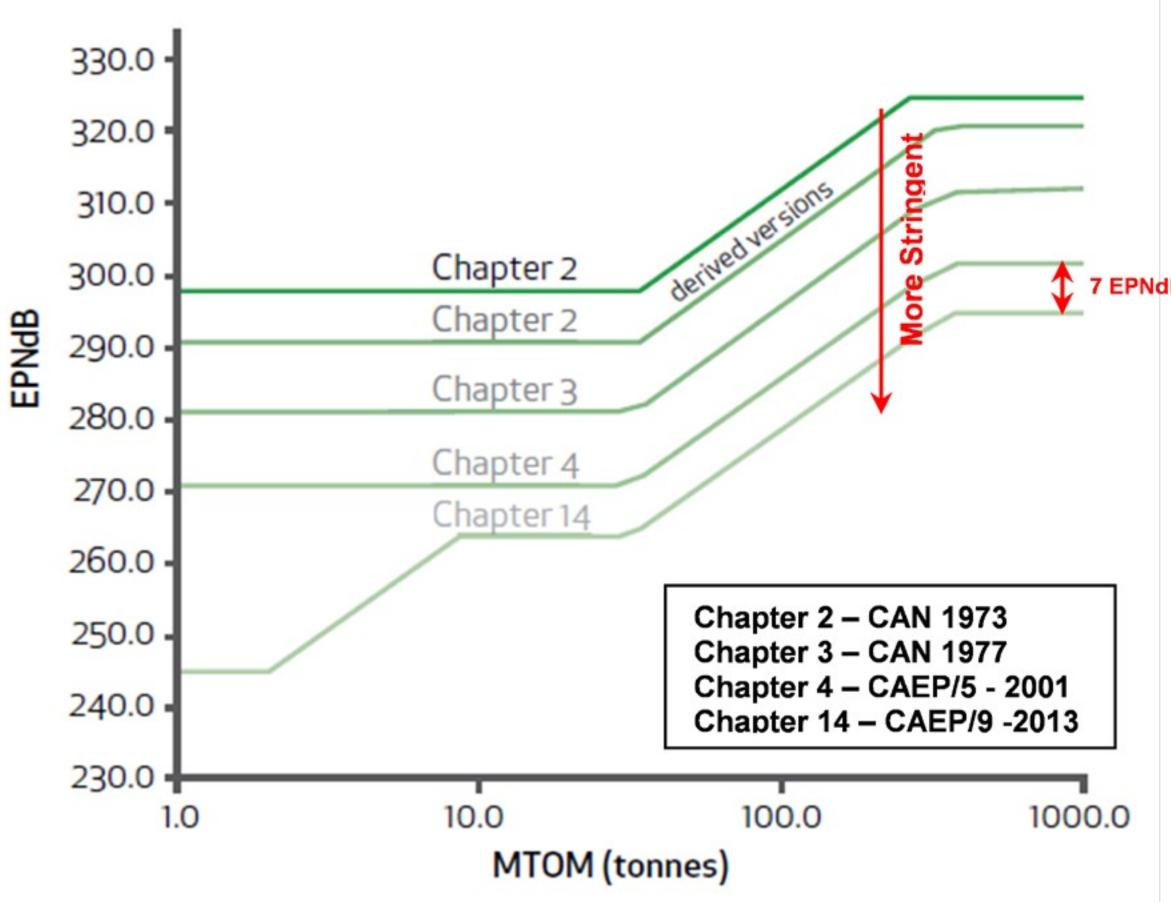


Figure 2 – ICAO Cumulative noise limits (Source: reproduced with permission - ICAO).

The view is that a new revision to ICAO's noise regulations may be in place by 2030 where it is expected a similar 7dB drop may be adopted. To remain competitive, any aircraft entering service in this timeframe should have a margin of approximately 15dB further which is broadly what is observed from historical trends.

Quick, low fidelity, noise engineering prediction tools were used to assess FlyZero's concepts starting with the initial scouts. This provided valuable ranking that led to the selection of suitable design features, including propulsion and overall aircraft integration, which then fed into the final FlyZero concepts.

In general, some design rules were identified, summarised as follows:

- Improvements to aircraft efficiency and weight have a significant impact on noise reduction due to the reduced thrust required at take-off, landing and during the flight cycle.
- Improvements to airframe design such as the design of high lift devices and landing gear plays a major role in noise reduction. High lift devices and landing gear cause flow discontinuities and can promote flow acceleration locally.
- Turbofan design: general rules include the reduction of fan pressure ratio, reduced fan speeds, turbomachinery flow Mach numbers and exhaust velocities. Other technologies such as acoustic liner treatment in nacelles will have a significant effect.

- Propeller design: general rules include the reduction of propeller loading by increasing the number of blades and/or the reduction of the tip speed.
- Powerplant installation effects: a study into the narrowbody concept shows that a fuselage mounted engine variant will be 2.4dB quieter at take-off compared to a wing mounted variant (equivalent to 6dB overall reduction). An embedded engines variant (embedded onto the fuselage) gives a further 2.5dB reduction (5dB overall) as shown in Figure 3.

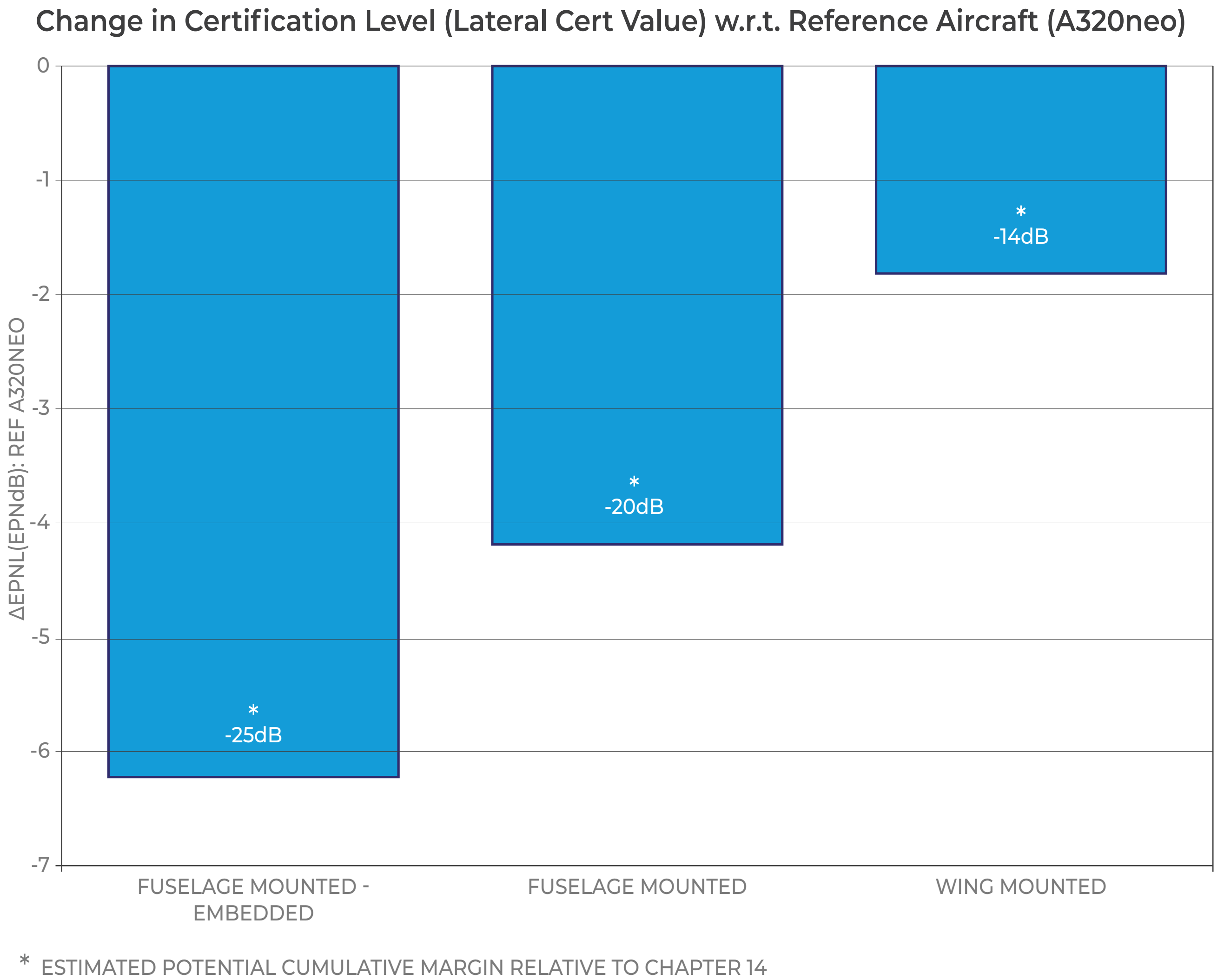


Figure 3 – Powerplant Installation Effects (Source: FlyZero).

The study concluded that FlyZero's three proposed concept aircraft have the potential to be competitive regarding noise with other worldwide future aircraft studies as shown in Table 2.

Concept Aircraft	*Estimated Potential Cumulative margin relative to Chapter 14*
Regional (FZR-1)	*-16dB*
Narrowbody (FZN-1) – Fuselage Mounted Engines	*-20dB*
Midsize (FZM-1)	*-9dB*

Table 2 – FlyZero Concepts Estimated Potential Cumulative Margin Relative to Chapter 14.

Finally, an assessment of technology gaps was completed together with the drafting of a technology roadmap to help the concepts progress through to the design stages to their required entry into service dates.

Further Research

It is recommended to continue to use quick, low fidelity noise prediction tools for supporting airframe, nacelle and engine design in a system engineering context. This must be done throughout all phases of the aircraft design to identify dominant sources of noise and aim to eliminate or reduce their impact by design.

To complement the existing work would include higher fidelity computational aeroacoustic modelling techniques to assess the design in terms of noise at aircraft level. This would include novel architectures such as distributed propulsion and the definition of design rules to prevent aeroacoustic interactions.

Noise source modelling is required for new propulsion architecture: compressor, turbine, electric motor and any bleed systems. Hydrogen combustion is a high-risk area so early measurements on test rigs would provide further understanding and help with mitigation.

Modelling and wind tunnel testing of novel features such as cooling intakes to the fuel cell stacks, distributed propulsion and open rotor engines is recommended.

Explore aircraft design and engine cycles with varying take-off and landing climb/descent gradient. How aircraft are operated has a significant bearing on noise, fuel-burn and emissions. Operational noise mitigation opportunities are available and may potentially influence aerospace management around airports.

It was also recognised during the project that opening collaborations between other organisations would be beneficial, for example;

- The aerodynamic design of high lift devices (Cranfield University) could be complemented with the technology’s impact on noise by the University of Southampton.
- Hydrogen combustion rig testing (Cranfield University) could aid the University of Southampton’s understanding of hydrogen combustion noise if the rig set up is adapted to acquire the relevant data.

02.2.3 ELECTRIC MOTOR DESIGN

This study with Nottingham University was commissioned in order to understand the current state-of-art in electric motor technology, along with future trends over 5-10 years, and associated performance characteristics.

The work package covers 0.5MW to 10MW motors. No constraints were given on motor technology, family, or topology, however considerations were made for the aerospace operating environment.

Research Findings including Areas for Further Research

The National Composites Centre provided specialist design advice to the project team. The main findings are as follows;

- The radial surface permanent magnet (PM) machine with high performance materials is the topology of choice for aircraft propulsion and represents the state-of-the-art (SOA). The construction typically features high energy density SmCo magnets, low-loss CoFe laminations, and coil designs for mitigating AC losses at high frequencies. This, together with the use of direct-cooling, and traditional machined lightweight passive components in aluminium/titanium, enable the topology to achieve power densities in the region of 4-6kW/kg between 1500-2500rpm.
- Higher power densities can be achieved by using lower TRL/MRL topologies, namely the Dual-Rotor Radial PM and Vernier PM topologies, with potential to improve power density by 30% and 50% respectively. The former needs addressing in terms of the mechanical design and assembly, whilst for the latter the benefits in motor power density need to be carefully evaluated with the implications on PE converter (VA rating, losses etc.).
- High frequency (>1kHz), high fill (>80%) preformed windings combined with a high temperature insulation recipe (300°C) have great potential for improving the kW/kg boundaries of SPM machines by as much as 200% compared to the existing SOA.
- Reducing the weight of passive components through the use of 3D printing and composites has the potential of reducing passive mass by as much as 50% and improving the machine power density by 30%.
- In general, for a given topology, the power density can be improved by accepting lower efficiencies. Taking the reference 500kW 2000rpm node as an example, the power density can be improved from 4kW/kg to 7kW/kg by accepting a 2% reduction in the efficiency.
- The power density increases with speed and does so markedly at low speeds. At higher speeds (>6000rpm), the advantage of increasing the speed for achieving higher power density is more significant if a higher fundamental frequency can be used.
- For high power propulsion motor (>1MW) a geared option has the potential to achieve higher overall kW/kg, especially if a high frequency machine design is employed.

02.2.4 HYDROGEN TANK DESIGN – COMPOSITES/ MULTI-MATERIAL

The National Composites Centre supported the FlyZero Energy Storage team with developing hydrogen (liquid and gas) and ammonia (with cracking) tanks concepts and solutions and deliver the following main outputs:

- Shape.
- Volume.
- Weight.
- Material choice and material properties.
- Structural sizing: loads, static and fatigue analysis.
- Insulation materials.
- Technology maturity.
- Flight physics performance (i.e., resonant frequencies, CG movements, etc).
- Tank cost drivers.
  - Cost to develop and validate underpinning materials & manufacturing technologies.
  - Identification of key capital and infrastructure costs for production.
- Manufacturability assessment of current MRL and timeline and key milestones to mature MRL aligned to industrialisation.
- Life cycle sustainability assessments.

