Research Councils UK
Nanoscience
Through Engineering to Application

AN INTERNATIONAL PANEL REVIEW OF RESEARCH COUNCIL SUPPORT FOR NANOSCIENCE

"Setting the Foundations for New Industries and Opportunities"

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CONTENTS

FOREWORD

This is the third review of Nanoscience and Nanotechnology research (NST) supported by the UK Research Councils following on from those in 1999 and 2005. I am pleased to have chaired the Panel and been able to witness at first hand the work of a lively research community.

The rapid worldwide development of NST is poised to have a massive effect on the global economy. The impact is expected to be greatest in areas such as healthcare, sustainability, security, clean energy generation, and information technology. The two previous reviews of UK activities in this field had reported a disparate community of researchers for whom common goals and ring fenced funding were required if an impact was to be made by the UK in this key strategic area. The current Panel welcomed the establishment of a strategy for Nanoscience in 2006, followed by the inception of the RCUK programme for Nanoscience in 2007. These and the effort of the researchers and Research Council staff have gone some way to uniting this highly interdisciplinary community and to focus their efforts on some of the most pressing scientific and societal challenges facing the UK. Research boundaries have been bridged and new collaborations have been established. There is undoubtedly an important window of opportunity for the UK within this field. The aims of the programme to harness the potential of public investment in Nanoscience to creating wealth and economic prosperity are in principle achievable. However, much more needs to be done to secure the long term impact of fundamental research in this field. NST is intensely competitive on a global scale, and other nations are moving forward with much greater speed. Some aspects of the present UK programme are well designed to facilitate progress, but other aspects are clearly unsatisfactory. In particular there is a conspicuous lack of coordination between successive stages of the overall research and development cycle. The UK needs to redouble its efforts, sharpen up its vision and leadership for NST, streamline the labyrinthine structure of national 'nano' committees, and give a major boost to longer-term strategic funding, if it is to have any chance of remaining internationally competitive in this vital area.

I would like to thank the Panel for their support of me in the role of chair as well as the administrative support provided through the Research Councils before, during and after this stimulating event. I was impressed by the numbers of top UK researchers who gave up valuable time to take part in this activity, and by their energy, enterprise and enthusiasm. This report makes a strong case for sustained financial support for their future efforts in NST research during the next five years and beyond.

George Smith (Panel Chair)

EXECUTIVE SUMMARY

Nanoscience and Nanotechnology (NST) form an important part of the research portfolio of the UK Research Councils. Success in these areas is vitally important for the long-term prosperity of the UK in the intensely competitive world of the 21st century. Multi-billion pound potential markets exist in areas such as healthcare, sustainability, security, clean energy generation, and information technology.

In the autumn of 2009, an eight-member Panel reviewed the NST research and development activities currently supported by RCUK. The Panel consisted of three UK academics*, two UK industrial scientists (one from a large company, the other from an SME), and three senior international representatives, from the USA, Korea and the Netherlands respectively.

The Panel reviewed a wide range of material, including a number of policy statements and strategic planning documents issued by the Research Councils and Government Departments; information on research grants awarded in this area; progress reports from grant holders; data on publications, patent applications and the creation of spin-out companies; citation data; and various measures to assess the overall impact of the work. In addition, a well-attended Nanoscience "Theme Day" was held in London on 23rd September 2009. NST researchers from 27 UK universities took part, together with representatives of EPSRC, BBSRC, MRC, ESRC, NERC, STFC, the Technology Strategy Board (TSB), and the Defence Science and Technology Laboratory (DSTL).

The Panel focused on a set of broad strategic issues, which it regarded as being of major national importance for the UK. It looked at the programme as a whole, and asked: "What works"? "What does not work"? "What needs to be changed, and how"? Comparisons were made between the UK programme and that of other countries with respect to both overall strategy and policy, and the outcomes of research. The Panel concluded that the UK has moved forward considerably since the last review was held in 2005. Many of the recommendations of that review have been implemented, and a more coherent core programme had been developed. However, other countries have moved ahead with greater vigour, and the UK's relative position had slipped back in certain key areas, rather than moving forward in the way that had been hoped for. Stronger direction and leadership of applied research, clearer and simpler lines of communication, better long-term support for strategic projects, and greater integration of all stages of the research and development cycle, are urgently required.

1. What works?

(a) The basic concept of the strategic programme. RCUK has identified NST as a priority theme for UK research activity, and has established a cross-Research-Council programme: "Nanoscience through Engineering to Application". Much remains to be done: the funding level for this targeted programme is extraordinarily low when compared to other cross-Council priority themes and the funding available is ramping down during the later years of this spending review period (with estimated commitments of £5.5 million for 2009/2010 and £5M for 2010/2011). The commitment of the individual Research Councils to the programme is also markedly non-uniform. However, this is a welcome first step in the creation of a coherent UK strategy for NST research.

(b) Grand Challenges. NST offers the potential for major scientific and technological breakthroughs in a number of key wealth-creating areas. To make significant progress, focussed and sustained effort is required on a national scale. The Panel welcomes the three "Grand Challenge" areas that have so far been identified (Nanotechnology for Energy; Nanotechnology for Healthcare; and Nanotechnology for the Environment), the first two of which were funded in 2008 and 2009 respectively, and the third funded in early 2010. There was concern that the funding for the Energy Challenge was very low indeed (£6.7 million) in comparison to the immensity of the scientific and societal challenges in this area. As a result, the programme had been tightly focussed on the relatively narrow area of solar harvesting. The Healthcare programme was somewhat larger (£16.2 million) and attracted a large number of exceptionally high quality interdisciplinary applications, ten of which were funded in March 2009. This latter programme has particularly exciting prospects.

(c) Centres for Doctoral Training (CDTs). The recent funding of three major new CDTs (in Bristol, Cambridge and Manchester) which will provide integrated training programmes for graduates prior to embarking on individual research projects is warmly welcomed by the Panel and by the research community. NST is inherently interdisciplinary, and such centres will play a pivotal role in training the next generation of leading-edge researchers.

(d) Shared Equipment Initiative. NST is a sophisticated activity, requiring routine access to expensive facilities which cannot be made available on every university campus. EPSRC has made six awards (to Bristol, Cardiff, Leeds, Imperial College, Manchester Metropolitan and Nottingham Universities) to enable access by the wider academic community to existing specialist facilities in those institutions for construction, manipulation and examination of nanoscale structures and systems. This is an excellent initiative, welcomed by the community, and deserving greater development.

(e) Mid-range Facilities. A special programme has been announced to support the provision and operation of a network of more sophisticated facilities, costing approximately £3 million - £30 million each, based at individual universities, and offering nation-wide services to UK researchers. Several of these facilities are, or will be, of major importance to NST, for example for specialist materials production and for nanocharacterisation. This network offers important new opportunities for UK NST research, and potentially offers excellent value for money. However, there is a lack of clarity about how users will pay for access to these facilities, and this issue needs to be resolved quickly. Funding uncertainties also need to be resolved swiftly.

(f) Access to large facilities. Very large installations such as the DIAMOND synchrotron and the ISIS neutron scattering facility at the Rutherford Appleton Laboratory provide outstanding, world-class resources for UK NST researchers. The feedback from the community was that the services provided by such facilities are excellent. There was particular praise for the "ticket system", by which researchers can apply for user time on these facilities, with (rapid) peer review, without having to make a separate funding application. It is strongly recommended that this quick and efficient system should be adopted for the Mid-range Facilities, as well.

2. What does not work?

(a) Strategic vision. At national level, and also at Research Council level, the system is top heavy with a labyrinth of advisory, consultative and coordinating committees. These impede decision-taking, rather than facilitating it, and create confusion both within the research community, and at higher policy levels. This should be addressed urgently, building on the success of the close working relationship between the Research Councils and the Technology Strategy Board.

(b) Funding of the directed programme. The overall level of funding for the directed programme is very small in comparison with investment by competitor nations, too fragmented, and too short-term to have any possibility of making a significant impact on the future economic prosperity of the UK. Virtually all major advanced industrial nations are investing heavily in this field. There is a danger of the UK being left behind, especially in comparison to the rapid expansion of funding in countries such as the USA, Germany, Japan, Korea and China. Instead of exploiting our position as a knowledge-based economy, we risk becoming almost totally reliant upon imports of high technology goods and services in key strategic areas such as electronics, computing, and next-generation medical diagnostics and therapeutics. Our knowledge base is being eroded by the lack of funding in these important areas. The next five years will bring large changes in each of these sectors, with many exciting new products coming to market. It is vital that the UK should play a vigorous role in these wealth-creating activities, which are capable of giving a much-needed boost to the manufacturing sector of the economy.

(c) The six-year limit on funding for major (~£10 million) projects. The two Interdisciplinary Research Centres (IRCs) for Nanoscience at Oxford and Cambridge, and the Interdisciplinary Research Collaboration on Quantum Information Processing (QIP) are no longer supported by the Research Councils. Although set up as six-year, fixed-term programmes, the Panel was disappointed by the decision to not offer further Research Council funding for each of these centres of excellence after the initial support expired. In each case, the teams of people involved represent a valuable reservoir of talent and experience, with huge potential for long-term success. For QIP, the lack of continuity of funding may prove highly damaging for future UK involvement in this strategically important field. Major new technologies of this kind cannot be created within short periods of time. A complete re-think of funding strategies is required to ensure longer term support for key initiatives.

(d) Weak links along the chain of innovation, from RCUK to TSB, to the Nanotechnology KTN, and on to individual UK companies. The Panel found it hard to identify evidence of joined-up thinking in the planning and execution of UK NST research. The initiatives announced by the various funding bodies have historically appeared almost completely disconnected. There have been no smooth pathways from laboratory bench to factory floor. In particular, there is little evidence of advance commitment by later-stage funding bodies, or other stakeholders, or investors, to take up the best results from early-stage research. This leads to the well-known "valley of death" scenario, in which the majority of potentially exploitable ideas never make it to the market place. The panel recognised that the role of the Research Councils only extends so far along the innovation chain but there is clearly more that can be done, working with later stage funders such as the Technology Strategy Board and the venture capital sector, to ensure that transformational NST research can achieve its potential. The panel noted some recent progress here where the RCUK programme was now working with the Technology Strategy Board to stage-gate its portfolio of Grand Challenge research. However no such mechanism is currently open to the much larger portfolio of investment made through responsive mode. Internationally, better practice appears to be in Korea, where the overall NST strategy operates on a twelve-year time scale. The first five years of any major programme involve mainly basic research, the next five years require academic and industrial partnership, and the final two years are centred on industrial development. There is a rigorous process of evaluation at each stage of the programme, but continuity is assured for the most promising developments. Such a strategy optimises the prospects of success, and the UK should consider adopting a similar approach to supporting the research and development pipeline without delay. This will be particularly important in the light of *impact agenda* that researchers and Research Councils are increasingly being asked by Government to address.

(e) Lack of clarity regarding responsive mode support for NST. It is far from clear how much funding is being provided via responsive mode for NST research, because the current methods of labelling research in this category do not appear to be robust. This generates major problems when attempting to quantify overall expenditure on Nanoscience, which is by far the biggest single element of the UK support structure for NST. Inevitably, there is a lack of clear distinction between certain aspects of research in chemistry, physics, materials science, etc. and NST. Overlap is unavoidable, but re-badging of such "mainstream" core subject research as NST is creating budgetary confusion, and the temptation for the true amount of funding for such research to be overstated. For instance, the EPSRC Nanoscience programme landscape document [1] claims that almost 19% of EPSRC's total budget is invested in the area of NST, a figure which seems very hard to support. Clearer and more robust criteria are required for the assignment of costs within the NST programme, including the costs incurred in support of responsive mode proposals. Currently, it is not clear what criteria are used to decide whether a specific project does, or does not, fall within the remit of NST.

(f) Communication of strategy to the research community, and involvement of the community in policy-making. While the UK NST community has welcomed the evolution of a more coherent research strategy by RCUK, their feedback to the Panel reveals a marked sense of frustration about the detail. Many do not understand how programme priorities have been arrived at, and do not perceive themselves to be part of the decision-making process. This undermines confidence in the system as a whole, and means that the knowledge and experience available within the community is not fully used when seeking to optimise research strategy. Greater effort needs to be made by RCUK to fully engage with the research community.

(g) Communication with UK industry. Industrial representatives were emphatic that the level of information that they were receiving about the UK NST research programme was inadequate. There were few relevant briefing meetings, little printed information, and a lack of a user-friendly web site where they could obtain news on the latest developments, obtain answers to queries, or find contacts with relevant university researchers. It is clear that Research Council programme managers would welcome feedback from industry regarding key areas where future research is needed. Better mechanisms need to be put in place to achieve this.

(h) Use of single subject review panels to evaluate responsive-mode NST research proposals. Outside of the relatively small directed programme, the majority of NST research proposals are evaluated by traditional programmatic peer review panels which are often regarded as single-subject This creates serious difficulties, because NST is inherently interdisciplinary. There is deep concern within the community that innovative NST proposals are failing at the review stage because they do not have sufficient support in any one traditional area of research. The value judgements made by referees and panels within this system are often perceived by the community as unduly narrow, and stifling to radically new ideas and concepts. The panel recognised that this criticism is not exclusive to NST research and could be applied to multidisciplinary research more generally.

(i) Environmental, health and safety aspects of NST research. The conventional peer review process presents particular problems for those who wish to carry out precautionary research on environmental or health aspects of NST, and so work in this area is taking a long time to get established in the UK. Proposals to investigate the toxicity of nanoparticles are perceived to fare badly, because reviewers do not regard either the Toxicology or the Nanoscience as being sufficiently innovative, even though the combination of methodology and application may be novel. For example, proposals to provide reference standard nanomaterials for such studies do not score highly under the heading of innovative research, despite the fact that the supply of such well-characterised materials is vital to underpin the whole field of safety-oriented research.

3. What needs to be changed, and how?

(a) Leadership and direction**.** Provide strong, clear leadership and direction. Simplify the management structure for applied research through the abolishment, pruning or merger of the multiplicity of committees that are holding back NST research in the UK. It will be imperative to set clear scientific and technical goals for the next five to ten years; making oversight of UK NST a direct responsibility of the Government's Chief Scientific Adviser might facilitate a joined-up approach to this, as would providing more structure to the role of the RCUK strategic Advisor for NST. In the original (2005) proposal, the holder of this post was envisaged as having a leadership role. In practice, the function has been downgraded to one of advice, liaison, and external communication. This falls short of the executive leadership function which is essential for national success.

(b) Funding arrangements**.** Prioritise applied research funding in the key strategic areas of healthcare, sustainability, security, clean energy generation and information technology. Improve the overall design of the funding system for key strategic projects. A long-term, inter-agency funding strategy is required for the development of major new technologies. This needs to be coupled with a rigorous stage-gating process, to ensure that only the very best and most appropriate projects are allowed to continue to the next phase of development.

(c) Coordination. Improve links between the Research Councils, TSB and other BIS agencies and with the business and investment community. Obtain up-front commitments from all stakeholders to ensure continuity of support for important long-term programmes of national strategic importance, so that they can be seen through from start to finish, without the policy and funding gaps that are so painfully evident at present. Responsibility for driving this programme forward should be taken at ministerial level, with the task assigned to a specific minister within the BIS team.

(d) *Communication*. Vigorous efforts need to be made to improve communication within the NST research community itself, between the research community and the funding bodies, between the scientific and industrial sectors, and between innovators and investors. A whole raft of measures could be beneficial, most of them very straightforward, such as a central web site; a directory of current research; easier on-line access to key research publications and patents; regular informal meetings to encourage interaction between researchers from different disciplines; blogs for better and more frequent communication between individual researchers, and between researchers and industrial companies; regular "road shows" to exhibit highlights of the research programme to regional companies; and a series of broader technical information meetings for the investment community. At present, no single person or organisation has overall responsibility for coordinating or leading such activities and so little progress is being made. A senior staff member within the Research

Councils should be assigned this task, and given the appropriate support to enable it to be achieved. An important first step to ensure that future NST policy development reflects the views of the research community should involve the submission of findings from this review to BIS to inform the further development of the policies set out in "UK Nanotechnologies Strategy – Small Technologies, Great Opportunities", published in March 2010. [2]

***(e) Peer review*.** A more flexible, more interdisciplinary approach is required to the review of responsive mode proposals in the NST area. There is a need to encourage proposals that are bold, adventurous and unconventional, as well as interdisciplinary. The introduction of more cross-disciplinary, cross-Research-Council panels may help here, along with the trialling of new initiatives, such as fast-track, proof-of-principle funding, to give radical new ideas the opportunity to demonstrate their potential quickly, before more extensive funds are committed to their support. The community have a key role to play here as they own the knowledge and the judgements that support the peer review system.

