Institution: Department of Chemical Engineering and Biotechnology

Unit of Assessment: UoA12

a. Overview The Department of Chemical Engineering and Biotechnology (CEB) is part of the School of Technology. Its vision is to underpin research pertinent to technology, methods and processes. CEB was established in 2008 through a merger of the Department of Chemical Engineering and the Institute of Biotechnology. Research is organised around three strands (processes, healthcare and materials), with flexible clustering of research teams, and recognition of key cross-cutting themes such as metrology. Academic staff undertake research activities across one or more core areas of fundamental science, within a culture of collaboration and entrepreneurship, providing a platform for new research with social and economic impact.

b. Research strategy

In RAE 2008, the Department of Chemical Engineering and Biotechnology (CEB) identified its strategic aim to "fuse leading-edge biotechnology research with chemical engineering skills within an ethos of commercial awareness and exploitation". Its research strategy targeted sustainable reaction engineering, product engineering and healthcare. During the research period, CEB has reviewed this portfolio, aligned with outputs of the World Economic Forum**,** in the global drive for sustainable resources. This has highlighted its work on functional materials and microstructure engineering, broadening its sustainability-focussed research strategy around three strands (as proposed by the World Business Council for Sustainable Development) – processes, healthcare and materials. The Department has delivered this through fundamental investigation in core areas such as process research (in which around 30% of its academic staff are active), reaction engineering (~30%), materials (~30%), modelling (~30%), metrology (~30%) and biotechnology (~40%). As these percentages indicate, many staff work across two or more core areas, highlighting cross-cutting activities which support its strategic direction.

***Processes*.** Given the central importance of energy efficiency within the sustainability agenda, CEB chairs the steering group of Energy@Cambridge (one of the University's Strategic Research Initiatives [SRI]), and hosts two initiative co-ordinators. Research in the Department highlights economically-sound processes, understanding and minimising negative environmental impact:

- Kraft has developed multi-scale models for soot formation in combustion devices, directly impacting low-emission Tier IV final compliant non-road machines
- Fisher has developed bioenergy technologies, showcased at international design festivals, that will be further developed within the Campus for Research Excellence and Technological Enterprise (CREATE) in Singapore
- Chase has produced an innovative microwave process, driving up recycling rates through separation and recovery of high-value chemicals present in wastes (Enval case study)
- Cardoso has shed light on the complex dynamics of multiphase plumes and how they mix and spread in the atmosphere or ocean. Work in this area has already allowed consideration of the spread of chemical spills, such as the oil and methane plume in the Gulf of Mexico and the radioactive release at Fukushima.

We continue to develop research tools to extend our understanding of complex multi-component, multiphase systems from the molecular scale through to modelling process operation. Within this framework there exists a strong interest in aspects of fouling and cleaning:

- Holland has developed a tomographic compressed sensing technique to permit high-resolution measurements of gas and liquid velocity in multiphase reactors
- Vassiliadis' research has produced realistic fouling mechanisms with rigorous optimisation for cleaning heat-exchanger networks
- Wilson has created effective tools to allow oil refineries to reduce fouling-related emissions
- Moggridge (in collaboration with Zoology) has achieved environmentally friendly mitigation of invasive zebra mussels in water supplies for the first time (Biobullets case study)
- Fundamental work by Barrie has developed understanding of the widely observed compensation effect in reaction kinetics, sparking international interest that may impact process design.

Metrology is centrally important in these challenges. CEB staff have developed innovative, robust sensors for real-time measurement of moisture vapour in industrial processes (Williamson), and

reported the first MRI measurement of bubble distribution in gas-liquid flows (Gladden) and ultra-fast sparse MRI to understand gas-liquid bubble flows (Sederman), thus enabling better design of reactors/separators/mixers/heat exchangers. Sederman, Dennis and Holland have also applied ultra-rapid MRI to observe fluidised beds. This has advanced our core understanding of chemical reactions and physical phenomena within such processes, enabling predictive process models, design and testing of new reactor types, and quantification of sustainability of new processes. Life cycle assessment (LCA) has been advanced by Dennis to validate environmental efficiency for processes at different stages of development, including methods of sustainability assessment.

