Institution: Imperial College London
Unit of Assessment: 12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

A. Overview

UoA 12 comprises four Departments; Aeronautics (AE, 30.6 FTE), Chemical Engineering (CE, 39.9 FTE), Earth Science and Engineering (ESE, 48.9 FTE) and Mechanical Engineering (ME, 53.4 FTE), together submitting 172.8 FTE. These four Departments, with the Departments of Computing, Materials, Bioengineering, Electrical and Electronic Engineering and Civil and Environmental Engineering, form the Faculty of Engineering at Imperial College London.

The four Departments share a common strategy that defines three categories of research activity, growing in scale and reach; *Exploratory Research, Developmental Research* and *Programme Research.* This UoA's research structure is therefore described by research activity category, rather than research themes. The highest activity category, *Programme Research,* has significant, large and long-term research activities or Centres, supported with significant investment in staff and new facilities. *Programme Research* activity has been established between Departments in the UoA (for example the £55M, 10-year Qatar Centre between CE and ESE, and the £4.5M Rolls Royce Civil Nuclear University Technology Centre between ME, CE, ESE and Materials), across Faculties and Universities (the £12M, 5-year Rio Tinto Centre between ESE, Chemistry and two other Universities), and Departments and industry (e.g. the 5-year, £2.5M AVIC Centre for Structural Design and Manufacturing in ME).

Over the REF period the vitality of the research environment has resulted in substantial growth in all areas. Compared to the RAE 2008 submission there has been a 15% increase in FTE(A) submitted and a doubling of total research income (Figure 1). The number of Research Assistants funded increased by 58% (90 more), the PhD intake by 28% and the PhD student population by 35% (141 more). This was supported by significant investments in facilities (more than £70M) and equipment (more than £26M).

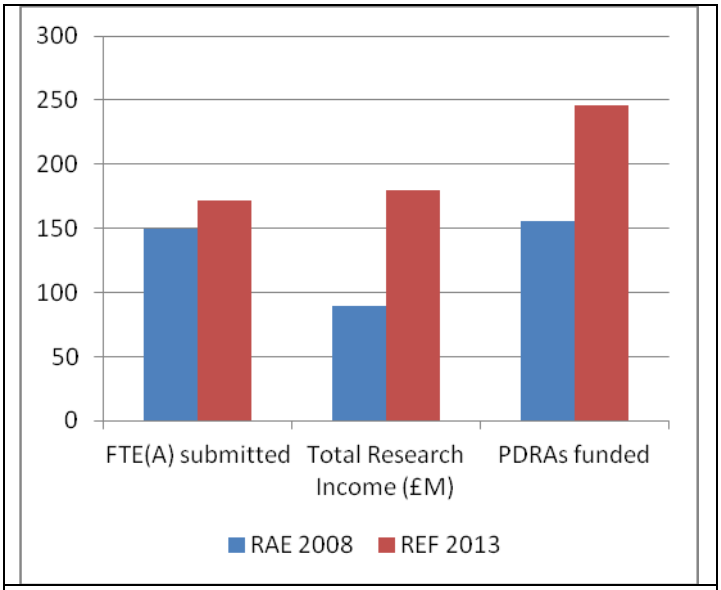

Figure 1: Comparison of RAE 2008 and REF 2013

Our mission is to conduct internationally leading research to provide the fundamental knowledge (31 papers were published in *Science* and *Nature* journals) that underpins technological innovation (5 new spin-outs formed, £9.3M spin-out equity realisation, 34 license agreements, 200 pending and granted patent applications).

There is a growing, sustainable and diversified research income, totalling £179.9M over the REF period (£972k/FTE). A strong portfolio of RCUK, EU and charitable funding supports fundamental research that advances the intellectual boundaries of our engineering disciplines. Our prestigious, fundamental research reputation attracts industrial sponsors and our relationship with industry is vibrant, with industrial research funding forming a significant proportion (38%, £69.5M) of our research income.

Staff are recognised leaders in their field; 18 are now Fellows of the Royal Academy of Engineering, and 7 Fellows of the Royal Society. During the REF period 10 were made FREng, one FRS and one awarded an OBE.

The Departments make significant strategic investments in people to support the research mission. Recruitment of excellent staff internationally has been facilitated by greater flexibility in salary

negotiations and significant start-up packages (more than £300k). More than 55 fully-funded PhD scholarships are awarded annually (approximately a third of the annual intake) of which 40% comes from Departmental funds.

B. Research strategy

The four Departments share a common high-level strategy; to encourage growth and to achieve critical mass in targeted research areas, through three categories of scope and scale:

Exploratory Research, with Departmental support for new ideas and research areas (typically 1-3 year duration, <£100k pa), by internally funded PhD scholarships and Junior Research Fellows, leading to:

Developmental Research, larger projects, in or between research groups, funded by industrial consortia, RCUK or other sources (typically 3-5 year duration, £100k-£1M pa), with RCUK studentships and Research Fellows from Royal Academy of Engineering, Royal Society or RCUK. This research level is supported by investment to enhance research facilities. From these projects, targeted, strategic activities grow into:

Programme Research, large and long-term (typically 5-years or longer, >£1M pa) industrial research Centres or RCUK Programme-type activities within or across Departments, and beyond Imperial College. At this level Departmental and College support includes significant strategic investment in staff, space and new laboratories.

B.1 Evidence of achievement of strategic aims for research since RAE 2008

Major achievements against the strategic goals identified in RAE2008 are presented here for each Department.

Aeronautics (AE)

Respond to the challenging goals for major reductions in emissions, noise and aircraft weight: *Green Aviation,* launched in 2011, provides a strategic focus for inter-disciplinary *Programme Research* in this area. A £4.2M EPSRC Programme Grant on laminar flow control is developing wings with significantly reduced drag. A €3.1M EU project focuses on structural acoustics and an EPSRC Programme grant (HiPerDuCT, with CE £6.5M) is developing high performance ductile composites. Ten specialised academic staff were appointed (Papadakis; Reader, Hewson; Senior Lecturer, Baiz, Kovac, Vincent (EPSRC Advanced Fellow), Bruce, Tagarielli, Li, Buxton and Schmidt; Lecturers).

Strengthen activity in critical aeronautical and non-aeronautical fields in which the Department has hitherto had little exposure: The new McLaren/Royal Academy Research Chair (Sherwin) is developing advanced transient flow simulations. *Developmental Research* activities include combustion instabilities (£1.2M, ERC) and control optimization (€4.5M, FP7).

Grow the application of our core strengths to specialised non-aerospace applications: Fluid mechanics research awards include €3.8M Marie Curie; €2.3M ERC Advanced Investigator, £1.6M EPSRC Platform Grant, and a £1.2M EPSRC Advanced Fellowship. Impact safety research was awarded £1.8M EU and £1.2M EPSRC grants. A €3.5M EU project is developing super-capacitors, and the Department is a leading member of the British Heart Foundation Centre of Research Excellence for cardiovascular research and training (Sherwin is co-Director).

Expand investment in advanced diagnostic equipment: Investment during the REF period by Aeronautics was £2.3M, for the enhancement of laboratories and experimental facilities (PIV, fast cameras, SEM and optical microscopy).

Continue to foster interdisciplinary teams and expand industrial links: EPSRC Programme Grants were awarded for Laminar Flow collaboration with Mathematics, and for Ductile Composites with Chemical Engineering and Chemistry. Major research relationships now include Airbus, BAE, Dstl, Rolls Royce, Alenia Aermachi, Thales, McLaren, Ferrari and Williams F1 racing teams, BP and UK Sports.

