Institution: University of Manchester

Unit of Assessment: UOA12b Mechanical, Aerospace and Manufacturing Engineering

a. Overview

The 39 members of staff (34.38 FTE) returned in Mechanical, Aerospace and Manufacturing Engineering are drawn from the Schools of Mechanical, Aerospace and Civil Engineering (32.38 FTE) and Materials (2 FTE), two of 9 schools in the Faculty of Engineering and Physical Sciences.

Research in the Unit is organised around themes that address multidisciplinary challenges of industrial and societal importance: *Nuclear Engineering*, *Innovative Manufacturing*, *Aerospace Engineering*, *Climate Change*, and *Bio-engineering*. These themes are underpinned by a cross-cutting theme in *Modelling & Simulation*, and discipline-based research groups in *Fluids*; *Manufacturing; Solids*, *Dynamics & Materials*; and *Project Management & Climate Change*. Reflecting the multidisciplinary nature of these challenges, members of the Unit are also active members of Institutes and Centres that bring together strengths from across the University, particularly: Tyndall Centre Manchester (TM), Sustainable Consumption Institute (SCI), Aerospace Research Institute (UMARI – Director Soutis), Dalton Nuclear Institute (DNI), Photon Science Institute (PSI), and Manchester Institute of Biotechnology (MIB). Significant achievements in the REF period include:

- Providing new insights into the effects of irradiation on graphite, contributing directly to extending the life of the UK Advanced Gas-cooled Reactor (AGR) fleet, and underpinning a Queen's Anniversary Prize, 2011;
- Developing the world's most powerful optical microscope, with 50 nm white-light resolution;
- Developing laser cleaning technology, adopted for diffusion bonding applications by Rolls-Royce and BAE Systems;
- Chairs, lecturers and fellows sponsored by Office for Nuclear regulation, EDF, Rolls-Royce, and Technology Strategy Board.
- Elected fellowships and prizes: Ainsworth (FRS, Welding Institute Brooker Medal), Lin Li (FREng, RAEng Frank Whittle Medal), Launder (Nusselt-Reynolds Prize), Hayhurst (Institute of Materials, Minerals and Mining Griffith Medal and Prize)
- £21.0m research income, 77 keynote addresses, 840 papers in international journals, 44% of recent outputs amongst the 10% most cited in the field.

b. Research strategy

Vision

Our focus is on major challenges of industrial and societal importance. To address these we maintain strengths across a broad range of engineering disciplines, engage with users of research to frame our research agenda, and establish multidisciplinary collaborations to draw on relevant expertise from across the academic spectrum. Our approach combines large-scale computational modelling and simulation with state-of-the-art experimentation – from nano- to macro-scale.

Strategic Planning

UoA research strategy is developed by a Research Committee led by a Director of Research, supported by a Head of External Affairs. Each Theme has an academic lead, who is responsible for developing a strategy for their theme, and is a member of the Research Committee. Similarly, each Discipline Group has an academic lead, who is responsible for staff development and is also a member of the Research Committee. The Committee consults widely with researchers in the unit via a range of mechanisms, including annual away-days. It also seeks input from Industry Panels for Centres and Institutes with which the UoA is associated, typically on a regular basis.

The context for the UoA research strategy is set by a University Strategic Plan that includes: valuing research excellence for its own sake, investing strategically in research excellence, broadening the range of funding sources, giving parity of esteem to translational research, and providing world-leading postgraduate research training. UoA and Faculty strategies are public documents that are refreshed in an annual planning and accountability cycle that includes a formal performance review for each unit, against agreed key performance indicators (KPIs). Current KPIs

include research income, industrial research income, PGRs and PDRAs per member of staff, and proportion of outputs in the top 10% of outputs in the field.

UoA Themes also contribute to broader University strategic priorities through involvement in multidisciplinary Institutes/Centres as follows: *Nuclear Engineering* (DNI), *Innovative Manufacturing* (DNI, PSI), *Aerospace Engineering* (UMARI), and *Climate Change* (TM, SCI). *Aerospace Engineering*, *Climate Change and Innovative Manufacturing* were well-established at RAE08 and remain core activities, but *Nuclear Engineering* has grown significantly over the period, as the result of strategic investment and engagement with industry, and is now a major activity. *Bio-engineering* is an emerging strength, following more recent investment, and is an area we intend to grow over the next assessment period. Research across all Themes ranges from applied industry-facing to blue skies; both are encouraged.

