Institution:	**University of Manchester**
Unit of Assessment:	**UoA12a – Chemical Engineering**

a. Overview

Amongst the broad range of engineering disciplines represented by UoA12, research in chemical engineering at the University of Manchester (UoM) (submitted here as UoA12a, the Unit) is undertaken in the School of Chemical Engineering and Analytical Science (37 researchers, 33.7 FTE), one of 9 schools in the Faculty of Engineering and Physical Sciences (EPS). Other disciplines within UoA12 are represented by researchers in the School of Mechanical, Aerospace and Civil Engineering and submitted separately as UoA12b.

Research is organised around a matrix of 5 informal groupings: 1) Sustainable Industrial Engineering, 2) Multi-scale Modelling, 3) Process Development and Integration, 4) Instrumentation and Analytical Science, 5) Molecular Systems and Biomaterials. The Unit also benefits from involvement in multi-disciplinary University Institutes – particularly the Manchester Institute of Biotechnology (MIB), the Photon Science Institute (PSI), the Dalton Nuclear Institute (DNI) and the Sustainable Consumption Institute (SCI).

Significant achievements of the Unit during the REF period include:

- Ranked 18th in the 2013 QS World University Rankings for Chemical Engineering, showing a significant improvement on the 2008 position of 45th.
- Development of pioneering life-cycle methodologies and tools for sustainability assessment and improvement of industrial systems.
- Development of coarse-grained and hybrid models for prediction of thermodynamic, structural and dynamical properties of soft materials such as polymers.
- Election of one staff member (Azapagic) as Fellow of the Royal Academy of Engineering.
- Obtained a silver Athena SWAN award for its commitment to advancing careers in STEM.
- £16M investment in new facilities, specifically for large-scale chemical engineering research.

b. Research Strategy

Vision – The overall vision of the Unit is to develop and promote chemical engineering as a discipline that creates practical and sustainable advances for the overall benefit of society. We encourage and enable researchers to attain research excellence in their chosen field whilst at the same time bringing this emerging and existing excellence to bear (via the research groupings) on challenging chemical engineering problems. We aim to employ our skills and expertise – ranging from the very fundamentals of theoretical chemical engineering science (e.g. molecular-based equations of state) to experimental process development and optimisation – to solve important multidisciplinary challenges. With traditional strengths in process integration, crystallisation, industrial sustainability, and bioprocessing we aim to extend the boundaries of the chemical engineering discipline. We also aspire to develop an exemplary record of knowledge transfer and to harness our research capability to produce the best environment for student education.

Strategic Planning – Our vision is closely aligned with the research elements of the Manchester 2020 strategic plan, and can only be achieved with strategic planning at all levels. Progress is assessed annually. The Director of Research has responsibility and chairs a committee composed of research group Chairs, PGR Director, an Early Career Researcher (ECR) and senior administrators. By a process of consultation, the committee develops a rolling annual strategic plan for the Unit, which feeds into the EPS Faculty research plans. Since RAE08, we have held several productive Away-Days to involve all staff in discussions of research group structure and strategy.

Research is organised in informal groups chaired by respected researchers who act as champions, develop research strategies, foster links between different research activities and between theory and experiment, seek new opportunities and other strategic roles. Groups provide a useful forum for tailoring messages and targeting initiatives. The groupings are evolving to meet differing needs across the Unit and beyond and maximising potential is also part of on-going strategic planning.

Strategy and Progress – The successful approach we adopted to foster inter- and multi-disciplinary activities during RAE08 has continued during the REF period, with a focus on active development of partnerships to tackle global and national grand challenges, using a combination of approaches, from theoretical to practical. The matrix-style group structure facilitates this through synergistic collaborations. For example, the high surface area to volume ratio in foaming systems has been successfully modelled, simulated and experimentally investigated through collaboration between groups working on the molecular transport of surfactant in foam fractionation with reflux.

We aim to be one of the world's top 10 chemical engineering departments (QS World University Rankings for Chemical Engineering) and the improvement, from 45th to 18th over the REF period, reflects the success of the Unit's research strategy. Since RAE08, we have enhanced the previous structure of four research groups to give the current five groups 1) Sustainable Industrial Engineering, 2) Multi-scale Modelling, 3) Process Development and Integration, 4) Instrumentation and Analytical Science, 5) Molecular Systems and Biomaterials. The changes since 2008 are designed to support our strategy to establish a continuum from fundamental to applications-oriented research addressing 4 key goals.

