INSIGHT

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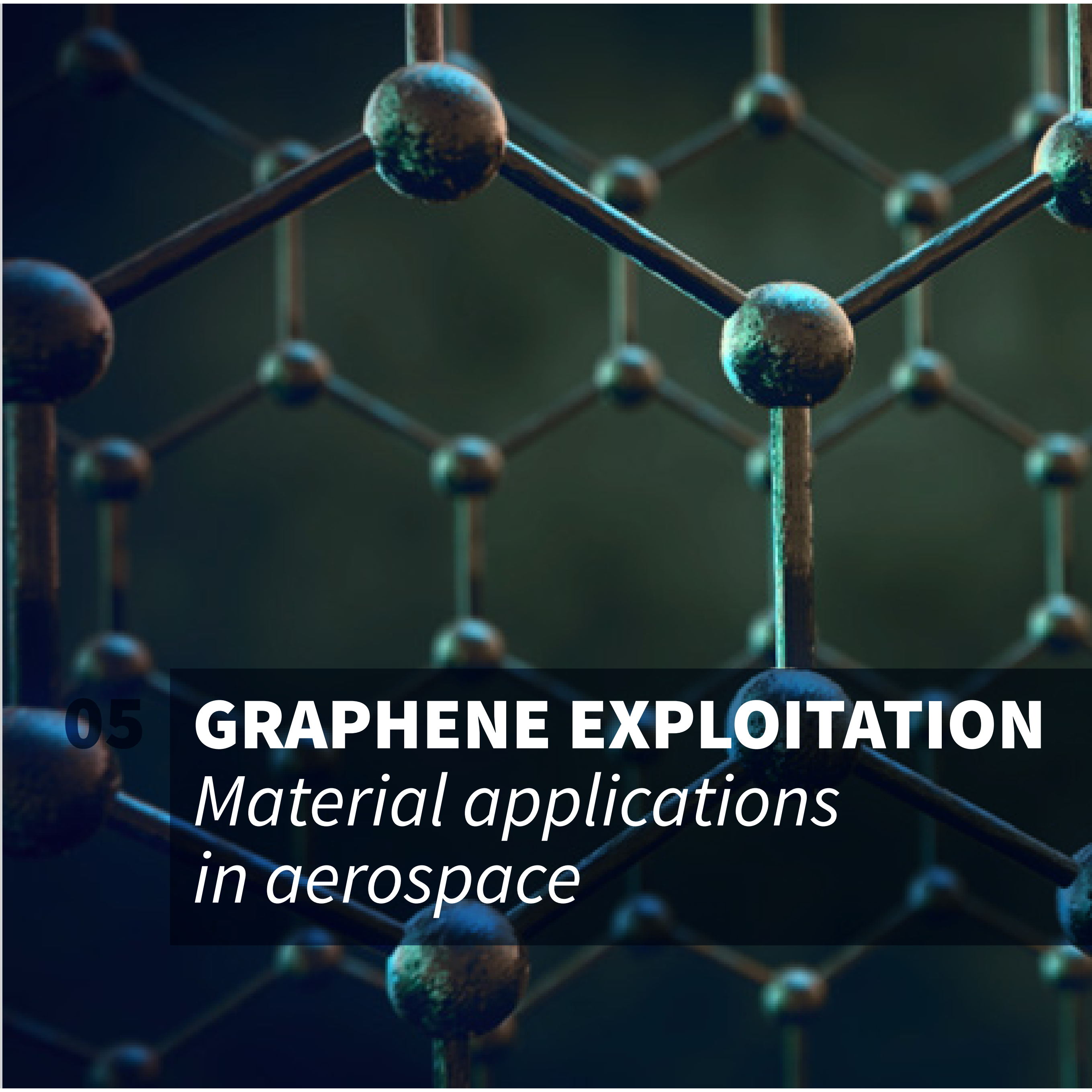
Introduction

This paper has been compiled to disseminate the findings from an aerospace sector consultation enabled through a partnership with the National Graphene Institute to identify applications of two dimensional materials, specifically graphene, that can be incorporated into structures, systems and propulsion components. The paper analyses the sector perspectives from academia, research organisations and industry to propose opportunities where investment in graphene could result in significant positive impact on productivity, product performance and fuel efficiency.



