Institution: Edinburgh Research Partnership in Engineering – ERPE (Heriot-Watt/Edinburgh)

Unit of assessment: B15 General Engineering

a. Overview

The Edinburgh Research Partnership in Engineering (ERPE, www.erpe.ac.uk) capitalises upon the complementary nature of engineering research at Heriot-Watt University (HWU) and the University of Edinburgh (UoE). The partnership was founded in 2004 following an investment of £22M, £11.7M of which was provided by the Office of Science and Innovation and the Scottish Funding Council (SFC). For RAE2008, engineering research in ERPE was submitted to five separate returns, three to General Engineering, one to Civil Engineering and one to Chemical Engineering. In each of these the importance of collaborative research across ERPE was identified as a central tenet of our future strategy. During the REF2014 period we have vigorously pursued this aim, maturing ERPE to the point where a joint submission best articulates our achievements and direction. This philosophy of co-working was reinforced in 2013 by an institutional Strategic Alliance between HWU and UoE which seeks to strengthen research capacity and commercialisation at an institutional level.

Staff contributing to ERPE are employed by four administrative units; the Schools of Engineering and Physical Sciences (HWU), Built Environment (HWU) and Engineering (UoE), and the Institute of Petroleum Engineering (HWU). These provide a coherent structure for staff management and financial planning. Research activity cuts across School and Institute boundaries and is organised in **four overarching themes**:

- Infrastructure and Environment;
- Energy and Resource Management;
- Manufacturing and Materials; and
- Sensors, Signals and Systems.

Research in ERPE is enriched through close collaboration with colleagues in the School of Geosciences at UoE and the Maxwell Institute in Mathematical Sciences (UoE and HWU collaboration, jointly submitted to RAE2008 and REF2014). In addition, interactions with leading researchers in medicine, physics, chemistry and biology and with external partners, including the British Geological Survey (BGS), the Scottish Universities Environmental Research Centre and the UK Astronomy Technology Centre, enhance the scale and intensity of our research and related postgraduate activities.

b. Research strategy

Our research strategy is to continue to advance both fundamental knowledge and its application across a broad front within the Engineering discipline, with emphasis on challenges of global importance, and to enhance internationally excellent work in all our research activities. This is supported by a KT process that facilitates the transfer of IP to industry and other research users. Over the REF2014 period we have supported existing areas of excellence and identified and developed new areas of opportunity. In all areas we:

- Collaborate with other world-leading research organisations, see below;
- Undertake leadership roles within our disciplines and scientific communities, see section (e);
- Actively promote interdisciplinary research collaborations with other disciplines, e.g. medicine, physics, chemistry, biology and geosciences, to exploit and add value to our core engineering competencies, see below for evidence of our successes;
- Pool resources to ensure an excellent research environment; including laboratories, computing facilities, support for knowledge exchange and staff accommodation, see section (d); and
- Recruit established and early career researchers (ECRs) to strengthen existing areas of excellence or exploit new research opportunities, see section (c).

ERPE recognises that delivering the vision requires the construction of world leading multidisciplinary research teams, and we have been particularly successful in this regard as

evidenced by our leadership of:

- The UK Carbon Capture and Storage Research Centre (UKCCSRC) which provides a national focal point for CCS R&D, bringing together the user and research communities to support the UK economy through an integrated research programme focused on maximising the contribution of CCS to a low-carbon energy sector;
- The UK's research effort in Flood Risk Management (FRM), by facilitating and undertaking collaborative research with industry and government organisations to develop innovative technologies, of benefit across international FRM practice;
- The UK Centre for Marine Energy Research (UKCMER) including the UK All-Waters combined wave and current test facility and IDCORE-Industrial Doctoral Centre in Off-Shore Renewable Energy. UKCMER conducts fundamental and applied research to accelerate deployment and ensure growth in generating capacity to meet the UK 2020 carbon reduction targets;
- The EPSRC Centre for Innovative Manufacturing in Laser-Based Production Processes; exploiting the unique capabilities of laser light to develop new laser-based manufacturing processes and drive growth in the UK Lasers in Manufacturing (LIM) community;
- The BRE Centre for Fire Safety Engineering, which works strategically with key industry partners (BRE, Arup, and IFIC Forensics) to set the agenda and lead fire safety engineering research and practice globally;
- The UK University Defence Research Centre with academic partners, Defence Science and Technology Laboratory (DSTL) and industrial partners, including Selex-ES, BAE Systems and Thales UK; and
- The IMPACT programme grant to develop implantable, smart sensors on silicon that will enable targeting of radio- and chemo-therapies for cancer treatment, this complements our key role in the Integrated Research Centre (IRC) in Healthcare Sensing.

During the REF2014 period ERPE has:

- Invested £106M of research income from UKRCs, EU, TSB and industry;
- Strategically invested by recruitment to 80 academic posts (14 Professors, 7 Readers, 7 Senior Lecturers, 39 Lecturers, and 13 tenure-track Research Fellows) to develop new activities and strengthen areas of existing excellence; and
- Invested £20M in improving research infrastructure most notably our unique wave tank facilities, our carbon capture and storage (CCS) laboratories and the Postgraduate Centre at HWU. A further £17M investment has been announced in the creation of the Sir Charles Lyell Centre for research in earth and marine science technology in collaboration with NERC and BGS.

Further examples of success and investment at the thematic level are provided below.

THEME: INFRASTRUCTURE AND ENVIRONMENT (47.65 Staff FTE; 87 PhD Graduations; 109 Currently Registered PhD/EngD students)

Our RAE2008 strategy centred on developing research activities in our core areas of; structural materials and geomechanics, structural engineering, water management and water quality. We have strengthened these and additionally developed high-profile activities in railway engineering and fire safety engineering.

Railway Engineering

Research in railway engineering focuses on techniques to reduce track construction and maintenance costs. We have responded to needs identified in the UK Government's HS2 plans, exploiting strong links with the railway industry (Network Rail, HS2, Balfour Beatty Rail, and Atkins). Woodward has focused on ballasted railway track behaviour and patented the XiTRACK ballast stabilisation technology which is now deployed throughout the UK and internationally. Our leading position is recognised by industrial consultancy from HS2 (www.hs2.org.uk/press/rayleigh-waves-statement) and by the Transport Select Committee (www.publications.parliament.uk/pa/cm201012/cmselect/cmtran/writev/rail/m53.htm). EPSRC and

TSB funding totalling £1M (EP/H027262 & EP/H029397, TSB-101204, TSB-101199) enabled our work on high-speed track design that has led to substantial innovation in ballasted railway track.

Fire Safety Engineering

Research in fire safety and structural fire engineering has grown considerably since 2008, with more than £1M in new industry support for three academic staff appointments. Torero evaluated fire risks from polymers and composites in aircraft fires (EU-FP6, 13998, €2.1M), with follow-on research by Welch to model the thermo-mechanical behaviour of high-pressure vessels in composite materials when exposed to fire (EU-FP7, 325329, €1.9M). Usmani, Bisby, Welch, Torero, and Gillie lead and stimulate the global research community on fire-safe design and sensor-linked fire-fighting strategies for tall buildings (EP/J001937, £818k), which led to Welch's participation in a collaborative grant with 15 partners (EP/K025155, £3.59M). The work has had impact on fire-safe building design by direct involvement of the above staff in building and fire code committees, advisory boards, and regulatory circles internationally (e.g. ACI, BSi, CTBUH, CSA, NFPA, SFPE, CEN, DCLG, NIST, etc). Bisby won network funding to incorporate holistic fire safety considerations in the design of buildings (Lloyd's Register Foundation, £340k), cross-disciplinary funding (w/ Williams, College of Humanities and Social Science, UoE) to integrate technical and social aspects of fire safety engineering (Arup/RAEng, £340k), and responsive mode funding to achieve resilience to fire and seismic events by hybridising societal and technical knowledge (EP/K022369, £566k, in partnership with UCL, EP/K022377).

Structural Materials and Geomechanics

Our development of smart materials, and innovation in industrial materials handling, with subsequent embedding of these technologies in industry codes of practice has generated significant global impact. In cementitious materials, McCarter and Chrisp have led the European research agenda through work to monitor and improve the performance of structural concrete in bridges. Work on remote interrogation and monitoring of concrete durability led to patent GB2487691 and to McCarter being invited to serve on RILEM (Réunion Internationale des Laboratoires et Experts des Matériaux) Committee 230: Performance-based Specifications and Control of Concrete Durability. Collaborative research with Queen's Belfast (EP/G025096 & EP/G02152X, £678K), the American Concrete Institute (ACI), the US National Ready Mix Concrete Association, Transport Scotland and Amphora NDT Ltd led to follow-on funding (EP/I005846, £99K) for further development of the technology.

Research by Ooi, Rotter and Sun on solids flow and pressures in silos continues to reduce the high incidence of silo failures worldwide. Exemplars include: major input to Eurocode 1 – Actions on Structures – Part 4, BS EN 1991 – 4, Silos and Tanks; £250k industrially funded research and consultancy for the 1M tonne solids storage installation for LKAB Sweden (2007-2009) and failure investigations worldwide (e.g. distressed cement silos in Phoenix, USA (2011), rupture of a 5000m^3 tank in Bordeaux, France (2012)); and licensing and launch of the Edinburgh Cohesion Tester in 2012 (www.ultradynamics.com.au). We have led several international programmes on Discrete Element Method (DEM) modelling, e.g. the ERPE co-ordinated PARDEM consortium (www.pardem.eu, EU-FP7, 238577, €3.2M), which involves 8 international companies (incl. BASF, P&G, Zeppelin, Nestlé, and John Deere) and 4 partner universities (Twente, Netherlands; Brauhschweig, Germany; BOKU, Austria; and Compiegne, France).

