Enabling the Future

A Perspective on UK Materials Research

An international review of materials science & technology research in UK universities

EPSRC
Engineering and Physical Sciences Research Council

IOM3
The Institute of Materials, Minerals & Mining

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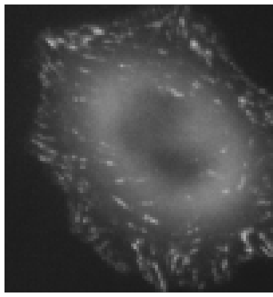


It is an exciting time for the engineering and physical sciences. The pace of progress has never been more impressive and the eminence of UK researchers in many fields of endeavour is realising significant benefits for the citizens of the UK through the contributions of research to economic competitiveness and quality of life. Crucial to this progress is the development of fundamental knowledge and understanding of materials science and technology which is often a prerequisite in determining the pace and range of technological change.

It is through research that barriers to progress can often be overcome and new opportunities realised. The underlying importance of materials science to the UK economy is illustrated by the wide range of industries which it underpins, from electronics to construction, transport to healthcare; all are reliant on a fundamental understanding of the structure, properties and performance of materials.

This review is timely, given the critical importance of materials researchers to new emergent technologies, the most significant of all of these being the ability to manipulate, design and create materials on the atomic scale – through nanotechnology. This area of technology has the potential to transform nearly every aspect of every day life opening up new capabilities and markets, making improvements to the quality of life.

This review is the fourth in a series aimed at providing international commentary on the core fields of the United Kingdom's science and engineering research base. The review follows on from those conducted in engineering, physics and computer science and arose from EPSRC's wish to obtain a better understanding of the strategic position of the subject, as perceived by international experts.

The Institute of Materials (now IoM^3), in association with the Institute of Physics, the Royal Society of Chemistry and the Royal Academy of Engineering. EPSRC's partners undertaking the review, were keen to ensure that it was conducted with rigour, accuracy and sensitivity. All agreed that in order to be useful, the review must command the respect of the research community.

The Institute of Materials provided a coordinator for event planning and liaison between the steering committee, panel members and universities. EPSRC took responsibility for preparation of background information provided to the Panel.

The Terms of Reference for this review were to:

- Report on the current standing of materials research and its likely impact on the UK science base and on the nation's future wealth and well being;
- Cover all materials research supported by the UK Research Councils in UK universities and central laboratories;
- To draw on existing data, international assessments and site visits.

The review was overseen by a steering committee comprising:

Professor Colin Humphreys (Chair), IoM^3 President, University of Cambridge
Professor Dame Julia Higgins, Imperial College
Professor Peter Main, University of Nottingham
Professor Tony West, University of Sheffield

The steering committee working closely with the panel chair, determined the membership of the international panel. The steering committee made every effort to cover the relevant sub-fields of materials, to represent perspectives from industry, academia and to achieve both international and gender balance. The panel members were:

Chair - Professor Anthony Evans, University of California Santa Barbara, USA
Professor Christian Colliex, Université Paris Sud, France
Professor Gordon Dunlop, The University of Queensland, Australia
Professor Arthur Heuer, CASE Western Reserve University, USA
Professor Robert Hull, University of Virginia, USA
Professor Sumio Iijima, Meijo University, Japan
Professor Brian Maple, University of California San Diego, USA
Professor Milan Mrksich, The University of Chicago, USA
Professor Klaus Ploog, Paul-Drude Institute, Germany
Professor Manfred Rüehle, Max-Planck Institute, Germany
Professor David Srolovitz, Princeton University, USA
Professor James Williams, Ohio State University, USA
Professor Claudine Williams, College de France, France

The EPSRC would like to extend its very sincere thanks to the steering committee, IoM^3 and the international panel. And in particular the Panel Chair Professor Anthony Evans for his time commitment to the review and his work in finalising the report. I hope that you will agree with me that the Panel is to be commended, for producing such an excellent and comprehensive report which will be a very important input in formulating future strategies for the support of materials research in the UK.

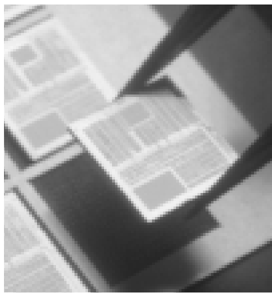
I would welcome comment on the report.

Professor John O'Reilly
Chief Executive, EPSRC

Professor A G Evans

Back row, *left to right: Milan Mrksich, Robert Hull, Manfred Rüchle, Brian Maple, David Srolovitz, Jim Williams*
Front row, *left to right: Gordon Dunlop, Klaus Ploog, Claudine Williams, Sumio Iijima, Cristian Colliex, Arthur Heuer*

Executive Summary



The Panel offers opinions about the materials research enterprise in the UK. It is a snap shot from a small group that, while broad in its perspectives, does not completely cover the field. While the visits were of limited scope, the Panel has tried to minimise bias both through independent knowledge of UK science and by becoming acquainted with the information provided by the EPSRC: this has been augmented by discussions between the Panel and members of the materials research community, as well as end users of the research outcomes. Names of specific UK universities are intentionally excluded in the report to avoid unintended omissions.

The Panel has found the breadth of the field a particular challenge. In recent decades, materials research and education have diffused throughout science and engineering programmes at most major universities. The resultant ensemble eludes concise definition. The field tends to be defined at a local level (within each country, within each university and within each department), causing international comparisons to be fraught with gaps, disconnects and a lack of universality. Despite the difficulties, the Panel has formed opinions about the strongest and weakest aspects of the UK portfolio in materials research. We have identified structural issues with research funding, academic salaries and industry involvement in academic research that have adversely affected the standing of the UK in the field of materials research.

As the industrial base in the UK, which is reliant upon materials innovation is small, concentrating precious resources into areas that most benefit competitiveness appears necessary. The Panel lauds the attempts to address such challenges through the Foresight exercise, while finding deficiencies in the materials area. We also applaud the UK for having several focused professional entities (the Institute of Materials, the Institute of Physics, the Royal Society of Chemistry and the engineering societies) having the authority to tackle difficult strategic issues and developing a vision of materials for the future (not the case elsewhere in the world). Ultimately, materials research benefits the UK when novel or improved materials appear in components and systems that compete on a performance/cost basis. This process is driven by original equipment manufacturers (OEMs). The Panel was unable to elucidate the explicit role of the technology organisations within the OEMs in the Foresight exercise and in affecting the materials research portfolio.

The assessment suggests a few world-class individuals and small groups operating effectively in the existing UK system, but a much larger cadre of researchers unable to develop their potential. While a similar situation applies elsewhere, the challenges confronting those outside the elite group appear to be greater in the UK. We have emerged with the following rankings, with the caveat that our perception of a sub-field may be biased by 1 or 2 stellar performers in that field. In transcending order: Organic Semiconductors (Excellent) → Biomaterials, Polymers, Photonics, Superconductors, Characterisation (Highly Competitive) → Inorganic Semiconductors, Functional Ceramics, Magnetics, Structural Metals, Nanotechnology, Modelling (Competitive) → Composites, Structural Ceramics (Non Competitive). Some areas with poorest ratings coincide with those that the Foresight study has suggested be de-emphasised. The Panel did not take this into account when reaching its judgement.

The UK has generally been effective in its approach to multidisciplinary research. Some of the IRCs and a few managed programmes have created a positive environment for such research. There are excellent examples in the biomaterials area, as well as in polymers. However, there are also examples of activities that, while they have developed the appropriate modus operandi, now struggle for fiscal survival. This suggests structural problems, which need to be redressed:

(i) Greater emphasis on "bottom-up" initiatives, proposed within a broad set of themes (based on Foresight-style, research landscape assessments);

(ii) More distributed investment in large-scale, expensive-to-maintain, facilities; and

(iii) Redesigned assessment procedures for multidisciplinary initiatives that rectify the tendency for a correlation between novelty and unfavourable panel-style review.

As detailed examination of EPSRC processes were not undertaken during the review, this issue is covered in a separate letter to the Chief Executive and EPSRC Council

The Panel has mixed opinions about interactions between the materials research enterprise and UK industry, and about the capture of intellectual capital at UK universities. There are examples where industry interactions have provided essential focus, but others where excessively-close direction by industry has adversely affected the international standing of the field. While the Foresight exercise, in conjunction with the TOP/UP panels, should be capable of addressing these issues, shortcomings in scope and implementation are apparent in the materials area. The capture of intellectual capital and the transition of technology appear to be in a state of flux. There are examples that can be favourably compared with the best in the US, but others where it is *ad hoc*, with a real potential for conflict of interest. We believe that the EPSRC should be pro-active in helping identify and publicise best practice for universities relating to the management of IP, technology transfer, and commercialisation.

A relatively inflexible funding structure causes materials research in the UK to lack the desirable diversity that exists in some other countries. The Panel comments on deficiencies that inhibit materials research in the UK from fully reasserting itself. We specify an "ideal" mix that, in the opinion of the Panel, would permit the academic community to have the greatest international impact. While some of the latest initiatives appear to be moving toward such a mix, the details (concerning materials research) were not transparent to the Panel. The obvious problems arise in two areas:

(i) The paucity of special funding for young faculty*, compounded by minimal start-up funds. A new initiative (Special Young Investigator Awards) would address this problem; and

(ii) The "top-down" emphasis of many managed programmes, accompanied by a broad perception that these programmes are of inferior quality. We suggest that "bottom-

**In this report "faculty" is used to denote salaried academic staff at the universities* up" initiatives within themes augmented by technology road maps would produce stronger programmes. To establish these new initiatives, the Panel strongly believes that the overall level of funding for materials research needs to be enhanced.

The UK has a long-standing issue with human capital: Globalisation of science and technology has had an increasingly adverse affect on the ability of UK universities to attract and retain the brightest minds into the materials research enterprise. Low university salaries in science and engineering, relative to other countries, coupled with the shortage of Young Investigator funding initiatives, are disincentives for entry-level researchers and faculty with greatest leadership potential. Within the UK, the superior career opportunities perceived in finance, biotechnology, information technology and so on, have dramatically diminished the applicant pool. While this is also happening in most developed countries, the situation is particularly critical in the UK. The seriousness of the problem is compounded by an inflexible educational system that lacks mechanisms to draw highly talented newcomers to the field at multiple stages of their career path. Providing a continuum of opportunities for engineers and scientists to seamlessly enter the materials field has emerged elsewhere as the paradigm for sustaining the field and retaining its excitement. Multidisciplinary initiatives centred on materials will help, as well as the ongoing marketing and 'advertising of the field' by the professional societies in conjunction with EPSRC. However, structural changes that address the role of materials within the UK university system may be necessary.

