School of Electrical and Electronic Engineering

Electrical Power Research Group

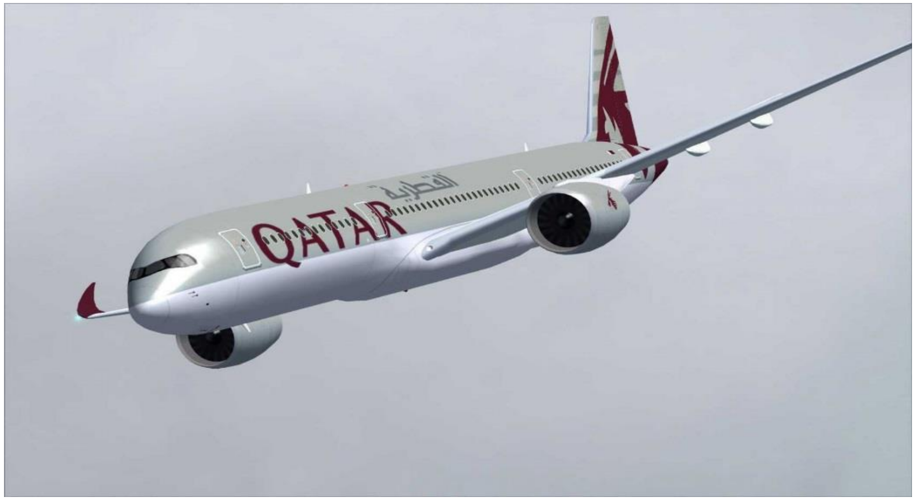
The Path to Hybrid and Electric Passenger Aircraft

Peter Malkin

Contents

- State of the (Large) Commercial Aircraft industry
  - Motivations for change
- Hybrid Electric for aircraft
  - Technology short-term
  - Technology long –term
- Electric vertical take off e-VTOL
  - Motivations for change
  - Technical issues
- Research Activities
  - Non UK
  - UK
  - Research Strategy

Aircraft Design Evolution



Boeing 767 EIS 1981

Airbus A350 EIS 2015

Many detail changes but basic layout has changed very little in 35 years or more!

Compared with mid range family car developments

Hyundai Ioniq Hybrid 2016
1.5L petrol 105Hp Atkinson cycle, 43Hp PM electric motor and 1.6KWh Lithium ion battery
CO_2 84g/km

Triumph Acclaim 1981
1.4L Petrol 69Hp
CO_2 ~205 g/km

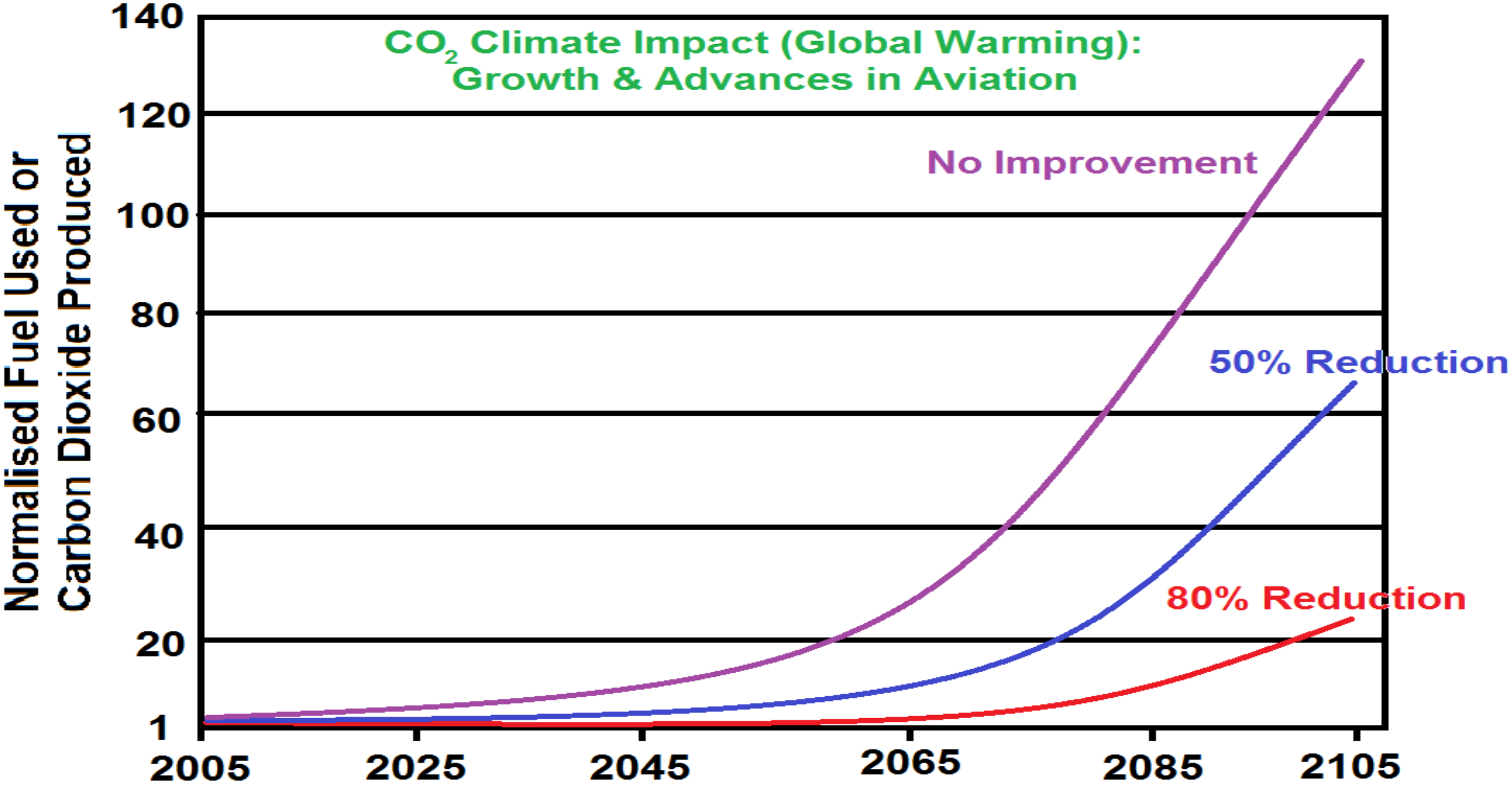
Suddenly new HEA Designs and Companies are appearing 2017/2018

Global Aircraft Emissions

- Aviation accounts for approximately 6% of total UK emissions.*
  - Of this, around 90% of these emissions arise from international flights; and 10% from domestic flights.
  - Aviation emissions have doubled since 1990.
  - Over the same time period, aircraft have become substantially more energy-efficient, through improvements in engine and airframe technology: but these improvements have not kept pace with the growth in emissions from increased air traffic.
  - Because of continued increases in forecast demand for aviation and a lack of low carbon alternative technologies, aviation will increase its relative share of UK's emissions if greater improvements are not made.
  - In addition other major emitters such as Energy and Ground Transport are making significant reductions with renewables and electric vehicles
- If global aviation was a country, it would rank in the top 10 emitters.
- In addition to CO_2 no account has been taken of other pollutants such as NO_x nor is the effect of ejecting these pollutants at high-altitude well understood

*Source CAA and IPCC

Impact of Aircraft Demand Growth



Courtesy of Cranfield University

Why is technology about to change?