05 GRAPHENE EXPLOITATION
Material applications in aerospace

EXECUTIVE SUMMARY

The UK has pioneered the research and development of graphene, the material that is inspiring a new generation of two-dimensional materials science. The properties of graphene have the potential to bring exciting applications for graphene materials in aerospace and accompanying economic benefits for the UK.

The exploitation of graphene in aerospace applications is in its infancy and as understanding of graphene materials develops, it is anticipated that the scope of potential applications will continue to expand. This paper highlights some of the potential benefits of graphene for aerospace from analysis of the current state of the art knowledge of graphene technology against the ATI's view of future industry needs. The graphene material application analysis has identified opportunities for improved fuel efficiency, aircraft performance and cost and reduced environmental impact.

The potential for graphene to solve enduring challenges within the aerospace sector presents real opportunities for the material to become disruptive, and a key enabler in future aircraft technology. We need to accelerate the opportunity for the UK to realise the benefits from graphene by creating a portfolio of graphene related research and technology projects which if undertaken would lead to real impact in our aerospace industry.

Sir Richard Branson

The ATI will seek to accelerate the maturation of these graphene technology opportunities through helping the formation of suitable technology projects that address the key requirements identified below.

1. **Materials Research:** Screen, optimise and functionalise candidate graphene materials where potential applications for 2D materials within aerospace exist.
2. **Component and Manufacturing Research:** Achieve TRL4 for structural, propulsion and systems applications. Ensure a robust study is completed to underpin the basic scientific discoveries within structures, propulsion and systems themes.
3. **Systems & Components Demonstration:** Invest in large scale industrial demonstrators that enable TRL6 to be achieved in target applications within secure, exploit and position timeframes.
4. **Industrialisation:** Ensure that the UK capability is realised to manufacture graphene materials at high volume, in suitable material forms, and at a competitive price, that addresses the sector requirements.
5. **High Value Design:** Develop 2D material knowledge that can be incorporated into future aircraft design to improve the performance, efficiency and cost of multiple platforms. Consideration will be given to the realisation of complex, computational modelling that minimises physical testing, reducing the overall development timeframe.
6. **Business Cases:** Detail and communicate example business cases that catalyse the aerospace sector to consider the rapid development of 2D material solutions.

MATERIAL CHALLENGE

Graphene was first isolated at The University of Manchester in 2004, leading to the award of two Nobel Prizes in 2010 within the rapidly growing field of two dimensional (2D) materials. The most common image of graphene is monolayer graphene, which consists of a hexagonal lattice of carbon atoms that is just one layer thick. This monolayer graphene has an intriguing combination of high stiffness, high strength, low density and high electrical and thermal conductivity[1]. In graphene, electrons are highly mobile, making graphene more conductive than copper and enabling faster electronic switching than silicon semiconductors. One of the key challenges within the Graphene research community (as with all nanomaterials) is how to translate these and other superlative properties, as measured on the nanoscale, into real components.

The development of graphene has been rapid compared to the previous adoption of technologies such as Carbon Fibre Reinforced Plastic (CFRP). The production scale of graphene materials has increased year-on-year, with materials such as nanoplatelets and graphene oxide already at the 1 to 1000 tonne/year capacity.

There is a developing list of commercial graphene related materials (GRMs) that can be characterised by their thickness, lateral dimensions and surface chemistry [2]. This range of GRMs gives rise to an exciting opportunity to develop and design structural and functional materials, particularly in aerospace applications.

Early work on graphene applied to the aerospace sector has shown its potential to reduce weight while increasing the strength of materials, which could contribute towards reduced emissions and use of fuel and hence contribute towards cleaner, greener aircraft for much wider benefit.

ACCELERATING EXPLOITATION

It is critical that the UK can accelerate the technology development cycle if it is to establish a competitive advantage in the emerging, disruptive graphene industry. Traditionally the development of technology from first isolation to in-service use can take more than thirty years. There are many top-level focus areas for graphene's use in aerospace which could halve the exploitation journey time.