Chemical Engineering (CE):

Clean Energy Engineering: A key strategic goal for both Chemical Engineering (CE) and Earth Science and Engineering (ESE) was expansion of activity into carbon dioxide capture and geological storage (CCS), and enhanced oil recovery. The *Programme Research* £55M, 10-year Qatar Carbonates and Carbon Storage Research Centre (QCCSRC) was established in 2009,

funded by Qatar Petroleum, Shell and Qatar STP to study CCS in carbonate reservoirs. Investments include a £1.2M facility hosting a £1.5M CAT scanner and recruitment of Boek (Senior Lecturer), La Force and Krevor (Lecturers), £2.5M in new laboratories, including solar hydrogen production. The recruitment of Markides (Lecturer) supports the £5.5M Energy Efficiency in Industry Programme (*Developmental Research*) funded from 2012 by Skolkovo and BP to improve refinery energy efficiency.

Biological Engineering (especially biomedical, stem cell bioprocessing, tissue engineering and biopharmaceuticals): This *Exploratory Research* was supported by constructing HEPA Level 2 containment laboratories (£300k), and £530k departmental support was provided for proteonomic facilities. Funding was won from charities (£0.9M), CEC (£0.7M), EPSRC (£0.7M) and BBSRC (£0.5M), and 2 lecturers appointed (DiMaggio and Chen).

Applications of Process Systems Engineering: Strategic diversification into *Developmental* Molecular Systems Engineering led to a £1.27M EPSRC Leadership Fellowship and an EPSRC Platform Grant (£1.53M). A £1.3M ERC Advanced Grant and a £5M EPSRC Frontier Engineering Award enhanced the *Programme Research* in Biological Systems Engineering, and Environmental Systems Engineering was consolidated with a staff appointment (Chachuat-Senior Lecturer) and £125k for computation. A further £190k was invested in a state-of-the-art computational cluster.

Formulation Engineering: Strategic, Departmental investment of £200k into Raman tools moved this activity from *Exploratory-* to *Developmental Research*; and led to a £1.1M ERC Advanced Grant, supported further with staff recruitment (Garbin, Lecturer) and a £300k nanofluidics laboratory.

Micro-engineering: Molecular scale fabrication for improved selectivity grew into *Developmental Research* with staff recruitment, materials synthesis facilities (£645k) and a £280k laboratory. The funding portfolio includes a £1.29M EPSRC Platform Grant, funded collaboration with MIT (Novartis, £0.95M) and £2.0M from the BP International Centre for Advanced Materials (BP-ICAM). *Exploratory Research* in nano-structured materials was initiated with the recruitment of Petit as Lecturer.

Earth Science and Engineering (ESE):

Climate Geoscience: We promoted and established climate geosciences as a major *Programme Research* theme through significant investments. A new 90m^2 Class 10 clean room, MC-ICP-MS and a TIMS mass Spectrometers (£1.5M), led to £2.7M of grant income (£0.9M NERC, £0.6M EPSRC, £0.3M Leverhulme and £65k DEFRA), attracted 7 (3 NERC, Royal Society, Danish NSRC and Marie Curie) funded Fellows and led to the appointment of Prytulak as a lecturer. The investment resulted in significant scientific discoveries of past climates by van de Flierdt, including persistent, near-tropical warmth on the Antarctic continents 50M years ago (*Nature*, 488, 2012) and ecosystem reorganisation 34M years ago (*Science*, 342, 2013).

Ocean Modelling: This *Programme Research* team was strengthened by the appointments of Piggott (Grantham Institute Reader) and Gorman (Leverhulme Trust Lecturer) and six fellowships (Marie Curie, Grantham Institute, NERC, Spanish Government, The Royal Commission for the Exhibition of 1851 and EPSRC). The team has led, or collaborated on, grants worth more than £9.5M since 2008.

Petroleum Geoscience and Engineering: The *Developmental Research* 2008-2015 Consortium on Pore-Scale Modelling includes BG, JOGMEC, Statoil Hydro, Shell, Total, BP, Saudi Aramco and Petrobras as partners, valued at £120k pa. The research developed digital rock technology, now commercialised as a spin-out company (2011, *www.iRocktech.com*).

CCS**:** In addition to the collaborative *Programme Research* with Chemical Engineering (above), *Developmental Research* for CCS in saline aquifers and depleted gas reservoirs grew significantly; £2.75M from NERC, EPSRC, EU and industry. Related *Developmental Research* into clean coal and energy technologies secured £1.38M from the EU, for exploiting underground coal gasification.

Reservoir geophysics: The (*Programme-level*) Centre for Reservoir Geophysics, formed in 2009, currently has a £5M industrial research portfolio and fully funds Professor Wang. A spin-out company (*Sub-Salt Solutions Ltd*) commercialises its activities.

Chair in Rock Mechanics: Zimmerman was appointed in 2008 to study rock mechanics for underground mining, nuclear waste disposal, carbon sequestration, and petroleum engineering, since when he has attracted £3.0M in funding, including £1.5M through the *Programme-level* Rio Tinto Centre for rock fracture in mining.

Fuel cells fabrication laboratory: Technology products from the refurbished facilities are now commercialised in the UK and internationally (home fuel cell combined heat and power systems in Japan) and will be used in commercial hydrogen fuel cell vehicles in 2015. Brandon (OBE, 2011) was appointed Director of the Hydrogen and Fuel Cell SUPERGEN Hub, funded by RCUK.

Mechanical Engineering (ME):

Grow all activities related to combustion: New funding for *Developmental* combustion projects totalled £9.25M (£4.4M RCUK, £1.2M CEC, £2.4M Industry, £0.75M UK Gov, £0.5M Other) and was strengthened with six staff appointments (Van Wachem, Beyrau, Navarro-Martinez, Rigopoulos, Rein, Touber), two of whom hold Royal Society young investigator fellowships (Navarro-Martinez, Rigopoulos).

Support growth in bio-tribology and nano-tribology by staff recruitment: Recruitment of Wong, EPSRC (£1.15M) and industry funding (£110k), and Departmental investment into molecular fluorescence facilities (£200k) have grown this activity from *Exploratory* into *Developmental Research*.

Extend current materials research in biomedical applications: Modelling of the cutting of biological soft-tissue gained €1.5M ERC and €5.6M FP7 grants and a joint grant with London School of Pharmacy (EPSRC, £295k to ME) develops drug-loaded adhesive-patches.

Build-up research and staff in design: Two new staff were appointed (Childs, Aurisicchio); the design engineering activity now has 15 PhD students and 2 PDRAs, and research contracts worth £3M.

Non-Destructive Evaluation (NDE): The *Programme Research* NDE work has won £4M of funding including an EPSRC platform grant renewal. New ultrasound tomographic methods have been developed for quantitative imaging of changes of properties of regions of materials. Funding during the REF period exceeded £5M, supporting 18 PhD, EngD and PDRA researchers. Current research includes an EngD programme facilitating technology transfer.

Further strengthen research in the energy area: The Rolls Royce Civil Nuclear University Technology Centre (UTC) was established across ME, CE, ESE and Materials (2010), with 6 academics, including a new lecturer. The Centre has won £4.2M of funding and supports 12 PhDs/EngDs and 2 PDRAs.

Develop research and recruit staff in structural ceramics: The Centre for Advanced Structural Ceramics (2008) between ME and Materials spent £2M on facilities and won £2.5M of funding by involvement in an EPSRC Programme Grant (Materials in Extreme Environments) and £1M from Dstl.

Extend the aero-acoustics work, already undertaken in the Rolls-Royce Vibrations University Technical Centre (VUTC), to encompass fluid-structure interactions. The Centre won £4.8M over the period and appointed two lecturers (Schwingshackl, Di Mare).

