Institution: University of Exeter

Unit of Assessment: 15 General Engineering

a. Overview

Exeter Engineering has used the period since RAE2008 to realise its ambition of becoming world-leading for research in areas of existing strength (water, renewable energy and materials engineering) and in developing a new area (for Exeter) of structures and dynamics. Progress has been marked and is evidenced throughout this document by our strategy, future plans and achievements so far, the most important of which include:

- major growth (over 50%) in numbers of top-quality academic staff;
- considerable enhancement to the research environment, facilities, organisational structure and management support;
- a rapidly growing reputation (Russell Group membership, UK top 10 and world top 150 ranking in all major league tables, 41st globally for natural sciences and engineering in the 2013 CWTS Leiden university ranking for scientific performance, the highest of any British University);
- a significant increase (more than double) in total research income;
- an increase of research income per FTE of more than 60%;
- an increase in the share of RCUK funding by more than 60%;
- an increase in PhDs awarded of almost 50%.

These achievements have made Exeter an attractive and productive place to work due to its excellent research environment, reputation and performance, and this in turn is attracting further top quality researchers. Our vision for 2020 is to become an established, internationally renowned centre for the highest quality engineering research in our areas of strength. We will do this by leveraging the investment and progress undoubtedly made over the REF period, by developing collaborations with elite research groups worldwide and by engaging with key industrial partners.

Exeter Engineering is housed within the College of Engineering, Mathematics and Physical Sciences (CEMPS) which, with almost 200 academic staff and an annual turnover of £45m, provides a critical mass and financial stability suited to the realisation of ambitious goals. Engineering is organised into six research areas: the Functional Materials Group, the Water and Environment Group, the Materials and Manufacturing Group, the Structures and Dynamics Group, the Renewable Energy Group and the Camborne School of Mines.

b. Research strategy

RAE2008 research strategy:

The main thrusts of our strategy in the RAE2008 submission concerned: (i) capacity building to attain critical mass in areas of strength and (ii) exploitation of interdisciplinary synergies between Engineering areas of strength and other internationally-leading cognate research areas at Exeter. Our successful realisation of this strategy has resulted in:

- Significant investment in infrastructure; we invested £14.2m in our research facilities by building new laboratories and purchasing new experimental equipment for nanomaterials engineering, graphene engineering, additive layer manufacturing, energy harvesting, vibration engineering and structural health monitoring;
- Exploiting interdisciplinary synergies with other groups at Exeter; for example, water systems research has been linked to weather and climate change research in mathematics, and our materials engineering research has been linked to the nanomaterials and metamaterials research in the Physics discipline;
- Strengthening and growing existing areas of expertise while also establishing world-leading activity in new areas.

Acutely aware of the major changes in the research environment over the last five years, coupled with the economic downturn, we have improved both the quality of our research base and

developed new expertise in areas of national importance. We have been able to do this by exploiting our reorganisation, in 2010, into a more agile and powerful College structure that fully supports interdisciplinary research and provides very significant levels of strategic investment. Investment and interdisciplinarity are also central to the University of Exeter's Science Strategy, which has spent over £83m on capital projects and £27m on staffing and infrastructure developments in five major cross-cutting research themes. Engineering staff play key roles in two of these themes, in the 'Climate Change and Sustainable Futures Theme', where we provide expertise in water management, and in the Engineering-led 'Functional Materials Theme'. The latter brings together over 40 academic staff and 120 researchers from Engineering and Physics, working in the cognate areas of nanomaterials, metamaterials, photonics and graphene. Evidence of the relevance and value of our interdisciplinary research approach is given by the award during the REF period of a £5 million EPSRC/HEFCE Science and Innovation grant to set up the Centre for Graphene Science, a joint venture between Exeter's Physics and Engineering disciplines (and the Departments of Physics and Pharmacy at the University of Bath).

The large-scale strengthening and growth of Exeter Engineering is evidenced by the appointment, during the REF period, of 25 top quality researchers at various stages of their academic careers, bringing the UoA up to 58 FTEs in 2013. Eight new Chairs have been added in pre-existing areas of strength and in cognate research areas (Structures and Dynamics).

