

Institution: University of Birmingham				
Unit of Assessment: UOA 12B: Chemical Engineering				
<p>a. Overview. The Centre for Formulation Engineering (CFE) forms the basis for this submission and comprises research carried out within Chemical Engineering and Physics at the University of Birmingham (UoB). The Centre was awarded a <i>Queen's Anniversary Prize for Higher Education</i> in 2011 for leadership on the national and international stage in formulation engineering, a testament to our underlying driver of international recognition for research carried out by our staff.</p> <p>Research is structured into five focused, interdisciplinary themes shown in the matrix below. Each group is led by two experienced Professors (see table) who ensure a resource balance within their group and across the School. Staff are identified in each group according to FTE below but there is considerable overlap as reflected in the RA2 papers.</p>				
Food, Health & Nutrition <i>Norton & Fryer</i> 7 FTE	Bioengineering <i>O. Thomas & Grover</i> 6.5 FTE	Green Technologies <i>Wood & Simmons</i> 6.5 FTE	Speciality Materials <i>Blackburn & Zhang</i> 8.0 FTE	Energy <i>Ding & Steinberger</i> 4.5 FTE
(i) Diet, Health and Nutrition	(i) Industrial Biotechnology	(i) Catalysis and Carbon Capture	(i) Materials Processing	(i) PEM fuel cells (PEMFC)
(ii) Product Structure and Function	(ii) Biomaterials and Tissue Engineering	(ii) Complex Fluids and Rheology	(ii) Particle Processing	(ii) Solid oxide fuel cells (SOFC)
(iii) Manufacture Safety, Hygiene	(iii) Bioprocessing and Bioenergy	(iii) Green Technologies	(iii) Nano-Engineering	(iii) Cryogenic Energy Storage
<p>Each theme has links to other disciplines, both within UoB and with other Universities both in the UK and overseas. Food, health, and nutrition links with pharmacologists, physicists, material scientists, food scientists, nutritionists, and psychologists, whilst bioengineering interacts with medics, bioscientists and physiologists. Research within green technologies dovetails naturally with chemists and biologists and speciality materials links with physicists, material scientists and pharmacists. Energy draws on wider expertise from mathematics and social sciences.</p>				
<p>b. Research strategy</p> <p>Vision and strategic plans. The Centre's vision is to sustain and enhance our reputation for international quality, world-leading research in the manufacture and characterisation of materials whose complex microstructure (at the nm to μm scale) is instrumental to delivery of a beneficial function, either within a process or to consumers. Working from a base of fundamental experimental and theoretical research in the underlying interfacial and multiphase science, the Centre has honed its expertise to translate and apply this knowledge to a range of challenging industrial problems. This provides a distinctive problem-based research environment.</p> <p>Our strategy is to build and maintain a portfolio of internationally leading research via a broad funding base. We have over <i>£16M in active research contracts</i> from EPSRC and BBSRC (£6.7M), EU (£3.2M), charities (£0.3M), industry (£3.1M) and TSB/DEFRA (£2.7M). Total research spend over the period is £21.5M. Research awards for 2012-13 have risen sharply to £6.8M, an increase of more than 80% on the previous three year average, which enables the Centre to look to the future with confidence.</p> <p>Moving forward, the Centre will focus its efforts to further sustain existing research activities via funding from a wide range of sources, grow activities in response to signposted areas which dovetail with our expertise and evolve our research portfolio to address new academic and industry-driven challenges. These activities are facilitated and monitored by the Centre's research committee (Chair: Prof Grover) with input from the Strategic Advisory Panel (Chair: Prof Stitt FREng, Johnson Matthey) which also carries out this task for our Engineering Doctorate in Formulation Engineering. Our strategy is further designed to:</p> <p><i>-Deliver impact, through strong partnerships:</i> our industry base is wide and cross-sector in the energy, chemical, biochemical, food, fast moving consumer goods (FMCG), personal care, and pharmaceutical industries. We have built on existing links with Rolls-Royce via a new £60M High</p>				

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Temperature Research Centre (HTRC) and developed new ones with Procter & Gamble, via a University-wide strategic partnership and with Highview Power Storage, through the new £6M EPSRC Centre for Cryogenic Energy Storage and thermal laboratories. ERDF and the RDAs have funded labs in Advanced Materials and BioHydrogen.

-Shape capability, particularly in areas such as high-added-value manufacturing: formulation engineering underpins the manufacturing sectors in food, pharma, personal care and chemicals, generating impact of international significance with major EPSRC and industrial investment.

-Promote excellence in doctoral research: we benefit from two EPSRC Doctoral Training Centres, the Formulation Engineering EngD and DTC in Hydrogen and host annual conferences to showcase the students' research. Over 130 doctoral researchers (72 PhD, 18 DTC, 39 EngD) are in full time registration carrying out research of strategic importance to the Centre.