(f) Precautionary research. A fundamentally different, cross-Research Council approach is needed in order to permit adequate commissioning of the precautionary research that is vital to the public acceptance of NST. Key goals should be identified, and consideration given to ring-fencing funds in order to achieve them. This topic could also be considered as a further potential "Grand Challenge" area for the UK NST community.

** One panel member, Professor Laurence Eaves, did not feel able to endorse the full recommendations as outlined in this report. In his view too much emphasis is placed on top-down management of NST research in the report and its recommendations. Prof. Eaves feels that history tells us that ground-breaking developments e.g. graphene, polymer electronics etc, have often emerged from the work of small university research groups, funded by modest responsive mode grants and that this recognition is not reflected in the report. Prof. Eaves feels that there is currently insufficient evidence that Grand Challenges and Interdisciplinary Research Centres and Collaborations in NST have led to major research breakthroughs and he does not agree with the panel views in the report to this effect. He feels that the recommendations lack a strong statement in support of responsive mode funding; which needs particular nurturing in the present adverse economic environment where it is unreasonable to expect new large financial stimuli to support managed initiatives. He would also oppose the suggestion that the UK adopts a Korean-style model of funding NST, feeling such a model to be ill-suited to the UK research environment.*

1. INTRODUCTION

This International Panel Review formed part of the overall evaluation of the RCUK Programme "Nanoscience through Engineering to Application". The membership of the Panel and its Terms of Reference are listed in Annex 1. The intention was to feed the outputs of the review directly into the business and strategic planning processes at the Research Councils. The central part of the overall evaluation was a three-day meeting in London. The second day of this meeting was constituted as a "Theme Day", during which UK NST researchers were invited to provide feedback to the Panel. A full list of attendees at the Theme Day is given in Annex 2.

This activity was commissioned specifically to review the health and balance of the RCUK NST portfolio as a collective whole and follows on from previous Nanotechnology Theme days held in 1999 and 2005 [3], and a Nanotechnology Town Meeting held in July 2006 [4]. The earlier Theme Days provided a valuable, independent review of the strengths and weaknesses of the UK research base and led to a number of Research Council interventions including the publication of a "Strategy for Nanotechnology" in October 2006 [5] and, ultimately, the formation of a Cross-Council Programme for Nanotechnology in 2007. A wide-ranging statement by the UK Government about Nanotechnologies was published in 2009 [6]. It is essential to note that the scope of the 2009 review was wider than the previous EPSRC-centric events, with the portfolio on this occasion taken to include EPSRC, NERC, MRC, BBSRC and ESRC research projects.

To support the Panel in their evaluation of the portfolio and the programme a range of evidence was provided:

1.1 Contextual Information

This gave background information on the Research Councils UK, the Nanoscience programme within RCUK, and activities taking place as part of the overall programme strategy. The RCUK approach to supporting NST is summarised in Annex 3.

1.2 Funding Data (across the Research Councils)

Following the classification system established through the development of the EPSRC Nanotechnology strategy in 2006, the portfolio is divided into 11 themes (see Annex 4):

- Nanofabrication
- Nanocharacterisation and Nanometrology
- Nanomodelling
- Fundamental Properties of Nanomaterials
- Extreme and Molecular Nanotechnology
- Bionanotechnology
- Nanomedicine
- Functional Nanotechnology: Devices and Machines
- Nanomanufacturing
- Nanodesign
- Nanotoxicology and the Environment

Funding data was provided on research grants, studentships, leading institutions, and key research outputs. The data are summarised in Annex 5. *(Note: There is currently little funded activity in the theme of Nanodesign which was therefore omitted in much of the subsequent analysis).*

1.3 Bibliometric Data

A bibliometric study was carried out using "Essential Science Indicators" tools in the Thomson ISI Web of Knowledge. The search used the keywords designated against each themes, to generate information on citations within the 12 years 1995-2008. These bibliometric data are summarised in Annex 5, Section 5.6.

1.4 Community Input

An on-line survey was used to provide members of the wider UK NST community with an opportunity to contribute in advance to the Theme Day and to indicate a preference to attend. Questions were posed on a range of topics, including awareness of the RCUK programme as well as recent and prospective developments in the discipline. Attendees at the Theme Day on 23rd September were selected to cover the breadth of RCUK interests in NST with an emphasis on current and recent grant holders. A number of participants were invited after indicating their interests on the on-line survey.

The Theme Day was an opportunity for the Panel to gain input from the community in addition to the evidence listed above. The agenda included small group sessions where the attendees were asked to discuss with the Panel areas of the programme which had worked well, those which hadn't worked well, how they would improve the programme and what had inspired them to work in the NST field.

1.5 Format of the Evaluation

Operating as a 3-day event, day one provided an opportunity for the Panel to familiarise themselves with the UK science base, and to review the written evidence provided by the Research Councils and the UK community. This prepared the Panel for meeting with the community on the second day, where discussions were undertaken at on a range of topics of interest to the community e.g. skills, the future of the discipline, and health and safety policy. Oral presentations were given to set the scene by the Head of the RCUK programme, Dr John Wand and the RCUK Strategic Advisor for Nanoscience Professor Peter Dobson. The day progressed on to a plenary session where the key issues raised through the morning session were discussed. A live record of discussion was kept so that the community could directly feed in to the final Panel report. At the conclusion of the day, a private stakeholders session was held with representatives of funding bodies, where the Panel were able to discus their initial reflections with relevant key stakeholders and seek clarity on a number of issues. On day 3, a closed Panel session took place, where members reviewed the earlier discussions, and drafted their initial recommendations to the Research Councils.

2. PROGRESS DURING THE LAST FIVE YEARS

2.1 Outcomes of Previous (2005) Review

The Panel reviewed and reflected on the previous 2005 Nanotechnology Panel Report and found significant evidence that Research Councils, particularly EPSRC, had taken a leading role in pro-actively addressing the key recommendations, with a few exceptions. The principle recommendations (in bold) and a summary of the Research Council interventions (in italics) were:

R1. EPSRC should, as a matter of urgency, carry out an in depth review of its strategy for Nanotechnology research to establish a funding framework that would address the relative weakness of Nanotechnology research in the UK. This could result in the establishment of a Nanotechnology Program analogous to its current programmes such as Chemistry and Materials.
The Panel noted that in 2006, the EPSRC Strategy for Nanotechnology was developed following extensive community consultation [3,4]. The establishment of a programme was achieved the following year.

R2. If the UK was to compete in Nanotechnology research new funding was required specifically directed to Nanotechnology.
As part of their input in to the comprehensive spending review 2007, the Research Councils established the cross-Council programme, Nanoscience through Engineering to Application [5].

R3. Nanotechnology was a dynamic research area and 5 years was too long a period between reviews. The Panel felt that the EPSRC Nanotechnology research portfolio should be reviewed again in two years time.
The Panel noted that this recommendation had not been implemented but recognized that the review due date of 2007 came during a period of immense change for the funding of NST within the UK. The current review encompassed NST research from across the whole discipline unlike the previous efforts that had focused exclusively on EPSRC funded research.

R4. The UK needed to make use of its strengths in Medicine, Biosciences and in Design Technology. The EPSRC thus needed to strongly encourage its Nanotechnology community to work with these communities and there needed to be increased cross-Council collaboration to ensure that these ties were formed and maintained. RCUK could help encourage this.
The Panel felt this recommendation had been partially achieved through the £15M investment in NST to underpin diagnostics and drug delivery. An impressive portfolio of research projects had been assembled, that could ultimately lead to significant advancement in the way healthcare is carried out in the UK and worldwide as well as offering the potential for significant economic pay-back.

R5. The EPSRC was the major funder of basic and applied Nanotechnology research in the UK and if the UK was to be a major world force in Nanotechnology, the current strategy for funding Nanotechnology research required revising. Nanotechnology was a complex research area and the strategy needed to be flexible and continually reviewed to maintain its currency.
The Research Council approach has encompassed many of the recommendation of the 2005 Panel and has been agile enough to include and address other issues affecting the field such as the health and safety implications of NST and the need for public debate to inform research and research priorities.

R6. The Nanotechnology Themes generated in 1999 still have some relevance but should be reviewed because the dynamic nature of Nanotechnology research has meant that some of the original themes are now redundant. The strategy required for funding in each of these themes differed from theme to theme and could involve any of the mechanisms previously used by EPSRC and might require new mechanisms, but it was clear that the current funding strategy needed drastic revision.

This recommendation had been partially addressed during 2006 through the establishment of a strategy for the EPSRC support of NST but the field is still evolving and further refinement is required. The importance of segmenting NST research into individual themes has diminished, as many research proposals encompass several themes, and integration is now viewed as vital.

R7. Training in Nanotechnology, perhaps by means of MSc courses, required further consideration. This was needed both for future workers in industry and researchers for Universities.

The Masters position has not been specifically addressed. There is still a lack of suitable one-year courses to train those who will then move on directly to work in industry. However, progress has been made in addressing the needs of new postgraduate researchers in universities. A significant investment had taken place to fund 30 students per annum through Centres for Doctoral Training (see Annex 6). These postgraduate students will receive structured training in NST during their first year, before they move on to full-time research projects. This commitment has been made in addition to significant single PhD awards on research projects across each of the Research Councils.

R8. Any strategy evolved needed to take into account industrial and societal needs and concerns.

The 2009 Panel was clear that the EPSRC strategy developed in 2006 and the ethos of the RCUK programme have societal needs and economic impact at their core.

R9. There needed to be a much better estimate of what the EPSRC was actually spending on Nanotechnology, the current methodology overestimated this. There should be an explicit view of what should be counted as Nanotechnology this could help to reduce the medium quality research that appeared to have been funded because of its association with the Nanotechnology research area.

The current classification methodology was developed as part of the EPSRC Nanotechnology strategy in 2006 but was still felt to be unsatisfactory. The Panel recognised that the main investments of the RCUK Nanoscience programme had Nano at their very core, but these are underpinned by significant responsive mode/investigator led portfolios of research where the link to Nanoscience and Nanotechnology is sometimes tenuous. Because of the interdisciplinary nature of this field, there is inevitably strong overlap with fields such as Physics, Chemistry, Materials and aspects of Engineering. Better metrics are still urgently required in order to properly measure the level of public sector support for this field. On a more positive aspect, the Panel noted how the interdisciplinary nature of the field was more obvious and better supported in the 2009 evaluation as compared to previous years, and that the inclusion of projects from across the Research Councils was a positive reflection on progress made.

R10. Cooperation between the DTI MNT programme and the EPSRC needed improving to ensure the exploitation of Nanotechnology research. Manufacturing industry in the UK had drastically reduced the amount of early

stage development that it did and DTI and EPSRC had to ensure that this funding gap (the so-called "Valley of Death") did not prevent the progression of research into products

The Panel probed as fully as possible into this issue, and despite assurances from the various funding agencies that the situation had improved, they could find little evidence that this was the case. This remains an area of great concern for the UK.

2.2 The RCUK Nanoscience Programme

In 2007, following the Government's Comprehensive Spending Review, RCUK designated NST as one of its six priority areas, and set up the cross-Council programme, Nanoscience through Engineering to Application (see Annex 3).

The programme seeks to capitalise on the ability of NST to revolutionise society and to exploit its potential to cause disruptive step changes in electronic materials, optics, computing, and in the application of physical and chemical understanding (in combination with biology) to generate novel and innovative self-assembled systems. The field is maturing rapidly, with a trend towards ever more complex, integrated nanosystems and structures.

In this respect, the RCUK Nanoscience programme is providing a focus for UK NST research to maximise international impact through:

- Undertaking interdisciplinary Grand Challenges in areas of societal and economic importance (e.g. healthcare, energy and the environment).
- Providing closer links with the Technology Strategy Board (TSB) to shorten the innovation chain.
- Establishing a network of existing Nanotechnology and Nanofabrication facilities for shared use by researchers.
- Supporting postgraduate training through Centres for Doctoral Training.
- Supporting fundamental research through signposting research areas of specific interest.
- Coordinating the Research Councils' contribution to the Government's agenda, addressing the environmental, health, safety and public engagement issues of Nanotechnology.
- Appointing an RCUK Strategic Advisor, currently Professor Peter Dobson (University of Oxford), and formerly Professor Richard Jones (University of Sheffield) for both scientific guidance and wider engagement with this broad community.

The aim of the Nanoscience through Engineering to Application programme is to focus UK NST research to enable the UK to make an international impact in this rapidly developing field. The programme has involvement from all other Research Councils and the Technology Strategy Board (TSB).

2.3 The Grand Challenge Approach

To focus the UK research effort, the Research Council programme has been implemented by means of a series of Grand Challenges in Energy, Healthcare and the Environment. These were developed in conjunction with researchers to address societal and/or economic issues where NST can make a unique and significant contribution (see Annex 7).

From the outset, each Grand Challenge project is required to be an integrated, interdisciplinary effort, encompassing basic and applied research intended to move the technology towards the point where it can actually be deployed. A stage-gate approach has been employed to drive basic research through to its application. Projects have also included studies on: risk governance, economics, and social implications.

The Stage Gate Process

Each Grand Challenge call is being operated through a two-stage process. Towards the end of the projects funded in Stage 1 substantial further funding will be allocated to the projects which show the greatest promise of producing a measurable impact. Stage 2 is aimed at taking the technology developed in Stage 1 towards its application.

Stage 1: Start dates for the 3-year Grand Challenge projects were: 2008 (energy), 2009 (healthcare) and 2010 (environment). The desired result from Stage 1 projects is credible candidate technologies for further development in Stage 2, demonstrated for example by significant involvement by an end user, or the ability to attract collaborative funding.

Stage 2: Projects which are successful in securing funding at this stage will receive funding for a further 3 years. This stage is liable to include a greater proportion of users, with joint funding expected from the TSB and other partners. At the end of the of stage 2 funding, the expectation is that the technology will be at a stage where it will be able to attract finance from other sources so that the project can meet its clinical aim.

So far, there have been three Nanotechnology Grand Challenge calls for proposals:

Grand Challenge 1 - Nanotechnology for Energy

The first Grand Challenge call was in energy, focussing on the harvesting of solar energy. Five projects were funded in March 2008 at a cost of £6.7M; four of these project focus on photovoltaic applications and one on the use of light to split water, resulting in hydrogen generation.

Grand Challenge 2 – Nanotechnology for Healthcare

The second Grand Challenge call focussed on healthcare, specifically Nanotechnologies for the targeted delivery of therapeutic agents and Nanotechnologies for healthcare diagnostics.

The scope for this call was developed using a wide ranging consultation process. This included a Town Meeting (April 2008), a web-based consultation, a public consultation exercise and discussions between Research Councils and other stakeholders.

Ten large-scale interdisciplinary projects were funded in March 2009 at a cost of £16.2M.

Grand Challenge 3 – Nanotechnology for the Environment
The aim of this Challenge was to use NST to provide environmental solutions, specifically to underpin carbon capture and utilisation. The final scope for this call was developed through community consultation at a Town meeting held in March 2009 with three projects being funded to start on 1st May 2010.

The successful proposals have attracted £4M of funding to address a range of scientific challenges in this area and also to demonstrate a commitment to *Responsible Innovation* by minimising risk associated with the development of NST through appropriate management of environmental, health & safety, societal, ethical and other concerns.

Further details of the Grand Challenge projects funded to date can be found in Annex 7.

2.4 Supporting Skills - Centres for Doctoral Training

A key aspect of the Research Councils' support for NST is to supply a future pipeline of trained researchers**.** There is a strong ongoing desire to establish highly innovative, exciting training environments that draw on research excellence with a view to producing the skilled and talented researchers needed to address challenging research problems that will benefit of the UK economy in the 21st century.

To support this, as part of a wider EPSRC investment of £310M in 52 Centres for Doctoral Training announced since December 2008, three Centres for Doctoral Training have been funded through the RCUK Nanoscience programme (plus another of relevance to NST from other funds). It is hoped these Centres will establish a strong cohort able to rapidly establish a pre-eminent international reputation for doctoral training, embedded within excellent research environments.