Goal 1 – to develop new methodologies for describing complex systems, which more closely represent the real world of industrially relevant applications.

Goal 2 – to develop next generation industrial processes and optimise current processes towards a more sustainable future.

Goal 3 – to develop new methodologies, techniques and devices for the analysis and control of processes.

Goal 4 – to improve pathways to impact by initiating, developing and supporting partnerships with industry and business (detailed in REF-3a).

Our strategy to achieve these goals includes utilisation of the ever-increasing powers of computation and the growing range of new methodologies, both for modelling and for experimentation. We can now model, for example, polymers, biomaterials, colloidal systems and protein-based formulations in an industrial context. Recognising the value of this strategy, we have created a coherent grouping around multi-scale modelling activities and grown this group through the addition of several ECR staff. At the same time, our large-scale experimental capabilities have been enhanced substantially, in a way that facilitates the synergistic collaboration between experimentalists and modellers. This leads naturally to a Process Development focused grouping, as well as the more fundamental focus of the Molecular Systems and Biomaterials group. In line with the University, the Unit has also recognised the likely strategic importance of nuclear science and engineering to the UK. We have bolstered activities in this area through the appointment of a RAEng Visiting Professor from NNL and an ECR, with links into the DNI and the DCF.

We have also developed enabling strategies around staffing, postgraduate training, funding, infrastructure and user engagement, which are covered in later sections.

Research Group Strategies and Progress

1) The strategy of the **Sustainable Industrial Engineering (SIE)** group led by Azapagic has been to focus primarily on Goals 2 and 4 above, by addressing the research challenges that arise for industry from the drive towards sustainable development. Our diverse but interrelated research covers process design, innovative manufacturing, life cycle sustainability assessment and optimisation, clean and clean-up technologies, sustainable resources (water, energy, bio-feedstocks) and pollution measurement and management.

   In line with the Unit's strategy to increase industrial collaboration, the SIE grouping has carried out research involving over 100 industrial partners including Areva, Battelle, Croda, Fujifim, GSK, Ineos, Kellogg's, Premier Foods, Procter & Gamble, Westinghouse, Whirlpool. This has been in particular through two major projects (£1m CCaLC project funded by EPSRC and the £4.3m BIOCHEM project funded by the EC). The CCaLC (Carbon Calculations over the Life Cycle of Industrial Activities) project has already led to significant impact (see REF 3b).

2) The **Multi-Scale Modelling** group, led by Masters, is addressing Goal 1 for industry-relevant research across length scales from atomic to macro by developing and using a full range of modelling methodologies including quantum mechanical, molecular dynamical, coarse graining

and bulk scale modelling. Since RAE 08, we have expanded the group's expertise base, largely through the appointment of ECRs. We have also worked closely with experimentalists in other groups within the Unit and beyond. An example of the success of our strategy is the £1.3M MBase project to understand the molecular basis of advanced nuclear fuel separations.

3) The **Process Development and Integration** group, led by Smith, is addressing primarily Goals 2 and 4 above, for processes in the petroleum, petrochemical, chemical, biochemical, pharmaceutical and food processing industries. The emphasis is on a holistic approach to the process, rather than concentrating on the phenomena occurring in individual operations. Part of the strategy for exploitation of research in this area (Goal 4) is the continual transfer of technology through the Process Integration Research Consortium and spin out companies such as Process Integration Limited. For an example of the success of this strategy see the case study in REF 3b. Another part of the group's strategy has been to re-invigorate our large-scale experimental pilot research. This has been achieved through investment in facilities and infrastructure (see later). Success of the strategy led to major industrial research support from companies such as Cameron and Unilever (see REF 3a).

4) The **Instrumentation and Analytical Science** group, led by Goddard, provides the Unit's main thrust for Goal 3. The strategy is to exploit new knowledge and technologies arising from multi-disciplinary activities and to translate this into commercially viable products. Research is concerned with the measurement of phenomena ranging from nano-scale molecular processes in biological cells through to macro-scale chemical processes in industrial reactors, including areas such as environmental monitoring, disease diagnosis, and molecular imaging for healthcare and the life sciences. Topics range from characterisation of Graphene membranes for devices (Schroeder), to stem cell fractionation (Goddard) and spectroscopic techniques for cancer diagnosis (Gardner).