This Panel strongly believes that the existence of healthy materials science/engineering departments is critical to the broader materials research enterprise. It is imperative that materials continues to be available as an undergraduate discipline but incorporate various modifications to enhance recruitment. The materials research mission of the UK would be substantially compromised if the techniques, methodologies and tools of the materials science/engineering discipline were no longer readily available.

Finally, we note nuances between the US and European members of the Panel about the overall research standing in the UK and its vector. The Europeans were generally more impressed by the health of the research enterprise than the US members. The Europeans felt that materials research in the UK has experienced a turn around and is now on a vector that places the UK at least on a par with France and Germany. They were particularly impressed with the progress made in the UK in fostering interdisciplinary activities, relative to the rest of Europe. The view of the US members is less sanguine and perhaps, more strongly expressed in the report. Their opinions are based on shortcomings perceived relative to a US system that embraces funding diversity and an extensive network for multidisciplinary activity, with well-developed mechanisms for interaction between universities and industry, including an effective role for technology road maps.

Recommendations:

- *Create a more diverse funding landscape for materials research in the UK with a range of predominantly "bottom-up" support mechanisms drawn upon best international practice and guided by technology road maps (emanating from the technology organisations at the OEMs). The funding portfolio should reflect the* *appropriate combination of technology pull and academic push. The Panel suggests an "ideal" mix of funding that would permit the academic community to have the greatest International impact. To achieve this desirable mix at a level sufficient to enhance UK competitiveness, the Panel strongly urges an increase in the overall level of support for materials research commensurate with the relative levels established in the US.*

- *Vastly enhance the career opportunities for young faculty through new funding vehicles (Special Young Investigator Awards). It is imperative to implement meaningful start-up support and internationally competitive salaries.*
- *Characterisation plays a unique role in materials research and provides special infrastructural needs. Funding agencies should consider a targeted and periodic competition for advanced instrumentation.*
- *The EPSRC should be pro-active in helping identify and publicise best practice for universities relating to the management of IP, technology transfer and commercialisation emanating from materials research.*
- *The UK has a special opportunity (unavailable in many other countries) to identify a research portfolio in materials research that benefits the country the most, through continued use of the Foresight exercise and its professional entity, the Institute of Materials together with associate UK organisations. The report comments on deficiencies and disconnects to be reassessed in the materials research component of this exercise.*
- *The current relationship between the materials research enterprise and UK industry is, at best, uneven. A fundamental rethinking of this relationship appears to be needed, predicated on best international practice, in order to overcome problems that have adversely affected the UK's standing.*
- *The UK has been successful in putting in place a culture for multidisciplinary research in materials. This portends well for the future, once some structural problems described in the report have been redressed. However, the EPSRC should guard against overly specialised peer reviews.*
- *Materials science/engineering should not be allowed to disappear as a vital discipline. Materials departments should continue to exist in numbers and at support levels that enable them to participate with other relevant disciplines as an equal partner in the materials research enterprise. Structural changes related to admission policies, scope and funding must be explored.*
- *Dispense with the research assessment exercise (RAE). The exercise has served the purpose of inculcating an appreciation for excellence and is no longer needed.*
- *Additional Recommendations are contained within the report.*

Introduction

I.1 Materials Research

Developments in materials enable modern technology and provide the cornerstone for industrial activity. While rarely in the public eye, the impact of materials on each nation's economy cannot be underestimated. Any country that fails to maintain expertise in this area cannot expect to remain competitive. Investment in materials research leads to new technologies and the economic growth they engender. It also develops the human capital that fuels the economy. Many recent studies conducted in the US, Europe and Japan have espoused sentiments of the type "Materials have been central to the growth - prosperity - security - and quality of life since the beginning of history ... without new materials and their efficient production, our world of modern devices, machines, computers, automobiles, aircraft, communication equipment, and structural products could not exist ... materials science and engineering is crucial to the success of industries that are important to the strength of the economy and security." Such sentiments are echoed by the Panel, but are not elaborated. Instead, we prefer to emphasise the evolving context for materials research and its influence on the structure of the field, as well as its impact on technology.

For many decades, materials research in academia, worldwide, was largely curiosity-driven, with a major emphasis on structural metals but with smaller and well regarded activities in polymers, composites and ceramics. Research on electronic and photonic materials started later and most typically grew within the electrical engineering discipline. From the outset this latter research was largely systems-driven. In its most successful manifestation, it comprises bottom-up, multidisciplinary research motivated by academics cognizant of systems issues that, in turn, define new materials opportunities. Such programmes incorporate device design and fabrication, coupled into a technology road map. A further broadening occurred as chemical engineering fostered polymer research and electrical engineering established MEMS initiatives. The physics, chemistry and mathematics communities became active participants in materials research over a decade ago and have been joined more recently by biology.

Currently, materials research and education can be found throughout science and engineering programmes at most major universities, but is difficult to categorise in a concise manner. It is everywhere, yet not easy to encircle. The positive consequence is that the field is endorsed as being critical to the wellbeing of a country as well as to the mission of a university. However, it is defined at a local level (within each country, within each university and within each department) such that international comparisons lack universality.

As the breadth of the field has expanded, research on many material categories has progressed from the curiosity-driven invention of novel materials into systems-driven areas. This is a natural evolution as research on materials becomes mature and the prospects for inventing new functionality or radically superior performance diminish. The transition into systems-driven research (following the semiconductor example) is a difficult one, especially in an academic setting. The reconfigured research enterprise requires that academic teams be created to acquire knowledge well beyond materials.

Interaction with the engineering communities is a prerequisite. Success is based on the ability to create effective multidisciplinary/multi-institutional research programmes that address systems challenges.

Systems research has become a necessity in some areas, whilst in others it remains in curiosity driven mode as the materials are still in infancy, but with real potential for new funtionalities. Bio- and nano-materials are in this category.

This complexity and diversity in materials research presents a challenge to the Panel in terms of the scope and the inclusiveness of its findings.

I.2 Mandate

EPSRC is conducting a series of reviews to provide a benchmark against which its research and training portfolio can be measured and compared, on an international basis. This review reports on the standing and potential of materials research in the UK and attempts to provide a comparison with materials research internationally. The review covers all materials research supported by the UK Research Councils in UK universities and central laboratories. It draws on existing data, international assessments and site visits. It includes non-EPSRC supported activity in UK universities, particularly pan-European collaborative projects and direct support by industry.

The review is performed with the understanding that the objective of EPSRC's Materials Science and Technology Programme is to support high quality research to underpin the exploitation of materials for the benefit of the UK, and to contribute to the materials postgraduate needs of industry and academia. The materials programme currently has a portfolio of research grants and training awards worth approximately £139M (grants and training awards extend typically over three years – the annual spend figures are £34M on research; £8M on training). Significant funding enters departments other than materials science and metallurgy, especially physics and chemistry. The core programme focuses on end use, which may be long term and speculative. The programme supports the complete range of structural materials [polymers (17%), metals (18%), ceramics (12%)] and functional materials for specific applications [photonics (21%), electronics (19%), magnetics (6%) and superconductors (7%)], underpinned by synthesis/growth, characterisation, processing and modelling. Materials research is also supported outside of the materials programme; notably, biomaterials and some aspects of the processing of structural materials, are both supported through the engineering programme.

Currently the majority of programme resources are within the responsive mode, sub-divided roughly equally between structural and functional materials. The remaining resources are in the directed managed mode, used for research areas identified as national priorities. Future programme strategy seeks to introduce shape into the responsive mode to strengthen the research base, through mechanisms such as platform grants, which allow key groups to retain staff longer-term and to actively encourage larger multi-disciplinary proposals, proof of concept feasibility studies and networks. The EPSRC regards its multidisciplinary research as a strength and seeks enhancement by placing managed funds at the programme interfaces.

International Standing of Materials Research in the UK

II.1. Context for the Assessment

The Panel was able to visit only a small subset (and these only extremely briefly) of the universities performing materials research in the UK and did not have the breadth to cover all pertinent areas. The following assessment is thus based on a combination of personal knowledge of the field, interactions with UK scientists and technologists at technical meetings and through the literature, site visits and discussions with colleagues. Because our contacts were not all-inclusive, the Panel elected to exclude names of specific UK universities when addressing a topic or sub-area.

The criteria used by the Panel for assessing research quality were as follows:

(i) Areas considered “Excellent” were those in which the Panel felt that recent research performed in the UK had fundamentally changed the direction of the field. The Panel members and their colleagues follow closely the research output from leading UK centres.

(ii) Areas deemed “Highly Competitive” were those in which Panel members value research collaborations with UK as equal partners. The Panel members and their colleagues typically visit UK centres and benefit from collaboration.

(iii) “Competitive” refers to activities where some results emerge from UK groups with sufficient impact to be cited by the International community.

(iv) “Non Competitive” designates areas where the UK is a follower.

The results of this assessment are summarised in Table I. Within each column, the topics are listed alphabetically. The arrows refer to the research vector (up refers to an improving stature during the last 5 years and down vice versa)

Table I. International Standing of UK Materials Research

Excellent		Highly Competitive		Competitive		Non Competitive	
Organic Semiconductors	•	Biomaterials	↑	Functional Ceramics	•	Composites	•
		Characterisation	•	Inorganic Semiconductors	•	Structural Ceramics	•
		Photonics	↑	Modelling	•		
		Polymers	↑	Magnetic Materials	↓		
		Superconducting Materials	↓	Nanotechnology	↑		
				Structural Metals	↓		

II.2. General Remarks

The Panel was exposed to a spectrum of programmes within the materials research enterprise in the UK. As expected, some universities exhibited a highly developed and very professional infrastructure that provides opportunity and support for a broad range of research programmes. Other institutions, lower in the RAE rankings, had legitimate materials research roles and, in certain cases, were pursuing some of the most novel research exhibited to the Panel. Most prominent universities have recognised that materials research spans all of physical sciences and engineering and have initiated serious efforts to define the scope relevant to their university, as well as encouraging multidisciplinary programmes across many departments. While such diversity developed earlier in some countries (such as the US), it has yet to happen in others. The Panel believes that the UK is well positioned to build its multidisciplinary materials research enterprise from this solid foundation.