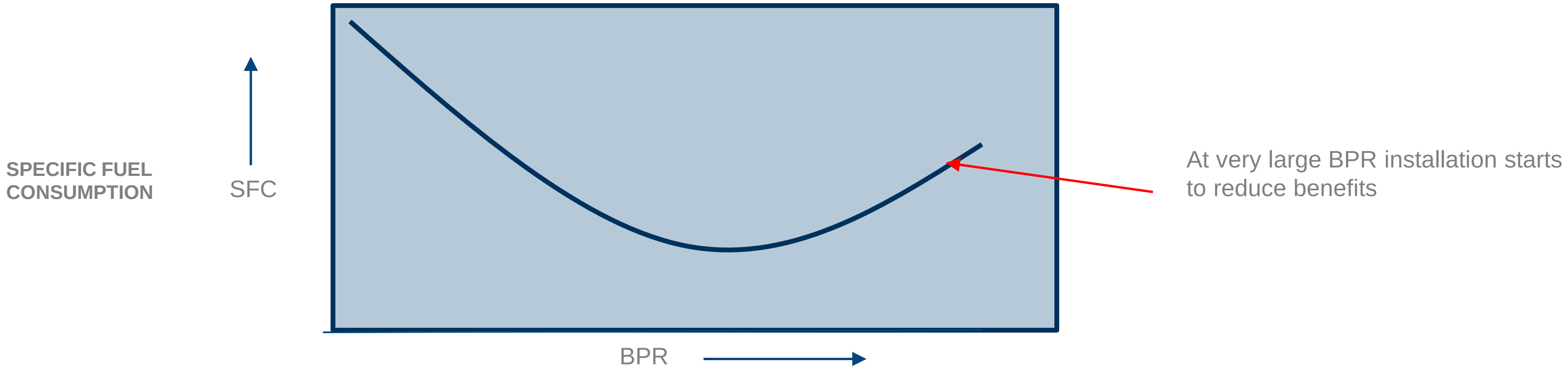
- Current technology for new aircraft has limited headroom for further improvements..
- Yet the industry has signed up to new emissions targets with further reductions of up to 70% in CO_2, 80% NO_x and 70db Noise. (NASA N+3 and Flight Path 2050)
- **Growth in demand forecast to continue at >5% p.a. - aircraft numbers double every 14 years**
- The industry must embrace new technology or see flight restrictions imposed
- Electrification of aircraft seems to be the only way of meeting these goals
- This has been taken up by Airbus and moving rapidly in the USA
- **It will be the biggest change in Aerospace since the introduction of the jet engine..**

.. Is this realistic , can this technology really work?

Current Aircraft Gas-Turbine technology

- For the last ~50 years many improvements have been made to Gas-Turbine technology but the biggest benefits have been achieved by increasing the bypass ratio (BPR) for gas turbines in underwing nacelles for aircraft propulsion
  - High bypass ratio (BPR) means that the fan size gets bigger compared with gas-turbine core diameter ..
  - ..which increases propulsive efficiency reducing fuel burn

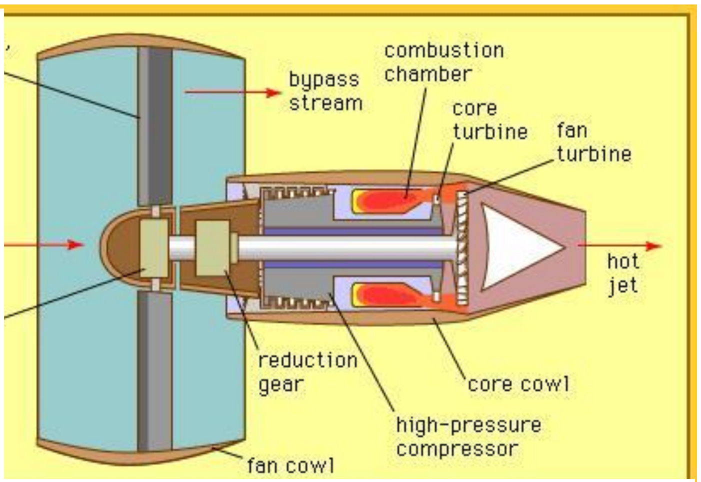
Current Technology Limitations



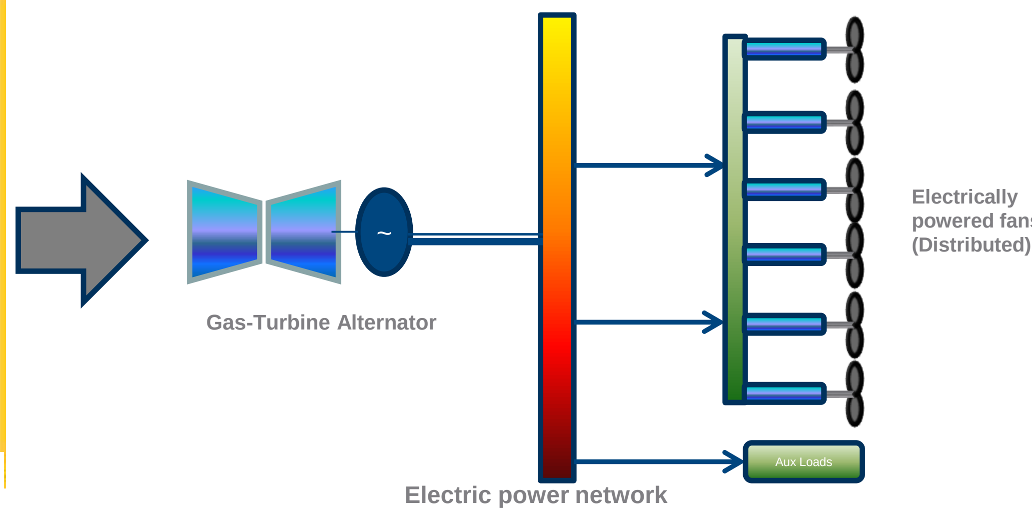
- The current approach has served us very well and produces reasonably efficient designs however..
- ..as engines grow in size and weight, installation becomes more difficult with weight and drag increasing reducing further gains.
- It also limits using more aerodynamic aircraft designs
- It also restricts optimisation as the GT has more design constraints
- And creates dynamic compromises across the operating cycle

Hybrid Electric Distributed Propulsion (HEDP)

What do we mean by HEDP?