An intake of ten doctoral students per year, for five successive years, is being supported at each Centre:

- **Bristol Centre for Functional Nanomaterials**
  Bristol University (Principal Investigator: Dr Terence McMaster)

- **Nano Science & Technology Doctoral Training Centre**
  University of Cambridge (Principal Investigator: Professor Jeremy Baumberg)

- **NOWNANO DTC: A North West Nanoscience Doctoral Training Centre**
  University of Manchester (Principal Investigator: Dr Irina Grigorieva)

- **Industrial Doctorate Centre in Micro- and Nano-Materials and Technologies**
  University of Surrey (Principal Investigator: Prof Julia Yeomans)

Students within each centre will:

- Be supported for four years;
- Receive a formal programme of taught coursework which will form up to 25% of the overall training package, and develop and enhance technical interdisciplinary knowledge as well as broadening skills;
- Be fully integrated with the research project and undertake a significant, challenging and original research project.

In addition to these Centres, the MRC has supported the Integrative Toxicology Training Partnership (ITTP), led by the MRC Toxicology Unit in Leicester. This will build capacity in Integrative Toxicology research through the award of approximately 25 PhD studentships to Universities throughout the UK.

A number of other postgraduate studentships (in excess of 40 per annum) are supported through the investigator led/responsive mode mechanism provided by all Research Councils.

2.5 Infrastructure/Shared Equipment initiatives

Following consultation, the RCUK Nanoscience programme has made a number of awards to enable access by the wider academic research community to specialised equipment:

- **Monochromated Transmission Electron Microscopy**
- **An Open-access Centre for Nanoscale Analysis and Fabrication**
- **Access to Multi-functional Nano-scale Analysis System**
- **Leeds EPSRC Nanoscience and Nanotechnology Research Equipment Facility**
- **Access to Nanoscience and Nanotechnology Equipment at Cardiff**
- **Guided Access to High-speed Contact Atomic Force Microscopy and Photonic Force Microscopy at the Nanoscience and Quantum Information Centre**

These complement a number of other facilities made available through EPSRC support for general materials research:
http://www.epsrc.ac.uk/funding/facilities/epsrc/Pages/materials.aspx

2.6 Mid-range Facilities

EPSRC has defined a Mid-range Facility as a research facility which provides resources that would otherwise be of limited availability to UK researchers for one of several reasons, including the relative cost of the equipment, the particular expertise that is needed to operate the equipment or interpret the results, or the need to share information and experience in order to enhance progress. Typically, such facilities are expected to cost in the range £3 million to £30 million to set up. A major review of the provision of such facilities was carried out during 2009, and tenders have been invited for the first six areas, which include epitaxy, electron paramagnetic resonance spectroscopy, a free electron laser facility, a national service for computational chemistry software and an X-ray crystallography service. It is expected that NST researchers will be major users of such facilities, which provide essential support for a wide range of nanoscale modelling, fabrication, characterisation and property measurement activities.

2.7 Further Targeted Investments

The Panel also noted other managed activities across the Research Councils, which were relevant to NST, including:

The Nano Engineered Materials Initiative
This provided support at levels of the order of £1 million each for projects in the areas of photonic crystals, bulk nanostructured aluminium alloys, polymer nanocomposites, and high performance nanotuble fibres. Further details of these grants are provided in Annex 8.

Science & Innovation Awards in Graphene and Metrology
In 2006, two grants were made of £4.3 million (jointly to Strathclyde and King's College London), and £5.6 million (jointly to Imperial College and University College London) for the development of new tools for nanoscale characterisation and metrology, and for their application in molecular science, medicine and manufacture. Details are provided in Annex 9.

More recently, in 2008, two grants were awarded of £5.3 million (jointly to Manchester and Lancaster) and £4.86 million (jointly to Exeter and Bath) for research on understanding the properties of graphene, and its possible applications in relation to materials science, chemistry and engineering. Further details are provided in Annex 9. The Panel noted that the original discovery of graphene in 2004 arose as a result of basic research carried out at the University of Manchester, which was not part of a managed programme. Yet graphene research is now rated by the community as the highest-impact aspect of all UK NST research (Section 4). This emphasises the need to preserve an appropriate balance between responsive mode funding for ground-breaking "blue-skies" research, and managed programmes for more applied and targeted research, in the overall strategy for NST support.

2.8 Interdisciplinary Research Centres and Collaborations (IRCs)

Interdisciplinary Research Centres and Collaborations (IRCs) are centres of internationally-acknowledged scientific and technological excellence, with sufficient critical mass to make a real impact in areas of key future industrial relevance to the UK. The collaborations are funded through large, long-term grants, typically around £10 million over 6 years. IRCs generally involve several universities together with industrial partners. The research of three recent IRCs has been of major relevance to NST; the Bionanotechnology IRC, the Nanotechnology IRC, and the Quantum Information Processing (QIP) IRC. The first two of these were designated as Centres, and had their main hubs in Oxford and Cambridge respectively, and operated during the period 2002 – 2008. The third (QIPIRC), designated as a Collaboration, was administered from a central hub in Oxford, and operated during the period 2004 - 2009. Further details of these IRCs are given in Annex 10.

2.9 Nanosafety and the Environment

While engineered nanoparticles offer significant potential benefits, there are also uncertainties with regard to the potential risks to human health. This was a key finding of the Royal Society and Royal Academy of Engineering report *Nanoscience and Nanotechnologies: Opportunities and Uncertainties* [7] commissioned by the UK Government and published in July 2004. The report concluded that many Nanotechnologies pose no new health and safety risks. However, there were concerns over the potential impacts of engineered nanoparticles and nanotubes (in a free rather than embedded form) and these materials were identified as a priority area for research. A subsequent (2008) report from the Royal Commission on Environmental Pollution entitled "*Novel Materials in the Environment: The Case of Nanotechnology*", has re-emphasised these concerns and noted that there has been no substantial progress within the UK in addressing these issues in the 4 years between the two reports [8]

RCUK has been taking a leading role in coordinating the Research Councils' contribution to the Government's response to the environmental, health, safety and public engagement issues of NST. The RCUK programme and the Research Councils have made the following investments to address the issues raised:

Environmental Nanoscience Initiative, Phase 1 and Phase 2 (ENI1 and ENI2)
The Natural Environment Research Council (NERC), EPSRC, the Department for Environment, Food & Rural Affairs, the Environment Agency and, for Phase 2, the United States' Environmental Protection Agency are collaborating on a major joint research effort in Environmental Nanoscience.

ENI1, now largely completed, aimed to begin to address some of the key questions about the environmental fate, behaviour and effects of manufactured nanoparticles and to build a community of scientists with relevant expertise and provide the evidence to support policy development in this area.

ENI2 aims to draw on complementary strengths in the UK and US to produce robust, validated models that accurately predict transport, fate and bioavailability of nanomaterials and their interaction with biological and ecological systems. It is anticipated that this collaborative research will generate valuable tools to support assessment of risks associated with the environmental release of manufactured nanomaterials. Applications were sought from strongly interdisciplinary consortia, comprising both UK and US scientists, to address these issues. Total funding allocated was approximately £8 million (consisting of 3.94 million pounds sterling and 6 million US dollars) for two consortia commencing research in 2010.

PROSPEcT LINK Project
The PROSPEcT LINK project will help to fulfil the UK's contribution to the Organisation for Economic Co-operation and Development's (OECD) programme to examine the environmental safety of nanomaterials important to UK industry. PROSPEcT will provide crucial data to the OECD work, by addressing gaps in the current level of industrially relevant scientific research. It is expected that research will lead to establishing scientific test methodologies to the physico-chemical and ecotoxicological properties of these materials.

Following the initial analysis of the current understanding of the physico-chemical and ecotoxicological properties of these materials, and identification of the knowledge gaps within, and application of fundamental science to address these gaps, the project will enable the identification of new nanomaterial-specific test methodologies for CeO_2 and ZnO nanoparticles. It is hoped that research here will overcome the scientific limitations of current tests, and give rise to novel methodology such as particle characterisation within living systems, detection of individual particles beyond current detection limits, new robust technologies for the real-time, in-situ detection of nanoparticles against the background reproduction of realistic exposure scenarios.

The project will establish generic protocols that can inform any potential risk assessments for products containing the candidate nanoparticles. It is hoped that the data and knowledge generated might allow for the use of approximation tools and model systems to assess the risk of other, similar particles.

As part of the UK financial support for the project, the RCUK Nanoscience through Engineering to Application programme has issued awards totalling £0.7 million to researchers at Imperial College London and the University of Exeter.

2.10 Signposting/Highlight Notices

In accordance with the Government response to the report [9], a cross-Government Nanotechnology Research Co-ordination Group (NRCG) was set up to coordinate research efforts relating to the potential human health and environmental exposure, hazards and risks posed by the products of Nanotechnologies. This work was aimed at leading to the development of an appropriate framework and measures for controlling any unacceptable risks. The NRCG's Progress Report [10], published in November 2006 set out a programme of 19 research objectives to characterise the potential risks posed by engineered nanoscale materials.

Medical Research Council (MRC) Nanotoxicology Highlight Notice

Objectives 11-16 of the NRCG Report are relevant to the MRC's Molecular and Cellular Medicine Board (MCMB) and include research to establish: a clear understanding of the absorption of nanoparticles via lung, skin and gut, their distribution in the body and potential target tissues; inter and intracellular transport and localisation of nanoparticles and their cellular toxicity; whether oxidative stress, inflammatory effects and genotoxicity apply to nanoparticles; and the deposition, distribution, toxicity, pathogenicity and translocation potential and pathways for nanoparticles in the airways and lung and their potential impacts on the cardiovascular system and brain.

MRC operates a system of "Highlight Notices", which are published to alert researchers to areas of biomedical science that are currently a high priority for the Council. Since the launch of the Nanotoxicology Highlight Notice four awards have been made. In the light of these recent awards, MCMB are now encouraging, in particular proposals which investigate the health impact of nanoparticles *in vivo* or aim to validate *in vitro* tests against *in vivo* models with emphasis on studies addressing the mechanisms of toxicity. This is in accordance with the recommendations of the Royal Commission on Environmental Pollution report (2008) [10].

EPSRC Signpost in Nanometrology and Nanotoxicology

Objectives, 2, 3, 4 and 9 of the original NRCG Report are most relevant to EPSRC researchers, these are:

- (2) Identify the most suitable metrics and associated methods for measuring and characterising nanoparticles;
- (3) Develop standardised, well-characterised reference nanoparticles;
- (4) Understand the properties of nanoparticles in the context of their ignition and explosion potential and assess/develop methods for evaluating this;
- (9) Optimise, develop and apply technologies that enable the measurement of exposure to nanoparticles in soil and water.

EPSRC uses "Signposting" to highlight priority research areas in responsive mode instead of issuing calls for proposals. Since the launch of the Nanometrology and Nanotoxicology Signpost in 2007, which followed the issue of a second NRCG report [11], two awards totalling £1.5M have been made on:

- *Nanoparticle Cytometrics: a quantitative analysis of the toxic effects of nanoparticles* (Swansea and Leeds Universities).
- *The radical nature of oxidative stress triggered by nanoparticles* (University of York).

3. ANALYSIS OF CURRENT ACTIVITIES

The Panel sought to analyse several key parameters of UK Nanoscience programme, namely funding inputs; peer-reviewed publications; bibliometrics; other research outputs; and technology transfer to industry; and the extent of international collaborations. Comparisons were made with the performance of other countries, to the extent that this was possible. Of the various parameters studied, the financial aspects were, perhaps surprisingly, the most difficult to quantify. As already noted in Section 2.1 of this report, outside of the managed programme, there is a lack of clarity as to what should, and should not, be classified as NST research. The same problem affects the analysis of activities in other countries as well, and hence quantitative international comparisons are fraught with difficulties.

3.1 Financial

The key financial details are summarised in Figures 1 – 6 (see Annexes 5.2 - 5.3). The RCUK managed programme on "Nanoscience through Engineering to Application" was started in 2006. The total new monetary commitment by the RCUK programme in the financial year 2006-7 was £6.5 million, in 2007-8 this rose slightly to £8.6 million, and in 2008-9 the total new commitment was £32.2 million. However, the overall budget for the managed programme for 2009-10 was substantially lower, at £6.3 million. The panel noted that this reflected the fact that the programme's investment strategy was front-loaded to the early years of the 08/09 – 10/11 comprehensive spending review (CSR) period. The total commitment by the programme within the CSR period will exceed the anticipated £42M, but the downward trend is a matter of serious concern, particularly at a time when our leading international competitors are accelerating their efforts in this field.

The managed programme funds have been mainly invested in the first two Grand Challenge project areas of Energy (£6.7 million) and Healthcare (£16.2 million) and on establishing three Centres for Doctoral Training in Nanoscience (£18.8M) to help ensure the future health of this discipline. However, the total sums invested are seriously sub-critical in relation to the scale of the applied research challenges being addressed and the opportunities which exist for both scientific and commercial success. As a result, the scope of the Grand Challenge in Energy programme was heavily circumscribed, and limited almost exclusively to photovoltaic materials for solar harvesting (for details see Annex 7.1). The Healthcare programme is somewhat more wide-ranging, and attracted a large number of outstanding applications focussing on drug delivery and diagnostic systems. Details of projects funded under this programme are given in Annex 7.2.The third Grand Challenge, in the area of Environment is supporting a number of interesting technologies to turn carbon dioxide from a pollutant into useful products that could help both industry and the environment (fuels, as polymers, carbohydrates). (Annex 7.3).

Support for the three major Interdisciplinary Research Centres / Collaborations in this area (see Annex 10), which were originally funded in 2002 – 2004, has now come to an end. In 2007, a one-off "Nano Engineered Materials Initiative" provided £5.5 million of funding for work on the manufacturing of nanoscale materials (see Annex 8); those projects are now approaching completion. In 2008-9, two Science and Innovation awards were made to build on the excellent reputation of UK groups and establish a critical mass of research in to graphene, totalling £10.5 million (see Annex 9). However, the Science and Innovation Award scheme has now been terminated, so further funding under that heading is no longer possible. Also in 2008-9, a one-off investment of £17.5 million was made to establish Centres for Doctoral Training for Nanoscience (see Annex 6) as part of a total EPSRC investment £310 million across 52 centres.

Taking into account the one-off nature of much of the funding just described, and the changing structure of funding mechanisms within the Research Councils, it is difficult to see any hard evidence of planning for future targeted investment in the NST field within the UK. In fact, it seems that overall funding for targeted programme in this area is now decreasing sharply from the (very modest) peak achieved in 2008-9. This should be a matter of great concern to the UK Government. It is putting at risk much of what has already been achieved in the UK, and is completely contrary to what is taking place in almost all other major industrial countries.

The level of responsive mode funding for NST research is very difficult to quantify. Published figures (Annex 5.2) suggest that such funding amounts to almost three times that for all the managed and targeted programmes put together. But the overlap with funding for other basic scientific disciplines such as Physics, Chemistry and Materials Science is so strong that it is impossible to deconvolute the data. Much better and clearer criteria are still urgently needed to assist this analysis. Despite these difficulties, it is still possible to draw some limited conclusions about the distribution of research grants and research studentships between the various themes of NST research. The data are summarised in Annexes 5.2 and 5.3. Support for four areas, namely nanofabrication, nanomodelling, functional nanotechnology, and molecular nanotechnology, dominates the scene. But support for the areas of nanomanufacturing, nanomedicine, and nanotoxicology, which are at least as important as the others, is at a disturbingly low level.

3.2 Journal Publications

Data on journal publications arising from EPSRC Nanotechnology grants is summarised in Annex 5.5. By far the most striking thing about these data is the apparent remorseless decline in the overall volume of publications, from about 1250 in 2004-5, to a level of just below 750 in 2008-9. The Panel could not find any obvious faults in the methodology used to establish these figures, but was unable to identify any simple or clear reason for the decline. It is possible that there is a degree of under-reporting, e.g. because of failure to acknowledge grant-giving organisations in the final publications, but nevertheless the decline appears to be real.

3.3 Bibliometrics

Standard bibliometric data on UK and global NST publications are summarised in Annex 5.6 (Figures 7 – 11). The most immediate observation is the dramatic growth in output from China and South Korea, and the overall decline in the relative position of the UK. Integrating the total number of publications over successive five year periods, the UK has dropped from sixth to seventh place, behind the USA, China, Japan, Germany, South Korea and France. A similar decline has taken place in the number of citations received per country, where the UK has been overtaken by South Korea. When analysing the world's most highly cited papers (Figure 11), it is found that the UK contributes about 5%, most of which are in the area of nanomaterials. This percentage is roughly in proportion to the overall volume of publications originating from the UK. In this respect, the UK's performance is average but not outstanding. A separate analysis of "hot papers" (papers which make a very rapid impact, and rapidly receive substantial numbers of citations) revealed a rather small presence of UK publications.