In the more specific area of heterogeneous catalysis, the Magnetic Resonance Research Centre (MRRC) has worked closely with Johnson Matthey and ExxonMobil to develop new *in situ* /*operando* methods to characterise competitive adsorption processes in catalysts, demonstrated to aid catalyst design and selection, and aspects of process operation - such as solvent selection. The development of these methods was the result of translation of methods developed by Mitchell for characterising rock core wettability; demonstrating the value of understanding the core physical/chemical processes occurring in porous media which can then be used across technology platforms. This work has been undertaken in a long-standing (>10 year) collaboration between MRRC and Schlumberger Cambridge (now Gould) Research. D'Agostino has also shown that NMR relaxometry has great potential to become an important catalyst characterisation tool, supporting an increasing interest in catalysts for next-generation energy production and product design. Fairen-Jimenez for example, has revealed unexpected structural flexibility on prototypical MOF for hydrogen and methane molecular sieving.

Healthcare. During the REF census period, CEB has extended its work (recognised in RAE 2008) on the formulation and delivery of sustainable highly potent biopharmaceuticals, to include the clinical interface – thus greatly broadening the scope for healthcare innovation. For example:

- Simplified, low-cost purification strategies to reduce overall cost of downstream processing, as exemplified by Lowe's novel manufacturing process for the £10M/g glycoprotein Factor VIII
- Slater's live bacterial oral vaccine formulation for Typhoid/ETEC
- A pre-API patent for an antimalarial drug based on artemisinin, helping to improve extraction in East Africa and Argentina (Lapkin)
- Mantle's pioneering quantitative multi-nuclear MRI techniques, addressing the pharmaceutical industry's "Quality by Design" (QbD) driver for drug development, to quantify and visualise behaviour of drug release.

Through an imaginative combination of biological science with electronics and materials science, CEB has, since 2008, made innovative progress in other sustainable healthcare technologies, e.g. designing novel heart valves (Moggridge), creating prophylactic nipple guards for nursing mothers in HIV endemic regions (impact case study), and developing smart contrast agents for ultrasound imaging (Hall).

In the area of metrology researchers have broken new ground in remote diagnosis and monitoring, including an inspirational RGB 3-channel lab-on-a-phone (Hall, with Nokia), the use of biomarker discovery directly integrated with diagnostic test development (Bahn, Psynova case study), and patient-centred holographic measurements (Lowe). In the area of imaging, highlights include the first mathematical theory accurately describing super-resolution microscopy (Rees) and pioneering super-resolution imaging of neurotoxic protein aggregation in neurones (Kaminski).

Materials. Research continues with a **microstructure engineering cluster,** to understand how to manufacture multiphase materials with structures at the micro- and nano-scale, and with desired characteristics, quality and sustainability (which determine the performance of a material or a product), directly impacts product and process design. This includes structured and colloid materials and bridges to the processes theme:

- Flow of solids and pastes continues to be an area of expertise; including Rough's work on the flow behaviour of hardmetal pastes incorporating viscoelastic binders, and Scott's discrete element modelling to characterise axial segregation of particles in horizontal rotating cylinders
- Wilson's work on micro-structured materials, found as fouling deposits on heat transfer surfaces that is closing the loop in fouling-cleaning cycles
- Routh's work on self-assembly of colloidal particles into bespoke multi-functional materials.

Fusion of leading-edge biotechnology research with chemical engineering (as proposed in

RAE2008) has also opened new areas of interest with this theme, with functional materials, aligning to the University's Synthetic Biology Initiative and its NanoForum:

- Hall has reported the first use of synthetic biology to produce an electrochemically 'wired' enzyme that uses an electrode as its substrate
- Slater has developed a theoretical basis for smart-nanostructured drug delivery formulations
- Christie, who is working on applications for bacteria (with a focus on animate materials), has shown the strongest evidence for the origin of the germinant binding site in bacterial spores and has solved the crystal structure for one of the key enzymes involved in spore germination
- Tunnacliffe has shown the catalytic and chaperone-like functions of intrinsically disordered proteins, which impacts designs for storage and packaging as well as the debate about life without water or in harsh environments such as Mars. Bains has also looked at life in other environments and proposed methods for its identification.

In the area of metrology, this strand also includes development of methods in MRI, terahertz imaging and X-ray microtomography, to identify structure-function relationships. This area attracts high industrial (and clinical) interest. One highlight is non-destructive terahertz imaging technology, where Zeitler – under TSB funding, and in collaboration with a local SME (TeraView) – has transformed terahertz technology from a niche technique, enabling materials design to be linked with hardware, and signal-processing techniques to be translated into high-value manufacturing applications. From this work, applications initiated in one field are being deployed elsewhere, e.g. to measuring the uniformity of pharmaceutical coatings (Oystar-Manesty), or to quality control of the manufacture of vehicle coatings (Aston Martin Lagonda).