-Develop academic and industry leaders: Academic staff hold or have held leading roles both nationally and internationally, such as Prof Fryer's position on BBSRC Council from 2006-12 and an EPSRC Advanced Fellowship awarded to Prof Mendes. Through these roles the Centre has provided input into national strategies and research priorities.

Micro-structured products encompassed by the Centre include foods, pharmaceuticals, detergents, personal care products, fuel cells, catalysts, and paints: these are tackled under five major research themes underpinned by the skills areas shown below.

Themes Skill Areas	Food, Health & Nutrition	Bio- engineering	Green Technologies	Speciality Materials	Energy
Structured Liquids	gels , creams and foams	fermentation broths	gas-liquid hydrogenation /oxidation.	shampoos and creams	inks for fuel cell manufacturing
Soft Solids	spreads, emulsions and confectionery	soft tissue regen. (skin & muscle)	crystal structures, sorbents	crystals, creams and foams	extrudates, pastes in fuel cells
Structured Solids	breads and starch products	hard tissue regeneration (bone/teeth)	catalysts, coatings, precipitates	controlled release, encapsulates	fuel cell catalysts, membranes
Particulate materials	extrudates, tablets, encapsulates	separation and delivery systems	catalyst: extrudates, pellets	granules, tablets, capsules	nano-electro catalysts, energy storage

Evaluation of current position (with reference to RAE 2008).

Since 2008, we have obtained substantial research investment in core areas of strength in formulation engineering and in energy. We have exploited new opportunities to drive formulation engineering into the nano-scale through *nanoengineering* via links to the School of Physics with Dr Robinson and Prof Mendes. We have refocused our research themes with 'energy and chemical industries' being split into two new themes: *Energy* and *Green Technologies*.

We have enhanced the quality of our research outputs by focusing on publication of internationally leading work in top journals. Staff have authored ~1100 refereed publications over the period (~8 per academic per year). We have increased research funding awarded via significant joint EPSRC capability grant funding in addition to responsive mode, by partnering with other leading UK research centres - £4.5M EPSRC Centre for Innovative Manufacturing in Food – led by Nottingham, £5.7M Centre for Sustainable Energy use in Food Chains – led by Brunel, £6M EPSRC Birmingham Centre for Cryogenic Energy Storage, £4.9M EPSRC MEMPHIS Programme Grant- led by Imperial College. In collaboration with industry, we have developed research-led taught programmes including a BBSRC Food Advanced Training Partnership in conjunction with the University of Reading.

All our major research areas continue to thrive from significant investment. Research into **food, health and nutrition** is focused on the reduction in obesity which is acknowledged as a major target for society. The aim is to build an engineering understanding of how food is manufactured and then digested, thus providing a knowledge base that can be used to make safer and healthier products. In *diet, health and nutrition*, Dr Bakalis is developing in-vitro models of the GI tract

focussing on nutrient absorption in the small intestine and taste perception in the mouth to develop a suite of models for in-mouth and in-body behaviour. This parallels with work underway in fields such as drug delivery. These dovetail with research into *product structure and function* carried out by Prof Norton and Dr Spyropoulos. One focus is the manufacture of novel stabilised food emulsion systems and biopolymer matrices for low fat and low salt formulations (EPSRC, BBSRC and industry funding). We have also developed the first model for phase behaviour in the casting of chocolate (Kraft, Magna) and this has been used to develop new low-fat chocolate formulations that have been patented and licensed to industry. In *food manufacture, safety and hygiene*, led by Prof Fryer, new models for process plant cleaning have been developed via a £3.6M DTI project (ZEAL) - our experimental work is being applied in industry to reduce water usage in process plants as part of the new EPSRC Centre for Sustainable Energy in Food. Surface pasteurisation models have also been developed using for food safety assurance (DTI LINK with 9 companies). This work will be developed further within the EPSRC Centres that have been funded from 2013.