Structural Engineering

ERPE influences government policies and international design guidance supporting enhanced efficiency, security and sustainability in the built environment. Bisby and Stratford exert influence on building codes internationally, related to the use of FRP composites in construction (e.g. Europe, USA, Canada) in issues related to thermal effects on FRP systems and adhesives. In particular, in the wake of destructive European earthquakes (e.g. L'Aquila, 2009). Laghrouche has developed new computationally efficient finite element models which have revolutionised acoustic and elastic wave propagation modelling, providing savings of up to 90% in computational effort compared to previous approaches (EP/D076587, £200k; EP/I018042, £409k).

Water Management and Water Quality

Our experimental and computational research informs government policy and engineering

decision-making regarding climate change, mitigation of the impact of flooding and drought and the development of novel technologies for sanitation and the removal of contaminants from water. Building on our leadership of the Flood Risk Management Research Consortium (FRMRC) (EP/F020511, £7.3M), Pender (with Wright and HR Wallingford) has extended work on flood inundation modelling to support risk and uncertainty analysis. Environment Agency (EA) funded work on inundation model benchmarking has had worldwide impact with contributions from 14 commercial organisations in the UK, France, Denmark, Netherlands, Australia, and the USA. The research is being used by the US Flood Management Association to inform their choice of modelling software for flood management decision making. Funded through the FRMRC and the EU Regional Development Fund (35-2-17-08, €8.1M, www.sawa-project.eu), Arthur has delivered a step-change in understanding debris blockage of culverts. Haynes' involvement in new flood research consortia (EP/K013661, £1.4M; EP/K013513, £1.7M) will sustain this research area in collaboration with the EA, SEPA, Arup, HR Wallingford, and CH2M Hill.

With support from RAEng and the Chinese NSF, Pender and Cao developed modelling techniques to address major challenges posed by natural disasters and climate change, including: prediction of the landslide dam created by the Wenchuan earthquake in 2008, and an assessment of the flushing capacity of turbidity currents in the Xiaolangdi Reservoir for the Yellow River Water Authority. This complements Beevers' work on valuing of eco-systems services (EP/J005274, £611k) to balance the competing demands of commercial water users and the environment.

Jack, L. and Gormley (EP/D027969, £162k) have developed the Dyteqta^{TM} device to identify the location of defective appliance trap-seals within building drainage networks. Environmental biosensor research focuses on systems for ultrasensitive detection of water-borne pathogens such as cryptosporidium (Bridle - EU-FP7, 311846, €8.9M; R Thomson - ST/K006509, £185k). Antizar-Ladislao has performed award-winning research (UK Water Engineering Awards 2010, 2013) in the development of water and wastewater treatment technologies for emerging contaminants under contrasting conditions (UKERI; EPSRC/Scottish Water; STFC; £438k total) and sustainability of water supply. Torero's work on the use of smouldering combustion for remediation of soil pollutants has been patented worldwide (USA US8132987 B2, China ZL 2006 8 0052554.X, Japan JP4934832, Australia AU 2006323431 B9), and exclusively licensed to Geosyntec, Canada who have undertaken large-scale field trials for DuPont (USA) and Imperial Oil (Canada) with a value of more than £2M. Torero's work has also been applied to remediation of human waste streams (Gates Foundation, CAD$400k, w/ University of Toronto).

THEME: ENERGY AND RESOURCE MANAGEMENT (53.97 Staff FTE; 120 PhD Graduations; 238 Currently Registered PhD/EngD students)

Global demand for energy is increasing exponentially and meeting this demand mandates improvements in resource exploration, diversification of efficient production, and development of appropriate strategies to reduce and mitigate the impact of CO_2 emissions. ERPE has a long-standing commitment to leading research in these topics.

Petroleum Engineering

Our research into "carbonate reservoirs" focuses on increasing the recovery ratio. In collaboration with Imperial College London and the University of Leoben, Austria, we host a Joint Industry Project (JIP) addressing challenges in fractured (carbonate) reservoirs (6 oil company consortium, £445k) and lead a recently announced NERC funded CT in Oil and Gas. Achievements in enhanced oil recovery include the development of water-alternating gas (WAG) and heavy oil recovery technologies. Building on this, Petroc Technologies Ltd was spun-out in 2009 and has developed unique technology to potentially prevent CO_2 leakage from geologic reservoirs (Scottish Enterprise, Proof of Concept award, Smart Award and Shell Springboard award).

ERPE leads research in two challenge areas for production chemistry: oil field scale build-up and gas hydrate management. The Flow Assurance and Scale JIP Team (Sorbie, Mackay and Todd) has 25 industrial sponsors generating a REF2014 income of £6.8M, with a further £2.9M from projects funded by individual companies. A key research output is updates to "SQUEEZE", industry standard software that is now a worldwide pre-requisite in scale management tender documents. This expertise has translated to other chemically enhanced oil recovery processes, such as low salinity water and polymer flooding. Gas hydrates research (Tohidi and Chapoy) has

involved projects (exceeding £8M in the REF2014 period) in Flow Assurance, Reservoir Fluid Studies, Low Dosage Hydrate Inhibitors, Hydrate Monitoring and Early Warning Systems, and Cold Flow. Hydrates research is licensed to ERPE spin-out Hydrafact.

Automation and optimal control are increasingly important in maximising recovery of oil and gas, and research in production technology (Davies, Muradov) has generated new techniques for well and field monitoring, and control and optimisation, funded by industry (£1.65M in REF period). Our novel, reactive well control methodology was used in 2013 by Grebenkin and Nexen oil company to justify the installation of intelligent wells in a field under development. This has been highly beneficial financially with the Capital Expenditure (CAPEX) reduction and the predicted Net Present Value (NPV) increase both being > £100M.

Christie (w/ Demyanov, El Sheikh) undertake rigorous assessment of uncertainties in forecasting oil and gas reservoir production. Key advances include application of novel techniques to calibrate models to data and to optimise their performance. TSB funded research with the Maxwell Institute (TSB-100729, £808k) has resulted in further development and dissemination of advanced optimisation and inference techniques and has been applied by BP and Epistemy, an ERPE spin-out. Christie has also been involved in knowledge transfer to the defence sector, with an AWE William Penney Fellowship and associated PDRA (£420k). Fundamental aspects in uncertainty modelling will be developed with Warwick University through the recently awarded Programme Grant (EP/K034154, £2M).

The Reservoir Geophysics research of Macbeth and Stephen has been innovative in integrating seismology, engineering and geology for reservoir description and effective reservoir management, using quantitative, dynamic 4D seismic interpretation of hydrocarbon reservoirs supported by 20 oil and service companies (£1.7M).

Carbon Capture and Storage

We have launched the UK Carbon Capture and Storage Research Centre (UKCCSRC), the largest research group working in this field in the UK, with support from EPSRC and in partnership with the British Geological Survey. Growth has been underpinned by the award of an SFC grant (£2M) and builds upon strategic recruitments through the EPSRC Science and Innovation Award for Carbon Capture from Power Plants and the Atmosphere (EP/F034520, £4.5M). Investment of £2M in facilities and grant income exceeding £15M has facilitated the development of a wide range of CO_2 capture technologies. The Gas-FACTS programme, led by Gibbins, provides underpinning research for UK CCS development and deployment on natural gas power plants (EP/J020788, £2.5M), and is complemented by Brandani's work on adsorption materials, processes (EP/J02077X, £1.1M) and innovative gas separators(EP/G062129, £1.9M).

Achievements in CO_2 storage include evaluation and injection, using petroleum and hydrocarbon geoscience, as well as monitoring and verification of storage, and novel sub-surface modelling methods, supported by RCUK, EU-FP7 and industry, e.g. the effect of impurities on CO_2 capture, transport and storage (£720k via 8 industry collaborators), CO_2 aquifer storage evaluation (DT/F007337, £1.7M); and prevention of CO_2 leakage (£408k via 4 industry collaborators). Further funding includes multi-scale short- and long-term behaviour (EP/K035967, £1.2M) and potential risks associated with storage of CO_2 below the seabed (EU-FP7, 265847, €10.5M). Maroto-Valer's Challenging Engineering Award has been enhanced with follow-on funding (EP/K021796, £1.2M) and industry-led projects included optimised compression in collaboration with Rolls Royce and E.ON (TS/G001693, £192k), and an Energy Technology Institute project on CO_2 mineralisation (www.eti.co.uk/technology_programmes/carbon_capture_and_storage, £1M). Finally, ERPE participates in European clean coal programmes and has developed high capacity sorbents, technologies for optimizing mercury capture (RFCR-CT-2007-00007, €2.5M) and abatement of trace pollutant emissions from co-combustion (RFCR-CT-2006-00006, €2.3M).

