Institution: Cranfield University

Unit of Assessment: 12 Engineering

1. Unit context and structure, research and impact strategy.

Engineering research at Cranfield centres on aeronautical, mechanical & manufacturing engineering; chemical engineering; and metallurgy, materials science & engineering. This research is pursued across six of the eight interdisciplinary Themes at Cranfield: our business sector-focussed Themes being the equivalent of Departments in other institutions. The six Themes leading on engineering - Aerospace, Transport Systems, Manufacturing, Water, Energy & Power and Defence & Security - are organised within three of the University's four Schools, the main business units of the University (REF5a, Fig.1. Academic line management structure). The remaining two Themes – Environment & Agrifood and the School of Management also contribute to engineering.

The engineering focused Schools (https://www.cranfield.ac.uk/about/our-structure) each led by a Pro-Vice-Chancellor (PVC), are:

- School of Aerospace, Transport and Manufacturing, PVC Prof Helen Atkinson CBE FREng CEng, FIMMM, FIMechE
- School of Water, Energy and Environment, PVC Prof Simon Pollard OBE FREng CEng, FRSC CChem, FCIWEM C.WEM
- Cranfield Defence and Security, PVC Prof Mark Richardson FRPS

The PVC-Schools are each supported by a Director of Research, who has a 'dotted line responsibility' to the PVC Research & Innovation, Prof Tom Stephenson FREng, CEng FIChemE. The business sector facing Themes are led by Directors who are senior Professors responsible for owning the Theme research strategies (www.cranfield.ac.uk/research/why-cranfield/theme-research-strategies).

Table 1. Staff for Cranfield's Themes submitted to Engineering

Theme	Director	No. Staff Submitted				Main Research Areas
		Total	Prof	Ind	ECR	
Aerospace	Prof Iain Gray CBE FREng FRSE FRAeS	76	16	9	15	aerospace engineering; aerodynamics, avionics; control and systems; turbo-machinery and propulsion
Transport Systems*	Prof Graham Braithwaite FRAeS FCILT	35	6	4	9	transportation engineering; human factors and ergonomics; photonics and its applications;
Manufacturing	Prof Mark Jolly FIMMM	45	9	9	8	manufacturing technology, processes, and systems; materials engineering;
Energy & Power	Prof Phil Hart	26	7	1	10	energy and power engineering; materials for energy applications; renewable energy
Water*	Prof Paul Jeffrey FICE	35	11	2	13	water and wastewater engineering; environmental engineering
Defence & Security	Prof Mark Richardson FRPS	68	10	9	8	aerospace engineering; control and systems; electronic devices; materials engineering

**For presentation purposes in Table 1, three staff from the Environment & Agrifood Theme have been included under Water and one from Management within Transport Systems.*

The total of 285 (269.74 FTE) Research and Teaching staff submitted to the Engineering UoA constitute 78% of staff submitted by Cranfield to REF2021 (Table 1). Of the 285 staff, 59 are professors, 34 are independent (Ind) researchers and 63 Early Career Researchers (ECRs).

The Water Theme hosts the pan-university Cranfield Centre for Competitive Creative Design (C4D) that applies strategic design capabilities across all Themes. Other cross-Theme research areas include artificial intelligence (AI); environmental engineering; composites; metals; risk, reliability, and resilience; recycling and green technologies; renewable energy; and sustainability engineering.

Strategic research objectives. Our REF2014 research plans stated the profound engagement we have with our business partners, fostering a practical research and innovation-led environment; delivering education to transform the professional lives of our postgraduates; and working in partnership to deliver transformational benefit. Over the REF2021 period, we have renewed our Corporate Plan, raised our research ambitions, and articulated our Research and Knowledge Exploitation Strategies. As an institution, we have (REF 5a):

1. **Capitalised on the success of our sector-focused Themes**, deepening our interdisciplinary approach to research. For the Unit, this includes infrastructure resilience, aviation and the environment, technologies for the hydrogen transition and the circular economy.
2. **Strengthened our research support through a new Research and Innovation Office** (RIO), with UKRI research income growth for the Unit from £6.17M in 2014/15 to £10.58M in 2019/20, EPSRC partnership status and a top 10 Innovate UK funding performance. Introducing internal review and proposal oversight has strengthened the quality of our 'new investigator', strategic research and Fellowship submissions (e.g., EPSRC New Investigator grant (Pidou); European Research Council (ERC) Fellow (McAdam); RAEng Research Fellow (Kissinger). Additional Chairs were funded (e.g., Gokhan, BAE Systems; Skote, Airbus).
3. **Driven strategic research infrastructure investment** of *ca.* £135M since 2014 and expanded our near industrial- and national-scale facilities, including the £67M RPIF Digital Aviation Research and Technology Centre (DARTeC) and the £7M UKRI water facilities of the UK Collaboratorium for Research in Infrastructure and Cities (UKCRIC). These investments have increased the appeal of the Unit as a place to build a research career and attract global thought leaders.
4. **Engaged strategically with industry research partners**, e.g., AWE, BAE Systems, Boeing, Dstl, Rolls-Royce, Scottish Water, Severn Trent, Thales, building unique engineering-based research relationships to support long-term company and sector transitions, e.g., aeroengine design, low carbon manufacturing and wastewater engineering.
5. **Improved the research environment** by implementing quality benchmarks and concordats, thereby professionalising the PhD and ECR experience further and enhancing the acquisition of transferrable skills for onward employment.

Over the next five years, our strategic goal is to **progress our reputation for outstanding transformational research**, with a **greater emphasis on employing academic staff recognised internationally as thought leaders**. For the Unit, we will build intellectual mass in areas aligned with our Themes, including leadership of national engineering facilities. We will:

- Build on our significant infrastructure investment, including grant procurement with industrial partners leveraged through government support.
- Continue development of our ECRs through the 'Academic Fellow' route and securing global talent through our 75th Anniversary Fellowships.
- Undertake innovative, business-engaged research; success measured by the number of research-active academics, research income, high-quality peer-reviewed outputs and research impact.
- Increase research efficiency through equipment sharing and the enhanced role of technical staff to support 'shared ownership' facilities.
- Drive interdisciplinary research further through our four Grand Challenges (www.cranfield.ac.uk/research/why-cranfield/grand-challenges).
- Grow international co-operative research with our partner institutions, selected for their technology and industry focussed missions; including the Université de Technologie de Compiègne (UTC), ESTACA and ESTIA in France; Jiangsu University, China; Purdue, USA; and the Royal Melbourne Institute of Technology, Australia.

Supporting interdisciplinary research. Cranfield's Theme-led approach encourages development of interdisciplinary expertise. Academics in the Unit cover a wide range of science and engineering disciplines and are often co-located in open plan space with Research Fellows, doctoral students, and support staff, promoting interdisciplinary interaction. To drive this interdisciplinary ambition, we have established four strategic **Grand Challenges** (connected resilience; smart living; green technologies; and security for development (www.cranfield.ac.uk/research/why-cranfield/grand-challenges), bringing together capabilities in engineering technology and management. Each is linked to one or more of the United Nation's sustainable development goals; is led by a senior academic; and supports a university-wide academic network. The challenges are rooted in our organisational strengths. For example, 'connected resilience' draws on Cranfield's depth of contribution to engineering safety, risk and reliability, for example, in aviation; management expertise in high reliability organisations and our expertise in engineering risk analysis, risk management and organisational risk cultures.

Self-organised **communities of practice** straddle our institutional structure, promoting agile response to research needs and ensuring that curiosity-driven ideas flourish (e.g. membrane processes; https://www.cranfield.ac.uk/centres/water-sciences-institute/cwsi-research-groups; circular economy https://www.cranfield.ac.uk/centres/centre-for-competitive-creative-design/our-communities-of-practice). An example of a needs driven project is our design of the nanomembrane toilet for the Gates Foundation's 'reinvent the toilet' challenge, which draws together chemical, mechanical and design engineering expertise from across 4 of the Themes (https://www.cranfield.ac.uk/case-studies/research-case-studies/nano-membrane-toilet). Other examples include helping organisations anticipate disruptive extreme events, using drones to reduce major alluvial flood impacts and producing energy from plastic waste.

Thematic research and impact strategies. Cranfield's curiosity-driven research is funded principally by UKRI and assures our competency as a research-intensive university. Unit staff pursue 'blue skies' research through:

- Crafting fundable research proposals
- Supervising Doctoral students
- Writing high impact papers
- Liaising closely with industry partners

Staff have considerable flexibility to pursue their research ambitions, supported by the Schools' Directors of Research and RIO. In line with the research strategy (Institutional REF 5a), the Themes set objectives, detailed below for the Unit's fundamental research, which underpins our

translational research with business (https://www.cranfield.ac.uk/research/why-cranfield/theme-research-strategies):

The **Aerospace** Theme uses aeronautical, control, mechanical and systems engineering together with design, mathematics, and materials science principles to address the 4As: defining and delivering future aircraft, future airspace management, future airports and future airlines.

Research addresses aeronautics, autonomous air vehicles, advanced propulsion and integration of air vehicle design, assembly and performance:

- Aerodynamics and systems engineering principles explore novel aircraft configurations and air vehicle design. Materials science, fuel technology and thermodynamics are applied to establish advanced propulsion concepts towards zero carbon.
- New AI model relationships between virtual and physical systems are applied to design optimisation processes and advanced airspace management systems for manned and unmanned air vehicles (UAVs).
- Advanced robotics, intelligent automation and mechatronic concepts are used for novel assembly solutions for aircraft, UAVs, and space robotics missions.
- Applied mathematics, computational and software engineering techniques are used to develop algorithms to support applied computational fluid dynamics, to digital wind tunnels, operation Beyond Visual Line of Sight (BVLoS) and automatic flight control systems for UAVs.

Delivery is supported by extensive capital investment in new facilities, such as the RPIF funded Aerospace Integration Research Centre (AIRC) and the Cranfield Global Research Airport (https://www.cranfield.ac.uk/business/access-our-world-class-facilities/cranfields-global-research-airport). Our wind tunnels are part of the National Wind Tunnel Facility of the UK (ATI/EPSRC), including a unique icing tunnel. Facilities also include large-scale gas turbine laboratories, avionics rigs and the AIRC's Aerostructure Assembly and Systems Installation Laboratory containing full-scale wings and aeroengines.

The research vision encompasses the challenges recognised by the Advisory Council for Aeronautics Research in Europe Flightpath 2050 ambition. We take an integrated approach to these goals, looking at alternative energy sources for aircraft from electrification, hydrogen, and other sustainable fuels; exploring novel aircraft configurations and UAVs; and researching how these platforms are managed in controlled airspace. This is complemented by new developments in design optimisation, autonomy, and cyber-physical systems.

These objectives are reinforced by the zero carbon goals for 2050 agreed at the Paris 2019 Air Show. The ambitious targets mean technology solutions will need to be demonstrated over the next 5-10 years. Within Cranfield, this will require close coordination across our Themes. Our Global Research Airport creates new opportunities for research on aircraft and airport electrification; development of alternative aviation energy sources including development of autonomous platforms; and the integration of air traffic management and unmanned traffic management systems. Our five-year research objectives are to:

- Focus on technologies to reduce the environmental impact of civil aviation, aiming for a fully sustainable and decarbonised future;
- Advance modelling relationships between virtual and physical systems through enhancing algorithms for computational fluid dynamics and AI leading to explainable machine learning;
- Advance our research on new robotic and intelligent assembly solutions to reduce the lead-time for 'factory of the future' concepts;

- Accelerate the R&D of autonomous systems and AI to enhance the safety of drones and future urban air vehicles, while improving their operational efficiency and reducing operating cost;
- Improve asset management over the whole life cycle to enhance safety, reduce emissions and ensure economic viability;
- Advance high operational autonomy in space engineering; our expertise in sensor technology, spacecraft/satellite design and mission design.

The **Transport Systems** Theme takes an interdisciplinary approach to air and ground-based mobility, applying electronic, mechanical and systems engineering together with applied mathematics, computer sciences, physics and psychology to the design and operation of air and ground-based transport:

- Knowledge of mechanical and electronic engineering is used to develop novel control systems to improve vehicle dynamics and unlock opportunities for connected and autonomous vehicles. Electrochemistry combined with control engineering is applied to battery management techniques to maximise their efficiency and safety.
- Psychology and physiology combined with systems engineering is applied to better understand the interaction between design and operators of vehicles and transport systems. A systems engineering approach informs the development of tools and techniques to manage safety-critical systems.
- Aerodynamics and optelectronic sensors are used to develop novel techniques to evaluate structural aircraft health.
- Computer sciences and applied mathematics are applied to AI and machine learning to unlock the potential of digital aviation in delivering safe, sustainable, and efficient air transport.

The vision is to design effective transportation systems that operate within the constraints of physical, human, economic, political, and social environments, to deliver affordable, safe and sustainable services. The Theme draws on the Unit's strengths in air transport, automotive engineering, transport safety and instrumentation to develop a substantial capability across a rapidly evolving transport and intelligent mobility sector. Since 2014, we have secured major funding for unique facilities including:

- £67M RPIF Digital Aviation Research and Technology Centre (DARTeC), supported by industry partners Thales, Saab, Aveillant, Inmarsat, Boeing UK and BOXARR.
- £9M Multi-User Environment for Autonomous Vehicle Innovation (MUEAVI), a fully sensor and LIDAR equipped test ground for autonomous vehicle research.
- An engineering photonics femtosecond laser workstation, for fabricating state-of-the-art optical sensors and devices (£1.5M investment).
- A Boeing 737-436 aircraft (*ca.* £1M) deployed as a ground-based research platform for diagnostic sensor work on damage-sensing robots.
- A Saab 340B+ aircraft, being converted to a flying laboratory (*ca.* £3M), enhancing the research capability of our National Flying Laboratory Centre (NFLC), awarded a Queen's Anniversary Prize in 2019. It will enter service in 2021, complementing our instrumented Scottish Aviation Bulldog light aircraft.

The five-year research objectives are to:

- Become research leaders in safe, affordable, sustainable, and efficient transport for road, rail, and air transport within the constraints of the physical, human, economic, political and social environments;
- Deepen our contributions to airport operations, airline management, digitisation, and the passenger experience;

- Expand our research on automotive engineering and niche vehicle sectors through the optimisation of vehicle performance, minimisation of environmental impact and through improvements in safety;
- Enhance our capabilities in off-road vehicle engineering, tyre dynamics, vehicle electrification and novel energy storage, advanced chassis control, connected and automated vehicle behaviour, integrated transport systems and non-petroleum fuels;
- Develop world leading engineering photonics technologies with applications for transport, aerospace, manufacturing, healthcare, and other sectors.