Research Findings

The National Composites Centre provided specialist design advice to the project team. The main findings are as follows;

- Weight benefit for composite wall tanks translates to significant lifelong cost saving. Positive $2000/Kg weight saving, 500 kg saving on inner wall, two walls and four tanks offer a compelling saving with an outer vacuum wall potentially offering a greater benefit.
- Stress sizing would give a very thin wall thickness with efficient use of plies. New technology ply spreading would help this.
- Microspheres can offer a good level of insulation and can be incorporated in MLI options, but the TRL level is currently low.

- Outer wall sandwich panels are identified as an opportunity for weight optimisation and redundancy where an extra thermal resistant filler would support a failed insulation material for thermal protection.
- Thermal shock is an uncertain phenomenon and research is required. It may be resisted by polar resin materials-H_2 being non-polar.
- Microcracking can be reduced through stringent manufacturing and possibly thin plies, ply spreading and pre-tensioning to align fibres.
- Crystalline and polar structures are known to improve cracking vs embrittlement and studies required to quantify.
- Tooling is a consideration for composite tank building. Collapsible tools may be feasible and mandrels which are used as liners can double up as tooling where tanks are wrapped externally.

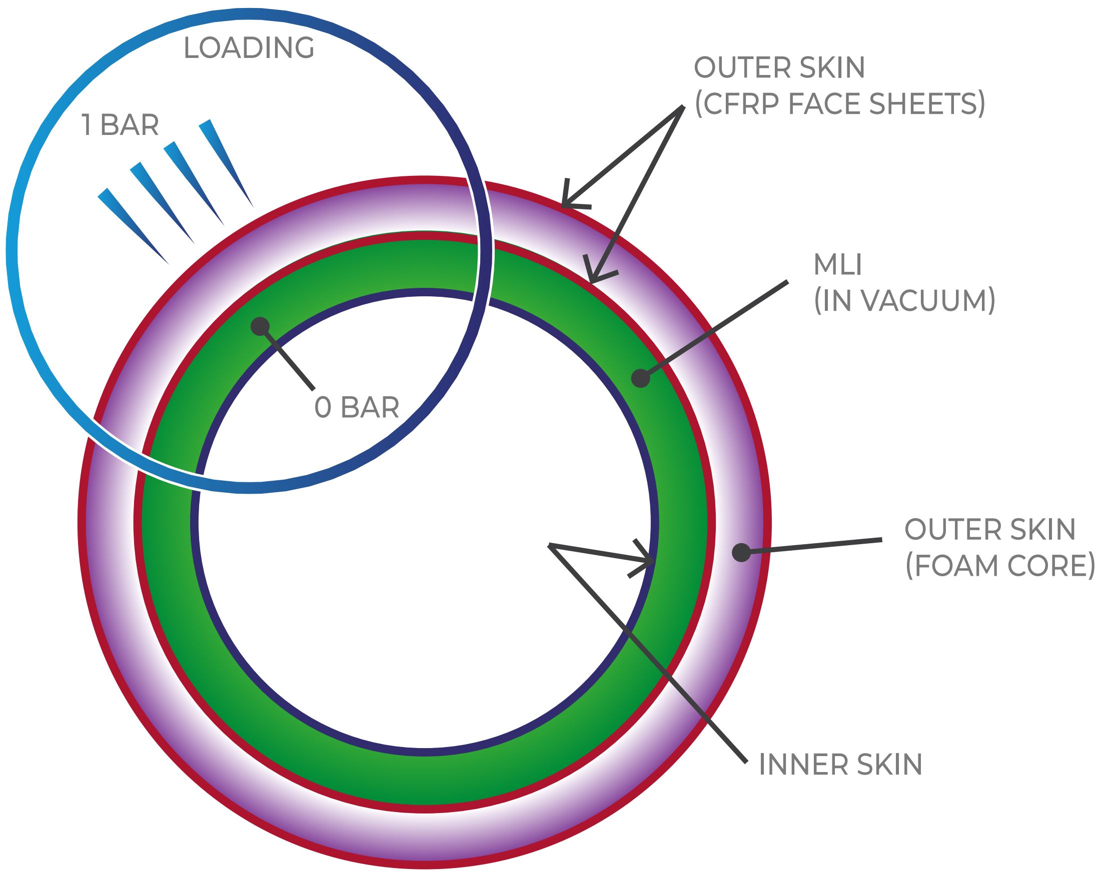


Figure 4 – Example tank cross-section (Source: FlyZero).

Further Research

The following priority further research activities have been identified;

- Material properties and efficacy at cryogenic temperatures and hydrogen; repulsion, embrittlement or permeation need further research. Thermal shock is predicted as a challenge area which may be mitigated by slow purging, but this needs to be better understood.
- Microspheres offer an opportunity for insulating material studies for use in multi-layer insulations.
- Resin technologies, materials, and matrices to maximise strength and durability offer opportunities. The properties of resin materials to optimise the benefit of repelling hydrogen through the non-polar nature of hydrogen and trade the counter benefit of embrittling crystalline structures.
- Specific studies on vacuum tank technologies and configurations are required. The most likely benefit is where the outer wall vacuum renders the tank wall susceptible to buckling. Sandwich panels with a structural and thermally insulating foam to part the carbon face plies could be a solution.
- Manufacturing techniques can be improved to eliminate voids and microcracking. NCC created a purposely envoided (a part with voids) and microcracked sample which they forced microcrack growth and recorded the progress of the crack. This requires studies on the manufacturing methods to improve material properties, inspection equipment for maintainability and testing must establish firm properties.
- Sensors for composite tanks and structural health monitoring should be studied and 3D printing for tanks.

02.2.5 HYDROGEN TANK MANUFACTURE – METALLICS

The Advanced Manufacturing Research Centre (AMRC) supported the FlyZero Energy Storage team with a small study reviewing the manufacturing options including identification of candidate materials, a sub-component breakdown of the tank production method, review of competing technologies and highlighting gaps in the current technology and supply chain capability.

Research Findings

For the manufacture of metallic tanks to store LH_2 there are several processes currently available that can produce the necessary constituent elements of the tank sides and ends. In some cases, there is no clear single technology choice as each process has its merits and limitations.

For the forming of the domed ends, both spin forming and stretch forming are commonly adopted for the fabrication of metallic tanks as well as being accepted routes to the production of aircraft components and structures.

The final detailed design of the tank configurations may favour one technology over another, this may be determined by size and shape or by the need to incorporate additional features such as stiffening ribs or ported fittings.

No significant technological barriers are anticipated, though some process efficiency improvements may be required to achieve ambitious build rates of 100 plus per month by 2050. This will likely focus on tooling, machining optimisation and the welding of large structures in thin material.

Alternative and emerging processes such as integrally stiffened cylinder flow forming, hot quench forming, additive manufacturing and mandrel-free spinning could realise additional cost or productivity benefits, but development would be required to scale these up to the size required for these large >2m diameter components.

There are several aerospace supply chain companies with the required capability to produce these tanks, though it is likely that further investment would be required in specific manufacturing cells if the volumes anticipated are realised on a commercial scale.

Future Research

An area that requires immediate focus is the lack of materials data representative of the in-service conditions. The long-term durability properties such as fatigue, fracture and corrosion within a cryogenic hydrogen environment do not exist at the present time. Without this data, design allowables cannot be determined and hardware cannot be verified as being fit for service.

02.2.6 PERI-DYNAMICS

Compared to conventional kerosene, there are various benefits of liquid hydrogen such as no CO_2 emission during flight, lower fuel weight and high energy density. Conversely, several disadvantages include reduced volumetric energy density and extremely low boiling temperature. Liquid hydrogen requires cryogenic tanks for storage potentially using fibre reinforced plastic cryogenic pipes with metallic liners. Cryogenic pipes are subjected to high pressures and extreme temperatures, making their durability an important concern.

Research conducted by University of Strathclyde assessed the optimisation of cryogenic hydrogen pipes using a new computational methodology called Peridynamics. Peridynamics is a powerful technique for failure prediction in materials and structures due to its mathematical structure based on integral equations.

The current peridynamic model for composite materials was extended to represent a cryogenic hydrogen pipe. The model was verified by considering a benchmark problem. Then, based on the material, geometry and loading information the model was used to analyse a cryogenic hydrogen pipe under pressure and temperature loading conditions. Next, an optimisation study was performed by changing orientations of composite material and liner thickness. Based on the optimisation studies, pipes' manufacturability assessment and pipes' cost drivers analysis is performed.

Research Findings

In this project, a cryogenic hydrogen pipe under pressure and temperature loading conditions was analysed using finite element method (FEM) and peridynamics. FEM was initially used to determine the stress variation and critical locations of the pipe. Peridynamics was then utilised to determine the failure load and to understand how the cracks initiate and propagate. Modelling results show that significant thermal stresses were generated due to the cryogenic temperatures of the liquified hydrogen and clamped boundary conditions of the pipe at two edges connecting the pipe to the engine and the fuel tank. It was also determined that the required pressure for damage initiation is higher for a steel pipe with respect to aluminium. To reduce the stress levels, different support conditions were investigated. First, the pipe was clamped at several locations along the pipe by fixing all motion of those locations. These boundary conditions were then relaxed by allowing axial movement. However, stress reduction was not observed although many different support configurations were considered. In addition to metallic materials, composite materials (CFRP) were also considered. It was observed that significant stress reduction can be obtained for a cross-ply lay-up sequence. The stress variation due to the inclusion of steel and aluminium liners on composite pipe was also investigated. It was observed that as the aluminium liner thickness increases, the stresses increase and exceed aluminium pipe stress levels. On the other hand, for the steel liner, stresses increase rapidly but converge to stress levels much lower than the steel pipe stress equivalent levels. There are several aerospace supply chain companies with the required capability to produce these tanks, though it is likely that further investment would be required in specific manufacturing cells if the volumes anticipated are realised on a commercial scale.

Further Research

The material properties used in this work were extrapolated from higher temperatures due to the lack of materials data at 20K. To improve the accuracy of the modelling results, materials data at 20K such as fracture toughness would be needed. One of the topics that has been identified as a priority to be investigated further is the influence of hydrogen (in addition to pressure and temperature) on metals and composite materials. The aim is to understand the hydrogen embrittlement phenomenon which may significantly change the fracture behaviour of metallic and composite materials. This can be investigated by performing multi-physics analysis to determine hydrogen concentration inside the pipe and to understand its behaviour. Finally, it would also be beneficial to perform fluid-structure interaction analysis to determine the potential leak of hydrogen in the event of pipe damage.

02.2.7 PROPULSION SYSTEM DESIGN

FlyZero's objective for net zero carbon emissions led to a number of options being considered for reducing mission fuel burn. FlyZero worked with Cranfield university to further understand the following questions:

- Whether water injection during take-off would allow a smaller, more efficient core during cruise while meeting the take-off thrust requirements without exceeding the maximum turbine temperatures. A feasibility study for cycle optimisation around this concept is required to understand the trades and maximum potential benefit.
- Mission optimisation: Significant excess fuel is burned because the aircraft is flown within a constrained flight trajectory. Assess the potential fuel burn reduction if the flight profile is not a constraint.
- Open rotor and hybrid propulsion: understand their feasibility and fuel burn benefit for the market sectors being considered. Highlight limitations and challenges, including technology maturity, installation constraints, and certification.
- Contrail avoidance: a number of technology proposals exist that would eliminate or significantly reduce formation of contrails. An assessment of the impact on a hydrogen-fuelled gas turbine cycle is required to understand their feasibility.

Topic	*Task*	*Questions to answer*
Baseline cycles	*Generate thermodynamic performance models of the baseline engines and assess against their respective flight profile*	*What is the baseline performance we're assessing against?*
Baseline cycles with different fuel	*Run the baseline cycles with hydrogen and ammonia. Re-assess their respective mission*	*What is the amount of fuel required relative to kerosene relative to kerosene?*
Open rotor	*Design and optimise open rotor equivalent of baseline cycles running on hydrogen and/or ammonia*	*What is the fuel burn benefit of open rotor for that market sector?*
Water injection	*Add water injection to the existing baseline cycles. Explore compressor and combustor water injection. Re-assess mission fuel burn.*	*What is the benefit of water injection with the baseline cycle?*
	Understand any penalty in engine cycle due to thrust requirement constraints. Optimise cycle for cruise with water injection used to augment thrust during high thrust phases (take-off and initial climb).	*What is the benefit of water injection if the cycle if optimised for cruise?*
		What is the maximum amount of thrust boost achievable?
	Assess feasibility of using water / steam from on-board sources.	*Can we combine water injection with other technology on-board, e.g. fuel cells?*
	Assess feasibility of recovering water from exhaust of hydrogen combustion and impact on cycle. Steam injection or hot water injection.	*Can we use the waste exhaust water in the hydrogen combustion products for water injection?*
		How much can this contribute to reducing contrails?
Mission optimisation	*Assess benefit of optimising mission for the engine (e.g. cruise climb)*	*How much are the mission constraints costing in fuel?*
Hybrid propulsion	*Convert baseline cycles to hybrid with the gas turbine driving an electrical generator. Assess impact on weight, drag, etc. Re-assess mission fuel burn.*	*Understand the trade of hybrid propulsion back-to-back with gas turbine.*
Contrail avoidance	*Literature and patent search, feasibility study, impact on cycle of proposed technologies. Assume SAF, hydrogen, and ammonia fuels.*	*What contrail avoidance technology is feasible for a gas turbine and what is the impact (sfc, etc..)?*

Table 3 – Scope of priority research questions.

Research Findings

The team at Cranfield University studied three hydrogen-fuelled aircraft to provide insight on the differences between a kerosene aircraft and its hydrogen equivalent: an A320-sized, 767-200ER sized jet aircraft powered by UHBR (Ultra High Bypass Ratio) geared turbofans, and a small ATR72-type turboprop regional. For the hydrogen version compared to its kerosene equivalent it was found that:

- It is lighter at take-off but lands heavier.
- Has higher cruise drag.
- Has more favourable thrust ratios for engine cycle design.
- Is comparable in mission block energy usage relative to kerosene or SAF within the level of uncertainty and assumptions.
- The optimum cruise altitude does not vary significantly over the mission, making a step-climb unnecessary.