Our 2008 strategy for **Bioengineering** was to drive this theme forward via research at the biological sciences-engineering interface and also with medicine. Links have developed with the University Systems Biology Centre and activities in synthetic biology led by Prof Dafforn (Biosciences, UoB) which has led to the creation of new *industrial biotechnology* sub theme focusing on development of biocatalysts for production of pharmaceutical intermediates (BBSRC) and on flow sensing using biological constructs (EPSRC). We have developed links to clinicians at the Queen Elizabeth Hospital in Birmingham and to industry via Prof Grover's research into *biomaterials and tissue engineering*. Research into models of bone-ligament grafts have influenced patient rehabilitation (Smith & Nephew, BBSRC) and we are in process of translating this tissue engineered structure to the clinic (ORUK). Prof Grover was part of the team that secured a £20M investment for the NIHR Centre for Surgical Reconstruction and Microbiology, a partnership between University Hospitals Birmingham and the UoB Medical School; he now leads research in bioengineering within the Centre. Prof. Adams has coordinated two multidisciplinary FP7 funded projects, NANOBIOACT and NanoBioTouch, which have made advances in understanding human tactile sensing and have led to a new EU-wide training programme (Prototouch). New links with medical and biological sciences at Keele (EPSRC) have seen Prof. Zhang's work on the mechanical properties of cells applied to regenerative medicine. In *bioprocessing and bioenergy*, Prof O Thomas continues to develop highly novel materials for bioseparations via EU FP7 funding and Dr Overton investigates microbial physiology for production of difficult recombinant proteins.

Research in **Green Technologies** has grown via multi-partner EPSRC programmes in *catalysis and carbon capture* led by Prof Wood focussing on extraction of useful products from sustainable sources (CASTECH), downhole refining of crude oil (THAI-CAPRI) and creation of novel adsorbents for carbon capture (STPCAP). In *complex fluids and rheology* we link to Imperial College via Prof Simmons' role as Deputy Director of the EPSRC Programme Grant in multiphase flows (MEMPHIS). A new £1.5M EPSRC grant led by Dr Leeke includes manufacture of composites from recycled materials (EXHUME).

Speciality materials has been reorganised into three new sub-themes: *materials processing* is concerned with Prof Blackburn's long standing research on investment casting of turbine blades with Rolls Royce, supported by the new £60M HTRC and the reduction of energy in milling and extraction of high value products from mineral waste led by Prof Rowson (IMERYS). Johnson Matthey has funded research into novel PIV/PEPT measurements (Prof Barigou) and into particle blending models and catalyst slurries (Prof Simmons and Dr Ingram). In *particle processing*, Prof Zhang's group have developed encapsulated biopolymer and mineral particles for FMCG formulations (EPSRC, EU, Procter & Gamble, Encapsys, Phillips, Lesaffre) and constructed drug delivery systems using microparticle and liposome based carriers (GSK, EPSRC). A new sub-theme of *nanoengineering* of material surfaces drives formulation engineering into the nm scale for the first time and will define the next generation of formulated products and sensors. Prof Mendes' group have constructed surfaces to probe and control bacterial adhesion (EU), develop intracellular electrochemical sensors (Leverhulme) and understand infertility together with the Birmingham Women's Hospital (Wellcome Trust). Her EPSRC Advanced Fellowship concerns the application of novel stimuli-responsive surfaces to detect cancer; she has recently been awarded €1.9M in ERC consolidator grant funding (GLYCOSURF). A spin-out company, Irresistable

Materials Ltd., is developing fullerene molecular resist materials and nano-surface patterning using carbon nanotubes and switchable surfaces (Robinson).

Energy has benefitted from the DTC in hydrogen, fuel cells and their applications, led by Prof Steinberger-Wilckens, which provides a number of studentships to support activities in fuel cell construction, characterisation, operation and control. Research has focused on low- to mid-temperature *PEM fuel cells* where we have made progress into bio-production of catalysts including the physicochemical differences in such catalysts compared to those synthesised via inorganic methods. We have developed fundamental understanding of the factors that affect performance of gas diffusion layers, used graphene derivatives in fuel cell systems as both catalyst support and membrane materials (Tata Motors) and used novel polyoxometallates as redox mediators (Acal Energy). We have researched into Pt replacement catalyst materials (EU, Royal Society) and gained insights into synthetic pathways utilising surfactants and microwaves to produce nanocatalysts. Research into *SOFCs* has focused on anode side processes, optimising the interaction of fuels and fuel cell materials using control algorithms and reducing the sensitivity of materials to fuel impurities. This includes studies into a variety of biomass derived fuels and their suitability and employment as SOFC fuels. System development is concerned with the combination of high performance hydrogen storage materials (developed in Metallurgy and Materials, UoB) with SOFC in order to make best use of the advantageous properties of both components.