Additional evidence of the resulting improvement in the environment, quality, scale and impact of Engineering's research since 2008 is given by the following key metrics and achievements:

- Research income at £28.5m over the REF period vs £13.4m in RAE 2008, comprising:
  - RCUK income at £7.8m in the REF period vs £3.3m in RAE 2008;
  - Income from industry and government at £11.8m in the REF period vs £4.8m in RAE 2008;
  - Income from the EU of more than €10m in REF vs €2.9m in RAE 2008;
- Present live awards totalling more than £34m, with a further £9m awaiting contracts, guaranteeing further post-REF improvement and acceleration in research activities;
- Award of a fellowship of the Royal Academy of Engineering for Savic;
- Award of two EPSRC Industrial Doctorate Centres (IDCs): STREAM and IDCORE (total £1.8m to Exeter) and leadership of two just-announced Centres for Doctoral Training (CDTs): WISE (total £15m) and Metamaterials (total £12.5m);
- Award of nine prestigious EPSRC, Royal Society and Leverhulme Fellowships;
- Leadership of large EU FP7, EPSRC and TSB consortia with aggregate project budgets in excess of £30m and involving collaboration with over 100 different industrial partners.

Strategy and Vision:

Our vision for 2020 is to be an internationally renowned centre for the highest quality engineering research in all our areas of strength. To achieve this we will:

- leverage the comprehensive investment and associated support mechanisms put in place by the university and external funders over the REF period;
- embed large scale interdisciplinary strength throughout our research portfolio;
- develop collaborations with elite research groups in our field;
- engage with key industrial partners to drive forward innovation and impact.

This vision accords fully with evidence (Adams, J., The fourth age of research. *Nature*, **497**, p557, 2013) of a growing divide between nationally and internationally focused institutions; the latter have more than 50% of their outputs co-authored internationally, attract far higher citation rates and will be places where the world's leading researchers want to work or to collaborate with. Exeter Engineering's way forward is to both foster and grow its current academic-driven international collaborations (detailed in sections below) and to exploit further its existing and new university-led partnerships in important countries (e.g. IIT Mumbai, IISc Bangalore, Tsinghua University, Beijing).

Similarly, a central tenet of Exeter Engineering's approach to research has always been engagement with industry, both to inform its research relevance and to ensure the efficient translation of that research into end use. Our strategy for the future is firstly to concentrate resources on our existing areas of impact strength distributed over all six Engineering groups, and develop a limited number of new ones that are aligned with key priority areas reflecting societal

and industrial needs (e.g. critical infrastructure). Secondly, it is to embed firmly and then support impact as a 'third mission' activity of equal importance as education and research (e.g. by focused staff recruitment and development, by practical facilitation of impact, and by structured business engagement). More detail on this strategy is contained in our REF3a Impact Statement.

Our strategy will, we believe, enable us to address global engineering challenges and real world problems with high-quality, interdisciplinary research, informed by international peers and industrial collaborators. We have identified the following areas for particular focus over the next 5 years:

- Environmental change mitigation and adaptation;
- Engineering the energy-food-water nexus;
- Sustainable energy production;
- Development of advanced (lightweight, sustainable) materials;
- Discovery and environmentally-sensitive exploitation of critical metals;
- Development of low power nanoscale electronic and photonic devices;
- Design, performance and health monitoring of critical infrastructure and
- Sustainable manufacturing.

Reviews and strategic vision statements for each of our research groups:

Functional Materials Group (FMG) (lead: Wright), includes **Centre for Graphene Science (CGS)**. **Professors** Wright, Eichhorn, S Zhang, Zhu;, **Associate Professors** Newman, Nash (EPSRC Leadership Fellow), Hrkac (Royal Society Research Fellow); **Senior Lecturers** Craciun, Aziz; **Lecturers** Xia, Kohary.

The focus of the group's research is the design and fabrication of novel nanoelectronic and photonic devices and nanocomposites, for advanced memories, graphene electronics and photonics, bio-medical diagnostics and nanomaterials for shock absorption and energy storage. The group also forms the Engineering part of the EPSRC/HEFCE funded CGS.

Future research directions will include a push towards:

- increased functionality in devices (e.g. memories that also compute),
- vastly reduced power consumption in memory and computing devices,
- more sustainable and environmentally-friendly materials (such as carbon-based electronics and bio-nanocomposities), and
- the application and exploitation of graphene in a host of important application areas (e.g. optoelectronic sources and sensors, optical displays, THz systems, photovoltaics).

Funded international collaborations with elite groups such as CEA-Leti Grenoble, ETH Zurich, University of Tokyo, Institute of Tropical Medicine, RWTH-Aachen and companies such as Toyota, IBM, Micron Semiconductor, Qinetiq and Oclaro will expand and underpin the group's future challenges in the field of memories, graphene devices and (with the Gates Foundation) low-cost diagnostics for in-the-field malaria detection.