For each aircraft, the possibility of hybridisation was studied in a configuration where an electric motor supplemented the engine fan shaft power through parts of the flight. This was powered by either a battery pack or fuel cell with results showing the weight of such systems, especially the fuel cell, significantly reduces most of the potential fuel burn improvement.

Batteries are indicated to be the more promising option to achieve a fuel burn benefit coupled with an engine re-designed with a smaller core. The systems can alternatively be used to improve engine life by reducing the core temperatures during take-off and climb, as well as reducing NO_x.

A similar study using water injection, showed some fuel burn improvement as the water is consumed during the initial phases of flight and therefore is not penalising the rest of the mission, but the more beneficial use is to reduce cycle temperatures and NO_x during take-off.

The Open Rotor study identified that the technology could deliver similar performance benefits for kerosene and hydrogen. An assessment on the viability of ammonia indicated that its utilisation is accompanied by a significant range penalty, despite the benefits at engine cycle level.

A review of contrail formation mechanisms and how these relate to a hydrogen cycle showed how theoretically a hydrogen cycle could produce more contrails, but with a large uncertainty on the sensitivity to the removal of soot particles in the exhaust compared to kerosene. Recent publications indicated this could result in less contrail formation than originally estimated. A study on possible contrail avoidance technologies indicated that methods such as heat exchanger-based water extraction require further developments as they pose a significant cycle efficiency penalty. The most practical solution is to change the flight trajectory for the small number of flights that could generate persistent contrails, depending on the weather conditions, for which a fuel burn penalty can be estimated.

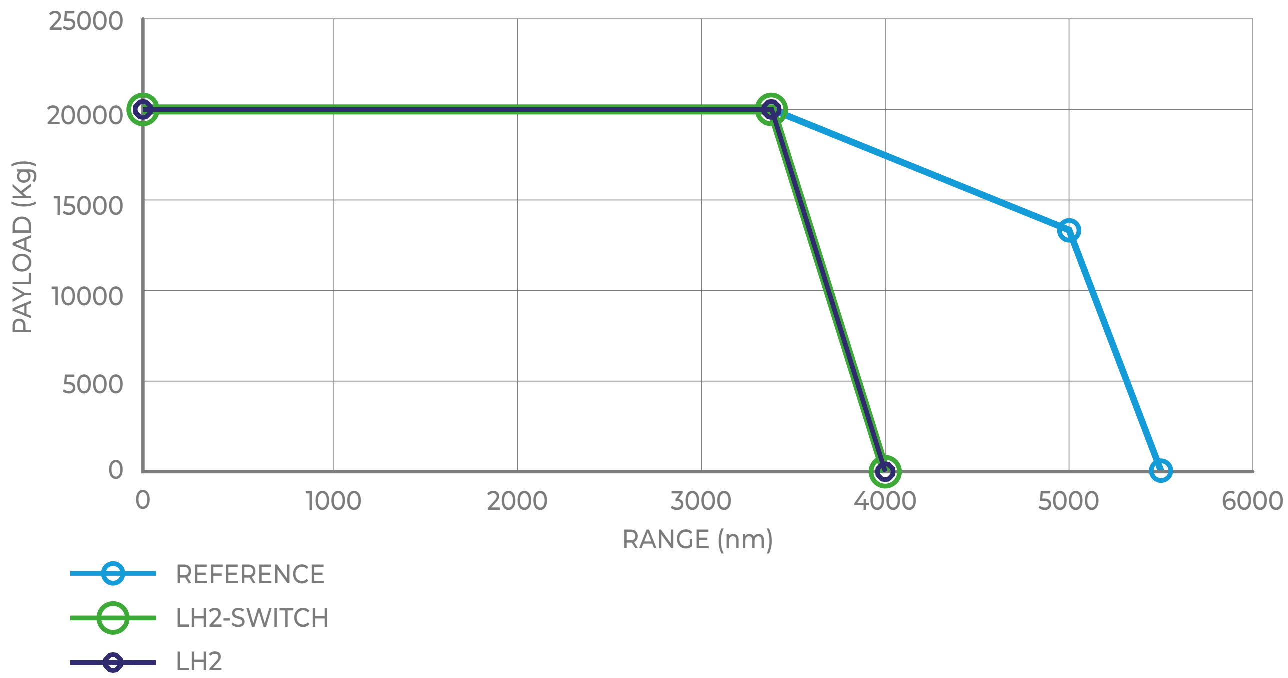


Figure 5 – Payload range diagram for a narrowbody A320-type aircraft: kerosene, direct switch to hydrogen, and optimised for hydrogen (Source: University of Cranfield).

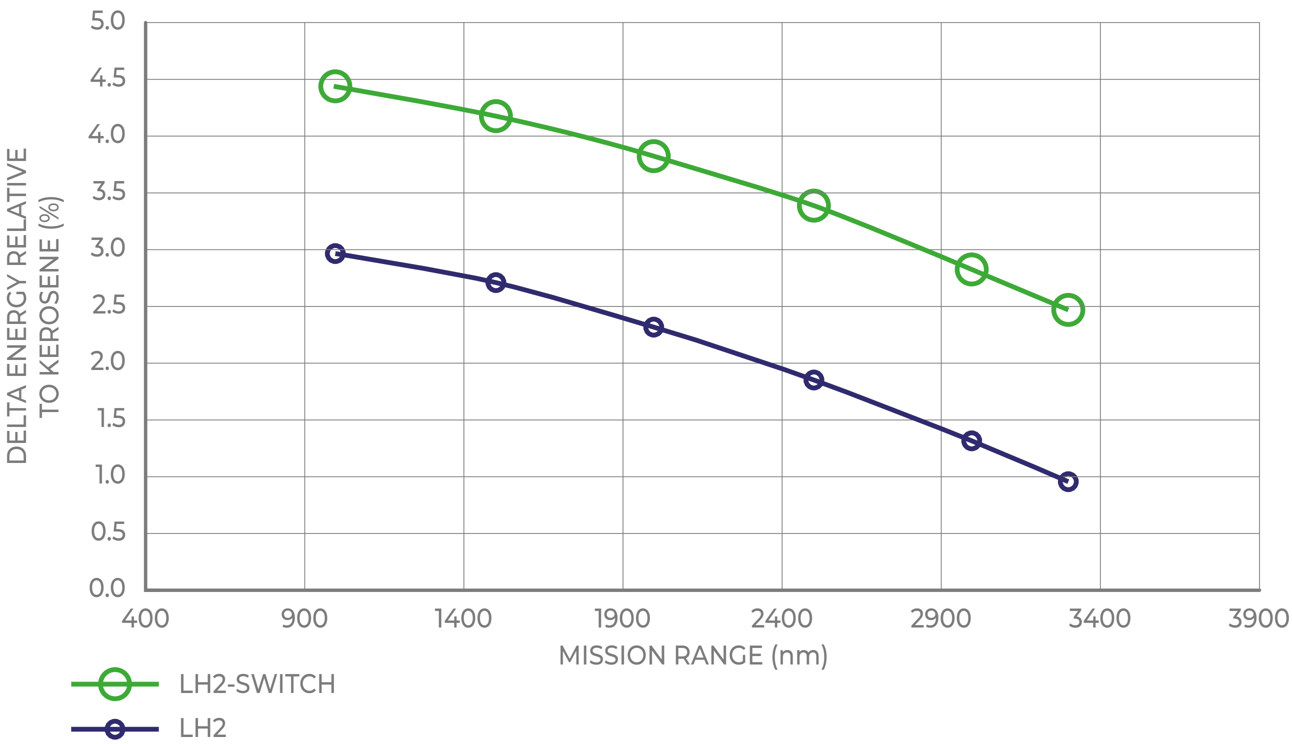


Figure 6 – Difference in energy of direct switch and optimised aircraft relative to kerosene equivalent at various off-design mission ranges (Source: University of Cranfield).

The outputs from this work package have been used to inform the Hydrogen fuel storage and distribution roadmap, which is a separate document available via the ATI with document reference FZO-PPN-MAP-0026 **[3]**.

Further Research

A comprehensive list of further research has been identified;

Gas Turbine

Fully assess the engine / aircraft design space in conjunction with future technologies:

- Explore the optimum thrust ratios for hydrogen aircraft and engine combination.
- Trades and optimise the engine SFC (specific fuel consumption) vs weight and drag for hydrogen aircraft.
  - For overall minimum mission fuel burn.
  - For both maximum and partial range capability of the aircraft.
- Trades between lower specific thrust cycles (geared high BPR, large fan diameters) and engine weight and drag, including assessment of future weight and drag reduction technology that could make larger fans more feasible.
- Detailed cycle modelling and assessment of a hydrogen engine aligned with new technology and future high BPR and OPR (Overall Pressure Ratio) cycles, including the modelling of the hydrogen fuel and thermal system (e.g. oil-to-fuel, recuperator).
- Technical and economic assessments.
- Certification challenges and scenarios for certification acceptable compliance.
- Alternative variable geometry actuation systems.

Dual fuel:

- Assess the aircraft and wings' design to accommodate this flexibility.
- Utilisation of fuels for block fuel/emissions reduction to quantify the benefits.
  - SAF, NH_3 as H_2 carrier maybe as an alternative for specific cases.
- Technical and economic assessments.
- Combustor feasibility and risks, integrating industrial gas turbines experience.

Open rotor:

- Assessing a contra rotating open rotor against an open fan.
- Noise, maintenance cost and certification.
- Technical and economic and mission / operational impact assessments.

Hydrogen Propulsion

Electrification has several synergies with low temperature H_2, since hydrogen may be used as a heat sink for the electric equipment, while hydrogen fuel cells can be incorporated for main or auxiliary power:

- Assess different/novel propulsion concepts (BLI (Boundary Layer Ingestion), distributed propulsion) (2035+), advanced integrated motor/generators in the core that can be used for hybridisation and change the work split across the flight cycle (transfer load across shafts) to give;
  - Better control of operability limitations.
  - More efficient extraction of power off-take.
  - Possible help with shaft overspeed in shaft failure conditions.
  - Reduce bleed-off and variable geometry weight/requirements.
- Look at engine redesign, since electrification extends the design space.
- Superconductive high-power systems for reducing weight penalty and increasing system efficiency capitalizing on hydrogen as heat sink would need investigation.

Fuel Storage

- Assess the integrated tank-propulsion system-aircraft design to identify an optimum combination energy wise for an LH_2 aircraft utilizing FC to power auxiliaries. The FC will be fuelled from tank venting (boil-off) that will allow for lighter storage tanks. The FC can also be utilized when the aircraft is on the ground. In this context it is important to assess gas turbine/fuel cell/tank optimum integration.
  - Optimise the tank to account for pressure release induced by utilization of vapour in the fuel cell.
  - Match gas turbine-fuel-cell-tank architecture for optimum performance.
  - An optimum integration will increase the venting mass flows when engines are switched off. Assess viable methods to deal with venting hydrogen when aircraft parked. Distributed electricity generation feed into airport, reliquefying trucks, catalytic conversion in aircraft are some technologies with promising solutions.
  - Assessment for long range applications.
  - Study opportunities for further reduction in tank weight, and novel approaches to storage such as removable tanks to improve part-range performance.

Fuel System- Thermal Management

Developing the fuel system, which encompasses equipment from tank exit up to the combustor, will be a challenge due to hydrogen's properties, the temperatures considered, the significant density change throughout the system and the need for fully controllable fuel heating.

- Integrated fuel and thermal management systems design requires:
  - Design system(s) at mission level, optimizing the energy and power management of the subsystems and considering component part load operation.
  - Perform operability and transient analysis for the feasible architectures using suitable dynamic models integrating all systems for assessing feasibility and controllability.
  - Identify solutions for the start-up and re-light of the fuel system/engine.
  - Establish requirements for different control mode categories including steady-state, transient control mode, and physical limitations.
  - Modelling of small- and large-scale leak and ignition scenarios for LH_2/H_2 for various aircraft accident scenarios.

The outputs from this work package have been used to inform the Fuel Cell Roadmap, which is a separate document available via the ATI with document reference FZO-PPN-MAP-0032 [4].

02.2.8 PERFORMANCE ANALYSIS - GAS TURBINE

We worked with University of Oxford on performance analysis to explore the merits and feasibility of a gas turbine using hydrogen and/or ammonia as a fuel. Baseline models were developed to assist with trades and look at how overall efficiency can be improved above 50%. This included topics like water injection, intercooled cycles, and hybridisation of the power train to improve the aircraft concept.

Research tasks	*Motivation*	*Reason to be answered*
Define a range or performance model for a geared turbo fan using H_2 or H_2/NH_3 mix, or kerosene for a range of payloads and ranges	*Baseline cycles to explore the design space*	*Architecture definition and cycle parameters. Pugh matrix to determine the best gas turbine solution*
Same as above using propeller or twin rotor/ open rotor	*Trade of fan, prop, open rotor, to see how missions effect the answer*	*Architecture definition and cycle parameters. Pugh matrix to determine the best gas turbine solution*
Add an intercooler in the compression cycle to exploit fuel heating; do intercoolers offer a large efficiency improvement (>5% overall efficiency benefit) architecture definition and cycle parameters. Pugh efficiencies for the favourable cycles from activities above	*Do intercoolers offer a large efficiency improvement (>5% overall efficiency benefit)*	*Architecture definition and cycle parameters. Pugh matrix to determine the best gas turbine solution*
Add water injection into the cycle to increase efficiencies for the favourable cycles from activities above (water injection for take-off and climb only)	*Does water injection offer a large efficiency improvement (>5% overall efficiency benefit)*	*Architecture definition and cycle parameters. Pugh matrix to determine the best gas turbine solution*
Explore interturbine combustion or heat exchanger cycles using the baselines from above	*Will interturbine combustion or heat exchanger offer a large efficiency improvement*	*Architecture definition and cycle parameters. Pugh matrix to determine the best gas turbine solution*
Model hybridisation of basic cycles where the gas turbine drives a generator, or has embedded electrical motor/generator capability, or the gas turbine is combined with a fuel cell or batteries	*Do hybrids help*	*Architecture definition and cycle parameters. Pugh matrix to determine the best gas turbine solution*

Table 4 – Scope of work and rationale.