While the foundations are present (and being further developed), there are problems in scope and implementation. The UK cannot compete in every area of materials science and technology. It should presumably focus its efforts in areas where UK industry has current and perceived future pre-eminence. The Panel recognises the dangers of limiting the scope of funding and, moreover, wishes to encourage a bottom-up approach, but the alternative of spreading the available support too thinly seems untenable. The UK has some advantages in pursuing such an objective:

(a) Unlike most other countries, all of the materials activities reside within a single professional society (the Institute of Materials). Working with other professional societies such as the Institute of Physics and the Royal Society, they have begun to reap benefits in forming strategic visions for the future of materials.

(b) The continuation of the Foresight exercise has created a forum for dialogue between most of the sectors having vested interest in materials research and technology. The outcomes thus far are impressive in general, but not yet authoritative in the materials area. Examples here include initiatives in materials processing, nanotechnology and modelling.

As work from Materials Foresight continues, the Panel is encouraged about the future of materials research, provided that funding and educational problems addressed elsewhere in the report can be solved. Still, there appear to be disconnects in the materials research portfolio. We draw attention to these in various parts of the report.

The Panel struggled to find a relationship between the Foresight exercise and areas of materials to de-emphasise in the research portfolio. We presume that quotes of the type, “staying out of commodity materials” and decreasing support for “dynamically loaded ceramics and new high temperature superconductors” are probable cause for diminished activity in some areas.

While Foresight is a laudable development, from the Panel’s perspective, the materials component lacks vision in several areas. We do not detect a “technology road map” culture facilitated by the Original Equipment Manufacturers (OEMs) in the UK about where to place priorities. While we understand that such an OEM-based vision should not dominate choices about the materials research portfolio, it should be a crucial input. This deficiency is a source of disconnects and negatives that emerge in the report.

The Panel believes that the lack of diversity in funding mechanisms in the UK has caused many faculty to devote an inordinate proportion of their time to securing adequate support for their research (a problem seriously compounded by the RAE). This deficiency has adversely influenced productivity and international standing in some research areas.

II. 3. Technologies and Systems

Structural Systems

Research on materials relevant to structural systems has progressed in the last decade from the curiosity-driven invention of novel materials (alloys, ceramics, intermetallics and composites) into systems-driven areas. While the mandate is clear, its implementation has greater complexity than the semiconductor paradigm. Interaction with the mechanical, aerospace and electronics engineering communities is a prerequisite. Most UK universities have yet to adapt. The Panel believes that there are two interrelated reasons:

(i) UK industries operating successfully in this arena have dwindled. Rolls-Royce and BAE are among the few remaining internationally competitive industries. Accordingly, there is a reduced motivation for a concerted effort at the universities and a diminished interest in the field by prospective students of the preferred calibre.

(ii) At UK universities, few of those involved in structural systems have embraced the concept of multidisciplinary/multi-institutional research involving colleagues in mechanical/aerospace/electronic engineering. This deficiency has impeded their ability to recognise technical opportunities and to create funding vehicles.

This situation is in marked contrast to preceding decades, during which a research focus was on the fundamentals of structure and properties. Then, the UK had an unparalleled tradition for excellence and invention. Stellar individuals abounded (for example, Cottrell, Frank, Eshelby, Ashby, Hirsch, Christian). The present situation is at best, fragmentary. Two illustrations calibrate the UK status:

(a) The UK has led the world in establishing metrics that allow mechanical/aerospace/electronic engineers to select materials based on engineering principles and thereby, identify performance deficiencies that create new research opportunities.

(b) UK universities have embraced materials processing and manufacturing science and technology to a greater extent than their academic counterparts elsewhere. This has emerged as a mixed bag. The investment in the associated infrastructure has been large, but the support for its indefinite maintenance is difficult to sustain. In a few cases, the research portfolio has been sufficiently diverse and the emphasis on the basics strong enough to allow a viable mix of industry, EPSRC and EU support to sustain the operation. In others, the lack of diversity and the overly strong reliance on EPSRC and EU funds has compromised viability. This latter problem has led to an overemphasis on direct support by industry, with consequent short-term goals and stringent limitations on academic flexibility.

This uneven situation, coupled with a perception that the EPSRC is unwilling to contemplate new funding in this area, has had two undesirable consequences:

(i) Except for pre-eminence in materials selection and for some efforts in process technology, the UK is perceived as a follower in structural materials research.

(ii) Rolls-Royce has set up its own research centres. These have been constructed around existing centres of expertise at UK universities in order to assure that the materials research relevant to advanced turbines remains in the UK. They have found by working in such positive partnership, they have been able to leverage substantial public funds. The positive consequence is that research relevant to Rolls-Royce is performed in the UK (we note that, without their commitment, plausibly this type of research would have disappeared from the UK portfolio). The negative outcome is that the research is perceived to mainly addresses near term issues (sometimes with publication restrictions), despite peer review, and that it has not received full international recognition.

In summary, the EPSRC should give further support for funding multidisciplinary/multi-institutional research on thermostructural systems (say, in aerospace or MEMS) that encourage the formation of bottom-up academic teams that span materials and the key engineering disciplines. Responsive mode would appear the appropriate means for this. While connections to UK industry should be required, in the form of "guidance by a technology road map", the research themes must be set by the academic team, with visions beyond a 5 year horizon.

Electronic, Photonic and Magnetic Systems

Electronic, photonic, and magnetic materials have a wide range of technological applications:

(i) Semiconducting materials impact on electronics, computational systems, and sensors;

(ii) Optoelectronic/photonic materials have expectations of high speed, large bandwidth, low power consumption, and low cost light emitting diodes (LEDs) and lasers; these impact telecommunications, optical detection, photoelectrics, optical computing.

(iii) Superconducting materials affect wireless communication, medical diagnostics, generation, transmission, and storage of electrical energy, high-speed transportation, digital electronics based on Josephson junctions, and interconnects.

(iv) Magnetic materials are used for information storage, magneto-resistive read heads, high strength permanent magnets for use in motors, generators, and magnetic levitation.

Research and development in the fundamental science and technological applications of these materials is highly interdisciplinary and involves chemists, engineers, materials scientists, technologists, and physicists. The synthesis and characterisation of new, novel and complex electronic, photonic, and magnetic materials and their integration into devices is a challenging enterprise that requires advanced techniques and sophisticated equipment.

In summary, the Panel believes that, while research in photonics and its subfields is competitive, the UK is not a world leader in this general area.

Biotechnology

Biological applications represent a relatively new theme in materials science and will be a frontier area for the foreseeable future. Because this sub-discipline is evolving rapidly, it is difficult to compare the status of research in the UK with other countries, or even to comment on the trajectory of biologically oriented materials science. As elsewhere, the UK has established a competitive basis in certain areas of materials-oriented biotechnology. The state of UK standing in three broad areas of current bio/materials research is summarised below:

(i) The most visible area concerns *biomaterials*, which refers to the development of materials for clinical applications;

(ii) The second concerns *biological materials* and biomimetics, and aims to understand the structure/property/development relationships of naturally occurring materials and to use this understanding to develop novel biologically inspired materials processing technologies; and

(iii) The most recent development is *biochips*: a portfolio of micro-array technologies aimed towards diagnostics and drug discovery.

The use of *biomaterials* for *clinical applications* is now common in a variety of settings, including catheters, arterial stents, prosthetic aids, contact lenses, and indwelling monitors and sensors. Many of the materials used in these applications were not developed for these purposes, but rather were developed for non-biological applications and were empirically determined to have acceptable properties. They are not optimised and their development is not grounded in fundamental understanding. The past decade has seen increased activity in *designing* materials, based on an understanding of biological mechanisms and the development of novel materials that have desired properties. Polymers for drug delivery represent a major focus of materials science to develop implantable vehicles with tailored properties, and have even led to several commercialised technologies. Although these approaches were not pioneered in the UK, several groups are now highly competitive in this area. A second important theme, which is still in its infancy, is the development of materials for tissue engineering. These materials are designed to serve as three-dimensional scaffolds that mimic the normal protein matrices that cells and tissue grow on, and will have applications in growing replacement organs. The UK has made strategic investments in this area and has established a competitive materials science effort.

The study of *biological materials* – both hard and soft tissue made by organisms – and the *biomimetic* development of novel biologically inspired materials processing technologies, has become an active area of materials research in the last decade. UK researchers have made early and seminal contributions to this field. Much of this work has developed outside mainstream materials departments, principally in biology and chemistry departments. The current UK effort is small but well-regarded; the vigorous growth of this subfield, as has occurred in the US for example, has not happened in the UK.

Biochips refer to substrates having patterned arrays of biomolecules and offer revolutionary advances in assaying biological samples for applications that include drug discovery, clinical diagnostics and personalised medicine. The first micro-arrays were based on the patterning of thousands of DNA strands to glass slides. They were described ten years ago and have now been commercialised and are in widespread use. The value of these chips is that they permit thousands of assays to be conducted with a sample in the time previously required to conduct a single assay. Success with the gene chip has motivated substantial research and development of other classes of biochips, including peptide, protein, and carbohydrate chips. Materials science has a central role in this development, since the biomolecules must be immobilised in ways that retain their normal activities and on surfaces that repel non-specific interactions. The UK has not developed a competitive programme in this area.

In summary, the biotechnology field is still in its infancy and provides opportunities for the UK to garner and maintain a leadership position.

II. 4. Materials and Phenomena

Inorganic Semiconductors

In this area, the panel found sub-fields where UK research was internationally competitive, but generally not leading. Research in other sub-fields was of lower quality or largely absent.

In the broad field of silicon processing and fabrication, there is relatively little research in the UK, other than pockets on basic mechanisms (e.g. diffusion, mechanical properties). The usual reason provided for this absence is that there are few industrial microelectronics research laboratories in the United Kingdom. There is, however, a major concentration of microelectronics manufacturing facilities in Scotland. In other parts of the world, such concentrations have frequently been leveraged to provide substantial new streams of research support from regional and industrial sources. This has not apparently transpired in the United Kingdom. Some panel members feel this is a lost opportunity, but perhaps one that may still be recovered. Partnering with European institutions may help provide the critical mass of facilities and expertise for the UK to yet become a major player in mainstream silicon microelectronics development (however, see later comment in this section on EC programmes).