   The group has continued to thrive, despite the loss of key academics (to retirement and promotion elsewhere). The development of intelligent gas-sensing systems by this group (Persaud) is the subject of one of the Unit's Impact Case Studies (see REF 3b).

5) **Molecular systems and biomaterials** is a new grouping formed to take advantage of the complementarity in research aims between members of the RAE08 groups *Self-Sustaining Biological Systems*, *Measurement Science and Instrumentation Systems* and *Multi-scale and Multi-phase Systems*. Led by Davey, this has resulted in a cross-disciplinary approach to molecular level engineering, spanning complexity levels from bio-organic soft matter to biological systems, and integrating predictive molecular modelling. This research at the interface between life sciences, engineering, materials science and the physical sciences facilitates collaboration with a broad range of industrial collaborators. An example is the £2.4M EPSRC Critical Mass Project in Molecules, Clusters and Crystals (Davey and Schroeder).

Future plans **–** In our future activities we will continue to foster multi- and trans-disciplinary research in a vibrant and creative research environment. Providing a first-class research and working experience for our research staff and students remains our priority. We believe that the Unit's success in dissolving barriers between disciplines will provide further benefits through exposure to a much wider range of disciplines than has historically been the case in Chemical Engineering Departments. We will focus increasingly on generating impact from our research activities by extending our outreach and exploitation.

We are leading the establishment of a new University Centre in the area of analytical science and instrumentation, to bring together research from many schools across all four faculties. We will also expand our activities in the area of industrial biotechnology (Winterburn**,** Martin) to recognise the UK priority need for process engineering research in this area, supported by the underpinning science base in the MIB. Industrial collaboration will be further expanded through the new EPSRC/ESRC Centre in Sustainable Energy Use in Food Chains, a consortium between Brunel (lead), UoM (Azapagic) and Birmingham, which involves 33 industrial partners in the food sector, such as Cargill, Heineken, Heinz, Kraft Foods and Tesco. We will also play a key role in building on UoM's world-leading graphene research by participating fully in the new Graphene Institute through, e.g. the £3.47M EPSRC Graphene-Based Membranes project (Carbone, Holmes**,** Roberts, Schroeder**,** and Siperstein).

c. People, including:

I. Staffing strategy and staff development

Staffing strategy:

The Unit pays close attention to attracting, developing, nurturing and rewarding its talent pool. Two main principles guide our staffing strategy: (i) to recognise and reward excellence; (ii) to strengthen/establish key areas, in line with our research strategy. Since 2008, nine new staff have joined the Unit at Lecturer level, strengthening the multi-scale modelling activity (Carbone, Avendano, Rodgers, Villegas**)**, and large-scale processing/bioprocessing research (Shokri, Winterburn) have been priorities, along with molecular systems (Fan) and the initiation of nuclear engineering (Sharrad). Following a tradition of recruiting the best academics from a wide range of nationalities and leading international institutions, recent appointments, in addition to those from the UK (Universities of Cambridge, Durham and UoM) have been from the USA (Cornell and Boston Universities), Germany (T U Darmstadt), and Australia (University of Queensland).

Staff Development:

We aim to create an environment in which research staff at all levels can reach their full potential with support from a range of personal, professional and career-development opportunities. Initiatives within the Unit are run in concert with those provided by the Faculty and UoM, and constitute part of our commitment to the Concordat to Support Career Development of Researchers (CSCDR). The university has received an HR Excellence in Research Award from the European Commission for its Concordat Implementation Plan.

The induction process for new research staff (including PDRAs) provides information to settle them quickly into their new roles and to realise their potential. This includes the EPS Research Staff Handbook, the Unit's Induction Pack and invitations to attend UoM and EPS Initial Courses for Research Staff. Mentors are allocated to staff at all levels taking up new positions. High quality PDRAs are nurtured for possible academic careers (Rodgers and Winterburn have been recruited through this route).

All researchers have the opportunity to discuss and plan their careers through regular performance and development review meetings with senior staff. The mentoring culture extends beyond ECR staff and is available to all through the award-winning Manchester Gold programme in which participants are matched to a more experienced colleague, who acts as their career mentor over a 9-month period. For senior researchers, the Headstart programme, run by the Leadership Foundation for HE, provides training to develop leadership skills. This is by invitation only and has been completed by 7 staff in the Unit during the REF period.