Energy Storage is a key national priority identified as one of the “Eight Great British Technologies”. Work led by Prof Williams and Prof Ding, recently recruited from Leeds, will develop research via the newly awarded EPSRC Centre for Cryogenic Energy Storage and thermal laboratories. This will provide £3.2M for equipment, £1.1M for lab refurbishment and £1.2M for plant equipment to provide a state of the art facility for cryogenic energy storage at Birmingham and a demonstration site in conjunction with Highview Power Storage (www.highview-power.com) and attracting a further £6M of industrial support.

c. People, including:

i. Staffing strategy and staff development

Our staffing strategy is to attract and appoint the best early-career and experienced researchers to support new and existing activities on an international basis within our five research themes. Implementation of this approach has enabled us to:

- *attract internationally-leading researchers at Professorial level*, to support new activities and replace retiring staff: Robert Steinberger-Wilckens who is leading the DTC in Hydrogen, following Kevin Kendall’s retirement; Richard Williams OBE, FEng and Yulong Ding (the University’s first Chamberlain Chair holder for frontier research) to develop the energy storage area and research into formulated particle products;
- *support and enhance existing activities with junior staff*: Dr Fotios Spyropoulos, Dr Thomas Mills and Dr Kostas Gkatzkonis to lectureships in food and Dr Neil Rees to a lectureship in energy. We have recently recruited two new lecturers in tissue engineering (Dr Anita Ghag, née Bassi) and multiscale modelling (Dr Alessio Alexiadis), who started in Sept 2013;
- *support early career research champions to senior fellowships*, we have built up research into nanoengineering via recruitment of a UoB research fellow: Dr Oppenheimer will research into surface enhanced Raman spectroscopy using novel patterned materials and via a Science City Fellowship to Dr Robinson, as well as Mendes’ EPSRC Advanced Fellowship.

Career development support. Promotion of existing academic staff has been made based upon research excellence to Chair level (Mendes, Grover, Rowson, Simmons, Wood), to Reader (Al-Duri, Bakalis, Leeke) and Senior Lecturer (Ingram). Over the next five year period we expect at least four staff to have strong cases for promotion to Chair. **Development of early career (EC) staff** is facilitated by a low teaching load in the first three years of appointment. EC staff are appointed a senior academic as a research mentor, to offer advice on preparation of grant applications and overall strategy as well as preferential access to Centre funds for PhD scholarships to enable them to build their own research teams and supervision expertise.

Sabbaticals and study leave are available to academic staff in line with University policy; opportunities exist for exchanges within Universitas 21. A number of staff have been awarded **personal research and industry fellowships** by EPSRC –Mendes, by RAEng - Robbins (GSK), Rowson (IMERYS) and Zhang (P&G), by NIHR – Grover and by the Royal Society - Norton

(Newton Fellowship), Simmons (Johnson Matthey) as well as industry supported secondments – Zhang (P&G, Granotec) and Bakalis (P&G), Spyropoulos (Pepsico) and Robbins (GSK).

The School Management Group (SMG) manages staff and students as defined by the University Codes of Practice. Fryer (Chair of group and Head of School) is responsible for annual evaluation procedures for academic and research staff which encourages academic leadership and development (Staff Development Review - SDR). The University was awarded the HR Excellence in Research accreditation in September 2011 and continues to work towards full implementation of the **Concordat to Support the Career Development of Researchers** by September 2013. A variety of University HR related policies have been revised / streamlined / updated including academic promotions, fixed term contracts, equality and diversity and redeployment. Within the Centre, specific local induction arrangements exist for research staff. All research staff are entitled to access the full range of development support provided by the People and Organisational Development unit (POD) at the University.

Equality and diversity. Staff submitted to this REF originate from eleven countries: UK, Algeria, Brazil, Greece, Italy, China, Poland, Iraq, Germany, Spain and Portugal. The Centre supports equality of opportunity and increased diversity throughout its activities; exemplified by the University's plans for an "equality and diversity year". The SMG is representative of the School's staff, with female members such as Mendes creating a successful and integrated multicultural environment. All CFE staff have completed the University's Diversity in the Workplace online training course. We will submit an application for Athena SWAN bronze status in November 2013 and will aim to achieve at least silver status by the next REF exercise.

We pro-actively support staff returning from maternity leave (e.g. buying out teaching, allowing staff to focus on re-establishing research) and offer flexibility in the scheduling of meetings and teaching hours to accommodate caring responsibilities; workload is allocated according to transparent models. Our strategy generates role models who are leading to behavioural change: a measure of success is the recent promotion of Mendes to a personal Chair following maternity leave in addition to her EPSRC Advanced Fellowship and recent award of the the GLYCOSURF ERC project.

In addition to the School's Athena SWAN activities, female academic staff have been encouraged to attend a series of College focus groups with the aim of identifying barriers to career progression. This has led to the development of a College-level Academic Women's Network, offering personal and professional development activities, such as promotions workshops. All female staff in the School are encouraged to attend these network sessions. Our Athena SWAN commitment is also highlighted in the further particulars for our research and academic vacancies.

ii. Research students

The School held two EPSRC Centres for Doctoral Training over the period: the DTC in Hydrogen Fuel Cells and their Applications and the Industrial Doctorate Centre (EngD) in Formulation Engineering, both of which provide up to ten studentships per year. Both Centres provide a multi-disciplinary program of taught modules for their students; delivering students with expert knowledge of their research field and a broad depth of knowledge of the overall landscape.