There is very strong (“highly competitive” to “excellent”) research in silicon-based heteroepitaxy (primarily GeSi/Si heterostructures), and the United Kingdom has one of the five strongest national research programmes in this area. On the other hand, there is little research on epitaxial crystalline high dielectric constant materials on Si. Equally, there are very strong UK programmes in synthesis of compound semiconductor heterostructures, which attain our rank of “highly competitive” in many projects. However, we believe that this particular strength has not been fully reflected in the use of such materials in novel structures. While we did see several examples of excellent research in III-V nanostructures, high speed electronic devices and optoelectronic devices, these frequently focused on either fundamental physics or device engineering. While fully recognising the importance of these areas, we did not typically see comparable advances in fundamental understanding of the materials involved. Thus we assessed the *materials* research in these areas to be only moderately competitive on an international scale. It is important to note that until about 15 years ago the materials research on compound semiconductor heterostructures was world leading. The disappearance of RSRE Malvern, British Telecom Research Laboratories and others had a very severe effect on the research on inorganic semiconductors in the UK.

Partnering with EC institutions and programmes, which many UK institutions/universities do very actively, has one important drawback, because the majority of EC programmes are relatively "reactive", i.e. they typically respond to activities which are already going on in the US or Japan. For example, in some recent exciting III-V materials research areas (such as ferromagnetic semiconductor hetero-structures, new quaternary III-V emitters at 1.3 - 1.8 mm lattice-matched to GaAs, and many aspects of group III nitrides), relatively few innovations or world leading activities have developed in the UK.

In summary, we assessed the materials research in these areas to be only moderately competitive on an international scale.

Organic Electronics

Developing semiconductors from organic polymers offers the principal advantage for conformal properties of organics being exploited; by creating inexpensive and flexible devices, enabling flexible displays, integration of electronics with fabrics, and the integration of electronics with a host of other non-silicon substrates. The organic components also permit milder processing and fabrication steps and therefore can take advantage of less expensive fabrication routes. While the performance of organic semiconductors is far inferior to the inorganic devices, they offer opportunities to extend solid-state technologies to settings that have been intrinsically incompatible with solid-state materials. The UK has been the international leader in organic semiconductors. It has developed an exemplary programme based on synergy between physics, chemistry and device engineering, and in developing a fundamental characterisation and understanding of organic semiconductors, incorporating these materials into device structures and in commercialising flexible displays based on organic components.

In summary, the UK will continue to be the leader in this area and influence the activities of other countries.

Superconducting Materials

Applications envisaged for superconducting wires and tapes with high current carrying capacity include electromagnets, high energy particle accelerators; magnetic energy storage; magnetic resonance imaging; levitation of high speed trains; electrical motors and generators; and electrical power transmission lines. Uses of superconducting thin films include microwave filters, SQUID magnetic sensors, and digital electronics. Most recent research has been on the high superconducting critical temperature T_c oxide superconductors, several with T_c surpassing the boiling temperature of liquid nitrogen (77K).

UK research on the fundamentals of the superconducting and normal state properties of the cuprates, on vortex dynamics, and on microwave properties is world class. UK researchers have also had a strong impact on the physics of novel superconductors such as Sr_2RuO_4 and the magnetic f-electron compounds $CeIn_3$, $CePd_2Si_2$, and UGe_2 that become superconducting under pressure. Although these materials are not high T_c superconductors, their unconventional superconductivity presents physics challenges, arguably relevant to the high T_c cuprates. The newly discovered high temperature superconductor M_gB_2 (T_c = 40 K) has recently attracted the interest of a number of UK investigators. Apart from such excellent work on the fundamentals, a less impressive effort on applications for high temperature oxide superconductors, with no obvious connections to initiatives within UK industries able to exploit the devices was evident.

In summary, the Panel concluded that the UK is not currently a world leader in the development either of new superconducting materials (perhaps by choice, if the recommendations of the Foresight study have been implemented) or of superconducting devices. However, strong activities remain in the physics of superconductivity.

Magnetic Materials

The UK has been a leader in the development of fundamental theories and the performance of groundbreaking experiments on a broad range of challenging problems in magnetism, which have had a major impact in the field. Important problems that have been addressed include band ferromagnetism; magnetic moment formation in metals; the Kondo effect; fluctuating valence and heavy fermion behaviour in f-electron systems; spin glasses; and quantum criticality.

Examples of cutting edge research can still be found:

(i) Theoretical and experimental studies of non-Fermi liquid behaviour near magnetic quantum critical points in d- and f-electron compounds, accessed through the application of applied pressure.

(ii) The development of methods for the processing of permanent magnet materials.

Much of the recent effort has shifted towards applications, such as nano-particles and nanostructures of magnetic materials; single molecule magnets; exchange bias effects; giant and colossal magnetoresistance materials; magnetic thin films and multilayers;

and spin electronics. The research is of moderate quality and is absent from a clear connection to UK industry.

In summary, while solid research is being performed on aspects of magnetic materials, the UK is not a world leader either in magnetics research or its application.

Polymers

Polymer research in the UK involves groups with international stature, mainly in Physics and Chemistry departments; this reflects in part, the change of emphasis from "solid" polymers (plastics and rubbers) to "softer" systems (gels, solutions, food additives, etc). The EPSRC support of the life sciences interface has helped attract good researchers to the bio-polymer area. As a whole, the field is healthy and competitive.

The UK has international recognition in *polymer theory*, and UK scientists were among the leaders who set the basis for modern statistical theory of polymers. Good theorists have been trained and have joined a number of physics departments in the UK. This effort should be sustained and adequately supported. On the other hand, modelling and simulation efforts are not much in evidence relative to the rest of Europe or the US. New initiatives in computer-based simulations (a field still in its infancy) would add substantially to the UK research and development portfolio in polymers.

One basic goal of advanced polymer research is to obtain new (or significantly improved) *property profiles*, by controlling the sequence of different monomers or the degree of branching. Research in this area involves a strong synthesis element. Significant advances have occurred in processing (block copolymers or semi-crystalline polymers, polymer blends) and in the unique rheology of branched polymers. The EPSRC innovative polymer synthesis initiative has been successful in bringing new people into this sub-area. Since synchrotron radiation and neutron sources are increasingly required in this research area, it is important that access to the national or the European facilities be facilitated.

Understanding the role of polymers at *surfaces and interfaces* has implications in problems of adhesion, friction, or nano-rheology, and this has been an active area for the last 15 years or so, with significant contributions from UK groups. Examples include the mechanical properties of blended polymers, the glass transition of polymer thin films, and the adhesion of polymer composites.

The field of patterned and nano-structured surfaces formed by self-assembled films has not had much UK involvement, although interest in this subfield in biophysics is emerging.

In summary, the Panel found polymer physics and chemistry to be strong and highly competitive.

Structural Metals and Composites

The UK has a rich history of invention in structural alloys and composites. However, its international visibility has declined dramatically in the last decade. This is also true in many other countries, because of the maturity of the field and the consequent transition to systems-driven research. However, the situation in the UK appears to be more critical than elsewhere. The Panel believes that there are enough competitive industries in the UK needing new and improved structural materials that this area should remain a strong component of the research portfolio. However, the university research community involved in this area do not appear to be making a compelling case, outside manufacturing and process modelling. Too many researchers appear to be continuing to measure properties, to characterise materials and to tweak microstructure. Few are exploring the introduction of such materials into novel structures and systems most relevant to UK competitiveness. The Panel is aware of exciting initiatives in other parts of the world, in such areas as multifunctional materials and structures, cellular materials and lightweight panels, high temperature composites for turbines and aerospace systems (such as ceramic matrix composites), coatings for various thermostructural and tribological purposes (such as thermal and environmental barriers for advanced propulsion and energy conversion systems), and modelling protocols to accelerate the introduction of new materials. While there are good individuals addressing aspects of this overall spectrum of possibilities, the Panel was not made aware of coherent initiatives of this type in the UK. This "hit and miss" approach does not provide tangible benefits to the UK.

There is a wealth of new opportunities for structural materials of all types in micro-electro-mechanical systems (MEMS). This field is no longer confined to "what can be done with Si to make interesting widgets". There are new methods to fabricate devices from metals and ceramics. Groups have made and tested micro-rocket engines and turbine generators. With the exception of one fledging effort, the Panel was not shown any evidence of initiatives in MEMS. This technology would appear to be relevant to the UK and should be explored as a potential research investment.

In summary, the area of structural materials and thermostructural systems in the UK needs to be re-evaluated in a systematic manner. The evaluation should address industry road maps, academic capabilities, and the potential for systems-driven multidisciplinary efforts, all within a global context.

Ceramics

Structural ceramics encompass oxide and non-oxide polycrystalline materials optimised for their mechanical properties, nuclear ceramics, ceramic composites and ceramic coatings, carbon and graphite, and aspects of glass science and technology. *Functional* ceramics include dielectric, ferroelectric and magnetic materials, ionic and electronic conductors for fuel cells, sensors, high T_c superconductors, and bioceramics. Optical fibres, non-linear optical crystals, and other inorganic photonic materials may also be included. As in other sub-fields, research topics include processing, characterisation and modelling.

The UK was at the forefront of international research in structural ceramics during the 60s and 70s. This leadership position has declined steadily, such that the US, Japan, and Germany now hold much greater prominence. There has been a worldwide decline in university research related to ceramics used primarily for their load-bearing abilities. However, because most of the fundamentals are already in place, there are healthy programmes in other countries conducted in the systems-driven mode, relating to a multiplicity of applications, such as ceramic composites for turbines and space vehicles.

Moreover, activities on ceramic coatings are widespread; indeed, a very important industrial need exists for such high-temperature materials. There are only a few active groups in the UK, and the overall activities are below the international standard. Research in the area of carbon materials and in nuclear ceramics is a continuation of leading research done in the 60s and 70s, without new breakthroughs. The Panel notes that the diminished competitiveness of the UK parallels the globalisation of companies that dominates this field, with most R&D activities occurring offshore. This finding resonates with the inability of the Foresight report to justify increased investment in ceramics designed for dynamically stressed applications.

The area of functional ceramics is quite different. The UK effort in solid oxide fuel cells (SOFCs) is first rate, as are the efforts in the area of bioceramics, and ceramic thin films with interesting electronic or magnetic properties. One other highlight is the UK activity in optical fibres, but this has developed in the UK (and elsewhere) outside the mainstream materials departments; it is an important subfield in optoelectronics.

In summary, the effort in selected areas of functional ceramics is first rate. The effort in structural ceramics is deemed pedestrian.