Recent studies from the ATI[3] suggest that new passenger aircraft worth $6.2 Trillion will need to be delivered between 2016 and 2035. Graphene enhanced components could have a significant impact on the economic benefit of components produced from a new emerging value chain. Through accelerated GRM adoption within the aerospace sector, new high value design and manufacturing skills can be realised, and high-volume bulk material manufacture and manufacturing conversion enabled, contributing to the UK economy.

The acceptance of graphene enhanced components is comparable to the introduction of Carbon Fibre Reinforced Polymer (CFRP) materials in aircraft design and manufacture, having the potential to be abundant structures, propulsion and systems technologies. The latest generation of aircraft have significant CFRP content. There is huge opportunity for graphene enhanced CFRP to contribute to weight reduction whilst maintaining strength, enabling improvements in fuel efficiency and reducing environmental impact.

KEY FINDINGS

There are numerous sector needs that can be addressed through graphene related materials. A number of subject matter experts from industry, academia and research and technology organisations have been consulted to consider potential graphene materials applications across the four ATI programme themes, identified in ATI's Technology Strategy publication[4]:

- Aircraft of the Future
- Smart, Connected, More Electric Aircraft
- Aerostructures of the Future
- Propulsion of the Future

Within these themes, key challenges where graphene could have an impact are highlighted, presenting opportunities for graphene to deliver effective technology solutions that could generate significant sector impact.

AIRCRAFT OF THE FUTURE

The prime objective of this theme is to strengthen the UK's whole aircraft design and system integration capability, positioning it for future generations of civil aircraft. Key challenges identified by the ATI Technology Strategy where graphene could have an impact include:

- Lower manufacturing costs
- Better use of CFRP and advanced materials

Lower manufacturing costs

Exploiting the thermal properties of graphene enhanced materials to reduce the cure times of resin based materials could lead to lower manufacturing costs for CFRP materials. The resulting graphene enhanced composite components could behave in a multifunctional way; acting as both structural components and heatsink and or electrically conductive devices. These multifunctional properties could in turn lead to lower parts count and reduced manufacturing times.

Better use of CFRP and advanced materials

The use of graphene enhanced CFRP in structures will lead to increased or equivalent performance at lower mass, in turn improving aircraft efficiency, burning less fuel and creating cleaner aircraft with lower emissions. In the near term, graphene will be added to the resin in thermoset CFRP to form a hybrid system, where the fibre provides the stiffness whereas graphene improves properties such inter-laminar shear strength and damage tolerance, allowing a reduction in ply-thickness. Graphene may be used as the main reinforcement for stiffness in high performance polymers, such as PEEK, to produce small parts and pipes which replace metal equivalents. In this case, graphene gives additional benefits in surface finish due to its small particle size and chemical resistance. It is suggested that Graphene could first be used in interior polymers based components, giving a, early non-flight critical route to application. Here the graphene is for reinforcement and fire retardancy.

Table 1 shows the outcome of the subject matter expert review for Aircraft of the Future.

Key Challenge	Secure	Exploit	Position
Predicting and simulating graphene performance enhancements during design stages.	Detailed, verified graphene enhanced materials databases.	Prediction models and software tools produced. Less re-work due to validated simulation.	Fully integrated into industry toolsets and processes.
Lower manufacturing costs.	Exploiting the thermal properties of graphene to reduce CFRP cure times.	Reducing quantity of CFRP materials required, while maintaining strength and integrity.	Multifunctional use of graphene materials to produce smart structures e.g. integrated structural wiring looms and sensors, hence reducing, major assembly and final assembly equipping times.
Novel wing architectures integration (aeroelastic tailoring, high aspect ratio wings).	Sub-scale lab analysis and flight test of next generation wing designs enabled by graphene's physical properties.	Qualification of design concepts for production aircraft. Introduction into existing aircraft.	Industry standard for production aircraft.
Better use of CFRPs and advanced materials.	Use of graphene enhanced CFRPs in tooling and aircraft structures.	Qualification, manufacturing, processes and health and safety standards for graphene. Establishing proof of concept for multifunction function of advanced graphene materials.	Qualification of multifunction applications in aircraft structures, propulsion and systems.