The **Manufacturing** Theme research strategy is based on mechanical, control and production engineering underpinned by materials science, physics, and data sciences to enhance the efficiency of operations (smart), processes (clean) and resources (green). Research addresses composites, surface engineering including high temperature materials, sustainable manufacturing and through-life services, welding, and laser processing:

- Manufacturing process engineering with applied mathematics and simulation and material science is applied to investigating models for the “eco-factory” based on circular economy principles.
- Materials science, novel sensor technologies and engineering modelling are applied to materials production with low carbon footprint for lightweight, high performance automotive, marine, aerospace and space structures.
- Monitoring and control engineering principles, data sciences and physical science sensor technologies are used to understand factory management, product service systems and eco-efficiency. Computer sciences along with electrical and electronic engineering informs research on the internet of things for traceability and authenticity, intelligent micro-factories and autonomous manufacturing systems.
- Mechanical and production engineering, along with laser physics and materials science disciplines support research into process automation for both additive manufacture and welding.

The concepts of ‘smart’, ‘clean’ and ‘green’ manufacturing are being applied through all tiers of the supply chain, with small and medium sized enterprises (SMEs) and original equipment manufacturers (OEMs) to support the aspiration of net zero by 2050. A £1.6M investment in new materials characterisation equipment supports the National High Temperature Surface Engineering facility, an associate member of the Henry Royce Institute http://www.royce.ac.uk.

Over the next 5 years we will:

- Develop multifunctional materials, processing technologies and new manufacturing directions for lightweight, high performance automotive, marine, aerospace and space structures;
- Advance thin film deposition techniques, precision manufacturing and in-process metrology in ultra-precision machines;
- Research manufacturing processes and systems with new models for the ‘eco-factory’, with reduced use of energy, water and materials.
- Develop and manufacture products enabled by Industry 4.0 technologies;
- Maximise the benefit of high value, long life assets supported by digital technologies (digital twins, virtual/augmented reality, real-time sensing) to characterise asset degradation, support condition monitoring and the application of digital systems to defence, aerospace, transport and manufacturing;
- Advance the engineering science of metal additive manufacture, laser processing and welding, through process physics and residual stress characterisation.

The **Water** Theme deploys chemical and civil engineering with biological, chemical, physical and social science disciplines to improve our understanding of fundamental processes applied to the management of water in natural and engineered systems:

- Fundamental chemical engineering principles combined with insights from chemistry, biology, physics, and surface science are used to identify new approaches to water treatment and develop nutrient removal and resource recovery processes.
- The boundaries of knowledge in sensors are being extended by combining expertise in water chemistry and microbiology with skills in device engineering and microfluidics.
- Using integrated mathematical modelling approaches, allied to irrigation engineering, to advance our understanding of extreme drought events and the impact of droughts on communities.
- Insights from the social sciences occasion important contributions on the transformation of water and sanitation services for the world's poorest communities and water governance globally. This underpins paths to adoption of achievable and financially credible solutions which improve the resilience and sustainability of water services, such as water reuse, nature-based systems, and decentralised supply.
- Design methods, rapid prototyping, mechatronics, business modelling, data analytics, and materials testing are used for circular economy, materials, and data driven innovation to deliver interdisciplinary solutions to challenge-led problems.

The Cranfield Water Science Institute (CWSI) has engineering specialisms in water and wastewater engineering, water and sanitation in the developing world, water for agriculture, catchment management, and the human and governance aspects of water services. The cross-cutting Centre for Competitive Creative Design (C4D) is an award-winning centre of excellence, focusing on developments for a circular economy. C4D hosts four communities of practice in breakthrough innovation, circular economy innovation, materials innovation and data driven innovation. The Centre has played a major role in addressing global sanitation challenges through innovations in toilet design and associated analytics. Our breakthrough designs have been taken up by other sectors leading to further research-driven advances in, for example, sanitation for the rail industry (Garrandale Ltd). C4D's interdisciplinary approach, bringing together researchers across the Unit has led to innovations in aircraft seat design (Safran), sustainable materials for food packaging (Cool Milk) and influential interventions for Unilever, Royal Mail, Jaguar Land Rover, Novartis, Perkins, and SAB Miller.

Since 2014, the Theme has cemented a national position in water infrastructure renewal. Water's objectives for the next five years are to:

- Support paths to maturity for financially credible engineering solutions that improve the resilience and sustainability of water services, such as water reuse, resource recovery (hydrogen and ammonia economies), nature-based solutions and transition to net zero;
- Exploit new industrial scale facilities for exploring water treatment and supply processes, and new laboratories for advanced sensors plus point-of-use treatment;
- Undertake fundamental engineering research on emerging threats to lives and livelihoods which materialise via the engineered and natural water systems;
- Finesse the use of design thinking principles and practices to rapidly mature engineering and technology solutions across a range of disciplines and sectors.

The **Energy and Power** Theme's research strategy centres on electrical, chemical, and mechanical engineering disciplines applied in combination with data and materials sciences to develop the next generation of energy technologies and facilitate global energy access. Our research addresses climate and environmental protection, energy systems, energy policy and strategy, offshore energy, renewables, alternative fuels, thermal energy systems and energy materials. The strategy spans widely across the energy sectors future needs:

- Fundamental electrical power and controls engineering along with digital and data science and social sciences address questions of how much energy is needed, where, how to move energy around distribution systems, and how to enable the energy transition to net zero.
- Mechanical engineering and materials science are applied to enable a step change in thermal power generation operating efficiency through raising process temperatures and using alternative operating fluids.
- Computational fluid dynamics, hydrodynamics, thermodynamics, materials, corrosion, mechanical and structural dynamics knowledge is used to research heat exchanging methods, waste heat recovery and industrial and domestic heat networks.
- Physics, materials science, and electrical, chemical, and mechanical engineering are applied to next generation renewable technologies, including concentrating solar power, geothermal, on- and offshore wind, wave and tidal marine energy devices.
- Chemical and process engineering, biological sciences and materials science knowledge is applied to enabling carbon capture, development, and production of alternative fuels from biological processes and waste sources, and hydrogen from fossil fuels.

The Theme has transitioned from researching power generation using a range of fossil and renewable sources, to a systems-based approach; the 'energy trilemma' of energy security, equity and sustainability.

Since 2014, we have developed subsea and pipeline flow technologies to enable new areas of marine oil and gas, to be developed with cheaper and less environmentally damaging infrastructure. We host one of the largest pipeline flow laboratories in Europe, uniquely able to develop, monitor and test pilot-scale flow enhancement techniques. We have developed technologies, materials, and coatings to allow the operational temperatures of conventional and alternative fuel turbines to be raised to unprecedented levels; dramatically improving plant efficiency, reliability, and capability. The resulting increase in power output per unit of fuel has directly reduced greenhouse gas emissions. We have focused on new technologies such as wind turbines, concentrating solar power (CSP), solar photovoltaics (PV), geothermal and marine renewable systems. New capabilities in industrial decarbonisation - in carbon capture and energy systems research - have been developed. Within wind energy, our improved structural designs and cutting-edge asset integrity methods have contributed to impressive capital and operation cost reductions leading to significant energy price reductions. Our CSP research on high performance mirrors and specialist maintenance techniques has led to economically priced power for those areas with regular sunshine. We have taken a leading role in carbon capture (Ca-looping; oxy-fuels), waste re-use technologies within power generation and industrial processes.

Our five-year objectives are to:

- Accelerate the energy and zero carbon transition, whilst mitigating challenges for this period of change;
- Develop materials technology for the use of very high temperature / alternative operating fluids (S-carbon dioxide, molten salts and molten metals) within thermal energy systems;
- Develop hydrogen production and distribution systems for the hydrogen economy;
- Support a 'just' energy transition by studying socio-technical aspects and devising strategies and policies that ensure 'best outcomes for all';
- Develop digital and data technologies to enable the smarter production, distribution and use of energy;
- Develop next generation PV technologies for greater efficiency and potential for deployment;

- Establish a leading research position on floating and offshore solar technologies, developing systems for harsh marine environments.

The **Defence and Security** Theme research strategy is focussed on a wide range of engineering, computer, human and physical sciences applied to research in cyber-security, 'defence' chemistry, electronic warfare, energetics, forensics, leadership, modelling and simulation, systems engineering, security, terrorism, and public safety. The strategy is focussed on solutions to military and security issues using engineering and applied sciences:

- Chemistry, materials science, and engineering sciences are applied to explosives safety and manufacture, blast survivability of structures and lethality.
- Fundamental imaging science techniques to undertake forensic analysis, chemical analysis, and electromechanical analysis (with applications to material analysis and failure modes, materials structure, control and guidance, sensors analysis, simulation and modelling).
- Applied mathematics, and computer science and modelling skills are combined with mechanical engineering and social sciences to investigate and develop innovative methods and tools for analysing complex military and security problems.
- The application of psychological, anthropological, and computational techniques being applied to civilian, security and military situations.

Our strategy since REF2014 has been influenced by the UK National Security Strategy and the Strategic Defence and Security Review of 2015. This set out three national security objectives: to protect our people; project global influence; and promote prosperity. In 2018, the UK National Security Capability Review implemented the 2015 fusion doctrine which deploys economic levers, through cutting-edge military resources, to our wider diplomatic and cultural influence on the world stage. Our partners range from Ministries of Defence and other Government departments and agencies, to industrial prime contractors and insurance underwriters, nationally and internationally.

We have invested in state-of-the-art, purpose-built facilities for energetic materials (£1.5M), to be used by strategic UK partners (AWE, MoD's Defence Equipment and Support (DE&S) and Dstl) to research new explosive formulations for the future. Other partners include Home Office, CPNI, GO Science, DfT, HSE. This new Centre of Excellence in Energetic Materials (CoEEM, https://www.coeem.org/?action=main) brings together key government departments, industry, and academia to ensure UK has access to the energetic materials capability into the future. We have also created new, state-of-the art forensics facilities for the Cranfield Forensics Institute at our main campus (£7.3M including South East Midland Local Enterprise Partnership (SEMLEP) funding).

Our five-year objectives include:

- Continuing to lead the CoEEM with Dstl, DE&S and AWE as strategic partners in collaboration with other Government bodies, funnelling research efforts through this national capability;
- Broadening our research capability in key UK sovereign domains, building on strong links to Government and industry;
- Building on our successes in the electronic warfare and cyber spheres to enhance positive impacts on society;
- Growing our forensics research capability, building on new facilities.

Achieving impact and associated case studies. The impact of engineering research is secured through the Knowledge Exchange Strategy

(https://webarchive.nationalarchives.gov.uk/20180405122213/http://www.hefce.ac.uk/ke/heif/strategies/) and its associated machinery, as signposted in REF5a, summarised:

1. Ensuring academic staff are **business-focussed** with KE embedded in their day-to-day roles.
2. Strengthening our support for academic staff and researchers through the **Research and Innovation Office.**
3. Focusing on **strategic partnerships** with industrial clients.
4. Progressing our **client-centric approach**, supporting learners in applying new knowledge to organisational challenges.
5. Increasing the impact of research and development projects through **active promotion of KE** by academic staff, supported by KE professionals.
6. Developing Cranfield and regional-focussed funds for **staff and student entrepreneurship.**
7. Promoting technology-led **graduate start-ups** and **spin-outs.**
8. Expanding the **Business Incubation** offer to provide incubation and acceleration for Aerospace/Aviation and Green Technology.
9. Reinforcing regional KE through **regional academic-led programmes**, in partnership with the SEMLEP, Milton Keynes 2050 Vision, the Oxford to Cambridge corridor and the Midlands Engine for Growth.
10. Achieving sustainable growth by **leveraging unique industrial and near-industrial-scale infrastructure and facilities**.

The Unit's impact case studies are cross-referenced below to the Knowledge Exchange Strategy objectives 1-10.

Case study	Summary
WAAM3D	WAAM3D is a Cranfield spin-out that arose from research on additive layer manufacturing using industrial scale facilities (10). The company has secured seed funding (2, 5, 8) through the **Midlands Innovation** Commercialisation of Research Accelerator (MICRA) and £1.5M from a Singapore investor, Accuron Technologies Ltd (6). Business-focussed staff from the Unit, with KE embedded in their every-day activities (1), are transitioning into the new company.
Safeguarding air quality: optical monitoring of gases and airborne particles	Optical sensing technology has been developed through fundamental research and multiple rounds of impact acceleration funding and patent protection, supported by Cranfield's KE and technology transfer staff (2). This builds on Cranfield's ethos of working closely with business, having KE embedded in everyday roles (1).
Countering art crime and protecting global cultural heritage	This antiquities case study has been enabled by the deep relationship between the Unit and major corporates in the antiquities world, often on a trusted consultancy basis (3). The ethos of supporting academics to be business focussed and to continue consultancy (1) has ensured the sustainability of this work, which draws on unique facilities in the Cranfield Forensics Institute (10).
Embedding formalised risk management in the international water utility sector	Risk management capability has been enhanced through a trusted, strategic level relationship with the US Water Research Foundation and international corporates (e.g., EPAL, Lisbon; Calgary Water; Yorkshire Water) (3). This has been possible through Cranfield's ethos of working closely with business, ensuring academic staff are business-focussed with KE embedded in their day-to-day role (1).