Further *Programme Research* Activities:

In line with our strategic vision for *Developmental* activities to grow into *Programme Research*, the UoA also created the following interdisciplinary Centres during the REF period:

- The Rio Tinto Centre for Advanced Mineral Recovery (RTCAMR) was established in ESE in 2008 with a £6M, 5-year investment. In 2010 the investment was doubled to £12M to collaborate with the Department of Chemistry, and the Centre life extended to 2015. A further £5.5M extension agreement to 2018 has been signed.
- The SKF University Technology Centre (UTC) in Tribology studying bearing performance and technology was established in January 2012 in ME, collaborating with CE. The initial funding is £2.5M for the first five years; the UTC initially involves 6 academics with 7 PhDs and 3 PDRAs.
- The Aviation Industry Corporation of China (AVIC) Centre for Structural Design and Manufacturing, based in ME, has 5-year funding (2012-2017) of £2.5M, supporting 9 PhDs, 3 PDRAs and involving 7 academics. The Centre aims to integrate design and manufacture, and develop innovative lightweight manufacturing processes for commercial aircraft.
- A second Aviation Industry Corporation of China (AVIC) Centre, for Materials Characterisation, Processing and Modelling, was established in October 2012 and involves 10 academics from ME and Materials. Funding of £2.5M for the first five years currently supports 8 PhDs and 3 PDRAs. It develops advanced materials characterisation and modelling techniques for the structures of large commercial aircraft.

- The multiphase flow research programme incorporating the Transient Multiphase Flow (TMF) Consortium of 12 major oil companies, and 7 specialist software and design companies underwent major expansion into complex multiphase flows through a £4.96M EPSRC Programme Grant (CE and ESE). Complementing the Programme Grant, Kalliadasis won a £1M ERC Advanced Investigator Grant.
- The Shell University Technology Centre (UTC) in Fuels and Lubricants was established in ME in July 2013 with a first tranche of funding worth £1.8M.
- The 6½ year, QCCSRC Phase II project suite worth £25M started in January 2013, and was awarded to CE and ESE to extend their CCS research.
- The Turbulence Fundamentals and Applications Research Centre was established in AE in 2013 with €6.1M from EU Marie Curie MULTISOLVE and an Advanced ERC Project, now supporting 13 PhDs and 4 PDRAs.
- The Laminar Flow Control Centre (AE and Maths) was established in 2011 with a £4.2M EPSRC Programme grant to lead development of a new generation of LFC wings with significantly reduced drag.

Examples of *Developmental Research* activities during the REF period include:

- Two more companies (Lilly and Syngenta) joined the *Pharmacat* consortium (CE, and Chemistry) in 2010. The consortium develops chemical technologies to effect best routes and processes for the production of pharmaceuticals, and typically funds 2 new PhDs annually.
- The Consortium on Pore-Scale Modelling in ESE fully funds each year a new PhD student and a PDRA.
- EDF and an EPSRC Career Acceleration Fellowship (Davies) study creep performance of power station steels.

Examples of *Exploratory Research* activity:

- Gupta was made Long Term Science Planner on NASA's Mars Science Laboratory *Curiosity* Rover mission. Departmental support included leave of absence and funding for extended periods at NASA during the mission. *Curiosity* has already revealed the first *in situ* evidence for sustained water transport on Mars (*Science,* 340, 1068-1072, 2013).
- A PhD study and follow-on EPSRC Doctoral Prize scholarship in collaboration with GSK on modelling inhaled drug delivery.
- Royal Academy of Engineering Fellowship holder (Misener) is developing a hybrid computational/experimental approach to modelling biomedical systems for the rational design of chemotherapeutic agents.

B.2 Future strategic aims and goals for research

The strategic vision for the UoA is to perform world-leading theoretical and analytical research, supported by computation and experiments that address the most challenging engineering problems facing the world and to translate them into sustainable solutions and practical applications. We will do this across length and time scales - from the molecular to the industrial scale, and from the instantaneous to millions of years.

Each Department in the UoA has defined specific strategic goals to achieve this vision.
Across the UoA, *the key strategic goal for the next five years* is to expand further our research activity. PhD numbers will increase with the recent award of several Centres for Doctoral Training (CDTs), including three funded by EPSRC:

- Fluid Dynamics Across the Scales (involving all four Departments in the UoA)
- Maths for Planet Earth, and
- Theory and Simulation of Materials.

The UoA will benefit also from the award of a NERC Doctoral Training Partnership (25 students per year across the College) and the NERC Oil and Gas Collaborative CDT. These Centres will provide high quality cohort-based PhD training to meet critical research and industrial needs.
The strategic goals for Aeronautics for the next five years and beyond are to:

- Make staff appointments that will focus their research specifically on reductions in aircraft emissions, noise and weight, through *Green Aviation* and the Composites Centre.
- Invest significantly in laboratory facilities for Micro Air Vehicles and Metal Matrix Composites, occupying a new building after 2017; further developments to include a low speed wind tunnel, a composite manufacturing laboratory and a new flight simulator.
- Diversify the existing flow control expertise into *Developmental Research* beyond aerospace, including transport and environmental aerodynamics, renewable energy and impact safety.
- Grow significantly composite materials research from *Developmental* into *Programme Research*, specifically targeting improved mechanical performance and added functionality for transport and armour applications.
- Consolidate our position as the world leading researchers in turbulent flow physics, modelling and applications, by attracting *Programme-level Research* funding and achieving industrial application.

The strategic goals for Chemical Engineering for the next five years and beyond are to:

- Expand research in catalysis and reaction engineering, specifically novel material transformations enabling CO_2, biomass and waste to replace fossil based feedstocks in the production of organic chemicals and fuels;
- Enhance CCS in Carbonate Reservoir research in collaboration with ESE through the (*Programme Research)* Qatar Centre, particularly by integrating experimental and theoretical research into properties and behaviour of matter in extreme environments;
- Increase our research into fabrication of molecularly structured materials and their performance in products and processes, building on recent appointments (Garbin, Petit) and strategically grow the funding we receive from the US$100M, 10-year BP-ICAM programme;
- Excel in research in systems control, design and optimisation platforms, reinforcing the £3M investment in the carbon capture and storage pilot plant partnership with ABB, and ensuring the vibrancy of the successful Centre for Process Systems Engineering and industrial consortium;
- Expand research in biological chemical engineering to achieve *Developmental Research* capability, through complementing the recent appointments in biomedical engineering (DiMaggio and Chen) with an appointment in bioprocessing;
- Build on the recent £5M frontier engineering award in synthetic biology, and renewal of £1M sponsorship from the MIT-Novartis Centre for Continuous Manufacturing, make significant investments in assets to demonstrate scale-up potential of future manufacturing technologies specifically 2D, layer by layer, thin film, and biological parts and devices techniques;
- Establish a Centre (*Programme Research* activity, with ESE) on transport phenomena in multiphase flows, exploiting the hiring of Markides and the £5.%M Skolkovo/BP programme in industrial energy efficiency and £5M EPSRC programme grant / TMF industrial consortium on multiphase flow.

