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Introduction

This paper has been compiled to provide a “Technology Watch” on developing technologies which are not necessarily integral to the Aerospace Technology Institute (ATI) Technology Strategy (as published in the 2016 document *Raising Ambition*) but may impact the future delivery of the technology strategy.

The topics covered are a selection of technologies which illustrate some of the diverse areas covered by aircraft propulsion systems but are not intended to be an exhaustive list of technologies. The paper identifies some key trends and areas of focus which will be important in the aerospace sector to meet forecast market opportunities and deliver economic impact in the UK.

02 EMERGING TECHNOLOGIES FOR PROPULSION

EXECUTIVE SUMMARY

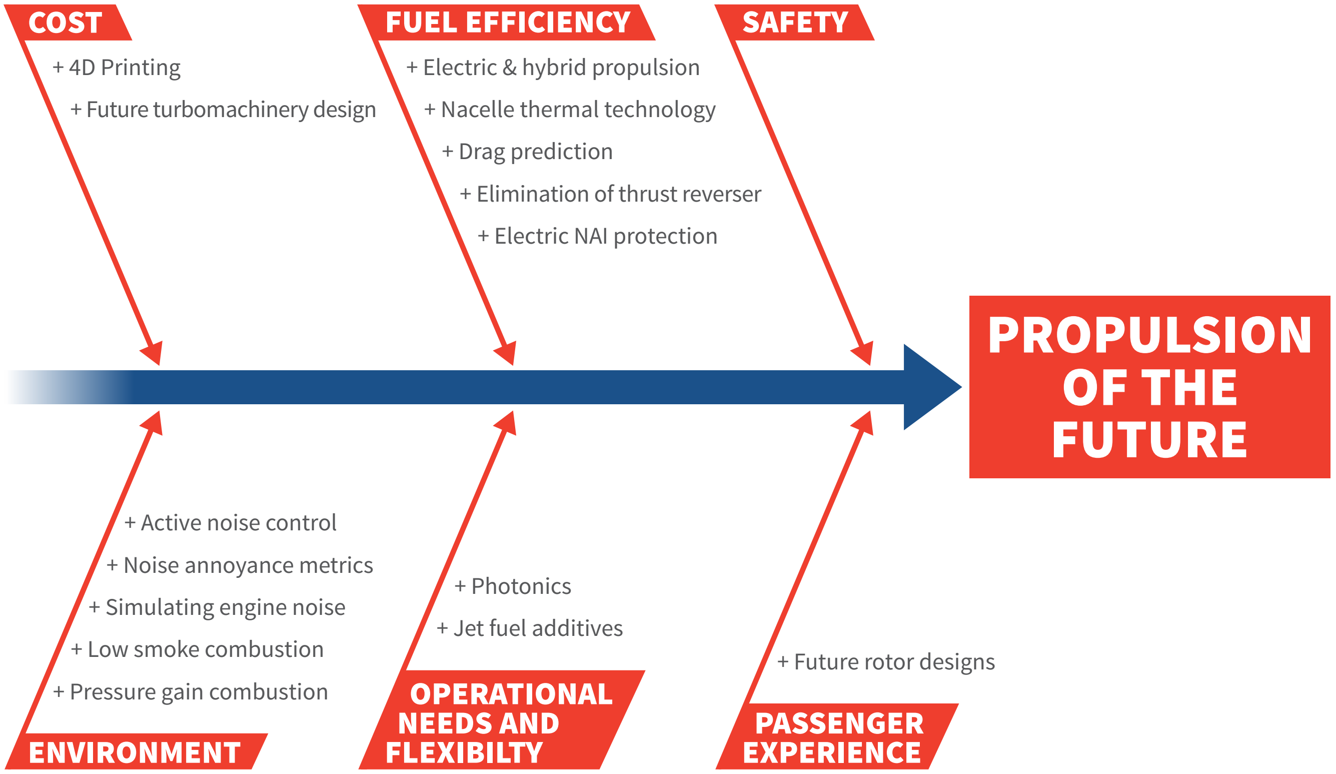
- More electric technologies are progressing within current and planned R&T projects although the overall roadmap for more electric aerospace technology in the UK still needs to be articulated and delivered. A follow up paper, specifically focussing on this field will be issued by the ATI later in 2017.
- Thermal technologies are increasingly important in aerospace architectures as new concepts create increasingly demanding thermal loads with reducing opportunities for conventional heat dissipation approaches.
- Noise is a specific target for ACARE Flightpath 2050 and continued research to develop active noise control, noise annoyance metrics, noise simulation and measurement and deployment of novel ATM to reduce noise impacts should be watched to ensure targets for aerospace can be achieved. In the nearer term, the local environmental impact is driving the need for further improvements in noise (e.g. the discussion around the third runway at Heathrow airport).
- Emissions targets in ACARE Flightpath 2050 may also drive change in low smoke producing combustion systems as well as looking at more disruptive technologies such as pressure gain combustion.