Looking forward, a prime objective of the Department is to capitalise on opportunities presented by a new state-of-the-art building to house its research on one site at West Cambridge from 2015 (see section d below). The building adopts an inspirational design promoting the interdisciplinary interface and the reconfigurable research clustering that has been the strength of CEB to date. The current research strategy and thematic structure will continue. We look forward to continuing to extend our research activities into increasingly complex systems (e.g., metabolic and disease-specific genetics) and taking research through from our fundamental research skills in chemical engineering, biotechnology and physical chemistry, into translation. In these endeavours CEB will benefit from closer engagement with researchers in Materials Science & Metallurgy, and the Institute for Manufacturing (IfM) who will be immediately adjacent to the new CEB building.

The Department will also continue to develop 'off-shore' collaboration, increasing its capacity to promote sustainability worldwide. Key to this strategy will be the use of excellence in CEB research outcomes to initiate outreach, both in commercial partnerships and international academic collaboration. In particular, links are being forged with the Middle and Far East that will develop over the next decade – e.g. 2013 saw the inauguration within CREATE of the Centre for Carbon Reduction in Chemical Technology (C4T), with Kraft as Director, involving both Nanyang Technological University (NTU) and National University of Singapore (NUS). C4T's research focus, in collaboration with CEB, is on minimising the carbon footprint of industrial-scale chemical processes. (See section e below for further details.)

c. People

Staffing strategy and staff development. Since 2008, in line with the strategy outlined in the RAE, CEB has increased its established academic posts by four (to 26), despite the departure of Mackley (retired), Murray (to a chair in Cardiff) and Johns (Winthrop Professor, UWA Australia). Four further unestablished appointments have also been made. With 25% of established staff submitted in RAE 2008 now within ten years of retirement, recent attention has focussed on balancing the strong mid/late-career profile with early-career appointments, and on investment in a Career Incubator programme for early-career independent researchers. Key elements of the Department's staffing strategy are as follows:

- *Mid-career and senior staff appointments:* In line with RAE 2008, CEB invested in a new Chair in Sustainable Reaction Engineering (Lapkin) to complement the existing Sustainable Processes and Products team, and appointed Bahn to a Lectureship and subsequently a Chair in Healthcare Biotechnology. This introduced a clinical interface to sustainable healthcare and

broadened the scope for healthcare innovation.

- *Early-career appointments and succession planning:* Further recruitment has been made to support cross-cutting themes. Holland, with skills in fluidisation and magnetic resonance techniques, is developing research capability in capacitance tomography and numerical simulation of multiphase flows and reactors, to combine metrology with processes (alongside Sederman, whose appointment was established in 2009 in MRRC). Another early-career appointment (Christie) adds an important nano-biotechnology capability between healthcare and materials, reinforcing CEB's commitment to bio-innovation. Two further appointments (Zeitler and Rees) strengthen the metrology research in terahertz and super-resolution laser imaging respectively, widening the scope of technology offered. The appointment to unestablished Lectureships of Hallmark, Williamson, Mahbubani and d'Agostino – each of whom brings valuable industrial experience, facilitating transfer to industrial end users – further strengthens the research base.
- *Early career incubator:* Good progress has been made with developing CEB's career incubator scheme for independent researchers. These ECRs are provided with mentoring in both teaching and research. The number holding Fellowships has increased from 10 in RAE 2008 to 15 (of whom four are female [zero in RAE 2008]) – including an Oppenheimer Fellow who has progressed to lecturer in the Dept of Engineering; an RCUK Advanced Fellow who now holds a Chair in CEB (Bahn); a Junior Research Fellow who was appointed to a Lectureship in CEB (Zeitler); and three Fellows who have taken up Lectureships elsewhere (Imperial, Loughborough, Reading). Others included five Marie-Curie Fellows, EPSRC Fellows, an RAE/EPSRC Fellow and merit Fellowships awarded from home countries of Sweden, Switzerland and Spain. A current Royal Society University Fellow (Fairen-Jimenez) is an important asset in the CEB materials agenda, using molecular simulations, advanced experimental techniques and synthesis to design new nanoporous materials, contributing to future catalysts and drug delivery, as well as the CO_2 capture drive. CEB's v*ision is that the numbe*r of independent researchers hosted in the career incubator should double over the next three years (when the Department occupies its new building), alongside a moderate increase in postdoctoral researchers to around 70.