A key objective is to carry out research of the highest quality and disseminate it effectively through leading outlets. We have published 840 papers in international journals in the assessment period. As a broad indicator of progress since RAE08, the proportion of University of Manchester (UoM) papers amongst the 10% most cited in the field of mechanical, aerospace and manufacturing engineering rose from 27% in 2008 to 44% in 2011 (most recent year with reliable citation data), and those amongst the 25% most cited from 56% to 80%.

Research Theme Strategies and Progress

Nuclear Engineering is led by Mummery (materials), with leadership team Ainsworth (structural integrity), Smith (welding), Abram (fuels) and Iacovides (thermal hydraulics), and 10 other staff. We have delivered on our strategy outlined in RAE08 to expand nuclear engineering, investing in new staff and facilities and setting up several specialist centres with external funding: *Modelling and Simulation Centre* with EDF funding, *Centre for Nuclear Engineering Technology* with North West Development Agency (NWDA) funding, and a *Rolls-Royce University Technology Centre* (UTC). We undertake research in nuclear fuel and reactor technology, structural integrity, manufacturing, decommissioning and waste disposal. Major consultancies on thermal hydraulics were undertaken for Magnox and EDF. Overall, our income in this area including related manufacturing has risen to £12m. Notable achievements in the REF period have included: new insights into the effects of irradiation on the structure of graphite moderator cores, allowing the life of AGRs to be extended; predictive modelling of thermal hydraulics in reactor Hot Box Domes, providing new insight into behaviour in both normal operation and during shut-down.

Innovative Manufacturing is led by Lin Li (laser processing, photonics and advanced manufacturing), with Mativenga (multi-scale and sustainable manufacturing) and other 6 staff. As well as having a key role in nuclear manufacturing, the Theme has expanded activity at micro/nano scales based on laser processing, optical imagery, electro-discharge machining and mechanical milling, covering industries as diverse as aerospace, automotive, medical, security, and domestic appliances. Sustainability and energy efficiency are key themes. The shift, planned at RAE08, from macro to micro/nano scales, with emphasis on design, fabrication and inspection is reflected in significant outputs in the area. Notable achievements in the REF period have been: the invention of the world's most powerful optical microscope, with virtual imaging at 50 nm – now used for imaging viruses and selected by RCUK for inclusion in their Big Ideas for the Future 2011 report; advances in laser cleaning technology with application in diffusion bonding, adopted by Rolls Royce and BAE Systems.

Aerospace Engineering is led by Soutis (structures), with Laurence (aerodynamics) and 13 other staff, and is part of the UMARI portfolio. Research covers a broad spectrum, including unmanned aerial vehicles (UAVs), efficient turbo-machinery, boundary layer control, vibration reduction, novel materials, and efficient manufacturing, with fundamental strengths in computational fluid dynamics and multi-physics. There are strong links with Rolls Royce and BAE Systems. Notable achievements in the REF period include: major advances in modelling and strengthening composites, including inkjet printing of nano-modified polymers; modelling of whole aero-engines with non-linear bearings, leading to more reliable designs for reducing vibration; efficient and accurate turbulence modelling based on statistical averaging, allowing practical applications in complex dynamic geometries, such as turbine blades.

Climate Change and carbon emissions is led by Bows in this UoA, with Gilbert, and is part of the Tyndall Manchester research portfolio. Research focuses on the contribution of transport,

particularly aviation and shipping, to carbon emissions, and involves significant engagement with national/international debate and policy makers. A notable achievement in the REF period has been to demonstrate through modelling that, contrary to previous assumptions, air and sea transport are set make a major contribution to carbon emissions over the next decades, directly influencing the decision of the UK Government to include aviation in the commitment embodied in the Climate Change Act 2008 to reduce carbon emissions by 80% by 2050.