Nanotechnology

Foresight makes a strong case for a viable UK effort in nanotechnology, and identifies eight broad themes: nanofabrication; nanometrology; functional nanotechnology; nanomechanical devices and machines; molecular nanotechnology; particles, clusters, and catalysis; nanostructured materials; and “extreme” nanotechnology. (As an aside, the Panel notes that this field has an uncomfortably large ratio of hyperbole to solid worth). Among these, nanofabrication, molecular nanotechnology at the biological/medical/functional materials interface, and “extreme” nanotechnology (building structures up from the atomic or molecular level) were selected for particular emphasis. The Panel endorses the view that nanostructures represents the most recent frontier in materials research. Many nations have made aggressive investments. Reasons for this current emphasis stem from the possibility of entirely new physics of materials at nm length scales. Moreover, nanomaterials transcends traditionally isolated disciplines—physics, chemistry, biology, engineering—and offers numerous opportunities in fundamental science. Current efforts embody three themes.

Synthesis and Fabrication. A principal limitation has been the preparation of matter having defined structure at the 10-100 nm scale. Potential advances have been rate-limited by the development of strategies to prepare materials. Therefore, developing methods for fabrication is a cornerstone of nanomaterials programmes. These methods take many forms, including chemical synthesis and self-assembly of building blocks, biological strategies based on protein and nucleic acid ligation, probe-based lithographies, replica moldings, and others.

Characterisation and Properties. The properties of bulk materials can deviate significantly when the dimensions approach the nanoscale and several are dependent on the nm-structure. The field requires protocols for the characterisation of these properties and of theoretical frameworks for understanding them.

Engineering and Devices. Many of the commercial technologies that stem from the development of nanomaterials will be incompatible with the current infrastructure for microfabrication. A substantial investment will be required for fabricating nanostructured components and integrating these with micron scale architectures.

The Panel members providing input to this report did not have the technical scope to provide an overall assessment of the readiness of the UK to exploit this area, except to applaud the awareness of its potential importance through the Foresight exercise. The following comments are restricted to perceptions about the UK presence in nanofabrication.

Techniques being explored worldwide to enable nanofabrication include extreme ultra-violet lithography, electron beam lithography, ion lithography (both serial and projection), various contact lithography techniques including nano-imprinting and micro-contact printing, and more exotic approaches such as quantum lithography and scanning probe techniques (BOM, AFM, NSSM). While some of these technologies are extremely expensive, such as those for semiconductor manufacturing (e.g. extreme ultra-violet), many are very well suited to research laboratory application. The Panel found minimal evidence of either significant advances in nanofabrication or new techniques being developed in the UK. There were, however, several universities equipped with highly productive electron beam lithography (EBL) systems. While the EBL technology was conventional, these systems were broadly applied to the fabrication of high-resolution structures in a broad range of fields, particularly novel compound semiconductor devices. Examples of ingenious and novel applications include high resolution pattern formation over ultra-high curvature scanning probe microscope tips, to enable active devices, (such as Hall probes or thermocouples) to be built directly onto the tips. High-resolution fabrication using focused ion beam (FIB) systems is also being performed at several universities within the UK, as well as application of scanning probe instruments to nanofabrication.

Essential facilities for nanofabrication, such as electron beam lithography, are relatively expensive with initial capital investments exceeding a million pounds and annual operating/maintenance costs substantially greater than one hundred thousand pounds. In addition, extensive ancillary systems such as reactive ion etching, photoresist deposition systems, and clean-room environments are generally needed. Such capabilities are naturally suited to a user facilities mode, centrally funded by a regional or national government agency and supported by expert staff. An example is the National User Nanofabrication (NUN) network in the United States. While the EBL, FIB and clean-room facilities in UK universities support an impressive range of projects, both within and external to their host institutions, they are neither regional nor national facilities. It is recommended that, for nanofabrication, the regional/national facility model be adopted within the UK.

In summary, nanotechnology is now a very "hot" area in materials research worldwide. A substantial UK investment is appropriate. A user facility mode is recommended for nanofabrication.

Modelling

Materials technology has been challenged to reduce the long time between invention and implementation of new engineering materials (10-30 years). The delay is associated with the large experimental matrix needed for optimisation and validation, with associated large costs. The perception in the community is that the introduction of materials can be accelerated by the development and judicious use of models across the entire spectrum from discovery to manufacturing to performance – a point expressed forcefully in the Foresight report. Modelling also provides a unique opportunity to test, reshape and evolve the scientific theories and concepts that are the foundations of this field. To remain competitive in materials research, the UK must be strategically placed, through shrewd investments in the appropriate areas of modelling. The Panel has had difficulty in providing a cohesive assessment in this area since much of the effort occurs outside mainstream materials funding (for example, in physics, solid mechanics and applied mathematics) and no UK plan for materials modelling was presented. We were thus left with the impression that, while several sub-disciplines remain strong and integrated over the entire field, the UK materials modelling effort is rapidly declining from its former role as a world-leader. We are heartened by the recommendation of the Foresight exercise that this area be given future emphasis.

The UK continues to show strength in the area of first-principles calculations. While several strong research efforts remain in this area, there are few strong groups. Programmes such as the Research Council Collaborative Computational Project on Condensed Phases, provides a certain level of vibrancy, although not much funding. The traditional UK excellence in empirical and semi-empirical descriptions of atomic bonding suitable for large-scale atomistic simulations continues to support an internationally competitive activity on small and medium scale atomistic simulations (10^2-10^5 atoms). This activity is diverse and distributed amongst materials, chemistry and physics departments. On an international level, the UK effort on first-principles and atomistic modelling is probably just after countries such as Italy, the US and Germany.

A topical area that distinguishes materials research from condensed matter physics and chemistry research is attention to microstructure. Microstructure evolution modelling at the level of ensembles of defects, phase distribution and morphology evolution is especially important for materials processing. There is little research of this type in the UK. At still larger scales, appropriate for engineering application, materials are commonly modelled as a homogeneous or coarse-grained heterogeneous continuum. While microstructure-scale modelling research is sparse in the UK, two areas stand out as competitive in the international arena: meso-scale modelling of polymeric materials and the incorporation of microstructural features into mechanics models.

There has been a growing realisation that no single class of simulation can span the length and times scales governing materials phenomena of practical interest. To predict these phenomena, materials modelling must either characterise behaviour using empirical descriptions and parameters (e.g. constitutive laws for plasticity) or develop a multi-scale approach wherein simulation on one scale informs the next. The worldwide materials modelling community is actively moving toward strategies that integrate different methods in order to overcome this deficiency. The UK community is not a player in this key, developing area.

In summary, the Panel found that while the UK retains some historical strength in materials modelling, it is not maintaining pace with the rapid expansion occurring elsewhere. While significant strength exists in first-principles, atomistic simulation and several topics in meso-scale modelling, the UK is simply being left behind in several important areas.

Characterisation

Characterisation plays a central role in all materials research, and a coherent investment strategy in this area is critical to remain competitive. The Panel believes that, in general, the UK has forged an effective strategy that has allowed it to retain a strong stance. It may now be prudent to re-examine the apportioning (currently bottom-up through peer review) of funds among the different techniques (say electron optics relative to scanning probe instrumentation) to optimally support the materials research portfolio.

Characterisation relies on many complementary instruments with an extensive associated infrastructure for their acquisition and maintenance. Both innovation in methods and instruments, as well as optimised use of existing techniques for revealing new structures and measuring their associated properties are key considerations in the present assessment.

Diffraction and scattering of photon and neutron radiation is largely performed in central facilities that can be accessed at sites within the UK (ISIS, SRS) or abroad (ESRF, ILL, APS). Efforts have been made to permanently improve the equipment and plans for future facilities are underway (e.g. Diamond). Care is required to ensure materials science users are engaged in the decision making process.

The UK has a long tradition of excellence in electron microscopy (EM). Investment in latest generation electron microscopes is being maintained, despite the decision of VG to discontinue manufacturing electron microscopes. The UK retains its competence in most aspects of high-resolution imaging and microanalysis, with centres of excellence in specialised topics (e-beam imaging of magnetic structures, 3D tomography, and three-dimensional atom probe (3DAP) analysis), as well as an investment in instrumentation for TEM specimen preparation using the focused ion beam (FIB) device.

Scanning probe microscopes (SPM) play a major role in nanofabrication and materials characterisation and permit many imaging modalities for studying various phenomena. The development of new sensors has enabled application for local measurements of fundamental phenomena occurring in crystal growth, surface reactions, tribology, wetting, and polymer crystallisation. UK laboratories are active competitors in many of these arenas. Scanning probe techniques have also revolutionised the science of surfaces, as they offer the possibility of direct investigations at the atomic level in real space.

The Panel was encouraged by extensive refurbishing and investment in new and replacement equipment, especially within new multidisciplinary centres, housing a wide range of skills and instruments. We regard the situation to be healthy in those aspects of characterisation related to innovation, funding of top level infrastructure, and quality and expertise of the academic and technical staff. The UK has world class activities in 3D atom probe analysis, high-resolution TEM imaging and microanalysis. The involvement of UK partners in most networks supported by EC is strong.

However, the Panel expresses the following concerns for the future:

(i) The level of support by technical staff is barely adequate, and there is a problem of maintenance in the longer term.

(ii) While the funding of new equipment is important, non-negligible operating costs are related to the exploitation of new facilities and must be built into future funding scenarios.

(iii) There should be competitions from the various funding agencies for advanced instrumentation using targeted funds.

In summary, there is much strength in UK characterisation capabilities but some concern for the future, particularly regarding infrastructure and operating costs. The Panel strongly recommends that targeted funds be made available for advanced instrumentation.

Interdisciplinary

While reference is made elsewhere in the report to the health of multidisciplinary materials research within the UK, several points are re-emphasised in this separate sub-section. Members of the Panel, especially those from Europe, were impressed by the interaction between disciplines in the UK. Multidisciplinary programmes spanning the physical sciences, engineering and life sciences are prevalent, particularly in the "newer" sub-fields of materials research (bio-materials and tissue engineering, photonics, soft materials, environment, etc.), as well as strongly encouraged by most UK universities. Cross-disciplinary research is broad based and not just restricted to organised programmes, such as the IRCs. It is more "a way of life" than in most other countries. The review process employed by EPSRC must ensure that such proposals are given adequate and judicious assessment.

In summary, there is a strong culture for interdisciplinarity in some materials subfields. However, the EPSRC should guard against overly specialised peer reviews

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Intellectual Property, Technology Transfer and Enterpreneurship

The Panel became aware of a disturbingly wide range of policies at UK universities for the ownership and management of intellectual property (IP) emanating from publicly funded research. The approach to this increasingly important issue was found to be often *ad hoc* and, in some cases, chaotic. Some universities are implementing a (negotiable) system of sharing net profits from commercialisation of IP: 1/3 inventors/researchers: 1/3 department: 1/3 university. Arrangements that reward researchers in the form of equity in spin-off companies are generally less clear and more negotiable.