IDC studentships are awarded on the basis of industrially linked projects; leveraging over £2.69M and £20M of cash and in-kind industry support (£40,000 per student per year) over the ten years of the programme. Recruitment of the final student cohort is underway, with more than 40 students on both programmes. The first ten will graduate from the Hydrogen DTC in the next 18 months, many of whom already have employment with industry. *Over 85% of graduated EngD students are in employment with formulation companies.* A small number of University and EPSRC DTA awards (5 and 3 per year respectively) are given on the basis of matched industry funding, with full studentships made available to staff in the early stages of their career or returning from secondments or major administration duties.

Recruitment is carried out to ensure we take only graduates of the highest quality, the entry threshold for funded PhDs is more than 65% in a Masters degree, or equivalent. The interdisciplinary nature of the research has led to students appointed from a range of disciplines including physics, chemistry, mathematics and biosciences as well as chemical engineering. Recruitment is made to advertised, funded projects and interviews are carried as part of the selection process by both academic staff and industry partners (if involved). The recruitment processes for the EPSRC DTCs are carried out by dedicated staff managing these programmes:

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Greenwood (EngD Manager) and Rees (Lecturer, DTC in Hydrogen Energy).

Training and support is provided by the University Graduate School and internally. Suites of Masters level modules are given for EngD and DTC students, who complete 120 credits of courses in fulfilment of their research degrees. These modules are open to other PhD students and also integrated with existing MSc courses. Choice of modules is made on the basis of a Training Needs Analysis process carried out with their academic supervisor. The courses cover fundamental science and engineering topics, reflecting the interdisciplinary nature of the cohort, and include cross-disciplinary and transferable skills elements. Teamworking courses are offered by the University's outward bounds Centre in the Lake District.

Progress monitoring is carried out via yearly review by the supervisor, with a focus on quality of output against individual project objectives. Barigou, as Director of Postgraduate Studies, chairs the School Progression Committee responsible for the performance evaluation of postgraduate research students, including progress and progression decisions. An additional progression step is carried out after 6 months (18 months for 4 year courses with a teaching element) by an independent assessor on the basis of a submitted report and oral presentation. Regulations are University-wide and include a robust appeals process.

d. Income, infrastructure and facilities

Provision and operation of specialist infrastructure and facilities. The CFE provides infrastructure to support research in each theme by operating a number of specialist facilities and general laboratories: the Centre's research is carried out in three proximate buildings on the UoB south campus: the Formulation Engineering Centre (within the Chemical Engineering building), Biochemical Engineering, and the Hydrogen Energy Laboratories. A Material Processing Laboratory on the north campus links with our research with Rolls-Royce and Metallurgy and Materials. Specialist facilities which underpin all the Centre's activities include the Positron Imaging Centre (PIC) in the School of Physics run by Prof Parker and colleagues and the Advanced Materials Laboratory (AML) which offers micro to nanoscale methods for analysis of material surface and structure including the first installation of 'environmental' AFM in a UK University. In addition, we have the first installation of an e-beam lithography tool within UK Chemical Engineering to support our nanoengineering research.

Evidence of investment in infrastructure and facilities. The CFE was founded in 2000 via £3M of JIF support and has won a combination of University and external support for specialist facilities over the last ten years. The PIC has been supported by EPSRC Platform funding since 2001; the current grant is £1.1M. Research in the PIC generates underpinning flow data on processes and has attracted significant industry investment and impact (see impact case study). The AML was created via £1.65 million of Science City (AWM) funding in 2009-10. Activities in Energy have been supported by the creation of a Biohydrogen pilot plant in 2008 using £600k of AWM funding, including new 2 x 100 L bioreactors, gas MS and pilot-scale equipment. A suite of Hydrogen Energy Laboratories dedicated to the electrochemical characterisation and testing of fuel cells have been financed from £400k of private and EU sources and the Royal Academy of Engineering. A further investment of £100k has been made in providing electrochemical equipment for the laboratories and will be further supported by the EPSRC Centre for Cryogenic Energy Storage.

Research Funding Portfolio. Research spending has averaged over £4.2m per year since 2008 with grant capture (reflected in part by the large awards above) growing to £6.8M for the current financial year, an increase of > 80% on the previous three year average. The Centre currently has over £16M in active research contracts from EPSRC and BBSRC (£6.7M), EU (£3.2M), charities (£0.3M), industry (£3.1M) and TSB/DEFRA (£2.7M). The Centre's strategy of consortia-building with other leading research centres in the UK in response to EPSRC Calls for large-scale capability funding has led to recent successes, the EPSRC Centre for Innovative Manufacturing in Food: £4.5M total, £1.4M to UoB; the Centre for Sustainable Energy use in Food Chains: £5.7M total, £1.2M to UoB; the EPSRC Programme Grant in Multiphase Flows (MEMPHIS): £4.9M total, £1M to UoB and the EPSRC Centre for Cryogenic Energy Storage: £6M.