Table 1 – Aircraft of the Future Analysis for graphene enhanced materials

SMART, CONNECTED AND MORE ELECTRIC AIRCRAFT

The prime objective of this theme is to develop UK advanced systems technologies, capturing high-value opportunities in current and future aircraft.

The high electrical conductivity of graphene related materials enables electrical systems of an aircraft as a near term opportunity. GRMs can be used either in printed structures, coatings or within structural CFRP. The printed structure builds upon growing international research into the ink-jet printing of 2D materials, including graphene, for sensors and conductive tracks. Likewise, the coatings and structural CFRP extend the extensive work on conductive, percolated graphene CFRP. These CFRP materials can be produced with through thickness conductivity, high surface conductivity or even controlled channels of conductivity.

Key challenge areas identified by the ATI Technology Strategy where graphene could have an impact include:

- Advanced aircraft fuel systems
- Novel heat management
- Advanced flight deck avionics
- Robust, high bandwidth integrated communications and antenna systems
- Development of an experimental propulsion system

Advanced aircraft fuel systems

Graphene oxide membranes can selectivity filter water from liquids, including oils, and have already been successfully demonstrated by Rahul et al[5] to remove water contamination from fuel tanks. Printed graphene sensors have already been demonstrated by the Graphene[6] Institute to detect the fuel level using a metal and hence corrosion free system. Finally, graphene's ability to provide antistatic dissipation, potentially chemical barrier resistance combined with fire retardancy properties could allow new CFRP low weight fuel tanks to be developed.

Novel heat management

The extremely high thermal conductivity of graphene (6000 W m-1K-1) makes it an ideal heat spreader to minimise heat spots, particularly for batteries and electronics. Such heat spreaders may be formed from compressed graphene sheets or through addition to a polymer or rubber. An additional benefit of using graphene is that it could potentially add EMI shielding to the packaging, whilst reducing weight compared to traditional metal components.

Advanced flight deck avionics

2D layered materials such as graphene, boron nitride and tungsten disulphide are stacked to form van der Waal solids, which can behave as novel electronic devices just a few atoms thick. The atom thin nature of these devices means that they are transparent. In the simplest form, graphene on a polymer substrate can be used as a flexible transparent conductor, which can then be combined with organic electronics to provide a new generation of head-up displays, directly integrated into the windscreen of an aircraft.

Robust, high bandwidth integrated communications and antenna systems

High frequency antennae are required to connect the evolving network of sensors throughout an aircraft. The high mobility (ultra-fast switching) of graphene makes it a suitable material for producing such antennae, with the sensor being directly screen or inkjet printed onto the component required. These antennae can be further developed into sensors by adapting them so that environmental conditions change their dielectric properties.

Development of an experimental propulsion system

Electrically propelled aircraft require both an electrical power source and a means to efficiently store the power. The high aspect ratio, surface area and electrical conductivity of graphene make it an ideal material for use in all electrochemical forms of power and storage, where graphene enhances or replaces existing materials. Energy storage can be broadly split into (i) high power devices (e.g. super-capacitors) which may be used to delivery sufficient power for a short task such as opening a plane door or a power boost for acceleration and (ii) high total energy devices (e.g. Lithium ion). Graphene has already been developed for a range of high power super-capacitor devices in laboratories and there is now a manufacturing challenge of how to formulate electrode production for larger cells without significantly reducing performance. Graphene combined other carbon materials also shows promise as additives with lithium ion batteries.

Hydrogen fuels cells have the potential to be a clean power source, but the engineering of the membrane which only allows protons is still a technological challenge. Graphene has recently been found to be impermeable to all species, except for protons; this leads to the exciting prospect of graphene as a Nafion replacement, or at least an additive.

Novel energy harvesting

The growing use of aircraft smart sensors leads to a demand to develop either passive sensors, such as those mentioned under communication and antenna systems above, or energy harvesting to locally power the system. In near term, the addition of graphene to oxide thermoelectric materials has increased their thermal operating window and figure of merit (ZT), allowing this new cheaper, lighter and less toxic generation of materials that operate uniformly over a wide range of temperature differences such as those that might occur during a flight. In the longer term, a GRM van der Waal solar cell has been demonstrated which is comprised of just five atomic layers. This gives rise to the possibility of solar cell coating which could be sprayed onto a wing or fuselage.