When universities do not have well established policies and practices for the management of IP, there is increased risk that valuable IP is not identified and protected prior to public disclosure. Subsequent management of the IP and efforts to commercialise technology can be less than professional and universities (and the nation) are unlikely to obtain full value for their efforts.

Some streetwise academics manage well in this situation, but there is a high potential for conflict of interest. A large proportion of academics, being mainly driven by their research curiosity, are understandably unaware of practices and pitfalls in management and commercialisation of IP. They need proper assistance in the form of policy, procedures and professional advice.

Some good models exist in the UK. The models embrace education on innovation and entrepreneurship at the undergraduate level, promotion of innovation at a business incubator or a technology transfer unit, as well as management of IP.

The Panel believes it is important that EPSRC urgently set about identifying best practice and disseminate their findings to universities.

In summary, EPSRC should identify and publicise best practice for universities relating to the identification and management of IP, technology transfer, and commercialisation. This practice should take account challenges related to conflict of interest and interaction with industrial co-sponsors of research.

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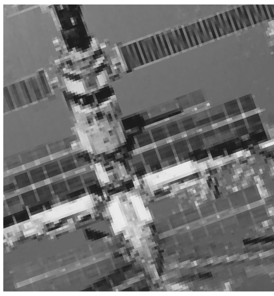
The Role of Industry



Because materials science and engineering is a key enabling discipline for industrial and economic development, it is important that there be a strong and healthy involvement of industry in academic materials research. The Panel is very impressed by the high level of industry involvement at many UK universities. This interaction brings with it many positive attributes, but also negative consequences that need to be controlled.

Examples of strong interaction and involvement range from collaboration on individual projects through to large-scale sponsorship of industry technology centres on university sites. This involvement contributes substantially to the dynamics and relevance of the overall materials research portfolio.

The positive aspects of industry involvement can be summarised as follows:

- Additional funding (sometimes substantial) is made available;
- Students and staff become aware of industry priorities and the industrio-economic context of their research;
- Industry often provides materials, large scale facilities and on occasion, personnel for projects;
- A ready vehicle is available for implementation of research outputs and commercialisation.

Conversely, if industry involvement is not well-supported by good policy and management, it may contribute to negative outcomes. These can be summarised as follows:

- Undue restrictions placed by industrial collaborators on publication and other dissemination of research outputs, thereby impeding academic careers, reducing the visibility of individual scientists, and adversely impacting publications considered in the Research Assessment Exercise (RAE);
- Restricting long-term innovation through maintenance of a short term industrial vision.
- Instability of funding, since R&D is not an approved business expenditure for taxation purposes in the UK (except for small and medium sized enterprises [SMEs]), causing funding to be sensitive to company profit and loss. (We note [*Science*, vol.296, 10 May 2002, pg. 999] that the government intends to increase tax credits for SMEs and give – for the first time – tax breaks for large companies for their R & D spending).
- Restriction of access to research outputs by SMEs when block funding is instigated by large corporations in certain sectors.
- Conflicts for researchers between the real and immediate interests of industry sponsors and long term public interests.

- Undue influence on the distribution of research funds. In current “responsive mode” funding, industry support (moral or financial) is perceived as a merit in the consideration of applications for research funding. This has the tendency to skew application success towards shorter-term outcomes rather than long term, high risk visionary research.

The Panel heard from one pre-eminent industry in the UK, which had set up research centres at several eminent UK universities, built on existing expertise to conduct the research they needed to sustain their international competitiveness.

The positive consequence has been that the research remained in the UK and has leveraged substantial public funds. The negative consequence has been an emphasis on the short term in some areas, as well as publication restrictions, that have adversely affected the scope and recognition of this research outside the UK. The Panel does not believe that this model benefits the International standing of materials research in the UK and may not even be in the best long-term interest of the industries involved. Moreover, we believe that this example highlights the importance of an organised UK vision of the relevant portfolio for materials research and a coherent plan for the modes whereby the universities interact with industry.

In summary:

- *Develop a diverse research portfolio involving industry, embodying input from the MoD and DTI as well as EPSRC, with an appropriate combination of industry pull and academic push. Programmes involving industry should be determined by a ‘bottom-up’ bidding process, based on a set of broadly defined themes relevant to the future well being of the UK. In such programmes, industry should not be the sole determinant of research directions. Instead, they should provide guidance and insight through technology road maps, technology exchanges, and co-organised research. EPSRC would do well to investigate successful examples of such Programmes in other countries. Examples include the Australian Cooperative Research Centres Programme and the Multidisciplinary University Research Initiatives programme in the US.*

- *A small number of top-down Managed Programmes that address high priority areas for the UK (perhaps the IRCs) in which industry has a dominant role are envisaged to continue. Issues related to publication (noted below) must be clarified.*

- *Consideration should be given by the UK Government to the provision of tax incentives for industrial investment in R&D. (This may now be a moot point.)*

- *Embargoes by industry partners on publication of government funded research outputs should be subject to clear guidelines that, for example, stipulate the maximum period of such an embargo. (Current guidelines do not stipulate a maximum period of embargo, though it is expected that all EPSRC funded research will be published.)*

The Funding Landscape

The Panel reviewed a large quantity of statistical data on the distribution and level of EPSRC funding. The data were supplemented through conversations with many faculty both at the academic sites formally visited by the Panel and, subsequently, at other institutions. We address issues of general importance to the future of the UK as well as specifics relevant to materials research.

Materials research in the UK appears to be hindered – even held back, by a relatively inflexible funding structure, lacking the diversity that exists in some other countries. The Panel appreciates that finding the correct mix of funding mechanisms and providing a sufficiently large overall budget presents unique challenges in each country. Nevertheless, we feel obliged to comment on deficiencies that should be addressed if materials research in the UK is to improve its standing within the international context. First we specify the "ideal" mix that, in the opinion of the Panel, permits the academic community to have the greatest international impact:

(i) Individual researcher grants, for research topics proposed by individuals. A significant fraction should be set aside for young faculty. These are designed to promote high quality, disciplinary research by encouraging originality and rewarding innovation. They should be peer reviewed and constitute the largest single component of UK materials research funding.

(ii) Small, multi-disciplinary group grants (~ 4 faculty) for a research topic proposed by the group. These should be designed to address more complex challenges. These again should be peer reviewed.

(iii) Multi-disciplinary/multi-institutional programmes within broad areas of science and technology especially relevant to the UK for topical areas that cut across the materials community. This funding mode will require requests for proposals in specified area; this also probably requires a programme manager to focus programmes to achieve goals. Industry involvement should be in a subordinate role. Five year programmes should be considered, which could be re-competed if renewal is appropriate.

(iv) Interdisciplinary research centres on topics of high priority/currency, coupled to a technology road map. These could be panel reviewed, with industry involvement encouraged. Five year programmes are envisaged, which could be re-competed if renewal is appropriate.

While the present EPSRC system has elements of this mix, a number of issues concerned the Panel.

Responsive mode funding is in a perceived "death spiral", wherein the perception of the researchers at UK Universities (especially the young faculty) is that the probability of receiving funding was only 15% (at the time of the Panel visit) and is decreasing by the year. Although this figure is significantly lower than that reported to the Panel by the EPSRC (23%), those statistics also show a declining success rate. The consequence is that the faculty respond with more proposals, in the belief that this will increase their chances of funding. This fosters inefficiency, as faculty devote much more time and resources to obtain research funding.

The overall balance between top-down and bottom-up research in the UK has been shifting toward the former with Research Council initiatives such as basic technology and e-science. Within EPSRC programmes, however, it was noted that this was not the case with the majority of funds allocated to responsive mode. Although not EPSRC policy, reviewers have developed a tradition of giving poor ratings to proposals that have little or no industrial involvement. This shift should be redressed.

The managed programmes in their present manifestation have perceived and real problems. Much of the community believes that managed programmes are not fairly competed for. That is, the announcements appear with too little time between requests for proposals and the application deadline, yielding an advantage to groups having advanced warning. There is an associated perception that the research performed in managed programmes is of inferior quality (compared to responsive mode). One manifestation is the mixed success of the first group of IRCs, which appears to be a consequence of misconceptions about the term of support, the role of industry and prospects for sustainability. Among the IRCs the Panel visited, only those on biomaterials and polymers appeared to have developed the infrastructure for continuance beyond the termination of EPSRC support.

Finally, we restate that, while materials science and engineering is an interdisciplinary field, it does not encompass all component disciplines. The health of materials research, as a field, can only be evaluated once the UK community adopts a definition. This is a key issue for EPSRC funding, since finite resources encompass a portfolio that necessarily overlaps condensed matter physics, chemistry and engineering.

In summary:

- *The EPSRC funding portfolio should be aligned more closely with the "ideal" proposed above in order to achieve proper balance between competing demands on available funds. The model portfolio embraces the diversity in funding sources that enrich materials research in other countries.*
- *Individual investigator grants must be protected from encroachment and should represent a majority of EPSRC funds. Small multi-investigator grants provide an excellent mechanism for cross-fertilisation within the basic research framework.*
- *Managed funding provides a mechanism for the nation to build capability in emerging research areas and areas of national need. Such areas and needs should continue to be determined primarily by the research community, with input from government and industry. This should be a small component of EPSRC research funding. Highly directed research projects should be the responsibility of other funding sources, although the EPSRC could perform a management function.*

The peer review system should be modified to ensure preferential funding for young researchers and speculative work. A new initiative (Special Young Investigator Awards) should be instituted to provide medium-term research funding for young faculty. Steps should be taken to ensure that neither the EPSRC nor reviewers penalise proposals that are neither industrially- nor applications-oriented. Continuity of individual research projects should be improved by allowing a renewal period, with slightly relaxed peer review. Mechanisms should be established to ensure appropriate review of interdisciplinary proposals and that EPSRC materials funds remain focused on materials research.

Human Capital

The UK faces serious human capital challenges for the future of its physical sciences and engineering research programmes at universities. One basic problem is that salaries at levels other than professorial are non-competitive in relation to:

(a) equivalent academic positions elsewhere in the world and

(b) other career paths in the UK. The problem is particularly acute at the lecturer and postdoctoral levels.

The Panel notes that, even in countries where salaries are competitive (such as in the US), there is an erosion of interest among the brightest students in a career path within materials. The salary problem compounds the concern in the UK.

