Institution: Imperial College London

Unit of assessment: 12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

A. Context

This unit brings together 172.8 submitted FTEs from the departments of Aeronautics (30.6), Chemical Engineering (39.9), Earth Science and Engineering (48.9) and Mechanical Engineering (53.4). The wide scope of the unit enables us to tackle large, multi-disciplinary challenges through research spanning a broad range of fundamental and applied studies involving experimental, theoretical and computational work. We cover the full range of industrial sectors and tackle key problems identified from contact with the major industrial players. This leads to research across a wide range of technology readiness levels (TRLs); we believe it is vital to cover the full range as blue sky (low TRL) work provides the seed corn for the next generation of applications, while higher TRL work generates more immediate impact. Low TRL work is typically funded via the research councils and internal resources, while higher TRL work is directly industry funded or via industry-government schemes. We actively encourage staff to undertake consultancy work as this both helps to transfer research findings to industry and generates ideas for future research. The overall goal is to improve engineering products and processes, to mitigate adverse effects of technology, and thus to enhance quality of life. The principal beneficiaries and forms of impact include:

- **Worldwide Industry**: Industry has benefitted through collaborative research and consultancy addressing key industrial challenges, through the creation of spin out companies offering new products and services, and through the patenting and licensing of new IP. Since 2008, we have raised £85M in new research contracts with industry and have provided £19.5M in consultancy services. All our case studies involve industrial application.
- **Government**: We assist government and policy formation via membership of advisory committees and direct work and advice for government agencies such as dstl (case study 18).
- **Safety**: Through the translation of our research results into widely adopted codes and standards (case study 1) and improved processes.
- **Health**: Research has led to improvements in pharmaceutical manufacture (case studies 11, 15), and work on joint replacement, robotic surgery and cardiovascular and respiratory physiology has impacted medical practice.
- **Public**: In order to raise public awareness, understanding and enthusiasm for science and engineering, whenever possible, we take the opportunity to actively disseminate our research through traditional and new media channels (TV, radio, web) and through dedicated outreach activities including public lectures, demonstrations and festivals.

B. Approach to impact

The unit makes maximising the impact of its research on industry, government and broader society a key priority, in line with Imperial's overall founding mission 'to provide the highest specialised instruction and the most advanced training, education, research and scholarship in science, technology and medicine, *especially in their application to industry'.* We describe below a number of specific mechanisms that we have in place to support our staff to generate impact from their work. Perhaps the most fundamental component of our approach to impact is the creation of a culture within the unit in which the importance we attach to impact is fully understood by all staff and is fully reflected in our processes of staff recruitment, development, promotion and reward. The specific mechanisms used to create and promote impact include:

1. Engagement and Collaboration with Industry

Consistent with the College mission, worldwide industry, and hence the global economy, is the major beneficiary of our research. We recognise that the probability of research outcomes being translated to industry is greatly increased if the relevant companies have been involved in it, and have either funded it directly themselves, or jointly with government agencies. Our strategy is therefore to seek industrial funding and we have raised £85M in new research contracts from **industry** over the 2008-13 period from a wide spread of industry sectors, primarily oil/gas, mining, manufacturing, aerospace/defence, electricity/power and automotive. The total represents an average of over £500k new **direct industry** funding over the REF period per FTE returned. (The £85M is new awards rather than income which is returned in REF4). Awards of over £1M have come from Shell, Qatar Petroleum, Rio Tinto, UNICAT, AVIC, Rolls-Royce (Aero), BG

International, SKF, Statoil, BP, Rolls-Royce (nuclear) and TOTAL.

Strategic Partnerships

We have found that one of the most effective ways of ensuring our research leads to industrial impact is to form strategic partnerships with key industrial players. We have two Rolls-Royce University Technology Centres (UTC) in Vibration (case study 4) and Civil Nuclear Power (collaboration with Materials Dept). A key to the success of the approach is the constant interaction between company staff at all levels and the UTC, and it is this interaction that ensures the translation of research findings to industrial practice. Other companies have replicated the model and we now have UTCs with SKF (in tribology - director Spikes), Aviation Industry Corporation of China (in manufacturing and materials - director Lin), Shell (fuels and lubricants – director Spikes). In addition to formal centres, we have long term strategic relationships with many companies, for example Rio Tinto (PI – Cilliers, case study 7), BP (PIs – Shah, Livingston), TOTAL (PIs – Jackson, Muggeridge) and Airbus (PI - Aliabadi). The Qatar Carbonates and Carbon Storage Research Centre (director Maitland) is a 10 year (2008-2018), $70M funded to date strategic partnership with Qatar Petroleum, Shell and Qatar Science and Technology Park.