The University has signed up to the Concordat to Support Career Development of Researchers, providing a comprehensive range of compulsory and voluntary training for early and mid-career staff, covering research, teaching, administration and leadership. Promotion is through a highly-structured and competitive annual exercise (with final decisions made by a Committee chaired by the Vice-Chancellor), and requires evidence of significant international research reputation, supported by objective criteria. CEB has been successful in promotions to Chairs for Bahn, Dennis, Kaminski, Kraft and Tunnacliffe; with Moggridge and Routh being promoted to Readerships.
In 2012, postdoctoral researchers (including Research Fellows) became the largest staff group in the University (>3500 of 9500); in response, the University has embarked on a £300m property development in North West Cambridge, due 2015-16, to provide high-quality and sustainable housing for more than 600 postdocs and their families, as well as graduate students.

Equality and diversity. CEB's equality and diversity policies and practices are aligned with those of the University as a whole (including its policies on Equal Opportunities, Dignity at Work, and Disability and Employment), and the Department provides mentoring for all new staff within the University's staff development programme. In 2011-12 the University won several awards for its work in engaging and working with staff, and became the highest-ranked UK HEI on the Stonewall list (2012 and 2013). Alongside generous maternity and sick leave arrangements, the entitlement to sabbatical research leave was taken up by around 60% of eligible CEB staff during the census period.

In order to increase applications to advertised positions from eligible women CEB has introduced development workshops (e.g. "New Perspectives for Women") and mentoring schemes designed specifically for female researchers. The University has a new scheme to provide financial assistance to returning carers in building up their research profiles and other academic activity after a period away from work. Members of CEB are encouraged to participate in the Women in Science, Engineering and Technology Initiative (WiSETI) – on whose committee Hall sits – and to contribute to a University-wide promotional venture, attracting EPSRC funding, portraying successful women in Cambridge. CEB will submit an application for a bronze-level Athena SWAN

award in 2014 (co-ordinator, Rough) underpinned by the University's submission of its bronze renewal application. CEB has 3 female professors on its staff; giving a % of female professors above the national average for the field and the University overall and STEMM average.

Research students. CEB recruits doctoral students from diverse backgrounds, both in terms of first degree and nationality. Around 33% have an MEng in Chemical Engineering; 13% enter with a BSc in Chemical Engineering, with the remaining 54% holding degrees in Engineering, Chemistry, Physics, Biology, Biotechnology and Biochemistry. We attract postgraduate applicants from across the world: typically 20% EU (other than UK), 50% Asia, and 10% North America. Student numbers have risen gradually from 22 new starters in 2008 to 40 in 2012/13. Circa 15% have received direct industrial or CASE awards (worth around £2m); 25% are RC funded, 20% funded from University trusts, and 25% privately funded.

As well as the Department's own DTG PhD studentships it also participates in other University-wide DTC/DTP studentship programmes including NanoDTC, the Photonics Systems Development CDT and BBSRC Doctoral Training Partnership. The progress of all PhD students regardless of their funding is overseen by the Director of Graduate Programmes (Routh). The progress of each student is presented as a Postgraduate Passport with targets and deliverables to assist development and provide feedback, supporting stage-gate assessment and decisions for progression. CEB adheres to recommendations in the Roberts Report, participates in the University's Researcher Development Programme (annual spend of £1.1m), and provides a comprehensive rolling programme of transferable skills training for all graduate students and researchers, including a weekend skills and team-building exercise away from Cambridge.

Graduate students also participate in the management of CEB: four PhD students and two MPhil students sit on the Staff-Student Consultative Committee and one elected representative also sits on the Department's governing Syndicate and the Graduate Education Committee. By this mechanism their interests are articulated and heard at all levels within the Department.

Academically, the research students have won numerous awards, both within Cambridge and globally. They have presented around 400 posters and gained awards at more than 30 meetings, as well as other recognition including the Ronald Belcher award (RSC) for electrochemically connected enzymes, and the Clinton Global Initiative University Outstanding Commitment Award for JustMilk (preventing HIV transmission in breastfeeding). International academic exchange is also encouraged – for example, project collaborations with German research institutions have led to more than 12 Diplom students undertaking research in CEB.

d. Income, Infrastructure and Facilities

As reported in RAE 2008, the merger of Chemical Engineering and Biotechnology created a sound infrastructure, with outstanding facilities to enable innovation in sustainable processes, healthcare, and materials. The main focus of the Department in the REF period has been to enhance these capabilities, in order to respond to current and future manufacturing and healthcare drivers.