Current Gas-Turbine



Hybrid Electric Distributed propulsion System

This removes the need for ever larger by pass ratios and large fans

Effect of “Distributed Propulsion (DP)”

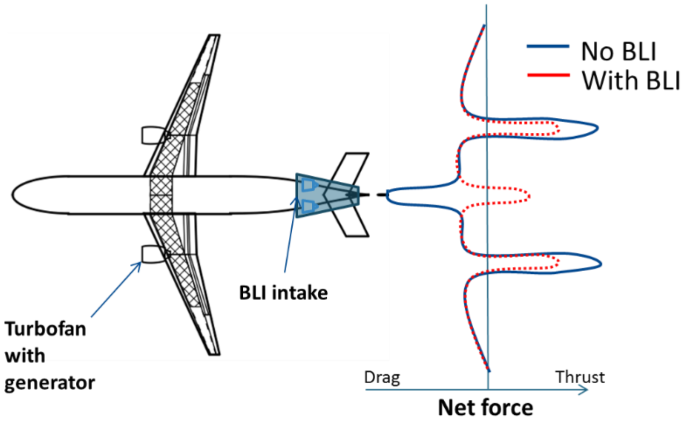
- If we can separate the gas turbine from the propulsion it would mean we could optimise each function more effectively..
- And if we can use a large number of smaller fans we can effectively further increase BPR without seeing the installation restrictions so that these can be distributed around the aircraft
- And freeing up the design of the aircraft for more aerodynamic designs
- The use of mechanical linkages /gearboxes to achieve DP has been extensively studied but has proved impractical from weight and lack of flexibility

Additional Aerodynamic Benefits

- **As we can now place the propulsors where we choose on the aircraft we can obtain additional gains**;

  - Boundary Layer Ingestion (BLI)

  - The boundary layer imposes drag on the wings and fuselage. If we now place our small fans in the boundary layer towards the rear edge of the wings or fuselage we can accelerate this layer and reduce drag.



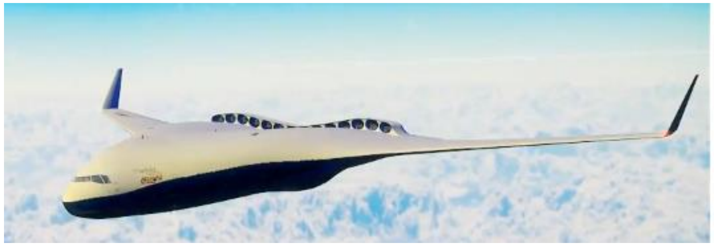
  - Blown Wing

  - If we now place our propulsors on the front edge of the wing the wing sees additional air flow at take off increasing lift. Hence we can use a lower drag wing

.

  - More Aerodynamic Designs of aircraft would be feasible

    Currently there is little point trying to make the aerodynamics of aircraft more effective if we are carrying large high BPR engines. Removing these makes it possible to look at lower drag configurations such as blended wing designs



Electric benefits

- Electric machines adapt to this DP approach because they scale with torque and not power
  - This means smaller motors running faster weigh less for the same power than fewer slower machines. This matches DP requirements very well and allows the use of many smaller machines/fans.
- Electric power gives much greater flexibility
  - We can easily run machines at different speeds for differential thrust and noise cancellation etc
  - Thrust vectoring and VTOL would be relatively easy
  - Very fast dynamics are possible e.g. acceleration leaving the GTs at optimum design point.
  - Failure cases could be accommodated more easily.

In addition gains from Hybrid Electric Operating Cycles will be possible using energy storage

Electric Power Systems Limitations

Electrical power systems when applied to aircraft suffer from a number of disadvantages

Power density- most equipment is bulky and heavy-particularly machines and power-electronic converters

Power cables at large currents are heavy and if we raise the voltage this gives corona discharge

Electric systems suffer from power losses with a typical system running 2-3% of losses. This may seem small but if we are carrying MWs of power this could give 100s of kWs of heat losses....which give thermal management problems

Power conversion and control requires significant power electronic devices which are large and heavy.

Faults can create fault arcs which also require heavy protection and switching devices. Fault arcs are also a safety issue

Lack of an integrated cooling system creates thermal management problems

The electric system suffers from environmental constraints

These will limit applications however there are actions we can take…

Improving Electrical Power Systems

- **The majority of applications do not require high power density**
  - **Marine**
  - **Traction**
  - **Energy**
- **Hence there are improvements that will give better power density and efficiencies**
  - **Increasing voltages gives lower currents and cable weights**
  - **New machine designs –advanced PM and SR machines**
  - **Lightweight networks using new protection device**
  - **Move to high band –gap semiconductors to reduce size of power electronics**

This could take us forward some of the way but this will not be enough for large aircraft!! There is another solution …

High-temperature Superconductivity (HTS)

Superconducting Wire

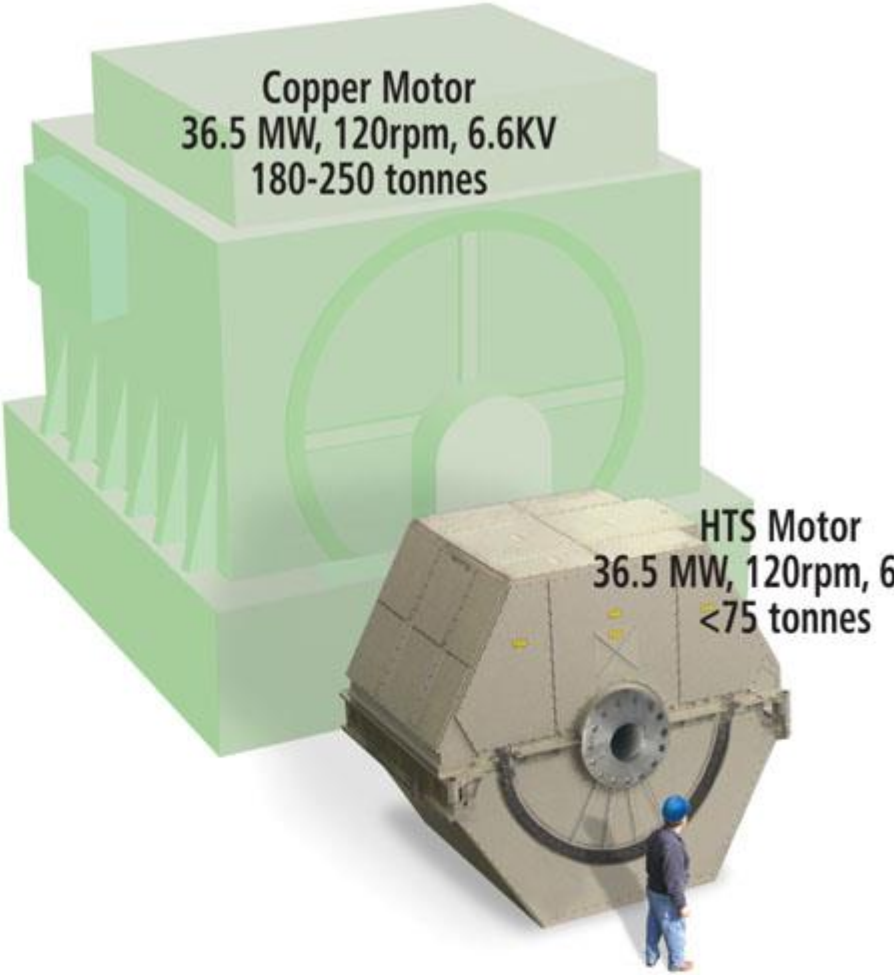
Copper cable for 13KA current (oil-cooled) Weight ~10kGs