The strategic goals for Earth Science and Engineering for the next five years and beyond are to:

- Integrate petroleum geology and engineering research for the exploitation of fractured and carbonate reservoirs by developing new seismic processing and enhanced oil recovery methods. We will make staff appointments in petroleum geophysics and engineering, and support *Developmental Research* linking petroleum geology and full-wave seismic inversion.
- Enhance our research in mineral extraction by developing, and implementing industrially, new technologies in minerals separation. This *Programme Research* will be achieved through the 2014 to 2018, 5-year, £5.5M Rio Tinto Centre that supports multi-disciplinary projects between ESE, Chemistry and CE.
- Lead world research in plate tectonic and mantle convection, in part through a new £3.7M NERC consortium project (£1.75M to Imperial), to address both fundamental science and societal aspects such as earthquake hazard and mineral deposition.
- Excel in low-carbon energy research. We will widen the fuel cell activity to include reversible fuel cells and energy storage technologies for low carbon transport and grid scale applications. Carbon Capture and Storage (CCS) research will expand in collaboration with CE through the Qatar (*Programme Research*) and ongoing RCUK (*Developmental Research*) activities. We will

build new computational tools using adjoint models and apply them to the design of marine renewable energy installations.

The strategic goals for Mechanical Engineering for the next five years and beyond are to:

- Create *Programme-level Research* in internal combustion engines, building on the College investments of £8M in experimental thermo-fluids equipment and £30M laboratory refurbishment and partnerships with Nissan, Honda, Volvo, Shell and Proton.
- Expand the *Programme Research* in materials testing and processing, particularly aluminium forming, building on the £5M investment from Aviation Industry Corporation of China (AVIC).
- Expand the scope of the *Programme Research* Rolls-Royce Vibration UTC, through the new director, Professor Hoffmann.
- Increase work on permanently installed monitoring systems for non-destructive evaluation.
- Expand *Programme Research* tribology activities in the UTC with SKF and establish new partnerships with oil companies;
- Grow substantially *Developmental Research* in implantable medical devices and robotic surgical assistance field through recent academic staff (Jeffers, Vaidanathan), EPSRC Early Career (Jeffers) and ERC fellowship (Rodriguez-y-Baena) appointments, and £3.9M recent funding;
- Exploit strategic positioning to take up new research opportunities when civil nuclear new-build starts. We have appointed an EPSRC career acceleration research fellow as lecturer (Eaton), established the Rolls-Royce Civil Nuclear UTC with CE and Materials, and appointed Professor Steve Garwood FREng, recently retired from Rolls-Royce on a 2 days/week basis.

Delivery of strategic aims and research goals

Progress and delivery of the research strategy in each department is overseen by the Director of Research supported by a Departmental Research Committee made up of senior, research-leading academics. These committees:

- keep abreast of emerging trends in the disciplines and funding opportunities;
- monitors large proposals in preparation to ensure the necessary support is made available;
- make recommendations to the Departmental Executives on shared capital equipment expenditure;
- work with the Departmental Services and Safety Managers to align the provision of technical services with the research needs;
- make recommendations to the Heads of Department on strategic recruitment of new staff;
- provide oversight of outreach and impact activities organised by each Department.

Collectively, the Engineering Faculty Directors of Research form the Faculty Research Committee (FRC), which has responsibility for advising the Faculty Management Committee on matters pertaining to research. The FRC also allocates 'seed-corn' funding (£200k pa) to promote novel ideas and strategic inter-departmental and inter-disciplinary research initiatives. The Directors of Research serve as a conduit for information and strategic advice between the FRC and the Departmental Research Committees. They also take the lead in publicising research opportunities, monitoring industrial interactions and funding opportunities, organising research away-days and coordinating the communication of the Department's research activities to potential sponsors. The Directors of Research are members of academic staff appointment panels; the recruitment of excellent research staff at all levels and their effective support (as described in section C) is a crucial mechanism for the successful delivery of our strategic goals.

C. People, including staffing strategy and staff development:

Imperial College has implemented fully the *Concordat to Support the Career Development of Researchers* and has achieved an *HR Excellence in Research Badge* from the European Commission. Specific instances of application of each of *The 7 Principles of the Concordat* in the UoA are indicated; the REF exercise addresses *Principle 7*.

C1.1 Staffing Strategy and Recruitment related to strategy and infrastructure

Recruitment and retention of academic staff are planned strategically to maintain international excellence in current activities and ensure it is embedded in new activities *(Concordat Principle 1)*. In each Department, strategic investment in salaries and facilities allows recruitment and retention of internationally leading researchers. Substantial investments (in excess of £300k per FTE) in research funding and infrastructure are made regularly to attract new staff.

Examples from Departments:

- AE invested £2.3M to refurbish laboratories and enhance research equipment. A Micro-Vehicle Flight Laboratory (£0.5M) allowed recruitment of Kovac.
- CE invested £3M in bespoke facilities, studentships and funds for the research of new academics (Markides, Boek, Chachuat, DiMaggio, Garbin, Chen and Petit) in proteomics imaging, porous media imaging, nanofluidics nanomaterials fabrication and characterisation.
- ESE, in 2008, increased clean room space and isotope analytical facilities that attracted 7 funded fellows (3 NERC; Prytulak, Goldberg, Willbold, Royal Society; Coggan, Danish NSRC; Andreasen and Marie Curie; Molino) and the appointment of Prytulak as a lecturer. The consequent growth in students and activity has necessitated a larger clean room, now being constructed (£2M). To accommodate growth in PhD numbers ESE increased desk- and meeting room space by 625m^2 (8%).
- ME, together with AE, is undergoing a major College funded refurbishment costing a total of £100M on buildings; ME has also invested £7.4M in Research Equipment. In the REF census period this has delivered 760m^2 of refurbished laboratory space for Combustion and Engine Development, allowing recruitment of Beyrau, Offer and Rein, and 870m^2 of refurbished Materials Testing laboratories, leading to the recruitment of Balint, Davies and Lin.

C1.2 Evidence of Career Development Support for All Levels of Research Staff

There are rigorous processes for developing and supporting research staff careers at all levels. Career development of academic staff and research fellows is managed through the same consistent and transparent process.

Academic Staff and Research Fellows

Mentoring and Support (*Concordat Principle 2*):

New academic staff have an academic advisor to mentor and guide them during their 3-year probation. In addition to regular meetings, a formal performance review takes place mid-way through the probation and near the end of the probation period. All PDRAs are assigned an academic mentor to assist with career development. The College's Post-Doctoral Development Centre offers career planning and advisory services.

Personal Review and Development Plan (*Concordat Principles 4 and 5*): All staff produce annually a Personal Review and Development Plan (PRDP) for discussion with their Line Manager when their overall performance is reviewed, targets for the forthcoming year are established and agreed, and their career development is planned. This encourages performance benchmarking, recognition of achievement and guidance for addressing weaknesses that need to be addressed for promotion or development. The PRDP process is independent of, but informs, the annual salary review and promotions processes.

Promotions: An independent promotions panel reviews each case and interviews each candidate. The Panel makes constructive criticism that may include improvements to the case or delaying the application, with specific guidance for strengthening their case. Mock interviews are provided, with feedback. Following the formal College interview, an interview is held with the HoD to give feedback. Unsuccessful candidates are supported at Departmental, Faculty and College level, and guided with a personal development plan discussed and agreed through the PRDP process.

Over the REF period the Departments promoted:

- 20 Lecturers (currently 36) to Senior Lecturer (currently 31)
- 13 staff to Reader (currently 24)
- 22 staff to Professor (currently 62).

A key criterion for the career development of PDRAs is to demonstrate research independence.

Departmental funds (£30k pa) have been established for PDRAs to 1) develop small, independent research project ideas, 2) gain experience in student supervision through UROP (summer vacation) projects and 3) for conference attendance or training not covered by their research grants. "Speed Research" sessions encourage PDRAs to collaborate, develop new ideas and to find research partners.

Training (*Concordat Principle 3*): The College, through the Learning and Development Centre, offers a range of professional development courses that include writing research proposals, managing research budgets, staff and students. Mandatory courses for new staff include, for example, PhD student supervision. The research and teaching performance of new staff are formally reviewed, with feedback and a development plan. In cases of unsatisfactory progress, additional support or alternative roles are developed.