Future Plans. *Food, health and nutrition* research is carried out by the largest food engineering group in the UK, supported by funding from EPSRC, BBSRC and a range of multi-national industries (including Cargill, £1.05M; Pepsico & Unilever £0.5M each). Its portfolio has been recently enhanced by the award of the CIM in Food and Sustainable Energy Centres. The long term aim is to develop models for manufacture and digestion of healthy foods which will be tackled

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via research into

- *obesity and nutrition* – by development of novel biopolymer formulations and emulsions to enable manufacture of low fat and low salt foods with improved nutritional value and development of self structuring foods for improved satiety. This work is currently supported by over £2M of BBSRC, EPSRC and TSB funding.
- *in-vitro models of the GI tract* for nutrient absorption in the small intestine and in mouth and in-body behaviour; improved understanding of motility and digestion can be fed back into food formulations for health benefit (£700k of BBSRC funding).

Bioengineering. We will continue to seek funding from EU, BBSRC and industry sources (current funding is over £2.3M), facilitated by *DRINC* and *BRIC* industry clubs and ongoing projects in

- *industrial biotechnology* – focussing on the generation of novel biofilm biocatalysts for pharma intermediates and development of innovative screening procedures and high productivity expression and fermentation processes for the production of novel therapeutic proteins in microbial systems (BBSRC and KTP funding with Cobra Biologics);
- *downstream separation technologies* - via intensification of bioprocesses using multifunctional chromatography, supported by EU and BBSRC funding;
- *tissue engineering* of soft/hard tissue interfaces to develop multi-tissue constructs for ligament injury and replacement and understanding of tactile sensation and touch;
- *separation of cells for cellular therapy* in collaboration with School of Cancer Studies and Institute for Biomedical Research at UoB.

Green Technologies. Research is focussed on the industry application of novel processes with reduced environmental impact. The award of over £3.3M of funding for significant consortia-based EPSRC projects will enable us to continue to grow our research into:

- *more efficient recovery of resources*, the THAI CAPRI programme is concerned with in-situ oil recovery and the STEPCAP project focuses on CO₂ capture using novel absorbents;
- *recycling of waste feedstocks into useful products*, via the EPSRC CASTECH programme to extract useful organic molecules from wood waste and the £1.5M EXHUME EPSRC programme to make composite materials from recycled feedstocks. EXHUME represents first the cross-sector research-inspired use of heterogeneous scrap material in manufacture.

We will continue to carry out research into the multiphase fluid mechanics and mixing of complex fluids underpinning industrial processes via the MEMPHIS programme grant and a recently awarded TSB project to Simmons (EMFormR, £1.015M with Unilever and Johnson Matthey). Other industry funded research focuses on recovery of actives using supercritical extraction with Dr Santos (Boots Heineken, Loders, PJH Environmental Technology).

Speciality Materials. Research into *materials processing* is supported by the new £60M High Temperature Research Centre and an additional £900k of funding from Rolls-Royce and EPSRC/TSB on investment casting of turbine blades via the SAMULET project. This research will continue to make a major impact in the capability and cost reduction within gas turbine manufacturing facilities operated by Rolls-Royce (see Impact Case Study).

Nanoengineering is a significant new sub-theme exemplified by Mendes' £1.2M EPSRC Advanced Fellowship and €1.9M of ERC funding (GLYCOSURF) for research into detection of cancer by reliable detection of glycosylated proteins produced by cancer cells. Research will continue to focus on novel biofunctional surface materials which can be applied as intracellular electrochemical sensors or stimuli-responsive surface materials to understand infertility (via charity funding and links with the Birmingham Women's Hospital). We aim to exploit novel lithography methods using fullerene resist materials and conductive resist materials generated from EPSRC funded research via the University spin-out company Irresistible Materials Ltd (Robinson).

In *structured particle processing*, work continues characterisation and development of manufacturing processes for microcapsules used in FMCG products including fabric care, oral care and nutraceuticals, supported by EPSRC and industry (Procter and Gamble, Phillips and Lasaffre). Work on improving the energy efficiency in milling processes will continue to benefit from novel insights into equipment operation using the PEPT technique (IMERYYS Ltd), described in the PEPT Impact Case Study.