PROPULSION OF THE FUTURE

Propulsion of the Future technologies are characterised by:

- Realisation of large ultra-high bypass ratio (UHBR) turbofan engines
- Enhancing the integration of advanced propulsion systems onto aircraft

The following sections of the document illustrate some examples of emerging technologies which could benefit “Propulsion of the Future” and can be viewed against the relevant ATI Whole Aircraft Attributes. The technologies were selected by the ATI Propulsion Specialist Advisory Group. The figure below shows how these technologies align with the most relevant whole aircraft attribute, although many of these technologies could contribute, either directly or indirectly, to multiple attributes.



Emergent Technologies for Large UHBR Turbofan Engines

Active Noise Control

Active noise control is used in the cabin of some turboprop aircraft to reduce cabin noise. In this case, the propeller results in dominant low frequency sound waves that an active control system can detect and respond to, hence significantly reducing the noise in the cabin. However, high bypass gas turbine engines produce a complex field of high frequency tones due to multiple interactions between rotor blade and stator rows. These are more difficult to attenuate. To reduce community noise (external to the aircraft), the noise would need to be reduced at source, which research has shown needs very high power sound sources to be put in the nacelle or on non-rotating turbomachinery blade rows. Noise would need to be reduced local to the airport whilst the engine speed is changing, meaning that the complex source needs to be measured in real time and the corresponding sound modes generated to exactly cancel those being produced. Test results in high bypass ratio fan system rigs have demonstrated that noise cancellation of targeted sound modes is possible, however integration of these capabilities into nacelles and engines is currently at low Technology Readiness Levels. Developments in digital, electrical and computing technologies are likely to accelerate the timescales to overcoming the current limitations.

Noise Annoyance Metrics For Quiet Aircraft Of The Future

The perception of aircraft noise by human beings depends on many factors. Many local communities believe that current noise metrics, including the use of average noise contours, do not fully reflect their experience of aircraft noise. The World Health Organisation regional office for Europe is reviewing the latest scientific evidence to help better quantify the consequences of noise on health and the effects of lower level noise indicators. Sustainable Aviation has published a noise road map (http://www.sustainableaviation.co.uk/wp-content/uploads/2015/09/SA-Noise-Road-Map-Report.pdf). This allows industry to target research gaps in weighting of the variables, develop more accurate noise models, understand individual reactions to aircraft noise, evaluate noise acceptability versus noise annoyance, and develop a basis for better noise metrics. The perception of aircraft noise will continue to drive research in the aerospace sector including noise simulation, suppression and measurement topics.

Simulating Engine Noise

Controlling and reducing propulsion system noise is critical to current and future aviation noise targets. Validated technologies for simulation and measurement of noise are essential to achieving these targets. More reliable and comprehensive simulation methods reduce time and cost to market, although they will not fully replace engine and rig testing in the near or medium term.

New propulsion architectures (e.g. UHBR, Hybrid electric) pose challenges for existing simulation methods which are more suited to predicting the effects of incremental changes in conventional engines. Broadband fan noise in conventional engines is a challenge for current hybrid prediction modelling techniques, requiring significant simplification of physics and geometry (using Stochastic Noise Generation and Radiation methods (SNGR) and artificial turbulence, idealised blade geometries, etc.).