A valuable way to cement relationships with companies and to ensure successful technology transfer is to invite staff from the company to spend an extended period at College; we have hosted 37 staff from 26 companies, some via Royal Society and RAEng schemes. We also have 15 industrial Visiting Professors, for example Garwood and Green - Rolls-Royce, Morris - EDF, Ott - Shell, Burgess - Akzo Nobel, Pretlove - ABB Oil and Gas. Imperial staff also spend time in companies eg Sherwin - McLaren, Thornhill - ABB and Heng - GSK via RAEng Visiting Fellowship. Company links are also frequently strengthened by them sponsoring chairs eg Johnson - Shell, Muggeridge - TOTAL, Jackson - TOTAL. Companies often sponsor chairs and senior fellowships via the Royal Academy of Engineering eg Nikbin – EDF, Sherwin - McClaren, Iannucci – dstl, Trusler – Schlumberger, Thornhill - ABB.

Joint Industry Projects

We have a number of research consortia/centres involving multiple companies around a particular common interest. Examples include:

- Centre for Process Systems Engineering (CPSE, PI Shah) is a collaboration with over 15 companies on modelling, optimisation, design and operation of process and energy systems and technologies, budget £5-6M pa (case study 12).
- Pore Scale Modelling (PI Blunt) on prediction of flow in porous media is currently supported by 5 major oil and gas companies paying £30k pa each (case study 6).
- The UK Research Centre in Nondestructive Evaluation (RCNDE, PI Cawley) is a collaboration involving 16 major companies each paying £35k pa, 27 supply chain companies (mainly SMEs) and 6 universities.
- Fullwave III Inversion is a consortium of 15 companies (PI - Warner) that is developing technology to improve seismic inversion (case study 8). Its budget over the REF period was £5.3M and a spin-out company, Sub Salt Solutions, is being launched.
- Transient Multiphase Flow (TMF, PI Matar) involves 15 large companies each paying £42k pa, 10 specialist 'design-houses' each paying £14k pa, and 3 universities (case study 13).

Collaborative projects across multiple European companies, many with substantial EU funding, are very important in the Aeronautics sector and have provided the Aeronautics department with over 14.4M€ funding over the REF period. Staff work closely with large multinational companies such as Airbus, EADS, RR, MTU, Bombardier, Thales, SAAB, Dassault, GKN Aerospace and many SMEs on both Large Integrated (high TRL) Projects and Specific Targeted Research Projects.

Doctoral Training

Doctoral students working in collaboration with industry and then going on to work for the collaborating company provide a strong conduit for taking research findings through to industrial impact. We are active in two EPSRC Industrial Doctoral Training Centres - in Nondestructive Evaluation (PI - Cawley) and Nuclear Engineering (joint with Manchester). In addition to these formal centres, we have had 63 CASE studentships over the REF period. Further, Imperial's Partner Research Institution scheme enrols students who are employees of companies to undertake a part-time PhD; 19 students have been registered on this scheme over the REF period. Our trained researchers make a key contribution to industry: 348 PhD graduates and postdocs who

left the unit over the REF period are now working in industry; case study 17 provides an example of their impact.

Knowledge Transfer Partnerships and Pathways to Impact

TSB Knowledge Transfer Partnerships, the EPSRC Pathways to Impact scheme and Knowledge Transfer Secondments have supported the application of research to industry; 29 staff from the unit have been involved in 34 such projects during the period.

Industrial Training Courses

Running short courses for industry is an attractive route to ensuring that industrial engineers are abreast of the latest developments in our research. 43 staff have been involved in 125 different courses over the REF period eg annual course on Structural Integrity and Component Life Assessment (Nikbin, Davies, average attendance ~30) disseminates research and in particular standards work (case study 1).