	Strategic corporate relationships are supported by Cranfield's business development function (2).
Design tools for modern and future aero-engines	Working closely with Rolls-Royce has been at the heart of this development and its rapid transfer into industry. This has been enabled by our strategy of supporting staff to work closely with industry, with KE embedded in their every-day roles (1) as well as focusing on key strategic partnerships (3) underpinned by business development support (2).
Process optimisation at water treatment works using zeta potential	Our ethos of working closely with business by ensuring that academic staff continue to be business-focussed with KE embedded in their day-to-day role (1) has facilitated this fundamental research being translated into a significantly improved process to transform the way water utilities operate. The strategic relationships we host with utilities enable rapid translation (2, 3) of our engineering science, and our industrial-scale water treatment facilities mean we can provide ongoing testing throughout the R&D lifecycle (10).
Development of PAS 280 for through-life engineering services	This framework, commissioned by the British Standards Institute has been enabled by the trusted research relationship academics in this area have with Cranfield's industry partners, many of them managed strategic relationships (1,2,3). Practical, useable and reliable guidance and standards rely on the deep knowledge of industry agendas and operational 'know-how'.
Efficient liquid to gas mass transfer in the water sector	Engineering principles on liquid-to-gas transfer, an energy intensive process, enabled deployment of technology to resolve compliance challenges for Scottish Water. This also influenced the structure and thresholds within the ISO 30500 standard on non-sewered sanitation, adopted by 18 countries. A client-centric approach (4), founded on a long-standing strategic partnership (3) with deep understanding of KE needs for the water utility (1, 10) made this possible.
Novel wastewater treatment process principles improves sales	Bluewater Bio (BwB) is a UK SME specialising in novel technologies for water and wastewater treatment with a 164% year-on-year revenue growth in 2018/19 and 300% in 2019/20. BwB was the 35th fastest growing technology company in the UK in the Sunday Times Sage Tech Track 100 league table 2020 (10). This was achieved through sales of its two technologies, HYBACS® (a hybrid biological process) and FilterClear® (an advanced depth filter) that have been supported through Cranfield research. The relationship began with the 2010 purchase of a Cranfield spinout, Water Innovate Ltd (founded in 2005; 1,2,3,4,6,7).
Reducing the impact of high temperature corrosion of alloys and coatings in power plants	Our ethos of working closely with business, ensuring academic staff are business-focussed with KE embedded in their day-to-day role (1), has allowed this research to be translated into a new methodology to test corrosion mechanisms and rates in alloy structures. Strategic relationships with these companies have enabled rapid translation (2,3) and our industrial-scale energy facilities mean that we can provide ongoing testing throughout the R&D lifecycle (10).
F-35B V/STOL Aircraft design and deployment	Deep relationships with industry and the MoD (1, 2,3) have enabled this research to be co-developed and translated into technology to save significant costs on operational aircraft build. Trusted relationships established over many years mean that continuing

	professional development programmes can be easily commissioned (4).
Airbus manufacturing optimisation	Research into the automation of manufacturing (3, 4, 10) has led to significant production improvements, time and cost-savings for Airbus UK. Another application of research has eliminated the need for pre-assembly and complex tooling, saving on production time and costs and has mitigated health and safety risks.

The approach to securing impact for the Unit's research is set out within the Schools' delivery plans. Annual submission of the plans to the Executive provides opportunity to adapt them by reference to the business environment, upcoming opportunities, and developments in a particular field. This coincides with resource requests for the forthcoming financial year. In this way, the Unit aligns its plans for sustaining the vitality of research impact with strategic grant submissions and investments in staff and facilities. An example for the REF2021 period is the Energy and Power Theme, where the research strategy has been reset with academic investment in data analytics and engineering mathematics to support blockchain technologies, and grid systems research.

The open research environment. The Unit delivers its research by reference to the University's Research Integrity Strategy and the Concordat on Open Research Data (REF5a). Cranfield's Research Data Management (RDM) policy (https://library.cranfield.ac.uk/knl/research-data-management) is delivered in the Unit through three academic champions (one per School) for open research data supported by Library specialists. Data and other outputs are stored in the Cranfield Online Research Data (CORD) repository (https://cord.cranfield.ac.uk/) when there is no suitable alternative (REF5a). Within the Unit, there have been 891 uploads since CORD was set up in 2016 and, over the year to February 2021, there were *ca.* 465,000 views and 250,000 downloads. The most downloaded paper from the Unit (4037 views; 1796 downloads) was on a novel signal processing framework to support dementia classifications. The Cranfield Research Information System (CRIS) hosts the Unit's publications, awards, and other research-related information and this feeds a scholarly profile on the University's website (REF5a). The Unit's doctoral students are encouraged to create a CRIS profile to promote their research, linked to their supervisors' profiles; technical staff are also encouraged to have CRIS profiles. Cranfield's open access repository, CERES, includes journal pre-prints and peer-reviewed reprints, digital theses and dissertations, book chapters, working papers and technical reports from the Unit.

Research integrity and ethics. Cranfield is committed to undertaking all research with integrity. All staff and students within the Unit are expected to act in accordance with Ethics Code / Research Ethics Policy via CURES (REF5a), in accordance with the University's Implementing and Monitoring Research Integrity Process (REF5a). Themes provide representatives to the Cranfield University Research Ethics Committee (CUREC) and the reviewer pool. The Unit delivers research in accordance with the Joint Code of Practice for Research (JCoPR), the governance framework for publicly funded research. Project checklists to assure compliance, improvements to sample integrity, reproducibility of experiments, templates for standard operating procedures and the provision of standardised laboratory notebooks are in place. A JCoPR working group oversees compliance and makes recommendations. For example, we have appointed a quality control/quality assurance Senior Technical Officer in our Environmental Analytical Facilities to uphold JCoPR requirements where the analysis of ultra-trace chemicals requires exceptional levels of analytical quality control.

2. People

Staffing strategy and staff development. This can be summarised as:

- Recruit and retain diverse talent globally at all research and academic levels.
- Support 'on-boarding' quickly through induction, mentoring, probation, development, e.g., PgCert in Academic Practice, Fellowship of HEA and Apprenticeship training.
- Encourage career progression through performance development and reviews (PD&Rs)
- Provide long-term career development through a range of interventions, including Cranfield's Researcher Development Programme.

A culture of regular 'one-to-one' meetings for staff with line managers is in place within the Unit, with annual PD&Rs (82% completion for Unit) as the formal opportunity to discuss contributions and agree career development plans.

We have tailored recruitment to attract a more diverse talent (REF5a), to include:

- Gender neutral language.
- Reference to our values (https://www.cranfield.ac.uk/about/about/values).
- Highlighting flexible working.
- Acknowledging historic under-representation.
- Diverse recruitment panel for all interviews.

These changes have been well received and interviewees now anchor their interview presentations around our values, expressing a desire to contribute beyond the role's advertised deliverables.

Of the 285 Research and Teaching (R&T) career pathway staff in the Unit, 95% (271 individuals) are on Open Ended Contracts. The Unit's focus over the REF2021 period has been to strengthen our thought leadership among the Professoriate, with 59 submitted (Table 2). We also ensure a pipeline of diverse, high calibre ECRs, especially at Lecturer grade (Cranfield Level 6), for progression at Cranfield (see below). Within the R&T career pathway, we offer a research-only route for independent researchers, with Senior Research Fellows equivalent to Lecturer, and Principal Research Fellows equivalent to Senior Lecturer/Reader (Cranfield Level 7). Including L5 Academic Fellows, 13% of the Unit's submission (34.49 FTE, headcount = 37) are independent researchers.

Table 2. Job titles of staff submitted in UoA12.

Job Title (HESA Return)	No.	%
Professor/SL with management responsibility, e.g., PVC, Director of Theme	22	7
Professor (L8)	39	14
Associate Professor, Reader, Senior Lecturer, Principal Research Fellow (L7)	95	33
Lecturer, Senior Research Fellow (L6)	119	42
Research Fellow, Academic Fellow (L5)	10	4

Staff who are R&T are expected to write research proposals, supervise PhD students, disseminate research outcomes and to discharge research responsibilities. New research staff complete an online 'Cranfield in Context' induction, are provided with a Research Handbook and attend a welcome event in their first three months to help them integrate into their new role. Unit inductions provide information on University policies, staff networks, personal development and wellbeing initiatives. New staff are assigned a mentor from outside their Theme. As new academics in the Unit build their careers, opportunities to lead grants, undertake secondments, manage Doctoral Training Centres or manage academic Centres are offered at a mid-career stage, to build experience of managing people, collaborations and strategic budgets. For

example, Ozkan, a Senior Lecturer, is a recent female Head of Centre for Energy Systems and Strategy (https://www.cranfield.ac.uk/people/dr-nazmiye-ozkan-1347515) and Mehmanparast successfully assumed leadership of an EPSRC CDT (REMS), as a Senior Lecturer when a Professorial colleague left (https://www.cranfield.ac.uk/people/dr-ali-mehmanparast-775915). In 2019, Longo (https://www.cranfield.ac.uk/people/dr-stefano-longo-822615) was granted a 2-year secondment as Head of Automotive at Embotech AG, an ETH Zurich spin-off specialising in optimisation techniques for autonomous vehicles. He will return full-time to Cranfield in 2021 to his Readership in Automated Vehicles.

Early career researchers. Cranfield is a signatory to the 2019 Researcher Development Concordat and has an HR Excellence in Research award demonstrating our commitment to career development (REF5a). New initiatives include proactive management of workloads, availability of secondments and a minimum of 10 days' development a year. The high levels of delegated responsibility and numerous development opportunities within the Unit provide excellent opportunities for Research Fellows to acquire the competencies for their next career stage. We have opened up our PgCert in Academic Practice (PgCAP), with 70 of 134 Research Fellows in the Unit beginning their studies in the REF2021 period (52%). To assist in the transition from fixed-term to open ended contracts, the Unit operates an 'Academic Fellow' acceleration route, for promising Research Fellows. This offers an excellent recruitment pipeline, several Academic Fellows already progressing to the Professoriate (e.g., Jarvis, McAdam, Soares). The Unit has recruited the first two Cranfield 75th Anniversary Fellows, a scheme to attract the most talented ECRs from around the world.

Due to Cranfield's exclusively postgraduate nature and its focus on industry relationships, we seek to develop staff that are aligned to the University's values. Therefore, in addition to key Professorial appointments, we have consciously sought ECR applicants for academic positions in the Unit since 2014: this policy has meant that 22 % (63 individuals) of those submitted are ECRs. These staff are attracted by a rapid start to their careers in a research-intensive University with moderate teaching loads, ready access to industrial collaborations and the benefits of shared facilities, many at a national scale. Specific development needs for ECRs, such as the presentation of research ideas to industry and understanding engineering research agendas, are supported through business skills training and coaching of new joiners. The Unit makes wide use of the professional and learned societies for networking, committee representation and agenda-setting opportunities, especially for its ECRs, many of whom hold 'officer' roles on society committees. For example, Sumner was Chair of the Institute of Materials, Minerals and Mining's 10th Parsons Conference (https://www.iom3.org/high-temperature-materials-committee/event/parsons-2019) and Dotro is a long-standing member of the IWA Specialist Group on Wetland Systems for Water Pollution Control (2012 onwards). The Advance HE 'Aurora Programme' has supported several women across the Unit with their career visions, and our 'Step up' network and 'Women as Leaders' programme have supported progression to the higher academic grades (e.g., Hodgkinson, Soares).

Strengthening and maintaining thought leadership. Strategic appointments to senior roles are made with reference to the Schools' delivery plans. Cases are made for strengthening thought leadership in the context of business growth or the strategic intent to move into new areas of research including the use of engineering facilities. New professorial appointments require full business cases to be approved by the Executive, maximising the opportunity for pan-University working on appointment. High profile engineering appointments to the Unit in the REF 2021 period have included:

- Prof. Helen **Atkinson** CBE FREng recruited as Pro-Vice-Chancellor for the School of Aerospace, Transport, Manufacturing in 2017 from the University of Leicester where she was Head of the Department of Engineering.

- Prof. Iain **Gray** CBE FREng FRSE in 2015 as Director of Aerospace; a former Chief Executive of Innovate UK recruited to progress strategic relationships with the world's major aerospace industrial organisations.
- Prof. Phil **Hart**, as Director of Energy and Power, joining in 2018 to transform Cranfield's energy offer; a recognised industry leader in wave energy conversion having advised the US Departments of Energy and Defence on innovation strategy and with experience working with Shell, BP, Huawei, and Petrobras.
- Prof. Krzystof **Koziol,** Professor of Composites Engineering and Head of the Enhanced Composites and Structures Centre, recruited from Cambridge University in 2017 to progress our advanced materials offer.
- Prof. Gokhan **Inalhan** recruited from Istanbul Technical University in 2020 to a BAE Systems Chair in Autonomous Systems and Artificial Intelligence to focus on design, modelling, resilience, and security aspects of autonomy and artificial intelligence.
- Prof. Martin **Skote**, recruited as the Airbus Professor of Landing Systems Engineering in 2018 from NTU Singapore, with a focus on turbulence, flow control and computational fluid dynamics.
- Prof Weisi **Guo**, a former Turing Institute Fellow and IET Innovation award winner, recruited from the University of Warwick as Professor of Human Machine Intelligence.

Promotions to Senior Lecturer, Reader or Professor, or to Principal Research Fellow, are merit-based and managed annually through a two-stage process. Stage one is a formal review by the School's Executive, which has a diverse make-up including at least one female member and a Senior HR Business Partner. The second stage is through the Senior Academic Promotions Board, chaired by the Vice-Chancellor. Candidates benefit from close mentoring, ensuring cases draw out research strategies and the candidate's portfolio of intellectual contribution. Line mangers help to identify staff who may have a case, not only to evaluate high performers but also to ensure candidates are representative of the overall staff make-up. Particular attention is given to underrepresented groups who may require greater encouragement to put cases forward. Part-time staff contributions are reviewed to ensure achievements are pro-rated and comparisons equitable. Support is provided where English is not a first language, so this does not undermine the ability to advance a case. Unsuccessful applicants are mentored and offered career planning to support a revised submission. Professorial cases that meet the requirement (e.g., Soares, Simms, Erkoyuncu) proceed to a Panel interview, chaired by the Vice-Chancellor, comprising the HR Director, the relevant PVC School, and an external referee. Since 2014, a triennial Professorial Salary Review Board, with external representation, seeks to ensure a parity of reward across the Professoriate, commensurate with scholarly excellence and impact in contribution.

Research students. The Unit had 890 Doctoral research students on 31st July 2020. 786 of these were PhD students (595 full-time; 191 part-time) and 42 were full-time EngD students. The Unit graduates 113 Doctoral students, on average, per annum (6-year average over the REF period). The Unit advertises all funded research opportunities openly and academics in the Unit promote opportunities for self-funded Doctoral students through their web pages (https://www.cranfield.ac.uk/research/research-degrees/research-opportunities). Students are recruited through formalised processes to ensure ED&I compliance. Our Head of ED&I sits on peer review panels for our EPSRC Doctoral Training Partnerships (DTP) awards. Across the Unit, research supervision arrangements have been revised to ensure all Doctoral students are assigned two supervisors as part of a supervision team for a tighter focus on intellectual contributions, scholarship, and timeliness of completion (REF5a). A comprehensive Doctoral Researchers' Core Development (DCRD) programme is based on the VITAE National Researcher Development Framework (REF5a).