> *Controlling and reducing propulsion system noise is critical to current and future aviation noise targets.*

Acoustic noise liners cannot be modelled with current approaches due to unsteady flow in individual cells within the liner. Current Impedance models do not deal well with high amplitude noise and grazing flows. Exploitation of novel liner concepts made possible by manufacturing advances will, therefore, require improved simulation approaches to optimise liner performance. Non-grid-based discrete methods, such as the Lattice-Boltzmann Method (LBM) have been advocated for aero-acoustic simulation. This may directly resolve tone and broadband sources in subsonic flows. If validated this could challenge (and possibly replace) current hybrid strategies.

Future Turbomachinery Design Methods

A full design and test cycle of an aero engine compressor is typically more than year. The computational design takes a team of people typically 6 months using 1D, then 2D and the 3D design methods. The compressor is then typically built and tested which takes around a year. If the test is not successful, the design/make/test loop is repeated.

Over the last 30 years, computation has been used to automate the design methods, but its underlying approach has not changed. High performance computing and rapid manufacture offer the opportunity to radically rethink the design system with the opportunity to reducing design time scales by at least an order of magnitude. High performance computing offers the potential to develop augmented design systems. Such systems allow the designer to manipulate aerodynamic design metrics instead of blade geometry.

The high-performance computer then optimises the geometry in the background, running hundreds of computational solutions, to achieve the designer's aerodynamic design goals. Prototypes of these systems show orders of magnitude reduction in the design time scale. The approach also gives the designers the time and control to design subtler aerodynamic features into the blades.

In addition, the recent development of rapid manufacturing technologies allows components to be manufactured in hours, which only a few years ago, would have taken weeks. This has allowed the development of rapid test facilities at the Whittle Laboratory in the University of Cambridge, which can experimentally test blade designs in days instead of months.

The challenge is to develop new turbomachinery design methods which exploit the coupled capability of rapid experimental testing with augmented design methods. This would have several major advantages: The design time-scale would be reduced by more than an order of magnitude. The increased control over the design process would allow more complex aero technologies, many developed within ATI programmes, to be more easily implemented into products. Full integration of experimental testing into design method would allow the aerodynamic penalty of through life geometry variation effects (i.e. surface roughness, clearance wear, fowling) to be more accurately assessed during design. Such a design system would offer a major strategic advantage to UK aerospace propulsion as well as other sectors.

Combustion Systems For Low Particulate Production

Recent epidemiological studies (https://uk-air.defra.gov.uk/assets/documents/reports/aqeg/ch3.pdf) are beginning to reveal additional links between ultrafine particulate matter and adverse human health effects. The smallest particles are more mobile and therefore, once breathed in, are more able to travel much deeper into the human body, where they can also cause irritation and respiratory problems. Aerospace pollutant emissions are regulated only near the airport, in a defined Landing and Take Off Cycle, which controls pollutant species within 3000ft altitude of the airport.

The pollutant species of concern are oxides of nitrogen (NOx), carbon monoxide (CO), unburned hydrocarbons (UHC) and non-volatile particulate matter (nVPM) or smoke. Until recently, smoke from aviation was mainly regulated based on visibility criteria alone and certification was based on traditional filter-paper techniques to assess a minimum "smoke number" to be achieved to guarantee no visible smoke trail from engines. In very simplistic terms, the filter paper smoke number is proportional to smoke mass – effectively assessing the mass fraction of particulate matter collected from a known sample volume.

Over the last few years, CAEP has developed a new regulatory standard for nVPM (defined in the Aerospace Information Report (AIR) 6241) to better characterise engine emissions. This is based on independent measurement of both particulate mass and number density with more modern, up-to-date instrumentation and sampling protocols. The focus on nVPM research needs to be adjusted and widened. Historically, using filter paper smoke measurements, the focus of aerospace nVPM reduction has been towards the highest power conditions of climb and maximum take-off (MTO) where smoke mass is at its peak. There has been little interest at the lowest power settings due to the very low smoke numbers measured there. Modern measurement techniques now reveal that additional focus needs to be concentrated on low power setting where unexpectedly high numbers of small particles are being produced.