Table 2 shows the outcome of the subject matter expert review for Smart, Connected and more Electric Aircraft.

Key Challenge	Secure	Exploit	Position
Fuel systems technology – Aviation fuel.	Prototype membrane of water removal, including stability across pressure and temperatures endured during flight.		Fuel systems technology – Aviation fuel.
Improved chemical resistance of thermoplastics for tanks and pipe lines.			Improved chemical resistance of thermoplastics for tanks and pipe lines.
Demonstration of graphene level sensors.	Qualification of membrane, polymers and sensors, including test flight of a secondary tank.	Production of graphene enhanced fuel system.	Demonstration of graphene level sensors.
Wireless connectivity.	Development of printing technology of antenna on aerospace appropriate substrates, including long term environmental tests for erosion and adhesion.		Wireless connectivity.

Table 2 – Smart, Connected and more Electric Aircraft analysis for graphene enhanced materials

AEROSTRUCTURES OF THE FUTURE

The prime objective of this theme is to ensure the UK is a global leader in the development of large complex structures, particularly wings. Graphene can be a key enabler for future smart aerostructures that contain multifunctional parts, performing sensing, control and actuation, for example. So-called smart structures are a departure from the usual use of solid metal or CFRP materials for purely structural purposes, and can displace components such as wiring for power and data by embedding them in structural materials. The multifunctional properties of graphene could enable a structure to carry data signals or measure its own stress and strain measurements, for example.

CFRP materials will form a vital and significant part of the manufacturing future in multiple sectors. They allow new transport concepts which are lighter and stiffer, with a wide range of compositions and functionalities. CFRP are also critical to the development of wind energy; large offshore turbine blades are reliant on a move from glass fibre to CFRP. One deterrent against the use of more CFRP materials has been the punitive safety factors adopted to allow for impact damage, hot-wet degradation and variability in properties.

Graphene infused CFRP can be a key enabler for future smart aerostructures that absorb less moisture, provide damage resistance and tolerance, contain multifunctional parts, and perform sensing, control and actuation. Smart structures are a departure from the usual use of solid metal or CFRP materials for purely structural purposes, and instead can displace components such as wiring for power and data by embedding them in structural materials.

Other benefits could manifest themselves in the form of shorter assembly times during manufacture, and reduced weight of the platform. Thousands of kilograms of CFRP thermoset CFRP are already used for cabin interiors on every commercial jet, along with reinforced high-performance engineering thermoplastics. The development and introduction of new graphene enhanced CFRP could quickly be used in many common applications such as floor, ceiling, door, and sidewall panels, overhead storage bin, window surrounds, ducting and bracketry, galley and lavatory components, passenger-service units and bulkheads/ partitions.

Key challenges identified where graphene could have an impact through its multifunctional properties include:

- Smart use of CFRP, metallic, hybrid materials and surface coatings to reduce cost and weight, add functionality, improve performance, and geometrical tolerance optimisation
- CFRP failure prediction models specific for structural components
- Technologies to reduce manufacturing cycle time
- Multifunctional materials (structural batteries) embedded sensors
- Damage-tolerant/self-healing structures (new materials)

Smart use of CFRP, metallic, hybrid materials and surface coatings to reduce cost and weight, add functionality, improve performance, and geometrical tolerance optimisation

The potential for graphene to be used as a coating has been investigated in several areas and has the potential to offer corrosion resistance due to its physical properties. Being an atomic scale structure, it has potential in coating materials to reduce drag, and by exploiting its conductivity and thermal properties could be used in de-icing systems and lightning strike protection.

The reliability of many resin structures can be improved by matching the properties of an interphase region to the matrix properties to ensure that a yield front rather than fibre/matrix de-bonding (a low energy absorbing damage mode) forms in the interphase region. In this way propagation of a fibre-break can be restricted, providing a mechanism of containing damage and hence enhancing strength and impact resistance. Pre-coating the fibre with a graphene modified resin of known properties to form an interphase with optimised performance becomes a desirable means of improving reliability and modification of safety factors in a positive manner.