The EPS Researcher Development Programme is a suite of training initiatives that promote personal development, active career management, and researcher independence, to help all research staff develop as flexible researchers who can excel in a global environment that calls for skills in collaboration, communication, public engagement, and knowledge transfer. A wide-ranging programme, comprising 38 different workshops and courses, is arranged around five key themes: Career Management, Communication, Leadership and Management, Research and Enterprise, and Teaching and Learning. These courses, specific to EPS researchers, add to the more general training available through the UoM Staff Training and Development Unit. Academic Promotions Masterclasses are held annually. These sessions provide an overview of the academic promotion route at the University, the role of Unit and Faculty Promotion Committees, CV hints and tips (with the offer of 1:1 guidance), and academic promotions case studies.

Staff Development – Early career researchers: Five staff (Avendano, Rodgers, Shokri, Winterburn and Fan) are ECRs and benefit from Unit, Faculty and University mentoring and support schemes, such as the New Academics Programme (NAP). All new academic appointees must attend the NAP, which covers teaching, personal skills, project management, grantsmanship, and reflective assignments, before completing probation. One ECR (Winterburn) is a beneficiary of the University's EPSRC Doctoral Prize Fellowship scheme (previously PhD Plus), which includes a challenging career development programme as well as support to help candidates take their research to higher levels. Our ECRs also benefit from the website "An Academic Career", developed by the UoM Careers Service. This provides a comprehensive guide to working in higher education and was the winner of the Times Higher Education 2011 Award for Outstanding Support

for Early Career Researchers. The University also received the 2011 Scopus Fostering Young Researchers Institutional Award. This award was given by the US-UK Fulbright Commission and Elsevier and was based on the University's number of highly-cited ECRs.

Personal Research Fellowships: The Unit encourages its researchers to establish and develop their research careers through fellowships. Candidates in the final stages are given mock interviews by staff experienced in peer review. Carbone, appointed as a RCUK Fellow in 2008 will continue to a lectureship at the end of her contract. Grassia was awarded a RAEng/Leverhulme Trust Senior Research Fellowship. E A Willneff attracted an AHRC/EPSRC Science & Heritage fellowship and PDRA Yvonne Gründer obtained a Royal Society Fellowship before moving to a Lectureship at the University of Liverpool.

Academic Leave: The Unit runs an active academic leave scheme that enables staff to concentrate on research for a semester or a year. During the REF period, 11 staff have taken such leave, making visits to top international universities and research institutes (e.g. Max Planck Institute, University of Melbourne, University of Barcelona, University of Utrecht). Several of these have involved externally funded secondments. For example, Curtis obtained a RAEng Industrial Secondment Award in 2012 and **Grassia** was granted a secondment to a CNRS lab (Theoretical Physics and Modelling) in Cergy-Pontoise, France. Siperstein was also granted a secondment at a CNRS lab (MADIREL) in Marseille, and ENSTIB in Nancy, France.

International Staff Appointments and Visitors: The Unit is an international community. For example, 54% of our current academic staff originate from outside of the UK. Most (24) are from Europe, 5 are from Asia, 3 from Latin America, 3 from Australia/New Zealand, 2 from Africa and 1 from North America. The majority of Research Staff are also from outside of the UK and are selected for their research excellence and relevance to the research being undertaken. Reflecting the strong international profile of the Unit, 7 of the 9 academic appointments made during the REF period were from outside of the UK.

The Unit hosts many international visitors for periods of up to one year. During the REF period, 66 people from 26 countries held visiting positions in the Unit. These included visitors from top international universities (e.g. Pennsylvania State University; University of Wisconsin; Tsinghua University; Tianjin University).

Equality and diversity: The Unit is committed to the advancement of equality and diversity in employment and career development for its staff. Equality data monitoring and action planning is embedded into its annual performance reviews. This includes monitoring and identifying actions in relation to recruitment, current staff profile and promotion. All staff involved in recruitment interview panels are required to have attended Equality and Diversity Training. The Unit provides a diverse and supportive environment, taking care to attract, retain and recognise talent. It supports women, especially at key career transition points, promotes and enables its academic and research staff to achieve a work-life balance and actively works to achieve equality in leadership and decision-making. As evidence of this, in 2012, the Unit was awarded a silver Athena SWAN award.