Fundamental research needs to be undertaken on the physics and chemistry of this phenomenon in terms of the root cause understanding and that will then drive mid and high TRL work to develop cleaner combustor technology. As with NOx reduction, it is expected that the changes are likely to be substantial and take time to mature and make their way into products. It is anticipated that a long term, concerted effort needs to be made to address this important issue, in a similar approach to the current level of attention to NOx related combustion technology.

Pressure gain combustion for gas turbines

Replacing the conventional combustor of a gas turbine with a pressure gain combustion offers the potential to increasing the efficiency of a gas turbine by 10-20%. The technology also has the potential to significantly reduces NOx while increasing the gas turbines specific power. The past two decades have seen increasing interest in pressure gain combustion. Two potential technologies exist, a confined deflagrative (subsonic) combustion process and a detonative (supersonic) combustion process.

The deflagrative combustion process was used in the V1 'buzz' bombs in World War II. Several international groups (SNECMA, NASA, US DoE, and University of Cambridge) have demonstrated deflagrative combustors that achieve a pressure gain from inlet to exit, although the maximum pressure gain achieved is currently around 10%. In 2008, the US Air Force carried out the first flight of a detonation combustor powered aircraft. There is now a significant amount of research being put into rotating detonative devices. Work at US Air Force and the University of Cambridge has looked at integrating combustors into gas turbines. Despite this progress, two key challenges need to be overcome to make pressure gain combustion a practical proposition.

First, the pressure gain needs to be significantly increased from today's best of 10% - pressure gains of more than 100% should be theoretically possible. Second is the demonstration of a pressure gain combustor integrated into a gas turbine.

Means to eliminate thrust reverser systems

Thrust reverser systems are used in conjunction with other aircraft retardation systems such as brakes and spoilers to decelerate the aircraft on landing. However, thrust reversers are used for only a fraction of the aircraft operating time and their impact on nacelle design, weight, aircraft cruise performance and overall aircraft operation and maintenance is significant.

In the whole aircraft architecture, the thrust reverser provides enhanced safety margins and operational flexibility. Future potential approaches are to better variable pitch fans for UHBR turbofans), deploy novel thrust reverser concepts to reduce the impact on forward thrust performance or ultimately to consider whole aircraft level solutions.

Photonic sensing for harsh environments

Optical and photonic sensing technologies are maturing for harsh-environment applications. They are already in use in several other sectors such as oil-and-gas and industrial applications for monitoring of structures and fluids. They have several potential applications within aerospace - for sensing in gas turbines, aircraft structures, and as “listening” devices for use as health monitoring. They could potentially displace existing sensors (strain, temperature, acoustic, pressure) and enable improved structural health monitoring or noise measurement.

Optical technologies are much more resilient to electromagnetic interference potentially reducing development costs. Existing thermocouple sensing technology is now reaching its ultimate temperate capability and hence is not keeping track with developing engine technology. Fibre-optics/photonics could offer a potential step change in capability. For strain and/or temperature measurement, Bragg-Grating sensors are already in use in for low-temperature applications (<250C) in energy, oil and gas.

Back-end opto-electronics are now reaching a point where they are becoming competitive on weight and reliability for aerospace applications. Higher temperature (sapphire) Bragg-Grating sensors are now producing feasible results for monitoring to 1700oC. Photonics could not only displace existing sensor techniques, but add new capabilities such as monitoring of structures, monitoring of critical components (eg. as bearings), and monitoring of noise. Cabled microphones or kulites are used universally to collect acoustic data from rig and engine tests.