Bio-engineering is led Alonso Rasgado with 3 other staff. This activity, which was initiated in the REF period, has built partnerships, won EPSRC grants, and is training significant numbers of PhD students. Important collaborations have been developed with the Manchester Institute of Biotechnology, the Department of Plastic and Reconstructive Surgery at Wythenshawe Hospital, and with the Christie NHS Foundation Trust. Research has been established in biomechanics, bio-fluid modelling, cell and tissue engineering, and assistive technology. Notable achievements in the REF period include new insights into the biomechanics of locomotion, with unexpected findings for the locomotion of elephants.

Modelling and Simulation is led by Yates, with Laurence and 14 other staff. It was established in 2008, with support from EDF for a Chair and Research Fellow, to develop large-scale computational capability in solid and fluid mechanics, principally for N*uclear Engineering*. It has developed over the REF period to underpin research across all the other themes in this UoA, and acts as a focus for interaction with industry including EDF (support for 16 PhD/EngD students), Rolls-Royce and others. Notable achievements in the REF period include advances in turbulence modelling combining large zone statistical averaging (RANS) with localised direct modelling of turbulent structures (LES – large eddy simulation) to simulate extreme fluctuating stresses and thermal loading, together with synthetic eddy modelling (SEM) to incorporate input turbulence. This underpinned the modelling of AGR hot box domes, and SEM has now been applied to simulation of flows in tidal stream turbines (UoA 14).

Future Plans

Our future strategy is to consolidate and grow research in *Nuclear Engineering*, *Innovative Manufacturing,* and *Aerospace Engineering*, whilst continuing to develop *Bio-engineering* capability, and exploiting opportunities to contribute to University-wide endeavours in Climate Change and sustainability. In Nuclear, multidisciplinary University research centres cover the full life-cycle from reactor design and operational safety, through to radioactive waste and decommissioning, under the umbrella of the DNI, and we will continue to benefit from University and industry investment. In aerospace, research on efficient turbo-machinery is highly promising and is set to accelerate with industry collaboration. The same applies to UAVs where the potential is high and industry interaction strong. In Innovative Manufacturing, we will continue to develop novel laser, EDM and ECM processing methods, but emphasis will continue to shift towards micro/nano fabrication methods, and sustainable manufacturing. In *Bio-engineering*, we will continue to build capacity and research quality, working with others as part of an emerging institutional strategy for healthcare technology.

Large-scale computational modelling is key to improving engineering analysis at a fundamental level. This is quite mature in the individual disciplines of fluid mechanics and solid mechanics with the scope of applications increasing as predictions improve and confidence increases. However, complex coupled fluid-structure interaction problems present a challenge where we expect progress over the next period, particularly through exploiting our expertise in smoothed particle hydrodynamics (SPH). Validation is vital for complex, e.g. high strain rate, high temperature, multi-phase, problems and Manchester is equipped with excellent laboratory facilities. Massively parallel computing is essential and novel efficient and inexpensive parallel computing through GPUs (graphics processing units) is an exciting avenue for research, already followed for SPH. Manchester intends to be at the international forefront in computational modelling and validation.

c. People

(i) Staffing strategy and staff development

Staffing Strategy. Our staffing strategy over the period has been to recruit and deploy staff across the core disciplines in the UoA to underpin our cross-cutting thematic approach and, given the multidisciplinary nature of our themes, open up interfaces to disciplines outside the UoA. Specific objectives have been to grow *Nuclear Engineering*, strengthen *Innovative Manufacturing*,

particularly at the interface to Nuclear, maintain strength in *Aerospace Engineering*, and build capacity in *Bio-engineering* and *Modelling and Simulation* (both through direct appointments and through targeted appointments in other Themes). Appointments have been made at all levels, including to key leadership roles; details (with external sponsor where relevant) are as follows.