CFRP failure prediction models specific for structural components

Work to analyse and document graphene enhanced materials will lead to reliable failure prediction modelling for structural components. The development of validated predictive modelling tools for GRMs is critical to support the rapid exploitation of graphene into aerospace use.

Work to analyse and document graphene enhanced materials will lead to reliable failure prediction modelling for structural components. The use of modern analytical and computational Finite Element Analysis (FEA) methods has long since passed into common usage as a means of solving stresses and deformation, but it is still unusual to use a FEA model to predict failure, other than buckling. Current targets for the effect of software tools in reducing design time and costs are 50% and 30% respectively. However, virtual testing must be more robust, reliable and user friendly. Simulation of the manufacturing process and the design strength remain a challenge for complex resin infused CFRP structures, especially with graphene nano-modified resins.

Technologies to reduce manufacturing cycle time

Graphene has the potential to help reduce manufacturing cycle time. Firstly its thermal and electrical properties can improve the cure time of resin materials. With large proportions of future aircraft structures adopting CFRP this could lead to significant production time improvements. Secondly, development of multi-functional components enabled by graphene should reduce integration and test times.

Multifunctional materials (structural batteries) embedded sensors

As graphene enhanced materials can be used for both structural and systems components, there is considerable scope for new innovation in this area, and recent developments in graphene battery technology could be progressed to create multifunctional materials capable of storing energy and self-sensing. The use of graphene reinforced CFRP materials and flexible manufacturing methods generates the possibility of creating novel structural forms, including schemes for active vibration and noise control and large shape changes which might eliminate the need for discrete secondary control surfaces on aero-structures or discrete actuators on propeller rotor hubs. These ideas may be coupled to the integration of Microelectromechanical Systems (MEMS) technologies for distributed sensing and/or actuation to improve the overall performance of aerospace systems and to reduce their operating and life cycle costs.

Damage-tolerant/self-healing structures (new materials)

The relatively poor damage tolerance of CFRP remains a weakness which has a major mass driving effect on the design of aerostructures. GRMs have the potential to provide a step change in the damage tolerance of CFRP which could lead to more lightweight aerostructures in the future.

Holes in graphene lattices can be repaired at the atomic level with the simple application of new graphene, and by mixing graphene with other materials some of these self-healing/repairing properties are expected to manifest themselves in the new materials. Effort to circumvent typical deficiencies by modelling of the actual nano/microstructure, including particle and nanoparticle distribution, porosity, grain boundaries, phase and crystal structure, is required. A microstructure can be transformed into a mesh and the intrinsic material properties assigned to the separate phase constituents. The material can be subjected to mechanical and/or thermal loads and the behaviour of the material determined. The data and numerical code derived from the materials modelling can then be transported into conventional software packages so that large scale structures can be better assessed.

Validated methodologies and tools for predicting the structural integrity of graphene modified laminated pre-impregnated CFRP and infused structures in a range of representative conditions experienced throughout the product life cycle need to be developed in parallel with schemes for in situ structural health monitoring (SHM). Another area where there is still work to be done is with regard to effectively supporting and maintaining these technologies on flight critical primary structures whilst in-service. This should not be the sole responsibility of the industrial end users because of the complexities of developing appropriate predictive theories, models and tools to efficiently address subjects such as high and low energy impact, repair, effects of defects (manufacturing and in-service), durability, inspection and fatigue life prediction.

At present any analytical methods for predicting the residual strength and/or life of CFRP structures have to be validated by test before confidence levels are reached which will be acceptable to aircraft certification authorities. Resorting to experimental tests and data sheets is exorbitantly expensive; it is estimated that when a new fibre/matrix system is introduced it can cost up to £10M to validate the material and components.

Table 3 shows the outcome of the subject matter expert review for Aerostructures of the Future.