The cabling required for these sensors limits the size and location of arrays whilst overall reliability of these sensors is further impacted by the impracticability of deploying multiple sensor redundancy in each location. A potential emerging technology is the use of distributed acoustic sensing with multiple sensing points along a single optical fibre. When combined with processing methods such as Optical Time Domain Reflectometry (OCDR), this offers the prospect of dynamic pressure measurement with a spatial resolution of the order of centimetres. If validated and shown to be robust, this technology could permit unobtrusive distributed acoustic sensing for rig and engine tests, but also the potential to embed sensor arrays in production engines for in-service fault diagnosis, and noise control with multiple redundancy.

Enhanced Integration Of Advanced Propulsion Systems Onto Aircraft

4D printing refers to the use of a programmable material which can adapt its form or function in the presence of a stimulus such as pressure, temperature, ultraviolet light or humidity. Opportunities in propulsion would be for actuation or variable geometry intakes, nozzles or valves. This offers the ability to deploy a simple actuation capability and eliminate conventional complex mechanical actuation systems, reducing weight and optimising the overall propulsion system performance.

In addition, the programmable material may offer novel solutions for complex assemblies in restricted space envelopes. Two of the more relevant examples of current research in this field are: (1) morphing composite structures at the University of Colorado, Boulder using integrated polymer fibres to change shape with temperature and (2) programmable carbon fibre components developed at MIT in conjunction with Airbus for movable surfaces or cabin air systems. Whilst research is ongoing to better understand material capability, the priority for aerospace is to characterise and establish systems requirements to provide targets for material capability.

Aviation Jet Fuel Additives

The number of new fuel pathways being developed has been growing, driven by airline operators for environmental and economic reasons. Properties of these alternative fuels may be different than standard kerosene andcan potentially impact both existing and new aircraft. Considerations include system design (e.g. fuel gauging systems), fuel icing and water content, microbiological contamination, as well as the overall aircraft and equipment design.

Today, the new fuels may already impact gauging systems but the impact tends to be mitigated through fuel blending. Water content in the fuel impacts maintenance and the systems and equipment operation. Reduced energy density in the alternative fuels could affect existing aircraft performance; for new aircraft designs consideration is needed to accommodate increased volumes. In situ-measurement of fuel calorific value could mitigate this. For all fuels, uncertainty in calorific value within the specified limits can contribute 2-3% of additional fuel load and associated take-off weight. Further research is also required on fuel properties, reduced sulphur or aromatics content and microbiological contamination.

For future aircraft, the design rules need to be developed to encompass the alternative fuel characteristics. This could drive new systems technologies (e.g. gauging) or increase the stringency of engine interface requirements for ice and water threats.

Electric & Hybrid Technology

Conventional gas turbine aero engines achieve overall efficiencies of around 35-50% but the advent of hybrid propulsion systems offers the opportunity for higher efficiencies through combination of two or more energy sources or power converters. Electro-mechanical systems can offer noise reduction but provide a limited operating range unless they can be re-charged during operation by another energy source. A hybrid system combining gas turbine and electro-mechanical technology could unlock quiet, efficient electric propulsion whilst taking advantage of energy dense liquid fuel gas turbines.

The aerospace industry is speculating the opportunity of a new regional aircraft in the 2030+ timeframe enabled by hybrid distributed propulsion. Electrical power systems for these applications are anticipated to require 10-20MW capability which is at least an order of magnitude greater than conventional in-service electrical power systems. Key technologies to support this trend are high performance electric motors, lithium-air batteries, superconducting materials and networks, and quiet propeller designs.

Ground and flying integration facilities will also be required to demonstrate and validate these new technologies. This topic is included in the ATI *Raising Ambition* publication as one of the key initiatives for integration and validation for future propulsion. This topic is also covered in the ATI publication on Emerging Technologies in Commercial Aircraft Systems.