Renewable Energy Generation

Our RAE2008 strategy prioritised the combined needs for efficient generating and security of supply through optimised technical/economic resilience. Building on leadership of the RCUK's flagship SuperGen Marine Energy Research Consortium (EP/E040136, £5.5M), Wallace, R.S., Bryden and Ingram secured funding to create the UK Centre for Marine Energy Research

(UKCMER) (EP/I027912, £2.9M). The new "All-Waters Current and Wave Test Facility" (EP/I02932X, £6M), a unique 30m diameter wave basin will allow testing in 360° wave and current fields in water depths of 2m. This is a globally unique facility with operations commencing in Q4 2013. Collaborations with China have been supported through Wallace's (R.S.) involvement in the "UK-China Joint Research Consortium on Sustainable Electric Power Supply", (EP/F061242, £1M). We are also expanding collaborative research activities in environmental impact of marine generation: EBAO (NE/J004227, £763k); FlowBec (NE/J004359, £1.2M); TeraWatt (EP/J010170, £981k) and EcoWatt (EP/K012851, £947k).

Research into solar energy generation has involved internationally leading work on the development of structures, material processing and photovoltaics. Upadhyaya (EP/H040218, £2.5M) is engineering excitonic solar cells, in collaboration with NSG-Pilkington, Solar Press UK Ltd and DuPont Teijin Films. Richards is leading the demonstration of world-record efficiencies (16.2%), achieved with broadband light relevant to silicon solar cells (DT/F007345, £383k) in conjunction with the project NANOSPEC (EU-FP7, 246200, €3M). New areas in which ERPE is engaging are scalable solar thermoelectrics and photovoltaics (EP/K022156, £2.5M).

Power Distribution Networks

Research into electrical power and machines, draws upon simulation and optimisation models of renewable resources and 'smart' power system operation, advanced design concepts for direct drive and superconducting generators and reliability of power system components.

Harrison has developed a sophisticated suite of spatio-temporal meteorological, oceanographic and hydrological modelling tools for enhanced long-term resource characterisation and grid integration studies. This includes high resolution weather models, whose output underpins the Scottish Government's Electricity Dispatch Model. New grid integration assessment approaches have evolved through the MARINA Platform (EU-FP7, 241402, €8.7M) and the SUPERGEN Flexnet activity (EP/E04011X, £6.9M). Harrison, Venugopal and Chick have enhanced ERPE's work on the implications of climate change on energy systems, culminating in the project "Adaptation and Resilience In Energy Systems" (EP/I035773, £1.35M) to develop a whole-systems risk management toolkit for deployment by UK utilities.

Through their research on electrical direct-drive systems for renewable energy converters, Mueller and Shek pioneered an integrated electromagnetic, structural and thermo-fluid modelling approach with condition monitoring and fault management. This is now applied to floating wind-turbines (MARINA) and multi-body models of wave converters (SNAPPER) (Engineer Magazine's Innovation Award 2012). The industrial reach of the research is evident in the 2009 NGenTec spin-out to exploit advances in air-cored permanent magnet generator design and the establishment of GE Power Conversion's UK Advanced Technology Group in 2010 with three of their staff embedded in ERPE.

THEME: MANUFACTURING AND MATERIALS (57.52 Staff FTE; 110 PhD Graduations; 143 Currently Registered PhD/EngDs)

Our strategy is to undertake fundamental research leading to solutions for industrially important challenges: the design and fabrication of micro- and nano- scale devices and systems; the application of digital tools to manufacturing; the development, use and control of high power lasers and laser driven processes; and the performance of materials at extreme conditions. In each of these fields we have achieved significant research advances. Bioengineering research was targeted as a growth area during the REF2014 period and as evidenced below we have been particularly successful in growing activity in technologies for stem cell medicine, medical diagnostics, biosensing, synthetic biology and biotechnology.

Bioengineering

Our strategy has been to develop critical mass and forge connections with UoE's world-leading clinical sciences and other internationally leading groups worldwide, including UC Berkeley, Stanford University and Tsinghua University. An example of our success is our role within the IRC in Healthcare Sensing (EP/K03197X, £9.4M). This multi-disciplinary collaboration in a clinical setting brings together engineers, scientists and clinicians to design, manufacture and test a bedside diagnostic platform based on advanced fibre optic technology and micro-optics.

In stem cell (SC) research we focus on engineering approaches for the provision of SCs for regenerative medicine and cell therapy. Major successes include: (i) 3D printing of SCs for tissue and organ regeneration (Shu); (ii) non-perturbing characterisation and monitoring of SC differentiation state via Raman spectroscopy & non-linear optical microscopy (Downes, Elfick; Challenging Engineering Award, EP/E007864, £1.1M); (iii) biomarker-free sorting of SCs to ensure phenotypic homogeneity to better than 96% purity using dielectrophoresis on a co-culture of myoblasts and fibroblasts (Pethig, Smith); and, (iv) scale-up of bioreactors for the *ex vivo* expansion of SCs, particularly for artificial blood production (Willoughby).

In medical diagnosis research high-resolution, dynamic ultrasonic imaging of invasive liver tumours has been achieved using micro-bubble perfusion, whilst lab-on-a-chip devices have been developed to detect cancer biomarkers and rare foetal/tumour cells in blood (Sboros, Koutsos). Reuben and Shu have created a probe to measure the mechanical characteristics of prostate cancer in partnership with Lothian Universities NHS Trust (EP/I019472 & EP/I020101, £801k). Walton and Terry's collaboration with Chemistry and Medicine at UoE (ITI – Chronic Wound Care £1.7M), has led to a device being commercialised by MoInlycke Health Care that tests for MRSA and other bacteria, enabling rapid diagnosis and treatment. Desmuillez is engaged in the development of an ingestible capsule with therapeutic capabilities (EP/K034537, £5M w/ Dundee, Glasgow) and needle-mounted ultrasound to provide minimally invasive high resolution imaging for neurosurgery (EP/K020250, £725k w/ Dundee, Birmingham). This engagement in Bioengineering is reinforced by the work of Murray and McLaughlin (with colleagues in Chemistry and Medicine at UoE), from our Signals and Sensors theme in the IMPACT programme grant (EP/K034510, £4.3M) using implantable sensors for cancer treatment monitoring.

In Synthetic Biology and Industrial Biotechnology (Elfick, Kersaudy-Kerhouas, Markx, Shu, Willoughby) the focus is on the development of techniques for the production of biological materials, for example, the creation of pluripotent plant cells for the production of natural products including drugs such as paclitaxel; enzymatic approaches to the degradation of woody biomass into simple sugars (BB/L003910, £359k; TS/K004808, £301k); and the development of automated liquid handling for DNA fragment assembly in collaboration with GinkoBioworks (Scottish Enterprise, £550k). This rapid growth in activity and funding has led to our participation in the UK Flowers consortium (EP/J02175X, £5M), Industrial Biotechnology Innovation Centre (SFC, £10M) and the Synthetic Biology Innovation and Knowledge Centre (EP/L011573, £5.1M).

Optical Engineering

We work with industry on the development of high-power lasers and related technologies for manufacturing: the manipulation and delivery of high-power laser light; the study of laser-matter interactions; optimisation, monitoring and control of high-power laser-driven processes; and their exploitation to provide new capabilities in manufacturing and medicine. Research activity has been supported with funding from EPSRC via (i) the Innovative Manufacturing Research Centre (IMRC) (GR/S12395 & EP/F02553X, £11.4M, 2003-2013) and (ii) the recently awarded Centre for Innovative Manufacturing in Laser-based Production Processes (EP/K030884, £5.6M plus £1.9M from industry) and (iii) the award of an EPSRC CDT in Photonics in 2013.

Our laser engineering research (Baker, Hall, Esser) on the development of high average power, ultrashort (pico- and femto-second) pulsed lasers builds on our activity to develop optics for improved pumping of high power lasers, with key industrial collaborators including Rofin-Sinar UK, GSI Lumonics, and PowerPhotonic, testifying to the industrial relevance of our research in this area.

In laser micro-machining research (Hand, Shephard) we focus on hard-to-machine materials such as ceramics and glasses, and their uses in associated applications, e.g. the manufacture of miniature fibre optic cantilever sensors (supported by Renishaw). Other laser manufacturing work includes surface modification to generate high friction surfaces (with MAN Diesel & Turbo and SPI Lasers), and hermetic sealing of miniature electronic devices (with QinetiQ, GE-Aviation and CMAC).

Building on the success of our collaboration with the University of Bath on novel photonic crystal fibre optics for industrial laser beam delivery (Hand, Shephard, highlighted in RAE2008) we are developing the technology for practical applications (EP/G039097, £319k; EP/I01246X &

EP/I011315, £690k), not only in manufacturing but also in surgery, in collaboration with clinicians (Dhillon, Clinical Ophthalmology and Simpson, Orthopaedic Surgery, both UoE; and MacDonald, Honorary Consultant, UCL Eastman Dental Institute).

The award of a 5-year STFC Advanced Fellowship (R Thomson, ST/H005595, £465k) underpins new laser manufacturing applications of ultrashort, (femto-second), pulsed laser waveguide inscription in developing novel photonic instrumentation for astronomy. This led directly to the development of large-core-count, three-dimensional integrated optical waveguide fan-out devices for coupling multicore optical fibres to planar photonic devices (US8,270,784, commercialised by Optoscribe Ltd).