3.4 Other Research Outputs and Technology Transfer

Data on patents granted and spin-out companies created are summarised in Annex 5.7, Figures 12 and 13. To date, 49 patents have been notified, with the largest number (20) being in the area of functional nanotechnology devices and machines.

The number of spin-out companies registered during the period 2004 – 2009 is 14, of which the largest number were in the functional nanotechnology area, which correlates with the patent data.

The Panel considered that a more detailed analysis of these data was needed. In particular, the number of spin-out companies registered is not a good overall indicator of economic activity. Other parameters, such as the number of employees, turnover, capital employed, total asset value etc., should also be taken into account.

3.5 International Collaborations

NST is an international activity, and it is clearly beneficial for UK researchers to engage with international partners in NST projects of potentially major scientific, economic and environmental importance. The data available on the extent of such collaborations are very limited. Many responsive mode projects involve either formal or informal collaboration with scientists from other countries, and there is a strong international element to the work on nanotoxicology and environmental impact. However, there appear to be only a limited number of substantive NST research projects that were designed from the outset to be international in nature. Of these, the main collaborations are with researchers in India, China and Taiwan, and are focussed in the area of nanophotovoltaics, nanorobotics, and nanoparticulates. Positive encouragement for such collaborations is desirable in future calls for proposals.

3.6 Global Comparisons

It was not within the remit of the Panel to carry out major international comparisons. However, the publication data and bibliometric analysis described above permitted an estimate to be made of the UK's scholarly position relative to other countries. In terms of the comparative overall scale of investment in this field, an authoritative guide has been published in the USA during the period in which the present report was undergoing preparation. The President's Council of Advisors on Science and Technology (PCAST) produced its Third Assessment of the National Nanotechnology Initiative in March 2010. [12] This showed that, from 2003 – 2008, global public and private investment in Nanotechnology grew at an average annual rate of 27%. In 2008, total investment in Nanotechnology was approximately $US 6.5 billion in Asia, $5.5 billion in the USA, and $4.5 billion in the E.U., with by far the most rapid rate of growth being in Asia, especially in China. Faced with this situation, the Panel must voice its strong concern at the low and apparently declining level of strategic investment in the UK. Unless this situation is reversed, the UK will become an "also-ran" in a field which is vital to our economic, as well as our scientific, future.

4. COMMUNITY FEEDBACK

A well-attended Nanoscience "Theme Day" was held in London on 23rd September 2009. NST researchers from 27 UK universities took part (most of whom were current holders of nano-related grants from the Research Councils). Representatives of EPSRC, BBSRC, MRC, ESRC, STFC, the Technology Strategy Board (TSB), and the Defence Science and Technology Laboratory (DSTL) also participated. In advance of this event, an on-line survey was used to provide members of the wider UK NST community with an opportunity to contribute their views and to raise issues for discussion. Questions were posed on a range of topics, including awareness of the RCUK programme as well as recent and prospective developments in the discipline. During the theme day, a number of small-group discussion sessions were held, each chaired by Panel members. These were followed by a plenary session at which the main issues which had arisen during the group discussions were explored in greater depth. A broad consensus was achieved on several major issues, although in some cases conflicting priorities emerged. The main conclusions and recommendations from the community are summarised below.

4.1 The RCUK Programme.

There was strong support for the establishment of a directed programme, which was already improving visibility, coherence and strategy in the UK NST sector. However, there was concern that policy was being formulated "behind the scenes". Members of the community said that they did not understand how priority research areas had been arrived at, and they did not feel part of the decision-making process. Being experts in the field themselves, they wanted more engagement with the process.

4.2 Sustainability and Longer-term Funding

There was dismay at the ever-changing funding priorities and the lack of continuity of support for major project areas. The decision not to implement a renewal process for the IRC programme after six years of focussed support, was a particular cause of concern, especially as these programmes were beginning to achieve real success,. Major new technologies could not be developed on this short time scale, and alternative funding strategies, such as rolling programmes, needed to be considered. Also, there appeared to be a chronic lack of joined-up thinking between the Research Councils and "downstream" bodies such as TSB and BIS, resulting in excellent projects struggling to secure follow-on funding just at the point where real economic and societal benefits might have been obtained.

4.3 Communication

There was much concern at the poor state of internal communication within the UK NST community, and between the academic research community and industry. Urgent RCUK-led action was needed to develop regular, informal, face-to-face communication between researchers, to establish a "one-stop" central web site containing all relevant information about current research, to provide links between individual academic and industrial researchers, and to stimulate on-line discussion and debate about NST matters.

4.4 Links between Academia and Industry

There was a widespread belief that these links were not working effectively. Excellent work was being carried out in UK universities, and this was not being efficiently exploited by industry. Both the investment and manufacturing sectors in the UK were risk-averse, and reluctant to support new technologies. The situation was exacerbated by poor communication between university and industrial researchers, and a lack of appreciation of the difficulties involved in translating academic research into industrial products. "Proof of Principle" funding was urgently needed, in order to help bridge this gap. There was support for the idea of establishing Fraunhofer-type centres in the UK, where researchers from academic and industrial backgrounds could come together to work on major projects having substantial wealth-creating potential.

4.5 Grand Challenges

There was strong support for the general principle of the Grand Challenge approach, because it provided a clear focus on certain key priority topics, attracted significant funding, and could potentially help to establish communities of interest across the UK in strategic areas of research. However, the scheme was still at a very early stage, and it was too early to judge the actual outcomes in any detail. There was also concern that a proper balance needed to be maintained between the directed programme and the funding of responsive mode proposals from within the NST community. It was apparent that by far the highest impact "breakthrough" NST research in the UK in recent years, on graphene, did not arise out of a directed programme, but from basic research at the University of Manchester.

4.6 Centres for Doctoral Training

There was enthusiastic support for the concept of Centres for Doctoral Training for the NST sector. Research in this area is inherently interdisciplinary, and such centres can in principle provide a superb initial training for young researchers whose first degrees will have been in a range of different subject areas. The main concern expressed was that such centres could end up denuding other universities of vitally needed graduate students to support their NST research. This is a key issue, which needs to be addressed as a matter of urgency. Whilst it is clearly beneficial for the first (training) year of a four-year graduate course to be spent in a structured environment, it is not obvious that the subsequent research project needs to be carried out in the same environment, or in the same place. Measures should be considered to encourage dispersal of some of these students to different universities at later stages of their doctoral research, to promote the overall health of the NST research community.

4.7 Shared Equipment Arrangements, and Access to Facilities

There was widespread praise for the Shared Equipment Initiative, which was felt to be working very well. The providers of these facilities were giving first-class help and support to the NST research community. The system for obtaining access to large-scale facilities such as synchrotron and neutron scattering also appeared to be working well. In particular, the ticket system was felt to promote speed and flexibility of access, with minimum bureaucratic delay. In principle, the newly-established Mid-range Facility scheme should provide similar benefits, especially in the areas of fabrication, characterisation and modelling. However, there were concerns that the arrangements for access to Mid-range Facilities were not clear. If research proposals needed to be written in order to obtain the necessary funds, then the vitally needed elements of speed and flexibility would be lost. A ticket system, as used for large-scale facilities, was felt to be a preferable arrangement. A further concern was the delay in funding the establishment of these facilities, which are urgently needed if the UK is to retain any prospect of international competitiveness in the NST sector.

4.8 Pump Priming Funds

Concern was expressed that the conventional responsive mode funding arrangements were not fast enough or flexible enough to deal with applications in the fast-moving, interdisciplinary area of NST. The overall time between submission and decision is long, success rates are low, and the use of predominantly single subject panels for evaluation of proposals was felt to be prejudicial to the prospects of success for more adventurous, unconventional, discipline-crossing proposals. The introduction of the "No resubmission" rules would be further prejudicial to the more speculative, high-risk proposals typical of NST. In order to alleviate this problem, it was suggested that a new funding mechanism should be introduced, based on speed and agility, and offering short, "pump priming" grants to promote the rapid exploration of new ideas. The review process would be kept to a minimum, and adventure would be the order of the day. Such an approach would have the twin benefit of speeding up the early stages of NST research, and also "de-risking" subsequent, larger grant applications for follow-up work.

4.9 Health and Safety of Nanomaterials

Considerable frustration was expressed at the way in which this vital topic was currently being dealt with. Proposals for research in this area should not have to compete with single-subject, conventional responsive mode applications. An interdisciplinary approach was required, with a different set of value judgements. The concept of "scientific novelty" in this research area should be regarded in terms of the novel ways in which diverse disciplines, such as toxicology, chemistry, environmental and materials science combine and interact to solve key problems. Ring–fenced funding is needed to ensure that vitally-needed precautionary research was carried out in a timely manner. Much better coordination between the Research Councils was needed in this area, which is crucial to the public acceptance of Nanotechnology.

4.10 Inspiration and Motivation

Delegates at the Theme Day meeting repeatedly stressed their pleasure and excitement at being able to work in this particularly stimulating, fast-moving and challenging area of research. The Panel was keenly aware of the energy and enthusiasm manifested by those working in this area, and regarded this as a priceless asset for the future of NST in this country.

5. RECOMMENDATIONS

5.1 Strategic Recommendations

1. Research priorities

In the overall strategy for Research Council support of NST, it is important to preserve an appropriate balance between responsive mode funding for ground-breaking "blue-skies" research, and managed programmes for more applied and targeted research. By definition, the occurrence of disruptive and transformational advances in the basic science cannot be predicted beforehand. All that can be done in that sector is to provide a research environment which is conducive to such discoveries, and an organisation and management structure which is well adapted to translating the results of such research into new products, services and processes. In the more applied sector, which involves managed programmes, it is necessary to set priorities and to identify areas where the greatest benefits are likely to be obtainable, whether in scientific, technical, economic and social terms. Areas where NST has multi-billion pound development potential, and which should be given top priority for applied research programmes within the UK are:

- ***Healthcare:*** diagnostics, therapeutics, targeted drug delivery, assisted living
- ***Sustainability:*** achieving greater functionality with less use of raw materials and energy
- ***Security:*** ultra-sensitive sensors, detectors and encoding systems
- ***Clean energy generation:*** more efficient photovoltaics, thermoelectric materials, and fuel cell catalysts.
- ***Nanoelectronics:*** faster and more versatile computers and communications systems, and for quantum information processing

2. Strategic leadership and direction

It is essential to provide strong, clear leadership and direction for the whole of the NST applied research programme in the UK. Ultimate responsibility for driving the programme forward should be taken at ministerial level, with the task assigned to a specific minister within the BIS team. Technical oversight of the programme should be a direct responsibility of the Government's Chief Scientific Adviser, who should seek to establish clear scientific and technical goals for the next five to ten years. The management structure for applied research should be drastically simplified. The multiplicity of committees that are holding back NST research in the UK should be abolished, pruned or merged. Within the Research Councils, the role of the Senior Advisor for Nanotechnology should be re-thought. In the original (2005) proposal, the holder of this post was envisaged as having a leadership role. In practice, the function has been downgraded to one of advice, liaison, and external communication. This falls short of the executive function which is essential for national success.

3. Funding arrangements**.**

It is vital to improve the overall design of the funding system for key strategic projects. There is a need for a shared funding framework across the Research Councils and more broadly across Government. A long-term, inter-agency funding strategy is required for the development of any major new technology, and this need is particularly acute in the area of NST. However, this needs to be coupled with a rigorous stage-gating process, to ensure that only the best and most appropriate projects are allowed to continue to the next phase of development. Regular tough reviews are required, with the ability to "close" ineffective projects. The Panel suggests looking at international funding models such as the translation grant model, Korean model, DARPA and rolling grant systems. Whilst it would be inappropriate to directly translate overseas models to UK, some selectivity and commitment to a long term, “end-to-end” funding approach would be greatly valued by the community.

4. Role of the Research Councils

Within the UK, EPSRC has taken the lead in funding and determining research programmes in NST over the last five years. However, while EPSRC has taken the initiative in developing cross-Council research programmes, the participation of the other Research Councils has been hampered by the lack of a common funding framework. We believe that RCUK has the potential to lead in a Nano alliance allowing funding of cross-disciplinary research across sectors. This will require some structural engineering to redefine the position of RCUK. It is also clear that some form of connectivity should be established with potential UK and EU industries – pharma, energy companies, biotech and emerging green technologies. There is also a need for the Research Councils to monitor progress and priorities in this fast-moving field on an annual basis, not just every five years.

5. Identification of Future Priority Directions for Applied Research:

There is a pressing need for academia and business to unite to map out the potential economic impact of new technologies and their societal implications, using horizon scanning / road mapping methodologies. For example, NST might have the potential to take us beyond Moore’s Law, it could deliver a revolution in the way healthcare is undertaken, it may offer a huge potential impact on the energy sector and, through QIP, a transformational approach to security may arise.

Metrology and manufacturing are also possible areas that merit investigation. There is a lack of a coherent vision coming from government as to what technologies will be needed in the future. This combined with a lack of investment means the research community is not focussing its effort in areas of national need. The current approach of the RCUK programme in bringing a societal focus to their Grand Challenges goes only part way to mobilising sufficient research effort to deliver these objectives.

6. Grand Challenges:

The Panel strongly supports the Grand Challenge approach. The Challenges are clearly excellent in terms of strategy and reflect current international proactive programmes. However, increased connectivity needs to be put in place with BIS, cross-Council funding (particularly with MRC), other funding agencies and industry. Researchers involved in these programmes would benefit from increased networking opportunities to further mutual awareness of research endeavours. The panel felt that the Energy Challenge programme, had too narrow a focus on one type of technology (photovoltaics) and that a more productive strategy would have been to encourage increased diversification of approaches at the first stage. Liaison with other energy programmes e.g. Supergen, should be strengthened as this programme moves forward. The panel recognised that limitations in scope may be a reflection of limited funding and recommended that RCUK should seek to address this in any future Challenges. The Healthcare Challenge is also an excellent strategic area and has attracted some excellent projects. These could also benefit from more coordination e.g. The Challenges need to be able to attract a broad range of researchers rather than alienating communities through the ‘lead-Council’ approach. In this respect, it should be immediately obvious which Councils are contributing to the funding of RCUK Programme activities. Reflecting on the third Challenge, the Panel felt that NST for carbon capture made little sense as an approach for the UK. Moreover, one of the strengths in the UK is in catalysis development: an area that has attracted increased funding in recent times, and one likely to provide an immediate route through to exploitation. The Challenge programmes were clearly developed as a top down approach as a response to developing economic sustainability and quality of life for the UK over the next 20 yrs however these programmes should also take on board the input of researchers in terms of selection of thematic topics by engaging with the community.

7. Commercial exploitation and integration: Proof of concept funding
There is a need to develop a model that allows the engagement of industry and venturing sector with academic research. The issue needs to be addressed at government level as the success of Research Council endeavours to deliver impact through linking research with application depends on these links being put in place.
The Panel was struck by the apparent separation between academia and industry (business and venture capital) in the UK. Whilst recognising that this is not unique to NST, given the commercial potential of this emerging and disruptive technology, the Panel felt that particular emphasis should be given to this area. Linkages should take into account the differences between different types of sectors and products. The Panel noted that the effect of Nanotechnology on commercial products was often incremental but they felt this was where the quick wins may exist and that incremental advances are just as important as transformative ones.

8. Health and Safety of Nanomaterials;
The Research Councils should provide more support for this area. Health and safety Nanosciences are the most challenging and commercially critical area of NST research. Current funding is fragmented and (with the exception of ENI2) small scale and unlikely to create international impact. There needs to be an immediate and concerted effort to address public concerns about nanoparticle toxicity as a lack of progress here is hindering commercialisation activities. This uncertainty also represents a potentially very large hidden cost to industry and therefore acts as a barrier to the development of nano-enabled products. The Panel noted an apparent lack of skilled toxicologists to meet this task and would expect an element of capacity building to underpin any future activities. With these limitations addressed, we recommend that RCUK considers this as the next topic for a Grand Challenge, as there is considerable scope for basic research, for example on structure-property relationships, correlating physical, chemical and biological properties and linking environmental and medical toxicology. In short, having a concerted and well funded approach will be essential to make strides here, and the area is well suited to a cross Council activity. The community should be involved in the scoping of any Grand Challenge, particularly with respect to identifying novel methods. Schemes are needed to attract and nurture young researchers into this area.