Total research spend was around £28 million in the five-year period from 2008/9, an increase of more than 30% compared with RAE 2008 (£27.5m in 6.5 years). Taking into account dates of appointment, this translates into an average per-capita annual spend of around £186k (up from £136k). A greater emphasis has been placed on EU grant funding and industrial collaboration (both within and outside the EU), as part of new partnerships discussed in sections (b) and (e). Collaboration with European industry and academics is strong through FP7 projects (such as TRANSCEND, BiognostiX, Ocmol, Schizdx) and within UK through schemes such as EPSRC Dial-a-Molecule Grand Challenge.

The University has provided around £2m additional funding to match infrastructure investment in the following:

- Refurbishment of the *Reaction Engineering* laboratory (2010), together with purchase of a Fischer Tropsch reaction rig, for research into low-carbon energy and fuels. Processes studied can include conversion of biomass to fuel, chemical-looping reactions for selective removal of CO_2 from combustion, clean H_2 production, and selective catalytic oxidation and manufacture of materials for use in catalytic reactions. This adds to investment in batch and continuous reactors for speciality chemicals and materials manufacture and integrated analysis, including

confocal Raman microscopy, in situ IR spectroscopy, HPLC, GC and tandem mass spectrometry. The laboratory also has a tapered element oscillating microbalance for characterising adsorption/desorption kinetics. Capacity for reaction-engineering modelling and new stochastic particle methods has also been expanded.

- Extension of the *Institute of Biotechnology* – which remains an important CEB brand – to include the Cambridge Unit for Bioscience Engineering (CUBE), established during the RAE period with an infrastructure investment of around £2m. It now encompasses a suite of refurbished laboratories for synthetic work on biopolymers; a further extension (2011) provides specialist laboratories for research on anhydrobiotic engineering under ERC Funding (Tunnacliffe, £2.1m), a prestigious award which was the first of its kind in the University.
- Creation of world-class optical imaging facilities for research on materials and biological samples on the microscale (*Laser Analytics Group* [LAG]), including optical superresolution microscopes, structured illumination microscopy systems, and whole-organism imaging methods. These are key enablers for research to uncover the molecular mechanisms of Alzheimer's disease. LAG is a member of the WT/MRC-funded neurodegenerative disease consortium, and grant funding has come from the Wellcome Trust, MRC, EPSRC, BBSRC and Alzheimer Research Trust UK. The LAG leader (Kaminski) was also co-founder of the Cambridge Advanced Imaging Centre (CAIC) and serves on its management board; initiated in 2010, CAIC has since received funding of more than £7m from the Wolfson Foundation, the University, Wellcome Trust, and MRC. Its mission is to make the latest technical advances in microscopic imaging available to the life science communities.

Other notable developments have included

- Establishment of the *Cambridge Centre for Neuropsychiatric Research* with funding of £5.2m (to 2016) from the Stanley Medical Trust. The Centre is equipped to conduct high-throughput proteomic and cytomic studies on clinical tissue samples (regulated by the Human Tissue Act), in order to identify molecular biomarkers and novel drug targets for improved diagnosis and treatment of neuropsychiatric diseases.
- At MRRC, three new spectrometers have been installed since 2008 bringing the total number to 7. In addition to EPSRC funding, direct industrial investment in MRRC in excess of £2m has included partnerships with Johnson Matthey, ExxonMobil and Microsoft Research Connections aimed at developing new magnetic resonance techniques to be applied in reaction engineering, and the continuation of the partnership with Schlumberger on hydrocarbon recovery; research into food foams and food powder dispersion has been undertaken with Nestle Research Centre in Lausanne; while AstraZeneca, GSK, MSD have funded investigations into drug delivery and dosage, alongside the continuing long-established collaboration with Pfizer.
- In the last five years, more than £3m in grant funding has underpinned the *materials* theme. Research topics have included nanocomposites, particulates and polymers (e.g. polymer nanocomposites for improved prosthetic heart valves, for the British Heart Foundation); and biological, multiphase and smart materials (linked to CEB's healthcare and processes strands). Applications range from fouling and cleaning (e.g. Procter & Gamble, Tioxide Europe) through sensing (e.g. BBSRC; Paramata) to Marmite (Unilever).