The focus of optical diagnostics research (Moore, with Wang, W.) is to develop optical techniques for measuring deformation, vibration, shape and fluid flow in engineering, science and manufacturing applications. A shape measurement probe for free-form surfaces (patent numbers WO/2009/024757, US20100158322, US20100142798), has led to development of two products for automotive and pharmaceutical applications, by collaborators Renishaw. Visualisation and quantitative analysis of shield gas flow profile and coverage during metal inert gas (MIG) welding, and its relationship to weld quality has led to reduced CO_2 use, plus reduced energy requirement for production and supply of the shield gas.

Micro and Nano Systems

In Micro and Nano systems research we engineer novel micro- and nano-scale devices and systems using innovative manufacturing processes: e.g. system-on-a-chip; detectors, bolometer arrays; and micro-electro-mechanical systems (MEMS).

The largest and most sensitive sub-millimetre bolometer ($x10^{-17}$ W/$\sqrt{}$Hz) array in the world (SCUBA-2) has been developed and manufactured, and is now operational on the James Clerk Maxwell Telescope in Hawaii (Walton and Terry). MEMS research includes biomimetics, energy harvesting, sensors for harsh environments, microwave devices, and prognostics and health management (Cheung, Mastropaolo, Hamilton, Goussetis, Flynn, Terry). Our biomimetics activity has provided stress-free resonant beam bridges (20Hz-20kHz) for the integration of resonant gate transistors and subsequently, neuromorphic circuits, as a bio-model to mimic the function of the cochlea, to be extended as a hearing aid, (EP/G063710, £869k). PZT/silicon carbide resonating beams/rings and systems have been developed for applications in timing devices up to 5 MHz, and in energy harvesting (GR/T06322, £826k (Pre-FEC) & Scottish Enterprise, totalling £1.24M). Prognostic systems have been developed for monitoring of subsea power cables to determine their remaining useful life (Scottish and Southern Energy, £350k) and for application in nuclear fuel clean-up. The latter are capable of surviving in potassium/lithium molten salts at 4-500°C.

Materials

Our research in this sub-theme focuses on how nano- and micro- structure affects material properties and influences performance in engineering applications; to this end experimental and modelling work at several scales is conducted.

A novel cold-room laboratory was created enabling fundamental research to understand friction of rubber on ice and snow (Blackford, Koutsos, w/ Michelin, £800k). Low-temperature scanning electron microscopy combined with bespoke friction testing instrumentation for research on snow in controlled laboratory conditions has explained, for the first time, the superior grip properties of certain tyre tread patterns. Zaiser has developed a novel theory of snow slab avalanche release (EU-FP6, 43386, €1.7M), and implemented these protocols for snow stability testing with the Swiss Federal Institute for Snow and Avalanches (industry partner ALEA).

Specialised instruments have been developed to study materials at extreme pressure (Kamenev) including (i) a new approach to compressing gases to pressures in excess of a hundred kilobars to enable neutron experiments on gases; and (ii) a device for sample rotation around two axes at extreme thermodynamic conditions, providing evidence for superconductivity in URhGe in very high magnetic fields. This multi-disciplinary work with UoE Physics and Chemistry and international collaborators has been underpinned by major research funding from EPSRC (EP/E031099, £3.8M), NSF, FTSC, and Leverhulme Trust, with active grants in the period totalling £7.7M. Future work on instrumentation for research at extreme conditions, in

collaboration with international synchrotron and neutron source facilities, is supported by the 5 year Platform Grant (EP/J00099X, £939k).

Fluidics and Interfaces

Our research in this sub-theme focuses on how flow and diffusion phenomena influence engineering process performance, using experimental, theoretical and computational techniques.

Fundamental flow phenomena are studied over a range of scales. Research using state-of-the-art micro-scale imaging techniques (Christy, Duursma, Sefiane, Valluri, EP/C541820, £498k (pre-FEC)), coupled with fundamental theoretical analysis, has revealed previously unknown flow phenomena in droplet wetting and evaporation. This has stimulated further collaborative work with industry and Brunel University on heat exchange for high-heat-flux conditions (EP/K00963X & EP/K011502, £882k). Research in this area extends to linear and non-linear process that cover a wide range of flow scales, using advanced computational methods.

Molecular simulation (Duren, Sweatman, Sarkisov) is being applied to chemical engineering problems, material science and biomolecular systems, adsorption and diffusion in porous materials, transport across lipid bilayers and description of material flexibility induced by external stimuli. Current projects include carbon capture, hydrogen purification, xylene separation, C3 separation, sensing, drug delivery and computational material characterization. Computational tools and methods developed are now widely used by many other academic groups, e.g. Imperial College London, University College London, University of Manchester, UC Berkeley, Georgia Institute of Technology, University of Queensland, Beijing University, Fudan University, and TU Dresden.

THEME: SENSORS, SIGNALS AND SYSTEMS (41.5 Staff FTE; 128 PhD Graduations; 128 Currently Registered PhD/EngDs)

Over the REF2014 period our development of the basic theory, techniques, algorithms, sensor technology and applications has led to a significant expansion in our activities in compressive sensing, defence sector signal processing and visible light communications. In addition, and as a development of our symbiotic relationship with SeeByte Ltd, we have set up a new sub-theme in *Robotics & Autonomous Systems*. Finally, through recruitment, we have established a new sub-theme of *Tomography* that has had notable success in chemical species tomography.

Signal and Image Processing

Our research addresses fundamental theoretical and generic problems in both sparse and distributed signal processing across interconnected networks of communicating sensor systems. We have also developed practical estimation and detection techniques for a variety of modalities including acoustic, radar and lidar systems. Major outputs have delivered on our RAE2008 aims, culminating in the recent award of a programme grant on “Signal Processing for the Networked Battlespace” (EP/K014277, £3.8M) and a platform grant in signal and image processing (EP/J015180, £1.1M). Other grants in this area during the period total more than £7.1M and cover a wide range of applications, e.g. in compressed sensing for dynamic MRI, (EP/F039697, £522k); Clark’s RAEng fellowship in multi-sensor multi-object tracking, (EP/049307, £409k), in adaptive hardware systems, (EP/F030592 & EP/F030657 with QUB & St Andrews, £1M), in novel algorithms for large-scale data, (EU-FP7, 225913, £1.9M), and in MIMO Radar and Sonar Signal Processing, (EP/F068522 & EP/F068956, £290k).

Davies’ work on compressed sensing imaging in wideband synthetic aperture radar (SAR) with missing spectral information led to DSTL commissioning SEA Ltd to pursue its exploitation with ERPE in a new experimental low frequency SAR system. Mulgrew and Clark have developed Automatic Target Recognition Algorithms, evaluated by the Defence Science and Technology Laboratory (DSTL) and included in their algorithm toolbox. Wallace, A.M. has led a group developing new Bayesian analysis techniques to recover both structural and physiological data from multispectral lidar profiles and images; the only academic work cited in the recent ESA call for tenders for a new laser ranger and altimeter (ESA TEC-MMO/2012/320). Concurrently, he has developed new approaches to methodologies for multi-core signal analysis applied to both lidar and video analytics.

We have collaborated with leading international groups including: Technion (Davies) on novel

compressive sensing methods; Tokyo Institute of Technology (Mulgrew) on distributed signal processing; National University of Singapore (Ratnarajah) on signal processing for functional magnetic resonance imaging; and ENSEEHIT Toulouse (McLaughlin) on hyperspectral imaging (winning the best paper prize in IEEE Whispers 2013).

We continue to be active in knowledge transfer, with 4 licenses to SeeByte from EPSRC, EU and MoD work on seabed classification and target recognition in sonar and video. Hydrason was spun-out in 2011 to commercialise new wideband sonar technology following RAEng Enterprise Fellowships (to Brown and Capus). Haas patented a signal feature extraction algorithm for anomaly detection with Agilent Technologies (US8175829), now implemented in a field programmable gate array (FPGA) within their instruments.

Communications

We focus on radio frequency, optical, and wired communication systems. Our major research outputs are aligned to the research strategy presented in RAE2008 and have led to significant advances in 4G radio frequency technology, energy efficient communications systems, and most notably in optical wireless communications, where the results are being commercialised through pureVLC Ltd. We have also contributed to the definition of future 5G wireless systems. We collaborate with international research groups, notably with KTH Stockholm on Multiple Input Multiple Output (MIMO) detection (Thompson, J.S.) and under the UK-China Science Bridge project (EP/G042713, £907k), which established research collaborations with Chinese groups such as Beijing University of Posts and Telecom (Haas) and Huazong University of Science and Technology (Wang, C.X.).

Notable achievements over the REF2014 period include: a novel beam-forming algorithm for wireless communications systems using antenna arrays (Chung), which exploits optimization concepts to tackle uncertainty in channel information; formal analysis tools to enable analysis and optimization of wireless networks employing multiple technologies such as cellular or WiFi systems (Laurenson); a theoretical analysis and practical hardware implementations of the Fixed Sphere Decoder algorithm for multiple antenna wireless communications systems (Thompson, J.S., EP/G060584, £1.4M with Bristol, King's & Swansea); and a novel channel model framework for cooperative MIMO wireless communication systems (Wang, C.X.). Jack, M. has completed the first analysis for usability of text-to-speech synthesis technology in mass-market telephone banking services, leading to widespread adoption in telephone banking, see related impact case study.