Research Findings

Studies were carried out into the use of cryogenic liquid hydrogen in heat exchanger cycles for UHBR (Ultra High Bypass Ratio) turbofan engines, with the goal of conditioning the fuel for combustion whilst utilising its heat sink capability to improve cycle efficiency and reduce fuel consumption. The studies assessed and optimised the use of oil-to-fuel heat exchangers, intercooling, core nozzle recuperation, cooled cooling air, and the use of an expander cycle.

The use of a core nozzle recuperator coupled with an oil-to-fuel heat exchanger was determined to be a viable solution with a 2% SFC (Specific Fuel Consumption) benefit over the baseline of using just an oil-to-fuel system. An extension to this is the use of helium as an intermediatory fluid to avoid passing hydrogen through the core nozzle, which had a small SFC penalty but significantly increases the safety of the system. The cryogenic liquid fuel pump was highlighted as a key challenge, due to its much smaller size and reliability required relative to the ones currently used in the space industry. The use of an expander cycle and cooled cooling air offered additional benefits in the order of 2% and 1% respectively, although they are more technically challenging. Although an intercooler can offer a SFC benefit, it is more beneficial to use the heat exchanger as a recuperator.

Use of an inter-turbine combustion, given the hydrogen needs a relatively shorter combustor, was also studied but found to not offer a benefit.

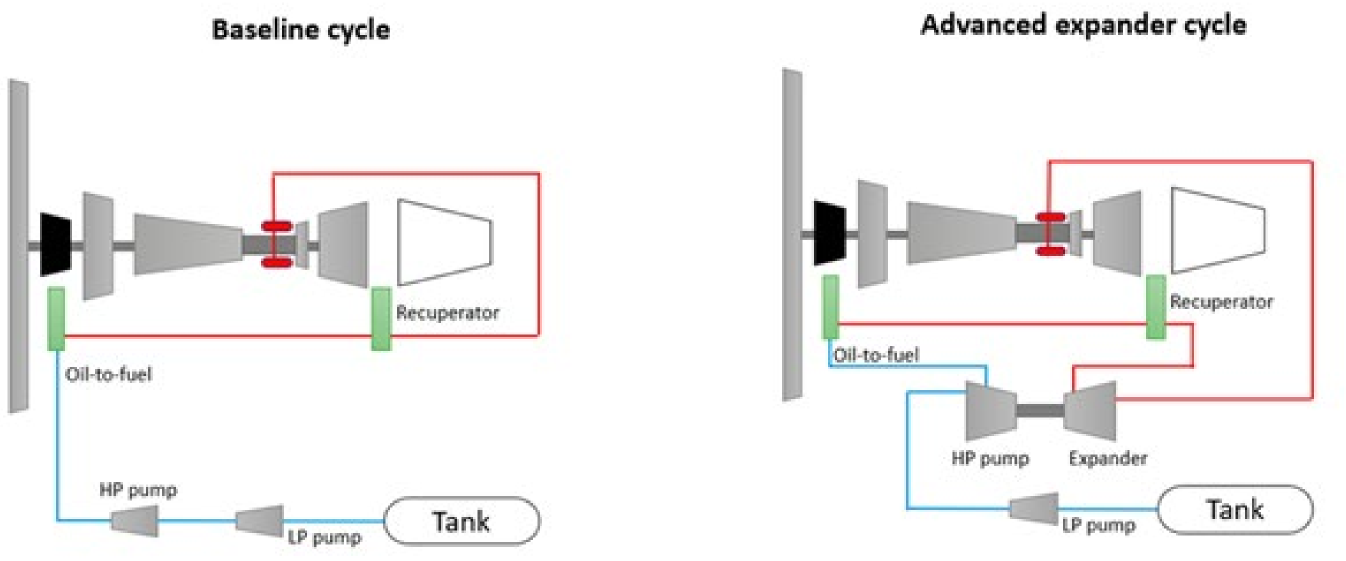


Figure 7 – Baseline and advanced expander cycle (Source: University of Oxford).

Further Research

Further studies targeting a first-generation engine would add an air system model to the current capability to refine the baseline oil-fuel heat exchanger and recuperator engine architecture as well as throughflows of the gas path to firm up radii, length of the compressors & turbines, bearing locations and the configuration of the LP outlet.

Assessment to find out if the stage matching for the HP compressor for the hydrogen engine needs to look different from the corresponding kerosene engine in view of the different slope of the working line.

Detailed design questions for the recuperator and the fuel/oil heat exchangers would refine the recuperator installation layout and define a plausible engine general arrangement.

Further studies to exploit the low temperature of the fuel through expander cycles, which were shown to be advantageous. Specifically address the design of the turbopump and the hydrogen machinery and transmission layout for such a system. This can include throughflow calculations for the hydrogen path, with the understanding that the best option to drive the pump may not be a direct drive from the expander.

Another way to exploit the low temperature of the hydrogen is to use it as conditioner for the cooling air. Explore further the option of using cavity air, on its way to or from cooling devices, for the recuperator. This can be done through the development of an air system network model to address these opportunities in more detail, and define a range of improved first-generation engines, or second generation engines with drastically different technologies.

02.2.9 CRYOGENIC FUEL SYSTEM, GAS TURBINE AND THERMAL MANAGEMENT

This research project provided consultancy based on Cranfield University's experience on the ENABLE H_2 work, as follows;

- A review of the ENABLE fuel system architecture, with rationale for design choices.
- An assessment of the FlyZero baseline architecture.
- Support for definition of alternate architecture.
- Discussion about requirements, operational constraints and how this will drive some design/ architecture decisions.
- A review of the safety scenarios to consider for the fuel system and an assessment of the various architectures.
- Sharing existing papers to develop the FZ team knowledge.
- Combustion discussions were also held as part of this package. Also, 2 workshops were prepared by Cranfield university (1 online and another on campus). These workshops helped to understand the capabilities and the latest advancements in hydrogen combustion, both experimentally and numerically.
- The FlyZero combustion roadmap was discussed and reviewed.
- Some insights and discussions on contrail formation.

Research Findings

The following alternate architecture for managing the over and under pressurisation of the tank and the system was defined:

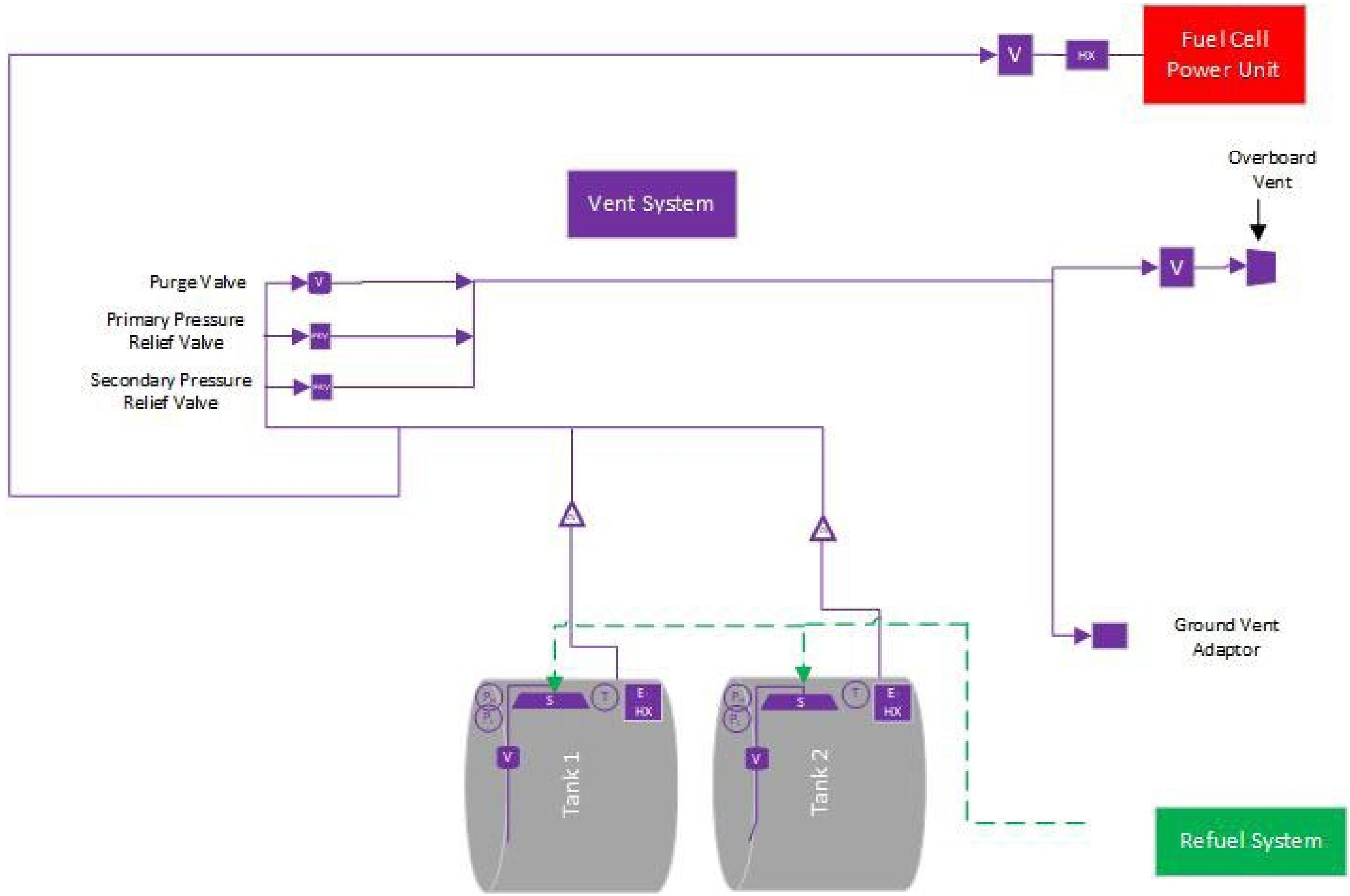


Figure 8 – Alternative Vent and Pressurisation System (Source: FlyZero).

Compared to our baselines and assumptions, alternate sizing cases, architectures and technologies can be considered:

- The tank insulation can be sized to balance the heat leak with the engine flow so that there is no venting during the chosen flight phase (cruise).
- The overpressure can be managed through recondensation of the gaseous hydrogen using liquid hydrogen recirculation within the tank.
- The tank pressurisation can be achieved through generating boil-off by heating the ullage, saving system complexity and weight.
- The dormancy time for a given tank insulation can be improved by introducing a stirring device to homogenise the temperature of the liquid & gaseous hydrogen in the tank.
- Other considerations include a buffer storage tank to ensure continuity of the fuel supply in critical phases where the boost pump may not be able to provide the fuel flow (in negative G condition).
- Installation of fibre optic around the foam could be used to detect leaks by measuring the temperature drop (Bragg interrogator).

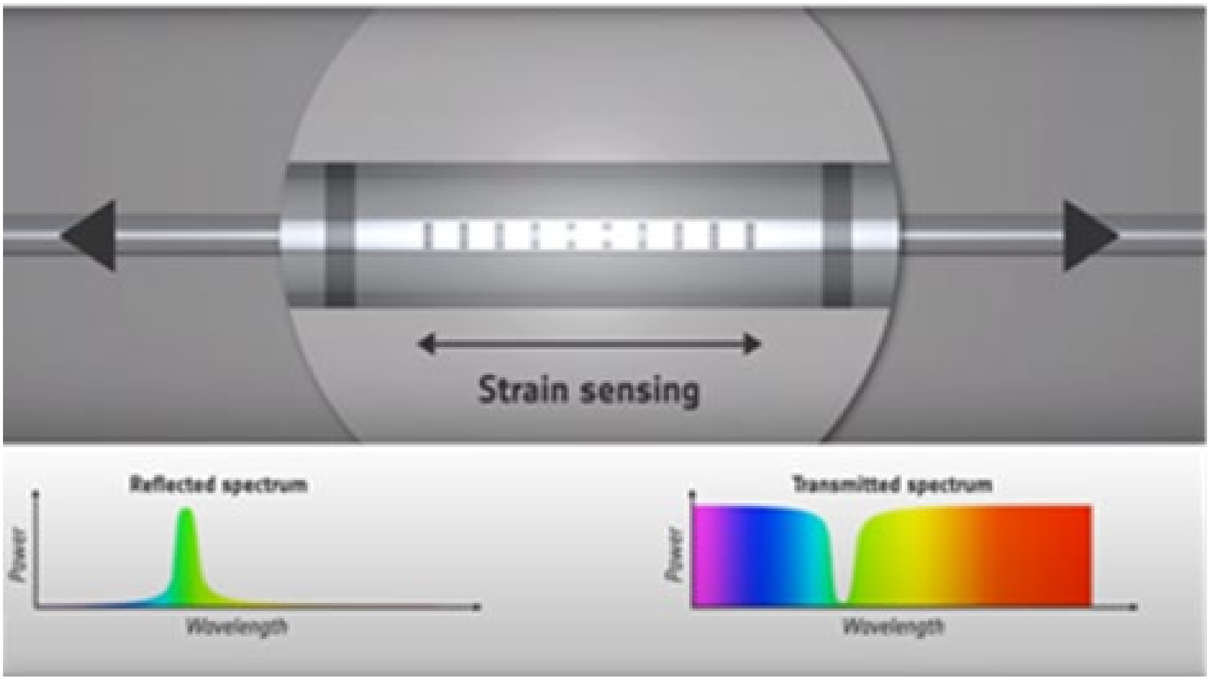


Figure 9 – Fiber Bragg Gratings principles (Source: Courtsey of FBGS International).

The outputs from this work package have been used to inform the Thermal Management Roadmap, which is a separate document available via the ATI with document reference FZO-PPN-MAP-0018 **[5]**.