5.2 Other Recommendations

The Panel agreed on a number of interventions of a less strategic nature that Research Councils and other stakeholders might consider pursuing.

9. Academic-business networking and communication
Vigorous efforts need to be made to improve communication within the NST research community itself, between the research community and the funding bodies, between the scientific and industrial sectors, and between innovators and investors. Appropriate dialogue needs to take place between business and academia at an early stage to ensure genuine industrial input into applied research projects to ensure they are addressing issues of commercial interest. The Panel recognised that these links are difficult for individual academics to form, so any assistance that Research Councils and other stakeholders can provide would be a step forward. The Panel suggested a number of ideas that would be straightforward and easy to implement:

- A central website for information and discussion about UK NST research

- A comprehensive directory of UK NST research facilities and activities
- Easier on-line access to key publications and patents (preferably free)
- Blogs for better and more frequent communication between individual researchers, and between researchers and industrial companies
- Networking events particularly for young scientists.
- Industry clubs, based on the BBSRC model
- Sandpit/funding scheme in this area
- Academic internships in companies
- One day workshops (like those organised by the Institute of Physics)
- More Industrial CASE awards.
- Encouragement for industrial staff to go into universities to give seminars
- Nano roadshows – showcasing research highlights to regional audiences.
- Grand Challenges networking meetings.
- Broader technical information meetings for the investment community
- Better links with science editors, journalists and broadcasters.

At present, no single person or organisation has overall responsibility for coordinating or leading such activities and so little progress is being made. A senior staff member within the Research Councils should be assigned this task, and given the appropriate support to enable it to be carried out successfully.

10. Seed-corn funding;
In the rapidly evolving world of NST there is a particular need for funding for short term feasibility projects. Whilst the Panel noted that there are existing mechanisms whereby the community can access such funds, these were not widely used; a particular example was the BBSRC process which could be extended to other Councils, for example by trialling this approach at EPSRC in Nano. Other considerations should be:

- Rolling (open) deadlines
- Agility of response
- Potential of 50:50 partnership (industry, academia and others).
- A trimmed-back, low bureaucracy review process
- Particular emphasis on supporting early-career researchers.

11. Support for interdisciplinary research, through cross-disciplinary panels
The Panel shared the strong concerns expressed members of the community that interdisciplinary grant applications in the area of NST suffered from being referred to single subject panels for evaluation. We recommend that the Research Councils should set up cross-disciplinary panels to assess such research proposals.

12. Reconsider the existing thematic analysis of NST research
The 11 themes used for analysing the existing NST programme are now of limited relevance – simplification and reclassification is required to reflect the integrated developments in NST over the last 10 yrs. Almost any "goal-oriented" nano project will require input from several of the existing themes in order to achieve success. For example modelling, design, fabrication, manufacturing and characterisation are all likely to be required to produce a single demonstration product. It is essential to ensure that the UK retains core capabilities in each of the thematic areas, but it is even more vital to be able to put together flexible teams of researchers to achieve major goals. A structure which over-emphasises individual thematic areas at the expense of integrative projects will almost certainly be counterproductive.

6. REFERENCES

1. *EPSRC Nanoscience Landscape Document (2009)*
http://www.epsrc.ac.uk/research/landscapes/Documents/LandscapeNano.pdf

2. *UK Nanotechnologies Strategy – Small technologies, great opportunities (2010)*
http://bis.gov.uk/assets/biscore/corporate/docs/n/10-825-nanotechnologies-strategy

3. *EPSRC Nanotechnology Theme Day (2005)*
http://www.rcuknano.org.uk/component/weblinks/8/2.html

4. *Report of the EPSRC Nanotechnology Town Meeting* (2006)
http://www.rcuknano.org.uk/component/weblinks/8/3.html

5. *EPSRC Nanotechnology Strategy (2006)*
http://www.rcuknano.org.uk/component/weblinks/8/4.html

6. *Statement by the UK Government about Nanotechnologies (2009)*
http://www.dius.gov.uk/~/media/publications/S/statement-nanotechnologies

7. *Nanoscience and Nanotechnologies: Opportunities and Uncertainties Royal Society/Royal Academy of Engineering (2004)*
http://www.royalsoc.ac.uk/document

8. *27th report: Novel Materials in the Environment: The Case of Nanotechnology* (2008)
http://www.rcep.org.uk/reports/27-novel%20materials/27-novelmaterials.htm

9. *Response to the Royal Society and Royal Academy of Engineering Report: Nanoscience and Nanotechnologies: Opportunities and Uncertainties*
http://www2.cst.gov.uk/cst/business/nanotech_final.pdf

10. *Characterising the Risks posed by Engineered Nanoparticles: A Progress Report, (2006)*
http://www.defra.gov.uk/environment/quality/nanotech/documents/nanoparticles-progressreport.pdf

11. *Characterising the Risks posed by Engineered Nanoparticles: A Second UK Government Research Report (2007)*
http://www.defra.gov.uk/environment/quality/nanotech/documents/nanoparticles-riskreport07.pdf5

12. *Report to the President and Congress on the third assessment of the National Nanotechnology Initiative (2010)*
http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-nano-report.pdf

Annex 1 Panel Membership and Terms of Reference

Professor George Smith, FRS, Oxford University (Chair)
* Professor Laurence Eaves, FRS, Nottingham University
Professor James Gimzewski, FRS, UCLA (USA)
Dr Victor Higgs, Applied Nanodetectors Ltd.
Professor Hanjo Lim, Alou University (Korea)
Dr Rob Potter, Johnson Matthey Technology Centre
Professor Arie Rip, University of Twente (Netherlands)
Dr Eugenia Valsami-Jones, Natural History Museum

The Terms of Reference for this review are that the Panel will:

1. Evaluate the Research Councils' portfolio in Nanotechnology, in terms of its quality and impact, since the previous review held in 2005.

2. Evaluate the influence of the Research Councils UK (RCUK) Programme in Nanotechnology.

* *One panel member, Professor Laurence Eaves, did not feel able to endorse the full recommendations as outlined in this report. In his view too much emphasis is placed on top-down management of NST research in the report and its recommendations. Prof. Eaves feels that history tells us that ground-breaking developments e.g. graphene, polymer electronics etc, have often emerged from the work of small university research groups, funded by modest responsive mode grants and that this recognition is not reflected in the report. Prof Eaves feels that there is currently insufficient evidence that Grand Challenges and Interdisciplinary Research Centres and Collaborations in NST have led to major research breakthroughs and he does not agree with the panel views in the report to this effect. He feels that the recommendations lack a strong statement in support of responsive mode funding; which needs particular nurturing in the present adverse economic environment where it is unreasonable to expect new large financial stimuli to support managed initiatives. He would also oppose the suggestion that the UK adopts a Korean-style model of funding NST, feeling such a model to be ill-suited to the UK research environment.*

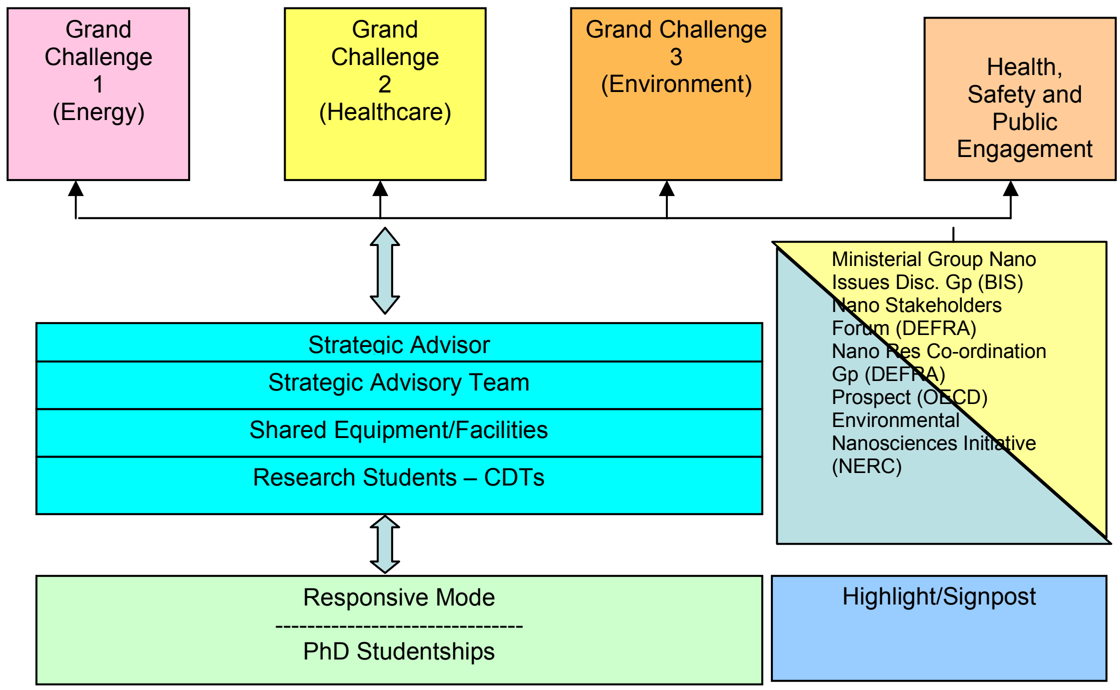
Annex 2 - Attendees at RCUK Nanoscience Theme Day

1	Professor	Jeremy	Baumberg	Cambridge
2	Professor	Jon	Binner	Loughborough
3	Professor	David	Birch	Strathclyde
4	Ms	Sharon	Burns	EPSRC
5	Mrs	Sue	Carter	EPSRC
6	Dr	Gabriel	Cavalli	Surrey
7	Dr	Paul	Christian	Manchester
8	Dr	Nigel	Clarke	Durham
9	Dr	Che	Connon	Reading
10	Dr	Adam	Corner	Cardiff
11	Professor	David	Cumming	Glasgow
12	Professor	Peter	Dobson	Oxford
13	Professor	Jon	Dobson	Keele
14	Professor	Ken	Donaldson	Edinburgh
15	Dr	John	Downer	LSE
16	Dr	Steve	Eichhorn	Manchester
17	Professor	Laurence	Eaves	Nottingham
18	Dr	Vassili	Fedotov	Southampton
19	Professor	Tamara	Galloway	Essex
20	Professor	Martin	Garnett	Nottingham
21	Professor	Henkjan	Gersen	Bristol
22	Professor	James	Gimzewski	UCLA
23	**Dr**	**Nicola**	**Goldberg**	**EPSRC**
24	Professor	Irina	Grigorieva	Manchester
25	Dr	Quanmin	Guo	Birmingham
26	Dr	Owen	Guy	Swansea
27	Mr	Andrew	Harris	EPSRC
28	Dr	Winfried	Hensinger	Sussex
29	Miss	Natasha	Hesson	EPSRC
30	Dr	Victor	Higgs	Applied NanoDetectors
31	Dr	Heinrich	Hoerber	Bristol
32	Professor	Peter	Houston	Sheffield
33	Dr	Helen	Hunt	EPSRC
34	Mr	Christian	Inglis	TSB
35	Dr	Doug	Imeson	DSTL
36	Miss	Rosie	Jackson	EPSRC
37	Professor	Richard	Jones	Sheffield
38	**Dr**	**Christopher**	**Jones**	**EPSRC**
39	Dr	Martin	Kemp	Nano KTN
40	Professor	Robert	Lee	Cardiff
41	Professor	Hanjo	Lim	Alou – Korea
42	Dr	Colin	Mackenzie	NERC
43	Dr	Phillip	Manning	Newcastle
44	Dr	Ian	Maclaren	Glasgow
45	Dr	Tracey	Melvin	Southampton
46	Professor	Richard	Palmer	Birmingham
47	Professor	Ivan	Parkin	UCL
48	Miss	Cassie	Philp	EPSRC
49	Dr	Rob	Potter	Johnson Matthey
50	Dr	Jonathan	Powell	MRC Human Nutrition Research
51	Professor	Arie	Rip	Twente
52	Dr	Katherine	Rooke	EPSRC
53	Professor	John	Ryan	Oxford

54	Professor	Mark	Sansom	Oxford
55	Professor	Paul	Sermon	Surrey
56	Dr	Sadhana	Sharma	BBSRC
57	Professor	Maurice	Skolnick	Sheffield
58	Professor	George	Smith	Oxford
59	Dr	Bob	Stevens	STFC
60	Professor	Geoff	Thornton	UCL
61	Mrs	Teresa	Tucker	ESRC
62	Dr	Eugenia	Valsami-Jones	Natural History Museum
63	Dr	Claire	Wagstaffe	EPSRC
64	Dr	John	Wand	EPSRC
65	Dr	Matthias	Wienroth	Durham
66	Dr	James	Windmill	Strathclyde

Bold = EPSRC theme day leads

Annex 3 – The RCUK Approach to Supporting Nanoscience



Annex 4 – Nanotechnology Theme Descriptions

Enabling Science and Technology

1. Nanofabrication

Methods for making materials, devices and structures with dimensions less than 100 nm.

Keywords: nanomanipulator, 'bottom up assembly', 'top down assembly', nanolithography, nanopatterning, optical tweezers, FIB, nanoimprint, evaporation, plasma CVD, sputtering, oxidation, MBE, nanotube growth, molecular vapor deposition, ion mill, reactive ion etching, plasma etching, deep reactive ion etching, hot embossing, self assembly, electrophoresis.

2. Nanocharacterisation and Nanometrology

Techniques for characterisation, measurement and process control for dimensions less than 100 nm.

Keywords: nanoprobes, nanoscale microscopy, atomic-force microscopy, nano with measurement.

3. Nanomodelling

Theoretical and numerical techniques for predicting and understanding the behaviour of systems and processes with dimensions less than 100 nm.

Keywords: Nano with: model, simulation, mathematical.

4. Fundamental Properties of Nanomaterials

Size-dependent properties of materials that become evident at dimensions of 100 nm or below.

Keywords: carbon nanotubes, nanopowders, nanoparticles, nanoclusters, nanocatalysis, nanofibers, nanocapsules, nanocomposites, nanofilms, nanowires, nanowhiskers, nanomesas, nanocrystals, ultra-thin films, Langmuir-blodgett films, nanocoating.

5. Extreme and Molecular Nanotechnology

Novel functional devices, systems and machines that operate at, and are addressable at, the level of a single molecule, a single atom, or a single electron and the application of synthetic chemistry at the nano level.

Keywords: quantum information, qubit, quantum transport, molecular materials, molecular sensing, molecular recognition, nano* with synthesis, nanomanipulation, quantum control, quantum coherence.

Devices, systems and machines

6. Bionanotechnology

The use of Nanotechnology to study biological processes at the nanoscale, and the incorporation of nanoscale systems and devices of biological origin in synthetic structures.

Keywords: Nano with: biomimetics, biopolymers, molecular probes, gene therapy, replacement structures, artificial cells, synthetic cells, biomineralisation, biostructures, molecular templates, biopolymers, bioceramics, biosensors, tracers, bio-imaging/

7. Nanomedicine

The use of nanotechnology for clinical diagnosis and treatment

Keywords: Nano with: therapeutics, diagnostics, drug delivery, drug vectorisation, tissue engineering, tissue replacement, regenerative medicine, medical sensors.

8. Functional Nanotechnology Devices and Machines

Nanoscale materials, systems and devices designed to carry out optical, electronic, mechanical and magnetic functions.

Keywords: protein motor, plasmon, NEMS, molecular machines

Nano with: electromechanical, mechanical, electronic, magnet, photonic, actuator, spintronics, spray, filtration, fluidics

Nanotechnology, the economy and society

9. Nanomanufacturing

Issues associated with the commercial-scale production of nanomaterials, and nanodevices.

Keywords: same as nanofabrication but combined with 'manufacturing'

10. Nanodesign

The interaction between individuals and society with Nanotechnology. The design of products based on Nanotechnology that meet human needs.

Keywords: Nano with: purpose, function, aesthetic,

11. Nanotoxicology and the Environment

Distinctive toxicological properties of nanoscale materials; the behaviour of nanoscale materials, structures and devices in the environment.

Keywords: Nano with: toxicology, dosimetry, exposure, testing protocols, immune system, pathways, inhalation, ingestion, dermal exposure, adsorption.