Haas has undertaken theoretical analysis and practical implementation of the spatial modulation technique for both radio frequency and optical wireless communications systems (www.youtube.com/watch?v=cPKIbxrEDho) (EP/G011788, £308k), now being enhanced at Princeton University, USA, INRS, Canada and Tsinghua University, China. He studied interference coordination in wireless networks in collaboration with DOCOMO Euro Labs (Munich), who proposed this for the 3rd generation partnership project (3GPP) long-term evolution (LTE), Release 9 and Release 10, the world leading mobile communications standard (EP/I013539, £1.2M). Haas has also pioneered visible light communications (EP/K00042X, £4.6M, led by Strathclyde) and led its commercialisation through the spin-out company pureVLC Ltd. His inventions have been widely publicised and have the potential to revolutionise modern hi-speed communication, and led to the award of an EPSRC Fellowship (EP/K008757, £1.3M).

Robotics and autonomous systems

In this new area our research has focused on sensing, control and persistent autonomy for unmanned platforms and delivered new approaches for collaborative vehicle planning and execution, linking sensing and action, autonomous manipulation and human robot interactions. We collaborate internationally: IIT, Italy; Universitat de Girona, Spain; IST, Portugal; NTUA, Greece; and TU-Munich, Germany. Our research is industry relevant and is illustrated by our relationship with SeeByte Ltd, which facilities technology transfer from academy to industry and informs our academic research direction. Our knowledge of their industrial need led us to develop semantic modelling concepts for multiple vehicle collaboration and to win MoD "Competition of Ideas" funding. The outputs of which enabled SeeByte to gain a $1.7M Foreign Comparative Testing programme in the US, leading to the Neptune product now being sold to the UK MoD and

Canada. Petillot was recently awarded a Royal Society Industry Fellowship to further strengthen links with SeeByte Ltd during 2014-2016. Petillot has also been involved in the first european autonomous manipulation using an autonomous underwater vehicle (EU-FP7, 601205, €3.2M) and Lane is currently leading a programme on persistent autonomy (EU-FP7, 288173, €3.6M). Wallace, A.M. and Petillot have proposed new sensor management for attentive automotive vision systems in collaboration with Audi that has led to the £650k EU-FP7 Locobot project, part of the *Factories of the Future* program.

The Edinburgh Robotics and Autonomous Systems partnership between ERPE and Computer Science at HWU and Informatics at UoE has been initiated to exploit synergies in manipulation, control, and robot collaboration, in outdoor and indoor robotics, marine, and humanoid settings. This partnership is a focus of our future strategy and will build on our £6.1M equipment grant (EP/J015040) and the award of a EPSRC CDT in Robotics in 2013 coupled to 2 new planned staff appointments in ERPE.

Tomography

The field of Agile Tomography has become established within ERPE during the REF2014 period by the recruitment of McCann, Polydorides and Jia. The group's research is characterised by bespoke low-noise multi–channel measurement systems, versatile image reconstruction algorithms, moulding of systems for unique or hostile measurement subjects, and high levels of user involvement. Achievements include publication of the first Chemical Species Tomography (CST) system to be applied in an operating multi-cylinder engine with Roush Technologies Ltd and AOS Technology Ltd, providing images of hydrocarbon fuel at 3,000 frames per second (fps) and leading directly to the EPSRC 2-ACE consortium project (EP/F05825X, £1.2M, with Brighton, Brunel, Leeds, Stanford, Innospec Inc and Ricardo plc). CST is the central theme of the new £2.7M FLITES consortium project (www.flites.eu) to use fibre lasers to image several species in the exhaust plume of aero turbines, co-funded by EPSRC (EP/J002151, £1.8M), Rolls-Royce and Shell, with partner SMEs Covesion, Fianium and OptoSci, and with Manchester, Southampton, Strathclyde and Stanford, with McCann as overall PI.

Sensor Technology and Electronics

System-on-chip research (Arslan, GR/S24053, £496k) has resulted in patented reconfigurable instruction cell array architecture (US patent 2010/0122105 A1) [text removed for publication]. Three licenced patents have led to start ups worth >£2.5M on reconfigurable technology and the design of new smart and low power reconfigurable antenna systems using low power MEMS technology.

Single Photon Avalanche Diode (SPAD) research (Henderson) has resulted in the design of two distinct time-resolved single photon image sensors and subsequent demonstration of the largest array of 92k SPADs. Additionally our CMOS SPAD technology is being commercialised by ST Microelectronics for a 3D ranging technology for mobile phones, and the recently announced IRC Sensing Systems in Healthcare (EP/K03197X, £9.4M) will exploit SPADs in fluorescence lifetime technology for *in vivo* monitoring of respiratory conditions in intensive care. The recently announced ERC Advanced Grant Award (TOTALPHOTON, €2.5M, Henderson, 2013) will investigate solutions to the challenging acquisition of the entire light flux generated by a fluorophore labelled biological cell, reaching a high temporal and spatial resolution with colleagues in Chemistry at HWU.

Murray's research in cell guidance and implanted sensing/activation (EP/G005508, £103k) with Japanese manufacturer Senju led to the Implantable Microsystems for Personalised Anti-cancer Therapy (IMPACT) programme grant (EP/K034510, £4.3M). IMPACT will use miniaturised wireless sensors to monitor physiological dynamics in tumours during chemo- and radio-therapy. These real-time data will allow clinicians to adapt treatment to optimise benefit whilst minimising side effects.

STRATEGY BEYOND 2014

Beyond 2014 we will build on our strong position, in terms of people, research expertise and KT processes to continue to deliver a significant impact on engineering practice. This will be underpinned by a policy of recruiting and developing the highest calibre staff, encouraging and

promoting interaction with industry, and facilitating the transfer of results to industry and other research users, either by direct engagement or through company formation. By theme our aims are:

In **Infrastructure and Environment** we will focus on the relationship between infrastructure design, maintenance and operation, and societal needs to improve the integrity, security and sustainability of infrastructure systems. This will include the development of novel technologies for sanitation and water quality improvement and computational research to understand the impact of climate change and natural disasters on human systems.

Energy and Resource Management research will uniquely encompass all aspects of the energy cycle: from resource exploration and exploitation, diversification of efficient production, and the development of methods and technologies to reduce and mitigate the impact of CO_2 emissions.

Manufacturing and Materials will devise solutions for industrially important challenges: the design and fabrication of micro- and nano- scale devices and systems; the development, use and control of high power lasers and laser driven processes; and the performance of materials at extreme conditions. In bioengineering research we will focus on technologies to assist stem cell medicine, medical diagnostics and biosensing, and synthetic biology and biotechnology.

In an environment of increasingly pervasive communications and interconnected sensing, **Sensor, Signals and Systems** will focus on the theory and technologies underpinning sensor acquisition, data communication and the ability to store and process large quantities of data.

c. People

Staffing Strategy

We recognise that the motivation, commitment and creativity of our staff and students are central to the achievement of our vision to create and sustain a world-leading research organisation. Throughout the REF2014 period this recognition has informed all aspects of our management of people, including: ensuring that research excellence is the principal factor in recruitment decisions, application of a promotions process that rewards excellence in research while recognising the link between research and teaching quality, providing a strong framework to support staff development; promoting equality and diversity in all our activities, and providing a first-class working environment.

We are returning 210 Category A staff (200.64 FTE) to REF2014 (76 Professors, 56 Readers/Senior Lecturers, 62 Lecturers and 16 tenure-track Research Fellows), an increase of 9.6 FTE compared with our combined RAE 2008 returns. Eighty of the staff returned are new appointments (14 Professors, 7 Readers, 7 Senior Lecturers, 39 Lecturers and 13 tenure-track Research Fellows) of which 52 are early career researchers (ECR). Additionally, 48 of the staff returned have been promoted into leadership roles during REF2014. Our staffing strategy has therefore been one of focusing on quality while supporting areas of strength and potential growth. As a consequence we have a vibrant, well-led staff group with an age profile that facilitates growth and sustainability.

In **Infrastructure and Environment**, our recruitment strategy has been to expand existing capability in water management, water quality, materials and geomechanics, exploit emerging opportunities in fire safety engineering and high speed rail, and reinvigorate our activity in structural engineering.

Accordingly, in water-related engineering, Cao, Haynes and Cuthbertson have been recruited to expand our research in sediment dynamics; research capacity in sustainable water supply and related bio-energy generation has been expanded through the appointment and promotion of Antizar-Ladislao, Li, Wright (transferred to Lecturer from RCUK Fellow), Beevers, Correia Semiao, and Chatzisymeon; and research in building drainage and water conservation has been enhanced by the strategic incorporation of the research of Jack, L., Campbell and Gormley into ERPE, along with the appointment of ECR Kelly.

New research opportunities in fire safety engineering have been pursued following the recruitment and subsequent promotion of Bisby to the Arup/RAEng Chair of Fire and Structures, the appointment of Simeoni as BRE-funded Chair, ECR Hadden as Rushbrook Lecturer in Fire

Investigation, and ECR Carvel. Similarly, the promotion of Woodward to the externally funded Atkins Chair of High Speed Railway Engineering, with support from ECR Connolly, will exploit research opportunities arising from the worldwide growth in the development and construction of high speed rail.

Major restructuring and staff investments have taken place within structural engineering, where Bisby's promotion has been complemented by the promotion of Val and Laghrouche into complementary leadership roles. These promotions have been further supported by the appointments of ECRs, Cotsovos, Christian, Mohamed, Suryanto, and Vasdravellis, to pursue research in sustainable and bio-based structural materials. Sun and tenure-track Research Fellow Papanicolopoulos have been recruited to expand our capabilities in granular flow of materials, which also provides the opportunity to grow multidisciplinary links with Geosciences.