Further Research

The work done is theoretical and no sizing activity was completed for the systems described. The principles explained could be modelled using GFSSP software, The modelling and sizing of the alternate architecture defined is proposed to be done by the FlyZero team in a further phase.

- Integration of the operational side: the requirements for being able to leave the aircraft on the ground not connected to a ground service equipment is currently the baseline case. These operational/airport requirements have not been considered.
- Consideration of fuel cell auxiliary power unit fed by boil off hydrogen in the architecture could be studied in a further phase.
- Impact of chosen insulation needs to be assessed for different engine flow demand, with trades studies.
- Discussion the possibility to run combustion tests at higher pressures.
- Integration of cryogenic system for further testing and validation of models.

02.2.10 BATTERY FEASIBILITY

Research Findings and Further Research

The primary attributes for electrical energy storage to be viable for zero-emissions flight are safety and gravimetric energy density (Wh/kg). One of the key engineering considerations for safety is thermal propagation containment. Achieving this typically will have a negative impact on the pack level energy density because more material must be added, increasing their physical size and mass.

State of the art battery technology development is being led by the rapidly growing automotive electrification sector, but this falls short of the level of safety and energy density required by aerospace. Large scale investment and venture capital money is entering the battery supply chain, but focused on automotive attributes and Gigafactory supply opportunities. Recent investments in Urban Air Mobility companies may help to push forward aerospace specific battery research and supply chain development.

Volume production capable battery developments within the next 15 years will not get close to the aspirational target from FlyZero for an electrical energy storage system that delivers >1kWh/kg whilst meeting all of the other attribute targets. However urban air mobility craft manufacturers believe that >200Wh/kg will be feasible within the 2025 timeframe. This level of pack energy density is feasible with current technology however there is likely to be a trade with pack life and this will result in lifetime that will be far shorter than existing automotive expectations.

This will mean that early aerospace applications will be very sensitive to the whole life costs of battery packs.

Batteries will be the first zero-emissions flight technology on the market and their penetration will grow as energy density improves enabling either longer life or extended mission profiles and larger forms of aircraft. However there needs to be ongoing research supporting safety, greater energy densities, developing a viable aerospace cell supply and recycling chain.

02.2.11 POWER ELECTRONICS AND HIGH VOLTAGE SYSTEMS

This research activity with Nottingham University assembled knowledge on the current state-of-art high voltage and power electronics technology, future trends (next 5-10 years) and their associated performance characteristics. This project explored the electrical system design space and its impact on the powertrain, providing technical expertise to the FlyZero team.

Research Findings

University of Nottingham delivered the exploratory work package on the research of high voltage system & associate power electronics for a zero-emission aircraft. These are the primary findings of the research.

- The biggest performance boast from power electronics & HVDC system can be achieved by an integrated design approach. Designing the motor, invertor & DC-DC convertors simultaneously open a lot of opportunities of overall system performance improvement, particularly gravimetric power density.
- Multi-level Neutral Point Clamped (NPC or ANPC) topologies show promising results by improving the waveform quality & reducing the overall observable voltage across semiconductor devices. This mitigates two issues primarily: **A**. It is reducing the need for passive filtering components due to superior waveform quality, and hence reducing the passive components (often heavy). **B**. It allows using lower voltage devices such as GaN due to the reduced observable voltage. This eliminates the need for a specialist aerospace semiconductor device with a high voltage requirement and use more commonly produced devices (lower voltage).

The outputs from this work package have been used to inform the Electrical Systems Roadmap, which is a separate document available via the ATI with document reference FZO-PPN-MAP-0029 [6].

Further Research

The following items have been identified as the key areas of research:

- For HTS (high temperature superconducting) powertrain, instead of designing only superconducting motors, further work is required to assess at the superconducting powertrain level. There is also a general gap in testing and development infrastructure for superconducting powertrain.
- Novel cooling technology such as oil-impingement and oil-spray need to be explored to improve the performance of the system. For thermal management this might appear trivial for devices with >97% efficiency but it has a large impact on the gravimetric power density due to the need for heavy components to transfer and dissipate heat.
- Another area of potential is cryogenic cooling for semiconductor devices. GaN devices show 5 fold performance improvement at temperatures of 75K. As the powertrain progresses towards superconductivity, power electronics need to leverage of full potential of the available cooling systems.
- Due to the high transmission voltages required for a megawatt powertrain, technologies that mitigate partial discharge at altitude need to be explored. These technologies already exists in other industries such as automotive, however there is significant amount of work to be done to apply it to aerospace applications.

02.3 INDUSTRIAL

02.3.1 MATERIALS: POST-SILICON POWER SEMICONDUCTORS

Electric machines powered by either fuel cells or batteries have the potential to replace conventional kerosene burning engines/turbines. Non-silicon-based semiconductors offer potential for these electric powertrains.

The project run by Nottingham University considers that relatively low technical maturity (TRL) and manufacturability (MRL) of silicon semiconductor replacements are preventing the increased adoption of electric machines for aerospace.

Research Findings

Although silicon is a mature technology it is the source of significant performance limits which prevent the demonstration of competitive high voltage electrical power systems and electric drivetrain technologies. Specifically, 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's 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 WBG semiconductor technologies which, among all silicon alternatives, have the highest TRL and MRL 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 the electric powertrain. GaN technology is better suited for relatively low power electrical systems. Ultra-wide bandgap technologies, for example, gallium oxide and diamond have the theoretical potential to induce the biggest impact, but they are still in the early research stage of exploration and concept demonstration.

Future Research

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 includes multiple silicon foundries which, with appropriate investment, have the potential to produce high power silicon alternative devices.

Further research in devices using Silicon Carbide and Gallium Nitride is needed, as is research into Ultra-wide bandgap technologies, for example gallium oxide and diamond.

02.3.2 MATERIALS: SUPERCONDUCTORS FOR CRYOGENIC POWERTRAINS

Liquid hydrogen is currently considered an option to replace conventional kerosene for future zero-carbon emission aviation. Liquid hydrogen at -253°C provides an opportunity to utilise materials that are superconducting at this temperature.

The project run by Strathclyde University understands that 'high temperature' superconducting materials including their technical maturity (TRL) and manufacturability (MRL) is one of the technologies that is preventing the adoption of a superconducting powertrains for aerospace.

Research Findings

There are currently 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 is a point where conventional powertrains, even with forced cryogenic cooling, cannot meet the gravimetric efficiency requirements without significantly increasing the voltage level.

Materials such as the rare-earth barium copper oxides (ReBCO) and Magnesium Diboride (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 large currents with minimized energy dissipation at voltage levels below 1kV. Superconducting propulsion powertrains above 20MW can be developed without significantly increasing the voltage level. Also, the zero-resistivity feature ensures the overall high efficiency of the powertrain reducing the fuel usage and the size of fuel tanks.

The uptake of cryogenic and superconducting powertrains can go collectively alongside UKAEA's STEP fusion program, because the two industries potentially will share some manufacturing capabilities and supply chains, e.g. superconducting magnets, high current leads and joints, cryogenic supporting components, and superconducting cables.

Further Research

Development of superconducting powertrains for aerospace including materials development of ReBCO and MgB_2.

02.3.3 MATERIALS: MATERIAL BASED HYDROGEN STORAGE

The storage of hydrogen via compressed, cryo-compressed or liquid form has many challenges including high energy requirements, thick-walled pressure vessels and limited capacity. The use of materials to store hydrogen offers significant opportunities for aviation including the potential for increased storage density without the energy required for compression / cooling.

The project conducted by the University of Bath explores material-based hydrogen storage for aerospace setting, including technical maturity (TRL) and manufacturability (MRL).

Research Findings

Work carried out assessed the suitability of a range of materials groups for the storage of hydrogen in the solid-state. The relative merits of each material groups have been summarised against the following scoring criteria: temperature and pressure of operation and gravimetric and volumetric efficiency. However, even for the best performing sorbents and hydrides the hydrogen gravimetric capacities are only 15 weight percent of the total system mass and a solid-state based system is, therefore, unlikely to compete with liquid hydrogen as a primary fuel carrier. However, there is great potential for solid state materials in niche applications such as the capture of leaked or boil-off hydrogen.

Novel systems, such as Kubas Manganese Hydride (No 1.) – a new type of hydrogen storage compound - appear to have very high volumetric capacity which could allow for a combined liquid hydrogen/ solid-state system that allows for the volumetric limit of LH_2 systems, governed by liquid density, to be exceeded at the expense of gravimetric capacity.

Future Research

For a useful, reliable, and objective comparison of the various hydrogen storage systems, further research effort needs to be devoted to:

- Developing an aviation specific, system level metrics, analogous to that of the US DoE light duty road vehicles.
- Explicit reporting of true and reliable system level capacities for conventional forms of H_2 storage.
- Development of material based, hydrogen storage systems using the highlighted technologies to allow like-for-like comparisons.

02.3.4 MATERIALS: CARBON FIBRE COMPOSITES FOR LIQUID HYDROGEN POWERED AEROSPACE

Liquid hydrogen is one option to replace conventional kerosene for future zero-carbon emission aviation. Carbon fibre is used extensively in aerospace structures and offers high strength combined with low weight, however, very little is known about the behaviour of carbon fibre at 253°C and/or in contact with liquid hydrogen. The University of Bath were contracted to assist FlyZero with the following areas:

- Carbon fibre composite vessels for the storage of liquid hydrogen in aerospace.
- The effect on carbon fibre structural materials in the fuselage in a leakage scenario.

Research Findings

The utilisation of carbon fibre reinforced polymer (CFRP) tanks for the storage of liquid hydrogen is considered to be a valid route for manufacturing. The mechanical performance of CFRP at cryogenic temperatures and the thermal effects induced by liquid hydrogen temperature were reviewed at the coupon level. It found that the macroscopic mechanical properties at cryogenic temperatures greatly depend on the fibre and matrix constituents, composite stacking sequence, architecture and temperature range. A general improvement in stiffness and mechanical fatigue performance at cryogenic temperatures is reported, but observations regarding static strength, fracture toughness, impact strength and thermal cycling are less conclusive, with several authors reporting a variety of outcomes. This highlights the need for further case-by-case coupon testing of CFRP at 20K, in particular since most testing to date has been performed at or above 77K using liquid nitrogen. Experimental characterisation and testing in these conditions are notably challenging, requiring customised strain measurement systems and acoustic emission techniques.

The changes in macroscopic mechanical performance at liquid hydrogen temperatures are caused by well-understood thermal residual stresses, micro-cracking, thermal effects on the constituent material properties and long-term effects, such as humidity. Other non-thermal effects, such as CFRP aging due to liquid hydrogen exposure are not well documented and require further research. Micro-cracking can also lead to leakage of liquid hydrogen in storage vessels when interconnected networks of micro-cracks are formed. CFRP design and manufacture are found to play an important role in leakage prevention. Solutions to these challenges include the use of dispersed plies, cross-plies, textile laminates and toughened resins with fillers can minimise leakage. Other solutions, such as metallic liners on non-metallic lightweight films, can also prevent leakage at the cost of additional mass and/or complexity.

In addition, manufacturing methods are found to have significant implications in storage vessel quality. In particular, vessels fabricated in sections and subsequently assembled have not been successful demonstrators. From a consolidation perspective, well-established autoclave solutions provide highest-quality, leakage-resistant vessels whereas lower cost Out-of-Autoclave manufacturing processes offer geometric flexibility.

Further Research

The UK currently lacks experience and capacity in the design, manufacture and testing of cryogenic vessels suitable for large-scale application in the aerospace industry to store liquid hydrogen. A concerted increase in research effort and growth in capacity to characterise and understand the effects of liquid hydrogen on CFRP materials at micro-, meso- and macro-scales is imperative.

02.3.5
MATERIALS: NEXT GENERATION MATERIALS FOR INCREASED BATTERY POWER DENSITY

Batteries powering power electric machines could be one of the key technologies to reach zero carbon emission aviation. However, battery power density is currently below the level required to make batteries viable as the primary energy source.

The project conducted by Qdot Technology recognised that novel battery materials (anode, cathode, electrolytes, separators, current collectors, cooling) have the potential to increase power density and this area requires further study.

Research Findings

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 10-20% of 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 for periods of minutes to enable take-off and landing.

Further Research

For significantly improved battery powertrain performance two battery chemistry combinations have been identified as being of significant interest. Through a novel, quantitative, down selection methodology lithium sulphur and lithium ion with graphite/silicon anodes were found to offer the highest promise in the near term. At longer timeframes, magnesium sulphur battery chemistry offers an additional performance boost.

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.

02.3.6 MATERIALS: NOVEL COMPOSITES AND COMPOSITE STRUCTURES FOR NEXT GENERATION AIRCRAFT

This research study was conducted by Avalon Consultancy. Polymer Matrix Composites are used extensively as a structural material in aerospace. The continued development of novel composites and composite structures is deemed to be of significant importance to future aerospace, for example;

Novel Composites

- Reduced environmental impact carbon fibre (alternative precursors and conversion process energy).
- Use of re-used composites in structures (e.g. aligned discontinuous fibres).
- Novel fibre and/or novel resins.
- Self-healing composites.
- Vitrimers.
- Structural batteries.

Novel Composite Structures

- Dual/Multi use Structures.
- Aeroelastic tailoring.
- Composite fibre steering.
- Integrated Primary Structures.
- Bonded structures.
- Opportunities that a 'dry wing' would present e.g. honeycomb structures.

Research Findings

Hydrogen-powered commercial aerospace will require the design of a new aircraft. The liquid hydrogen fuel can be stored in the fuselage or pods, rather than the wing. A 'dry wing' provides opportunities for both new materials and novel manufacturing methods. Technologies for weight saving, aerodynamic performance improvements and structural optimisation will be needed to reduce non-CO_2 emissions (i.e. NO_x and water vapour), hydrogen fuel burn and cost.