Despite infrastructure investment, CEB has now become challenged by space. In July 2012 the University approved a new CEB building in the heart of the University's West Cambridge science campus, and construction has now begun. Costing £60m, the building will offer 6,300m² net usable space over four floors of offices and three floors of laboratories, accommodating the whole Department on one site, and designed to realise its vision of an interactive environment of research excellence that promotes enterprise. The building will focus on core chemical engineering and biotechnology, reinforcing its sustainability-focussed research strategy around the three strands of processes, healthcare and materials (with cross-cutting activities in metrology and modelling). It will also support and promote versatile research clusters and exchanges, and allow alignment to strategic initiatives adopted by the University. Additionally, the University is making a £20m investment to provide an energy-efficient high-performance computing centre on the West Cambridge site that will house the Department's computing cluster.

e. Collaboration or Contribution to the Discipline or Research Base

Strategic collaboration. Recognising the impact of globalisation on future research, CEB has placed particular emphasis on forging links with the Middle East and Far East. Sino-Cambridge collaboration is being pursued as a priority; honorary chairs have been established with Tianjin University of Science and Technology (Slater), Beijing University of Chemical Technology (Gladden), NTU Singapore (Gladden), and several other formal collaborations have been initiated (e.g. work under a BBSRC China Partnership Award has led to a new optical imaging technique which has secured further bilateral research funding).

Also in Asia, the Cambridge-Singapore CREATE programme "Centre for Advanced Research in Energy in Singapore" (CARES) was approved for funding in 2012 by NRF, Singapore (CEB Director in Singapore, Kraft). The initial project within the Centre is C4T, which involves the reaction engineering team at CEB; the electronic and information engineers in Cambridge's Dept of Engineering; and (in Singapore) both NTU and NUS, as well as close collaborations with the National Climate Change Secretariat, the Economic Development Board and the Energy Market Authority; total project funding is ~£35m. The project will include 40 PhD students and 20 PDRAs, and aligns with CEB's strategic plan for sustainable process engineering, seeking to reduce the carbon footprint though process modification and new engineering technologies (e.g. integration of energy flows on Jurong Island into a smart grid energy distribution system across Singapore).

CEB is also taking its existing Cambridge-based collaborations to Singapore with Johnson Matthey and ExxonMobil, as well as setting up new collaborations with Singapore-based companies such as Memsys, IBM, DLRE renewable energy solutions, Horizon fuel cell technologies and the ITC corporation. Another strategic partnership is developing with Saudi Arabia and the King Abdulaziz City for Science and Technology through the KACST-Cambridge Research Centre, which receives patronage of His Highness Dr Turki S AlSaud. At present the Centre involves three Cambridge Departments (Physics, Engineering and CEB) and works on five strategic themes, including biotechnology for high valued healthcare products (led by Slater).

Research collaboration. As well as CEB being in itself a multidisciplinary environment, its staff are proactive in collaboration across the University. CEB staff lead the University's Strategic Research Initiative in Energy (Energy@Cambridge) and its Strategic Network for sensors (CamBridgeSens). They are also active within two further University Strategic Initiatives of Neuroscience and Infectious Diseases. The Department also partners with the BP Institute for Multiphase Flow, IfM, the Nanoscience Centre, Physics of Medicine, and many colleagues across the School of Biological Sciences, Addenbrooke's Hospital and others. To take just one example: in a radical re-think about reactor design and operation, CEB is part of an industry-funded initiative involving Plant Sciences, Biochemistry and Engineering, and a major oil company, to scale-up and intensify algal production and downstream harvesting so that it is sustainable and economically competitive, thus securing a greener energy source for the future.

CEB staff also work jointly with many universities worldwide to bring together critical expertise in support of new approaches. For example, energy efficiency/fouling in oil refining is being investigated together with Guanajuato University, Bath, Imperial and British Columbia, while Bath, Porto, TU Braunschweig, TU Dresden, Granada, Tsinghua, Santa Fe, and Canterbury (NZ) have joined forces to investigate fouling and cleaning for FMCG, water, food and pharmaceutical applications. Such collaborations are particularly evident in the healthcare strand. Since RAE 2008, the strategic expansion to include the clinical interface has been reinforced by the links (through Bahn) to the Erasmus Medical Centre, Rotterdam. This imaginative collaboration allows resources to be shared and access to clinical samples and data to be used in support of the clinical translation of research within CEB. The group is now focussing on unravelling the molecular mechanisms of schizophrenia to develop blood-based diagnostic tests for psychiatric disorders with Stanley Medical Trust funding (Psynova case study). Similar collaborative approaches have enabled ultrasound contrast agent bubble technology, to begin to enter clinical study through a Wellcome Trust ISSF clinical internship and collaboration with Cambridge Health Partners.