c. II. Research students

In the Unit, the aim has been to ensure that we have a vibrant research student community, conducting world-class research. A total of 190 PGR students have graduated from the Unit since 2008, at an average of 1.13 per academic FTE per year. More than 85% graduate within five years of initial registration. The Unit was the lead partner in the University's first Doctoral Training Centre (DTC) in Systems Biology (led by Westerhoff) as well as actively participating in the NowNano and Nuclear FiRST DTCs. Examples of the success of our PGR students include: Joanna Stevens (awarded British Association for Crystal Growth (BACG), Young Scientist of the Year 2010); Rafael Lopez Rodriguez (2012 Roberto Rocca Fellowship); Paul Bassan (Royal Society of Chemistry Ronald Belcher Award, 2010) Ayeesha Mujeeb (Robert Mathys Foundation award, 2010); Ruchi Gupta (awarded a RAEng Enterprise Fellowship, 2013).

Approaches to recruitment: While the proportion of masters students staying on to study for PhDs is small (in common with other engineering disciplines) we have substantially increased the number of masters level research projects undertaken in the Unit by both undergraduate and postgraduate students (195 in 2012/2013 compared to 91 in 2008/2009), thus ensuring a larger pool of potential internal recruits. The Unit also takes a proactive approach to attracting the highest

quality external candidates by offering scholarships and participating in overseas recruitment activities (e.g. with CONACyT and PEMex in Mexico). As a consequence we receive a large number of applications (>250 per year) from all over the world (34 different countries; typically ~65% overseas). All short-listed applicants are interviewed.

The Unit has benefitted from the President's Doctoral Scholar Award which is a flagship funding scheme, launched in October 2011, providing a bespoke set of development opportunities, focusing on leadership activities. Of the first cohort (10 across the EPS Faculty) two were granted to chemical engineering applicants. Further studentships (known as Dean's Awards) are awarded annually within the Faculty (10 for 2012). These are open to all nationalities and research areas and, again, two were won by chemical engineering applicants. Also, many of our overseas PGR students have won prestigious scholarships from their home governments, choosing UoM as their host (e.g. Brazil, India, Indonesia, Malaysia, Mexico, Nigeria and Pakistan). Additionally, the Unit works closely with industrial partners (e.g. AWE and Shell) to manage split-site PhD programmes.

Training and support for PGR students: PG matters are the responsibility of a senior academic acting as PG Director and the PG Committee, which includes student representatives. Each student is assigned a supervisor (responsible for directing an agreed programme of research), co-supervisor (specialist available for additional consultation/advice) and advisor (unconnected with the project, providing pastoral support and oversight). Two academic mentors monitor overall PG welfare and provide extra assistance to individuals, when needed. PGR students attend weekly group meetings where they have the opportunity to present their work and obtain feedback. The meetings also serve for informally monitoring progress and as a platform for communication.

The Faculty offers a Graduate Development Programme (GDP) for personal and professional development and skills training, to help PGRs complete courses successfully thereby maximising future employability. In 2012/13, 98 EPS training sessions were scheduled, tailored to different stages from introductory modules, academic writing, critical reading and project planning, through to thesis writing, viva preparation, publishing, career planning and enterprise skills. The GDP also provides advice and support for supervisors, advisors and mentors. Around 70% of PG students take up the opportunity to undertake tutorials and laboratory teaching, after suitable training, to assist career development. More general sessions in higher-education teaching are also popular.

Students are also encouraged to participate in international conferences related to their field of study. The Researcher Development Framework is a skills audit used to help PGRs map out their future development goals. In addition, all students present their work at an annual PGR conference in the Unit and awards are made for the best presentations, both oral and poster forms. PGR students and PDRAs are involved in all aspects of the organisation and staging of these events.

Progression monitoring: The online progression monitoring system, eProg, provides all research students with clear direction on the critical milestones for their research degree. The eProg records provide evidence of a student's engagement with training and progress and allow students to export a file of their completed training and milestones to help with further personal development or to add to their CV. eProg provides access to a range of training opportunities across the institution and also provides a structured framework of progression monitoring meetings for research students. The system has been so successful that it has been commercialised under the name "Progress Platform" and contracts have already been signed with three other HEIs.