Our **Energy and Resource Management** theme contains the largest UK research capability in Carbon Capture and Storage (CCS) and unique large-scale facilities for research in renewable energy. Maroto-Valer was appointed to the Buchan Chair in Sustainable Energy Engineering to strengthen our work on sorbents for CO_2 capture; Gibbins and Chalmers, supported by a Royal Academy of Engineering Fellowship to Lucquiaud and ECR Li, to develop the capability of capture-ready conventional power plants; and Ahn, Ferrari, and Yu to develop next-generation technologies and whole power system analysis. In Renewable Energy, Borthwick and Viola have been recruited to pursue a wide range of hydrodynamics research on marine energy extraction and coastal engineering, to exploit the new FlowaveTT facility; the promotion of Richards and appointment of Upadhyaya have strengthened our research in Solar Energy; and Andresen strengthens our work on sustainable processes on the interfaces between water, energy, and bio-mass. Underhill has been recruited to the Shell Chair in Exploration Geoscience to lead the new Shell Centre for Exploration Geoscience. Our research in energy systems and networks has been strengthened by the promotion of Harrison and the appointments of Swingler and tenure-track Research Fellow Shek.

In **Manufacturing and Materials**, appointments have been made not only to pursue major challenges within these fields, but also to provide fundamental underpinning of other themes, e.g. bioengineering, micro- and nano-systems, and the Oil and Gas and CCS sub-themes in the Energy and Resource Management theme. To strengthen research in computational fluid dynamics, multi-phase flow, and fluidics at nano-, micro- and macro-scales, Reese has been recruited to the Regius Chair in Engineering, along with Fan and ECRs Chen, Dadzie, Lee and Valluri. Fundamental and applied research on adsorbents and processes are being pursued by new appointees Sweatman and ECR Santori. ECR Stokes has been recruited to the Scottish Microelectronics Centre to develop advanced manufacturing for devices and machines made of soft materials. To strengthen research in laser-based manufacturing, Esser has been recruited to the Selex Chair in Laser Device Engineering, Thompson, R. to Reader and Metzger to Lecturer. The interface with life sciences has been strengthened by recruitment of tenure-track Research Fellows Callanan, Hands and Krueger, respectively working on tissue engineering, integrated sensors and systems, and simulation of blood flow. These appointments, coupled with the promotion of Elfick to a Chair in Synthetic Biological Engineering, the conversion of RCUK fellows Downes and Smith to Lecturer positions, the appointment of Bridle and Kersaudy-Kerhoas to RAEng Fellowships in Biosensing and Sboros to a Readership in ultrasound imaging, have contributed to our success in bio-engineering activities.

In **Sensors, Signals and Systems**, we have identified several areas of growth to address exciting research challenges. Haas, Thompson, J.S. and Wang, C.X. have been promoted to Personal Chairs to build our research in optical wireless and radio frequency communications, and ECR Safari has been recruited to work with Haas. The appointments of Gousettis and ECR Mateo-Segura have strengthened our work in electromagnetic modelling. In signal processing the appointments of Sellathurai, Ratnarajah and Wiaux have enhanced our activity, which is the largest in the UK. Escudero has been appointed as tenure-track Research Fellow to strengthen our existing research in Biomedical Signal Processing and build links with Biology and Medicine. ECR Mastropaolo has been recruited to work in support of our smart sensors research activities. McCann was recruited to a Chair, and subsequently supported by the appointments of ECRs Jia

(hardware) and Polydorides (image reconstruction), to build new research activity in tomography.

Research environment and links to teaching and learning

HWU and UoE have attained Athena Swan Bronze status, and were amongst the first Universities in the UK to qualify for the award of the European Commission's HR Excellence in Research, confirming: (i) full compliance with the QAA Code of Practice for Research Degree Programmes, (ii) the Concordat to Support the Career Development of Researchers, and (iii) alignment with the principles of the European Charter for Researchers and Code of Conduct for their recruitment.

All ERPE staff are committed to excellence in research and embed this within their learning and teaching activities. Support to ensure this is achieved is provided through our Performance and Development Review (PDR) which entails the setting of annual objectives covering research, knowledge exchange, teaching and learning activities. PDR takes place within a positive and supportive environment with staff encouraged to reflect on their work and seek support to undertake appropriate personal development activities. In particular, we encourage our staff to make substantive contributions to their disciplines as detailed in section (e). Underpinning PDR is an extensive programme of university-level courses and workshops organised by specialist staff in ERPE's Centre for Academic Leadership and Development (CALD, HWU) and Institute for Academic Development (IAD, UoE). The quality of this specialist support is evidenced by recognition from the European Commission (Sept 2010), through short listing as a finalist for the Leadership Foundation for Higher Education Awards (Nov 2011) and the Times Higher Education Award for "Outstanding Contribution to Leadership Development" (Nov 2012).

In addition, we are committed to assisting our ECRs to develop as confident independent researchers and are proud of the support we provide to facilitate this. All receive additional support in the form of reduced teaching loads, priority access to career development courses, scholarships for PhD students and financial support for travel and participation in activities that will enhance their research careers. Mentoring is provided by experienced academics, all of whom have undergone formal training and are qualified to provide advice on publication strategy, proposal writing, Knowledge Exchange activities and balancing research with teaching and learning activities. In addition, HWU leads the 'Scottish Crucible,' which won the 2010 Times Higher Education Award for Outstanding Support for Early Career Researchers. This scheme enables 30 talented senior post-docs, and ECR lecturers from a variety of disciplines, to come together to explore and expand their creative capacity and problem-solving potential.

Attaining and enhancing standards of research quality and integrity

To support this vital body of talented and committed researchers, ERPE has vigorously developed its ability to manage and promote research, increasingly consolidating work on common systems and processes. HWU and UoE both operate a single "Research and Commercialisation" office model, so that, overall, 90 staff are charged with supporting and promoting all forms of research from the first stirrings of an idea, through the funding application process, to realisation, publication, IP agreements, and maximising impact. Effective liaison takes place across the two institutions, with protocols in place to decide which leads on contract negotiations and licensing development for joint projects. We adapt and adopt from each other and as a result there are mirror systems to enable joint research. Included in this are rigorous processes for reviews of research funding proposals and ethical approvals, with all external grant applications since 2011/12 undergoing multiple internal peer review as well as scrutiny by administrative and finance staff. This not only assures quality for ERPE and the research funders, but also facilitates mentoring of ECRs, as discussed above.

Promoting equality and diversity

ERPE is proud of the diverse range of nationalities contributing to its research and recognises the importance of gender equality in reaching its aims, as demonstrated by the Athena SWAN Bronze awards to HWU and UoE (institutional level) and to the School of Engineering (UoE). We are committed to further developments in this area in the forthcoming period. We have targeted the achievement of the Athena SWAN Silver Award. These aspirations are supported at institutional level and underpinned by a set of HR policies that advocate responsiveness to individual circumstances and needs. Our commitment to Athena Swan is evidenced by the appointment of 9 female ECRs, a further 5 new female appointments and the promotion of 5 female colleagues. As

a result, this submission shows an increase to 11.9% female staff in comparison to RAE2008.

Research Students

ERPE contributes substantially to the cultivation of the next generation of international research leaders. We currently have a total of 640 students registered for higher research degrees, and 443.6 ERPE students have graduated with higher research degrees during the REF2014 period, compared with 422 graduations during the RAE2008 period, given the different census periods this equates to an increase of 24 graduations per annum. This builds upon our ability to attract excellent students, provide an environment within which they flourish, and develop their skills in a manner that ensures success in their future careers in academia or industry. All research students experience a positive research culture where staff and research students work as colleagues to achieve their research goals. Our commitment to providing an excellent study environment and educational experience spans: our handling of student enquiries and applications, provision of scholarships, effective management of the research period, access to state-of-the-art equipment and laboratories, and our transferable skills programme.

Following matriculation all ERPE students are members of a supportive and collaborative environment, which places mutual obligations on staff and research students which are formalised in Postgraduate Research Student Codes of Practice. These require all ERPE research students to have 1st and 2nd supervisors. Training for supervisors is mandatory and ensures that a minimum baseline quality of supervision is maintained throughout the study period. Students are encouraged and expected to take joint responsibility for their research, aiding development of a high quality student/supervisor relationship. Progress towards satisfactory completion is monitored through the submission and assessment of a project plan, an interim project report, and a thesis outline.

Building on the Roberts Agenda, students are supported by supervisors and the careers service to seek out training courses provided by CALD or IAD. These enhance students' generic skills and employability and include topics such as career management, winning funding for research, and exploiting the knowledge that their research has produced. ERPE hosts annual postgraduate conferences to allow research students to present their work and network with fellow researchers; second year PGR students are required to display posters and give short presentations, and prizes are awarded. ERPE has made major investments to upgrade office, teaching, professional development and social space available to its research students, not least the £9M invested in a new postgraduate centre. This new facility is accessible by all ERPE postgraduates and provides lecture, seminar and social space of the highest quality.

d. Income, infrastructure and facilities

Grant portfolio and strategy

A key aspect of our strategy is diversification of our grant portfolio resulting in a considerable broadening of research funders and involvement of industrial sponsors has led to an expansion of ERPE's research activities since RAE2008 which has been made possible by a significant increase in grant income. Over the REF2014 period we have secured £106M in research income from UKRCs, EU, TSB and industry funding, representing a substantial growth compared to RAE2008.