Energy. Fuel Cells (PEM and SOFC). The primary mechanism for funding of postgraduate

students is the £5.5M DTC in Hydrogen, funded in 2009. Research is carried out in fuel cells via many European projects: MMLCR=SOFC, SCORED, SUAV, SAPIENS, SAFARI, STAMPEN, SWARM with a total income of close to £1M.

Energy Storage. The recently awarded EPSRC Centre for Cryogenic Energy Storage will provide £3.2M for equipment, £1.1M for lab refurbishment and £1.2M for plant equipment to provide a state of the art facility for cryogenic energy storage and thermal laboratories at Birmingham enabling us to extend our national and international research profile into this new area.

Consultancy and professional services. There is a strong entrepreneurial culture in the School. Over the period, staff have worked with over 10 international and national companies including Pepsico, Unilever, Surepure, Mondelez and P&G. Intellectual property services and consultancy are operated within the University by Alta Innovations Ltd. 24 patents have been filed in the UK based on the Centre's research over the REF period, with 9 further filings in the USA and 6 in Europe. Two spin-out companies: Adelan Ltd (fuel-cells) and Irresistable Materials Ltd (nano-lithography) have been created based on research carried out in the Centre.

e. Collaboration or contribution to the discipline or research base

Contribution to the discipline. The Birmingham Centre in Formulation Engineering remains unique in the depth of its scope, despite other universities developing this specialism subsequently (including Manchester and Leeds). Staff contribute to national policy in research councils, professional activities and political advice. Together with our industrial partners, we have significantly influenced the UK research agenda, with the first TSB "Formulation" call in April this year and formulation groups being established by both the IChemE and the RSC. CIKTN and the TSB are proposing a national 'Formulation Centre' in which we will be one of the key partners. The EngD was central to the award of a Queen's Anniversary Prize in 2011, acknowledging us as a
"..... world-leader in applied, innovative research which supports multinational industrial partners in the development and manufacture of high quality products with complex microscopic structures."
 (www.royalanniversarytrust.org.uk)

The EngD encompasses more than 25 partners to date (incl. Unilever, Procter & Gamble, Boots, Cargill, Premier Foods, Pepsico, Kraft, Johnson Matthey, BASF, Ross Ceramics, IMERYYS, Akzo Nobel, Rolls-Royce, Dupont Teijin Films).

Research collaborations, including interdisciplinary research. The Centre's collaborations reflect the diverse backgrounds of the academic staff, whose first degree disciplines include materials science, chemistry, geology, physics, bioscience and microbiology. Exemplars of our linkages on the national and international stage are noted below:

within the University: we link to Physics via the Positron Imaging Centre (EPSRC platform grant) and to materials via the IRC in Materials Processing. We link to other Schools via the DTC in hydrogen and by research grants held by individual staff including Chemistry (Wood, Zhang, Steinberger), Medicine (Mendes, Grover) and Biosciences (Overton, Simmons).

to other UK Universities: our focus is to collaborate with leading Universities in the UK with complementary expertise including Brunel and Manchester via the EPSRC Centre in Sustainable Energy and to Nottingham via the EPSRC CIM in Food. We link to Chemical Engineering at Cambridge and QUB on catalysis (Pacek, Simmons: EPSRC, Johnson Matthey), to Newcastle via a DTI project on process plant cleaning and joint EngDs (Fryer, Robbins) and to Imperial College via the MEMPHIS EPSRC Programme Grant (Simmons). We also link to Medical and Biological Sciences at Keele (EPSRC) and Chemistry at St. Andrews (BBSRC) and Bristol (EPSRC).

with industrial partners: we have set up exchanges with key industry groups: Bakalis - P&G funded six month secondment to Brussels in 2012; Robbins - RAEng with GSK in 2012; Spyropoulos - Pepsico R&D in 2011; Simmons - Johnson Matthey from 2007-11. Research scientists from Pepsico and Kraft (USA) visited our labs to learn and apply our leading edge knowledge on food microstructure. Senior industrialists (such as Stitt at Johnson Matthey, Skuse at IMERYYS) advise our research agenda via visiting Chairs.

Internationally: Our international strategy is to (i) encourage staff to attend key international meetings to ensure their work is recognised. Our staff have carried out over 60 Keynote/Plenary lectures over the period, including talks by Adams - EuroNanoForum 2009, The BioTribology Conference, 6th International Granulation Workshop; Barigou - CECAM workshop on Computer Simulation in Food Science; Cox - Biofoams 2013; Fryer - Int. Heat Transfer Conference, Int. Conf

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on Engineering in Food; Leeke - World Renewable Energy Forum; Mills - Food structure and functionality 2013; Norton - 8 including EFFoST 2011, Faraday Discussion on soft matter approaches to structured foods; Pacek - 3rd Annual World Congress of Nano-Science and Nano-Technology; Robinson - 10 invited international talks since 2010 incl. 30th International Conference of Photopolymer Science and Technology; Simmons - ChemEngDay UK 2013; O Thomas - scientific committee of 22nd, 24th, 25th & 26th Int. Symp. on Preparative Chromatography (PREP); Williams – 15 invited talks, co chair World Congress in Process Tomography; Wood - International Energy Agency Enhanced Oil Recovery Symposium 2013; Zhang – 20 including 4th Int. Conf. Multiscale Structures and Systems in Process Engineering, Particulate Processes in the Pharmaceutical Industry III.