Related problems that exacerbate the challenge for young faculty include deficiencies in the funding landscape, discussed in this report, ill-defined academic opportunities and inadequacies in start-up support. The Panel appreciates that some first rate individuals will remain at UK universities despite these impediments. However, it seems a dangerous policy to rely on this as the increasingly international nature of research provides more and more opportunities in other parts of the world.

The two most critical problems are:

(a) the vastly diminished attractiveness of the field to prospective students of the highest calibre and

(b) the poor (by international standards) support given to young faculty trying to establish a viable career path in internationally competitive areas.

Excitement of the Field

Many sub-areas in materials are experiencing a serious drop in interest among prospective students and traditional areas (e.g. metallurgy) may be losing a disproportionate number of students. (This problem was extensively discussed in the Foresight report). This is a worldwide phenomenon, but is especially visible in the UK. There are many erudite studies of this effect, mostly in an engineering context, and the Panel does not have any special insight. We simply draw attention to the growing interest among students in bio-and nano-technology and in systems-related research, such as MEMS, photonics, and power systems, at the expense of structure/property relations in metals, polymers, ceramics and semiconductors. There is an obvious correlation with the trends in research funding. Consistent with this worldwide phenomenon, we detected strong interest and enthusiasm in the multidisciplinary biomaterials programmes at several locations. We also note that it is increasingly difficult to attract interest at the secondary school level. We note finally that relatively greater success may be achieved within a syllabus that allows a materials option to be chosen part way through the undergraduate programme.

One consequence is the difficulty of attracting students (particularly undergraduates) into areas considered the "core of materials science/engineering" without embedding the syllabus in a more attractive exterior. The Panel does not have any "silver bullets" to address the problem in the UK context, given the constraints of the university admission process. However, gaining awareness of the approaches having the best success elsewhere should be encouraged, perhaps facilitating a broader look at the issue, eventually resulting in changes to the system. For example, in the US, many students are admitted to a general engineering programme and are given the opportunity to opt for materials after their second (of fourth) years, when they have had some exposure to the subject. In other US universities, materials is treated strictly as a graduate discipline that attracts students from a broad range of science and engineering undergraduate backgrounds. These have been very effective materials recruitment mechanisms. Regardless of the outcome of such a proposed assessment, the Panel endorses the initiative by the IoM to create an A-level in Materials to include strong elements of materials science.

Many of the Countries that compete with the UK benefit enormously from talented foreign students who remain after the BSc or PhD. While this is also true in the UK, one aspect of the funding system places the UK at a disadvantage relative to the competition. Namely, graduate student fellowships given to departments as a consequence of their EPSRC Research Grant income are unable to cover tuition expenses for non-citizens: *we were astounded to discover that this even applied to EU students*. This stipulation should be changed to align the UK with the US and the rest of Europe. The Panel also notes that the student debt accumulated in the present system discourages many individuals from progressing to an advanced degree.

Young Faculty

Young faculty and postdoctoral fellows at UK universities are not afforded the incentives for success found in other countries. There are problems with low salaries, a shortage of funding specially allocated for career development, and minimal start-up support. These factors discourage talented young scientists and engineers from embarking on an academic career in the UK. Moreover, they slow the development of faculty choosing a career in materials science, with consequences to both the faculty and the discipline. This dilemma places the UK at a serious disadvantage relative to other countries in terms of attracting as well as retaining the brightest individuals into the discipline. While this is an overall structural problem in the UK, with solutions beyond the scope of this report, the Panel feels very strongly about the need for this to be addressed, if materials research in the UK is to enhance its international competitiveness.

A major problem is the small start-up resources provided to faculty to initiate their independent research programmes. The starting resources are typically smaller by factors of 10 to 20 relative to the US. There are several consequences of this issue for the future of materials science in the UK:

(i) Young faculty find it necessary to restrict their research programmes to take advantage of resources already present in their home departments. As a result, their research often follows that of senior faculty in that department.

(ii) More seriously, young faculty cannot even consider starting a capital-intensive, innovative programme that may require the acquisition or construction of expensive instrumentation.

(iii) The imbalance between resources available to young and established faculty makes the young researchers more dependent on the goodwill of senior colleagues for the recruitment of students and for the provision of laboratory space.

A consequence is that young faculty require substantially longer times to develop visibility as leading independent figures. This is of concern to the future of materials science in the UK, since young researchers in competing countries are often responsible for the development of new sub-disciplines. In the US, a young person at the best universities is expected to become an innovator and leader of a field within several years.

The Panel heard many anecdotal stories from young faculty (primarily at the lecturer level) and postdoctoral fellows about the frustrations they face in advancing their careers. In many cases the routes for promotion are not clear. Young faculty must wait for a position to become available, and often do not have a predetermined time for advancement or a formal mechanism for review. These uncertainties dissuade highly qualified candidates from pursuing academic careers in materials science, with an especially heavy toll on females. Many young faculty expressed a real interest in foreign positions for superior career opportunities. Everywhere, the demand for outstanding young scientists (and the resources set aside for their recruitment), exceeds the pool of highly qualified applicants. Most departments in the US look internationally for candidates, and the UK is a prime target. If the environment for young faculty in the UK remains unchanged, it will face an unprecedented 'brain drain' in materials research.

In summary, the position of the UK in materials research will erode unless structural changes are implemented that once again render the field attractive to new students and faculty, following approaches that have been successful elsewhere. A study of these approaches (most covered in other parts of this report) would reveal ideas that best fit the UK system. They concern changes in the salary structure, career development initiatives for young faculty, modifications to undergraduate admissions policies, broader implementation of multidisciplinary programmes centred on materials, and equalisation of support for non-UK graduate students. The start-up packages for young faculty should be increased to allow them to get off to a quick start and to attack more ambitious problems. There should be a better definition of the career track and review processes for academic advancement.

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Research Assessment Exercise

The Panel was discomforted if not appalled to discover that departments within UK universities are evaluated by a single number resulting from the Research Assessment Exercise (RAE). While this system has simplicity, in the sense that one number attempts to characterise the quality of the research activities within a department, we believe it has failings that adversely affect the UK standing in materials research. The correlation between the assessment and the government funding received by a department through a set formula diminishes the opportunities for novel and multidisciplinary research within the overall UK funding scene. Moreover, the inordinate amount of time consumed in preparing for the exercise detracts from more productive devotion of time to research competitiveness.

As expected, we found that much strategic manoeuvring is done to improve the RAE ranking. As soon as the evaluation is over, the manoeuvring starts to improve the rankings for the next evaluation. This of course leads to grade inflation (indeed, during the Panel's visit to the UK, the latest RAE was made public – the number of 5* departments had increased from 170 to 284).

The ramifications of a drop in grade (or indeed maintenance of an existing grade if lower than 5*) are serious. Such a grade deals a crippling financial blow to a department, from which it may never recover. The Panel felt that the procedures for assigning grades in the materials science RAE, as they could understand them, were too imprecise to warrant such a discontinuity in funding.

In summary, dispense with the exercise, but if politics requires its survival as a funding vehicle, the bar to achieve the highest ranking should be raised.

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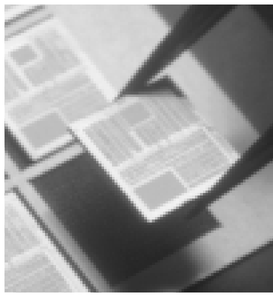
The Future of Materials Science/Engineering Departments



Materials science/engineering departments in the UK have been closing at a significant rate. While it is true in the UK that most disciplines in the physical sciences have experienced reduction in the numbers of departments in recent years, the situation in materials is more acute, because of the small numbers. Enrolment in materials undergraduate degree programmes is also declining. (This concern was also expressed eloquently in the Foresight report). While recognising and applauding the fact that the broad field of materials research is carried out in many departments other than those devoted specifically to materials science (physics, chemistry, and mechanical, chemical and electrical engineering), the Panel strongly believes that the existence of healthy materials science/engineering departments is critical to the broader materials research enterprise. In particular, we believe it imperative that materials continues to be available as an undergraduate discipline, incorporating structural modifications needed to enhance recruitment discussed above. We also believe that the research mission would be substantially compromised if the techniques, methodologies and tools of the materials science discipline were no longer readily available to the materials research community.

Each of the materials departments we visited appeared to be operating in one of two broad research modes:

(i) Emphasis on traditional materials sub-disciplines, primarily structural materials. This generally appeared to reflect the origins of such departments (e.g. those that had evolved from metallurgy departments).

(ii) Breadth across sub-fields, with wider coverage of more recent sub-areas such as biomaterials, photonics and nano-technology. For obvious reasons, the latter were contending more effectively with issues of recruitment and sustainability.

In summary, and based upon these observations, the Panel has the following recommendations

i) *Materials should not be allowed to disappear as a vital discipline. Materials departments should continue to exist in numbers and at support levels that enable them to continue to participate with other relevant disciplines as an equal partner in the materials research enterprise. Structural changes that facilitate recruitment of students should be explored.*

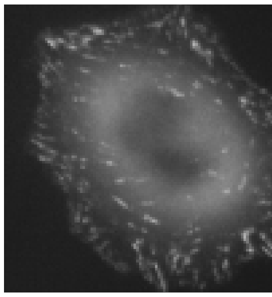
ii) *Careful consideration should be given to the optimum number of materials departments that emerge from the current phase of consolidation and loss of academic departments. The most effective research portfolio should also be considered, recognising that the optimum may vary from institution to institution.*

The teaching of materials science/engineering as an undergraduate discipline is a critical platform for materials research, and should be encouraged and supported through all possible mechanisms.

Acknowledgments

The Panel appreciates the excellent preparation by the Steering group and for assistance throughout the review. We are most grateful for the diligence and dedication of Annie Davison who provided comprehensive planning and logistical support, as well as editing the report. The Panel acknowledges the time and effort invested on behalf of the EPSRC in briefing and in answering follow-up questions. Finally, the Panel would also like to express its gratitude to the universities visited, where both staff and students invested immense effort in assuring that the visits were informative and congenial.

Background Information



The **Terms of Reference from the EPSRC for this Review** can be found on page ... at the front of this report.

The background for the Review was overseen by a Steering Group comprising:

Professor Colin Humphreys, IoM^3 (Chair), University of Cambridge
Professor Dame Julia Higgins, Imperial College
Professor Peter Main, University of Nottingham
Professor Tony West, University of Sheffield

The Steering Group was responsible for selection of International Panel members and for providing the preliminary guidance to the Panel Chair on his responsibilities in accomplishing the Terms of Reference. The Steering Group did not participate in site visits and met with the Panel members on the final day of the week's schedule to hear presentation of the Group's initial findings that would make up this report.