In section (b) we highlighted major multi-disciplinary research initiatives that we lead and which have received significant external research income:

- The UKCCSRC was created with a £10.1M grant from EPSRC (EP/K000446);
- The second phase of the Flood Risk Management Research Consortium (FRMRC) received £7.3M from EPSRC (EP/F020511);
- The UK Centre for Marine Energy Research (UKCMER) received £3M from EPSRC (EP/I027912) with an additional £7M to construct the UK All-Waters Combined Wave and Current test facility (EP/I02932X & EP/H012745) and £6.5M for the IDCORE-Industrial Doctoral Centre in Off-Shore Renewable Energy (EPSRC/ETI, EP/J500847);
- The Centre for Innovative Manufacturing in Laser-Based Production Processes is supported by a £5.6M grant (EP/K030884);
- Our BRE Centre for Fire Safety Engineering, which has secured more than £3.2M in

external/industry support: the Building Research Establishment (>£1.5M), Arup (>£510k), Ove Arup Foundation (£200k), Lloyd's Register Foundation (£342k), IFIC Forensics (£200k), FM Global (£240k), Royal Academy of Engineering (£200k) and Leverhulme Trust (£52k);
- The UK University Defence Research Centre was created with an EPSRC-DSTL grant of £3.8M (EP/K014277) and has additional support in the form of an EPSRC Platform Grant £1.1M (EP/J015180) on Sensor Signal Processing; and
- The IMPACT programme grant from EPSRC totals £4.3M (EP/K034510).

Facilities

Our investment in both major research infrastructure and laboratory refurbishment and renovation have been crucial for the enhancement of the research environment over the REF period, particularly as new staff are recruited and new research areas initiate and grow. To achieve this we have allocated over £20M in internal resources to building refurbishment and renovation. We enjoy exclusive use of three dedicated video-conferencing rooms for ERPE activities, e.g. broadcasting of seminars, PG training and interactions with external collaborators. Among our excellent general facilities are large libraries (including the newly constructed Noreen and Kenneth Murray Library in Science and Engineering (UoE), opened 2012) subscribing to an exhaustive range of paper and electronic journals.

Within **Infrastructure and Environment**, investment in research facilities includes more than £200k to support new staff (Bisby, Carvel, Hadden, Simeoni) recruited to the BRE Centre for Fire Safety Engineering. The investment in this field has created new opportunities in the investigation of fires in tall buildings and has resulted in successful bids for more than £3M in EPSRC funding, £3M in European funding and £376k in research-led consultancy, in addition to more than £1M in external industrial support. To support Woodward's research in high-speed rail, ERPE has invested £250k in the creation of GRAFT II, the largest railway test-track facility in Europe. This facility has resulted in grant awards for strategic research from EPSRC and research targeted directly at industry needs from Balfour Beatty totalling more than £1.2M. In Water Management and Water Quality, ERPE has invested £600k to support the research activities of Antizar-Ladislao and £300k to support new appointees Haynes and Cuthbertson.

Within our **Energy and Resource Management** theme the research activity of the UK Centre for Marine Energy Research and the EPSRC Industrial Doctoral Centre in Offshore Renewable Energy requires world class laboratories with test systems that range from small linear wave tanks to a 30m diameter circular wave facility. Further strategic investments in research space include more than £230k for the refurbishment upgrade of a semi-circular wave tank (10m radius) and more than £2M co-investment (a further £6M provided by the EPSRC and ETI) to create the unique state-of-the-art UK All-Waters Wave and Current test facility. In addition, ERPE has made significant strategic investments in the multidisciplinary activities necessary to develop technologies for carbon capture and storage. Three laboratories have been established with £1.8M of investment linked to academic staff recruitment and strategic investments in new equipment. Initial investments in 2008 have enabled the establishment of the adsorption and membranes carbon capture laboratory led by Brandani. We host the UKCCSRC Pilot-scale Advanced Capture Technology (PACT) national specialist R&D facilities for combustion and carbon capture technology research. Further investment combined with support from the Royal Society Wolfson Laboratory Refurbishment scheme (£1.6M) allowed development of the Solvents Capture Laboratory led by Gibbins. The Carbon Capture and Storage research undertaken by Maroto-Valer and the Solar Energy research of Upadhyaya were enhanced by £1.2M investment in laboratories. Over £15M of research grants awarded in this area have been secured over the REF period as a consequence of these investments.

The development of smart and integrated devices within our **Manufacturing and Materials** theme requires access to state-of-the-art fabrication facilities. Accordingly, we have invested £650k in nano-fabrication and laser micro-machining to support our EPSRC Centre in Laser Manufacturing, and have invested £132k in the Scottish Microelectronics Centre (SMC) to ensure access to state-of-the-art clean rooms and microelectronics manufacturing tools, supported by staff experienced in the processing and design of components and systems. The SMC research

facility supports activity linked to the development of applications which range from biomedical systems and labs-on-a-chip, to sensors for extreme conditions, including applications in nuclear engineering. The SMC has undergone a recent restructuring to release academic resource to develop new strands of research, linked to the research activity of newly appointed academic staff (Stokes and Hands). Bioengineering research has been boosted with the injection of £250k for biomaterials characterisation equipment and £225k for liquid sample handling robotics.

Within our **Sensors, Signals and Systems** theme we have invested £350k in Visible Light Communications, Wireless Communications and Audio Signal processing laboratories.

ERPE has recently upgraded the support of its technical workshops through staff training and the recruitment of additional technical staff. Investment of over £100k has been made in computer numerical control (CNC) machining. This essential capability underpins rapidly growing experimental research in the Energy and Resource Management, Manufacturing and Materials and Sensors, and Signals and Systems themes, which require the design and construction of components for various devices and processes. The new manufacturing tools allow the development and rapid replication of the production of complex components. Our expanding high-powered computing needs are very well catered for and we benefit from the Edinburgh Parallel Computing Centre (EPCC) hosting the UK's main scientific supercomputer, HECToR, as well as several other high-end facilities.

e. Collaboration and contribution to the discipline or research base

Our academics lead or influence within their international research communities and professional disciplines in a variety of ways: collaborations with leading research organisations (evidenced in section b); inter-disciplinary research with leading scientists; collaborations with research users whose business and influence extends internationally; engagement with internationally recognised Learned Societies; contributions to UK, EU and international Research Councils; editorial duties for international journals; and organisation of and participation in major international conferences.

We recognise that engineering is the key to solving many problems but that inter-disciplinary engagement is essential to assist in problem definition and the translation of engineering research into practical outcomes. ERPE is strongly engaged in inter-disciplinary research of this nature, as evidenced throughout section (b) and further by our leadership and involvement in new initiatives, e.g. the IRC in Healthcare Sensing, the Flood Risk Management Research Consortium, the EPSRC Healthcare Technology Challenge for Engineering, the Synthetic Biology Innovation and Knowledge Centre, the Centre for Innovative Manufacturing in Laser based production processes and the wide range of projects we have underway in Carbon Capture, where our staff are working alongside geologists, chemists and physicists within the UKCCSRC framework.

Our contribution to the engineering discipline has been recognised by our 14 Fellows of the Royal Academy of Engineering (Forde, Grant, Hall, Jowitt, Lane, McCann, McLaughlin, Mulgrew, Occone, Pender, Reese, Rotter, Torero, Underwood) and to the broader scientific community by our 22 Fellows of the Royal Society of Edinburgh (Corbett, Forde, Grant, Hall, Jowitt, Lane, McLaughlin, Mulgrew, Murray, Rotter, Forde, Hall, Lane, Occone, Pender, Sorbie, Stow, Todd, Torero, Underhill, Underwood, Walton) and 5 members of the Royal Society of Edinburgh Young Academy (Bisby, Harrison, Shu, Haynes, Antizar-Ladislao). In addition, Grant was awarded the OBE in 2008 and Jowitt the CBE in 2011 for Services to Technology.

We also contribute significantly to Learned Society activities: Jowitt was President of the Institution of Civil Engineers (09/10); Thompson, J.S. is an invited Member of the Royal Society's International Fellowship Panel; McLaughlin chaired the RAEng Research Fellowships panel (09-12); Grant, was a member of the RAEng Research Exchanges with India and China Panel (07-10) and its Research and Secondments Panel (08-11); McCann Chaired the IET Scholarships Committee (06-09); Shu is an elected Member of the ASME Mechanics and Robotics Committee; Thompson, J.S. is a member of the Board of Governors of the IEEE Communications Society; McLaughlin is a member of the Signal Processing Theory and Methods Committee of the Signal Processing Society; and Pender is a member of the ICE Research and Innovation Panel. In addition, Elfick contributed to the Royal Academy of Engineering's report 'Synthetic Biology:

scope, applications and implications' which identified the steps necessary to build UK capacity in the field, McLaughlin contributed to Royal Society of Edinburgh's 'Digital Scotland' report, adopted by the Scottish Government in defining its broadband delivery strategy. Gibbins is a member of the Scientific Advisory Group of the Department of Energy and Climate Change. Underwood (2009-2012) and Reese (2011-present) are members of the Scottish Science Advisory Council which advises Scottish Government on scientific matters. Pender is a member of the Scottish Government's Hydro-Nation Forum advising on water related research and development issues.