Todays HTS wires can give between 100 to 1000 times conventional current densities

Image courtesy of CERN/LHC Geneva

Superconducting (HTS) Machines

- Moving to Superconducting motors and generators will give significant improvements in power density and efficiency.
- To date some superconducting rotor machines have been developed for other applications.
- However fully superconducting machines with an HTS stator is difficult due to AC losses in the magnetic fields.
- However new developments using newer MgB_2 wire may enable these ..
- Giving extremely compact machines



This is a key technology for HEDP

Design of Superconducting Power Networks (SPNs)

- Parameter choice
  - As wire size/weight is no longer a factor we can increase normal currents (In) significantly..
  - …this allows the use of “low voltage” systems even at high powers avoiding corona onset issues at altitude
  - High fault currents will be controlled by Fault Current limiters and therefore are no longer a design constraint
- Zero DC resistance means significantly reduced losses and high system efficiencies
- Control and Switching is possible using new system parameters such as local temperature and magnetics
  - This should lead to reduced mechanical switching and power electronics

Newcastle University

Cryo-cooling

- All superconducting require cooling systems which add complexity and weight to aircraft. There are two main approaches;
  - Use of a mechanical cryocooler. This effectively uses a compressor, coolant fluid and heat exchanger with a “cold head” arrangement.
  - Cryogenic fluids such as Liquid Nitrogen as a “heat sink”
- If a cryogenic liquid that can be used as fuel considerable weight savings can be achieved
- Two choices looked at have been;
  - **Liquid Hydrogen – matches superconductors perfectly and is lighter than kerosene and leaves no CO_2. However it’s expensive, has no infrastructure and can be viewed as hazardous**
  - **LNG –it’s cheaper than kerosene and produces less CO_2 and NO_X and has a strong infrastructure. However it still requires cryo-cooling as it’s temperature is too high. Nevertheless it reduces cryo-cooler size significantly**

HTS Benefits Summary

- HTS provides benefits giving
  - Power Densities up to 2-3 Orders of magnitude (OM)
  - Systems efficiency gains, particularly for DC
  - Power network operational gains
  - Scaling of power systems. Low voltages at high power levels
  - Managing fault conditions
  - Switching
  - Reduced size and use of power-electronics
  - Reduced machines sizes

Cryogenic cooling is required but this can justify the use of Cryo-fuels!!

These changes will unlock new aircraft designs

200 +

100

50

Full BWB TEDP HTS System

150 Seater with MEE and Battery Assist

BLI Electric Assist

Now

Time

2040

BLI Electric Assist

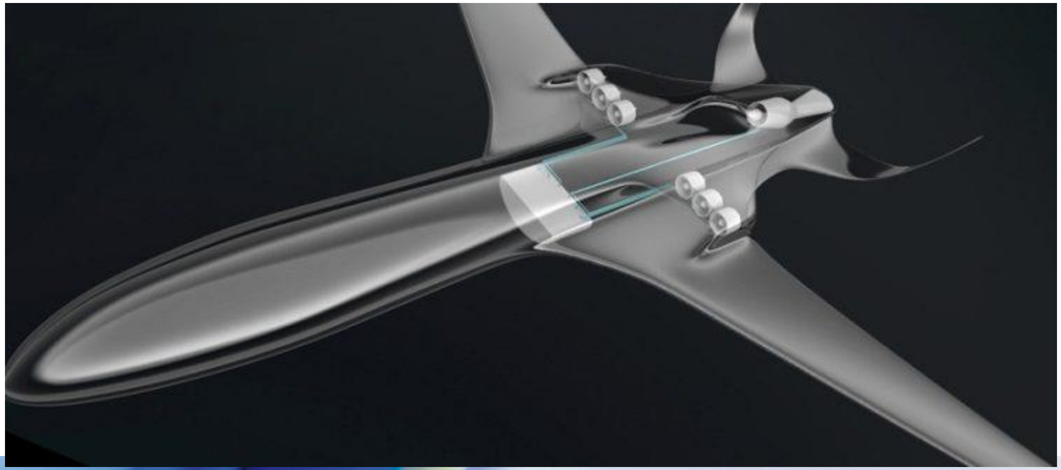
"Modification" of existing aircraft

- **Probably around 100 Seater**
- **Date EIS target early 2020s**
- **Benefits**
  - **Low risk (non dispatch critical)**
  - **Target 5-10% Fuel Burn savings in cruise**
  - **Built in electric taxi capability**
  - **Experience on HEA design and flight**

Image courtesy of GKN Aerospace

MEE Aircraft with Battery Storage Assist

- New aircraft but “flattened tube and wing
- EIS late 2020s
- Target 150 seater market
- Engines have significant Motor/Generator capability
- Back up battery store
- Batteries support engine in part of operating cycle
- BLI effect from propulsors
- Target benefits
  - 15+% fuel saving
  - Electric Taxi
  - Improved operating cycle



Blended wing body Large Hybrid Aircraft

- Hybrid distributed propulsion with full BLI
- Will require fully superconducting power system
- Use of Cryo –fuel for cooling and propulsion
- Significant increase in efficiency giving up to 70% savings in fuel and 60db in noise (NASA figures)
- To impact emissions profile needs to be in service by 2035!