The UoA supported 544 PDRAs during the REF period, of which 244 remain in post. The quality of the training in performing research that PDRAs receive is evidenced by a strong record of them becoming permanent academic staff; 66 (22%) have done so since 2008, of which 8 positions were at Imperial.

Career Development of Fellows (*Concordat Principle 4*): This UoA has a very strong record in attracting researchers holding competitively-won fellowships. Currently 20 hold competitively won Fellowships. Seven of these Research Fellows have become academic staff during the REF period (Navarro-Martinez, Rigopoulos, Offer, Eaton, Reddyhoff, Davies, Prytulak). In collaboration with the Post-Doctoral Development Centre, a bespoke Fellows programme has been developed to enhance their career prospects when their Fellowships end.

Sabbaticals
Sabbaticals allow staff to pursue dedicated research in academia or industry. Sabbaticals are financed by the Department, through learned Societies or by industry. Eighteen academic staff (11%) took sabbaticals during the REF period.

C1.3 All Staff: Competitively-won Fellowships and Chairs
There is a strategic effort to encourage and assist young researchers to win competitive Fellowships to progress their careers (*Concordat Principle 2*). A rigorous process of identifying suitable candidates during their PRDP and linking them to opportunities (for example ERC, EPSRC, RAEng and Royal Society), assistance in developing the application, mock interviews and feedback has been developed. Imperial College also funds Junior Research Fellowships for excellent researchers.

Academic staff in the UoA currently hold 19 competitively-won fellowships. This includes four staff members (Vassilicos, Kalliadasis, Kazarian, Pistikopoulos) who were awarded prestigious European Research Council Advanced Grants to **"**allow exceptional established research leaders of any nationality and any age to pursue ground-breaking, high-risk projects that open new directions in their respective research fields or other domains"; these are among the most competitive competitions for research grants globally.

Other competitive fellowships awarded to academic staff include:

- Leverhulme Early Career (Gorman)
- EPSRC (Adjiman, Vincent, Jeffers, Davies, Reddyhof, Cegla)
- Royal Academy of Engineering Research Fellowship (Neethling,Thornhill)
- ERC Starting Grant (Rodriguez y Baena, Morgans)

C1.4 International Staff Appointments (incoming & outgoing), international recruitment and visiting scholars

International recruitment:
Three strategic incentives have made a significant impact on our ability to recruit successfully exceptional candidates in the international market:

1. Greater flexibility on salary levels is available at Departmental level; suitable adjustments

are possible for recruitment of exceptional staff.
2. Support for housing through Shared Equity, Housing Allowance or Deposit Schemes.
3. Significantly increased start-up packages, in excess of £300k, have been utilised.

This strategy has already borne fruit, with the recruitment of seven lecturers from leading North American institutions (Chachuat (McMaster), DiMaggio (Princeton), Garbin (UPenn), Petit (Columbia), Kovac (Harvard), Vincent and Krevor (Stanford)) in the REF period. During the REF period, 17 academic staff were recruited internationally. Thirteen academics left to take academic positions in other countries. Bland (ESE) joined Curtin University as an ARC Laureate Fellow in 2012.

Visiting Scholars and Professors:
The UoA welcomes visiting scholars from around the world for sabbaticals and academic visits. More than 200 academics from institutions around the world stayed for periods from a few weeks to a year.

Visiting Professorships form part of our *Programme Research* strategic activities, to support the creation and sustaining of Centre scale activity. Eminent persons from industry, Government and other academic institutions that can add excellence to our research may be nominated as Visiting Professors. They are vetted at Departmental level and appointed by the Faculty.

Examples of industrial Visiting Professors who support Centre activities include Garwood FREng, Rolls-Royce), Green (Rolls-Royce), Harris (Rio Tinto), Perkins (CSA of BIS) and Burgess (Akzo Nobel).

C1.5 Evidence of Equality and Diversity
Imperial College and this UoA take very seriously their responsibility for the promotion of equality in science and engineering (*Concordat Principle 6*). The UoA works with the College's Equality and Diversity Unit to promote and embed all aspects of equality. Within the UoA every attempt is made to ensure representative constitutions for all interview panels for appointments and awards whenever possible.

Chemical Engineering and Earth Science and Engineering achieved individual Silver Athena SWAN awards during the REF period, with Imperial College as a whole achieving Silver Athena SWAN status in 2013. The UoA has 27.3 FTE female academics (16%), of which 7.3 FTE are Professors (11.7%). Female candidates (27% of applicants) won 30% of Junior Research Fellowships awarded to the UoA in the last year. Initiatives to further reduce traditional barriers to progress for women scientists include Departmental prizes and Lectures named after distinguished Imperial female scientists (for example the Janet Watson and Julia Higgins prizes, and the Dame Julia Polack Lecture).

The College's flexible working policy is applicable to all staff, allowing part-time work and other mechanisms to cope with the demands of a family or other caring responsibilities. Teaching load is managed to take part-time working into account. The majority of meetings and seminars are held in the middle of the day in order to allow those with evening commitments to better manage their work and personal commitments. All staff in the UoA who returned from maternity leave were awarded a College-funded Elsie Widdowson Fellowship that allows relief from teaching and administrative responsibilities for a year. There is also provision of an early years education centre and child care vouchers for parents of young children.

The UoA encourages staff to engage with the Occupational Health department and accommodates the special requirements of staff with disabilities.

Imperial College is also a Stonewall diversity champion, and has Two Ticks accreditation.

These initiatives and measures help to create a culture that actively supports female, less-abled and ethnic minority researchers pursuing careers in science and engineering and provide a

supportive environment for prospective PhD students.

C2. Research students

We provide high quality education and training for PhD students, underpinned with career and pastoral support. The UoA awarded 631 PhD degrees over the REF period; AE 84, CE 194, ESE 155 and ME 173. A further 25 PhDs were awarded, shared with other Departments.

C2.1 PGR recruitment: approaches and discipline-related issues

The reputation of Imperial College encourages applications from the very best PhD students. A major strategic initiative has been taken to grow the number of PhD scholarships offered and support *Exploratory Research*. PhD candidates are vetted through a rigorous evaluation and interview, with the most excellent applicants being supported through their studies. Funding from the Research Councils and College Scholarships support approximately 33 candidates annually. In addition, the UoA annually funds approximately 22 candidates, which allows the recruitment of the very best national and international applications based solely on merit. This significant financial commitment (approximately £4.5M annually) is in line with our strategy; the *Exploratory Research* activity is supported so that it can grow into *Developmental Research* and then to *Programme-level Research*. New PhD student numbers have grown in each of the Departments; for the UoA the annual PhD student intake has grown by 28% from 146 in 2008 to 188 in 2012.

C2.2 Information on training and support mechanisms

Research students are given working space, separate from their laboratory, and a computer. They are encouraged to attend any relevant lectures in the College. Vibrant seminar programs in each Department expose all students to the very best researchers from around the world. Attendance of at least 50% of these seminars is a formal requirement for progression of PhD students. Seminars are held at least weekly in each Department. Attendance at external conferences is actively encouraged, and funded by the Departments.

PhD students have a structured first-year training programme in research skills, planning, presentation, technical writing and other transferrable skills, delivered through the Graduate School. All research students are required to attend generic training and transferable skills courses provided by the Graduate School. Each research group also provides specialist skills training and knowledge modules, details of which are compiled for safety and training records. Students that are deemed to require English tuition, through a rigorous test, receive the necessary help through the Language Support Unit. Safety training is given and recorded, both general and specific to the project, supported by the Departmental and Faculty Safety Officers.