Key Challenge	Secure	Exploit	Position
Smart use of CFRP, metallic, hybrid materials, and surface coatings to reduce cost and weight, add functionality, improve performance, and geometrical tolerance optimisation.	Graphene coatings for de-icing, corrosion resistance, drag reduction. Embedded graphene based sensing in structures for continuous real-time monitoring. Lab and flight demonstrations of above.	Development of efficient production methods for coating application and repair. Ensuring performance and reliability of embedded graphene multifunction materials for sensing.	Application of graphene coatings to wide range of aircraft components, propulsion and systems. Widespread integrated sensing to support health monitoring enabled through multifunction graphene.
CFRPs failure prediction models specific for structural components.	Development of validated predictive modelling tools for graphene enhanced materials.	Incorporation of the analytical and software tools into industry's design processes.	Verifiable prediction tools for multifunctional graphene use.
Technologies to reduce manufacturing cycle time.	Graphene enhanced AM, replacing metal components. Reducing cure times by exploiting graphene's thermal properties.	Reduced cycle times through embedded sensing and systems.	Established production methods for graphene enhanced AM, embedded sensors and smart structures.
Multifunctional materials (structural batteries) embedded sensors.	Proof of concept for graphene based energy storage devices e.g. batteries and capacitors.	Proof of concept for energy storage within structures and materials. Lab and flight demonstrations.	Adoption in all new aircraft, incremental upgrade and replacement in existing aircraft.
Damage-tolerant/self-healing structures (new materials).	Characterisation of robustness and self-healing properties for graphene enhanced coatings. Rapid evaluation of emerging graphene type materials to enhance damage tolerance. Development and qualification of more damage tolerant CFRP materials for aerostructures.	Processes and procedures for application and repair of self-healing materials. Lab testing and flight testing. Validation of modelling and simulation tools to support the exploitation of polymer CFRPs in aerostructures.	F ull qualification and adoption in new aircraft and retro-fit/ upgrade of existing platforms.

Table 3 – Aerostructures of the Future analysis for graphene enhanced materials

PROPULSION

The key objective of this theme that provides potential graphene opportunities is through a new generation of more efficient propulsion technologies, particularly within large turbofan engines. Challenges identified by the ATI Technology Strategy where graphene could have an impact include:

- Ultra-high bypass ratio (UHBR) turbofan: to validate an entirely new engine architecture; a full engine system with CFRP fan, power gearbox, high pressure core and accompanying manufacturing technologies will be tested, including the capability to effectively integrate this new generation of efficient engine onto aircraft
- New or updated turboprop platforms: which enhance passenger experience and improve environmental and operational performance, and keep these aircraft competitive
- The Rotorcraft Technology Validation Programme (RTVP) is the culmination of effort to design, develop, manufacture and test active trailing edge technology embedded within a real helicopter blade

Ultra-high bypass ratio (UHBR) turbofan

Some of the challenges of the development of an Ultra-high bypass ratio (UHBR) turbofan will include the achievement of very demanding cost and efficiency targets. Common methods to meet these challenges include weight reduction and increased aerodynamic efficiency of aircraft components. As the propulsion system, including the turbo-fan engine, nacelle and associated pylon support structure, represents a significant element of the whole aircraft mass, addressing weight reductions in this area is likely to represent an efficient overall aircraft weight reduction approach. A key area of focus for the UHBR will be the fan blade and containment system.

The main attraction to engine companies (and airlines) of graphene enhanced CFRP will be the improved impact resistance (and other improved properties). It is envisaged that the application of graphene enhanced CFRP to aero-engine fan blade and associated static structure (such as fan case, bearing support structure, etc.), as well as engine nacelle components (such as the intake, fan cowl doors and parts of the thrust reverser) and pylon, could help to achieve a substantial propulsion system weight reduction. Any propulsion system weight reduction would also have a direct impact on the wing weight as loads would be reduced. It is also conceivable that the improved (graphene enhanced) CFRP material properties would allow thinner fan blades to be designed, yielding aerodynamic and therefore engine performance improvements.

New or updated turboprop platforms

Some of the challenges of the development of a new/ updated turboprop platform could include the development of CFRP propellers. A key issue with CFRP propellers is their ability to withstand impact from foreign objects such as bird strike and hail. As with the application to aero engine fan blades, the main attraction to propeller companies (and airlines) of graphene enhanced CFRP will be the improved impact resistance (and other improved properties). This will allow lighter and potentially more aerodynamically efficient propellers to be designed.