Materials and Manufacturing Group (MMG) (lead: D Zhang), includes Centre for Additive Layer Manufacturing **(CALM)**, Centre for Alternative Materials and Remanufacturing Technologies **(CALMARE)**, Exeter Advanced Technologies **(X-AT)**. **Professors** Evans, D Zhang; **Associate Professor** C Smith; **Senior Lecturers** Marmier, Hao, Ghita.

MMG will focus on sustainability aspects of structural and composite materials, lightweight structures made from those materials, and their manufacturing processes and systems. Also, it will involve technology transfer between innovators and end users, large corporations and SME businesses.

Established collaborations with industry, such as EADS on additive layer manufacturing, and Rolls-Royce for multifunctional materials for vibration damping, will expand with continuing significant institutional backing. Partnerships with companies, such as Innovia Films and Unilever on cellulosic materials, Beijing General Research Institute of Mining and Metallurgy and Beijing COMPO on agile and lean manufacturing strategies, will continue to deepen. Both **CALM** and **X-AT** will expand the portfolio of companies with whom they work on embedding new manufacturing technologies into their businesses. **CALMARE** is a new Business Technology Centre (BTC), funded by European Research and Development fund (ERDF). It will support regional business on

use of composites and plastics in a rapidly changing legislative and environmental landscape, particularly on recycling and remanufacturing of waste materials.

Water and Environment Group (WEG) (lead: Kapelan), includes Centres for: Water Systems **(CWS)**, Business and Climate Solutions **(CBCS)**, and Energy and the Environment **(CEE)**. **Professors** Savic, Butler (EPSRC Established Career Fellow), Kapelan, Djordjevic, Javadi; **Associate Professor** Memon; **Senior Lecturers** Farmani, Tabor; **Lecturers** Fu, Gomez, Eames (EPSRC Career Acceleration Fellow).

CWS leads the world on the planning, design, operation and rehabilitation of urban water systems, with particular expertise in hydroinformatics. It has pioneered the development of many of the techniques and tools, such as evolutionary multi-objective optimisation, used by professionals worldwide. It develops evidence-based best practice guidance, and has long-term partnerships with key players across the sector in the UK and internationally, e.g. the Environment Agency, United Utilities, Mouchel, HR Wallingford, ABB, IBM, Hong Kong Water Supplies Dept. Its key academic partners include Tsinghua, Monash, and INSA Lyon. Future research areas for **CWS** lie in understanding and developing mitigation and adaptation approaches to future uncertainties (e.g. climate change, urbanisation), and in representing and engineering the global energy-food-water nexus. This will be underpinned by developing a far greater understanding, handling and exploitation of 'Big Data'. Its pre-eminence in the field was recently confirmed by its leadership of a new Centre for Doctoral training in water and informatics (**WISE**).

CBCS is an ERDF-funded BTC, and has supported over 100 SMEs to date on mitigation methods and the development of business opportunities in climate change. It is steered by practitioners from the Met Office, Regen SW and IBM.

CEE works with businesses on energy and sustainability problems, providing practical tools for companies involved with the UK energy infrastructure. Partners include Jacobs Engineering, and RIBA. Future research will concentrate on sustainable building design, energy policy and the increasingly important impacts of climate change on the built environment.

Structures and Dynamics Group (SDG) (lead: Pavic). **Professors** Brownjohn, Pavic, Reynolds (EPSRC Leadership Fellow), Edwards, Young; **Senior Lecturer** Wadee; **Lecturers** Kripakaran, Alwi, Koo.

This group has recently been restructured and state-of-the-art equipped to tackle a range of fundamental problems in infrastructure, aerospace, and biomedical systems. It has international leads in vibration serviceability and structural health monitoring that it will apply to meeting the challenges of managing the performance of new-build and ageing critical infrastructure, in particular bridges. It will focus on managing real-life performance of constructions, supported by operations of its spinout company Full Scale Dynamics Ltd. Its vision is, by partnering with key groups in Asia, Europe and USA, to develop new business models for life-cycle management of critical infrastructure.

SDG will also tackle problems of control of dynamic structures, such as aeroplanes or space craft alongside its partners Airbus and the European Space Agency, allowing it to implement advances quickly. For example recent fault tolerant control systems devised by us are currently being 'flown' in flight simulators by Airbus.