(ii) *identify key collaborators within the EU* which has led to consortia building for EU funded projects including *MagPro2Life*, *NanoBioTouch* and *Prototouch* – with ETH Zurich, Karlsruhe Institute of Technology, U Gothenburg, U Catholique de Louvain, U Lille; U Bremen and TÜV Süd. We additionally link to U Wuerzburg and U Jena via Grover.

(iii) *build linkages to internationally recognized academic institutions outside Europe* via exchanges, sabbaticals and joint funding, with key staff taking leading roles. We link to the following institutions in North America: McGill - Grover, Cox, Rowson; UC Davis, Harvard Medical School - Grover; UC Berkeley, San Diego and Washington - Mendes. In China we link to the Chinese Academy of Sciences and Tsinghua University - Wood; Sichuan University, SCUT and ECUST – Zhang. We also link to King Abdullah University of Science and Technology - Simmons; NTNU, Norway – Zhang and Hong Kong Baptist University – Mendes. We encourage staff to undertake appointments to visiting/honorary chairs with staff currently holding nine positions: Grover - Sao Paulo; O Thomas - Karlsruhe; Cox – McGill; Zhang - Sichuan Uni, SCUT and ECUST in China; Williams - UNSW in Australia and Chinese Academy of Sciences.

Academic leadership. Academic staff carry out leading roles both nationally and internationally. Fryer was on BBSRC Council from 2006-12 and is a member of the DSAC - Defence Science Advisory Council - MoD; Williams is on the scientific advisory boards of NetScientific (2011-); PSB Academy (2012-) and King Abdullah Institute for Nanotechnology (2008-). Spyropoulos is a member of the Diet and Health Research Industry Club (DRINC) steering group. O Thomas is member of EFB's European Society of Biochemical Engineering Sciences Working Group on Downstream Processing (WG DSP) and is the first downstream processing expert to serve on the UK's Clinical Trials and Biologicals and Vaccines Expert Advisory Group (CT-BVEAG). Greenwood and Wood have chaired the IChemE Special Interest Group Committees in Formulation Engineering and Catalysis. Through these roles the Centre has inputted into both UK and international strategies and research priorities. Several staff have membership of EPSRC College and have chaired grant review panels, contributing to the Centre's external profile. Other highlights include:

- *Membership of Professional Bodies and Awards.* Fryer, Adams and Williams are FREng, seven staff are FICHEM (five MICHEM), two are FRSC, (one MRSC) and one is FIMMM. Rowson is ex-President of the Minerals Engineering Society. Parker won the IoP Joule medal in 2008 for his work on PEPT. Blackburn won the IOM3 Jenkins Medal in 2008 for his significant contribution to particulate processing. Williams won The Society of Chemical Industry "R&D for Society" Award in 2009. Adams received a special award for his outstanding contribution to agglomeration science at the 6th Int. Granulation Workshop in 2013.
- *Editorship roles in Journals.* Several staff hold editorships or editorial board positions: Adams - *Powder Tech., Lubricants, Tribology Int.*; Barigou - *Int. J. Chem. Eng., Int. J. Food Properties, Int. J. Pharmaceutical Eng.*; Cox – *Int. J. Food Sci.*; Fryer - *J. Food Eng., Food Bioprod. Proc.*; IFSET; Grover – *Adv. Applied Ceramics and Biotech. Lett.*; Leeke - *Renewable Energy and Open Catalysis*; Mendes – *J. Exp Nanosci.*; Robinson - *Recent Patents on Nanotech.*; Simmons - *Chem. Eng. Res. Des., Multiphase Sci. Tech.*; C Thomas – *Biotech. Lett., Eng. Education.*; O Thomas – *J. Chem. Tech. and Biotech., Food. Bioprod. Proc.*; Williams – *Chem. Eng. Res. Des.*, Zhang – *J. Microencaps, Artificial Cells, Blood subs and Biotech, Inter, J. of Chem. Eng., J. Eng.*

In conclusion, the growth of the Centre in this period has provided a sustainable platform to carry out internationally-leading academic research for ultimate industrial benefit. We will continue to further our international reputation by promoting individual research excellence and by building consortia for future research and funding together with our academic and industrial partners.