Employability Support: The University of Manchester Careers Service is widely recognised as one of the best in the UK and was voted best in the country for three years running by the Association of Graduate Recruiters and Barker's Graduate National Media Audit. Postgraduate support is a central component of their work. The annual "Pathways" event supports delegates in career choices, exploring future plans and discovering the breadth of opportunities available to them through open discussion with PhD graduates from a wide range of job sectors.

d. Income, infrastructure and facilities

Research Funding Portfolio:

The Unit's total research spend during the REF period was £28M, a 15% increase compared to RAE 2008. In terms of spend per FTE over the period this equates to £850k per FTE compared to £746k. During the period, however, several senior staff retired, passed away or moved on. Whilst

these have been replaced with ECRs, maintaining the FTE count, their departure has reduced the overall rate of increase in grant income.

Given the fundamental nature of much of the work carried out, many of the grants are funded by RCUK (£17.3M), predominantly EPSRC and BBSRC but funding has also been obtained from most of the other RCUK bodies (NERC, ESRC, MRC, AHRC, Royal Society). The Unit's BBSRC portfolio (£3.5M at September, 2012) is the highest of all UK chemical engineering departments. Beyond RCUK, our funding portfolio also includes EU government bodies (£3.4M) central government (TSB, DSTL, MoD, AWE, DECC, DEFRA, HGCA; total £1.4M) and industry/other sources (£5.7M).

Future funding plans - In line with the research strategy outlined in section b) we plan to strengthen our RCUK funding and continue to broaden the funding base with increased EU and industrial funding. Increased support for these activities has recently been provided at faculty level.

Consultancies and Professional Services - Our staff engage in a range of professional service activities such as executive education, continuing professional development, acting as Expert Witness, as well as direct industrial and government consultancy. For example, Smith leads the BP project management, executive education programme; Azapagic**,** runs regular CPD courses to disseminate environmental sustainability principles to industrial users. Westerhoff is advisor to several companies on systems biology, including: AstraZeneca, Unilever, Waters, Sanofi-Aventis.

Specialist Infrastructure and Facilities:

The Unit's research is undertaken in a number of buildings across the campus but, primarily, in three main sites, namely *The Mill,* the *John Garside* building and the newly built *James Chadwic*k building (JCB). Together, we utilise a total of 11,200 m^2 of laboratory and research office space in these three buildings. The majority of the laboratory space is equipped for bench-scale research but a significant amount (ca. 2,000 m^2) of high quality flexible space, enabling large-scale specialist experimentation, is also available, mostly in the JCB. The latter has enhanced facilities previously provided in our Morton Laboratory. In addition, our researchers also make use of equipment in other multi-disciplinary Research Institutes and Centres around the campus and beyond.

The *John Garside* building houses the *Manchester Institute for Biotechnology (MIB)* in which 10 of our academics are based (Curtis, de Visser, Gardner, Goddard, Saiani (nee Miller), Snoep, Sutcliffe, Vickerman, Westerhoff, Yuan). This provides a specialist environment for biotechnology related research and was purpose-built in 2006 with a view to facilitating interdisciplinary science through open-plan, multi-functional laboratories, high-tech analytical facilities as well as generous meeting and atrium areas to promote interaction, spontaneous discussion and shared research for up to 600 research staff and students. Amongst the specialist facilities, some have been developed by our staff such as the micro-fabrication facility (Goddard, Fielden) and Secondary Ion Mass Spectrometers (SIMS) (Vickerman, Lockyer).

The *James Chadwick Building* provides state-of-the-art infrastructure for industrially relevant research and hosts a range of chemical engineering facilities, from equipment for complex fluid processing to fully instrumented pilot scale equipment. This has already attracted substantial collaboration with international leading companies such as Cameron, Siemens and Unilever. Cameron selected the Unit to collaborate on the development of their PureMEG pilot plant (12 m in height over 3 floors) valued at over £1M. This is complemented by a Siemens PCS7 control system (donated by Siemens and valued at £100k) which is used for equipment control throughout the building from a central control room. Other state-of-art specialist facilities include the modular structured fluids processing equipment (donated by Unilever) and a range of fully instrumented mixing tanks equipped with electrical resistance and capacitance tomography systems.

The *Mill* has been the traditional home of chemical engineering at UoM since 1956. It houses many research laboratories and numerous items of specialist equipment, e.g. the recently refurbished bioprocess engineering laboratories (around £0.8M) equipped with multi-scale bioreactors, high speed centrifuges, autoclaves, cold rooms, and incubation facilities. Milling and particle processing, high pressure catalytic reactors, fuel cells, crystal characterisation and analytical equipment make up part of the wide range of specialist facilities used and developed by our researchers.