The spinout company Simpleware Ltd arose from **SDG** research on bio-fidelic mesh generation, and work will continue to innovate in underpinning theory for FE and CFD mesh generation. Simpleware's interaction with its worldwide, sector-spanning user base (including NASA) lends it an excellent data-feed of new problems, all of which inform the research of the group. Related to this, the group will also venture into the new biomedical engineering field of *in-silico* medicine. It will adapt its state-of-the-art technology for measuring human-induced dynamic loads on as-built civil structures to monitor and study real-life forces applied on human musculo-skeletal systems while walking/running/jumping during normal daily activities. The vision is to move from science fiction to reality in personalised computer models for prognosis of musculo-skeletal pathology and decision support on prostheses.

Renewable Energy Group (REG) (lead: Johanning). **Professors** the late George Smith; Mallick, Belmont; **Senior Lecturers** Johanning, Abusara, Connor; **Lecturers** H Smith, Thies, Peng, Sundaram, Yan.

REG addresses issues of power production in offshore renewable energy devices and via solar energy. Research focuses on; i) understanding spatio-temporal variation of waves, coupled dynamic behaviour of ocean energy devices; ii) the control and failure of highly dynamic components; iii) integrated photovoltaics, and iv) new materials for power concentration in photovoltaic devices. As a core member of EPSRC's SuperGen Marine phase 3, the group will partner with many of the key marine energy companies, and with a leading international profile in photovoltaics, will help determine the shape of renewable power in the UK and the developing world for the next 50 years. The group's strong support from government and industry (EPSRC, NERC, EU, Fred Olsen Renewables, Ocean Power Technologies), together with its central role in the EPSRC/ETI Offshore Renewable Technologies Industrial Doctorate Centre will be pivotal in training the next generation of research and practicing engineers who will build and manage our power infrastructure. For example, the new cohort of wave converter devices by Fred Olsen Renewables (the largest marine renewable energy company in the world) which emerged from its collaboration with this group, is now in trials off the Cornish coast.

Camborne School of Mines (CSM) (lead: Wall). **Professor** Glass; **Associate Professors** Coggan, Wall; **Senior Lecturers** Andersen, Foster, Pascoe, Williamson; **Lecturers** Kennedy, Moore. CSM also submits some staff to UoA 7 Earth Systems and Environmental Science.

CSM celebrates its 125th year in 2013. Its strategy concentrates on the multidisciplinary engineering issues of responsible mining, including themes of energy and resource efficiency, ore deposits and critical metals, and environmental protection. CSM's research vision is to ensure continued access to important metals and minerals using extraction techniques that minimise environmental harm and maximise societal benefits. Rio Tinto and First Quantum each sponsor a Chair at **CSM**, and the British Geological Survey sponsor a Lectureship in Critical and Green Technology Metals, part of the Critical Metals Alliance.

c. People, including:

i. Staffing strategy and staff development

Recruitment of all new staff in the REF period was in accord with the strategy outlined above. Therefore appointees have been either internationally leading researchers or those at differing career stages with the potential to lead, in both cases based in pre-existing areas of strength or cognate research areas.

As of October 2013, 25 new staff (including eight Chairs) had joined Engineering in the REF period, with a further two appointments (including another Chair) joining before 2014. Six staff (including three Professors) have been appointed in **FMG** (Craciun, Eichhorn, Kohary, Xia, Zhu, S Zhang); one in **MMG** (Ghita), four in **WEG** (Farmani, Fu, Gomez, Eames); seven (including four Professors) in **SDG** (Brownjohn, Pavic, Reynolds, Edwards, Kripakaran, Alwi, Koo); seven (including one Professor) in **REG** (Mallick, Peng, Yan, H Smith, Thies, Abusarra and Sundaram). The majority (20 out of 25) of these new staff have trained and spent parts of their careers outside of the UK, leaving prestigious institutions to join us from, for example, Qinetiq, Ecole Polytechnique Federale Lausanne, the Universities of Tokyo, Yale, and Rice. Five staff have left to join institutions such as the Universities of Oxford and Nottingham, resulting in a net additional 20 staff. Engineering has been much more selective in returning staff into the Category A than in RAE 2008, returning 44 of the 58 academic staff.

A comprehensive programme of laboratory refurbishment and new building is running alongside this expansion in staff numbers, including location of staff into interdisciplinary centres such as the new Environment and Sustainability Institute (ESI) in Penryn. The very significant improvement in our research infrastructure has helped attract the high quality staff mentioned above. Recruitment has also benefited from the continuing rise of the University of Exeter in league tables and its joining of the Russell Group.

Exeter Engineering adapted to the changes in the research landscape and focused on capturing large grants in the form of multi-institutional consortia and personal fellowships. The research development required major upgrade in the corporate support which has resulted in the award of EPSRC and Royal Society Fellowships (see below) and success in winning a number of large EPSRC grants (Section d below).