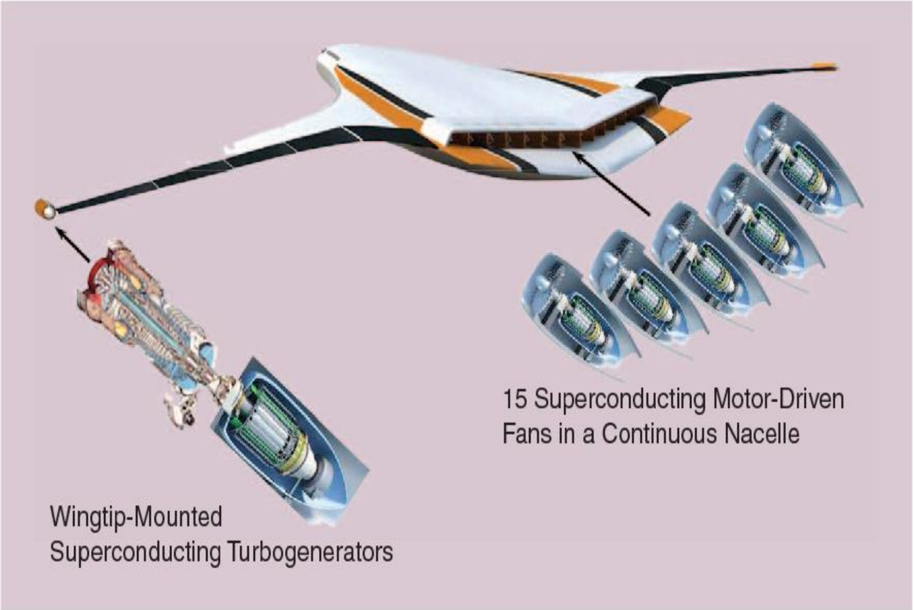
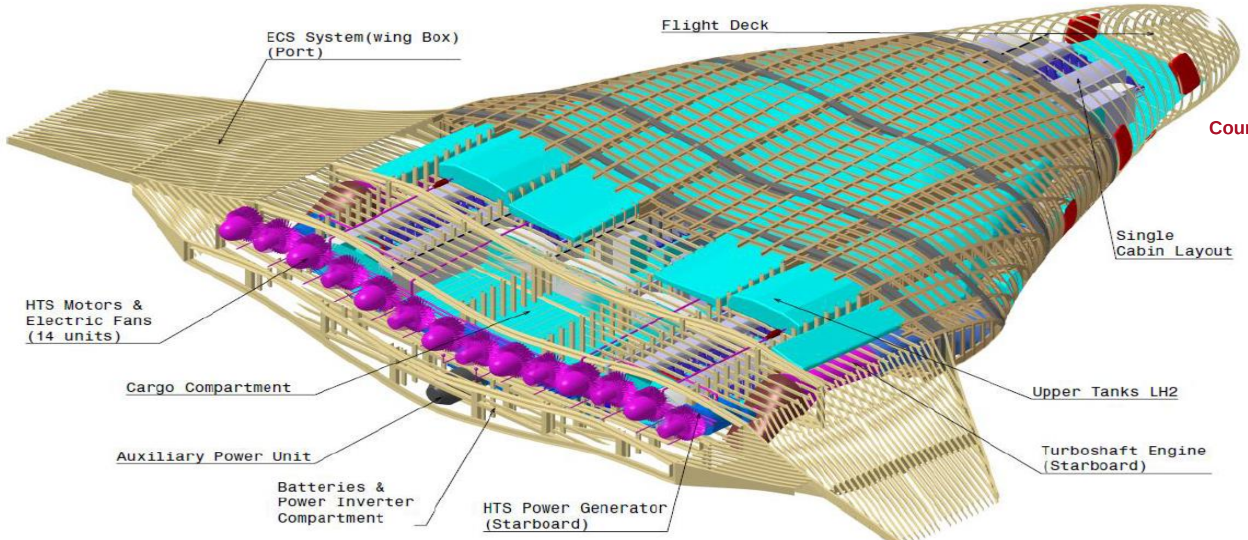


Figure 2. N3-X hybrid wing-body aircraft with a TeDP system.

Image courtesy NASA

The Route to Zero CO2 Flight?

- Using cryo fuels such as LH_2 could provide zero CO_2 long distance flight
- This uses the LH_2 for both cooling and the electrical losses create a fuel boil off which should be an extremely efficient system.
- This is possible but much work and development would be required.
  - i.e we do not need new fundamental technology to do this



Courtesy Prof Howard Smith Cranfield Aero Group

Design Study of a large superconducting HEDP blended wing aircraft fully fuelled and cooled with LH_2

Long –distance air travel without CO_2 emissions is possible

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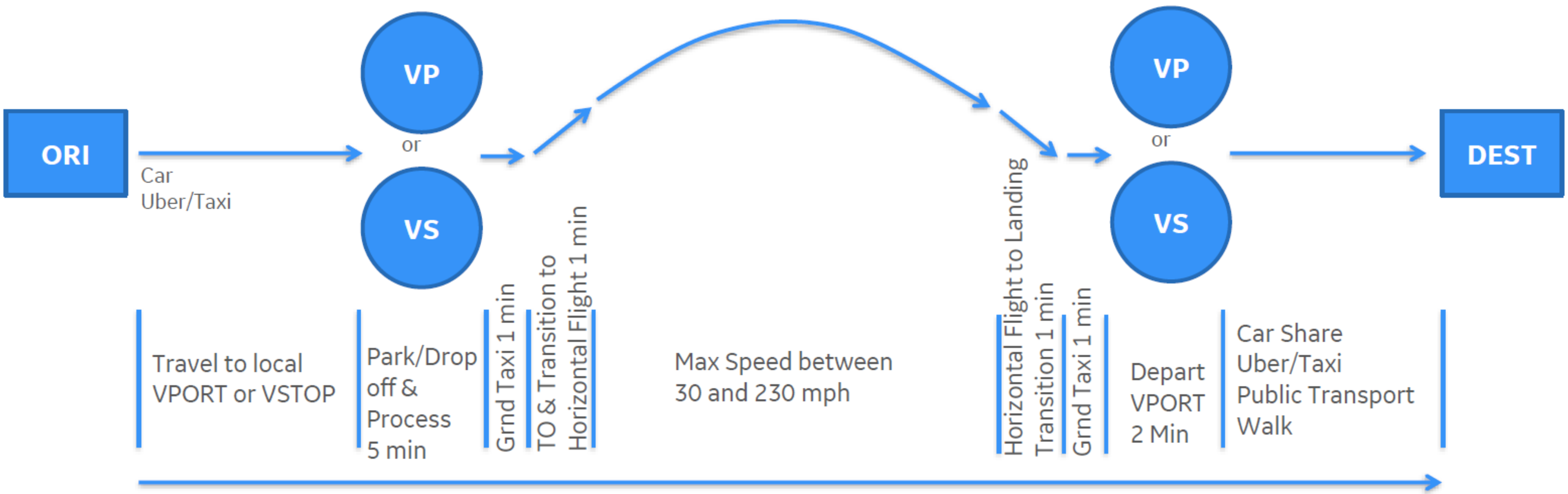
Will it really change everything???

OVER 100 COMPANIES WORLDWIDE NOW BUILDING eVTOL VEHICLES

eVTOL a new form of transport?

Uberverse – On demand sub regional flights...



- **On Demand Aviation - Order service from home and travel to a local Vertiport (VP – larger aerodrome with supporting facilities) or Vertistop (VS – pick-up drop-off point with minimal facilities)**
- **Clear VP/VS facilities (security & pax briefing) board transport and travel close to destination VP/VS**
- **Access local Uber service/taxi/public transport to final destination**
- **Presumed to be 'on call' service with no scheduling of service**
- **SETops you ask? Why has it not taken off? Runways & proximity to where people really want to go**

Courtesy Darrell Swanson

Electric benefits and Issues

- Clearly the attraction of this market is that these would be
  - Clean with no inflight emissions
  - Quiet with little or no noise
  - Flexible systems and have synergies with automotive developments
  - Relatively small electrical systems
  - Possible autonomous control /flight

However these are only partially true….