The Cranfield Doctoral Network (CDN) brings together research students and staff across the University to provide networking and development opportunities. Positioned within the CDN are Thematic Doctoral Communities (TDCs) – one per Theme (www.cranfield.ac.uk/research/research-degrees/cranfield-doctoral-network). In the Unit we have developed an annual international defence and security conference supported by Dtsl and AWE since 2016, which Cranfield runs on behalf of the UK community. Approximately 200 students from up to 40 different universities present 20-minute papers, 3 Minute Thesis (3MT), posters or a digital image with prizes for the best in each category. Outputs are posted onto our open access data repository: https://cord.cranfield.ac.uk/collections/2019_Defence_and_Security_Doctoral_Symposium_DSDS19_in_conjunction_with_DSTL_AWE_and_GCHQ_Symposium_outputs/4578305. Similarly, the student-led Aerospace conference is in its 4th year (140 attendees in 2020). The conference includes both student presentations and key-note speakers. The Water TDC has also developed an Early Career Women in Water conference which first ran in 2020 (221 attendees). The views and recommendations of the Unit's Doctoral students are captured through University-level activities via Student Voice (https://www.cranfield.ac.uk/about/student-charter), including participation in the Postgraduate Research Experience Survey (PRES) and committee representation (REF5a).

Over the REF2021 period, we have had considerable success with UKRI calls for Doctoral Training Centres (www.cranfield.ac.uk/research/research-degrees/doctoral-training-centres), developing a prominent position for the Unit in the field of water energy and environmental engineering research and in materials science.

STREAM, the £6.4M industrial doctoral centre (IDC) for the water sector, was co-funded by EPSRC (EP/L015412/1; PI Jeffrey; £3.73M; 2014-2022) with the water utilities (e.g., Severn Trent, United Utilities, Thames Water) and consulting engineers (e.g., AECOM, MWH, HR Wallingford) who sponsor research (http://www.stream-idc.net/). The programme is enabling 97 talented researchers to develop their skills and careers, while obtaining an EngD or PhD degree. The IDC has also attracted international support, e.g., PUB Singapore. STREAM is led by Cranfield in partnership with Exeter, Imperial, Newcastle, and Sheffield: all EPSRC Platform grant holders at the time of award.

WIRe (EP/S023666/1; PI Jarvis; £6.64M; 2019-2027) seeks to nurture a new generation of 60 engineering research leaders to provide the multi-disciplinary, disruptive thinking to enhance the resilience of water infrastructures (https://cdtwire.com). The CDT is led by Cranfield with Newcastle and Sheffield.

Water-WISER supports 50 PhDs in water and waste infrastructure systems engineered for resilience (EP/S022066/1; Co-I Tyrrel; £6.45M; 2019-2027). The CDT aims to deliver the generation of new knowledge to improve water, waste and sanitation infrastructure and services for the poorest and most marginalised members of our global community (www.waterwisercdt.ac.uk). Led by Leeds, Cranfield and Loughborough are partners.

The **Sustainable Materials and Manufacturing** CDT (EP/L016389/1; Co-I Jolly; £3.39M; 2014-2022) seeks to secure long term, real world manufacturing impacts in critical UK industries (https://sustainablematerialsmanufacturing.com). Working closely with Airbus, JLR, Granta Design and others, 46 EngD research engineers in the CDT are developing innovative production processes that allow new feedstocks to be utilised; dematerialisation and light weighting of existing products; and the design of novel production technologies. Cranfield, Exeter and Warwick co-operate to offer a joint EngD degree.

REMS, the EPSRC-funded CDT in renewable energy marine structures (EP/L016303/1; PI Mehmanparast; £4M; 2014-2022) partners industry (e.g., Orsted, Ramboll, Eon, RWE, TWI, Fraunhofer) to ensure research engineers (55 EngDs) have the knowledge of integrated structural systems to support offshore and marine renewables sector growth (http://www.rems-cdt.ac.uk) . Cranfield leads the CDT with partners Oxford and Strathclyde.

The ultraprecision manufacturing **CDT-UP** (EP/L016567/1; Co-I Morantz; £3.8M; 2015-2022) educates research engineers to collaborate with SMEs related to next generation displays; plastic electronic devices; low-cost consumer products; low-cost photovoltaics; and defence and security technologies (https://www.cdt-up.eng.cam.ac.uk). Cambridge and Cranfield partner to deliver the programme.

The IDC in **Composites Manufacture** (EP/K50323X/1; Co-I Partridge; 3.93M; 2012-2019) is a future-composites manufacturing hub with plans for a step-change in research for the production of polymer matrix composites. The Hub is supported by 4 High Value Manufacturing Catapult Centres and backed by 18 leading companies from the composites sector, offering a further £12.7M in support. Bristol is the lead, originally with Cranfield, Manchester and Nottingham as Co-Is (Skordos) (https://epsrc.ukri.org/skills/students/centres/2013-cdt-exercise/compositesmanufacture/) .

Equality and diversity. Cranfield is committed to equality, diversity and inclusion embedded in its Charter (REF5a). The Diversity and Inclusion Strategy directly addresses how staff are supported (www.cranfield.ac.uk/about/working-at-cranfield/diversity). Policies and procedures cover all protected characteristics under the Equality Act 2010, with flexible working, dignity at work and support for carers going beyond the legal requirements (REF5a).

The gender balance across the University has remained stable in recent years at *ca.* 46% female, with more female staff in professional and support roles, reflecting sector trends. The proportion of female academic and research staff is 19% (25% within this Unit); we are working hard to increase female representation. Cranfield's Athena SWAN Bronze action plan (2017) highlights progress since our last award in the areas of recruitment, selection, retention and development. As the University's ED&I plans have matured, we have continued with an institutional Bronze Award in 2020, valid for the next five years. Since 2015, 56 women have participated in the Aurora programme, 25 from across the Unit (Research Fellows and Lecturers) and 29 females have participated in the 'Women as Leaders' programme, 7 from the Unit. We have over 200 members in our 'Step-Up' network, which focuses on developing women's careers. We have sponsored the International Women in Engineering Day (INWED) in 2018, 2019 and 2021 (two women from the Unit were included in the top 50 women in Engineering), and have carried out activities related to INWED over recent years (www.cranfield.ac.uk/about/community-and-public-engagement). We are members of the Women in Aviation and Aerospace Charter and of Women in Defence.

The overall BAME population at Cranfield is 16%; UK staff identified as BAME is 9%. The percentage of BAME staff from outside the UK is 39%, higher than the sector benchmark of 30%. Staff at the University who have declared a disability represent 3% of the workforce; we are encouraged by declaration rates improving. Cranfield has joined Working Families (1 of 13 universities), became a Level 1 Committed 'Disability Confident' employer and joined the Business Disability Forum (1 of 21 universities). Cranfield has introduced mandatory ED&I training for all staff and a Diversity in Learning and Teaching module for academic staff. Staff across the Unit are required to complete these modules every 3 years and completion rates are over 90%. Staff involved in REF2021 decision making within the Unit have all undertaken REF-specific ED&I training. Examples of support to Unit staff include working with the government's 'Access to Work' scheme to support an individual diagnosed on the autistic spectrum to craft the

adjustments required to support them in role. A researcher was recently appointed who, during the hiring process, disclosed she was pregnant and would go on maternity leave a few months into the project. We worked with her to identify the best outcome and have engaged two job share researchers to cover her maternity leave on a temporary contract. She will re-join the project later this year. Due to COVID, a number of adjustments within the Unit have accommodated all academics classed as extremely clinically vulnerable.

ED&I considerations for the REF2021 submission. Cranfield has had full regard to ED&I issues in its REF2021 submission (REF5a). These support our approach to REF2021 as articulated in our REF Code of Practice (www.cranfield.ac.uk/research/why-cranfield/research-excellence-framework). An independent REF Strategy Board was chaired by a senior academic with representation from all the Themes, the Head of Diversity and Inclusion and other support staff. Through our training and individual circumstances process, we have ensured our selection processes are fair and inclusive for staff from a range of different backgrounds and circumstances. Through our Equality Impact Assessment process, we have monitored selection processes to ensure no group of staff is disadvantaged.

Promoting well-being, flexible and remote working. Cranfield's Wellbeing Strategy ensures Unit staff understand the value of proactively managing mental health (REF5a). We run 'promoting wellbeing in the workplace' workshops for managers and in 2019 we launched a programme of wellbeing activities, with an enhanced programme in 2020, that all Unit line managers have attended. COVID has accelerated our efforts to develop a portfolio of additional resources including Women's Health, 'Know your Numbers' and Mental Wellbeing. Academic staff in the Unit benefit from flexible working that promotes a reasonable work-life balance. The flexible working steering group (2018) included 5 members from the Unit, who revised our flexible working policy (2019) in line with best practice. It was endorsed by 'Working Families', the UK's leading work-life balance organisation; was made a 'day one' right for all staff; and made more inclusive to embrace staff with caring responsibilities. Staff in the Unit can access monthly drop-in sessions with HR on flexible working. Working Families advised the Senior Management Team in 2019 on how flexible working enhances performance, wellbeing, motivation, retention, and attraction. Where possible, Unit meetings are held between 10am and 4pm, in line with our Athena SWAN principles. We have seen numerous examples of flexibility within the Unit and the number of staff working remotely has increased over the last 2-3 years. Two Professors have moved to reduced hours contracts to enable them to carry out roles overseas. Following the bereavement of their spouse, one academic works from home 2 days a week to facilitate childcare. A Lecturer requested a move to part-time working following childbirth and we worked with her to ensure the balance of her work would still contribute to career progression. She has since been promoted to Senior Lecturer. COVID has accelerated the number of ways in which we work flexibly. Remote working has proved successful in many settings and we are exploring how we can consolidate these to bring mutual benefit to the Unit.

Career paths for part-time and fixed-term staff. Within the Unit 95% (271 individuals) of all eligible staff are on permanent contracts and 5% (14) on fixed term contracts. All staff in the Unit are supported to develop their careers. Discussions are held at their P&DR and during regular 'one-to-ones'. Independent researchers that demonstrate specialisms that attract repeat funding can be supported into open-ended roles within the Unit. Part-time staff develop their careers in the same way as full-time colleagues and have access to the same range of development opportunities. Staff considering increasing their hours, or transitioning to full-time roles, are supported with trials or interim arrangements. In line with our Athena SWAN commitments, we seek to agree all requests from females in senior roles, particularly when they may be working compressed hours.

Study leave. Through the Apprenticeship Levy, staff in the Unit can be supported with some of their development through an apprenticeship programme (REF5a). For example, Mehmanparast and Hanak undertook the Executive MBA at Cranfield. Under the arrangements, 20% of their working week was dedicated to study and both completed the Level 7 Senior Leadership programme in 2020. We also support staff to undertake part-time PhDs alongside their careers. Paid time during working hours is flexed to support their studies. One Lecturer has, during the course of her PhD, been promoted to a Senior Lecturer role.

Conferences and travel for staff with caring responsibilities. As members of 'Working Families', we provide benefits including nursery provision for staff and students. Flexible working, carers' leave, dependents' leave, and parental leave are in place (REF5a). Line managers in the Unit take an empathetic approach to supporting colleagues' individual circumstances. Staff are encouraged to attend conferences and travel on business taking account of their caring responsibilities. The University is developing a carers fund to support carers attending conferences. For example, an academic who is a single parent has been given flexibility around how and where she works to enable her to pick up school-aged children. This has extended to attendance at conferences, and working hours are flexed accordingly. This individual was recently promoted to Senior Lecturer.

Equality and access to internal funds, promotions, and leadership opportunities. All staff within the Unit have equality of opportunity to funding and development e.g., Aurora, Women as Leaders, the University's Business Skills programme, and other training provided by the Learning & Development Team or RIO (REF5a). Access to internal funds e.g., HEIF, EPSRC DTP PhDs, EPSRC Impact Acceleration Account (IAA), World Class Laboratories and Strategic Priorities Fund, is based on merit and specific funding criteria. Unit staff have internal proposals reviewed and evaluated by senior staff so that they can benefit from improvement. The Head of Diversity and Inclusion sits on peer review panels for these funds and/or provides advice and guidance on fairness and transparency. Where appropriate, external representatives are included in peer review panels to provide a benchmark e.g., industry representation for IAA and another university for EPSRC DTP.

Returning from parental leave, ill-health or caring. The Unit has a supportive approach to maternity/paternity and adoption leave/benefits and ensures transparency of its guidance on the intranet. Before staff take leave, they have a one-to-one meeting with their local HR Business Partner to discuss time off for appointments, leave entitlement, keep in touch (KIT) days and the support available. Staff and their line manager agree up to 10 KIT days for team meetings, training and contact with colleagues to ease a return to work. These enable them to combine a successful research career whilst balancing childcare commitments. For example, a female Research Fellow was promoted to the post of Academic Fellow in 2017 and, following maternity leave, promoted to Lecturer. Cover for staff on leave often continues beyond their return, as they use accrued leave to manage a smoother transition. Line managers hold 'return to work' meetings and seek to accommodate flexible working requests. Parental buddies help alleviate any concerns. We provide support and facilities for staff who wish to breastfeed/express on their return. Breaks and flexible start/finish times are discussed, and we support staff on fixed-term contracts similarly. For those on funded contracts, we follow the maternity/paternity guidance from the appropriate funding body and suspend projects for the duration of leave, where possible.

Staff returning from long-term leave due to ill health are supported with a phased return to work plan agreed with their line manager and HR/occupational health. Several staff within the Unit have had phased returns for a range of health conditions. For example, an academic has been supported through significant mental health difficulties with a comprehensive return to work programme which slowly increased whilst on full salary. Through a mixture of the individual's

clinical support and help from the University, this member of staff made a successful return and is performing strongly in role, as evidenced by a discretionary award for sustained high performance. Flexible working is also allowing a senior academic to support their partner through cancer treatment. Other staff receiving treatment for cancer have requested to work from home for significant periods on a flexible basis, which has enabled them to continue their careers and manage research contracts whilst recuperating.