There are now a range of potential solutions to support sustainability goals, which include bio-based materials, recycling technologies and low energy manufacturing. However, there are technical and supply-chain related challenges hindering the implementation of these solutions. Alternatives to oil-based feedstocks are being offered by naturally sourced products, although work may be required to improve reliability of supply, reproducibility of properties and durability. Thermoplastics and vitrimers provide benefits in terms of recycling and repair. For bio-sourced materials, the prime issues are reliable supply, reproducible properties and durability.

Nanomaterials provide the capability to develop multifunctional structures which can provide inbuilt sensing, de-icing and lightning strike protection. Modified carbon fibre composites are also providing the potential for structural power units (integrated batteries and supercapacitors).

The current costs associated with new materials and manufacturing methods qualification and subsequent certification disincentivises innovation and the adoption of new design concepts into manufacturing such as: non-standard lay-ups, curved fibre paths from fibre steering and hybrid processes such as overmoulding. A significant proportion of this cost is associated with material and component level testing.

Further Research

Multifunctional composites - composites that fulfil a role in addition to that of structure - are seen as a significant area of opportunity. Four areas have been identified as being of particular interest:

- Structural batteries and structural supercapacitors.
- Lightning protection and anti/de-icing.
- Data transmission.
- Heat management.

To reduce testing costs, virtual testing and simulation of digital twins to create ‘virtual allowables’ requires development. This would need to be supported by increased in-process monitoring, non-destructive testing and through life structural health monitoring.

02.3.7 MATERIALS: ALLOY COMPATIBILITY WITH HYDROGEN

Liquid hydrogen is an option to replace conventional kerosene or Sustainable Aviation Fuels for future zero-carbon emission aviation. This liquid hydrogen will be vapourised and used either as propellent or fuel for a fuel cell. The materials of construction for the hydrogen systems are yet to be determined, however it can be assumed that typical aerospace engineering alloys be considered.

This research project conducted by Reaction Engines, understands that neither the interaction of typical aerospace engineering alloys with hydrogen nor how this is affected by temperature, time and stress are well understood.

Research Findings

Hydrogen can have a detrimental effect on the material performance of various alloys. Hence, an awareness of the ways in which hydrogen can interact with metallic materials, the effect of hydrogen on an alloy's mechanical properties and methods to test and mitigate against hydrogen embrittlement are necessary to support material selection for hydrogen service. In general, aluminium alloys, oxygen free copper, and most stable austenitic stainless steels are deemed suitable for both liquid and gaseous hydrogen applications. Carbon steels have been used in gaseous hydrogen applications and can be used if suitable test data and design parameters are implemented. Similarly, nickel and titanium alloys can be used in hydrogen applications if appropriate hydrogen embrittlement mitigation techniques, such as metallic coatings are in place. There are several factors that influence the extent of embrittlement which include the material's microstructure (which is a product of the chemical composition and processing route), temperature, pressure and applied or residual (tensile) stress.

Further Research

New materials test facilities are needed to qualify materials for hydrogen containing environments across a wide range of temperatures (including at cryogenic and combustion temperatures). Greater fundamental understanding of the interaction of hydrogen with materials at the micro scale leading to new materials developed for use in hydrogen is required.

02.3.8 MATERIALS: MAGNETIC MATERIALS FOR ELECTRIFICATION

Electric machines powered by either fuel cells and/or batteries have the potential to replace conventional kerosene burning engines / turbines.

The project with University of Nottingham looks at whether hard and soft magnetic materials including their technical maturity (TRL) and manufacturability (MRL) are preventing the increased adoption of electric machines for aerospace.

Research Findings

Permanent magnet machines offer the greatest potential for high power density since they are inherently more efficient than other currently available options. 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 (NdFeB), 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 (SmFeN) offer superior energy density, compared to NdFeB magnets but are not yet commercially available.

Cobalt-iron is currently the preferred soft magnetic material for high power densities, although some of its magnetic properties under operational conditions such as stress are not yet well understood.

Sustainability, both environmental and social is of particular importance as well as security of supply. Cobalt has been identified as being of particular concern and hard magnetic materials could be subject to supply chain issues. The UK has the potential to become a leader in recycling of these materials with several organisations already developing solutions.

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. The Democratic Republic of the Congo (DRC) is the world’s largest supplier of cobalt. The expected increase in demand without the benefit of good regulation could lead to an increase in environmental impact as a well as negative social impacts.

02.3.9 MATERIALS: COATINGS AND INSULATION

Liquid hydrogen offers an option to replace conventional kerosene for future zero-carbon emission aviation. This liquid hydrogen will be vapourised and used either as propellent or feedstock for a fuel cell. TWI completed a study to help the FlyZero team assess the potential from coatings and insulation. The materials of construction for the fuel systems, propulsion and airframe are yet to be determined, however, it can be assumed that typical aerospace engineering materials (metallics, carbon fibre, ceramic matrix composites (CMCs)) would all be under consideration. Some engineering materials are susceptible to hydrogen (-253°C to 1200°C) or the water vapour produced by the combustion of hydrogen.

Research Findings

Coatings and insulation are an essential part of realising powered flight. Coatings provide an essential means of protecting components from wear, corrosion, high temperature corrosion & oxidation and thermal effects. Advanced coating systems, developed over many decades, are a key part of any modern aero engine and their performance is well understood for kerosene fuels. However, the change to hydrogen fuel presents several challenges, including changes to the combustion characteristics (flame temperature and velocity), increased amounts of water vapour, and also potential effects of unburnt hydrogen.

The effect of hydrogen as well as increased levels of water vapour (more than 250% compared to hydrocarbon combustion) will need to be understood. All the existing coatings (including environmental barrier coatings (EBCs), thermal barrier coatings, wear coatings and abradable coatings etc.) will need to be requalified and new coating systems developed if required.

Insulation is an integral part of any cryogenic storage and fuel delivery system. Insulation is required to have low thermal conductivity, low emissivity and low density and volume whilst preventing excessive heat leak and boil off. Any insulation systems applied must also not increase the risk of tank failure, for example by trapping moisture and creating increased potential for corrosion under insulation.

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, known as composites for extreme environments (LCX), could offer significant performance improvements.

Further Research

Based on the findings of this work, the top 5 areas for coating and insulation related R&D are as follows:

- Performance evaluation of insulation materials in cryogenic service, and cost-performance-environmental impact assessment to identify best candidate materials.
- Understanding the permeation of hydrogen through tank materials / coatings and insulation, and the testing of the materials systems to determine the leak rate for various combinations of tank materials, barrier layers and insulation materials.
- Understanding of the effects of thermal cycling and potential degradation mechanisms of tank materials, liners and insulation in service e.g. corrosion under insulation for metallic tanks or microcracking of PMCs with and without coatings and liner materials.
- Understanding the effects of liquid and gaseous hydrogen on coated bearings, valves and pumps in the fuel delivery systems.
- Failure investigation / materials characterisation of components / coatings in industrial gas turbines running 100% hydrogen to enable the materials degradation mechanisms to be better understood to enable future coating development / optimisation and re qualification of coatings for service in hydrogen fuelled aeroengines.

02.3.10 SPACE AND CRYOGENIC CAPABILITY MAPPING

FlyZero identified the space sector as an industry with technical expertise in the use of hydrogen as a fuel for rocket propulsion. This study from the Satellite Applications Catapult was to map the capability of the space sector in hydrogen, as follows;

- Map the UK space sector's industrial (design and manufacturing) capability in liquid hydrogen propulsion (storage, engines, fuel cells), including UK capability in sensors and gauges for cryogenic systems.
- Map the UK space sector's development and test capability relevant to liquid hydrogen propulsion (storage, engines and fuel cells), with potential relevance to aerospace applications.
- Document how the space industry qualifies liquid hydrogen propulsion systems today and how this capability or process could be adopted by the aerospace sector.
- Document how the space industry manages the logistics for hydrogen propulsion including transportation, safety and management of related issues including relevant standards from a logistics perspective.

Research Findings

There is almost no current use of liquid or gaseous hydrogen by the UK space industry for the following reasons.

The UK space sector has no large rocket launch capability and as liquid hydrogen is primarily used as a propellent in the secondary stages of heavy lift launch vehicles (rockets), there is no demand for liquid hydrogen in the UK.

The UK government followed a policy to abandon rocket launch in the early 1970s and subsequently the main activities in this area have been testing rocket prototypes (none using a hydrogen propellant) and developing smaller engines for satellite manoeuvring.

A UK Government decision was also taken in the 1980s not to invest in the European Ariane launcher programme. This in turn has meant that a substantial UK supply chain was not established to develop products and services for the European launch industry.

The report identified a small number of space companies with specialist cryogenic, propellent handling, equipment and engineering services applicable to a future hydrogen fuel economy, especially with the high technical quality, safety critical aviation sector in mind.

The study also identified testing procedures followed by the wider space industry with many processes already present in the aerospace sector. Nonetheless, liquid hydrogen introduces specific testing regimes which must be completed requiring considerable investment. Moreover, the logistical supply chain across several countries was described focusing on tanks and pipelines. Relevant technical standards have been provided for both studies. Finally, it was noted that lessons learned from the space sector must be carefully assessed before applying them to the aerospace industry due to often diverging needs of both industries.

The space sector is considered to be a strong accelerator towards liquid hydrogen powered zero-carbon emission aircraft due to the experience on usage of both liquid hydrogen and other cryogenic fuels. Considering the nature of aircraft operations and quantities of vehicles expected to enter in service, it’s expected that aviation will become the driver for future cryogenic propulsion systems’ development.

02.4 AIRFRAME

02.4.1 WING ICING DRIVERS

The University of Nottingham provided the FlyZero team with a literature review of wing icing drivers that needed to be considered for the relevant FlyZero concepts. The objective was to understand whether and/or how FlyZero concepts fundamentally change the way ice builds up (e.g. for dry wing concepts) and providing advice on what changes need to be considered by FlyZero in the next phase. Research was focused as follows;

- The impact on wing icing where no heat is being used from the powerplant?
- Considerations of wing shape need to be taken into account (e.g. in case of dry wing) that may lead to a different ice build-up?
- How or if the absence of kerosene in the wing affects the temperature and thermal inertia and if the wing is more, or less prone to ice.
- Consider the scenario of having a water management system on the wing (e.g. from a fuel cell) for the purposes of loads alleviation and how this may affect the ice build-up.
- In addition to the above, any other potential drivers for a change in ice build-up for the FlyZero concepts compared to a conventional wing that carries kerosene.

Research Findings

The purpose of this research was to quickly determine ways of reducing, if not entirely mitigating, the chances of ice building up on the wing. This research would then tie into the planform shape, twist, and dihedral of the wing, as well as new technologies that can be invested in for a dry wing, and not for a typical aircraft.

In terms of shape, it was seen that ice more efficiently builds on the wing when it has a larger thickness. This problem can be easily controlled with a dry wing, as it lends itself to a thinner aerofoil thickness to chord ratio. Combining this with other technologies such as morphing wing can reduce the area available with which the ice can be captured.

Furthermore, it was suggested that a hybrid concept of an active ice protection approach integrated with the use of ice phobic coatings would be most beneficial for a combination of anti-icing and de-icing. The active ice protection would occur with heated leading-edge devices such as pulse electro-thermal ice protection (PETIP) as this encourages an increase in drag. The remaining area of the wing would be passive ice protection with a self-heating layer on the leading edge, together with ice phobic coatings covering the main body of the wing.

Further Research

Research to be conducted with a specific concept wing geometry in mind with this configuration of ice protection to study energy consumption compared to current aircraft. In addition, further new technologies such as surface acoustic waves (SAWs) can be further investigated to determine their effectiveness versus energy requirements.

02.4.2 SUSTAINABLE CABIN TECHNOLOGY

Provision of cabin interior products for commercial aircraft accounts for between 5% and 10% of the income of the UK aerospace sector (based on ATI/ADS data). FlyZero's goal is to build capability within the UK for the design and manufacture of more sustainable aircraft. The team worked with Cranfield University to consider how the design, manufacture, operation and end-of-life disposal of the cabin interior components can be improved in this respect.

A detailed understanding of the ways in which existing products negatively impact the environment is required and the relative scales of those impacts. Also, a comprehensive and detailed understanding of new and emerging technologies which could enable cabin products to be more sustainable was needed.

There is very limited data available currently on these topics, and so this project seeks to establish an accessible and comprehensive body of relevant knowledge and a robust technology road map for the development of more sustainable future cabins.

This project focuses on developing our understanding of the processes and technologies that will enable the UK to compete more effectively in aerospace, as sustainability becomes and increasing priority in the years ahead. We must also work to promote a model for a greener UK aerospace sector that delivers both prosperity and sustainability.

Research Findings

The project sought to provide an evidence-based approach to designing more sustainable aircraft cabins through an exploration of key design parameters, an examination of the state of the art in terms of products and design practices, identification of technologies that target existing problem areas and the creation of a bespoke design toolset for industry.

A body of knowledge was established including:

- Relevant policy and legislation.
- Comprehensive list of stakeholders.
- Summary of circularity challenges and opportunities developed from conversations with diverse industry stakeholders.
- Cabin specific environmental impact mechanisms, categories and compounds.
- End-of-life treatment options.
- Detailed lifecycle assessment (LCA) of key cabin products.
- Comprehensive capability map created of UK cabin supply chain.
- Detailed model created of cabin product circularity routes.
- Extensive technology list targeting identified sustainability issues.
- Solutions roadmap for more sustainable future cabin designs.
- Bespoke LCA based cabin design tool (as shown below).