The IoM^3 provided a coordinator for event planning and liaison between the Steering Group, Panel members and universities. The EPSRC took responsibility for preparation of background information provided to the Panel.

Each Panel member was provided with a preliminary set of information prior to the Review (Appendix A) and this was augmented by a resource 'library' available throughout the week at the IoM^3. Completed information specifically related to the university visits was presented to each Panel member on arrival in the UK.

Each of the universities had been invited to participate in the review from a letter from EPSRC CEO to the Vice-Chancellor. University selection was on the basis of a cross section from those who had departments/schools with a strong Materials research element rated a 4, 5 and 5* rating in the 2001 RAE tables. Therefore, deliberately the Review involved departments/schools/centres across the Materials, Chemistry, Physics and Engineering disciplines.

Each university provided an abstract of overview of the department's or individual groups research in the context of other work in the UK, (as indicated by EPSRC in the Methodology guidelines) prior to the visit taking place. This Methodology is appended. (Appendix B.1)

Each site visit varied according to length of time and the universities chosen schedule, but all encompassed the methodology visit guidelines to complete the common objective. Additionally, the Panel Chair requested that each Panel group on their site visits, have open informal discussion with separate groups of postgraduate students, post doctorate and 'young faculty' (university staff researchers/lecturers within 5-10 years of their career). A series of questions from the Panel Chair was provided to the universities immediately prior to the visits.

The universities and individual departments involved in the review were:

The Panel members

Chair - Professor Anthony Evans, University of California Santa Barbara, USA
Professor Christian Colliex, Université Paris Sud, France
Professor Gordon Dunlop, The University of Queensland, Australia
Professor Arthur Heuer, CASE Western Reserve University, USA
Professor Robert Hull, University of Virginia, USA
Professor Sumio Iijima, Meijo University, Japan
Professor Brian Maple, University of California San Diego, USA
Professor Milan Mrksich, The University of Chicago, USA
Professor Klaus Ploog, Paul-Drude Institute, Germany
Professor Manfred Rüehle, Max-Planck Institute, Germany
Professor David Srolovitz, Princeton University, USA
Professor James Williams, Ohio State University, USA
Professor Claudine Williams, College de France, France

Appendix A

Data Supporting the Review

A.1. Prior to the Review the Panel members received an information folder including the following:

UK Government Research Support

The Support of UK Universities

The Engineering & Physical Sciences Research Council

Business Planning Process – Materials Science & Technology

Materials Science & Technology Business Plan

Materials Programme Evaluation Report

Data for the 2001 "Balance of Programmes" Exercise

Trends in EPSRC Materials Programme Support

Destination of EPSRC Funding in Materials Science

2001 Research Assessment Exercise

EPSRC Sector Briefs

EPSRC 2001 Landscapes

Platform Grants information

International Perceptions of UK Research in Physics & Astronomy

International Review of UK Research in Computer Science

A.2. During and immediately following the Review the following information was provided to the Panel and Panel Chair:

Foresight Report 'Materials: Shaping the Future' , 2001

EPSRC 2001 Research landscape

EPSRC Strategic Plan April 1999 - March 2003

EPSRC 2001 Operating plan (2001/2004)

EPSRC Guide to directly funded Postgraduate Training – 2001-2002

EPSRC Annual Report 2000/2001

Technology for the Future *(report from 'Foresight' on UK Science & Technology base – Particle Physics & Astronomy Research Council 2000)*

EPSRC Review of Photonics (2000)

An example of EPSRC grant application forms

Current Higher Education salary guidelines

Notes taken from Panel discussions with staff and students

A.3. Presentations

Prior to the site visits the Panel were given presentations, including question and answer sessions on the following:

- Scene setting and objectives, Professor John O'Reilly, CEO, EPSRC.
- Overview of Research funding in the UK, Professor John O'Reilly
- The role and work of the IoM, Dr Bernie Rickinson, CEO, IoM[3]
- Panel Chair Introduction, Professor Anthony Evans, UCSB
- Briefing on the Research Assessment Exercise (RAE2001), Professor Colin Humphreys, University of Cambridge
- Background briefing on EPSRC support for Materials, Dr Clive Hayter, Programme Manager Materials, EPSRC

A.4. A 2-hour meeting in London was convened with some Panel members and a selection of invited industrial collaborators on EPSRC funded projects.

Appendix B - Methodology

B.1. Methodology for Panel Visits (as sent to universities prior to review)

1. Visit Objectives

The objective of the international review is to report on the standing and potential of Materials Research in the UK and provide a comparison with materials research conducted internationally. It is the intention to look at all research in this category, irrespective of the Department or Centre in which it takes place. In this context key issues for the Panel visit include an assessment of;

i) the quality and impact of materials research in the UK in compared with that conducted internationally.

ii) whether the balance between curiosity driven blue-skies research and user driven applied research within the portfolio is reflected internationally.

2. Visit Format

Each Institution will be visited by one of a small sub-set of the full review Panel, consisting of 4 to 5 people. Each visit will last between one half and one full day *(exact timings will be confirmed)* and should incorporate the following basic elements;

Presentations to the group (*These should last no more than one-third of the total visit time*). Presentations should cover current research activity, provide an overview of the balance between research themes and highlight the context of the work in the light of current international activity. Presentations should focus on the quality and impact of materials research and as a consequence it is recognised that some discussion of problems and barriers to progress may be necessary. It is important to note however that several forms already exist for feedback specifically on Research Council processes through quinquennial reviews and visiting panels.

Presentations should be based within a single department but represent and be inclusive of materials research activity across the institution.

Discussion, Question & Answer Session. This will provide a forum for the Panel group to explore further issues for example, is the level of multidisciplinarity comparable to that prevalent internationally. *This session should immediately follow presentation slots.*

Visits to key facilities and departments. *The group should divide and if necessary make visits individually and in parallel to other Departments.*

Interaction with Research Staff & Students. *An opportunity to meet with a selection of Postdoctoral and Postgraduate research staff either within individual Departments or as part of a general forum. This could be scheduled as part of lunch or incorporated into the overall programme.*

3. Information

It is requested for each department or centre being visited an abstract should be prepared (*of no more than 2 sides of A4*).

This abstract should include an overview of the department's or individual group's research in the context of other work in the UK, detailing, the main research highlights, any UK collaborations between institutions and any significant international collaborations in which the department/centre is involved. A summary table detailing the level of external (non-EPSRC) support (e.g. European programmes, Industrial support, etc) for the department **which is relevant to Materials Science & Technology** over the period 1997-2001 should also be included together with the current number of research staff and students.

It is requested that these summaries be produced in advance of the Panel visits as they will form part of the background information supplied to Panel members on their arrival.

4. Secretariat & Contact for the review

It is asked that each institution nominate a point of contact to coordinate the visit to that particular institution.

The Institute of Materials are providing the secretariat for the International Review and the contact for the visits is: Annie C. Davison *(details were provided)*

B.2. Title and Terms of Reference for Panel Members:

"The Standing and Potential of Materials Research in the UK"

To report on the standing and potential of materials research in the UK and provide a comparison with materials research internationally.

The study will cover all materials research undertaken by the UK Research Councils in UK universities, and central laboratories.

The study will assess the current standing of materials research and its likely impact on the UK Science Base and on the Nation's future wealth and well being;

The study will draw on existing data, international assessments, and site visits;

The study will result in a report to be published and made available to the sponsors and the UK materials community.

B.3. In order to provide contextual information to support the Review, the Panel members visited 13 universities. Universities had been invited to participate from those chosen by the Steering Group and who had RAE rated 4, 5 and 5* departments undertaking materials research. Selection for the visits was based on geographic diversity as well as feasibility within the timeframe. The Panel was split in 3 sub-groups, and the visits were over 3-4 days. The whole review was over 7 days.

The universities and participating departments, centres were:

Birmingham University	School of Engineering Materials & Metallurgy IRC in Materials Chemistry Physics & Astronomy
South Bank University	School of Engineering
Imperial College of Science, Technology & Medicine University of London	Faculty of Engineering Faculty of Physical Sciences Materials Physics Chemical Engineering Mechanical Engineering Chemistry
Queen Mary, University of London	Materials Chemistry BioPhysics Dentristry Medical Engineering IRC in Biomaterials

University of Glasgow	Physics & Astronomy Electronics & Electrical Engineering Mechanical Engineering
University of Strathclyde	Bioengineering Physics & Applied Physics Electronic & Electrical Engineering Mechanical Engineering Pure & Applied Chemistry
University of Leeds	Materials Physics & Astronomy Polymer IRC School of Chemistry Mechanical Engineering Textiles
University of Manchester & UMIST	Materials Science & Metallurgy Chemistry (Manchester) Corrosion (UMIST) Electrical Engineering & Electronics (UMIST) Physics (Manchester) Physics (UMIST)
University of Cambridge	Materials Science & Metallurgy Physics Chemistry Engineering IRC in Superconductivity
University of Sheffield	Engineering Materials Electronic & Electrical Engineering Chemistry Physics & Astronomy
Sheffield Hallam University	Materials Research Institute
University of Nottingham	School of Mechanical Materials Manufacturing Engineering & Management School of Chemistry School of Pharmaceutical Science School of Physics & Astronomy

IOM3

The Institute of Materials, Minerals & Mining

Institute of Materials

Following a merger with the Institution of Mining and Metallurgy (IMM), from June 2002 the new organisation is known as the Institute of Materials, Minerals & Mining. With a membership of over 19000 it intends to develop to be the leading international professional body for the advancement of materials, minerals and mining to governments, industry, academia, the public and the professions.

EPSRC

Engineering and Physical Sciences Research Council

EPSRC

The Engineering and Physical Sciences Research Council is one of the United Kingdom's seven government funded research councils. Its mission is to support the highest quality research and related postgraduate training in engineering and the physical sciences. EPSRC aims to advance knowledge and technology and provide trained engineers and scientists for the benefit of the United Kingdom and the quality of life of its citizens. It has the further role of promoting public understanding in engineering and the physical sciences.

EPSRC
Engineering and Physical Sciences
Research Council

Polaris House North Star Avenue
Swindon Wilts SN2 1ET

www.epsrc.ac.uk

IoM3
The Institute of Materials, Minerals & Mining

IoM^3
1 Carlton House Terrace
London SW1Y 5DB

www.iom3.org

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