2. Intellectual Property and Commercialisation

Spin-outs and Licensing

Through Imperial Innovations plc, academic staff are supported to create, build and invest in pioneering technologies, combining the activities of technology transfer, company incubation and investment. Innovations has a team dedicated to engineering, and staff disclose inventions to them prior to publication; the Innovations team then discuss whether patenting is appropriate and, if so, manage and pay for the process. They then discuss the most appropriate exploitation route, which is usually a license agreement with an existing company, or creation of a new spin-out company. This mechanism has been very successful with 257 patents filed from research in the unit over the REF period (2008-13) and 34 new licence agreements signed. License revenue derived from post 1993 research in the unit exceeds £2M in the REF period and equity realisation has yielded over £9M; examples of licences are in case studies 2, 11, 14. Staff from the unit are also involved in 17 spin-out companies and several of these form the subject of case studies 2, 3, 5, 11, 12, 15.

Consultancy

Staff are encouraged to undertake up to 1 day/week consultancy work, and this is a key means of ensuring that our research work is used by industry. Imperial Consultants Ltd is wholly owned by College and is the vehicle by which most consultancy is undertaken. 154 staff from the unit have undertaken 736 consultancies with industry over the REF period at a value of £19.5M. Consultancy has assisted impact in case studies 4, 6, 8, 9, 12, 13, 14, 17.

3. Health and Quality of Life

Staff in Mechanical Engineering work on joint replacement (Amis is 50% funded by the Faculty of Medicine, giving a direct link to impact on clinical practice via surgeons) and robotic surgery (Rodriguez-y-Baena - Acrobot spin-out company was acquired by Stanmore Implants Ltd). Emphasis is on translation to clinical application via product design and development, and pre-clinical evaluation methods. Impact has been achieved via collaborations with 13 companies during the REF period, leading to patented/licensed products for 2 hip and 3 knee joint replacements, and ligament and meniscus reconstructions. In addition there is extensive translation into clinical practice via demonstration of functional anatomy/biomechanics, leading to novel surgical procedures. Aeronautics research on cardiovascular and respiratory physiology is translated via direct spin-off and training. Doorly and Sherwin are two of the founding shareholders in Imperial spin off, Veryan medical, and Sherwin is co-director of the BHF Research Excellence Centre. We also collaborate in the training of ENT surgeons for MD and PhD degrees. Peiro and Sherwin have collaborated with Parker in Bioengineering on the numerical modelling of Wave Intensity Analysis which is increasingly being used in clinical practice to diagnose cardiovascular related pathologies, and forms a case study in another UoA. Chemical Engineering research also has a significant impact on the pharmaceutical industry (case studies 11, 12, 15) and hence on the health sector.

4. Government and Regulatory Bodies

Government is a key audience via membership of advisory committees; 20 staff from the unit are members of 31 committees eg Ewins - Chairman EU CleanSky - Scientific and Technological Advisory Board; Maitland - Chair, UK Offshore Oil and Gas Regulatory Review, 2011 (The Maitland Report, DECC). We also do direct work for government agencies eg MOD, dstl; an example of impact from this is given in case study 18. Our research also contributes to safety via membership of regulatory bodies eg Walker - naval nuclear regulator, and 13 staff are members of

17 standards committees (case study 1).

5. Public Engagement and Outreach

We are active in raising the profile of science and engineering via TV, radio, websites, open days, museums, festivals, public lectures and conferences, and working with the professional institutions. Examples include Gupta - Halstead Lecture, British Association of Science Festival 2008 and Cheltenham Science Festival 2013; Bastow - Lord Kelvin Award Lecture at British Science Association Festival, Aberdeen; van de Flierdt - blogs from research expeditions to Antarctica 2010 and 2011; Childs - Royal Institution, 2013. The Rio Tinto Sports Innovation Challenge (leader Childs) has involved over 20 public exhibitions, and its celebration of Innovation Design Engineering resulted in over 100,000 web hits in one month, along with exposure on news outlets such as C4, Sky, BBC, CNN, ABC. Energy is an area where Imperial staff have been very effective in informing the public about the real facts eg over 50 broadcasts on the 2010 Gulf of Mexico oil spill (Maitland, Blunt), Carbon Capture and Storage (Fennell) and Shale Gas (Fraser, Maitland).