Researchers involved in multi-scale modelling have access to the ***UoM Computer Shared Facility (CSF)****,* a High Performance Computing (HPC) cluster built on a shared model (which Sutcliffe led).

The current system has 3,824 cores allowing efficient use of parallel computing approaches. Use is also made of the *N8 HPC* shared across a consortium of 8 northern research intensive universities.

Extensive materials and surface characterisation facilities are available and used by several of our staff. For example the *Manchester X-ray Imaging Facility (MXIF)*, the associated Manchester beamlines at DIAMOND and the *Electron Microscopy Centre* including a dedicated E-SEM for chemical engineering research. State-of-the-art analytical facilities in mass and nuclear magnetic resonance spectroscopies based in the School of Chemistry are also used by our researchers.

Other research facilities used by our staff include the *Photon Science Institute* (PSI; Martin (Philip), Scully), which provides access to advanced laser spectroscopy research facilities in a new research building opened in 2009 and the *Dalton Cumbria Facility* (DCF; Sharrad) opened in 2011, which provides specialist nuclear facilities, including radiation sources and access to Sellafield.

Investment in Infrastructure and Facilities:

The UoM estate is currently undergoing the largest ever capital investment programme in UK higher education – providing excellent infrastructure fit for a 21st century research environment. As part of this investment, the £16M first phase of a two-phase project to re-locate chemical engineering was completed during 2012. The second phase of our building project, part of the ambitious new £265M *Manchester Engineering Campus Development* (due for completion by 2019), will complete our relocation to leading edge accommodation. Members of the Unit are also based in the state-of-the-art environment afforded by the MIB (£38M; 2006) and the PSI (£28M; 2009), soon to be enhanced by a recently announced £23M investment in multidisciplinary materials characterisation facility. The University has also invested significantly in facilities outside of Manchester – of particular relevance to research in the Unit are the recently opened Dalton Cumbria Facility (£20M; 2011) in West Cumbria, with direct access to the National Nuclear Laboratory and Sellafield, and an imaging beamline at Diamond (£9M; 2012). BP has recently invested around £70M in the *International Centre for Advanced Materials (ICAM)* involving staff from the Unit, which provides a hub with Cambridge, Imperial and Illinois as spokes.

e. Collaboration and contribution to the discipline or research base

i) Support for Research Collaborations:

Local collaborations – Our staff are encouraged to collaborate widely within the University. Of the staff returned with this submission, 16 are actively engaged in local collaborations, including 7 with the MIB, which also hosts academics from Chemistry, Physics, Computer Science, the Faculty of Life Sciences, and the Faculty of Medicine. In addition, many individual collaborations exist within, and beyond, the Unit and these are supported through credit-share arrangements. For example, Schroeder has a joint appointment with Chemistry (10%), Westerhoff leads a DTC where PGR students are registered to the home School of their lead supervisor. Beyond the University, Gardner collaborates with local NHS trusts and the People's History Museum. The Unit, as a whole, collaborates with local industry, e.g. Unilever and Siemens.

National collaborations – Support for national level collaborations is provided through, for example, a travel fund administered by the Head of Research to facilitate attendance at networking events and pre-project collaboration meetings. Outcomes resulting from such activities include an EPSRC consortium led by Yuan (£905K) on *Rheology of Complex Fluids in Microscopic Flows*. Large-scale collaborations involving staff from the Unit include the EPSRC Centre for Innovative Manufacturing in *Large Area Electronics* (Persaud) with Cambridge, Imperial and Swansea.

International collaborations – Support, in the form of study leave and hosting visiting researchers from overseas, ensures that our staff have good opportunities to build international links and collaborations. For example, on return from study leave, Pandiella initiated an EU network of more than 200 academic and industrial partners from Europe, USA, Japan and Australia in the area of gastro-intestinal health research (ENGIHR). A total of 26 EU funded collaborative projects (value to the Unit, £5.4M) have been awarded during the REF period.

ii) Interdisciplinary research:

Much of the Unit's research is interdisciplinary (e.g. in the MIB, PSI etc.) and is supported through a cost sharing mechanism at Faculty level as well as through sector specific funding sources (e.g. EPSRC, BBSRC, NERC, ESRC, Wellcome Trust, HGCA and ESA). For example, the joint EPSRC