Nacelle Thermal Technologies

The thermal environment surrounding the engine core/turbine will become more challenging over the next 5-10 years due to architecture changes in the engine to reduce further fuel burn and emissions. Introduction of a power gearbox creates an extra heat source within the engine space, leading to thermal energy being increased, regardless of additional thermal energy which may be caused by increased capability in engine systems or compressors/turbine sub-systems. Future Ultra-High Bypass Ratio engines, with a typical power of 22MW (an estimate for small-medium aircraft engines) incorporating a power gearbox with 99.5% efficiency, would generate 110kW of thermal energy which could be evacuated into the core compartment around the engine and beneath the nacelle structure. Larger engines may increase this thermal energy by as much as a factor of three. Current state of the art use of epoxy composite structures protected through thermal blankets will struggle to survive in this increased temperature environment, leading to the need for research into novel cooling/protection solutions.

These solutions should aim to be no thicker or heavier than today's solution, even though fan diameter increases will lead to larger nacelles. An increase of size and weight of the thermal protection in line with fan diameter increase would lead to a nacelle that reduces or even eliminates the fuel burn gains due to larger, slower UHBR fans. Today's solutions for nacelles consist of several different approaches. The structure itself may be made from titanium, aluminium or composite (made with either epoxy or bismalemide resins systems). Thermal protection is employed for the aluminium and composite systems, and sometimes for the titanium depending on locations.

The structure of the material drives the level of protection that the thermal protection must provide. Nacelle technologies are driving further development of lightweight composite structures which are robust to operating with a 400oC temperature with a structure only 5mm thick. New material combinations, carbon-carbon or silicon-silicon could be developed to support this. One over-riding requirement is to ensure damage tolerance as well as smart thermal protection to ensure that the thermally capable nacelle system is robust to operational and maintenance related handling issues.

Nacelle Electric Ice Protection Systems

For nacelle suppliers, the challenge to manage ice formation and accretion has evolved bleed air anti-icing systems and more recently (for large commercial transport aircraft) consideration of electric anti-icing systems. Technologies include electro-thermal heater elements, electro-expulsive systems and electro-thermal heater mats embedded within the structure.

There are many challenges of these systems. These include: high energy consumption (5-20kW/m2), optimisation of configurations to limit the ice build-up / shed size in the event of any failure, understanding of ice ingestion limits in future propulsion systems, managing system complexity, weight and cost compared with conventional bleed air systems, repair methods and aircraft dispatch reliability (compared with bleed air systems being "locked open" for dispatch under failure conditions). However, the drive for the technology may well be in the delivery of ambitious future propulsion systems which may use hybrid and electric technology for propulsion. In this case, electric anti-ice may be the only choice.

Drag Predictions

CFD methods are extensively used to predict drag for all parts of the airframe and propulsion units with air flowing over them. There are numerous methods of predicting drag with increasing levels of complexity. The drag can either be calculated by integrating local surface pressures and adding an estimate of skin friction, or by integrating momentum changes within a control volume containing the airframe/propulsion unit. The first method is sensitive to rapid local changes in pressure and geometry and capturing the effect of shock loss.

The second method can have problems with numerical dissipation effects. Sensitivity to meshing and turbulence models is also significant. For rotating components, the impact of sliding mesh interfaces needs to be considered. An example is evaluating the net performance of a propeller installed on a nacelle and wing which requires calculation of the effect of the nacelle and the wing being immersed in the wake. For the installed propeller, good quality wind tunnel test data is required to isolate the sources of drag generated by the nacelle and the wing structures in powered and unpowered modes. This testing can then be used to verify the CFD predictions.

Future Rotor Designs

Conventional helicopter configurations have reached the plateau of improvement in performance capabilities through evolution of conventional technologies. Step changes are required in rotor capability to meet customer requirements for improved operational capability and to enable greater use of rotorcraft beyond their current roles. All major helicopter manufacturers are working on active control technologies for the helicopter main rotors.

These concepts deploy moveable surfaces in the helicopter main rotor blades trailing edges to improve vehicle performance, vibration levels and the noise footprint. Development of enabling analytical tools is required to predict the performance benefits and understand flap dynamic stability. In addition, design tools need to be developed specifically for active rotors together with establishing anticipated requirements for future active rotor platforms. Novel electrical actuator technologies will be key to unlocking these concepts, with demanding requirements for both high precision and dynamic performance in a demanding harsh environment.