3. Income, infrastructure and facilities.

The Unit has raised its ambition on leveraged investments for engineering research over the REF2021 period. This has been possible through a clearer articulation of corporate intent; improved research and innovation support; the development of our Research and Knowledge Exploitation strategies; and through investments in thought leadership. Average annual research income (all sources) for the Unit stands at £32.7M over the REF2021 period; £10.5M from UKRI sources in 2019/20, up from £6.3M in 2014/15. In addition to a second Platform grant in Engineering Photonics (Tatam, £1.36M, EP/N002520/1), four strategic research grants from UKRI with a value of >£5M over the REF2021 period have been won:

- Water infrastructure engineering (PI Jeffrey, EPSRC, £7.38M, EP/P017460/1)
- Hydrogen technology demonstrator for the UK Hydrogen Supply Programme (PI Clough, BEIS/Innovate, £7.44M)
- Water resilience CDT (PI Jarvis, EPSRC, £6.64M, EP/S023666/1)
- Additive Manufacturing Programme Grant (PI Williams, EPSRC, £5.89M, EP/R027218/1)

Strategies for generating research income. RIO was set up in 2014 to strengthen the support for generating research income (REF5a). In the Unit, AIRC, DARTeC, UKCRIC and MUEAVI facilities are the results of an enhanced approach to strategic research. A further development since REF2014 has been the incorporation of our Estates infrastructure into our research ambitions, with our airport, roads, wastewater treatment works, biomass plant and solar farm comprising a 'living laboratory' - an urban observatory that includes instrumented infrastructure as part of UKCRIC (https://www.ukcric.com/facilities/cranfield-urban-observatory/) . Together with MUEAVI and the UKCRIC Urban Water Innovation and Test Facilities, the observatory is generating research data to inform the smart city and infrastructure renewal agendas.

Diversity and the acquisition of research funding. The Unit makes good use of opportunities to introduce ECRs as 'Researcher Co-investigators' and to make project management opportunities available to ECR staff plus supporting an ECR network in defence and security. Our ED&I training has improved statements within proposals related to ED&I practices (e.g., for CDTs), the recruitment of Research fellows and PhD students and the make-up of research groups. A progressive set of accessibility improvements have been made to technical facilities within the Unit and to several offices to improve access for disabled staff and students. Individuals are supported, for example, we have recently made a reasonable adjustment for a Research Fellow in the Unit with dyslexia.

Regional and global alliances. A significant change for the University and Unit for REF2021 has been our positioning with regional university groups able to exert a collective influence on strategic research funding. We are core members of the research alliance 'Midlands Innovation' (https://midlandsinnovation.org.uk/), particularly engaged in two research pillars of transportation and energy, aligning with our Aerospace, Transport Systems and Energy & Power Themes. Staff in the Energy & Power Theme are active in the £180M Innovate UK and industry funded MI Energy Research Accelerator (ERA) that supports 23 major research facilities. The Unit is also engaged in the MI Research England Development Fund TALENT programme aiming to enhance technician careers. Further, the reassertion of sense of place in the Cambridge-Milton

Keynes-Oxford economic corridor (https://www.nic.org.uk/wp-content/uploads/Cambridge-Milton-Keynes-Oxford-interim-report.pdf), and regional alliances with the newly formed Arc Universities Group (https://www.rubbaglove.co.uk/work/the-oxford-cambridge-arc/) and the South-East Midlands Universities Group (https://www.semlep.com/modules/downloads/download.php?file_name=199) have allowed access to larger research consortia and underlined our growing ambition within a regional context.

Strategic grants for specialist research infrastructure. A significant shift since REF2014 has been our success in securing large strategic grants to support infrastructure within the Unit. This has allowed the Unit to address priority research agendas and add to our portfolio of national-scale facilities. In this REF period, investments in the Unit have totalled £120M and have included the following developments that are part of a 25-year plan to develop the Cranfield campus:

UKCRIC. In 2017, EPSRC announced £125M of investment to upgrade the nation's research capacity on infrastructure resilience. The UK Collaboratorium for Research on Infrastructure and Cities (UKCRIC) generates knowledge to prioritise, de-risk and evidence investment in the UK's infrastructure systems. The Unit is part of a nationwide group of 14 universities funded under UKCRIC. The £7.38M UKCRIC facilities at Cranfield (PI, Jeffrey; EP/R017727/1), alongside those at Sheffield and Newcastle, provide capabilities to advance the performance and serviceability of water infrastructures to deliver more environmentally benign approaches to water treatment. The facilities also support testing of new approaches to water infrastructure design and operation that use advanced sensing and AI techniques. Senior staff in the Unit serve as a Director on the UKCRIC Coordination node (Jeffrey) and on the urban observatories management group (Jude). UKCRIC investments in the Unit underpin the new National Research Facility for Water and Wastewater Treatment at Cranfield and have been used to create a unique observatory network blending sensing data from the natural and built environments. Early research success has been delivered through the Plexus (EP/R013535/1; Co-I's Jeffrey, Jarvis, Jefferson; £1.01M) and CORONA EPSRC projects (EP/R013411/1; Co- Jude; £1.01M). Cranfield's own urban observatory ('living lab') is part of the network of observatories funded through UKCRIC for the rapid trialling of solutions at scale, and for gathering large volumes of diverse data about current and proposed infrastructures. At its heart is a £1M campus-wide sensor network to monitor air and noise pollution, ecosystem dynamics and resource flows.

AIRC. The award-winning £35M Aerospace Integration Research Centre (AIRC) was opened in 2017 (PI, Gray). Funded by Airbus, Rolls-Royce, Cranfield University and the Higher Education Funding Council for England, the Centre is a flagship facility for boosting aerospace research in the UK, cementing the University's reputation as a globally leading aerospace research institution. AIRC uniquely focuses on integration, where new technologies are rapidly developed and tested for current and future aircraft and airspace concepts. Researchers from the Unit and our business partners are co-located. The Centre is researching ways of integrating advanced technologies, to reduce the time from innovation to application. Its laboratories connect our 'land-side' ground-based research with 'air-side' flight research, taking aerospace concepts from theory to flight demonstration and allowing us to move our fundamental research on to higher technology readiness levels. The AIRC is equipped with cutting-edge aerospace research technology, including air traffic management (ATM) and unmanned aerial vehicle (UAV) laboratories; flight simulators; a virtual wind tunnel; an industrial robot; and a 1500m^2 open work area currently housing a full-size wing from an Airbus plane.

DARTeC. Co-funded by Research England, a consortium of leading aviation organisations and Cranfield, DARTeC is a £67M investment in state-of-the-art facilities to leverage the University's airport and its autonomous vehicle research facility (PI, Braithwaite). In 2020, Boeing joined the existing consortium of Aveillant, Blue Bear Systems Research, BOXARR, the Connected Places Catapult, Inmarsat, the International Air Transport Association (IATA), the IVHM Centre, Saab, the Satellite Applications Catapult and Thales. DARTeC will provide a new digital research environment protected from, and yet accessible to, an operational airport; allowing research at a variety of technology readiness levels. Opened in 2021, DARTeC will address the research challenges facing the aviation industry such as:

- the integration of drones into civilian airspace;
- increasing the efficiency of airports through technological advances;
- creating safe, secure shared airspace through secure data communication infrastructures; and
- increasing the reliability and availability of aircraft utilising self-sensing/aware and self-healing/repair technologies.

Game-changing technologies such as the first operational digital air traffic control tower in the UK and next-generation radar technologies on the University's licensed airport create a unique research and development environment. Research areas include a covered hangar laboratory housing our Boeing 737-400 aircraft and next-generation technologies such a Holographic Radar System capable of monitoring and controlling airspace around Cranfield's global research airport.

MUEAVI. The Multi-User Environment for Autonomous Vehicle Innovation (MUEAVI) is a £9M research facility, co-funded by SEMLEP and Cranfield. It is a purpose-built experimental facility for the rapid development of on- and off-highway ground and airborne autonomous solutions. These include vehicles, infrastructure, data, logistics, sensors and their implementation and management (PI, Brighton). Central to the facility are vehicle workshops, vehicle electrification, autonomous vehicles, simulation, mechatronics and control systems laboratories. MUEAVI data is relayed in near real-time from the communication network running alongside the road. In association with the test tracks, a range of vehicle and infrastructure instrumentation is available to measure the position of the test vehicle, other vehicles and other actors. This enables real traffic situations to be recreated faithfully in a controlled manner, with rapid fault-finding and systems development. A wide range of instrumented vehicles support experimental programmes, with the facility being used for infrastructure sensor development and advances in 'vehicle-to-vehicle' (V2V) and 'vehicle-to-everything' (V2X) communications capabilities.

AVIATE +. Cranfield was awarded £1.2M (PI, Stephenson) in 2020 to create a UK Aviation Innovation and Technology Entrepreneurship cluster, AVIATE+, helping Cranfield and small businesses develop the technology of the future. One of 20 University Enterprise Zones (UEZs), Cranfield will use its world-renowned expertise to support start-ups and SMEs with specialist facilities, programmes and collaborations. The new facility is being built during 2020/21. Cranfield already has the Cranfield Eagle Lab, supported by Barclays, on site (https://labs.uk.barclays/locations/cranfield). This is a business incubator for early-stage companies supported by the Royal Aeronautical Society, the Garfield Weston Foundation and aerospace industry partners. The UEZ will build on this and deliver more 'grow-on space' for businesses with new workshops and facilities that have capacity for large components and data connectivity.

Infrastructure and impact. The Unit's facilities play a key role in securing repeat research commissions from industrial sources and are at the heart of Cranfield's engineering capability.

They generate authentic engineering data that can be scaled-up by business and are used to promote new ideas as leverage within UKRI proposals and to accentuate the distinctiveness of the Unit's research during Ministerial or Director-level industrial visits. Our engagement with the **Aerospace Technology Institute** serves as an exemplar. Recent investments in engineering photonics and sensor platforms have led to three ATI funded projects (a) 'BladeSense' https://www.cranfield.ac.uk/research-projects/bladesense ; (Project 102381; with Airbus Helicopters UK Ltd and BHR Group; PI Lone; £640k; 2015-2019) to design and implement novel optical fibre sensors to measure blade strain and shape in the rotating frame, culminating in a ground test at full blade speed; (b) 'WINDY' (Project 113074; with Airbus UK, Aircraft Research Association Bedford, Renishaw; PI Tatum; £569k; 2016-2021) involving a measurement campaign using fibre sensors designed and fabricated at Cranfield on the ARA standard test model and in the ARA transonic tunnel, the first fibre optic pressure sensor measurements from a transonic wind tunnel; and (c) End to end equipment health management (Project 113095 with Rolls-Royce; PI Lawson; £250k; 2016-2021) deploying an instrumented aerospace fuel pump with fibre optic strain sensors for improved fidelity in harsh operating environments, the first programme undertaken in the AIRC fuels lab between Rolls-Royce and staff in the Unit.

Collaborative use of facilities. The Unit supports pan-University equipment sharing through our Research Asset Booking System (RABS) developed to ensure the visibility of equipment at University level. RABS enables the monitoring of equipment usage and ensures risk assessments and training have been completed. It purposefully records project funding sources to help quantify returns on investment. We have responded to the Diamond Review through establishing an equipment register to make our facilities more accessible across the sector (https://www.cranfield.ac.uk/facilities). As a direct result of our collaboration with industrial partners, we frequently welcome clients to build and develop research rigs on the Cranfield campus, to allow us to work on joint projects. These include companies such as Aqua Enviro installing and running a rig within our water pilot hall and Autonomous Devices Ltd using our wave tank to test flotation devices for sensors. Staff within the Unit make use of a number of externally funded facilities through STFC to the value of over £1M over the REF2021 period, including the Diamond Light Source and ISIS neutron and muon source at Harwell and Institut Laue-Langevin (ILL) in Grenoble, France. Technical staff have taken advantage of exchange opportunities through Midlands Innovation; for example, to develop expertise in specialised gas chromatographic techniques. Our facilities also support schools activities through a comprehensive outreach programme (https://www.cranfield.ac.uk/about/community-and-public-engagement).

High Performance Computing. A new, £695K High Performance Computer (HPC), Delta, was installed in 2017 to provide faster processing, greater storage capacity and better energy-efficiency than its predecessor. The facility has 1,920 cores which provide 60TFlops of computing power, plus 4 GPU nodes and remote visualisation capability offering a dedicated resource for 250-300 research users, including over 100 PhD students since 2019, to investigate engineering, scientific, data analytic and machine learning applications including modelling and simulation tasks. The procurement process for Delta's successor began in March 2021.

Donations and sponsorship related to research. Our industrial links have fostered several strategic equipment donations over the REF2021 period, facilitated by modest investments from Cranfield. Across the University, £13.4M of Cranfield investment has leveraged £59.2M of donated or sponsored equipment, totalling £72.6M. Donations, or in kind-benefits, have been made to the Unit by British Airways, Saab and Rolls-Royce and have included a Boeing 737 aircraft with capability as a ground-based laboratory, a SAAB340 flying classroom, and specialised engineering equipment for the AIRC and DARTeC.

Technicians, administration, IT support and estates. The Unit benefits from a substantive expert community of 89 technicians that manage facilities on a day-to-day basis and ensure wide access for users. We develop staff from apprentices through to the senior technician grades. Technicians play a pivotal role as nominated safety managers for high hazard experimental areas, maintaining a vigilant safety culture in conforming to our ISO45001 accreditation. Many are co-authors with the Unit's academic staff on papers. The Unit has led Cranfield's work under the Science Council's Technician Commitment (https://www.cranfield.ac.uk/about/working-at-cranfield/technician-commitment) and the £5M Research England Development (RED) funded TALENT programme (https://www.mitalent.ac.uk/) to promote technician careers; taking advantage of bespoke training and secondments across the Midlands Innovation universities. SWEE's Head of Technical Services, Jane Hubble, was 'Highly Commended' in the Times Higher Outstanding Technician of the Year Award 2020 and was recently the first female technician promoted to Cranfield Level 7. Similarly, the Unit benefits from coordinated, high quality administrative provision at a Theme level, and access to centralised IT and estates support for high performance computing, facilities design, and project management. Cranfield believes that fundamental to the research infrastructure is our primary regard for health and safety and for environmental stewardship. We have institutional accreditation across all operations for ISO45001 (REF5a). We have ISO14001 Environmental Management System (EMS) accreditation for all our operations with an ambitious carbon reduction plan (REF5a). Health and safety issues in the Unit are managed through local, School-level and University-level health and safety committee structures.

Major grants by Theme. In addition to the strategic grants and investments above, major grants from external bodies won on a competitive basis, are summarised below.

Aerospace. Cranfield leads the UK Aerospace Research Consortium Network linking the leading aerospace research universities (Gray, EP/V009354/1). Key aerospace engineering projects include ENABLEH2 (EU H2020) on maturing fuel systems and ultra-low NOx combustion technologies, whilst addressing key challenges associated with the introduction of liquid hydrogen for civil aviation; PROTEUS (EU H2020) on multi-fidelity models to predict the idle, and sub-idle, performance and operability of large, very high bypass ratio geared turbofan engines; APROCONE (Innovate UK) developing the design environment for innovative aircraft wings and turbofan concepts; IFAN (Innovate UK) advancing aerodynamic and aeromechanical prediction methods, from low to extremely high-fidelity computational fluid dynamics to enable predictions of the performance and stability of an installed fan system; Factory of the Future for Aircraft Wing Manufacture and Assembly (Innovate UK) to maintain and strengthen the UK's aero-structures manufacturing capability for conventional and next generation airframe structures in an environmentally friendly way; and ICORE (Innovate UK) developing new engine core technologies to reduce fuel burn and emissions.