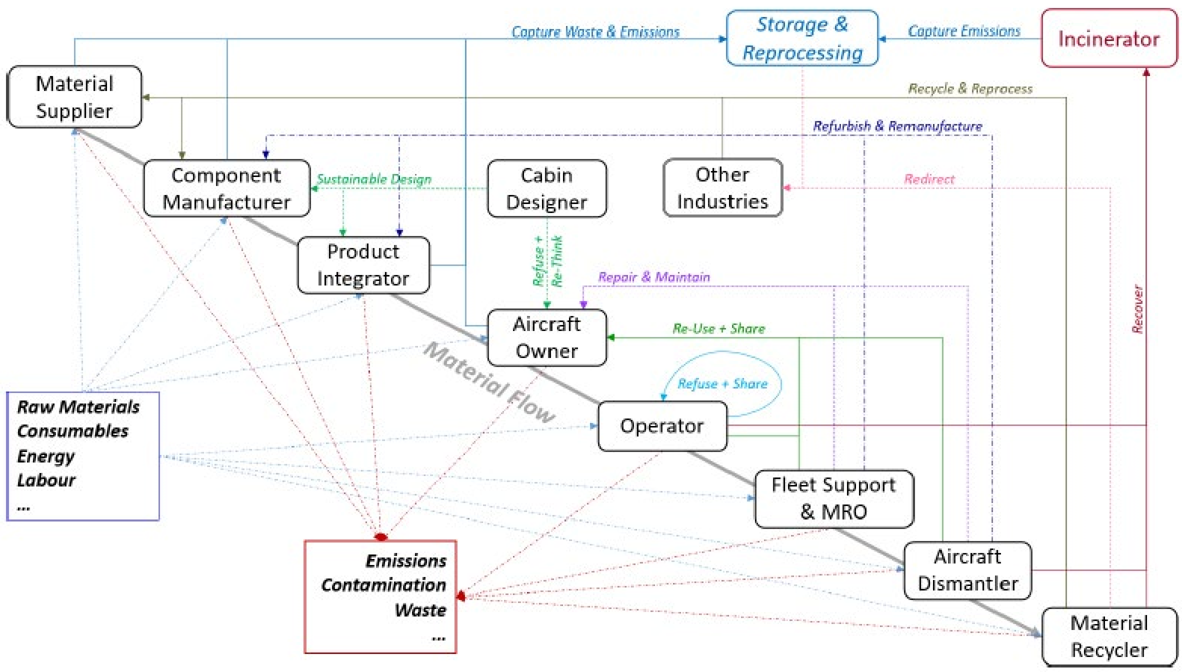


Figure 10 – Circular Cabin life cycle (Source: University of Cranfield).

Further Research

Aircraft OEMs and airlines are pushing for greater sustainability performance from cabins, providing a strong incentive for cabin suppliers to develop a new generation of less environmentally impactful products. The knowledge and capabilities developed within FlyZero have value in this context if developed into a service proposition for airlines, cabin suppliers and design specialists. If this were to happen the UK could be viewed as a leading in sustainable cabin technologies.

02.4.3 SUSTAINABLE CABIN DESIGN

This project seeks to build a model for how the passenger cabins and the experiences they afford can support the overarching goal of sustainable aviation. Working with Central St Martin's (CSM) school of design at University of London, we wanted to assure people that greater sustainability does not mean a poor deal for passengers. Whilst the functional aspects of the interiors will be to some extent be determined by the overall architecture, ergonomic and safety considerations, design has a key role to play in bringing these disciplines together into a coherent proposition. It is vital that we demonstrate how the environment and the objects within it will contribute, directly and indirectly to an ambitious approach to sustainability that meets or exceeds that demonstrated by other industries today and into the future.

The aim was for this project to provide ideas and design direction to help articulate a vision that is conceptually robust, demonstrates tangible sustainability advantages and will inspire aircraft makers in the UK and abroad to build on our ambitions for a cleaner and more positive flying experience.

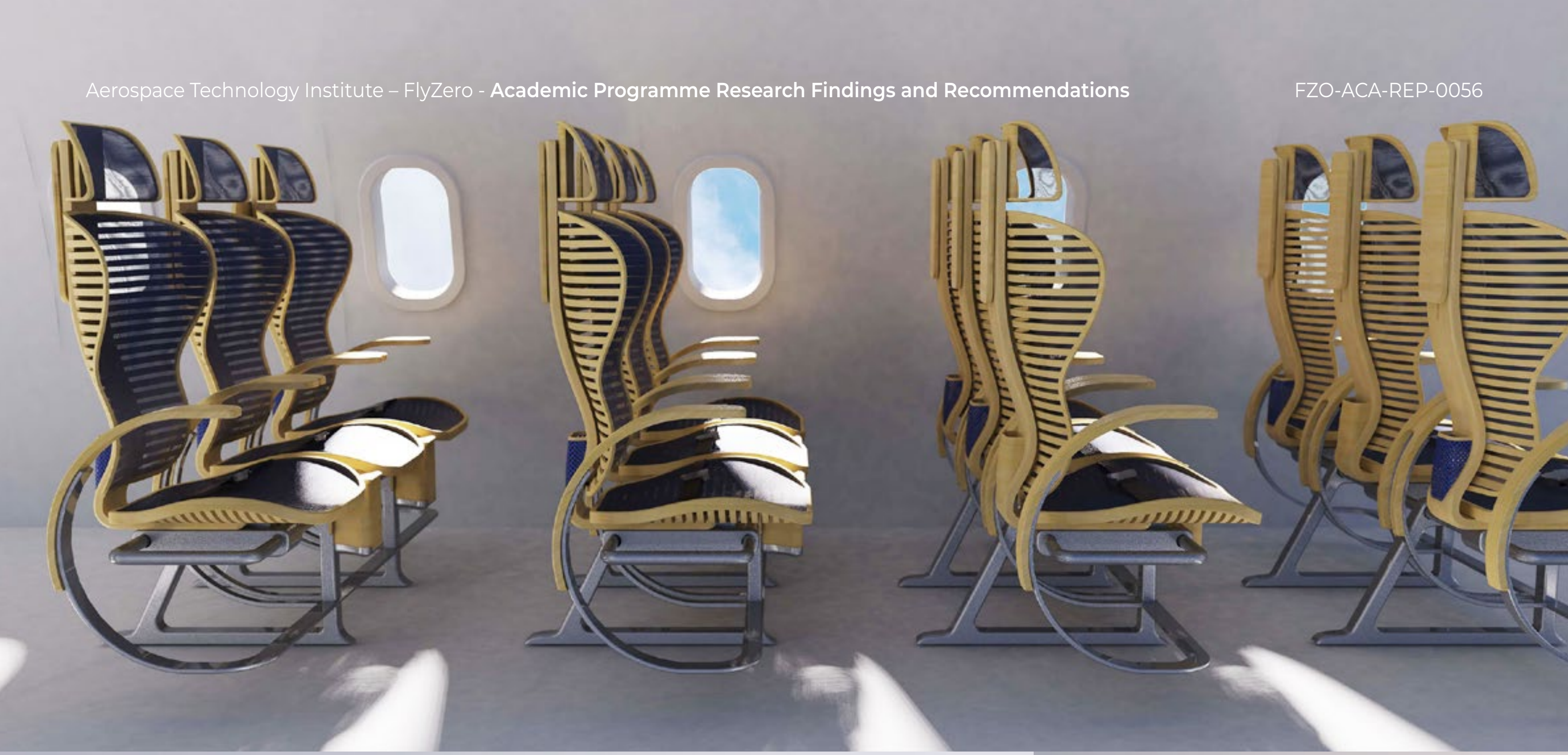
Research Findings

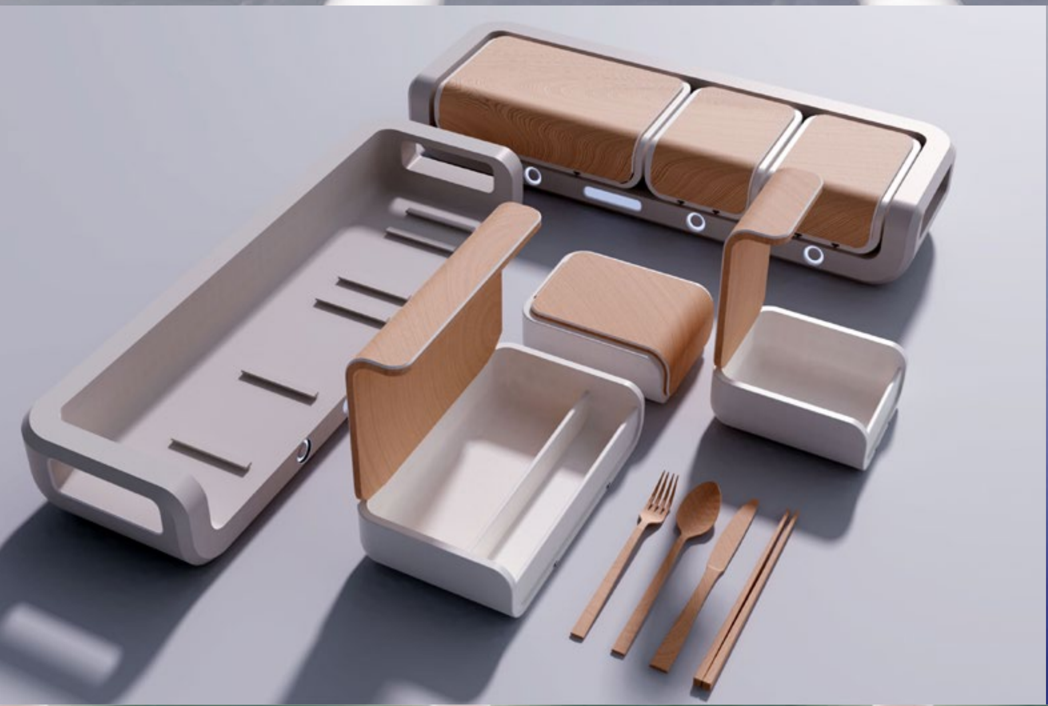
19 Industrial Design Masters degree students were tasked with exploring what a more sustainable aircraft cabin might be like in 2030. The project was supervised by the Cabin and Sustainability teams from FlyZero.

The project delivered a range of design studies demonstrating how a diverse range of sustainability concepts might be applied to aircraft cabins. These included:

- Sustainable materials selection to meet certification, structural and comfort requirements.
- Modular design approaches that reduce the need for airlines to discard usable furniture components during regular repair/upgrade cycles.
- How design can encourage environmentally responsible passenger behaviours.
- How design can enhance airlines' operational efficiency.
- Using cabin furniture to harvest and store electrical energy.
- Design for weight reduction.
- Encouraging passenger acceptance of novel airframe forms (e.g. blended wing).
- Establishing a visual language appropriate to sustainable design for future aircraft interiors.

A number of concepts developed can be seen on the next page.





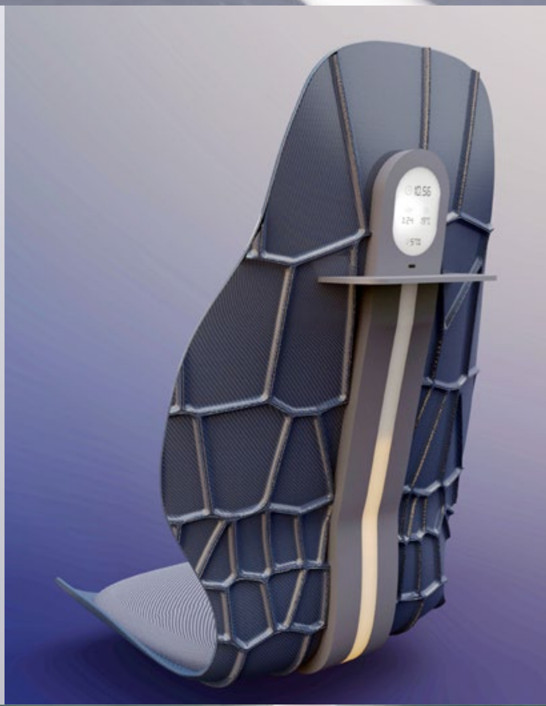


Figure 11 – Examples of conceptual design language (Source: Central St. Martins).

Further Research

Several of the design results have been incorporated within the development of FlyZero cabin interiors. The strength of a research organisation such as CSM is in design research and synthesis of disparate ideas including an understanding of human requirements into initial product concepts. Continued development of the FlyZero aircraft would benefit from such expertise in the definition of the aircraft identity and livery and its interior design in order to maximise the positive market adoption of zero carbon aircraft with a new hydrogen fuel.

02.4.4
HIGH LIFT AND MOVEABLES DESIGN

The aim of this research package with University of Cranfield was to define moveable concepts and designs to improve aircraft efficiency during the take-off/climb and approach mission phases by reducing drag. Further to this, a reduction in noise as a result of the new concepts would be an added benefit due to the ACARE targets for noise reduction.

Research Findings and Further Research

Key findings are as follows;

- Scope for further refinement of current devices through sensing and automation.
- Passive Air Jet Vortex Generators (PAJVG) should be pursued to replace traditional slats to reduce weight and improve maintainability by the introduction of a simpler system.
- Hot air blowing into rear cove region for anti-icing purposes could allow Coanda blowing on trailing edge devices.
- FlyZero Regional (FZR) Proposal:
    - FZR wing provides good coefficient of lift (CLMax) and high lift (HL) devices will increase this dramatically.
    - Best aircraft to try and integrate new technology and have good margin of safety.
    - Passive air jet system for the leading edge with single slotted trailing edge (Fowler flap) or with a blown morphing trailing edge.
- FlyZero Narrowbody (FZN) Proposal:
    - The presence of inboard hybrid laminar flow suction means that leading edge slats and passive air jet vortex generators in this region are unfeasible.
    - Baseline wing does not provide enough CLMax to meet take-off and landing requirements, therefore HL devices are essential for safe operation.
    - In order to achieve some laminarity, the inboard section of the wing has been modified with a new aerofoil. The new wing provides a favourable pressure gradient, a weaker shock wave and a reduction of three drag count in terms of viscous drag.
    - Position of canard investigated. Canard wake will either impact wing, engine or both depending on position. More analysis required on the extent of impact to performance.
    - An Engineering Science Data Unit (ESDU) assessment showed morphing leading edge/trailing edge (LE/TE) insufficient to meet CLMax alone, even with chord/span extensions.
    - FZN is more challenging than FZR in that it may require a combination of inboard morphing and outboard slatted LE devices with either blown morphing TE flaps or extended fowler flaps with 10% gap to safely achieve landing condition.