Nuclear Engineering: Chair in nuclear fuel technology (Abram, Westinghouse); Chair in nuclear materials (Mummery*, Office for Nuclear Regulation – ONR); Chair in structural integrity (Ainsworth, BNFL endowment); Chair in deep waste disposal (Jivkov*, BNFL); Lecturer in nuclear graphite (Hall, ONR); Lecturer in nuclear graphite decommissioning (Jones); Lecturer in thermal hydraulics (Cioncolini*). *Innovative Manufacturing:* Chair (Smith M*) and Senior Lecturer (Francis) in welding technology, both with a strong nuclear emphasis; Lecturer in electro-chemical and electro-discharge machining (Diver); Lecturer in micro-replication (Griffiths); Lecturer in micro-machining, machining science and technology (Heinemann); Lecturer in bio-manufacturing (Weightman). *Aerospace Engineering:* Chair in aerospace structures specialising in composites (Soutis* - also Director of UMARI and the NW Composites Centre); Lecturer in aerospace systems (Hollingsworth); Lecturer in spacecraft propulsion and design (Smith K). Also a cognate lecturer (Katnam) returned in UoA 14. *Climate Change*: Senior Lecturer, now Reader in energy and climate change (Bows); Lecturer in climate change (Gilbert). *Bio-engineering:* Lecturer in musculo-skeletal modelling (Ren); transfer of two existing staff (Mandal – UoA 14, Zou) into biomechanics and cell and tissue engineering. *Modelling and Simulation:* Chair in solid mechanics modelling (Yates, EDF), with 5 new appointments (marked *) also contributing to the cross-cutting Theme.

Career Development. Staff at all levels are encouraged to develop their skills. For, research staff, the EPS Faculty Researcher Development Programme provides over 70 training workshops and events each year in 5 categories: Research & Enterprise, Communication, Career Management, Leadership and Management, and Teaching and Learning. For example, the 2011/12 programme included Project Management courses (leading to a Certificate in Applied Project Management), and the 2012/13 programme introduced a course on Supervising for Researchers. Since the programme was introduced in 2011/12, research staff have participated in training events 53 times. The website *An Academic Career*, developed by the UoM Careers Service, is a comprehensive guide to working in higher education and was the winner of the Times Higher Education 2011 Award for Outstanding Support for Early Career Researchers.

All new academic staff undertake the New Academics Programme, which involves around 50 contact hours over an 18 month period, and a collection of associated mentoring and development activities. The research elements include grantsmanship, managing a research portfolio, publication strategy, and postgraduate recruitment and supervision. Also, recognising the importance of knowledge transfer and non-academic impact, the programme covers intellectual property rights, collaborating with industry, regional development and public engagement. New members of staff are introduced to key people, policies and resources through a school induction pack, and new academics have a personal mentor within the school, as well as a mentor associated with the New Academics Programme. New staff are also provided with travel funds. A senior member of staff (Hayhurst) takes responsibility for mentoring staff in relation to promotion.

For more senior staff, the University offers the Headstart leadership development programme (Leadership Foundation for Higher Education), preparing research leaders for more senior academic roles. Two members of staff have completed this in the review period.

To review career development and plans, the university implements a Performance Development and Review (PDR) scheme, which includes a written preparation document, a one-to-one discussion, and an agreed written conclusion. All staff, whatever their level of experience, are expected to have an annual PDR.

Concordat to Support the Career Development of Researchers. The university has developed a Concordat Implementation Plan that has received an HR Excellence in Research Award from the European Commission. The University participated in the Careers Research Online Survey 2011 to find out the views of research staff and has incorporated the results into the Concordat Implementation Plan, especially through improving research staff representation on University committees and expanding training opportunities (see above). The UoA also has an active programme supporting promising researchers to apply for personal fellowships, providing bridging funding, and tenure-track appointments for successful candidates.

Research Fellowships. During the assessment period, the following staff have held competitive personal fellowships (with funder; outcome): Bows (SCI; Reader, UoM), Heinemann (Leverhulme; Lecturer, UoM), Jivkov (BNFL; Research Lecturer, UoM), Rigopoulos (Royal Society; S. Lecturer, Imperial), Jaworski (EPSRC; Chair, Leicester).

International Staff Appointments, Visitors and Sabbaticals. The school is an international community. For example, 46% of our academic staff, 63% of our research staff and 61% of our research students originate from outside the UK. Reflecting the strong international profile of the school, 6 of the 19 academic appointments made during the REF period were from outside the UK.

To foster new collaborations and share best practice, the UoA has an extremely active visitor programme. During the REF period, 86 people from overseas held visiting positions in the UoA. These included visitors from 14 international universities and from a wide range of commercial organisations.

The UoA also runs a sabbatical scheme; during the REF period, 25 staff have been on sabbatical for periods ranging from a semester to a year, visiting international universities, research institutes, and industry.