Pastoral assistance is provided through the Departmental Post-Graduate Tutors, an advisor to women students and the mentoring scheme; in addition there are College Tutors and health-care professionals to assist where necessary. Interruption of studies can be made on health or compassionate grounds.

C2.3 Research Student Progress Monitoring

Each PhD student must prepare a research plan for independent assessment within 9 weeks of starting, followed by an Early Stage Assessment at 9 months and a Late Stage Review at 18-24 months. The Early Stage Assessment features a written report accompanied by a half-hour presentation and is conducted by an independent member of staff approved by the Director of Postgraduate Studies. At the Late Stage Review, sufficient progress is equivalent to being the major contributor to, and oral presenter of, a peer-reviewed archival paper at a conference.

PhD student performance and feedback on their research experience are monitored via twice-yearly progress reports. Departments also participate in, and take action from, research student experience surveys run by the College (ROLE) and nationally (PRES). In the 2013 PRES survey, both participation and satisfaction increased across Imperial College, with Departments in this UoA having the highest scores in the Resources, Progress & Achievement and Research Skills categories.

All PhD students are expected to submit their PhD theses within 4 years. For exceptional

circumstances, a special case can be made to the College for an extension.

D. Income, infrastructure and facilities

The UoA has state-of-the-art facilities and equipment to support its researchers and the RAE period has seen significant strategic investment.

D1. Information on provision and operation of specialist infrastructure and facilities

Aeronautics (AE):
Wind tunnel facilities include six smaller and four large, low-speed, closed circuit wind tunnels, two with rolling roads and vehicle testing capabilities. A supersonic wind tunnel allows air speeds up to Mach 2 and the hypersonic wind tunnel is capable of Mach 9. The brand new hydrodynamics laboratory houses a highly instrumented 9m water flume, supported by high speed cameras and laser systems for flow measurement and visualisation. The flight simulator has full 6 degree motion. Mechanical testing facilities comprise electromechanical and hydraulic Instron test machines (50–250kN), a 250t compression machine for stiffened panel testing, and an Instron low velocity impact test (2000J) with bespoke facility for loading panels in compression (150t) during impact tests. A 50mm gas gun produces velocities up to 1.4km/s for masses up to 250g, and the 25mm gas gun ejects masses up to 10g at velocities up to 400m/s, monitored with high speed video cameras, acoustic emission facilities and digital image correlation equipment.

Earth Science and Engineering (ESE):
The Isotope Geophysics laboratory was refurbished in 2008 from Departmental funds to host two state-of-the-art mass spectrometers; the existing Nu Instruments MC-ICP-MS and a new £420k Triton TIMS were installed in late 2008. These are used for environmental element tracking, climate change and medical geology studies. The Palaeomagnetism Laboratory was refurbished and fitted with a dual-head magnetometer (2011, £195k) by Imperial College, and a magnetometer and paleomagnetic oven (£56k) funded by NERC and STFC grant. A high-resolution Positron Emission Particle Tracking (PEPT) laboratory was set up by installing a Siemens PET scanner sourced from Hammersmith Hospital to the iThemba (nuclear isotope) Labs in South Africa. This facility has the highest resolution available worldwide. The move, installation and ongoing support costs are funded through the Rio Tinto Centre. The Reservoir Physics Laboratory capability was expanded using £250k (of £2M grants) from Shell and TOTAL to provide a unique facility to measure (i) electrochemical and thermoelectric potentials across intact rock core samples, and (ii) streaming potentials across intact core samples at elevated temperature and pressure, saturated with multiple fluid phases (i.e. at hydrocarbon reservoir conditions). In 2012, a further 625m^2 of desk space was created to accommodate the growth in student and researcher numbers; capacity now stands at 284.

Chemical Engineering (CE):
A £9M College investment during the REF period in pilot-plant laboratories (1000m^2) established a pilot-scale CO_2-capture plant with a state-of-the-art control room. The investment included a new analytical services laboratory, electronics workshop and two new research laboratories (part-funded by a Royal Society Wolfson Foundation grant) with special facilities for toxic and flammable gases. The Qatar Carbonates and Carbon Storage Research Centre (QCCSRC) equipped three new laboratories: the Imaging Laboratory with a medical CT and a micro-CT scanner for studying porous multi-phase flow, uniquely under reservoir conditions. The complimentary Complex Fluids Laboratory has confocal laser scanning- and optical microscopes, while the Thermophysical Laboratory has bespoke apparatus for measuring physical and chemical fluid and mineral properties under reservoir conditions. Customised mass spectrometer facilities for proteomics data collection and analysis, and a suite of membrane fabrication facilities in climate controlled environments, have been added in the REF period.

Mechanical Engineering (ME):
The Department is undergoing a major refurbishment of its building with over £37M spent so far on the enhancement of research facilities (2300m^2 of research lab space), plus £7.4M on new equipment. Work has now started on refurbishing all the remaining research laboratories, teaching

areas and office space, and moving Aeronautics into adjacent space, at an estimated total cost of about £63M. Examples of research equipment purchased include: Optical Engines and Dynamometers (£1.09M), Laser diagnostics (£1.38M), Gleeble machine (£469k) for high frequency, high strain materials cycling, plus other High Temperature materials testing equipment (£414k), 2500kN Instron test machine (£423k) plus smaller scale tensile and compression machines (£318k) and High Performance Computing clusters (£584k).

Shared Facilities

At Imperial College, Departments share large-scale and/or expensive facilities; this UoA benefits, for example, from the extensive range of electron microscopes in the Department of Materials. As a *quid pro quo*, other Departments have access to ME's state-of-the-art mechanical testing facilities and the composites processing equipment in AE.

The Imperial College High Performance Computing facility is available to Departments for use and to invest in for preferential use. IC-HPC currently has a 13622 core capacity cluster and a 5272 core SGI Altix ICE 8200 EX capability machine. There is also a 384 core SGI Altix 350 shared memory machine. College investment into IC-HPC exceeds £1.3M annually.

D2. Evidence of Investments (both current and planned) in infrastructure and facilities

Capital Equipment

During the REF period, the UoA spent £26.8M on capital equipment, of which £20.5M (76%) was for equipment costing more than £50k. This included a number of significant investments, as described above:

- More than £1M on X-ray tomography (CE and ESE)
- £1.3M on mass spectrometers (CE and ESE)
- £275k on a rapid manufacturing (3D printing) systems (ESE and AE)
- A £467k high frequency-high strain Gleeble machine (ME) and £432k Inston testers (AE)
- £938k in high performance computing facilities
- £835k on PIV and other laser equipment
- £574k on electron- and other microscopes
- £199k on high speed cameras and imaging facilities.

In line with our three-level strategy, *Programme Research* activity investment is the largest in value and highly specialised. Significant investment to support research at all activity levels includes computation, microscope and imaging systems.

Laboratory and Facility Refurbishment

- Chemical Engineering invested £9M in pilot-plant laboratories (1000 m^2) to establish a pilot-scale CO_2-capture plant with a state-of-the-art control room. The Qatar Carbonates and Carbon Storage Research Centre (QCCSRC) equipped three new laboratories, as detailed above.
- The Aeronautics Department invested £736k on equipment in the refurbished Structures laboratory and a new Hydrodynamics Laboratory that houses a water flume and associated equipment. Significant investments in new laboratories for Micro-thruster and Nano-Composite research and a flight arena for autonomous Micro-Air Vehicles were made. A dedicated technology workshop will house high precision micro laser cutting machines and 3D rapid prototyping printers. Over the next three years, an investment of £3.1M will be made in equipment and wind tunnels in the refurbished, dedicated Aeronautics research laboratories.
- The Aeronautics and Mechanical Engineering Departments have spent £37M to date on refurbishing the main research laboratories. Work has now started on refurbishing all the remaining research laboratories, teaching areas and office space, at an estimated total cost of about £63M. This last phase will be completed by 2017.
- In Earth Science and Engineering, the £1M Clean Room, constructed in 2006, is being upgraded and doubled in size (to 71m^2) at a further cost of £1.1M. A general laboratory (72m^2), to be used for isotope sample preparation, is being constructed at a cost of £0.7M. A further 70m^2 of general laboratory space will be converted to clean space during 2014. This will accommodate the activity of recent appointments (Prytulak and Willbold).