EARLY eVTOL Aircraft

- **Battery limitations will prevent all-electric in the short –term unless some design “tricks” can be developed**
- **However some Hybrid systems could appear such as for example the RR design..**
- **…although these might have noise and complexity issues**
- **Battery developments will be critical here**

The initial concept vehicle uses gas turbine technology to generate electricity to power six electric propulsors specially designed to have a low noise profile. It also has a battery for energy storage. In this hybrid-EVTOL configuration it could carry four or five passengers at speeds up to 250mph for approximately 500 miles, would not require re-charging – as the battery is charged by the gas turbine – and would be able to utilise existing infrastructure such as heliports and airports.

Text and Image Courtesy Rolls-Royce plc

eVTOL Technical Issues

- Noise – these clearly will be quieter than existing helicopters but they may be far from silent(Rotor noise)
- Batteries –**energy density is still a very significant problem**
  - VTOL demands a lot of energy even for small vehicles!!!
- Safety- these clearly will be less safe than existing large aircraft . Is this acceptable?
- Electrical systems – these are still complex electrical systems and require significant design effort.
- Control and infrastructure could be problematic

However these developments seem unlikely to have a major impact on overall aerospace emissions. Hence whilst interesting for infrastructure in the bigger picture they may not be significant.

RESEARCH ACTIVITIES

Activities in mainland Europe

- Airbus (D) and Siemens
  - New group at Ottobrunn with new 20MW test facility with 200+new engineers.
    - Just setting up new group on superconducting systems – recruiting in the UK
  - Extensive research support for DLR, German Universities.
  - German National and regional funding
- Airbus France
  - New support from Government and supply industry for IRT Saint Exupery now dedicated to HEA
  - University and EU support
  - Research Support-significant funding from French government

Airbus –"A central hub for electric aviation in Munich"

The E-Aircraft System House will serve as a resource for the entire Airbus.

A central hub for electric aviation in Munich

The E-Aircraft System House is at the heart of Airbus's electric aircraft activities. This large test and development facility near Munich, Germany will serve as an Airbus focal point to validate electric and hybrid aircraft propulsion technologies.

To reach the necessary levels of maturity for e-aircraft technology, the E-Aircraft System House is initially focusing on:

- Advancing basic technological expertise and capabilities for individual components
- Investigating incorporation of components into sub-systems such as electric fans and propellers, high-voltage platforms, turbines, generators and thermal systems

Ground was officially broken on the facility in Spring 2016 – which will enable the start of construction in early 2017 and a planned opening by late 2018. The site will be jointly operated by the Airbus Innovations research and technology network and the Group's three divisions: Airbus, Airbus Helicopters and Airbus Defence and Space.

US Activities in HEA

- Led by NASA through dedicated support fund started in 2014
  - SBIR study programmes
  - University Collaboration Research
  - NEAT 30MW facility
- Additional Support from US Industry
  - GE Research EPI Centre
  - Other work ongoing
- Significant funding via NASA +

The US has a Fully Funded University Programme

WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON

- Electric Machines

THE OHIO STATE UNIVERSITY

- Center for Automotive Research—Batteries
- Center for High Power Performance Electronics—Power Electronics

CASE WESTERN RESERVE UNIVERSITY EST. 1826

- Batteries

NASA

- NEAT Test Facility

Georgia Tech

- Systems Integration

NORTH CAROLINA A&T STATE UNIVERSITY

- Thermal Management

UNIVERSITY OF MARYLAND 1856

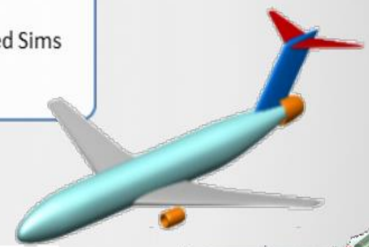
- Thermal Management

Fully Integrated University Team Working Together

NASA Programmes USA

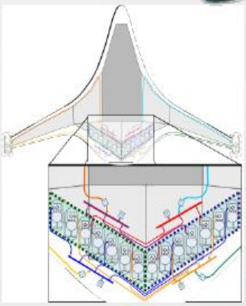
Technical Areas:

- **Propulsion System Conceptual Design**
- **High Efficiency/Power Density Electric Machines**
  - Superconducting (cryo)
  - 1 MW Superconducting Motor Test
  - Non-superconducting
  - Superconducting Wire
- **Flightweight Power**
  - Power System Architecture & Modeling
  - Intelligent Motor Drive
  - NASA Electric Aircraft Testbed (NEAT)
- **Enabling Materials for Machines and Electronics**
  - Insulation
  - Advanced Magnetic Materials
  - Wide Bandgap Semiconductors
  - Conductors
- **Integrated Flight Simulation & Testing**
  - Hybrid Electric Integrated Systems Testbed (HEIST)
  - Piloted Sims

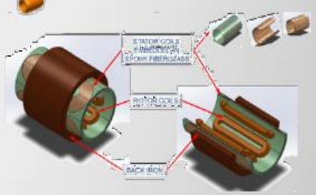


Approach:

- Detailed assessment *of reference design concept* through modeling and analysis
- 200 kW Subscale System Demo's on *hardware-in-the-loop* testbed
- Select Component Demo's at *1-2 MW Level*
- Component maturations for key enabling materials and subcomponents



Propulsion power grid architecture



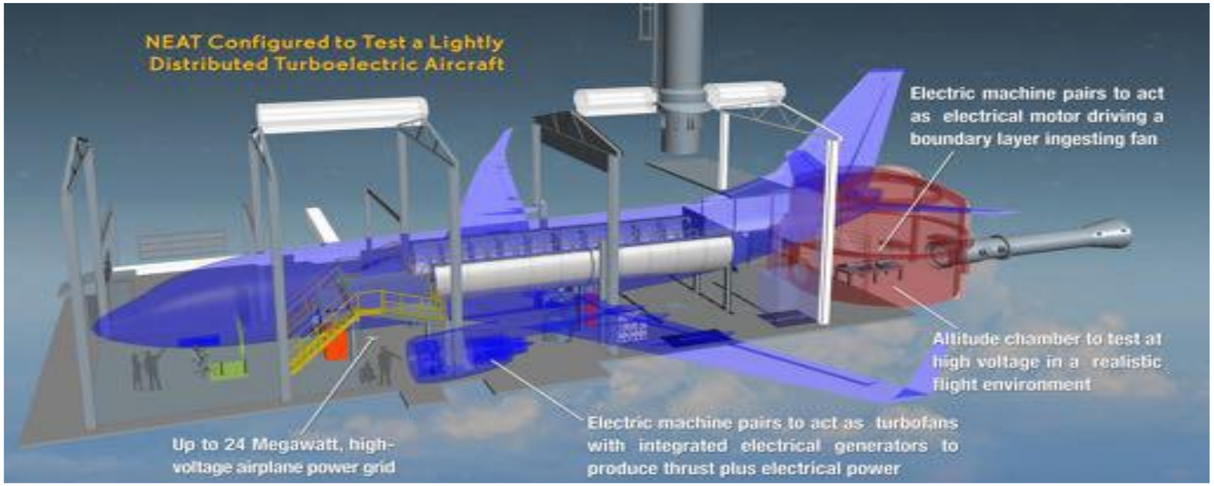
Electromagnetic Components

NASA Demonstrator

Full 24MW Powertrain Testing Capabilities at NEAT Facility USA

Reconfigurable NASA Electric Aircraft Testbed (NEAT) being developed to support full-scale large aircraft powertrain testing for community use