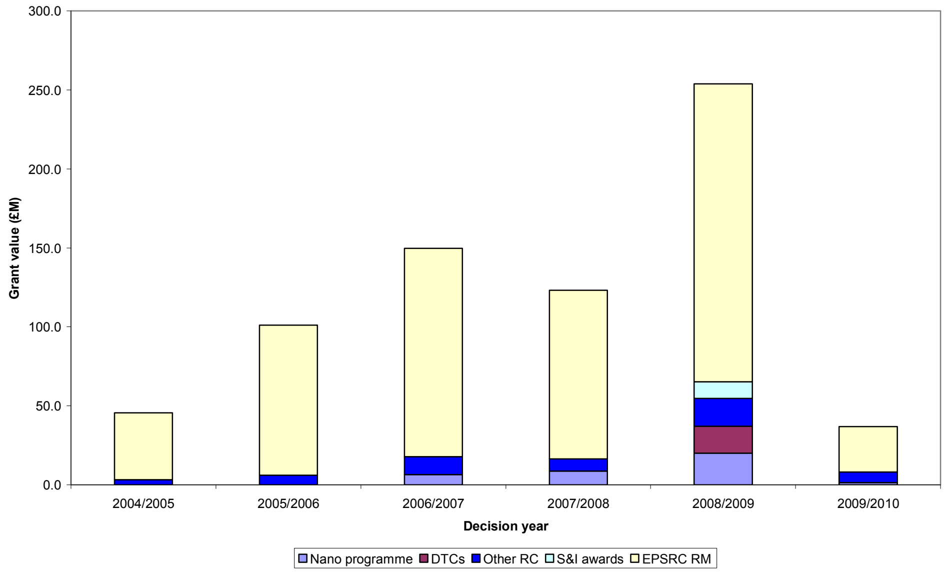
Annex 5 – Detailed analysis of themes

5.1 Introduction

These graphs and tables have been produced by combining the data available on grants and studentships funded by EPSRC, BBSRC, MRC and NERC relevant to the 10 major Nanotechnology themes (There is currently little funded activity in the Nanodesign theme). Data was not provided by STFC. Collaborative grants with the Technology Strategy Board are included in the theme analyses. All these figures are quoted as year of commitment not by spend year.

5.2 Research Grant Funding

Figure 1 Overall research grant commitment by decision year broken down into funding type/origin. Please note 2009/2010 data is for an incomplete financial year.



Nano programme = RCUK Nanoscience through engineering to application programme
CDTs = Centres for Doctoral Training
Other RC = Funding from Research Councils other than EPSRC
S&I awards = Science and Innovation awards
EPSRC RM = EPSRC Responsive Mode

Figure 2 Research grant commitment by decision year for 5 of the themes

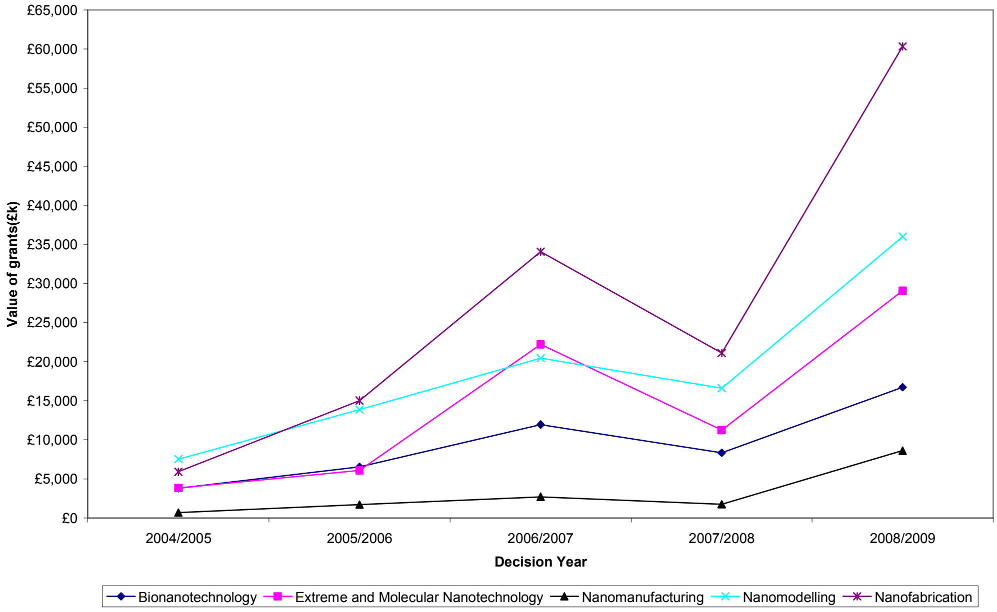
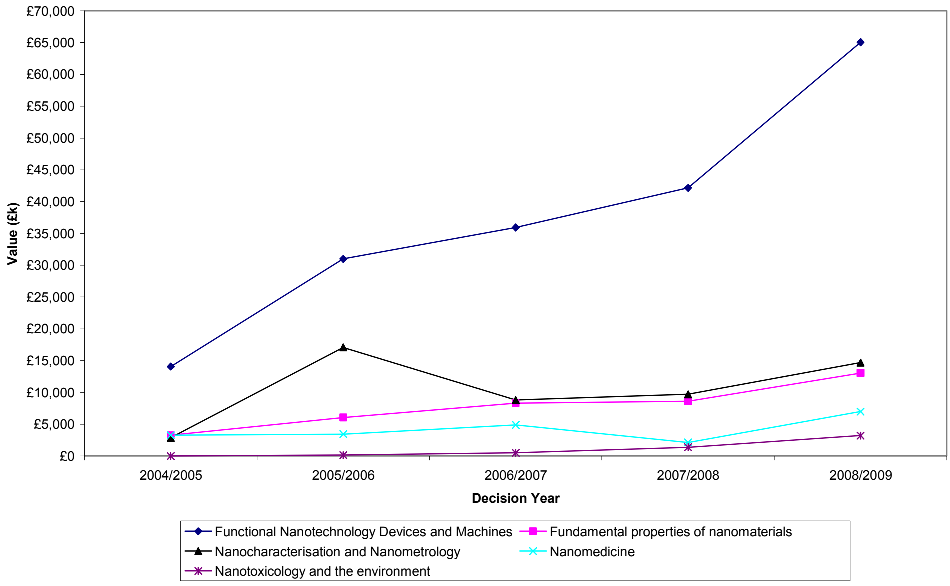


Figure 3 Research grant commitment by decision year for 5 of the themes



5.3 Studentships

Figure 4 Studentships funded by decision year for 5 of the themes

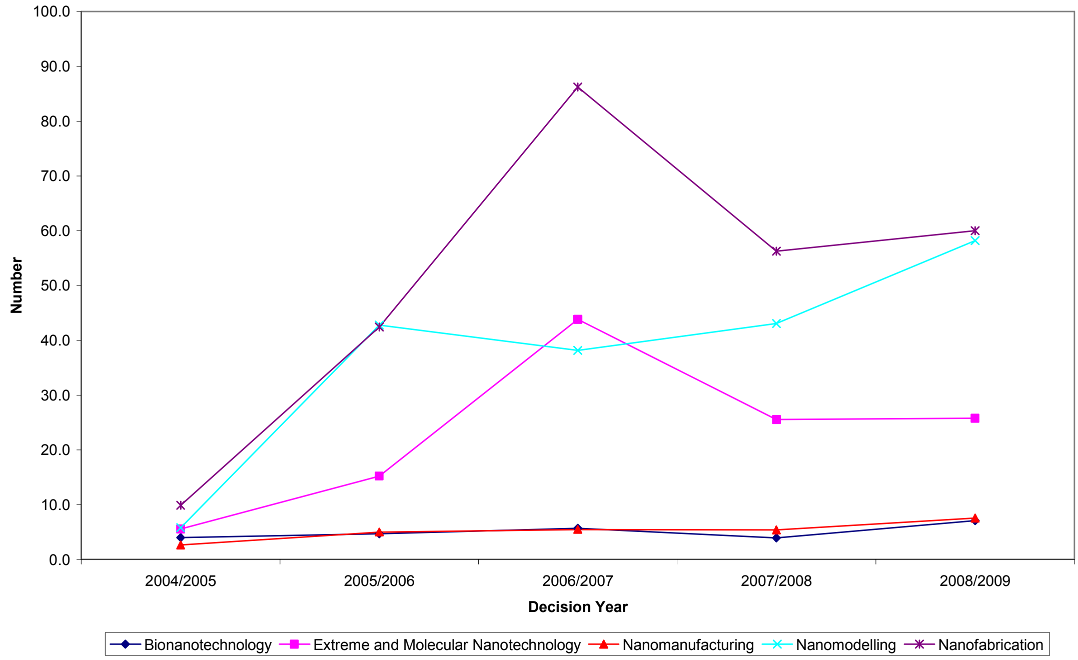
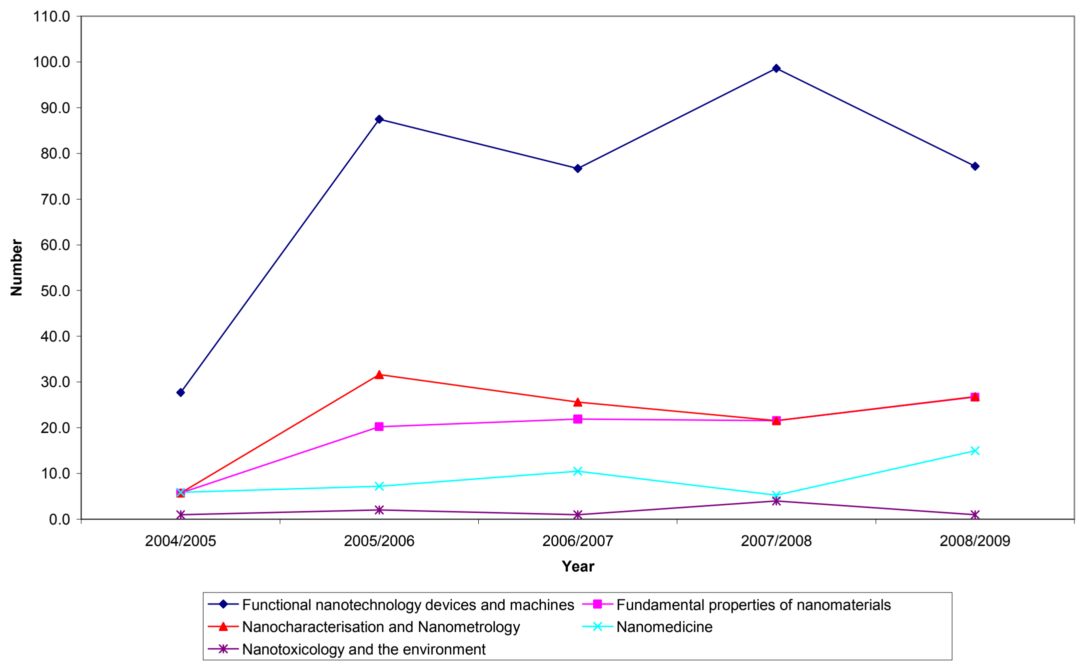


Figure 5 Studentships funded by decision year for 5 of the themes



In addition to the above themes 3 grants totalling £355,879 and 2 studentships have been funded by ESRC on the economic and social aspects of Nanotechnology:

Investigator	Institution	Grant Title	Decision Year
Dr AG Anderson	Plymouth	Nanotechnology and News Production: Scientists', Journalists', and Editors' Views	2004
Prof P Macnaghten	Lancaster	Nanotechnology, Risk and Sustainability: Moving Public Engagement Upstream	2004
Ms M Ebling	Surrey	Spinning science: The nanotech industry and financial news	2005
Mr D Thmopoulos	LSE	Nanotechnology as a quasi-social movement	2005
Ms HF Lee	Manchester	Innovation in Nanotechnology	2006

5.4 Top Institutions

Figure 6 Overall Top 5 institutions for 2005 and 2009, in terms of Research Council funding

2005 Institution	2005 Value	2009 Institution	2009 Value
Cambridge	11,798,004	Imperial	54,683,323
Imperial	10,104,584	Cambridge	46,478,959
Manchester	8,010,413	Oxford	34,702,578
Sheffield	7,601,080	UCL	24,422,685
Glasgow	6,624,015	Surrey	15,855,185
Total	44,138,096	Total	176,142,731

5.5 Journal Publications

Numbers of Journal publications resulting from EPSRC nanotechnology grants by theme and by year

2004/2005		
NanoTheme	**Total No of Journal Publications**	**Average No of Journal Publications per grant equivalent**
Nanofabrication	353.4	7.2
Nanocharacterisation and Nanometrology	52.0	1.3
Nanomodelling	61.7	1.5
Fundamental Properties of Nanomaterials	104.0	2.5
Extreme and Molecular Nanotechnology	39.0	1.9
Bionanotechnology	10.3	1.7
Nanomedicine	4.2	0.6
Functional Nanotechnology Devices and Machines	623.4	5.6
Nanomanufacturing	2.3	2.3

2005/2006

NanoTheme	Total No of Journal Publications	Average No of Journal Publications per grant equivalent
Nanofabrication	142.5	3.2
Nanocharacterisation and Nanometrology	78.6	1.5
Nanomodelling	111.3	2.3
Fundamental Properties of Nanomaterials	28.8	0.9
Extreme and Molecular Nanotechnology	375.1	10.7
Bionanotechnology	43.5	6.2
Nanomedicine	2.0	0.4
Functional Nanotechnology Devices and Machines	323.3	4.3
Nanomanufacturing	8.0	2.0

2006/2007

NanoTheme	Total No of Journal Publications	Average No of Journal Publications per grant equivalent
Nanofabrication	175.8	3.1
Nanocharacterisation and Nanometrology	38.0	1.7
Nanomodelling	120.0	3.4
Fundamental Properties of Nanomaterials	83.6	1.7
Extreme and Molecular Nanotechnology	131.6	5.1
Bionanotechnology	4.6	0.4
Nanomedicine	12.3	3.1
Functional Nanotechnology Devices and Machines	356.5	3.8

2007/2008

NanoTheme	Total No of Journal Publications	Average No of Journal Publications per grant equivalent
Nanofabrication	84.1	1.9
Nanocharacterisation and Nanometrology	45.3	2.4
Nanomodelling	133.1	4.6
Fundamental Properties of Nanomaterials	137.0	3.7
Extreme and Molecular Nanotechnology	119.4	2.5
Bionanotechnology	12.2	1.1
Nanomedicine	19.7	2.2
Functional Nanotechnology Devices and Machines	220.9	5.7
Nanomanufacturing	1.6	0.4

2008/2009

NanoTheme	Total No of Journal Publications	Average No of Journal Publications per grant equivalent
Nanofabrication	130.8	2.4
Nanocharacterisation and Nanometrology	64.8	2.6
Nanomodelling	124.7	3.0
Fundamental Properties of Nanomaterials	43.3	1.9
Extreme and Molecular Nanotechnology	83.8	2.9
Bionanotechnology	0.5	0.2
Nanomedicine	13.6	2.7
Functional Nanotechnology Devices and Machines	274.0	7.7
Nanomanufacturing	7.8	2.6

5.6 Bibliometric Summary

The bibliometric study was carried out using the Essential Science Indicators tools in the Thomson ISI Web of Knowledge. The search used the keywords for each of the themes and papers cited within the 12 years 1995-2008 were included in the study.

Since citation rates vary by field and older papers are cited more than recent papers, the selection procedure for highly cited papers takes these factors into account. The first step is to count the number of papers cited at different levels of citation and construct distributions for each field and year. These distributions are then used to set selection thresholds by taking the same fraction of papers for each field/year.