Impact Resistance

The improved impact resistant properties of graphene enhanced CFRP could support some of the other technology challenges, such as the Rotorcraft Technology Validation Programme. Graphene enhanced CFRP materials could improve impact resistance and vibration characteristics of the rotor blade.

Table 4 shows the outcome of the subject matter expert review Propulsion of the Future.

Key Challenge	Secure	Exploit	Position
Lightweight CFRP fan and rotor / propeller systems for Ultra-high bypass ratio (UHBR) turbofan.	Establish material suppliers. Develop a graphene enhanced CFRP material test and development plan. Identify and implement a launch material test programme to assess viability. Understand optimised properties / manufacturability aspects of the material (material database).	Complete material test and design /development plan leading to UHBR CFRP fan blade bird test and fan blade off (for CFRP fan case, etc) tests. Full engine development test of graphene enhanced CFRP fan blade, fan case and bearing support structure. Identify weight and cost reduction potential. Complete material test and development plan leading to propeller and / or helicopter rotor blade bird strike test. Identify weight and cost reduction potential.	Graphene enhanced UHBR CFRP fan blade, fan case and bearing support structure in production. Propeller and / or helicopter rotor blade using graphene enhanced CFRP material in production.
Increased aerodynamic efficiency for Turbofans and Rotorcraft.	Carry out structural / aerodynamic analysis studies on potential of graphene enhanced CFRP to improve performance of fan blades, propellers and helicopter rotor blades.	Improved aerodynamic performance fan blade, propeller and / or helicopter rotor blade design / development / test programme.	Improved aerodynamic performance fan blade, propeller and / or helicopter rotor blade in production.

Table 4 –Propulsion of the Future analysis for graphene enhanced materials

NEXT STEPS FOR THE ATI

The ATI will seek to identify suitable opportunities for 2D materials such as graphene that generate technology impact and economic benefit for the sector through helping the formation of suitable technology projects that address the key requirements identified below.

1. Materials Research: Screen, optimise and functionalise candidate graphene materials where potential applications for 2D materials within aerospace exist.

2. Component and Manufacturing Research: Achieve TRL4 for structural, propulsion and systems applications. Ensure a robust study is completed to underpin the basic scientific discoveries within structures, propulsion and systems themes.

3. Systems & Components Demonstration: Invest in large scale industrial demonstrators that enable TRL6 to be achieved in target applications within secure, exploit and position timeframes.

4. Industrialisation: Ensure that the UK capability is realised to manufacture graphene materials at high volume, in suitable material forms, and at a competitive price, that addresses the sector requirements.

5. High Value Design: Develop 2D material knowledge that can be incorporated into future aircraft design to improve the performance, efficiency and cost of multiple platforms. Consideration will be given to the realisation of complex, computational modelling that minimises physical testing, reducing the overall development timeframe.

6. Business Cases: Detail and communicate example business cases that catalyse the aerospace sector to consider the rapid development of 2D material solutions.

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GLOSSARY

2DM	Two Dimensional Materials
AM	Additive Layer Manufacture
ATI	Aerospace Technology Institute
CFRP	Carbon fibre-reinforced plastics
EMI	Electro Magnetic Interference
FEA	Finite element analysis
GRM	Graphene Related Materials
MEMS	Microelectromechanical Systems
NGI	National Graphene Institute
PEEK	Polyether ether ketone (thermoplastic CFRP)
RTVP	Rotorcraft Technology Validation Programme
SHM	Structural Health Monitoring
ZT	Figure of Merit

WHO WE ARE

The **Aerospace Technology Institute** (ATI) is the objective convenor and voice of the UK's aerospace technology community. The Institute defines the national aerospace technology strategy that is used to focus the delivery of a £3.9 billion joint government-industry funded aerospace technology programme.

Graphene was first isolated at The University of Manchester. Since then, the University is now home to the National Graphene Institute (NGI), a world- leading centre for graphene research and commercialisation, where academics and industry work side by side to develop future graphene applications. Due to open in 2018, the Graphene Engineering Innovation Centre (GEIC) will see industry-led development in graphene applications in partnership with academics. Together, the NGI and GEIC will provide an unrivalled critical mass of graphene expertise.

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