Key projects on advanced asset and air traffic management have included AIRSTART (ATI and Innovate UK) researching unmanned air systems to enable safe operation beyond visual line of sight with increased endurance; COMPINNOVA (EU H2020) developing innovative inspection methodologies for composite aircraft structures to allow more efficient and reliable damage inspections; AIRMES (EU H2020) validating an innovative maintenance architecture for the goal of 'no technically-induced aircraft operational disruptions' in European air traffic; INCEPTION (EU H2020) advancing the design of automatic flight control systems through sensor-based control laws; and PARTAKE (EU H2020) advancing digital tools for air traffic management. Automation and robotics help achieve environmental goals in a manufacturing context as well furthering autonomy objectives. Projects include CASCADE (EP/R009953/1) developing a step change in aerial robotics by addressing safety, autonomy, agility, capability and scalability; AUTORAMP (Innovate UK) developing the automation of positioning, drilling, bolting and sealing

for aircraft wing production into the Airbus assembly process; and A4BLUE (EU H2020) developing and evaluating a new generation of sustainable, adaptive workplaces.

The Theme has secured several achievements in the space sector, notably through two European Space Agency missions, G-CLASS to design an innovative radar space mission to transform our understanding of the water cycle across Europe and Africa; and F-CLASS to develop trajectory models for ESA's comet interceptor mission. There are many examples of research interactions with the Energy and Power Theme, including TURBOREFLEX (EU H2020) assessing the impact of flow addition and extraction on gas turbine performance and combustion system thermo-acoustics; and Supercritical CO_2 Waste Heat Recovery for Marine Gas Turbines (Innovate UK). The Propulsion Engineering Centre hosts the Rolls-Royce University Technology Centre (UTC) for Aero Systems Design, Integration and Performance. Through the UTC and the AIRC, the Theme has received >£5.6M for numerical and experimental projects related to aircraft and propulsion system integration; for aerodynamic studies of intakes and nozzles; for turbomachinery and compressor instability modelling; for flight simulation; open flight decks; and electric aircraft concepts, among others. Successful collaborations are in place with other original equipment manufacturers (OEMs) such as Safran (thermal system integration and landing systems research), Pratt and Whitney (high speed compressors) and the Aero Engine Corporation of China (engine gas path diagnostics, prognostics, lifting and low emissions combustion systems). Airbus has provided significant funding for research related to wing manufacture and assembly concepts, with Webb appointed to the Airbus Chair in Aero-Structures Design. In the defence sector, Dstl has funded experimental and numerical studies into convoluted intake ducts and aircraft integration; unmanned ground systems; and surveillance through competitive mechanisms. The European Defence Agency has supported research into unmanned swarm of sensor platforms; and The United States Air Force and Chungnam National University have funded research into real-time decision making for autonomous systems. Other bilateral research projects include an assessment of chemically-induced ageing mechanisms in aircraft engines (Lufthansa Technik); the simulation of integrated gas turbine systems (Siemens); an examination of airport connectivity (Thales UK); and air flow modelling for the GT-26 gas turbine engine (RWE Generation UK).

Transport Systems. Our work on connected and autonomous vehicles has grown into an international centre of excellence, securing funding from government and industrial sources. Key research projects have included TASCC: Driver-Cognition-Oriented Optimal Control Authority Shifting for Adaptive Automated Driving (EP/N012089/1); HumanDrive (Innovate UK) on the validation and end user acceptance of autonomous road vehicles; AID-CAV (Innovate UK) to develop an autonomous driving controller, accounting for the complex vehicle dynamic behaviour in limit handling conditions and exploiting the enhanced control authority available through multiple actuators and novel flexible control architecture; CORAM (Innovate UK) which examined connected on-road autonomous mobility; and ALLOYED (Innovate UK) which examined vehicle to network communications. The Department for Transport appointed Cranfield as the Independent Reviewer of the HELM UK platooning truck trial. In battery management, key projects include REVB (EP/L505286/1) for the integration of novel state estimation/control algorithms and system optimisation techniques; LISA (EU H2020) on the use of lithium-sulphur technologies to increase range and safety whilst reducing cost and charging time; LiS:FAB (Innovate UK) to develop advanced state estimation and management algorithms; ALISE (EU H2020) on the development and use of advanced lithium-sulphur batteries for electric vehicles; and Zephyr (ATI) to develop novel lithium-sulphur battery management and state estimation algorithms for UAVs. Our sensor instrumentation and development research continues under an EPSRC platform grant (EP/N002520/1) on advanced photonics.

In safety and human factors, projects include Future Sky Safety (EU H2020) using flight data monitoring data to model runway accidents; commercial research for the European Aviation

Safety Agency (EASA); the Civil Aviation Authority; Airbus Helicopters; and Rolls-Royce Germany. Collaboration across our engineering photonics and aerospace dynamics capability has led to novel fibre-optic based instrumentation for the harsh operating environment of a helicopter main rotor hub (ATI). Further collaboration has developed innovative processes for wing design and manufacturing through project WINDY (Innovate UK); and E2EEHM (Innovate UK) which uses real time aircraft and engine data to predict performance, adapt control and manage maintenance.

Manufacturing. The Theme has continued its involvement in four EPSRC Centres of Innovative Manufacturing (CIMs) in Industrial Sustainability (EP/I033351/1); Through Life Engineering Services (EP/I033246/1); Composites (EP/I033513/1); and Ultra Precision (EP/I033491/1) to drive sustainable manufacturing objectives as key targets for manufacturing operations research, whether with industry or other academic partners. Additional to the CIMs, research funding of more than £23M from UKRI and EU including more than £2M from KTP projects and >£15M from bilateral agreements with industry has been secured in this period. Key research into the 'smart' agenda have been EPSRC projects Through-life performance: from science to instrumentation platform grant (EP/P027121/1); Secure ultrasound - low cost, secure, point of care ultrasound imaging for prenatal care for India (EP/R013950/1); Manufacturing automation within the supply chain to ensure patient safety (EP/N508937/1); STRAINcomp - self-tuning fibre-reinforced polymer adaptive nanocomposite (EP/R016828/1). Innovate UK funded projects include: development of RFID to enable ATMP manufacturing, cryogenic supply chain scale-up and productivity gains with Cryogatt Systems (Innovate UK); Dynamic seat reservation and customer loyalty system with Unipart Rail Systems (Innovate UK); Metrology and digital manufacturing for servitisation of manufacturing machines with machine tool technologies (Innovate UK). Key EU H2020 projects have been LASIMM (EUH2020) on additive manufacturing cost reduction; NOSY (EUH2020) on miniaturised sensors and security; and SCORE (EUH2020) forecasting new innovative technologies; and ADMIRE (EU Erasmus+) on additive manufacturing cost reduction. Examples of industry-funded projects include with Safran Landing Systems modelling manufacturing operations; with BD Medical, modelling, and simulating factory floor operations for productivity improvements; with IN2SMART on robotics monitoring; with Network Rail; and with Petronas on the interaction of electromagnetics and nanomaterials in a porous medium for oil mobility.

Key research on the 'clean' agenda has been EPSRC projects 'T-of-PET' advanced radiation detector materials for time-of-flight positron emission tomography (EP/S013652/1); Photoelasticity for sub-surface stress measurements in structural ceramics and ceramic coating systems (EP/N018141/1); Robotic wire plus arc additive manufacture (EP/P031064/1); and the Circular Economy Network Plus in Transportation Systems (EP/S036237/1). Innovate UK funded projects include: EDEN – automated high throughput laser-based tab attachment for cans with Crown Packaging Manufacturing Ltd (Innovate UK); The Learning Camera, for contract disputes on construction sites with BAM Nuttall Ltd (Innovate UK); Flexible thermographic borescope with pyroelectric detection with Applied Materials Technology Limited (Innovate UK). Key EU H2020 projects have been SIMCODEQ, a simulation tool for a composite manufacturing process default prediction integrated into a quality control system (EUH2020). Examples of industry funded projects include with Airbus on the development of a metal 3D printer demonstrator for the International Space Station and for the United States Air Force on a study of the IN718 alloy for aerospace applications.

Key research projects around 'green' manufacturing have been the EPSRC NEWAM Programme Grant on new wire additive manufacturing for large area additive manufacturing (EP/R027218/1); Small is Beautiful 1 and 2, developing a toolkit to identify energy and resource hotspots in manufacturing (EP/M013863/1, EP/P012272/1); LOCUST, low cost, high performance copper transparent electrode materials for solar photovoltaic cells (EP/N50984X/1);

Modular system for production of heating, cooling and electricity using ejector-boosted absorption in solar concentrators (EP/P016316/1). Innovate UK projects include: OAAM, open architecture for additive manufacturing or large parts with The Welding Institute (Innovate UK); MALIT – robust lifting methods for single crystal turbine blades with reduced specific fuel consumption with Rolls-Royce plc (Innovate UK); ARCS - affordable high rate composite structures with Sigmatex (UK) Ltd, Nissan (UK) and GKN Autostructures (Innovate UK); Nano-reinforced coatings with improved thermomechanical properties with Monitor Coatings Ltd (Innovate UK). EU H2020 projects include: MULTI-FUN on the production of structures using directed energy deposition additive manufacture using multi-materials (EUH2020); ECOBULK, a circular process for eco-designed bulky products and internal car parts by promoting greater re-use, upgrade, refurbishment and recycle of products, parts, and materials (EUH2020). Examples of fully industry funded projects include; Rolls-Royce on corrosion of coatings; with MTU on corrosion life modelling; Dstl on high speed additive manufacturing; BAE Systems on developing an additive manufacturing capability; Safran Landing Systems on the design of carbon fibre composite landing gear spring components; Babcock and the Royal Navel Davenport Dockyard on through-life engineering; and the Société Anonyme Belge de Constructions Aeronautiques on advanced manufacturing. More than 10 technology translation projects via KTPs have enabled us to work with SMEs including Midland Lead Operations; Haddonstone Ltd; Garrendale; SPI Lasers; and McFarlane Telfer.

Water. Prestigious fellowships from the European Research Council on sustainable chemical alternatives for re-use in the circular economy, and contract research overseas funded by, amongst others, the Water Research Foundation in the US (on risk governance for the international water sector and on resilient water infrastructure) and with Melbourne Water (on reducing greenhouse gas emissions) expose our research community to global challenges and evidence the international standing of our contributions. We have made significant advances in understanding the dynamics of drought vulnerability (NE/L010070/1; NE/L010186/1) and the impact of drought on global communities (ES/R001049/1). Importantly, we have progressed this work to develop tools to help agriculturalists make more informed engineering decisions about their responses to drought risk and its onset (NE/N017471/1 and NE/S013997/1). Extending this work to international settings has delivered actionable research findings in South America (NE/R015759/1) and Asia (NE/N015541/1), complemented by explorations of the fundamental processes that underpin interactions between land use and hydrological regimes (NE/S01232X/1; NE/M005259/1; NE/N018753/1).

Our research leads the way in generating new understandings and technologies for resource recovery from water and wastewater engineering processes with European collaborations. This is quickly becoming an important foundational area for delivering the circular economy (EU H2020 projects on Scale-up of low-carbon footprint material recovery techniques in existing wastewater treatment plants; Towards the next generation of water systems and services for the circular economy). Supplementary work for UK water utilities at lab and pilot scale on phosphorus removal to meet tighter discharge regulations has provided additional recovery and reuse options (Severn Trent). Through our advances in membrane science, we are developing new approaches to biogas enhancement and resource recovery. Ensuring our engineering interventions benefit our communities continues to be a vital feature of our portfolio, with important contributions on the impact of rainwater harvesting in India on groundwater quality (NE/R003351/1); on disinfection by-product formation in potable water (Defra, Drinking Water Inspectorate); on the rapid monitoring of bioaerosols in urban, agricultural and industrial environments (NE/M010961/1) and the characterisation of inflammatory agents associated with bioaerosols from biowaste processing and intensive agriculture (NE/M011631/1); lab-on-a-paper techniques for point-of-use microbial source tracking (NE/R013349/2) and the transformation of water and sanitation services for the world's poorest communities (ES/R006865/1). The Kiran and Pallavi Patel Grand Innovation Award (presented to an outstanding example of innovation in

the water sector) and the International Water Association's Gold award in 'Breakthroughs in Research and Development' signal the merit and impact of our research. Positioning Cranfield Water Science Institute with a view to long-term industry transitions has allowed us to tackle some challenging topics on, for example, demonstrating synergies in combined natural and engineered processes for water treatment systems (EC) and cultivating high value strategic relationships with nationally and globally influential stakeholders (Water & Sanitation for the Urban Poor, Bill & Melinda Gates Foundation, Severn Trent and Anglian Water) as well as cementing our leadership role in international (e.g. Global Resilience Research Network) initiatives.

Energy and Power. The Theme has continued to support the global energy transition, addressing the challenges through four research centres. These consider all elements of the energy and power sector, from social engagement in future energy systems to energy distribution systems, improving energy efficiency in traditional thermal sources, driving innovation in renewable energy systems and the study of alternative fuel systems and carbon capture. Key research addressing renewable energy systems have included Solar Steam: A novel application of Fresnel lenses as a solar thermal collector to benefit industry (EP/P031072/1); Parametric study for flapping foil system for harnessing wave energy (Supergen ECR Research Fund); Centre for Doctoral Training in Renewable Energy Marine Structures (REMS; EP/L014106/1); Assessment of Crack Arrest Behaviour in Modern Structural Steels (EPSRC ICASE EP/P510464/1); Energy harvesting for electronic tracers (EPSRC ICASE EP/V519509/1); and Renewable energy integrated intelligent charging system for electric vehicles (EPSRC Researcher in Residence EP/T517306/1). Innovate UK projects include HH-Gen: High performance green hydrogen generation from solar energy – short focus parabolic cline optics CSP (SIF1 No. 79783); Low carbon heating and cooling with PCM storage and gender-based temperature-based regulation for public and commercial buildings (SIF1 No. 78689); A CSP and TFG hybrid energy system – CSP and waste heat harvesting in Nigeria (Energy Catalyst 7); with Lark Energy, Solar Steam Fresnel lens (KTP 009639); CoolerSun: creating a clean and reliable cooling, heating, water treatment and electricity (Innovate 133971); Second Life Batteries for Commercial Energy Use (Innovate 78920); Advanced grid services provided by optimised EV community and fleet charging (Innovate 81425). Key EU Horizon H2020 projects have included DESOLINATION – Demonstration of concentrated solar power coupled with an advanced desalination system in the Gulf region; SOLWARIS – Solving Water issues for CSP plants; INSHIP - Integrating National Research Agendas on Solar Heat for Industrial Processes; WASCOP - Water Saving in CSP plants. Examples of fully industry-funded projects include with Eider Investors on waste heat from gas engines; Solar Water plc – on CSP-aided desalination; Parametric investigation and optimisation of a novel ocean-going robotic platform with Autonomous Devices Ltd; with the Carbon Trust Offshore Wind Accelerator Programme on a Foundation Flange Study; and with Mobile Broadband Network Limited on Renewable energy integrated base stations and their energy management.