Figure 7 Numbers of papers published by country (1995-2008)

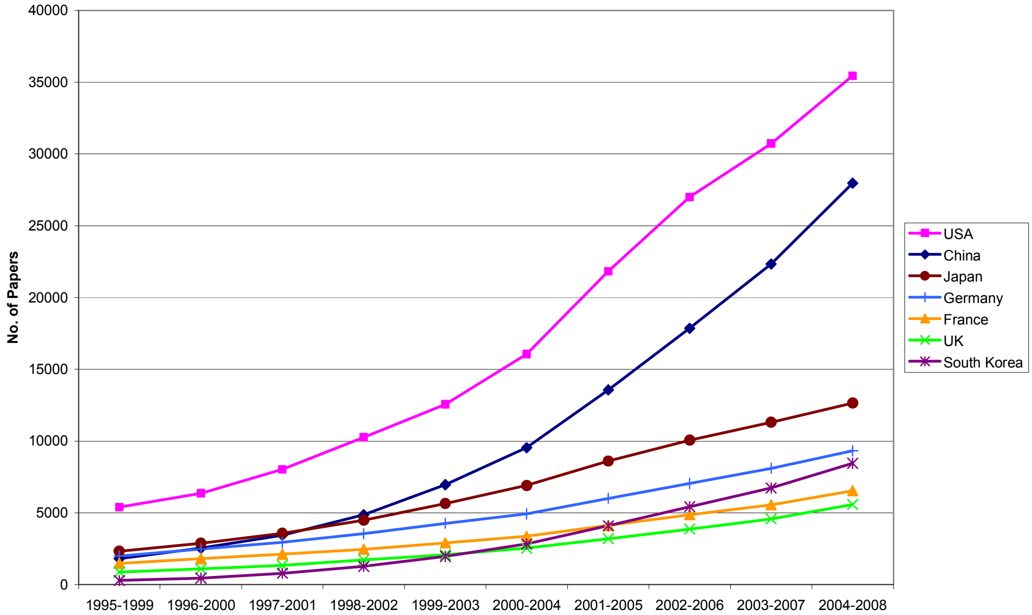


Figure 8 % of world papers published by country (1995-2008)

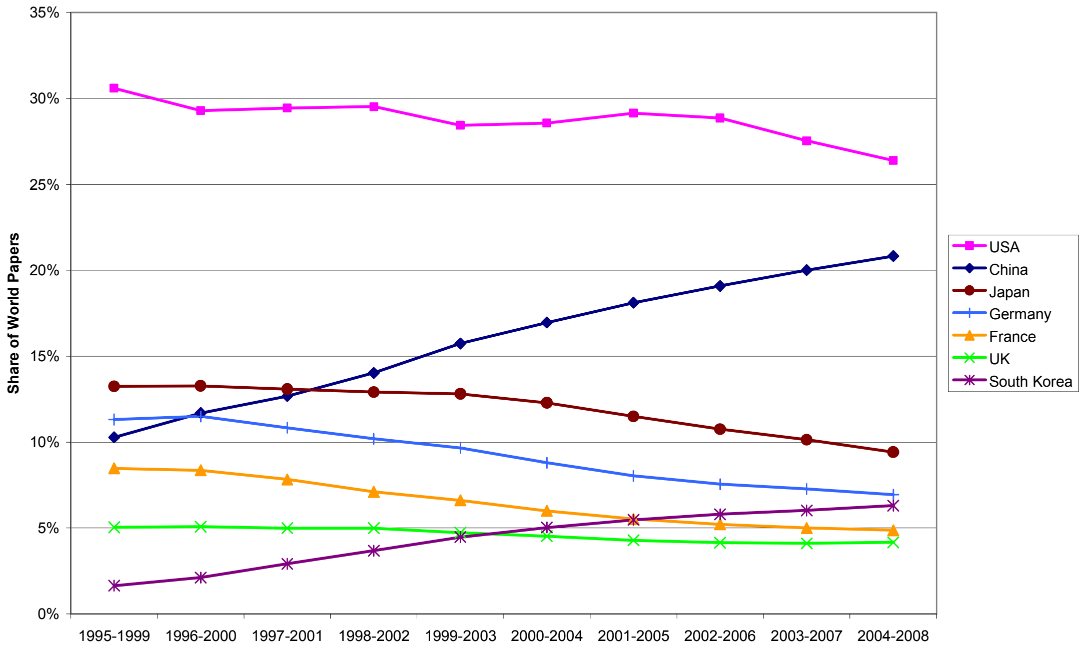


Figure 9 Number of citations received by country

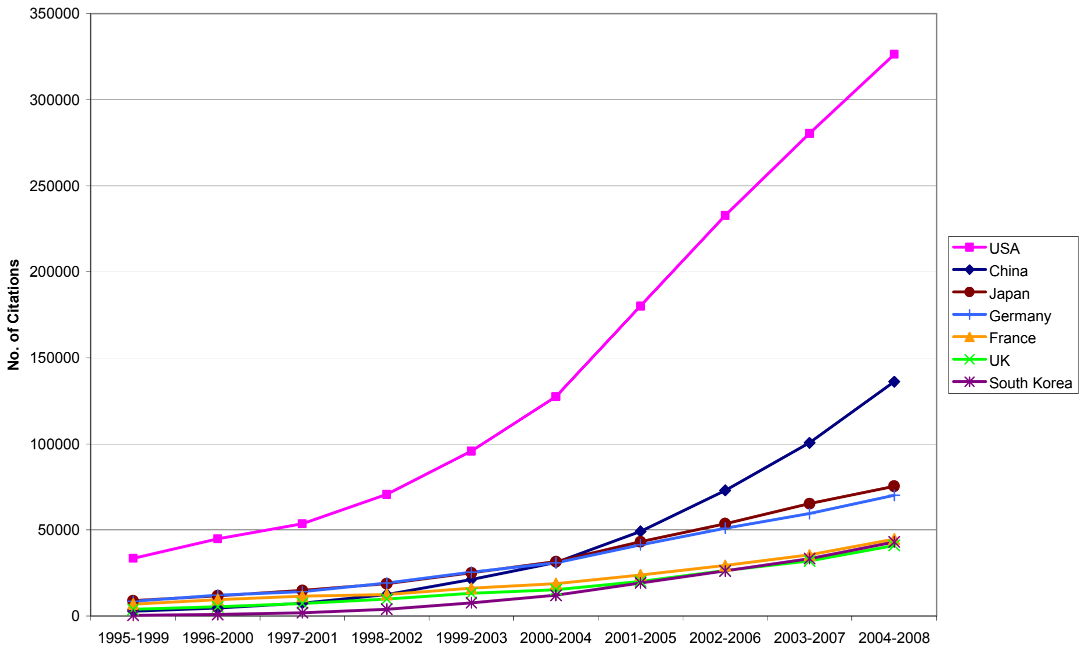


Figure 10 % of world citations received by country (1995-2008)

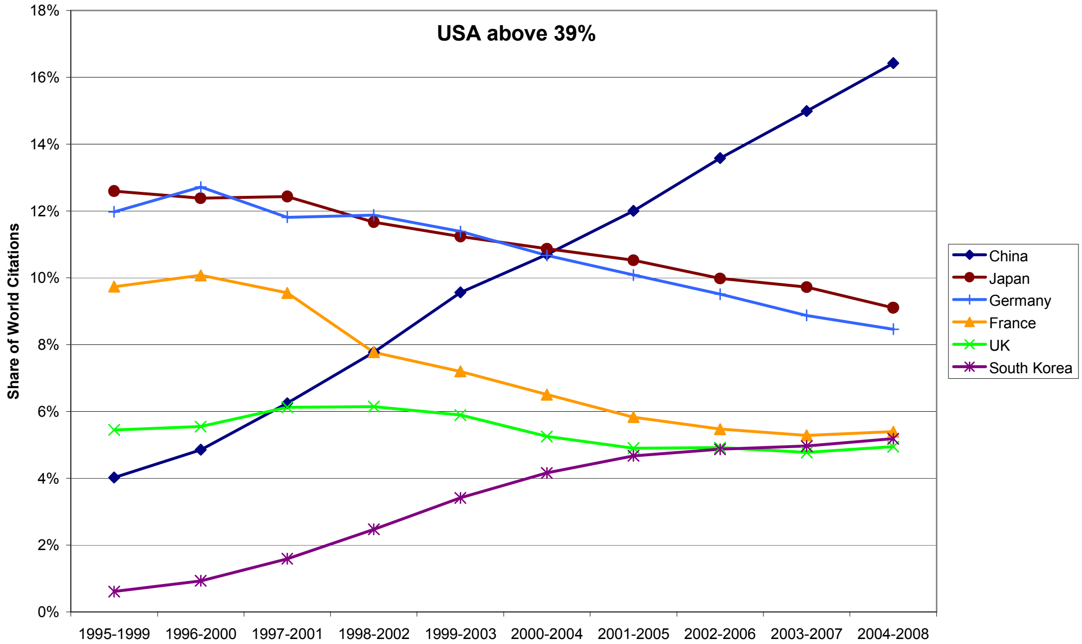


Figure 11 Summary of bibliometric data

Nanotechnology Theme	World Total No. citations	UK Total No. citations	UK Rank on Total Cites	World Cites/Paper	UK Cites/Paper	World Highly Cited Papers	UK Highly Cited Papers
Nanofabrication	558,148	33,093	6	11.97	14.65	112	5
Nanocharacterisation	142,088	9,055	5	10.19	11.68	12	1
Nanomodelling	576,809	40,026	5	10.94	13.04	87	3
Nanomaterials	1,810,618	92,169	6	12.30	14.93	2247	113
Extreme and molecular	236,569	14,815	6	17.80	18.78	6	0
Bionanotechnology	115,771	6,950	5	17.05	18.99	38	0
Nanomedicine	118,425	10,224	3	13.65	21.21	58	6
Functional	1,119,429	80,817	4	14.37	17.32	320	16
Nanomanufacturing	8,583	590	2	18.26	14.75	0	0
Nanodesign	259,182	18,380	4	11.97	15.10	16	0
Nanotoxicology	91,322	6337	3	13.53	13.75	19	4
Total	5,036,944	312,456	5?	12.72	15.39	2,915	148

5.7 Other research outputs and technology transfer

Figure 12 Numbers of patents resulting from EPSRC Nanotechnology grants 2004-2009 by theme

Theme	Number of Patents
Nanofabrication	7
Nanocharacterisation and nanometrology	5
Nanomodelling	7
Fundamental properties of nanomaterials	2
Extreme and molecular Nanotechnology	5
Bionanotechnology	0
Nanomedicine	2
Functional Nanotechnology devices and machines	20
Nanomanufacturing	1
Total	49

Figure 13 Numbers of spin-out companies resulting from EPSRC Nanotechnology grants 2004-2009 by theme (fractions indicate that the spin-out was relevant to more than one theme)

Theme	Number of Spin outs
Nanofabrication	1.5
Nanocharacterisation and nanometrology	2
Nanomodelling	2
Fundamental properties of nanomaterials	0.5
Extreme and molecular Nanotechnology	0
Bionanotechnology	0
Nanomedicine	1.5
Functional Nanotechnology devices and machines	6
Nanomanufacturing	0.5
Total	14

Annex 6 - Centres for Doctoral Training

Cambridge NanoScience through Engineering to Application DTC: Assembly of Functional NanoMaterials and NanoDevices

Prof J J Baumberg Cambridge £6,146,052 EP/G037221/1

The Nano DTC will operate as a distinct PhD nursery, with the entry co-housed and jointly mentored in the initial year of formal courses and project work. Students from a range of undergraduate disciplines will thus spend considerable time together while each postgraduate will have a selection of 1st year courses crafted on entry by the DTC management committee, depending on their specific skill set and aspirations. The initial year provides additional skills in disciplines outside their degree, understanding of the Enterprise landscape relating to Nano-Innovation, specific knowledge of the nanoscience and application of self-assembly to NanoDevices and NanoMaterials, and miniprojects spanning different disciplines to broaden students' experience and peer networks, aiding final PhD project selection. A range of joint activities are programmed in later years including Nano DTC cohort student-led conferences, and industry reviews.

Doctoral Training Centre in Functional Nanomaterials

Dr T J McMaster Bristol £6,416,963 EP/G036780/1

The Bristol Functional Nanomaterials (BFN) DTC will pioneer an integrated and sustainable doctoral programme consisting of 50 postgraduates who will be housed as a unified cohort in dedicated and bespoke space within a new purpose-built facility: the Bristol Centre for Nanoscience and Quantum Information (NSQI), representing an £11M infrastructure commitment by the University of Bristol, and opening in Autumn 2008. The established interdisciplinary network of academics, supported by ongoing University investment, will make BFN a vibrant world-class training environment.
The high-calibre and motivated postgraduates recruited to BFN will be educated initially through a 1-year taught and practical programme in the principles and practice of nanomaterials science and engineering, with a strong emphasis on interdisciplinary approaches, applications, and associated societal issues. They will participate in novel and ground-breaking Exploratory Training Assignments, an Extended Project, and a PhD project that connect basic research in the bottom-up fabrication of nanomaterials to the manufacture and application of these materials as novel products and functional components. Novel training protocols will instil the highest level of scientific and technical competence, whilst maintaining a breadth of vision and commitment to interdisciplinarity, and a focus towards the promotion of nanomaterials into real-life uses. Specifically we will develop an innovatory online training resource, the Nanomaterials Science Dynamic Laboratory Manual (NS-DLM), a new benchmark for doctoral training in this field, and the Personal Development Passport, to ensure true interdisciplinarity and encourage a culture of self-guided decision-making and peer-learning.

NOWNANO DTC: A North-West Nanoscience Doctoral Training Centre

Dr I V Grigorieva Manchester £4,441,648 EP/G03737X/1

The NOWNANO-DTC will train students in a multidisciplinary centre, concentrating on the broad fundamentals of nanoscience and technology prior to the choice of a cross-disciplinary PhD project focussing on the scientific and technological advances required and covering two major research directions:

A. From nanoscience through electronics to information technology:
The students will acquire expertise in fabrication, measurement and theoretical understanding of matter at the nanoscale. In particular, they will learn nanofabrication techniques, as well as new soft matter approaches, and develop hybrid structures based on combinations of traditional and new materials such as graphene, nanoparticles and molecular systems. These will be complemented by development of theoretical models which will then be used to describe the physics of carrier dynamics and other properties of nano-scale devices, e.g., devices operating at THz frequencies, opto-electronic and spintronic devices, hardware for quantum information processing and many others.

B. Nanoscience in medicine: the potential to transform medicine to become more individualised and hence safer lies behind the use of nanotechnology.
Physical nanoscience could provide bioresponsiveness, higher detection capabilities, connectivity to advances in the digital world and can address security issues (counterfeiting, privacy). Specifically, our students will work to produce individualised and safer medicines: predominantly in the perspective of the diagnosis and treatment of (auto) inflammatory diseases and solid tumours, nano-structured materials will allow biologically triggered release of drugs and/or accurate mapping of biological variables e.g. combining single molecule analysis with fluidodynamics of tissues, encompassing also toxicology and the impact of nanomaterials on public health.

Annex 7 – Grand Challenges

7.1 - Grand Challenge 1 projects: Nanotechnology for Energy

Self-organized nanostructures and transparent conducting electrodes for low-cost, scalable organic photovoltaic devices

Dr SA Haque	Imperial College	£1,143,247.59	EP/F056710/1
Dr MS Hill	Univ of Bath	£309,352.03	EP/F056494/1
Dr N S-Stutzmann	QMUL	£352,216.87	EP/F056648/1

Collaborators: Pilkington Technology, Merck Speciality Chemicals Ltd

This project focusses on two issues that are widely recognized as being key for the development of low-cost efficient and stable photovoltaic devices: (i) the development of low cost alternatives to indium tin oxide (ITO) as the transparent conducting electrode and (ii) control of nanomorphology of the donor-acceptor interface. This project will involve the design and synthesis of new electrode materials and the use of molecular self-organization strategies to control the donor-acceptor film morphology at the nanometre length scale to deliver high efficiency organic solar cell that are capable of being scaled up cost effectively. This project will also lead to an improved fundamental understanding of device function. This multidisciplinary project brings together chemists, physicists, materials scientists and engineers with world-leading expertise in metal oxide electrode design, polymer synthesis and manufacturing. This project also involves collaboration with Pilkington Glass, Merck Chemicals and BP Solar.

Engineered Hierarchical Nanostructures for Optimised Hybrid Photovoltaic Devices

Dr M Ryan	Imperial College	£604,197.94	EP/F056362/1
Prof TS Jones	Univ of Warwick	£376,571.60	EP/F056184/1

In this Grand Challenge we intend to develop novel hybrid-cells consisting of cheap inorganic electron transport matrices and readily manufactured organic molecules that both absorb light and transport holes. The efficiency of the cells will be maximized by engineering the interface between the materials on the nanoscale. A key consideration throughout our development of hybrid-cells will be the minimization of scale-up and production costs. The route we propose is based on sequential solution processing of each component of the solar cell; low temperature and pressure; minimal waste and low tech. The approach is inherently scalable and readily integrated into current manufacturing practises including roll-to-roll technology. Our Grand Challenge is to develop inorganic-organic-hybrid-photovoltaic cells which through interface engineering at the nanoscale are significantly more cost effective than currently available devices.