Personal Research Fellowships:

- Butler: EPSRC Established Career Fellowship (2013 - present);
- Eames: EPSRC Career Acceleration Fellowship (2011- present);
- Hrkac: Royal Society University Research Fellowship (2009 - present);
- Kapelan: RCUK Academic Fellowship (2005 - 2010);
- Nash: EPSRC Leadership Fellowship (2012 - present);
- Pavic: EPSRC Advanced Research Fellowship (2004 - 2009);
- Reynolds: EPSRC Leadership Fellowship (2011 - present);
- Young: Leverhulme Senior Research Fellowship (2009 - 2010).

Other prestigious fellowships include:

- Savic: Royal Academy of Engineering - FREng (2013);
- Fu, Royal Academy of Engineering (RAEng), Distinguished Visiting Fellowship for Prof Mujumdar (Indian Institute of Science, Bangalore, India);
- Foster, RAEng Visiting International Academic for Prof Jim Joy (University of Queensland);
- Glass, Erasmus Mundus scholar for Prof Doug Stead (Simon Fraser University, Canada);
- Djordjevic, RAEng Distinguished Visiting Fellow for Prof Pasche (Hamburg University, Germany);
- Tabor RAEng DVF for Prof Paterson (Penn State University, USA);
- Brownjohn, Marie Curie Fellowship for Dr David Hester (Queens University, Belfast);
- Wright, Marie Curie Fellowship for Prof Tania Tsvetkova (University of Sofia).

The University's Staff Learning and Development unit provides overall support for all research staff and students. The Performance Development Review (PDR) Process provides annual review and monitoring for all research staff. The added value of this process is that it stimulated the 'organic growth' stemming from the existing staff (Section d). All training and support programmes are consistent with the Concordat to Support the Career Development of Researchers and respect equality and diversity; indeed, the university holds an EC 'HR Excellence in Research Award' for its Early Career Research Staff programme.

Engineering has seen a sea change in its research culture from early career researchers to established academics. In particular, research leadership development is fully encouraged at all career stages through collegiate and collaborative working across institutional, national and international borders. For instance:

- New academic staff manage and agree goals with their Academic Leads, and are automatically promoted to Senior Lecturer when goals are met;
- Particular emphasis is placed on winning EPSRC First Grants as the kick-start to a successful career. New staff are supported by a College doctoral studentship, generous equipment allowance and seed corn money;
- The College operates a workload model which promotes a research-active culture;
- The College operates an EPSRC-style formal peer review process.

There is a number of other human resource management policies aimed at proactively stimulating research and impact. For example:

- Salaries are highly competitive, nationally and internationally, with a 40% increase in average salary for Engineering since 2008;
- Annual merit awards are given for research performance;
- Salary and bonuses are linked to research performance for professorial staff;
- Research income, impact, publication and other targets are set appropriate to grade;
- Full buy out from teaching and administration is available to those with 100% research loading;
- Flexible study leave is awarded based on merit and initiative.

Engineering and the University are engaging in the Athena Swan process to ensure that Exeter Engineering is an ideal place for female engineers to research in the UK. The University currently holds a Bronze award and Engineering is working towards application for the Silver award. Of the new academic staff joining Engineering during the REF period 20% are female. The University has an Equality and Diversity (E&D) team, which ensures compliance with and review of equal opportunities, diversity and equality policies. The University supports a Family Centre for day care of children of staff and students.

ii. Research students

Postgraduate research (PGR) students are an integral part of Engineering's research. Recruitment of PGR students has improved radically since RAE2008, and 82 FTE PhDs were awarded in the REF period *vs* 56.5 in RAE2008. This was achieved by:

- exploiting the significant improvements (described elsewhere) in our research base;
- improving the quality of our PGR intake by introducing cohort recruitment and only awarding studentships to applicants of the highest calibre;
- improvements in supporting and managing student progression.

The PGR journey with Exeter Engineering starts through two main routes: *individually* for self-funded students, typically attracted by a particular supervisor and their research profile, or through *cohort* recruitment which pulls all internal and external resources given to Engineering to recruit the best candidates. Cohort recruitment is managed annually, pooling all available studentships and with a unified advertisement and application process. Decisions on acceptance are based on merit and made separately from studentship awards. We adopted cohort recruitment from 2009 to improve the quality of PGR student experience, strengthen the collaborative research environment, streamline institutional management and support for research programmes, and to increase the profile of Exeter's Engineering PhDs through national and international 'big splash' advertising.