& ESRC *Centre for Sustainable Use of Energy in Food Chain*s partnership between Brunel, Manchester (Azapagic) and Birmingham Universities with over 20 industrial partners (total funding: £7M) supported by the SCI.

iii) Influence of collaborations on research activities and strategy:

The influence of collaborations has been to increase overall research activity and extend the reach and impact of the research undertaken by our staff. Collaboration is now embedded in our research strategy as a core principle. For example, all PGR students now must have at least two academic supervisors. The existence of many individual collaborations with industry has led to the development of strategic partnerships at School, Faculty and University level, such as with Tesco, BP, Astra Zeneca, Shell, Siemens, AWE and NNL.

iv) Leadership in the academic community:

Advisory Boards – Examples include: Azapagic**:** Member of the REF panel for UoA12, 2011-2014; Member of the EPSRC Strategic Advisory Committee (SAC) for Energy (2005-2010). Gardner: Member of International Scientific Advisory Board of DIAMOND (the largest UK-funded scientific facility). Webb: International Scientific Advisor to Kobe University in Japan (2008 – 2010), panel member for Hong Kong Research Assessment Exercise, RAE 2014 (2013 – 2014).

Leadership roles (industry & professional) – Martin **(**Philip**)** was Technical Director for TDL Sensors, Ltd.**;** Martin **(**Alastair**)** is Technical Director of Keld Energy Ltd. Smith is Company President and Zhang is CEO of Process Integration Ltd. Persaud is Director of Multisensor Systems Ltd., Vickerman is Director of SurfaceSpectra Ltd., and Roberts is Director of Arvia Ltd. Webb is Vice-President of IChemE (2011 – 2015), Azapagic is Chair of the European Federation of Chemical Engineers (EFCE) Sustainability Section. Davey was president of the BACG from 2010 to 2013.

Conference programme chairs – Staff have been involved in the organisation of 54 national and international conferences, several of which have been hosted by the Unit. For example, Avendano, Masters (Chair) and Siperstein were on the local organising committee of *Thermodynamics 2013*, Manchester, September 2013;

Invited plenary and keynote lectures – At international conferences staff have given 24 plenary talks, 29 keynote talks and there have been 89 other invited talks. For example, Azapagic gave the plenary talk on *Sustainable Chemical Engineering: Opportunities and Challenges* at the 9th World Congress of Chemical Engineering. Seoul, 18-23 Aug 2013.

Election to fellowships of learned societies – During the REF period the following staff have been elected as Fellows: FREng: Azapagic**;** FIChemE: Campbell, Sutcliffe; FRSC: Gardner, DeVisser**, Saiani (**nee **Miller),** Yuan; FInstP: Yuan**;** FAPS: Davey**.**

Journal editorships – staff in the Unit hold a total of 38 editorial board positions for international research journals. Of these, 5 are Editors-in-chief or Executive Editors (Azapagic, Campbell, Gardner, Webb and Westerhoff) others have been Guest Editors or are Associate Editors. For example, Webb is Editor-in-Chief of *The Biochemical Engineering Journal* and Grassia is Associate Editor of *Chemical Engineering Science.*

Research Fellowships Awarded – Carbone**:** RCUK Fellowship (5 years); Yuan**:** MRC Discipline-Hopping Fellowship (1 year); Grassia**:** Leverhulme Trust Royal Academy of Engineering Senior Research (1 year); Sharrad: Nuclear Decommissioning Authority Research Fellow (4 years).

Awards and Prizes – examples of awards to staff in the Unit, during the REF period, include Azapagic**:** IChemE Award for Outstanding Achievement in Chemical and Process Engineering (2010), the GSK Innovation Award, from the Chemical Industries Association (2011) and the Chemistry Innovation Award for the Best Collaborative Project (2011). Curtis: RAEng Industrial Secondment Award (2013). Webb and Theodoropoulos**:** IChemE Innovation and Excellence Award for bioprocessing (2011). Vickerman**:** Theophilus Redwood Award of the RSC (2009), Médaille Chevenard of the Société Française de Métallurgie et de Matériaux (2012). Sutcliffe**:** Rita and John Cornforth Award (promoting and rewarding scientists working in collaborative teams) RSC (2009). In addition, Davey and DeVisser were both awarded the degree of DSc.