Equality and Diversity. The University is committed to the advancement of equality in employment and career development for its staff, and equality data monitoring and action planning is embedded into annual performance reviews. All staff are encouraged to undertake equality and diversity training, and 45 did so in the assessment period. All those involved in recruitment and promotion panels are required to undertake more specialised training – 30 in the period.

WiSET (Women in Science, Engineering and Technology), formed in 2005, is a network for all female students and staff in the EPS Faculty. It is funded by the Faculty and aims to encourage more women to enter and develop careers in science, engineering and technology. There has been an improvement in the gender balance of the UoA with 4 women submitted in this exercise compared to 2 in the equivalent grouping in RAE08.

To ensure that all groups are well equipped to engage with the promotions process, Academic Promotions Masterclasses are held annually. These sessions provide an overview of the academic promotion route at the University, the role of the School and the Faculty Promotion Committees, CV hints and tips (with the offer of 1:1 guidance), and academic promotions case studies.

(ii) Research students

The unit sees the development of the next generation of researchers as central to its mission. Over the period our PhD graduations per annum have remained stable, with 182 (159.13 FTE) awards in total, but we have increased our participation in Doctoral Training and EngD Centres (Manchester Doctoral College in Engineering for Manufacture, Nuclear First DTC, Nuclear Engineering DTC), providing 23 students with the extended training experience those schemes deliver, and enhancing the UoA's engagement with industry and other disciplines. Funding for research students is from a variety of sources, reflecting the fundamental-to-applied research portfolio of the UoA, with students receiving funding from: EPSRC DTG (6%), CASE (5%), EngD/DTC (11%), industry (7%), EPSRC project (10%), UoM (16%), overseas (45%).

Recruitment. The unit has a Student Recruitment and Admissions Office that manages publicity and student recruitment. The unit seeks to attract the highest quality candidates by advertising projects widely on www.findaphd.com and on its own web site, as well as actively promoting research opportunities at graduate careers events. The University International Office also attends many overseas recruitment events, and uses local agents to promote and triage applications. UoM-funded President's Scholarships and Dean's Scholarships, advertised internationally, are designed to attract elite students with an enhanced training package and stipend; the UoA has benefitted directly from 2 of these awards since they were introduced in 2011, and indirectly from a resulting improvement in the quality of applicants. The UoA receives applications from all over the world (normally ~70% overseas). Applications are made online, to ensure efficient processing, and all applicants meeting a strict entry threshold are interviewed, sometimes using Skype or telephone if overseas.

Training and Support. Every research student has a supervisory team consisting of a main supervisor, a co-supervisor and an advisor; the two supervisors are responsible for technical guidance and progress, whereas the advisor is principally responsible for mentoring and pastoral support. Specialist courses are drawn from the School of Mechanical and Aerospace and Civil

Engineering' s extensive portfolio of MSc courses. Skills training is provided by the Researcher Development Programme (shared with research staff), offering a broadly based foundation in reusable skills (more than 70 workshops per annum – see above), including topics specifically aimed at research students such as: managing PhD progression, working with your supervisor, thesis writing, viva preparation, library and IT use, and PhD careers. Research students have participated in training events 930 times over the assessment period.

Postgraduate Research Poster Display days are a highlight of the year. These are attended by industrial sponsors and provide both an opportunity for students to place their work in a broader context, and preparation for conference participation. Prizes are awarded to the best posters. Students are expected to present at one international conference at least during the course of their degree, and are funded to do so. For the most promising students, UoM offers EPSRC-funded Doctoral Prize (was PhD+) awards, that support successful applicants for 6 months to 1 year in the transition to independent researcher.

Progress Monitoring. The online progression monitoring system, eProg, provides all research students with direction on the critical milestones for their degree. eProg captures engagement with training, and includes quarterly progress reports with elements completed by students and supervisors. Prior to progression to a new year of study, each student provides a written report that describes their progress and plans, and both gives a presentation and is interviewed by a panel. Where progress towards a PhD is not considered appropriate, there are exit points to research masters degrees.