6. Assistance and Encouragement to Staff

The Faculty of Engineering is supported by 4 dedicated members of the College Corporate Partnerships team to provide support for staff in setting up strategic partnerships with industry. The team also provides a main point of contact for industry, and facilitates the relationship between the College and each company. The Corporate Partnerships team led engagement with BP on a 10 year initiative to explore nanostructured membrane developments for oil and gas applications (PI: Livingston; this is further research leading from case study 11). The team has strengthened the College's relationships with Shell, Airbus, Statoil and Procter & Gamble through the development of framework agreements. Such efforts contributed to the recent establishment of the Shell UTC in fuels and lubricants. In the last 2 years these companies have funded £6.6M of new research collaborations in the unit, with commitments running through to 2021.

The raison d'être of Imperial Consultants Ltd and Imperial Innovations is to encourage and help staff to conduct consultancy work and to commercialise IP respectively. Their role is both to negotiate contracts and to assist with making the appropriate contacts. Since it floated on AIM, Imperial Innovations also has a significant venture fund and so is able to fund commercialisation, which it often does in partnership with other funders. Imperial Innovations have recently appointed an Innovations Fellow in each department to act as a champion to promote engagement with Innovations. Staff are strongly incentivised by direct payment from consultancy and via a well-developed 'rewards to inventors' scheme for the proceeds from licence agreements; staff setting up spin-outs have a significant shareholding in the business at the outset.

Imperial has formed cross-departmental centres to promote research in particular sectors and the unit is heavily involved in these. Examples include:

- The Energy Futures Lab (director – Brandon) integrates research across the energy sector.
- The Manufacturing Futures Lab (director – Shah) integrates research on future manufacturing technologies and underpinning science to facilitate the creation of large projects.
- The Imperial Space Lab is a multidisciplinary research network that facilitates collaboration and idea generation across Imperial, and with external academic and industry partners.

Imperial Consultants, the Corporate Partnerships team and the cross-departmental centres all facilitate an agile response to opportunities – industry can approach the College at many different levels and these points of contact can quickly assemble the relevant academics to give advice, carry out short feasibility studies or plan longer term research as appropriate.

The departments have industrial advisory boards that assist with research direction and contacts; they also run regular events to help academics, particularly newer members of staff, to make contacts with industry. For example, Mechanical Engineering runs an annual research showcase that brings together 50-100 visitors from across industry sectors, Chemical Engineering has an annual PhD Research Symposium linked to an Annual Research Partners Dinner for 50-70 high level company executives, Aeronautics has run two 'Green Aviation' days with 300 industrial/government participants from USA and EU, and Earth Science ran an Oil and Gas centenary event in 2013.

The Imperial College Press Office has a media guide that lists the expertise of staff who are available to appear on TV and radio, and to give interviews and background to the print media; they also run media training courses that are open to all staff.

C. Strategy and plans

1. Overall Strategy

Generating impact is central to our mission and will continue to be so. We have analysed the history of the impact generation described in our submitted case studies and other successful examples; common to all of them is initial contact with industry defining a real problem whose solution will make a significant difference to industry, and which industry will therefore invest in. The appropriate academics then devise a route to a solution and seek funding; if the work is at a low technology readiness level, initial funding is usually internal (eg for a feasibility study) or from public sources (research council or EU), often with some industry input. Higher TRL work is usually funded by industry, either via a single company or a joint industry project; again there is often a contribution from public funds. This analysis has informed our research strategy set out in REF5 where we identify three categories of activity:

- *Exploratory Research* - new ideas and research areas (typically 1-3 year duration, <£100k pa), by internally funded PhD scholarships and College funded Junior Research Fellows.
- *Developmental Research* - larger projects in or between research groups funded by industrial consortia, RCUK or other sources (typically 3-5 year duration, £100k-£1M pa).
- *Programme Research* – large, long-term (typically 5-years or longer, >£1M pa) industrial research Centres or RCUK Programme-type activities, usually with additional industry financial support, that cross research groups and departments.