- System sizing & integration:
  - Two approaches to sizing taken; empirical and component:
    - CFD Aerodynamic forces are considerably higher than ESDU predictions, both methods have inaccuracies as they do not model all features. For the study the higher values produced from the CFD have been used for sizing.
    - CFD method shows outboard flap is more highly loaded than inboard. Need to query this as it is usually the other way round.
    - Empirical methods severely underestimate LE system mass compared to component sizing method for novel /morphing structures. This highlights a key pitfall using methods based on conventional systems.
    - Only the inboard area of the inboard flap would allow for rear spar mounted electrical hydraulic actuation (EHA) systems, all other locations require space within the wing box. However electrical mechanical actuation (EMA) systems would allow external mounting.
    - For traditional systems local actuation may provide substantial mass savings. However, a detailed safely assessment will be required to ensure symmetric deployment.

Final points

- FZR can achieve CL requirements easily with PAJVG LE and either blown morphing TE or single element fowler flap.
- FZN is far more challenging to achieve CL requirements and would require significant work on HL devices to enable more novel concepts buy on to next gen aircraft.
- Recommendation for FZN is morphing inboard LE (with possible Kruger flap) and slatted outboard LE with either blown morphing TE flaps or flower flaps (both covering an extended area). However, a resized and slightly larger FZN wing could provide a platform needed to safely and successfully integrate a fully morphing solution and clean wing configuration for cruise.
- Morphing systems suffer from large mass penalties over traditional architecture due to greater torque required through gearboxes. These could be eliminated by adopting specific lever-arm configurations for morphing structures.

02.4.5 WING MORPHING AND MDO

The aim of this research package with University of Bristol was to review complete wing morphing (shape changing) technologies and multi-disciplinary optimisation (MDO) modelling framework options to develop concepts to improve the aircraft (A/C) performance across the full mission. Where wing morphing is seen as a continuous smooth and flexible change of the wing shape in order to maximize aerodynamic efficiency whilst minimising structural weight.

Research Findings and Further Research

Key findings are as follows;

- A qualitative assessment of different morphing strategies against the following criteria was conducted, shown below, highlighting camber, span, active winglets and passive twist to be the most promising to improve aircraft performance, and were selected to be investigated in more detail.

SELECTION CRITERIA →	HIGH POTENTIAL FUEL SAVING	HIGH MATURITY	LOW IMPACT ON PRIMARY STRUCTURE	LOW ACTUATION ENERGY	LOW MASS	LOW COMPLEXITY	
CRITERIA WEIGHTING (1-5) →	5	4	3	2	3	3	
MORPHING STRATEGIES ↓							TOTAL SCORES ↓
CAMBER	4	4	5	4	3	3	77
TWIST (ACTIVE)	3	2	2	2	2	2	45
SWEEP	2	3	2	3	2	3	49
SPAN	4	4	3	3	3	4	72
ACTIVE WINGLETS	3	4	4	4	4	4	75
CHORD	2	2	2	2	2	2	40
THICKNESS	1	2	2	3	3	2	40
CONSIDERED IN PARALLEL:							
TWIST (PASSIVE)	4	4	4	5	4	3	79

Figure 12 – Morphing strategy comparison (Source: FlyZero).

- The selected morphing strategies were assessed in terms of technical maturity.
  - Camber morphing is the most mature technology at TRL 6 following extensive testing of the FlexFoil by FlexSys on a modified Gulfstream G-II, however FlexFoil Camber setting was fixed on the ground with no active actuation in flight.
  - Active camber morphing solutions could be rapidly developed.
  - Active winglets are an offshoot of camber morphing and are only slightly less developed at TRL 5 on projects like SARISTU.
  - Both strategies are expected to be TRL8+ by 2030 and TRL 9 by 2050.
  - Span morphing was considered to be still in its infancy at TRL3 as although historical examples of test aircraft deploying this strategy exist, technology needed for civil aircraft will be significantly different.
  - Span morphing could be developed quite rapidly in the wing tip region, with hydrogen aircraft having the advantage of the dry wing to accommodate mechanisms.

  - Concurrently to the other morphing strategies aeroelastic tailoring has been developed to TRL8 on the X-29 experimental fighter aircraft but is TRL3 in civil aerospace. Given current concept & manufacturing trials have been performed using aeroelastic tailoring and sufficient support and investment is provided TRL 9 is achievable before 2030.
- FZN Morphing Strategies:
  - FZN is a good wing platform to explore camber morphing strategies.
  - It's likely 25% of the chord would need to be dedicated to camber morphing based on literature and previous research.
  - Full span camber morphing may be used to replace aileron, with local actuation providing sufficient deflection for pitch control.
  - As the wingspan is 4m outside Cat C gate limits there is also an opportunity to employ active winglets or span morphing at the wing tip. This could also be used for active load alleviation.
- FZR Morphing Strategies:
  - Although FZR has 6 propulsors interrupting the wingspan camber morphing it is still a relevant technology owing to the fact real world operation of this type of aircraft will lead to significant mission variation and thus significant variation of CL (coefficient of lift), Mass and Mach number.
  - Further iteration of nacelle sizes would be required to increase the 10% chord available, but this amount could still provide sufficient changes in CL for spanwise load tailoring.
  - As the regional concept studied has a high aspect ratio wing with fairly low wing loading, span morphing could be employed in the clean region of the outer wing.
  - Although winglets are rarely used on regional aircraft, due to their short missions not enabling sufficient fuel savings for the additional weight, active winglets could provide bending moment relief which may be required with a dry wing. A trade study should be conducted to ascertain their viability.
- FZM Morphing Strategies:
  - While the wing aspect ratio is more conventional, there could be more to be gained from spanwise load tailoring and morphing.
  - As this aircraft operates a longer mission range and spends more time in cruise there would be more motivation for employing active winglets for load alleviation.
  - While under wing engines interrupt the wingspan and would impact the continuity of a camber morphing trailing edge, this would impede no more than the impact on conventional LE/TE devices.
  - Most of the discussion points made on the narrow body are equally applicable to the midsize concept.

- Aerodynamic Analysis of Morphing Concepts:
  - Both 2D (Euler) and 3D (Vortex Lattice) methods were used for the analysis.
  - 2D camber morphing analysis showed no benefit at design point but appreciable gains off-design, but this was for significantly higher or lower CL than are normally used.
  - Improvements shown are for wave drag only, however improvements in other forms of drag are likely feasible by controlling spanwise load and shockwave boundary layer interactions.
  - Analysis results conclude ~5% improvement in Lift/Drag (L/D) can be achieved off-design by relatively small displacements (6.56mm of 2.625m).
  - The 3D analysis along the wingspan highlights a trend of considerable mobility of ML/D region due to camber morphing, which shows the efficacy of tailoring the lift coefficient.
  - It also shows the 2D benefits of camber morphing readily extend to 3D.
  - Results are in line with previous studies concluding possible fuel burn reductions of 2.72% are achievable by camber morphing.
  - However, analysis is limited to constant camber morphing along the span. Further work is required to assess complex distributions of camber morphing along the span to control lift distribution.
  - Span morphing was also assessed for the FlyZero narrowbody concept, but only in the context of optimal aerodynamic geometry, not structural.
    - Analysis assumes rectangular constant chord wing in order to solve for optimum wing aspect ratio.
    - Study assesses change in aspect ratio (AR) impact on CL, starting from an optimal AR=9.2 for CL=0.6.
    - By altering AR over a range of 7.1 to 11 an L/D improvement of up to 5% is deemed feasible.
  - All three FlyZero aircraft concepts are concluded to gain from span morphing, reading across from the narrowbody analysis.
- Morphing system design:
  - Fish-bone camber actuation system was proposed and estimates of integration of the system would be a net mass penalty of 150kg for a 2% fuel burn reduction. System would require 716W per cycle for the largest inboard motor.

- Conclusions:
  - The scope of work was limited due to time and resource constraints, but the team explored the possibilities of morphing and MDO for hydrogen aircraft.
  - The introduction of morphing structures on aircraft have no insurmountable barriers.
  - 1.5-2% fuel reduction is feasible with the introduction of morphing structures at rather low weight & cost penalties.
  - The use of MDO coupled with morphing structures can enable further optimisation and performance gains.

02.4.6 WASTE HEAT UTILISATION FOR AERODYNAMIC PERFORMANCE IMPROVEMENTS

The purpose of this research conducted by TWI was to discover if the effects of heating the underside of the wing would increase aerodynamic efficiency and therefore performance of the aircraft.

Research Findings

The work focused primarily on the heat output of the fuel cell, with the heat channelled to the wing as it was unclear if the increased performance would be significant to offset the added complexity of this extra system.

Research suggested there are highly irregular effects depending on Reynold's number, aerofoil choice and angle of attack (i.e., an angle of attack of 2 degrees could have lower drag reduction than 4 degrees for one condition, but similar drag reduction for both angles at another condition). However, what should be noted amongst the research is that many authors agree that a drag reduction is seen albeit in a non-linear manner.

Further Research

Research is needed to reflect a 3D wing which is likely to be the final geometric shape for the concept at high Reynold's number akin to the concepts. This would provide optimisation of wing heating, and a clearer understanding of the expected heat output and transference from the fuel cell.

02.5 ACADEMIC INNOVATION

02.5.1 INNOVATION MANAGEMENT

The establishment of FlyZero during the middle of the COVID-19 pandemic forced certain behaviours on the project team, namely the recruitment and remote working of a team who have previously never worked together. This research project, conducted by University of Southampton, was set up to analyse the processes set up to enable effective communication and management of the project which may provide lessons for future project management and innovation, and the very nature of this highly challenging and exciting project may provide further insights on how teams are built.

An analysis of the FlyZero innovation processes was conducted in order to understand;

- Is the innovation process suitable, effective, and how could it be further improved?
- How the team was formed and the impacts of the virtual homeworking project management environment.
- The framework for future innovation processes in a UK zero carbon aircraft supply chain.

Research Findings

The research team stated that FlyZero represents a radical innovation context, as it will require multiple major advances in technology. This radical innovation process is complex and includes several elements of uncertainty, including the specific project outputs. The project organisation had several notable features including the use of secondees, virtual working, low project constraints and low technology readiness.

The Southampton study concluded that the innovation management approach taken by the FlyZero project had excellent team working and top management support. The process could improve with respect to the coordination across multiple teams.

Taking forward lessons from FlyZero, the UK aerospace supply chain could improve their recruitment and motivation by emphasising sustainability and could improve innovation by integrating professional internal communications. Both hybrid working, combining the workplace and other locations, and the use of Agile principles in managing uncertain projects, are worthy of significant strategic effort.

The wider UK supply chain should consider adapting their approach to innovation management given the inherent uncertainty of zero carbon aviation, and the unsuitability of rigid contracts and governance structures. The political and commercial uncertainty, and the absence of a UK airframer, make specific recommendations for managing the project very difficult.

The findings were presented under three themes: people, process, and strategy. FlyZero attracted some highly capable personnel, in part because of their motivation to work on sustainable aircraft. Onboarding 'mini sprints' were a particularly valuable method, both for building social networks, and as a learning mechanism. In terms of process, the flexible approach enabled a broad exploration of new technologies but did not fully support the coordination of multiple interdependent teams. This problem will increase with scale as FlyZero continues. In terms of strategy, innovation was very well supported by top managers, and the wide external engagement was extremely valuable. As an early-stage project representing a major shift in a very large industry, the political environment has a major bearing and adds significant uncertainty.

Further Research

One of the key recommendations from an innovation perspective is to invest in organisational design, focusing on the structures, processes, and practices that are most suitable, firstly in this radical innovation setting and secondly using leading edge digital tools and methods. Combined, this can be considered as a management innovation project. Questions to address in this future management innovation project include:

- Should large organisations create new separate entities; Skunk Works?
- Should the project transition back into the existing companies, and if so at what stage of development / TRL?
- How should remote and hybrid working be managed?
- How should the work outputs of small teams be coordinated and integrated?
- To what extent should Agile working practices be applied?
- How should contracts be structured to maximise benefits and minimise risk?
- How should risk management be incorporated into the innovation process?
- How should the wider travel and transport stakeholders be incorporated into the design process, balancing the need to ensure suitable designs but to prevent delays?

APPENDIX A - METHODOLOGY

The FlyZero team was largely recruited during quarter 1 2021 after which some time was spent defining and prioritising the academic research work packages, with scopes of work published mostly during quarter 2 2021. To engage academia on this new project we reached out directly to specific centres of expertise as well as working with the UK's Aerospace Research Consortium (UK-ARC) who provided a doorway to the UK's leading aerospace universities. Well over 50 direct discussions were had with research groups where capabilities were explored and our interests shaped, including having at least 20 groups present on their detailed capabilities to the FlyZero team.

All academic research scopes of work were drafted by a FlyZero technical lead before being published on the FlyZero website, the UK-ARC website and included in their newsletters. Given the short timeline of the project, bidders were generally given two weeks to submit a short proposal with guidance on what this should contain. With all bids in, the technical lead then scored all applications against equally weighted criteria; [price, understanding requirements, relevant experience, resources to meet project timescales, strategic alignment and past performance], the results were reviewed and selection made by the academic co-ordinator and leadership team prior to procurement.

It should be recognised that there are many UK academic research groups able to provide valuable input to the FlyZero mission that we were unfortunately unable to contract during 2021.

With each off-load research partner chosen and spend internally approved, procurement then followed with contracts sometimes involving several weeks of negotiation. This was generally due to the FlyZero contract having to take into account various unique requirements of the wider FlyZero contribution agreement as well as universities commercial offices having a range of contractual expectations.

With research procured, ongoing governance included monthly management trackers to monitor progress against activity scope, timeline and budget. A RAG (red, amber, green) status report was reviewed by the leadership team and any amber or reds followed up to understand the issue in more detail and put together a supporting action plan.

APPENDIX B - TABLE OF FIGURES

APPENDIX C - REFERENCES

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ACADEMIC PROGRAMME RESEARCH FINDINGS AND RECOMMENDATIONS

FLY ZERO

AEROSPACE TECHNOLOGY INSTITUTE