New PGR students are allocated research office space, a desktop computer and access to appropriate laboratory and networked IT facilities. The two-supervisor model is the 'norm'; the first providing the main technical input and the second providing complementary technical and general guidance. For projects with involvement from industry or other bodies, external supervisors may also be appointed. Each student also has an independent mentor to offer pastoral support.

All PGRs follow a programme of advanced technical training comprising a compulsory College module on 'Research Methodology', together with *at least* one additional technical module. All PGR students are obliged annually to select at least two courses of more general training and skills development from the University's Researcher Development Programme. This offers over 150 full-day or half-day training workshops dealing with important skills such as time management, research methods, writing papers, presentation skills, thesis writing and interview skills, and also covering topics such as entrepreneurship, intellectual property and spinout creation.

Key benefits to PGR students studying at Exeter include:

- funding to present their work to at least one major international conference;
- the option to present a thesis for examination based on publications (high-quality journal papers, in print, press, under review or submitted); this ensures early publication, accelerated career development and improved job prospects;
- the support and expectation to publish at least two high-quality, thesis-based, journal papers.

The monitoring of student progress is designed to add value rather than burden and is carried out formally by a central process – the Annual Research Student Monitoring Exercise. This entails several events and processes each year. In the first year of study each student is required to produce a project summary and plan, a literature review, a 1st year written report and oral presentation, written notes of a minimum of ten supervisory meetings and a report on training activities. In subsequent years the focus is more on external activity (paper publications and conference presentations). All reporting is facilitated by two university-wide online systems, *MyPGR* for research and *ePDP* for training activity, on which all reports and other outputs are uploaded and viewed. These systems also generate automatic alerts and reminders for staff and students alike. The student voice is represented formally via PGR representation at the engineering discipline meeting, via a student-led Engineering PGR Liaison Forum and through the

College-wide PGR Student-Staff Liaison Committee.

d. Income, infrastructure and facilities

Research income for Exeter Engineering has increased markedly over the REF period. Total income has increased by over 100% compared to RAE2008 and now stands at £28.5m (vs £13.4m in RAE2008) and research council income has also increased by 65% now standing at £7.8m (vs £3.3m in RAE2008). Our share of national RCUK funding has also increased by more than 60%. Research income from EU programmes, the UK Government (e.g. TSB) and industry exceeds £11.8m. Engineering has a healthy mix of income sources, with approximately 25% from research councils, 40% from industry and government (including TSB), and 25% from the EU.

Large awards led by Engineering in the REF period include:

- FP7 Probe based Terabyte Memories ProTEM (€9.6m);
- FP7 Collaborative Research on Flood Resilience in Urban Areas CORFU (€5.1m);
- FP7 Smart Water: Smart Meters: smart Societies iWIDGET (€5.0m);
- EPSRC/HEFCE Centre for Graphene Science (£4.8m);
- FP7 Carbon based resistive random access memory materials CareRAMM (€3.9m);
- Marie Curie ITN Sustainable and Integrated Urban Water System Management (€3.5m);
- FP7 Graphene on Silicon Free Electron Laser (€2.95m);
- FP7 Magneto-optical Technology MOT (€2m);
- ERDF/SWRDA/EADS establishment of **CALM** (£2.6m);
- EPSRC CDTs: in Water Informatics (£15m) and Metamaterials (£12.5m).

Our future plans include growing the number and scale of such large grants and projects, including working in, and leading further EU grants, EPSRC Programme Grants, and joint authorships from interactions via bilateral funding and agreements such as the UK-India Education and Research Initiative. This is in line with, in fact driven by, our vision for 2020 to play a leading role in the emerging '4th age of research' described earlier.

In addition to this increasing external income, there has also been a very significant investment, by both the University and external funders, in infrastructure and facilities for the Engineering UoA in the REF period. University investment totals to £14.2m and has been used to provide major new facilities including the following:

- **CALM**: 200 m^2 refurbished space, equipment for the future of additive layer manufacturing in aerospace, including EOS P800 Polyether ether ketone system (one of only two in Europe), Accufusion Laser Consolidation system, MCP SLM Realizer system (total cost £1.5m);
- **CGS:** Two 30 m^2 class 100 clean rooms for the coming generation of graphene optoelectronics + 100 m^2 graphene deposition lab, e-beam lithography (total cost £1.5m);
- **SDG**: 190 m^2 vibration engineering laboratory, equipment for world leading vibration serviceability research, forced and ambient vibration testing and modal analysis of large scale built infrastructure (total cost £1m);
- **FMG**: 120 m^2 biocomposites laboratory, 150 m^2 materials processing laboratory, 120 m^2 nanocomposites laboratory, and equipment for production and analysis of nanocomposite materials and electronic devices, including imaging equipment, chemical vapour deposition systems, high-pressure/high-temperature sintering station (total cost £2.5m).