CEB has also collaborated extensively with Cambridge's Institute for Manufacturing (IfM) and other partners. The outcome of collaboration on sustainable, cost-efficient light sources has been widely exhibited in the design industry in the form of a small-scale photovoltaic device/table, which generates enough power to illuminate a lamp; this was demonstrated at the Royal Society's 350th Summer of Science Exhibition, and subsequently featured in *New Scientist*. CEB and IfM are also involved in collaboration with European-based SMEs and the research organization VTT (FL),

developing a generic diagnostic for infection that can be configured at the point of manufacture; and as co-partners with Bath's Centre for Sustainable Chemical Technology in a global research collaboration with academics in Germany, Norway, France, Portugal, Spain, Denmark, Sweden and USA, improving technology for production of antimalarial drugs, with biomass and raw material suppliers from Africa, Madagascar, India, Vietnam, China and Argentina.

Similarly, Saskatchewan, Milan, Leoben, and Belfast have come together with CEB and industrial partners to investigate paste processing in innovative and responsive manufacturing (hard metals, pharmaceuticals, food), while Santiago de Compostela and South Carolina have added to core CEB expertise in collaborations on microstructure engineering of complex fluids, rheology, and processing. MRRC continues to collaborate with numerous academic and industrial partners; long-established academic partners include Queen's University Belfast, and the Universities of Birmingham and Cardiff, as well as being members of the EU FP7, OCMOL consortium.

Staff at CEB are encouraged to undertake consultancy work, which in many cases leads to project collaborations. Indeed, CEB's historic strength at the business interface, in both product design and entrepreneurship, has been further reinforced through a new mid-career recruitment strategy focussing on industrial secondment and on independent researchers with experience in entrepreneurship and exploitation. This has been initiated with a Research Fellow working at the enterprise interface (Bains), a Johnson Matthey collaborator (York) embedded within CEB, as well as a secondee (Noda) from MERCE working on aspects of mineral scale formation.

The ongoing strategy is to bring multinational industrial and academic partners and serial entrepreneurs together under the CEB roof. The Department has attracted 23 exceptional international visiting academic staff from all continents, including Prof Soren Keiding (Head of Danish Femtolab, iNANO); Prof. Lisa Zurk (Director of the Northwest Electromagnetics and Acoustics Research Laboratory, USA); Prof. Thomas Rades (Chair in Pharmaceutical Sciences, National School of Pharmacy, NZ); Prof. Sue Harrison (South African Research Chair in Bioprocess Engineering, former Head of Chemical Engineering, University of Capetown). The number of relationships with industry have increased by around 12% since 2008.

Committees and Councils. CEB members have served on national and international governance, strategy or advisory committees including: Royal Society Council; Home Office Science Advisory Committee; NICE Diagnostics Advisory Committee, EPSRC Council; Government Decontamination Service; Board of the Royal Commission for the Exhibition of 1851; BIS Research Sector Transparency Board; EPSRC Technical Opportunities Panel; Innovation Strategy Board; ERC PE8 Advanced Grant Evaluation Committee; Chemistry Innovation Knowledge Transfer Network; Gates Biological Sciences Panel; Queen Elizabeth Prize for Engineering; Future Development of NPL Project Steering Group; MoD Strategic Research and Technology Committee; Defra Programme Management Committee; BBSRC BRIC Steering Group; EPSRC Engineering SAT; Joint Advisory Board of Texas A&M University in Qatar; Chemistry & Chemical Engineering Panel of Fundacao para a Ciencia a Technologia; IBTI Club Steering Board; and the Academic Advisory Group for Energy and Carbon Reduction. In addition to RCUK, TSB, Royal Society, Leverhulme, Wellcome Trust and British Council, CEB members also act for funding bodies in around 20 countries, as well as Gates, ESF and Framework Programme 7.