ERPE staff are recognised internationally through appointments as Visiting and Adjunct Chairs: Val is Guest Professor in the Institute for Geotechnical Engineering, ETH Zurich; Pender is Guest Professor at the University of Wuhan, China; Torero is Visiting Professor at EPFL Lausanne; Bisby is Adjunct Associate Professor at Queen's University, Canada; Davies is Visiting Professor at EPFL (Switzerland), Rice (USA), and University of Rennes, France; McLaughlin is Visiting Professor at ENSEEHIT, France; and, Wang C.X. is Guest Professor at Shangdong University, China.

ERPE expertise is further recognised by endowed chairs: Mulgrew, Selex-ES/RAEng; Esser, Selex-EO Research Chair; Torero, BRE/RAEng Research Chair (to 2012); Simeoni BRE/RAEng Research Chair); Bisby, Arup/RAEng Chair of Fire and Structures (2013); Maroto-Valer, Robert M Buchan Chair in Sustainable Energy Engineering; Corbett, Total Chair; Sorbie, Cairn Energy Chair; Underhill, Shell Chair of Exploration Science; Woodward, Atkins Chair in High Speed Railway Engineering. Research fellowships at senior level have been held by: Bisby, Arup/RAEng (to 2013); Sefiane, ExxonMobil/RAEng; Petillot, SeeByte/Royal Society.

Staff also make contributions to their wider discipline through membership of appropriate standards bodies such as: British Standards Institute (BSi) (Bisby, Rotter, Val); European Committee on Standardisation (CEN) (Bisby, Rotter); International Standards Organisation (ISO) (Rotter, Val); American Concrete Institute (Bisby, Rotter, Forde); Canadian Standards Association (CSA) (Bisby); International Federation for Structural Concrete (FIB) (Cairns); American Society of Mechanical Engineers (ASME) (Arthur); Réunion Internationale des Laboratoires et Experts des Matériaux (RILEM) (McCarter); International Association for Bridge and Structural Engineering (IABSE) (Val); and UK Concrete Society (Stratford).

ERPE staff have gained significant recognition through the award of prizes during the REF2014 period. In 2012, Salter received the Royal Academy of Engineering Sustained Achievement Award and the first Saltire Prize medal for his pioneering role in the development of marine energy. Maroto-Valer won the Royal Society of Chemistry Environment, Sustainability and Energy Division Early Career Award in 2011, for outstanding contributions in carbon capture and storage, and the Philip Leverhulme Prize in 2009; Pender received the Robert Alfred Carr Prize from the Institution of Civil Engineers in 2009; Sorbie was awarded the SPE IOR Pioneer Award for his contributions to Improved Oil Recovery in 2008 and a Lifetime Achievement Award from The Royal Society of Chemistry for his contribution to Oilfield Chemistry research in 2013; McKay was awarded the Arthur Charles Main Paper Prize in 2010; Underhill was awarded the Geological Society Petroleum Group Silver Medal in 2012; Muradov was awarded the 2012 SPE Cedric K. Ferguson Medal for the best paper published in SPE journals by SPE members younger than 36; and Cuthbertson was awarded the Karl Emil Hilgard Hydraulic Prize from the American Society of Civil Engineers in 2010. Couples is the Society of Petroleum Engineers (SPE) Distinguished Lecturer for 2013-14.

ERPE staff have given numerous invited lectures and keynotes; to illustrate the range of individuals and themes involved, we highlight the following: **Invited Lectures** - 2nd Kiewit Lecture, Oregon State University, Corvallis (Jowitt 2010); Hopkins Lecture, University of Canterbury/IPENZ, New Zealand, (Jowitt 2010); Dugald Clerk Lecture, Institution of Civil Engineers, (Borthwick 2011); 13th International Symposium on Laser Precision Microfabrication, Washington, (Hand 2012); World Plumbing Council Conference, New Delhi, (Jack, L. 2013); 6th International Conference on Fluid Mechanics, Guangzhou, China (Cao 2011). **Keynotes** - IEEE International Conference on Electronics, Circuits and Systems, Malta (Flynn 2008); 6th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, Pretoria (Sefiane 2008); UK/USA workshop on Uncertainties in Flood Model Predictions, Vicksburgh,

(Pender 2008); 8th World Congress on Computational Mechanics/ 5th European Congress on Computational Methods in Applied Sciences and Engineering, Venice, (Reese, 2008); 2nd International Conference on Risk Analysis and Crisis Response, Beijing, (Borthwick 2009); IEEE Globecom, Miami (Grant, 2010); 6th International Conference on Forest Fire Research, Coimbra (Torero & Simeoni, 2010); 22nd Triennial Congress of the International Commission for Optics (Moore, 2011); International Conference on Bond in Concrete, Bresica, Italy (Cairns, 2012); Thales EO and Algorithms Conference (Wallace, A.M., 2012); 13th International Symposium on Spatial Media, Japan (Belyaev, 2013); Visible Light Communications at "TED (Technology Entertainment and Design) Conference", (Haas, 2011, viewed online 1.3M times, tinyurl.com/3rcf5z5); 22nd Triennial Congress of the International Commission Progress in Ultrafast Laser Modifications of Materials, Corsica (Thomson, 2013); Global Phosphor Summit New Orleans (Haas, 2013); International Workshop on Fracture, Acoustic Emission and NDE in Concrete, Kumamoto (Forde, 2013).

ERPE staff have hosted and organized these and other international meetings: IEEE International Conference on Microelectronics Test Structures, 2008, Walton; 8th International Symposium on the Characterisation of Porous Solids, 2008, Duren; European Solid State Devices Research (ESSDERC) and European Solid State Circuits Conferences (ESCIRC), 2008, Walton; 4th International Conference on Advanced Composites in Construction, 2009, Stratford; ASME Turbo Expo, Glasgow, 2010, Reese; 3rd Joint Workshop on Hands-free Speech Communication and Microphone Arrays, 2011, Hopgood; 10th International Symposium on Scanning Probe Microscopy, 2011, Koutsos; Signal Processing with Adaptive Sparse Structured Representations Workshop, 2011, Davies; 3rd International Conference on Metal-Organic Frameworks and Open Framework Compounds, 2012, Duren; ICE Coasts, Marine Structures and Breakwaters, 2013, Bruce; and 12-14th International Conference on Structural Faults & Repair, 2008,10,12, Forde; Chair European Workshop on Optical Fibre Sensors, 2010 and 2013, MacPherson; Chair Organising Committee, 1st IAHR European Congress, 2010, Edinburgh, UK, Pender.

ERPE staff have also assisted with many other international conferences e.g. General Chair: 6th Mediterranean Combustion Symposium, 2009, Porticcio, Simeoni; Co-Chair 3rd Micro and Nano Flows Conference, Thessaloniki, Greece, 2011, Reese; 4th Fire Behavior and Fuels Conference, 2013, St. Petersburg, Simeoni; and Workshop on Fracture, Acoustic Emission & Non-Destructive Evaluation of Concrete, 2013, Kumamoto, Forde; Technical Programme Chair (TPC) 57th International Conference on Electron, Ion, Photon Beam Technology and Nanofabrication, Nashville, 2013, Cheung; TPC Co-Chair, IEEE Globecom 2010, Miami, Thompson J; and IEEE VTC Spring 2013, Dresden, Thompson J; Track Chair/Leader: IEEE Chinacom, 2010, Beijing, Thompson J; 7th International Conference on Structures in Fire, 2012, Zurich, Usmani; Scientific Organiser and Workshop Chair at 11th International Conference on Nanostructured Materials, 2012, Rhodes, Koutsos; Symposia Organizer: 5th and 6th International Conferences on Multiscale Materials Modelling, 2010, Freiburg and 2012, Singapore, Zaiser; International Conferences of Numerical Analysis and Applied Mathematics 2009, Kreta and 2011, Chalkidiki, Zaiser; Workshop Organizer/Chair: IEEE VTC Spring, 2011, Budapest, Thompson J; IEEE Globecom, 2011, Houston, Haas; IEEE International Conference on Communications, 2013, Budapest, Ratnarjah; IEEE Wireless Communications and Networking Conference, 2013, Shanghai, Ratnarajah; IEEE Vehicular Technology Conference, Spring 2013, Dresden, Wang C-X; Symposium Co-organiser, 2008 ASME Mechanisms & Robotics Conference, New York, 2008, Shu.

We act as editors, associate editors or members of editorial boards for many international journals: Associate Editor IEEE Sensors Journal (MacPherson); Associate Editors for IEEE Transactions on Signal Processing (Sellathurai); IEEE Signal Processing Letters (McLaughlin); Editor in Chief IET Signal processing (Thompson, J.S.); Associate Editor Mechanisms and Machine Theory (Kong); Chief Editor of Fire Safety Journal (Torero); Editor in Chief Construction Building and Materials (Forde); Associate Editor Fire Technology (Bisby); Associate Editor Cement and Concrete Composites (McCarter); Co-Editor Petroleum GeoScience (Underhill); Editor Fuel Processing Technology (Andresen); Stephen was awarded the SPE Award for Outstanding Technical Editor Award, in 2012 for his contribution as Technical Editor to the SPE's scholarly review journals.