- Infrastructure for up to 24 MW input power with regeneration, cryogenic fluid and fuel handling, multi-MW cooling and 120,000 feet altitude flight environment capability
- Plans to demonstrate high fidelity turbo-generation and ducted fan transient emulation, test MW-class research motors, inverters, and single-and multi-string powertrains



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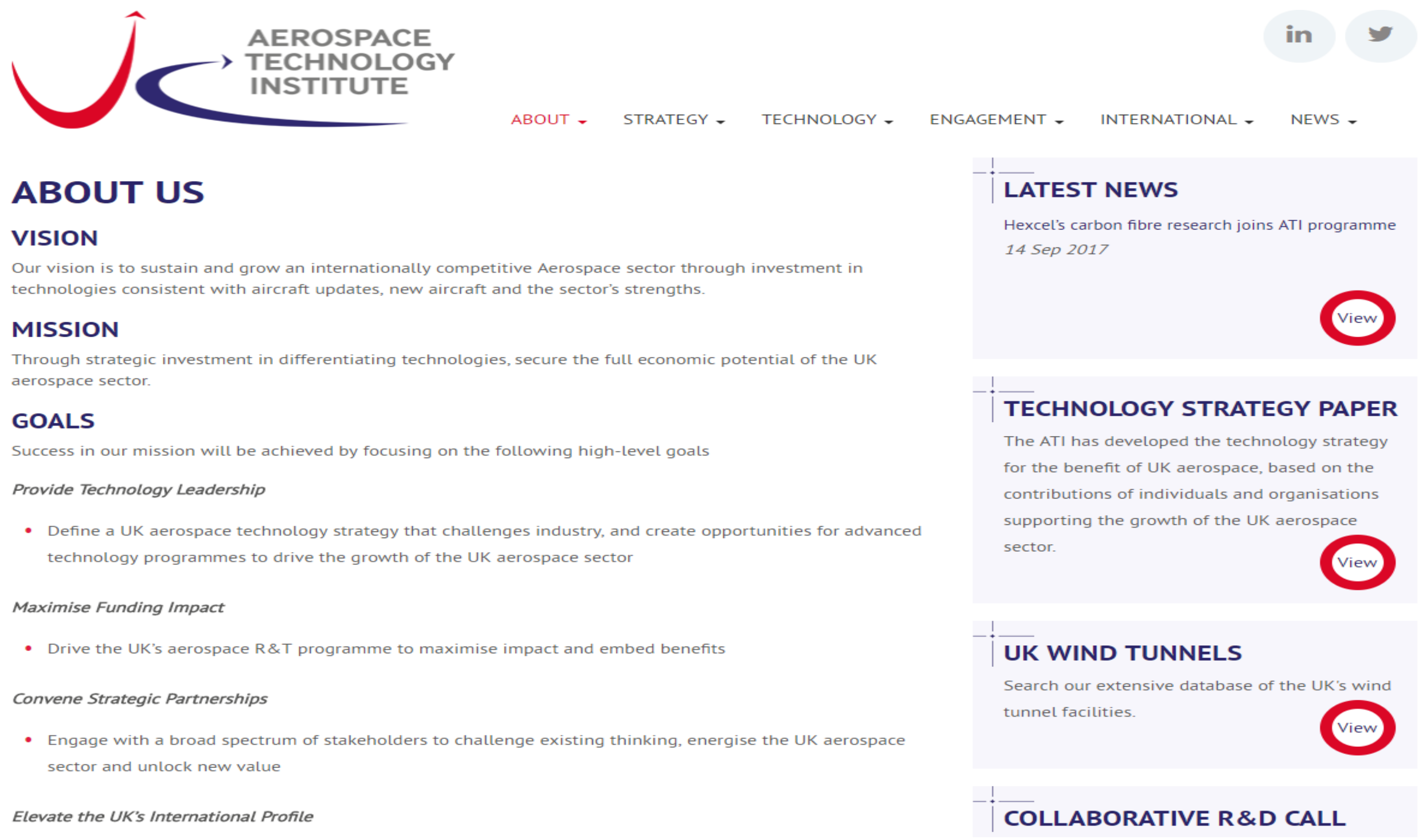
UK Response



AEROSPACE TECHNOLOGY INSTITUTE

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ABOUT STRATEGY TECHNOLOGY ENGAGEMENT INTERNATIONAL NEWS

ABOUT US

VISION

Our vision is to sustain and grow an internationally competitive Aerospace sector through investment in technologies consistent with aircraft updates, new aircraft and the sector's strengths.

MISSION

Through strategic investment in differentiating technologies, secure the full economic potential of the UK aerospace sector.

GOALS

Success in our mission will be achieved by focusing on the following high-level goals

Provide Technology Leadership

- Define a UK aerospace technology strategy that challenges industry, and create opportunities for advanced technology programmes to drive the growth of the UK aerospace sector

Maximise Funding Impact

- Drive the UK's aerospace R&T programme to maximise impact and embed benefits

Convene Strategic Partnerships

- Engage with a broad spectrum of stakeholders to challenge existing thinking, energise the UK aerospace sector and unlock new value

Elevate the UK's International Profile

LATEST NEWS

Hexcel's carbon fibre research joins ATI programme

14 Sep 2017

View

TECHNOLOGY STRATEGY PAPER

The ATI has developed the technology strategy for the benefit of UK aerospace, based on the contributions of individuals and organisations supporting the growth of the UK aerospace sector.

View

UK WIND TUNNELS

Search our extensive database of the UK's wind tunnel facilities.

View

COLLABORATIVE R&D CALL

AEROSPACE TECHNOLOGY INSTITUTE

ABOUT STRATEGY TECHNOLOGY ENGAGEMENT INTERNATIONAL NEWS

THE TECHNOLOGY

Having the right technology on-stream is clearly essential to competitiveness; the challenge is knowing *where* and *when* to invest finite resources for maximum outcome. The Institute is studying emerging trends and anticipating future market needs, in areas including:

- *Future propulsion*
- *Highly integrated aircraft structures & systems:*
- *Electric aircraft*
- *Connected and intelligent aircraft*
- *World-class integrated design & high value manufacturing*

LATEST NEWS

Hexcel's carbon fibre research joins ATI programme

14 Sep 2017

View

TECHNOLOGY STRATEGY PAPER

Good News is that HEA is now recognized but we need to move quickly to funding!

Recent Work at Newcastle University

"A further allocation of institutional sponsorship is being made available to those institutions which have a coordinating role in the research community related to the Aerospace and Automotive sector, specifically around the four pillars of the Aerospace Technology Institute's Technology Strategy and those which host Advanced Propulsion Centre Academic Spokes. Newcastle University is one such Institution and the amount of investment available for this activity is £250,000 for Aerospace in Advanced Systems and £250,000 for Automotive in Electric Machines. EPSRC expects Professor Barrie Mecrow to take a leading role in working with the research community, EPSRC and the Aerospace Technology Institute on the Advanced Systems pillar of the ATI strategy."