d. Income, infrastructure and facilities

Research Income

Research income for the UoA totalled £21.0m for the REF period, increasing by 60% between 2008-09 and 2012-13. Over the period funding has come from a range of sources with the main contributions RCUK (25%), Central Government (44%), EU (9%), and industry (20%, including EDF, BP, Rolls-Royce, Westinghouse, BAE Systems), giving a reasonably balanced and sustainable portfolio, though large awards have resulted in shifts in the balance from year to year. As a result of our investment in capacity-building, *Nuclear Engineering* income rose by 45% between 2008-09 and 2012-13, totalling £7.1m, and *Innovative Manufacturing* (with a strong nuclear bias) by a factor of three, totalling £7.5m over the same period. Modelling and Simulation grew by 28%, totalling £1.7m in direct funding, but also played a significant part in other funded grants, again as a result of our investment. Funding for Aerospace remained roughly constant during the period, totalling £3.2m, whilst *Climate Change* and *Bio-engineering* grew, from a standing start in this UoA, to generate income totalling £1.3m. Over 70 consultancies with a total value of £570k were also undertaken during the period, often pump-priming research collaborations. These funding outcomes demonstrate a significant and successful reshaping of the UoA over the assessment period, to align with our strategic objectives.

Our future funding strategy will be to maintain a balanced portfolio, with respect to both funding sources and Themes, over a 5 year cycle, with an emphasis of further increasing industry and EU funding.

Infrastructure

The University's estate is the largest single campus of any Higher Education institution in the UK providing 850,000 m^2 with a replacement value in excess of £2b. Since 2004 the University has completed a £750m capital investment which has transformed a major part of the estate providing state-of-the-art buildings, contemporary refurbishments and public realm works fit for a 21st century research HEI. The University has recently begun work on a new Estates Masterplan, including an investment of £250m (funding secured) to collocate all engineering and science on a single campus by 2018.

The UOA is presently housed in the George Begg and Pariser buildings, which are a short distance apart. Members of staff, including research fellows, have individual offices, clustered according to research activity; research students are in open-plan 'villages', two in Pariser and one in George Begg. Research associates are either in a village or a room close to their laboratory. There are rooms for video conferencing, seminars and meetings. Both buildings have a small café ideal for informal meetings and networking.

Facilities

These buildings house excellent laboratory facilities, supported by a large workshop with standard machining and a CNC machine. There are three wind tunnel laboratories for research, a dynamics laboratory, an impact testing laboratory, a thermal hydraulics laboratory with four rigs (funded by EDF, Magnox and the NW Development Agency – NWDA), laboratories for structural testing with two Instrons, and laboratories for nuclear graphite research and nuclear fuels. The Laser Processing Research Centre houses internationally leading facilities with the widest range of high-power laser processing facilities in the UK, recently upgraded with £1.9m funding from EPSRC and NWDA. Over the past three years the UoA has invested just under £200k in establishing bio-engineering and bio-mechanics gait laboratories, enhancing the robotics and nuclear fuels laboratories, and expanding office space for Tyndall Manchester.

Advanced nuclear manufacturing technology research laboratories, including laser processing, welding, and structural and weld-testing facilities, are housed in the basement of the nearby Sackville Street building, established with £8m funding from BIS and NW Development Agency (NWDA), with state-of-the-art manufacturing and material characterisation facilities as part of the Nuclear Advanced Manufacturing Research Centre (AMRC) with Sheffield University.

In addition to these facilities on the main campus, the University has invested £10m in the Dalton Cumbria Facility (DCF) with £10m from the NWDA. The DCF is unique within the EU, housing state-of-the-art irradiation facilities, including a 5 MV tandem accelerator and self-contained cobalt-60 gamma irradiator, dedicated analytical chemistry and environmental and material science laboratories, and a computer modelling suite. A major application for this UoA is in studying the effects of irradiation on graphite moderator cores.

The UoA also makes use of extensive facilities available in University multi-disciplinary Institutes and Centres: the Manchester Institute of Biotechnology, and the Bio-materials Centre (UoA 13), in *Bio-engineering*; the NW Composites Centre (UoA 13), with Instron and non-destructive testing, in Aerospace; the Photon Science Institute, with state-of-the-art laser facilities, in *Innovative Manufacturing*. Equipment sharing is facilitated by the common N8 database.

For computational modelling, parallel processing is an essential resource and the School has invested £475k in 950 cores on the University's Computational Shared Facility; it also has access to the 5200 core N8 HPC facility, and makes extensive use of the national facility HECTOR for parallel processing with 1000s of cores. On EDF projects use is often made of their Blue-Gene parallel processing facility also with 1000s of cores.