Key projects within thermal energy and materials have been: Flexible and Efficient Power Plant: Flex-E-Plant (EP/K021095/1); Investigating Corrosion in Supercritical Fluids (EP/S028757/1); Novel Unsteady Conjugate Cooling Mechanism (EP/T006382/1); Decarbonising Transport through Electrification, a Whole System Approach DTE (EP/S032053/1); Intelligent Grid Interfaced Vehicle Eco-charging (iGIVE, EP/L001063/1); Vehicle Electrical Systems Integration (VESI, EP/I038543/1); CO2 shipping compression, liquefaction and dehydration (EP/N029429/1); Ca looping for cement and steel industry (UKCCSRC). Innovate UK projects have included: Ultra High Temperature Nickel Powder Alloy - Laboratory Solutions to Component Level; Advanced Surface Protection for Improved Renewable Energy (ASPIRE). Key EU projects include: Preparation for Commercial Demonstration Plant for 700°C Operation (RFCS); Meeting the materials and manufacturing challenge for ultra-high efficiency pulverized coal-fired power plants with carbon capture and storage (NEXTGENPOWER, FP7); Ca looping

with extreme oxy-coal combustion conditions in the calciner (CaO_2 RFCS); Multiphase Flow Metrology in Oil & Gas Production-MultiFlowMet I (EMPIR ENG58) and Multiphase Flow Reference Metrology-MultiFlowMet II (EMPIR 16ENG07). We continue to support the US Department of Energy on the Environmental Validation of Materials and Design Concepts to Enable Operational Flexibility of Existing Coal Power Plants (DE-FE-0031749); and Component level modelling of materials degradation for insights into operational flexibility of Existing Coal Power Plants (DE-FE-0031831). Industry-funded projects include with BP for oil-water slug flows in pipelines; with EDF Nuclear for oxidation/carburisation of heat exchangers in advanced gas cooled reactors; with Porvair Filtration Systems Ltd for oxidation/sulphidation of gasifier hot gas filter components; with Siemens (UK, USA, Germany) for high temperature corrosion / oxidation of components in large industrial gas turbines; with Rolls-Royce for icing in aviation jet engine fuel systems; and with Intecsea Ltd for pseudo dry gas in-line separator research and development.

Key research projects within energy systems and strategy have been Theory of Change Observatory on Disaster Resilience (EP/V006592/1); Optimising Energy Management in Industry (EP/P004636/1), Harmonising and UPgrading GREENhouse gas removal (GGR) consequential Life Cycle Assessment (NE/P019668/1) and Grid flexibility by Electrifying Energy Networks for Airport -GREEN Airport (EPSRC Supergen Energy Networks Fund, SENFC1-023). Innovate UK funded projects including the Smart home EV charger based on Entrust Smart Home Management with Entrust Smart Home Microgrid (Innovate UK); Second life batteries for commercial energy use with Brill Power Ltd (Innovate UK); and Advanced grid services provided by optimised EV community and fleet charging with SNRG Ltd (Innovate UK).

Key research projects within our climate and environmental protection domain have been Cleaning Land for Wealth (EP/K026216/1); Combined Energy Recovery & CO_2 Removal (EP/N508615/1); Redefining power generation from carbonaceous fuels with carbonate looping combustion and gasification technologies (EP/P034594/1); Pre-commercial technology validation of a clean cold renewable syngas production plant (EP/P510336/1); Redefining power generation from carbonaceous fuels with carbonate looping combustion and gasification technologies (EP/P034594/1); UKCCSRC - The United Kingdom Carbon Capture and Storage Research Centre (EP/K000446/2); UK Carbon Capture and Storage Research Centre 2017 (UKCCSRC 2017) (EP/P026214/1); Oxy-hybrid Power Cycle with Advanced Heat Recovery Network (EP/L505845/1); Flexible and Efficient Power Plant: Flex-E-Plant (EP/K021095/1); Gas-FACTS: Gas - Future Advanced Capture Technology Options (EP/J020788/1); Application of microwaves on the production of liquid biofuels (EP/P022863/1). Innovate UK funded projects include Combined Energy Recovery & CO_2 Removal (CoERCe); Balanced Energy Networks; Peterborough Integrated Renewables Infrastructure (PIRI); HyPER - bulk low-carbon hydrogen supply by sorption enhanced steam methane reforming; with industrial funding secured for the Material development of CO_2 adsorption technologies (Aviation Works); on Machine learning for materials selection and optimisation (UKCCSRC); Waste plastic gasification with machine learning process control (Turkish Ministry of education); and the Scale up of chemical looping technologies (UKCCSRC).

Defence and Security. The current REF period has seen further development of our forensic science and technology research through the Cranfield Forensic Institute, comprising £3.5M of investment directly from Cranfield with £3.5M SEMLEP. This facility will be unparalleled in the UK. Research progress is reflected in a diverse range of grants funded by EPSRC on the development of medical instrumentation to support healthcare needs (EP/R024316/1) on point-of-care high accuracy fracture risk prediction (EP/K020196/1) and on detectors for use in industrial applications (HALO, US Department of Homeland Security). Allied to the Cranfield Forensic Institute, we are leading the Academic Resilience and Security Community (A-RiSC), a network of 30 UK universities to help Government and industry access academic experts and

the latest research and knowledge in national security. As an example, research focused on VSTOL system development and deployment has helped underpin a move to the new F-35B system whose movable jets lead to complex vortex effects when near to the ground, while also providing a core base for enhanced aero-systems education. We have continued our electronic warfare and cyber related activities at the classified and unclassified levels. Some of our unclassified work has been sponsored by MOD and Dstl and we are increasingly working in the traditional research and commercial domains on topics such as on pothole identification and management for autonomous systems (EP/R005400/1). This trend is set to continue with funding secured on topics such as copacetic smartening of small data (EP/R030987/1); on platforms for conversational agents to enhance engagement and disclosure (EP/S027211/1); and people-powered algorithms for desirable social outcomes (EP/R033382/1 in conjunction with EPSRC, GCHQ and Sunderland City Council), which examines the use of algorithmic decision making.

4. Collaboration and contribution to the research base, economy and society.

Arrangements for research collaborations

The Unit maintains formal 'ladders of engagement' with industrial collaborators (e.g., BAE Systems, Airbus, Boeing, Dstl, Unilever, Severn Trent, Bill and Melinda Gates Foundation) to facilitate strategic discussions on future research, led by members of the University Executive (PVCs). At operational levels, senior academics in the Unit maintain 'expert-to-expert' relationships liaising with Directors of Research/Chief Engineers to ensure a responsive approach to collaboration. Interdisciplinary collaborations for the Unit are pursued across the University, notably with the School of Management on technology transitions and business sector developments; and externally with a host of prestige scientific institutions.

For example, as one of only 5 universities who engage with **AWE** (£7M of business partner turnover for REF2021) at a strategic level, our partnership is underpinned by a binding agreement and a robust governance framework, enabling the agile placement of research commissions. Contracts have averaged £1M per annum over 7 years and in 2019/20, this was the highest amount placed with any university. Cranfield has benefitted from 3 AWE-funded 'William Penney Fellowships' over the REF2021 period, joint appointments to enable the free exchange of strategic information, advocacy and expertise e.g., in energetic materials, where research benefits from shared facilities, co-investment in a major explosives capability and a vibrant cohort of *ca.* 10 PhD studentships.

Our Centre of Excellence in Energetic Materials (CoEEM) is a partnership with DE&S, **AWE** and **Dstl.** In its fourth year, CoEEM forms the core of the government national governance framework in energetics and it has helped shape the new National Energetics Science and Technology Strategy. CoEEM has developed a number domain-wide collaborations and technical clubs involving over 150 scientists in over 30 organisations so far.

Cranfield is one of the few universities to have a strategic relationship charter with **Dstl** (£8.4M research funding for REF2021 period, all of which was won through open competition). The Charter was originally signed in 2014 and overseen by a Steering Board including the Defence Academy of the UK. The charter enables greater cross-working of the organisations, enhancing the sharing of information, knowledge, and expertise., as well as providing facilities for research, consultancy test evaluation and education. This is enabled through joint appointments, visiting positions and secondments on cyber security, energetics, aerospace and systems thinking. Contracts, gained through open competition, and placed by Dstl have averaged £1M per annum since 2014, including a cohort of 5-10 PhDs. Such work has also been underpinned by research grants won from EPSRC for example in cyber security. AWE and Dstl are major sponsors of the

annual Defence and Security Doctoral symposium that the Unit runs on behalf of the wider community. Initiated in 2015 (160 delegates, 16 HEIs), it has grown to include students from 21 universities and representatives from many industry partners. Dstl invested ca. £600k in aerospace research, including in experimental and computational studies of convoluted intake ducts, unmanned ground systems, the semantic compression of surveillance video based on dictionary learning and the flow physics of advanced aero-engine nozzles. All the research funding was won under open competition demonstrating that Cranfield was best placed to deliver this research.

The Unit has had a long-lasting partnership with **Rolls-Royce** (£14.9M turnover for REF2021) which, over the reporting period, has resulted in >£5.6M of direct research income. The Unit is part of the Rolls-Royce University Technology Centre network though its Aero Systems Design, Integration and Performance Centre which accounted for >£3.6M of research on systems integration, power compatibility testing, flow field measurements and cabin blower tests. In 2015, Rolls-Royce extended its commitment by investing in the AIRC; specifically, in new experimental rigs for thermal management, open flight deck simulation, aircraft configuration simulation and a capability for the structural modelling of powerplant and wing. Cranfield is supporting Rolls-Royce in developing its engine architectures for increased efficiency and reliability and is progressing the next generation of high performance environmentally-friendly engines. The unit is also an academic partner supporting Rolls-Royce's materials research in relation to coating systems, high temperature surface engineering and high temperature systems under conditions of oxidation, corrosion, erosion, and corrosion-fatigue. Over the REF2021 period, the major activities have been in the design of improved thermal barrier coatings; on the calcium-magnesium-aluminosilicate attack of these coatings; and on the high temperature corrosion performance of future turbine alloy systems. Rolls-Royce is working with Cranfield to develop an ultra-high bypass ratio geared turbo-fan engine – its next generation engine for the civil gas turbine market. To underpin this, it is necessary to develop material systems capable of working at ultra-high temperatures in adverse environments. The first exploitation of this technology is expected to be the Rolls-Royce UltraFan® product range.

The Unit also maintains on-going relationships with parts of **Siemens** in the UK, USA and Germany related to materials performance in a growing range of power generation systems. This has been active for more than 20 years through many projects and networks. Larger EPSRC contracts in which Siemens UK and Cranfield have collaborated include the Supergen 'Conventional Power Plant Lifetime Extension' Consortium (Phases 1 & 2) and the 'Flexible and Efficient Power Plant' consortium, giving 12 years of research funding supporting a series of PhD students and Research Fellows. In parallel, activities have been developed with Siemens USA from the US-UK collaborative programme on 'Advanced Materials for Low Emission Energy Systems' which started in 2003. This multi-phased networking programme has drawn funding from UK BEIS and the US Dept of Energy and has resulted in spin-off activities to tackle different energy materials related research. This relationship has resulted in many directly funded contracts to address materials related challenges in gas turbines and heat exchangers from Siemens in UK, USA, and Germany.

Similarly, the Unit maintains a strong engineering research commitment to **Airbus** (£3.3M turnover for REF2021) through ca. £1.25M of directed research on wing automation and assembly; Airbus having committed £10M of investment in the AIRC in 2015. In 2016, Cranfield became a member of the Airbus Global University Partner Programme (AGUPP) of 26 universities in 13 countries. There are currently 8 Airbus Chairs across 7 universities in the UK: Cranfield is the only one with two (**Skote, Webb**) with a third in Space and Defence (under advert). Together, we have worked on the FOAF (Innovate UK Project 113045) and AutoRAMP (Innovate UK Project 113196) projects to develop the next generation of manufacturing technologies for Airbus' future wing. Cranfield has delivered disruptive technologies deployed in

the manufacture of A320 wings at Broughton. A member of staff from the Unit is permanently seconded to Airbus to support manufacturing R&T activities. APROCONE (Innovate UK Project 113092), a project on improved methods of collaborative product design using novel information systems technologies was a case study used the Royal Academy of Engineering.

Cranfield built a relationship with **Boeing** (£1.2M turnover for REF2021) during the early 2000's based on 'flying' aircraft configuration studies which culminated in Cranfield managing the Boeing/NASA flying wing X-48B and X-48C flying wing demonstrator programme. In 2019, Cranfield and Boeing renewed their 'Working Together' Agreement to create a 'World leading Aviation System Integration (Platforms and Operations) and Technology Demonstration Hub by the end of 2025. Cranfield University was awarded a 3+2 year research grant of US$297k from **NASA** to study turboelectric distributed propulsion using Cranfield's techno-economic environmental risk assessment concept. The research quantified the performance and environmental benefits of turboelectric distribution on kerosene-fuelled and hydrogen-fuelled variants of NASA's N3-X blended wing body aircraft, relative to a kerosene-fuelled conventional tube and wing aircraft. The Unit's strategic framework agreement with **BAE Systems** (£8.1M turnover for REF2021) was signed in 2016 to establish a long-term relationship in research, education, and consultancy. Cranfield was the first of five selected universities in the UK to sign such an agreement, after BAE Systems announced it would focus on partnerships with a smaller number of universities with shared expertise in areas of future capability. BAE Systems has sponsored a Chair in Autonomy and Artificial Intelligence within the Unit. In July 2019 Cranfield and **Thales** announced plans to collaborate on unmanned aerial systems (UAS) and unmanned traffic management (UTM), aerial and ground autonomous systems, airspace data communications and digital aviation security. This has led to significant investment by Thales in DARTeC. **Babcock** is a member of the Through-life Engineering Services Centre between 2018-2021. As part of this partnership, we have successfully completed three PhD projects, with two ongoing. The collaboration has opened up new business opportunities with the Ministry of Defence and additional dissemination through the Team Defence initiative.