EPSRC
Investing in research for discovery and innovation
August 2016

- Newcastle University was the only University asked to lead in both Aerospace and Automotive studies
  - Other Aerospace work was Propulsion (Cranfield), Operations (UCL) and Structures (Bristol)
- Work was to define key technology roadmaps in these areas
- Results were widely seen as "successful" with future work likely to go ahead
- The ATI future work is now based around Hybrid and Electric Aircraft Systems following our recommendations

ATI Systems Study –Key Achievements

- **We have created a highly effective "network" of Universities and Industry**.
  - We have held Launch meeting and five well attended steering meetings around the UK
  - We have used a virtual research environment to exchange information
  - We have monitored significant research and developments in this field outside the UK
- **We have chosen four key technical research areas relating to HEDP that have been broadly welcomed by Industry**
  - We have agreed a work share for each programme
  - All partners have completed their programmes
  - We have attracted strong and active industry support from both major UK enterprises and an SME.
  - These have demonstrated the requirements to continue work in these areas and already early IP seems possible
- **We have worked closely and interacted with two of the other themes**
  - We have shared programmes with Propulsion
  - Active work with Whole Aircraft

We believe it is important to maintain this successful momentum

Some Proposed Study Areas from our Roadmap

Short-term

HV AERO POWER SYSTEMS	Current aircraft systems operate at low-voltages to avoid dielectric problems at altitude. However if we wish to increase power increasing voltage allows a much lighter weight system rather than increasing current. The dielectric issues can be avoided by careful design.
BLI MOTOR	Conventional electrical machines have been designed around other applications rather than Aerospace. By choosing a BLI tail fan gives the possibility of optimising their design for a reasonably small application to obtain better performance.
BeLIEF BLI AIRCRAFT	HEDP is a highly integrated system design issue. This means that much of the early "IP" is at full system level. DEAP showed a BLI aircraft with Electric Fans could provide benefits and therefore it is logical to bring the BLI motors study to a full large aircraft study (~100 seats)
SUPERCONDUCTING POWER NETWORKS	Large aircraft will require >10MWs of electrical power. To achieve the required power densities and efficiencies full superconducting networks will be required. The materials are now ready but the understanding of these networks requires much more research.

Long term

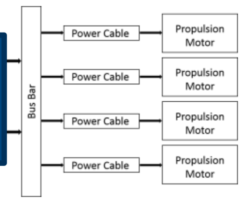
HV System Roadmap Example

Combine with BLI Motors to provide BeLIEF Power System

2kV/1000kW demonstrator

MEDIUM TERM GOAL

HV System



Now

2019

2020

2022

Specification for baseline system

Power level 1-3MWs

System voltage 0.69-3.3kV

Dielectric optimized components

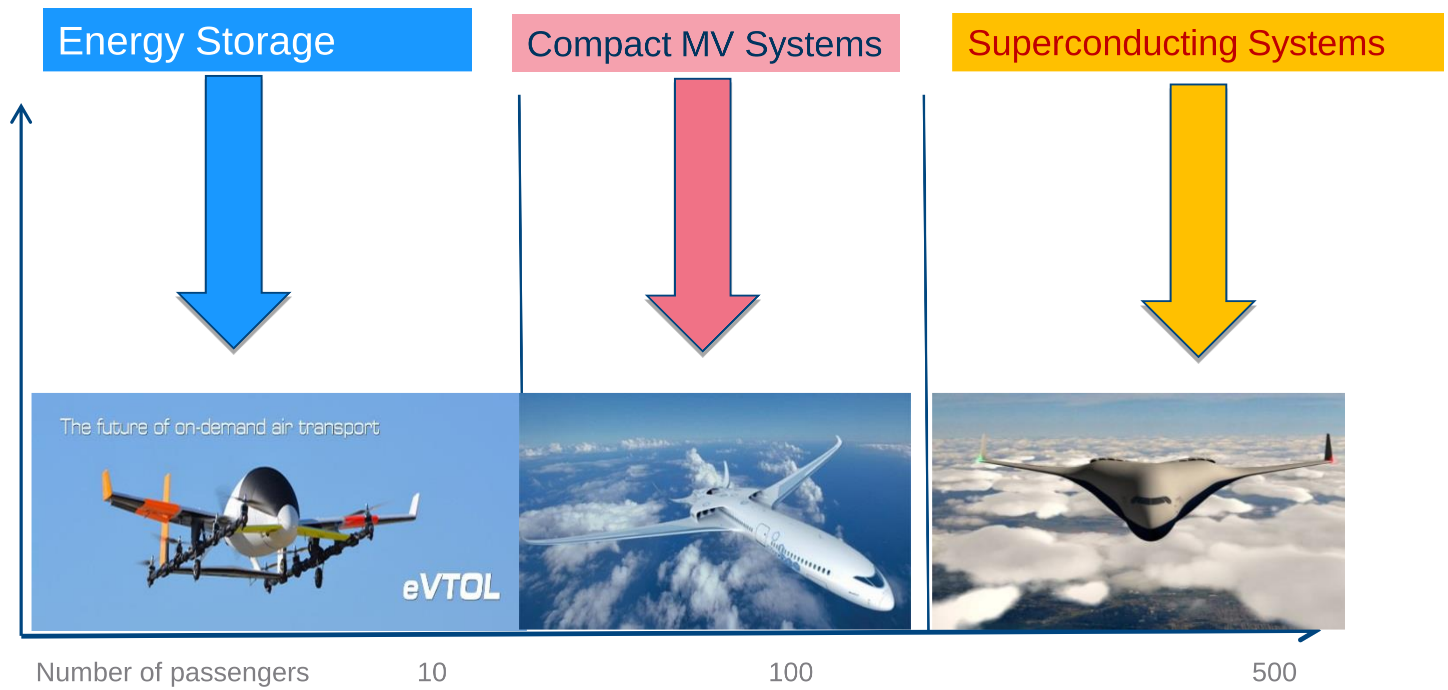
Fault management study

Novel switching device single-phase

HV Power system

Design and build full size power system operating at optimized voltage with full protection and fault management capability

Required electrical technology strategy



These are three separate fields of research which must be studied in parallel

These are specific areas and will not fall out of other sector work

Conclusions

- It seems now very likely that the Civil Aerospace industry is about to undergo a radical and significant period of change.
- This will be based around HEA and these changes seem to be coming much sooner than predicted. Three types of aircraft seem likely with the first appearing within five years
- eVTOL vehicles are currently being developed by over 100 companies around the world and if battery issues can be resolved may well represent a new transport sector.
- Whilst some research is starting up in the UK we are already at risk of falling behind extensive work in mainland Europe and the USA.
- ***If the UK wishes to retain its leading role in aerospace in my view we must accelerate our efforts in the field of aircraft electrification urgently!***