Most of the impact case studies from this UoA resulted from programme research activities. Our strategy is to continue to develop these long-term, strategic partnerships with single- or groups of companies that support a common research theme. As the partnership and the research mature, a 'research-to-impact-to-research' cycle develops in which the research produces impact, leading to further research producing more impact etc. We have found that industry readily makes further research investments once value (or impact) has been derived. A typical example is case study 7, which encouraged the second, £5.5M, 5-year funding cycle from Rio Tinto; programme scale activity also encourages new exploratory and developmental scale research that also produces impact. We will continue to work across a broad range of industrial sectors, as exemplified by our funding portfolio discussed in Section B, and the span of our case studies discussed in Section D.

In addition to industrial impact, we recognise that academia has an important role to play in offering impartial advice across government and we will continue to promote this activity. Developing public awareness of the importance of Science and Engineering, as well as explaining key Science and Engineering issues in an accessible way, is ever more important and we will aim to increase our media profile.

2. Management and Incentives

Leadership is crucial to promotion of impact; the department heads in the unit are committed fully to the achievement of impact and have contributed three case studies (2, 7, 11). They will continue to strongly encourage research translation to industry via:

Management

- Impact is a standing agenda item at all departmental management committee and staff meetings;
- We will create senior departmental posts with responsibility for overseeing translation and impact, reporting to the Departmental Research Committees;
- Impact will be discussed at all annual appraisals, together with an exploration of the extent of industry contacts, what key industrial problems to address have been identified, what avenues to impact are being explored, what consultancy work is being done etc.
- We will continue to work with the Corporate Partnerships office to help the establishment of further programme scale activities.

Incentives to Staff

- Impact will be a major criterion for promotion, alongside research papers and teaching;
- Consultancy, particularly that associated with technology transfer, will be actively encouraged;
- We will continue to financially incentivise staff to generate impact. This is done directly for consultancy, licensing and spin-outs as discussed in Section B.

Assistance to Staff

- We will undertake horizon scanning exercises, jointly with our strategic industrial partners and

key overseas academic collaborators to identify the main technological and institutional trends - we are developing a model for these events based on a successful trial with Shell executives;
- We will organise seminars around impact case histories;
- Imperial Innovations and Imperial Consultants will give presentations at staff meetings;
- Senior staff will work with newer staff members to introduce them to key industry contacts;
- We will continue to organise regular research showcase events for potential industry sponsors;
- We will encourage staff in the appropriate areas to link with the Energy Futures Lab, the Manufacturing Futures Lab and the Space Lab discussed in Section B;
- We will encourage greater interaction with SMEs; this will often be via CASE conversion studentships, Engineering Doctorates and KTP schemes. Imperial Consultants has appointed a manager for the KTP scheme and he helps academics in setting up KTP schemes;
- We will develop a new communications strategy and encourage staff to take media training, and to make themselves available to both print and broadcast media.

D. Relationship to case studies

The case studies presented were chosen to cover a range of pathways to impact, and to show examples of impact via large and small companies. The studies are listed in the matrix of Table 1 where the chief route to impact is denoted by a bullet, and other routes by an open circle.

#	Short Title	direct industry use	spin-out	licence	consultancy	government/regu-latory/standards	supply staff to industry	Main Sector
1	Standards for Materials in Industry	o				●		Cross sector
2	Guided Wave Inspection	o	●	o		o	o	Oil & gas
3	Lubricant Testing	o	●				o	Automotive
4	Rolls-Royce Vibration UTC	●			o		o	Aerospace
5	Advances in CFD		●					Cross sector
6	Digital Core Analysis	●	o		o		o	Oil & gas
7	Froth Flotation in Mineral Production	●		o			o	Mining
8	Full Waveform Seismic Inversion	●	o		o			Oil & gas
9	Deconvolution in Well Test Analysis	●			o		o	Oil & gas
10	Underground Coal Gasification	●		o		o		Mining
11	Organic Solvent Nanofiltration	o	●	o			o	Pharma
12	Process Systems Enterprise Ltd	o	●		o		o	Chemicals
13	Multiphase Flow in Plant Design	●			o		o	Oil & gas
14	Modelling for Complex Fluids	o		●	o		o	Chemicals
15	Advanced Sorption Instruments	o	●			o	o	Pharma
16	Runway Debris Protection	●						Aerospace
17	Aerodynamic Performance in F1	●			o		●	Automotive
18	Protective Structures for Blast	o				●		Defence

Table 1. Selected case studies and how they exemplify different types and routes to impact (● main route; o additional route)