The Unit's 10-year strategic partnership with **Severn Trent** (£3M turnover for REF2021) was established in 2009 following a competitive process. Working through an open innovation model, the partnership has involved four staff from the Unit embedded within Severn Trent's Innovation Team as technical leads for projects and supporting activities, including business cases for research, capital investments and technology road maps. Through the partnership, the Unit has developed bespoke training and other initiatives that maximise impact from innovation projects and retain core technical knowledge within the business. As a result, the Unit has played a leading role in several national research initiatives, including in national trials for phosphorus removal, fats oils and grease control, the commissioning of Severn Trent's first thermal hydrolysis plant, full scale trials for nutrient recovery with anaerobic treatment, and coagulant recovery sludges. By March 2019, the partnership had leveraged >£3.7M on research projects through external funding (e.g., EPSRC, EU H2020) and delivered 70 projects, with >20 funded through PhD projects. From 2016 to 2019, the partnership produced 21 publications in conferences and journals and featured in Nature as a 'top 100 global corporate–academic partnership in earth and environmental science' (https://www.nature.com/articles/d41586-018-05482-6). Similarly, with **Scottish Water** (£0.9M turnover for REF2021), staff in the Unit have played a leading role in supporting drinking water research and development. Commitment to a long-term collaboration has enabled a blended funding model to finance research on disinfection by-product abatement, membrane filtration, organic matter removal, flow cytometry for microbiological water quality, new approaches to process resilience and the removal of natural organic matter using ion exchange processes. Project delivery has involved 6 PhD/EngD research students, the majority sourced from UKRI funded CDTs, and staff embedded at Scottish Water to ensure impact within business operations.

Cranfield University was appointed by the **Bill & Melinda Gates Foundation** (B&MGF) (£7M turnover for REF2021) as one of several strategic investments across their 'Reinvent The Toilet Programme', to develop a next generation solution for low cost single household sanitation. Working directly with the project team at the B&MGF for over eight years (2012-Present), staff across the Unit developed the Nanomembrane Toilet Technology (NMT) (total value $9.1M; https://www.gatesfoundation.org/How-We-Work/Quick-Links/Grants-Database#q/k=cranfield). Subsequent contracts were awarded to support technology transfer to a commercial partner via a licensing agreement (2019, $179k). Based on the tacit knowledge developed collectively through this relationship, research staff in the Unit supported a broader suite of collaborative projects developed either through the B&MGF (Williams (PI), sensor platform, $909k, 2016), or indirectly through partners such as Duke University (Bajon-Fernandez (PI), faecal sludge dewatering, $179k, 2018), and the Georgia Technology Research Institute (McAdam (PI), membrane separation, $161k, 2020). Other impacts include key contributions to the development of the new ISO30500 standard on non-sewered sanitation (published 2018 adopted in > 18 countries - https://sanitation.ansi.org/Standard/ISO30500) and the awarding of several patents. Recently, a licensing agreement has been signed between Cranfield and Jomoo (a nationally leading manufacturer and supplier of sanitary ware) to develop the NMT into a commercial product for the Chinese market. A display version of the NMT in the Bill & Melinda Gates Foundation Discovery Centre in Seattle has been demonstrated over 15,000 times since it's installation in 2018 and the technology was awarded the International Water Association's Grand Innovation Award in 2018 (https://iwa-network.org/press/18-winners-at-the-12th-iwa-project-innovation-awards/).

Similarly, the Unit enjoys close collaborative relationships with leading **Universities** that complement the engineering expertise in the Unit (notably, the Universities of Nottingham, Cambridge, Birmingham, Exeter, Loughborough, Warwick and Imperial) and this facilitates innovative proposal generation, co-supervision in Doctoral Training Centres and ideas generation to shape future UKRI calls. International research partners for the Unit are selected for their technology and industry focussed missions. Several of these are based on formal double or joint degree arrangements with 111 European institutions in 18 countries (www.cranfield.ac.uk/about/international-students/european-partnership-programme). Strategic research partners in Europe are **Université de Technologie de Compiègne Compiegne, ESTACA** Ecole d'Ingenieurs, Ecole Supérieure des Technologies Industrielles Avancées (**ESTIA**), and the **Universidad Politecnicas in Barcelona** and **Madrid**. In China, we have a newly approved Sino-UK Joint Institute in technologies for the green economy with **Jiangsu University. Purdue University** USA is a strategic partner focussed on military engineering and sustainable technologies. Water and environment are topics of our research partnership with **Royal Melbourne Institute of Technology** (RMIT), Australia and with **NTU Singapore** with whom we also collaborate on autonomous vehicle technology. Likewise, the Unit has excellent relationships with Government Departments (MoD, Defra, DfT, MHCLG, FCDO) and their executive agencies (e.g., Environment Agency, Civil Aviation Authority, Drinking Water Inspectorate) and is a repeat provider of applied research on technical policy development issues such as aviation safety, safety regulation, regulatory design, micropollutants in potable water, and on energetic materials.

Engaging with end-users to secure research impact. The Unit organises and contributes widely to agenda-setting conferences, workshops, and seminar series as a powerful means to secure impact from the Unit's research. We are frequent contributors to the Farnborough and Paris Air Shows, the International Water Association Leading Edge Technology conference and we host a defence and security research colloquium series at our Shrivenham campus. Industry clubs and topic-specific industrial consortia prove instrumental in securing pre-competitive impacts from new engineering research in the Unit. For example, the **WAAMMat industry club** (https://waammat.com/) includes BAE Systems, Airbus Group, Airbus Defence and Space,

Arcelor Mittal, Lockheed Martin, Glenalmond Group, FMC Technologies, DSTL, Thales Alenia Space, AWE, Air Liquide, Constellium, Weir Group, Gobal Robots and others; all focussed on securing impact from an EPSRC funded programme on Wire plus Arc Additive Manufacturing (NEWAM; EP/R027218/1). The club seeks to mature the technology to a level where it can be adopted for the production of components; establish a supply chain for the technology; and promote WAAM technology to potential industrial adopters. The WAAMMat programme, combined with the NEWAM programme grant and the WAAM3D spin-out (case studies) represent a fully integrated technology programme providing a rapid route to exploitation of wire based additive manufacturing from TRL1 to TRL 9. Similarly, the Unit's relationship with **Network Rail** (NR) started with the EPSRC Autonomous and Intelligent Systems Partnership, working on autonomous maintenance scheduling for track diagnostics. Network Rail is a partner in the platform grant "Through-life performance: From science to instrumentation" (EP/P027021/1) examining the relationship between sensed degradation and decision making. Network Rail appointed Cranfield as a "Linked Third Party" to deliver part of its commitments to the Shift2Rail joint undertaking, specifically on inspection regimes using vibrometry and thermography; simulations for autonomous inspection and repair; physical demonstrators for robotic inspection; unmanned ground vehicles (UGV) for inspection and repair; and self-adjusting switches and crossings (with SNCF). Total funding has been £2.1M through EPSRC and £1.16M through Shift2Rail, Network Rail and SNCF. The Cranfield Water Science Institute has had a particularly productive relationship with the **UK Centre for Ecology and Hydrology** (UKCEH) over the REF2021 period. Research funded by the EU, UKRI, and the Welsh Government has involved the monitoring and modelling of environmental conditions and rural livelihoods, the impacts of climate change on agricultural systems and the construction of vulnerability/adaptation scenarios for natural resource management. These have led to an Integrated Modelling Platform being commissioned by the Welsh Government alongside advice for the Welsh agricultural sector on alternative Brexit outcomes. Models developed through the relationship with UKCEH have been adopted by the Climate-ADAPT, a partnership between the European Commission and European Environment Agency (https://climate-adapt.eea.europa.eu/metadata/tools/climsave-integrated-assessment-ia-platform). Further impact has come through staff appointments as technical adviser to the Korean Environment Institute and to Defra's Environmental Land Management Modelling Expert Panel. Finally, a highly productive research relationship with the **US Water Research Foundation** and its participating utility members has transformed the fragmented risk management capabilities of a set of water utilities into influential corporate units, allowing these utilities to secure business value from enhanced regulatory relationships and reduced losses, making them more resilient.

Wider contributions to the economy and society, including with diverse communities. Our Engineering academics hold 98 elected Fellowships at 31 July 2020 including 5 Fellows of the Royal Academy of Engineering (FREng); 4 Fellows of the Institute of Engineering and Technology (FIET); 17 Fellows of the Royal Aeronautical Society (FRAeS); 8 Fellows of the Institution of Mechanical Engineers (FIMechE); 5 Fellows of the Institute of Physics (FInstP); and 3 Fellows for each of the Royal Society of Chemistry (FRSC), the Institution of Chemical Engineers (FIChemE) and the Chartered Institution of Water and Environmental Management (FCIWEM). Elections to overseas bodies include 2 Fellows of the American Society of Mechanical Engineers (FASME) and 2 Elected Fellows of the International Water Association (IWAF). Our ECR engineering researchers hold 18 Charterships, including CEng, CChem and C.WEM and held 162 roles on professional committees during the REF period.

Recognition of contributions to the engineering discipline are evident in the Unit's 85 Honours, Prizes and Awards secured during the REF 2021 period. The Unit hosted two out of three Queen's Anniversary Prizes for Further and Higher Education in the REF period (https://www.cranfield.ac.uk/about/rankings-and-awards/queens-anniversary-prize); one for

education and research on water and sanitation for developing countries (2015) and the other for the National Flying Laboratory Centre (2019).
Atkinson and **Gray** were awarded the CBE in the 2014 New Years' Honours, and **Pollard** the OBE in the 2020 Birthday Honours
Atkinson was elected a Fellow of the Smeatonian Society in 2017
Tatam won the International Association of Advanced Materials' Medal of the Year, 2017
McAdam was named in the Financial Times 'Top 50 Ideas to change the World' 2017, secured 1st Prize in the environmental engineering category at 'CleanEquity, Monaco 2015' and, with colleagues, the International Water Association's (IWA) Kiran and Pallavi Patel Grand Innovation Award for 2018.
Jolly was awarded the 2019 Institute of Cast Metals Engineers' John Campbell Gold Medal; **Atkinson** having been awarded the same Medal in 2016.
Williams won The Welding Institute's Larke Lillicrap Award for 2016 and the 2019 Jaeger Prize awarded by the International Institute of Welding.
Chermak received the Selwyn Award from The Royal Photography Society in 2017 and **Laskaris** won the Kenneth Harris James Prize for the best paper on an aerospace subject in 2013 by IMechE
MacManus received the AIAA Best Paper Award (2016) for his work on propulsion systems.
Competitive research fellowships were won by **McAdam** (ERC) **Kissinger** (RAEng, 2020) and **Stennett** (William Penney), **Inhalhan** (Boeing Research Fellowship, 2018-19) and **Zachos** (RAEng Industrial Fellowship 2020).

The Unit's researchers have supported the integrity of academic scholarship through 218 positions on Editorial Boards of 164 Engineering journals over the REF period, including 10 posts as Editor-in-Chief, **Jarvis** being appointed one of the Editors for Water Research (2019). As leaders in their fields, our academics have presented their research at over 250 universities over the REF2021 period, including leading international institutions such as Harvard, Yale, TU Munich, and TU Braunschweig and in France at ESTIA, ESTACA and UTC. Our researchers held key organisational roles in over 300 international conferences over the REF period. **Richardson** chaired successive SPIE Europe Security and Defence Technologies for Optical Countermeasures conferences 2015-2020; **Tsourdos** the 2016 IEEE International Conference on Unmanned Aircraft Systems; **Soares** hosted the IWA Leading Edge Technology Conference on Water and Wastewater Technologies 2019; and **MacAdam** the 10th IWA Membrane Technology Conference for Water and Wastewater Treatment in Sydney 2020; **Coulon** has been a successive Steering Committee member of AquaConsoil 2015 to 2020; and **Summer** chaired the 10th International Charles Parsons Turbine Conference, 2019. Notable keynote addresses have been made at the Australian International Aerospace Conference (**Webb**, 2018, 2019); the Global Power and Propulsion Forum, Zurich (**Pachidis**, 2017); and The International Water & Climate Forum, San Diego (**Pollard**, 2015).

Interdisciplinary research and support for national and international agendas. Staff in the Unit are active contributors to Government policy guidance, national and international advisory committees and scientific fora that exist to secure consensus on various research agendas. **Ringrose** chairs the statistical computing section of the Royal Statistical Society; **Appleby-Thomas** chairs the IoPs Shockwaves in Extreme Conditions Group; **Tyrrel** is the principal UK expert on CEN TC264/WG28 on Ambient bioaerosols; **Pachidis** Chair of the ASME/IGTI Cycle Innovations Committee 2015-2017; **Tsourdos** Chair of the Federation of Automatic Control's Aerospace Technical Committee since 2015; **Coulon** Vice Chair of the Academic group of the EU Network for Industrially Co-ordinated Sustainable Land Management in Europe); **Jarvis** supported WHO guidance on microplastics in drinking water; **Gray** is a member of the Prime Minister's UK 'Jet Zero Council' (2020), of the ATI Technology Advisory Group and chairs the Royal Society of Edinburgh's Business Innovation Forum; **Atkinson** CBE FREng Chaired a Task Group on Specialist Engineering Skills instigated by Prof John Perkins, then Chief

Scientific Advisor to Business, Innovation and Skills; **Stephenson** is a member of the RAEng Research Committee (2019-) and a jurist on the nominating committee for the Singapore Lee Kuan Yew international Water Prize; **Atkinson** was an elected member of the RAEng Council to 2016; and **Jolly** is an elected Trustee and Board member of IOM^3 (2019-). Academics in the Unit also serve widely on research proposal review committees, acting as Deputy Chair of the Strategic Advisory Board of the Henry Royce Institute (**Atkinson**); chairing EPSRC's Engineering Panel (**Pollard, Jolly**); supporting EPSRC's Strategic Research Equipment Panel (**Atkinson**) and Expert Panel for the Tier 2 National Computing Centres (**Savill**); serving on the RAEng Research Fellowships Panel (**Pollard**); the French National Research Agency's Scientific Committee (**Coulon; Dossi**) and supporting the Dutch Research Council (NWO) Sustainable Water Technology committee (**Stephenson**).