As a designated National Research Library, the UoM Library offers a range of tailored products and services, providing access to an unparalleled range of electronic resources including over 40,000 e-journals and a complete range of research databases. Through Manchester e-scholar, it offers researchers a premium resource to both deposit and disseminate research outputs; it also provides researchers with a comprehensive research data management service, launched in 2013. The Library also delivers a range of bespoke training services to researchers, supporting all aspects of the research life-cycle.

e. Collaboration and contribution to the discipline or research base

Collaboration

The multidisciplinary nature of the challenges represented by UoA's research Themes mean that collaboration is fundamental to our research. Collaborations cover the complete spectrum: large-scale collaborations with other UK HEIs, international collaborations with centres of excellence, interdisciplinary collaborations to tackle broad industrial and societal challenges, and collaborations with users of research to frame our research agenda and drive impact. As an indication of the success of our approach, 21% of the outputs in this return involve an author from industry, 21% from another discipline (in UoM), 20% from another UK university or research organisation, and 24% from outside the UK.

Supporting research collaboration. The UoA has a wide range of mechanisms to support and encourage collaborative research. These include a visitor programme (86 visits of more than 3 months during the REF period), a sabbatical programme (around 25 sabbaticals during REF period), and active encouragement to take up visiting chairs (11 in the REF period in Universities in China, Korea, USA, Norway, and France). The University provides a dedicated service to support researchers in applying for EC funding and, as a member of the N8 partnership of research

intensive universities, proactively explores opportunities for collaboration (eg N8 HPC, supporting high-end computational modelling and simulation). The UoA has also developed long-term strategic relationships with users of research (eg EDF, Rolls-Royce, ONR, BAE Systems, Westinghouse), establishing partner-of-choice status.

Supporting interdisciplinary research. All the mechanisms described above for supporting research collaboration in general, apply to interdisciplinary research. In addition, the University provides direct support via its multi-disciplinary Research Institutes, which provide a cross-institutional focus for challenge-led research. As outlined previously, Tyndall Centre Manchester, the Sustainable Consumption Institute, the University of Manchester Aerospace Research Institute, the Dalton Nuclear Institute, the Photon Science Institute, and Manchester Institute of Biotechnology (MIB) are all of direct relevance to this UoA. There is also an overarching University of Manchester Research Institute, that provides seed-corn funding (around £1m pa) to support new interdisciplinary collaborations. Financial and administrative arrangements are also designed to remove barriers to cross-institutional collaboration, with a unified Research Support Service across the institution. The UoA's participation in multidisciplinary Doctoral Training and EngD Centres, provides another route for seeding collaboration, with joint supervision (across disciplines, or with industry) compulsory.

Examples of Collaborative and Interdisciplinary Research

National collaboration. A prime example of a major national collaboration is our partnership with Sheffield in the Nuclear Advanced Manufacturing Research Centre, with £8m TSB funding to Manchester. Another example is our participation with 9 other universities and major UK aerospace companies (Rolls-Royce, BAE Systems, GKN, Bombardier) in the SAMULET project to develop affordable environment-friendly manufacturing technology. We are also one of ten universities in the FLAVIIR project on UAVs, managed by BAE Systems, with EPSRC funding.

International collaboration. International collaborations have been pursued via the FP7 programme. For example, CARBOWASTE is a 28-partner (academic and industry) project on the treatment and disposal of irradiated graphite and other carbonaceous waste. FANTASIA is an EU project 18-partner project to develop generative manufacturing and repair processes for complex-shaped aero-engine parts, involving universities and industry partners (including Rolls-Royce and TWI in the UK).

Interdisciplinary collaboration. All the UoA's research Themes, are fundamentally multidisciplinary, and are pursued in collaboration with colleagues in other disciplines. For example, our research in *Nuclear Engineering* involves working with materials scientists, physicists, chemists, computer scientists, and earth scientists, to meet the challenges of safe operation, decommissioning and waste disposal. Our research in *Bio-Engineering* is also fundamentally multidisciplinary, bringing together expertise in engineering measurement, computational modelling, cell biology, and clinical medicine.