Editorial committees. CEB has provided members of editorial committees for around 30 high-impact journals across the full range of its activities, as well as IChemE Books (Scott). Members have also served in key positions (e.g. International Advisory Panel of Chemical Engineering Science [Gladden]; RSC Publishing Board Science & Publications Sub-Committee [Lowe]; IChemE Publication Awards Committee [Wilson]; Assistant Editor of Transactions of IChemE [Moggridge]; Chairman of the Editorial Board of Analyst [Hall]). Hall was also acknowledged by RSC for her contribution to their Queen's Award for Enterprise.

Conferences and Publication. According to WoS data, around 900 refereed primary research journal papers have been published by CEB staff in the REF period, including: "Hot Article" Phys. Chem. Chem. Phys. (Cardoso); 2009 Most Cited Articles, J. Coll. Int. Sci. (Routh), Green Chemistry (D'Agostino, Gladden, Mantle); top ten accessed articles Sept 2012, Analyst (Hall); and Ricardo Award for best UK paper, IoP, Combustion Physics Group (Kraft).

CEB members have presented work at more than 500 meetings during the census period; at least

10 plenaries have been delivered, with the majority as opening presentations at major international conferences in Asia, USA and Europe. In addition to invited lectures, more than 50 keynotes have been given by CEB staff, including an IET Prestige Lecture (Lowe) and Gates Scholars Distinguished Lecture (Lowe), highlighting the CEB multidisciplinary approach to processes, healthcare and materials. Kaminski won the iNano Distinguished Lecturer award, and Kraft the best paper award at REV2010-Remote Engineering and Virtual Instrumentation; Holland and D'Agostino have both won Young Investigator Awards at international conferences on Magnetic Resonance Microscopy and Catalysis respectively, with Gladden also being announced as the 2014 Bakerian lecturer at the Royal Society.

As a result, CEB members are much in demand in the planning of international meetings. Since 2008 they have contributed to the organisation of more than a dozen international conferences, on the use of energy, chemical looping, fouling and cleaning, metrology, and particles, pastes and colloids. Hall has been elected Gordon Conference Vice Chair 2014 (Chair from 2016); Kraft has become Chair of IChemE PTSG Workshop on population balance modelling for particle processes, and Colloquium Co-Chair at the 32nd International Symposium on Combustion 2008; Sederman has served as Chair for the International Conference of Magnetic Resonance Microscopy 2013; and Wilson as Chairman, Fouling and Cleaning in Food Processing, 2010.

Membership and awards. CEB staff include Fellows of both the Royal Academy of Engineering (Gladden, Chase, Lowe, Slater) and the Royal Society (Gladden). The Department is fully engaged with the professional institutions: >30% are Fellows of the Royal Society of Chemistry, American Chemical Society, and/or the Institution of Chemical Engineers, some holding offices (e.g. RSC VP, Analytical Division 2008, Hall; RSC Treasurer of Colloid and Interface Science Group, Routh) or contributing to subject group committees (e.g. IChemE: Food & Drink, Wilson; Particle Technology, Rough; University Accreditation, Dennis and Wilson). The diversity of CEB expertise is also reflected by elections to other professional bodies (e.g. IoP; Academia Europaea; IPEM; AMPERE; Soc. Automotive Engineers; Combustion Inst; DECHEMA; V. Deutscher Ingen; Royal Coll. Psychiatrists: British Med. Assoc; Amer. Neurosci. Assoc; Brit. Assoc. of Psychopharmacology; World Fed. Soc. Biological Psychiatry; New York Acad. Sci). Recent visiting positions include the DFG Mercator Fellow Visiting Professorship, Duisburg (Kraft), SAOT Laureate Guest Professorship, Friedrich Alexander University, Erlangen (Kaminski), Nanyang Visiting Professorship (NTU Singapore) and Honorary Professor Beijing University of Chemical Technology (Gladden) and TU Braunschweig (Wilson).

Specific merit has been recognised through the following awards: International Young Researcher in Advanced Optical Technologies, 2008 (Kaminski); Alec Hough-Grassby Memorial Award, 2009 (Hall); IChemE Donald medal for Biochemical Engineering, 2009 and 2010 (Chase, Slater); ACES Prize, 2011-12 (Chase); McBain Medal, RSC/SCI 2010 (Routh); Coatings Science International Science Award, 2012 (Routh); BBSRC Commercial Innovator of the Year, 2011 (Lowe); Lowe and Gladden's contributions have been recognised by the awards of CBE and OBE, respectively.