D.3 Research Funding Portfolio and Future Plans

The research funding portfolio is described both in terms of *research income*, as detailed in the REF 4 documentation, and *grants awarded*, to demonstrate the vibrancy and sustainability of the research.

Portfolio Balance

The UoA has a large and vibrant research funding portfolio, which has grown consistently over the REF period.

Income (REF 4 data) Portfolio

Total research income during REF was £179.9M. Annual income grew from £28.9M (2008/9) to £45.8M (2012/13) during REF (Figure 2), a growth of 58.6%. The research income portfolio continues to be well balanced, with funding from UK and EU Research Councils, and industry currently being about equal.

Research income from UK Research Councils, Charities and Government grew from £17M (2008/9) to £19.5M (2012/13) over the REF period. As a proportion of the total income this has decreased from 59% to 42%, due to the significant increase in industrial research support.

Since 2008, there has been significant growth in industrial research income, increasing from £9.1M in 2008/9 to £20.6M (225%) in 2012/13, and now making up 44.9% of the total research income. It is anticipated that industrial income will continue to grow in line with our strategy to support growth into *Programme-level Research*, and long-term, large value industrial funding, such as the Rolls-Royce, Qatar and Rio Tinto Centres.

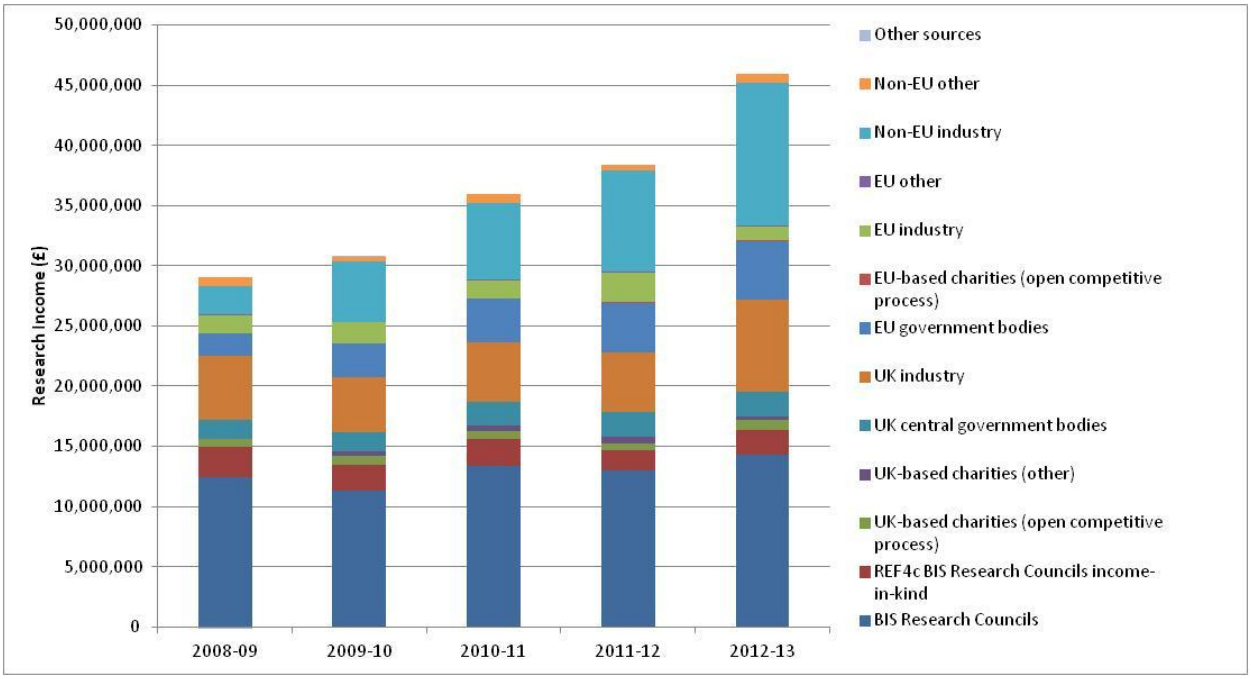

Figure 2: Total Annual Research Income (REF 4 data)

The global reach of our industrially funded research is evidenced by the significant fraction of income coming from beyond the UK and EU; 18.9% of the total income over the period. Growth in the international part of the industrial income portfolio also has been significant; funds from industry beyond the EU currently constitutes 57.3% (£11.8M) of all industrial research income, a five-fold increase from £2.3M in 2008/9 when it only made up 25.6%.

Research Grants Portfolio

During the REF period, the total value of grants awarded was more than £224M. The value of grants awarded increased year-on-year by more than £2M on average. The research grant portfolio is well-balanced with all industry and RCUK contributing approximately equally, and together making up 81% of the REF research grant portfolio. Of the total grants awarded, 26% came from industry beyond the UK and EU, while European Council funding contributed 17%.

D.4 Consultancies and Professional Services

Consultancies

ICON (Imperial Consultants), is a wholly-owned subsidiary of the College which provides consultancy and laboratory services to industry, commerce and government agencies. Staff have the opportunity to use 1 day a week to do consultancy.

The consultancy income through ICON to the UoA was more than £19.5M during the REF period, completing almost 1000 projects. More than 40% (£7.9M) of the consulting activity was from large value projects (>£100k) for 36 organisations, including BG, BP, Chevron, Total, Unilever, Hyundai, Shell, Rolls-Royce and Sinopec.

Technology Transfer

The UoA works very closely with *Imperial Innovations*, an independent company established by the College to combine the activities of technology transfer, company incubation and an early stage venture-capital fund.

During the REF period, Imperial Innovations formed five spin-out companies based around technologies from this UoA:

- Permasense Ltd manufactures and markets wireless corrosion monitoring for extreme installations; offshore oil and gas rigs, refineries, chemical processing and power generation.
- Impression Technologies Ltd commercialises a forming process for aluminium to produce automotive and aerospace components.
- HexxCell Ltd markets technology to increase the efficiency of heating and cooling stages in oil refining.
- iRock Technologies provides innovative digital core analysis software and services to improve recovery in conventional and unconventional oil and gas reservoirs.
- Sub-Salt Solutions develops and commercialises full-waveform seismic tomography for oil-and-gas applications (in the process of being launched).

During the REF period, staff from UoA12 made 276 new invention disclosures, which have resulted in 200 pending and granted patent applications and 34 commercial licence agreements. Licence income since 2008 exceeded £2M, and spin-out equity realisation was £9.3M, mostly from the sale of Ceres Power (Brandon).