Collaboration with users. Much of the UoA's research involves collaboration with users of research; several examples have already been given under other headings. As noted above, we have strategic relationships leading to multiple projects with EDF, Rolls-Royce, ONR, BAE Systems, Westinghouse and others. Another leading example is our collaboration with the Office of the Nuclear Regulator, where our research on the effects of irradiation on the microstructure graphite has provided new insights into nuclear safety. In Climate Change, we have collaborated with government agencies and NGOs, to influence public policy, providing the scientific evidence that led to the inclusion of aviation the 2008 Climate Change Act, and subsequent recognition by government that shipping should also been included.

Impact of collaborations on research activities and strategy. Our research strategy is fundamentally aligned with industrial and societal priorities, with Themes that address the challenges of specific industry sectors. Over the REF period we have developed our capability to support these Themes, in consultation with, and often funded by, our partners. Much of our research involves collaboration with users of research, and that interaction helps to shape our research strategy and tactical decision-making. Through long-term strategic relationships with companies, we have more formal mechanisms for developing a shared research agenda, though joint governance Boards. We also invite industry partners to participate more broadly in the life of the UoA, interacting with research students at postgraduate poster display events, and advising the

Research Committee on overall research strategy for the UoA.

Contribution to the discipline and research base

At the highest level contribution to the research base has been recognised by elections as Fellow of the Royal Society in 2009 (Ainsworth), as Fellow of the Royal Academy of Engineering in 2013 (Lin Li) and as Fellow of International Academy for Production Engineering in 2008 (Lin Li).

Recognition for notable contributions to the research base has been through major awards: Nusselt-Reynolds Prize 2013 (Launder); RAEng Sir Frank Whittle Medal 2013 (Lin Li); Institute of Materials, Minerals and Mining Griffith Medal and Prize 2011 (Hayhurst); Welding Institute Brooker Medal 2010 (Ainsworth). The Queen's Anniversary Prize, 2011, to the Dalton Nuclear Institute made particular reference to research on graphite in the UoA.

Because of their reputation in research UoA members have been on external advisory boards including The Welding Institute (Ainsworth), UK Technical Advisory Group on Structural Integrity (Ainsworth), Office for Nuclear Regulation (Marsden), and have given evidence to six government committees on climate change (Bows). Internally engagement with users of research is delivered through advisory boards of the industry funded Centres.

UoA members have contributed to many international and national learned societies including: College International pour la Recherche en Productique (Hinduja), European Research Council panels (Hayhurst); Royal Society committees: Geo-engineering (Launder), International Joint Project(Hayhurst); committees for EPSRC Frontier Engineering (Soutis), European Union FP7 (Kontis), American Institute of Aeronautics and Astronautics (Kontis), Agence National de al Recerche France (Kontis)**,** Advisory Council for Aviation Research and Innovation in Europe (Kontis), Aerospace Council (Kontis), Institution of Mechanical Engineers (Soutis), European Academies Science Advisory Committee Energy Steering Group (Ainsworth).

There is considerable leadership in the broad research base through journal editorial panels. UoA members are editors of Int J Pressure Vessels and Piping (Ainsworth, Editor-in-Chief), Int. Journal Heat & Fluid Flow (Launder, Editor-at-Large), Int J Fatigue and Fracture of Engineering Structures and Materials (Yates until 2011). Staff hold positions on 47 editorial boards including Phil Trans Roy Soc A (Launder).

Dissemination of research is made through international conferences and the UoA has played a leading role by hosting the following successful conferences at Manchester: 36th and 37th International MATADOR Conference (2010 and 2012) on Manufacturing Processes, Technology, Systems Design and Integration, Metrology and Management (Lin Li and Hinduja); 28th Int. Symp. Shock Waves 2011 (Kontis); 1st Int. Conf. Protective Structures 2010 (Q Li). Members have also given 78 keynote presentations at international conferences in the REF period.

Dissemination of research and practice is also enabled through the delivery of Continuing Professional Development (CPD) courses. Courses delivered in the period include: CFD-Computational Fluid Dynamics, Nuclear Graphite technology, Laser Material Processing, Machining, Aircraft Flight and Performance, Impact and Blast Effects: Theory Analysis and Design, Smoothed Particle Hydrodynamics, Introduction to Maintenance Engineering and Asset Management . Most courses run annually.