TRENDS AND INSIGHTS IN COMMERCIAL AIRCRAFT PROPULSION SYSTEMS EMERGING TECHNOLOGIES

For the selected topics covered in this paper the following summary compares potential market penetration in aerospace and UK positioning.

Topic	Estimated maturity timeframe	Aerospace sector approach	Current maturity	UK competitors	UK positioning to develop	UK positioning to exploit	Key attributes impacted
Active noise control	Position	Drive	Medium	USA, Germany	Moderate	Weak	*2, 4*
Noise annoyance metrics	Exploit	Watch	Medium	Germany	Moderate	Weak	*2, 4*
Simulating engine noise	Exploit	Adopt	Medium	USA, Germany	Moderate	Moderate	*1, 2*
Future turbomachinery design methods	Exploit	Drive	Medium	USA, Germany	Strong	Strong	*1, 3*
Combustion systems for low particulate production	Exploit	Drive	Low	USA, Germany	Moderate	Moderate	*2, 3*
Pressure gain combustion for gas turbines	Position	Drive	Low	USA, Germany	Moderate	Weak	*2, 3*
Means to eliminate thrust reversers	Position	Watch	Low	USA	Weak	Weak	*1, 3, 4*
Photonic sensing for harsh environments	Exploit	Adopt	Low	USA, Germany, Japan	Moderate	Weak	*1, 2, 3, 4*
4D printing	Position	Watch	Low	USA	Weak	Weak	*1, 2, 3, 4*
Aviation jet fuel additives	Secure	Drive	Medium	USA, Germany, France	Strong	Moderate	*1, 4*
Electric & hybrid technology	Position	Drive	Medium	USA, Germany, Japan	Strong	Moderate	*1, 2, 3, 4*
Nacelle thermal technologies	Position	Drive	Medium	USA	Moderate	Moderate	*1, 3*
Nacelle thermal technologies	Position	Drive	Low	USA	Moderate	Moderate	*1, 2, 3*
Drag prediction	Exploit	Drive	Medium	USA, Germany	Strong	Moderate	*2, 3*
Future rotor designs	Position	Drive	Low	USA, Germany, Italy	Moderate	Moderate	*2, 3*

Key

Estimated maturity timeframe:
+ **SECURE** (next five years)
+ **EXPLOIT** (next 10 years)
+ **POSITION** (next 15+ years)

Key Attributes: **1** - Cost, **2** - Environment, **3** - Fuel efficiency, **4** - Operational, **5** - Passenger experience, **6** - Safety

Some of these topics have complementary activity in other industries and sectors as well as aerospace but in general the propulsion related topics tend to be aerospace specific.

- For aviation jet fuels, technology continues to evolve to mitigate changing fuel properties. The aerospace community should continue targeted engagement with the fuel industry to look at future trends and mitigation strategies.
- Electric and hybrid propulsion technologies will most likely share some learning from other sectors, notably automotive.

NEXT STEPS FOR THE ATI

1. More electric technologies are progressing within current and planned R&T projects although the overall roadmap for more electric aerospace technology in the UK still needs to be articulated and delivered. A follow up paper, specifically focussing on this field will be issued by the ATI later in 2017.
2. Thermal technologies are increasingly important in aerospace architectures as new concepts create increasingly demanding thermal loads with reducing part of the UK aerospace system design. There is an opportunity for the ATI to provide technology leadership and increase exploitation of UK thermal management technologies across the aerospace sector.
3. Noise is a specific target for ACARE Flightpath 2050 and continued research to develop active noise control, noise annoyance metrics, noise simulation and measurement and deployment of novel ATM to reduce noise impacts should be watched to ensure targets for aerospace can be achieved. In the nearer term, the local environmental impact is driving the need for further improvements in noise (e.g. the discussion around the 3rd runway at Heathrow airport).
4. Emissions targets in ACARE Flightpath 2050 may also drive change in low smoke producing combustion systems as well as looking at more disruptive technologies such as pressure gain combustion.

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Contact us

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