E. Collaboration or contribution to the discipline or research base

E.1 Research Collaborations

We pursue collaborations that enhance our research strategy; within the UoA, across College, with other Universities and Industry. Collaborations, in line with the research strategy, are targeted in three categories:

- *Exploratory Collaborations* are with institutions and researchers to establish research in new areas. These collaborations are encouraged through travel funding and PhD studentships. Successful collaborations result in joint publications and winning *Developmental Research* funding. Virtually all staff have *Exploratory Collaborations* with other Universities.
- *Developmental Collaborations* are between researchers, both within Imperial College and at other universities or industry. *Developmental Collaborations* are exemplified by researchers having collaborative research grants. Evidence of *Developmental Collaboration* success includes publications, invited lectures, and *Programme Research* funding.
- *Programme Collaborations* result in, and support Centre or RCUK Programme research activity. These are long-term collaborations between Departments, Universities and industry, with research supporting students, staff and facilities. Establishing and maintaining *Programme Collaborations* is a key strategic goal. Collaboration with industry is one of our great strengths and is evidenced by the significant proportion of our research income (44.9%, £20.6M in 2012/13). Most of our industrial collaboration is *Programme Research*; the Rio Tinto, Qatar, AVIC, SKF, CPSE and TMF Centres, together are worth £65M, and were detailed in Sections B and D.

During the REF period, we have had more than 300 *Exploratory* and *Developmental Collaborations* with UK Universities, more than 450 such collaborations with International Universities and Research Institutes, and 500 industrial collaborations.

Collaborations within Imperial College London
Imperial College establishes and supports strategic cross-departmental and cross-faculty activities that act as a focus and facilitate *Programme Collaborations*, which in many cases include industry. The Energy Futures Lab, Manufacturing Futures Lab and Industrial Biotechnology Hub involve the four Departments of this UoA at their core, and have resulted in, for example, the *Scaling up Synthetic Biology* Frontier Engineering Award [EP/K038648], *Sustainable Chemical Feedstocks* [EP/K014897] and the *Grand Challenge in Nanocatalysis* [EP/K035274].

Examples of cross-College *Programme Collaborations* were noted in Section B, and include the EPSRC Programmes in Laminar Flow (AE and Mathematics) and Ductile Composites (AE, CE and Chemistry), and the Centre for Advanced Structural Ceramics (ME and Materials).

Programme Collaboration, industry-funded research Centres hosted in the four Departments collaborate across other Departments in College (see Section B), for example:
- The £4.2M Rolls-Royce Nuclear UTC (CE, ESE and Materials).
- The £55M Qatar (QCCSRC) Centre (CE, ESE and Chemistry).
- The £12M Rio Tinto Centre (ESE, Chemistry and the Division of Molecular Biosciences).

Collaboration with Industry and other UK Universities
In many cases, the industrial *Programme Collaboration* extends beyond College to include other universities, for example:
- The BP International Centre for Advanced Materials is a 10 year, $100M collaborative research programme between Imperial, Manchester, Cambridge and Illinois.
- The Rio Tinto Centre that integrates activities from ESE, Chemistry at Imperial, Physics at Cape Town and Kings' College London, the Manchester University Diamond facility, Chemical Engineering at Nottingham and University College Dublin.
- The UK Research Centre in NDE (RCNDE) has its headquarters in Mechanical Engineering at Imperial and is a collaboration between six universities (Imperial, Bristol, Warwick, Nottingham, Bath, Strathclyde) and 16 end user companies.
- The Centre for Process Systems Engineering (approximately £6M annually) has its centre of gravity in CE and includes ESE, Computing and Civil Engineering and UCL's Chemical Engineering Department.

International University and Industry Collaborations
In addition to the *Programme Research* activities noted already, further examples are:
- The Skolkovo Foundation sponsored programme in Industrial Energy Efficiency.
- CE participates in the Novartis-MIT Centre for Continuous Manufacturing as a subcontractor to MIT under the main award between MIT and Novartis. In this USD$1.451M sub-award CE work on the use of solvent stable membranes for continuous purification of pharmaceuticals.
- Gupta is Long Term Science Planner on NASA's Mars *Curiosity* Rover mission.

E.2 Support for and Exemplars of Interdisciplinary Research
The *Programme Research* activities described in Section B epitomise interdisciplinary research. Strategic support is given to these Centres; Departmental support includes refurbished laboratories, specialised equipment and high-speed computation and PhD scholarships. In some cases, staff appointments have been made specifically (eg Hadler) to ensure sustainability.

An exemplar is the Rio Tinto Centre mentioned above. A non-industrial example is the EPSRC DTC on *Theory and Simulation of Materials*, based in the Department of Physics that involves 50 academics from 5 Departments (including ME) across the faculties of Natural Sciences and Engineering.

E.3 Research collaboration with Research Users (including industry)
Industrial research users span research and consulting (see D, above). Our *Programme Research* activities generally have industrial involvement, and, in many cases, are fully industrially funded. The Rio Tinto and Qatar Centres and the UTCs are significant examples. The significant

proportions both of the research income and grants from industry attest to the close collaboration with research users.

In the UoA, the salaries of 13 staff are part- or fully- funded by industrial research partners (Thornhill, Wang, Nikbin, Sherwin, Boek, John, Krevor, Johnson, Cilliers, Neethling, Jackson and Muggeridge). These positions ensure close collaboration and communication with the companies.

E.4 Leadership in the Academic Community

The UoA makes a significant contribution to the wider research base and influences the discipline by acting as journal editors (77), organising conferences, and presenting keynote and plenary addresses.

The scale and breadth of our research contribution to the discipline has been independently recognised through, amongst others, prizes and medals (45, including Royal Academy of Engineering Silver Medal; Livingston 2009), new FREng (10; Brandon, Thornhill, Imregun, Taylor, Pantelides, Cilliers, Spikes, Plant, Pistikopolous and Curtis), an FRS (Cawley), and honours (Brandon OBE – "for services to relations in science between the United Kingdom and China"), during the REF period.

During the REF period, the UoA served on more than 130 funding panels and boards. Notable examples are:

- Blunt acted as BP's Principal Testifying Expert for Phase 2 of the Deepwater Horizon Civil Trial, presenting calculations of the volume of oil spilt during the accident.
- Sephton serves on STFC Space Science Advisory Committee and Astronomy Grants Panel;
- Collier is on the US National Science Foundation Grant Panel for Marine Geology;
- Shah serves on the EPSRC Manufacturing SAT and the BBSRC Industrial Biotechnology and Bioenergy Strategy Advisory Panel;
- Cilliers is on REF Panel 15 (General Engineering);
- Brandon was appointed (by Sir John Beddington) to the review panel for the use of Science by DECC.

The UoA presented more than 250 keynote and plenary lectures and were involved in organising 260 conferences during REF. Examples of significant conferences with eminent speakers organised by the UoA are:

- ESE organised the "*100 Years and Beyond: Future Petroleum Science & Technology Drivers*" conference (2013) with presentations by Lords Browne and Oxburgh. Topics included climate change and carbon sequestration, sustainable energy systems and unconventional resources.
- *Green Aviation* Symposia were held in 2011 and 2012. Presenters included Willie Walsh (BA), Ric Parker (Rolls-Royce), Alex Krein (Airbus), Steve Ridgway (Virgin Atlantic) and Jean Botti (EADS).
- The first *UK Chemical Engineering Conference* in a decade (*ChemEngDayUK 2013)* was organised and held in CE, attended by 270 academics, researchers and students.

SUMMARY

Over the REF period the UoA has increased:

- FTE(A) submitted by 15%;
- research income, which doubled to £179M (£972k/FTE);
- industrial research income to £69.5M, now 38% of the total.

The UoA invested more than £70M in research facilities and more than £26M in research equipment, and published 31 papers in *Science* and *Nature* journals. It started 5 new spin-outs, and realised £9.3M from mature ones. Staff are recognised research leaders; 18 are now Fellows of the Royal Academy of Engineering, and 7 are Fellows of the Royal Society. During the REF period 10 were made FREng, one FRS and one awarded an OBE.