These facilities are supported by 20 experimental officers and technicians.

Considerable University investment has also been made in new buildings (amounting to £7.1m) to support Engineering, including new **REG** laboratories in the recently completed £30m ESI building. A further £0.8m spend on new laboratory and equipment on energy harvesting and an enhanced mechanical workshop is planned for late 2013 and early 2014. A new £50m multidisciplinary 'Living Systems' building is under construction on the Streatham campus (to be completed in 2014), in which £16.5m of spend on space is for a further 10 Engineering academic posts working on bio-engineering and bio-composites. At the Penryn campus, £5m is earmarked for new facilities and equipment for Engineering in a new Science and Engineering Research Support Facility building.

External access to the above specialist facilities, and to staff expertise, generates around £150k of

consultancy annually, and is managed by UoE Consulting Ltd. Consulting plays a role in Engineering's two-way mode of working with industry: it promotes translation of research into industry but also informs fundamental research. Larger scale consulting gets moved into spinout companies and has already transitioned into SEAMS, ChocEdge, Simpleware, Full Scale Dynamics and Theta Technologies. Engineering benefits from University-subsidised consultancy for SMEs as a pathway to deeper interaction and as a route to enhancing collaborative research. **CALMARE** and **CBCS** are BTCs providing business access to Exeter's academic expertise, while other centres (**CALM, X-AT, CWS, CEE**) specifically target high TRL end user engagement.

e. Collaboration or contribution to the discipline or research base

Collaboration has been facilitated by top-down initiatives such as the creation of multidisciplinary colleges and the university-wide interdisciplinary research themes. Engineering has also led bottom-up interdisciplinary initiatives, in particular via a £600K EPSRC-funded *Bridging the Gaps* project (Exeter Science Exchange, led by Butler, **WEG**) that has pump-primed over 60 interdisciplinary feasibility-type projects.

Leadership of consortia:

Engineering has lead consortia with aggregate project budgets in excess of £30m, including:

- Djordjevic (**WEG**) leading CORFU EU consortium on developing flood resilience in cities in Europe and Asia, whose members include the Technical University of Hamburg-Harburg, the University of Nice-Sophia Antipolis, and the DHI Group. The project is developing and disseminating strategies to better manage the consequences of urban flooding;
- Wright (**FMG**) leading PROTEM EU consortium on ultra high density memory whose members included IBM, Numonyx Srl, and Fraunhoffer ISIT. The consortium achieved a then world record beating storage density of 7.8 Tbits/sq.in;
- Hrkac's (**FMG**) work with Toyota on high-energy magnets for electric motors in hybrid cars; Toyota's next generation hybrid cars will use Hrkac's designs in production;
- Glass's (CSM) work with Anglo American and Rio Tinto on mine planning - savings of over £400m have been made using Glass's Cave Planner software.

Collaboration with end users:

Exeter Engineering has extensive collaborative experience, with links over the REF period to well over 100 different industrial partners. Experiences collaborating with end users have fed back into tactical and strategic research developments at a range of TRLs. For example **SDG** staff, through their spinout Full Scale Dynamics Ltd, have engaged with operators and designers of new and existing structures (e.g. Rugeley Chimney, Forth Replacement Crossing, Stretto di Messina Bridge) for structural health monitoring solutions. Such engagements have shown the need for a shift of research emphasis from sensors to data interpretation and decision support that SDG is pursuing. **MMG** have used their mature link with Beijing General Research Institute of Non-Ferrous Metals (China's largest research and industry complex in the non-ferrous industry), in particular the detailed training of their most senior staff undertaken by Zhang, to inform the development of strategies for implementation of agile and lean manufacturing methods.

International collaboration:

Exeter research has a growing international reputation, such as the rise to the UK top-10 ten to 148th globally in the Times Higher Rankings. 'International Exeter' supports this across the University, by for example funding 70 inward & outward mobility fellowships per year (Engineering typically securing 10%). More than 20 applications to UKIERI have been submitted from Exeter with partners such as The Indian Institute for Science, Bangalore. Exemplars of internationalisation include **FMG's** EPSRC-JST projects with the University of Tokyo for study of graphene-based organic electronics and **WEG's** EPSRC/US National Science Foundation funded *Clean Water for All* collaboration with the Universities of Utah and Arizona. Engineering also hosts approximately 100 research visitors per year, staying for periods of weeks or months, and from countries such as China, USA, Denmark, Germany, Egypt, Israel, and India. Sixteen visits have been for extended stays longer than 3 months.

Leadership and participation in international bodies:

Eleven Engineering staff have sat on governmental advisory bodies, such as i) UNESCO's International Federation for Information Processing, ii) NATO's Vessel Motion Prediction SG61 Committee, iii) the Chinese Natural Science Foundation. Staff have also contributed to review bodies for example in i) Canada NSERC, ii) Israel Science Foundation, and iii) EU frameworks. Ten Engineering staff hold honorary positions in other organisations including i) Beijing Compo Advanced Technology Co Ltd, ii) visiting professor at Harbin Institute of Technology, and iii) visiting Professor at UNESCO-IHE (Delft, Netherlands).

Other international collaborations leading to high quality journal papers outputs have included: Russian Academy of Sciences, IBM Zurich, RWTH-Aachen, Micron Semiconductors, Tel Aviv University, Vienna University of Technology, University of Munich, Monash, Nanyang Technological University, Chinese Academy of Sciences, Georgia Institute of Technology.

Nationally, 17 Engineering staff have been EPSRC College members in the REF period. Professor Butler sits on the REF Expert UoA 15 sub-panel. Seven staff sit on advisory, national or professional bodies including i) The Institute of Materials Minerals and Mining, and ii) the HSE Quarry National Joint Advisory Committee, iii) the IStructE stadia guidance working group, iv) the BSI Mechanical vibration, shock and condition monitoring committee.

Staff are Fellows of the following societies: the Royal Academy of Engineering, the Royal Society of Chemistry, the Institution of Mechanical Engineers, the Institution of Civil Engineers, the Institute of Engineering Technology, the Chartered Institution of Water and Environmental Management (CIWEM), the Institute of Materials, Minerals and Mining, the Geological Society, the International Water Association, the International Society for Health Monitoring of Intelligent Infrastructure, and QinetiQ.

Prizes and awards:

Staff have been awarded the following prizes; i) The Institute of Materials, Minerals and Mining Rosenhain Medal 2012 (Eichhorn, **FMG**); ii) 2012 CIWEM President's Award (Butler, **WEG**); iii) 2011 QinetiQ Inventors Award (Nash, **FMG**).

Conference organisation and talks:

Staff have organised or sat in technical or management committees of more than 20 conferences, for instance; the International Conference on Structural Engineering, Mechanics and Computation, Cape Town 2013 and hosting 'Computing and Control for the Water Industry' 2011 in Exeter. Staff have given invited, plenary and keynote talks at more than 50 international conferences, notably at the following: i) Gordon Research Conference on Nanomechanical Interfaces, Hong Kong, 2013; ii) Marine Energy Symposium, Hawaii, 2011; iii) World Conference on Structural Control and Health Monitoring, 2010; iv) Global Manufacturing Science Forum, 2011, v) Nature Conference on Frontiers in Electronic Materials 2012, vi) MRS Spring Meetings in San Francisco 2012 & 2013, vii) IEEE NVMTS in Singapore, 2012; viii) IEEE ICECS in Athens, 2010.

Editorships:

Engineering staff edit (as editor in chief or lead editor) numerous journals including the *Journal of Materials Science*, *Urban Water Journal*, and *Production Planning and Control*. They serve on editorial boards or guest edit a further 27 journals, including *Biomacromolecules*, *Journal of Nanomaterials*, *Journal of Sound and Vibration, Geotechnique,* and *Experimental Mechanics*.

Patents:

Engineering filed a total of 20 patent applications in the REF period. Three were on additive layer manufacturing and arose from **CALM** and **X-AT**'s activities. One of these is currently being discussed with a multinational sale or regarding licensing. Three were on magneto-optical detection techniques, with one of these supporting the award by the Bill and Melinda Gates Foundation of more than $1m. **CWS** made two patent applications on leak detection and management, one of which was licensed to Unite Utilities in return for a £130k investment in further research project. **MMG** submitted eight applications, on auxetic materials manufacture, in-line process monitoring, real time compositing of materials via ALM, and jointly with Rolls-Royce on new technology for vibration damping. **FMG** made two applications on carbon coated nanoparticles, and three applications regarding a new graphene based material - GraphExeter.