The programme will be a joint venture between the London Centre for Nanotechnology at Imperial College London and Warwick University. Collaborations are in place with Colleagues from the McDairmid Institute for Advanced Materials and Nanotechnology in NZ (specifically in the area of modelling of deposition processes) and with Kodak, UK (with links to scale-up activity). The project team are uniquely placed to capitalise on recent developments in the processing of nanostructured inorganics and in organic semiconductor small molecules; and brings together the range of complementary techniques required for such an interdisciplinary programme.

Manufacturable nanoscale architectures for heterojunction solar cells

Prof Sir R Friend	Univ of Cambridge	£1,265,800.52	EP/F056702/1

This project will produce manufacturable nanoscale architectures for heterojunction solar cells. Though routed strongly within 'science', the objectives are to achieve engineering solutions to allow the breakthrough needed in this field (target efficiency 10%). We propose therefore to develop generic routes to separate the control of the nanoscale morphology from the selection of the donor and acceptor semiconductors. This will represent a critical advance in allowing a stable process window, and should allow improved photovoltaic performance through better morphology control and the ability to use semiconductors better matched to the solar spectrum. These routes will be compatible with low temperature processing (this is critical for low-cost manufacturing). The general principle we will use is to separate the processes needed to form the desired nanoscale architecture from the subsequent formation of the active semiconductor-semiconductor heterojunctions at which charge separation is achieved.Central to our approach is the use of 'sacrificial' polymer structures that provide excellent control of nanoscale morphology, and their later replacement with active semiconductors. We will use the controlled nanoscale structures produced using di-block copolymers

High-efficiency Block Copolymer Solar Cells: A Scaleable Prototype for Low Cost Energy Generation

Prof ML Turner	Univ of Manchester	£475,809.34	EP/F056397/1
Dr N Clarke	Durham Univ	£167,349.70	EP/F056303/1
Prof A Ryan	Univ of Sheffield	£427,841.03	EP/F056370/1
Dr J Nelson	Imperial College	£364,241.94	EP/F056389/1

This proposal assembles a consortium of chemists, physicists and materials scientists from Imperial College London and the universities of Manchester, Sheffield and Durham to produce new prototype polymer solar cells that have high power conversion efficiencies and could be mass produced cost effectively. We propose new polymer solar cell designs that integrate flexibility with inexpensive materials and solution based processing. In one approach, block copolymers are used to direct formation of nanostructured thin films to provide high efficiency polymer solar cells. In a second approach, block copolymers will be used to direct crystallisation within nanostructured films. Independent optimisation of the optical and electronic properties, together with theoretical modelling input, will provide design rules for maximising power conversion efficiency. The project will establish strategies for scaling up the device designs which have the highest efficiencies. Our objective is to construct affordable and scalable polymer solar cells that have an energy conversion efficiency of at least 7%.

Nanocrystalline Photochemical Diodes: Novel Devices for Water Splitting

Prof A Mills	Univ of Strathclyde	£502,142.88	EP/F056230/1
Prof IP Parkin	Univ Coll London	£458,474.14	EP/F056168/1

Collaborators: Johnson Matthey plc Technology Centre, Millenium Inorganic Chemicals, Nanotecture Ltd

In this programme, novel, inorganic water-splitting systems, called macro-photocatalytic diode cells, MPCDs, utilising a range of new and established visible-light absorbing photocatalyst materials, will be developed for splitting water using sunlight in separate compartments. The latter feature is important as it will minimise, if not eliminate, the various efficiency-lowering recombination reactions associated with mixed product generation. The work programme involves a number of novel aspects including: the preparation of new nanoparticulate, crystalline photocatalyst materials, fabricating them into different novel photodiode formats and the synthesis and utilisation of new redox catalysts. The use of nanoparticulate semiconductor photocatalysts, made via continuous hydrothermal flow synthesis, CHFS, in conjunction with gel casting for robust porous supports, is a particularly important and novel advance, as too is the proposed combinatorial approach to the preparation of photocatalyst films by CVD. The project will develop a significant amount of the underpinning science required for the fabrication of the final, optimised, efficient MPCDs and include a study of the underlying reaction mechanisms, using time-resolved transient absorption spectroscopy. The proposal offers a route to achieving a step change in efficiency for energy capture from the sun and aims to deliver efficient, scalable demonstrators of the MPCD technology, suitable for development into pilot plant systems in the second phase of funding.

7.2 - Grand Challenge 2 projects: Nanotechnology for Healthcare

Point of Care nanotechnology for early blood clot detection and characterisation in disease screening, theranostic and self monitoring applications.

Professor P Williams	Swansea	£923,647	EP/G061882/1
Professor K Kostarelos	Sch of Pharmacy	£630,210	EP/G061998/1

Collaborators: Abertawe Bro Morgannwg NHS Trust, Boots Centre for Innovation

This project will exploit our recent advances in blood clot detection and ultra-sensitive nanomaterials development for device applications to overcome these shortcomings. Our Grand Challenge proposal involves combining this nanotechnology with our haemorheological work to develop the first point of care (POC) device capable of the early detection and characterisation of abnormal clots. By a "point of care" device we refer to technology suitable for widespread use outside hospitals (i.e., within pharmacies and surgeries) and which will ultimately be developed for use by patients at home. This will exploit the piezoelectric properties of ZnO nanowire arrays as a transducer to detect shear wave propagation within coagulating blood. Our aim is to drastically improve the sensitivity of early clot detection for more accurate assessments of (i) coagulation abnormalities and (ii) therapeutic targeting of abnormal clots at the earliest stage of development.

The project involves in vivo and in vitro disease model (Stroke) work at University of London, and work intended to enable our device to perform a therapeutic function. In this way we propose to lay the foundations for a POC system for Patient Self Assessment and Patient Self Management in anticoagulant applications, in addition to a new technological basis for thromboembolic disease screening. The project also includes anticoagulated Stroke patient volunteers at Morriston NHS Hospital.

We have two partners. The first is the NHS who will provide clinical facilities and governance of clinical research. Our second partner is Boots Centre for Innovation (BCI) whose involvement anticipates healthcare provision involving POC applications in next-generation pharmacies. BCI's role is to inform design relating to customer needs/experience, the POC market and environment.

Bio-functional Magnetic Nano-particles: Novel High Efficiency Targeted Agents for Localised Treatments of Metastatic Cancers.

Professor Q Pankhurst UCL £1,561,415 EP/G062072/1

There is a pressing need for viable alternatives, and clinicians and scientists have been pursuing such goals for decades. Although there have been successes, for the most part it has been impossible to deliver therapeutic agents to the sites of metastases in sufficiently high doses. Attention has turned to 'payload' methods, where the targeting biomolecule is used to carry a therapeutic agent to the cancer, and some external stimulus is applied to activate it. The best of these are based on the use of inorganic nanoparticles which, under stimulation, are designed to release heat. These hyperthermia approaches are ideally suited to cancers, which are highly susceptible to heat-induced cellular stress. Hyperthermia also has great potential as an adjuvant therapy, since just a degree or two of local heating can significantly increase the effectiveness of chemotherapy and radiotherapy, reducing their required doses and thereby reducing the harmful side-effects.

Even so, to date there has been little real success in attempts to implement localised hyperthermia, despite promising bench results. The key failure lies in the required dose-response characteristics of the therapy, which exceed the capabilities of the best approaches attempted so far. One approach, volumetric induction heating of magnetic nanoparticles using megahertz applied fields, is intrinsically efficient. However, even here efforts are hampered by a reliance on 30-year-old induction heating electronics - more befitting an arc-welding workshop than a hospital clinic - so that only one clinical trial has yet been attempted.

It is therefore no wonder that our announcement earlier this year of a new breakthrough invention - an induction heating circuit we call the Magnetic Alternating Current Hyperthermia (MACH) system - was greeted with enormous media attention. The MACH system embodies three ground-breaking innovations which together enable, for the first time, construction of an extremely high performance, robust system that can feasibly be used in the clinic. Of particular note, it allows for a hand-held coil to be attached to the heater, and for miniaturisation or even catheterisation of the applicator. The prospects are suddenly wide open for real clinical application of hyperthermia to treat metastatic cancer, and for widespread exploitation of this UK-owned technology in an exceptionally large market.

To translate this promise into achievement requires significant efforts, and most importantly, well-focused efforts. To this end we have consulted widely and brought together an excellent team of academics, clinicians and companies, from start-ups to conglomerates, to work together on an implementation plan. Key to this plan is to move as fast as possible to clinical outcomes, to engage quickly with patients, clinicians and health services to establish efficacy and credibility, and to build a platform for innovation for years to come. We have chosen to adopt a dual approach of (1) proving the clinical efficacy of the MACH system for localised hyperthermia on two especially well suited cancer exemplars - head and neck cancer and lung cancer; and (2) developing 'stealth' antibody-tagged magnetic nanoparticles suitable for intravenous injection, and able to evade the reticulo-endothelial system and accumulate at metastatic sites. These then are the goals of our Nanotechnology Grand Challenge.

Detecting infectious organisms: A concerted approach using genomics, molecular engineering and nano-enabled bio-MEMS technologies (AptaMEMS-ID)

Professor C McNeil   Newcastle   £1,818,779   EP/G061394/1

This project, which lies at the heart of the confluence of nano-, bio-, micro- and genomic technologies, proposes to use nano-enabled biological sensor technology for the development of a point-of-care system for the rapid detection of infectious organisms. The proposal is based around the clinical and societal need for rapid detection of specific nosocomal infections for screening, diagnostic and epidemiological uses and involves a combination of technologies encompassing; comparative genomics, novel bioinformatics, confirmatory proteomics, molecular engineered peptide aptamer ligands and microelectromechanical (MEMS) sensor technologies which exploit effectively at the nano-scale: design, manufacture, functionalization and molecular patterning.

The ability of Newcastle University researchers to use e-Science Grid-based workflows to exploit data from microbial genome sequences is at the heart of this proposal. This technology will be used for the characterisation of proteins displayed at bacterial cell surfaces (SAPs). Once putative SAPs are identified and characterised, the composition of the surface proteome will be analysed to identify proteins that are common to target groups of organisms. If performed manually this would normally take many weeks whereas our approach takes less than a day to establish the workflows and to process the data. Once target proteins have been identified, a combination of proteomics and transcriptomics will be used to determine the expression of the target genes in clinical samples.

These developments will then be combined with molecular engineering to produce a range of bespoke engineered biomolecules, peptide aptamers, which will recognize specifically the SAP proteins. Peptide aptamers, which are small, robust peptide sequences designed to act as protein recognition modules, will be prepared by the commercial collaborator Aptuscan. The selected aptamers will then be integrated with nanometre resolution, using our patented photolithographic 3-dimensional patterning technique, into solid-state MEMS microsystems which will be designed and developed to incorporate multi-analyte capabilities on a single sensor surface, using a combination of our patented sensor and molecular patterning technologies, to simultaneously detect multiple diverse harmful microorganisms. Finally, the technology will be assessed in healthcare demand-driven application areas by collaboration with Dr John Magee, Director of the Health Protection Agency regional laboratory in Newcastle and Professor Kate Gould, Director of Infection Prevention and Control at the Newcastle upon Tyne Hospitals NHS Foundation Trust.

Silicon Nanowire Arrays for Viral Infection Markers

Professor P Ashburn   Southampton   £1,091,781   EP/G061696/1

Collaborators: MHS-Electronics, TMRC, Synairgen

For the analysis of disease-related proteins and antibodies in clinical samples, silicon nanowires are the only technique that combines the main biomedical requirement of high sensitivity with the main technological requirement of cost-effective multiplex potential. This project aims to solve the outstanding issues with top-down manufactured silicon nanowire devices for protein biomarker analysis: cost-effective mass production, microfluidics-facilitated multiplexing and biofunctionalization, and validation with clinically relevant samples.

Because the final device should be suitable for scaling-up and mass production, eventually resulting in disposable diagnostic chips for a wide range of diseases, the project will benefit from continuous input from industrial partners. We have divided the pre-commercialization objectives into two parts. During the first 18 months the nanowire fabrication and functionalization methods will be developed and tested with model samples that are realistic for clinical assays. In the next 18 months the objectives are the integration with microfluidics for multiplexing and the analysis of protein biomarkers in real clinical samples.

Throughout the scientific development of the nanowire arrays the project will engage with the range of stakeholders involved in the potential application of the device in everyday use. Our aim is to short-circuit the usual chronology from science to technical application followed - finally - by practical implementation by raising practical questions of public acceptability and fit with existing modes of healthcare delivery from the outset.

Multi-marker nanosensors for HIV

Dr R McKendry	UCL	£1,889,786	EP/G062064/1

Our mission is to establish a world-leading consortium to engineer and commercialise the next generation of multi-marker HIV smart chips to rapidly diagnose, stage and monitor HIV in resource-limited environments, including district hospitals, GP surgeries and developing countries. This Grand Challenge is a large scale multidisciplinary joint venture between scientists at the London Centre for Nanotechnology (UCL/Imperial), clinical virologists in the UCL/MRC Centre for Medical Molecular Virology, Royal Free and UCL Hospitals, the DoH-funded Comprehensive Biomedical Research Centre at UCLH NHS Trust, in conjunction with the Health Protection Agency and industrial partners Cambridge Medical Innovations, Sphere Medical Ltd and the BionanoConsulting.

Our novel nanodiagnostic & monitoring device builds on our remarkably strong multidisciplinary, entrepreneurial team of scientists, engineers and clinicians, and a series of recent breakthroughs by our team in diverse fields, including nanomechanical sensing in serum, nanofabrication, nanosorting, magnetism, nanoparticles, optical devices and novel single domain llama antibodies. The radical step change we now seek to implement, seamlessly integrates the scientific promise of these advances, to "sort and sense" very low copy number HIV markers, via magnetically driven force rupture, ultimately towards the single marker level.
The development of our handheld HIV multiple-marker device will ultimately result in more effective management of HIV infection, thereby significantly improving the prospects of millions of HIV infected people across the world.

Engineering Virus-like Nanoparticles for Targeting the Central Nervous System

Dr G Battaglia Sheffield £2,060,809 EP/G062137/1

Collaborators: UCB Pharma

We seek to use polymer nanotechnology to engineer biocompatible and nanometer-sized vectors that are able to pass through different extracellular and biological barriers, opening up the possibility of selectively targeting potentially effective treatments to where they are needed. We will combine recent advances in both polymer nanotechnology and neuroscience implementing experimental design and biological evaluation with whole body imaging techniques and modelling approaches. Targeted delivery of therapeutic agents direct into the CNS has the potential to cut down on debilitating side effects associated with current treatments and minimize neuronal damage in CNS degenerative disorders, both of which have major implications for life long health and well being for both patients and carers. Our long term aim is to demonstrate the potential of this technology in the clinic using the example of motor neuron disease where members of the team have excellent combined scientific and clinical expertise.
By the end of the three years, we aim to identify at least one delivery mechanism that has efficacy data for one disease/target in a preclinical model.
In order to realize this effectively we will engage with patient groups and the general public throughout the process, stimulating interest, managing expectations, addressing ethical and safety concerns and the regulatory agenda. So as to facilitate any potential clinical evaluation we also aim to engage from the early stages of the programme with the Medicines and Healthcare products Regulatory Agency (MHRA), and clinicians and patient groups. Finally we will liaise with technology transfer and business managers and integrate the multidisciplinary training including companies that have already established collaborations with our team such as: Biocompatibles Ltd, Oxford BioMedica Ltd, GlaxoSmithKline, and UCB Pharma.

New imaging methods for the detection of cancer biomarkers

Professor R Bayford Middlesex £1,318,192 EP/G061572/1

We propose using Multi-frequency Electrical Impedance Tomography (MfEIT), a novel technique based on low level electrical measurements for imaging which will be enhanced by the introduction of gold nanoparticles. The concept is based on the principle of combining the detection of biomarkers of malignancy with the innovative MfEIT imaging technology. This has the potential to not only help visualise the primary lesion, but greatly enhance the chance of early diagnosis and localisation of (micro) metastasis and/or early cancer spread. It can be achieved by targeting the nanoparticles to the tumour, for example by coupling antibody fragments specific for these cancer biomarkers. This not only renders such foci highly visible by MfEIT but also presents novel imaging-therapeutic modalities. Thus, our goal is to use MfEIT bio-imaging to localise tumours and by coupling metal nanoparticles not only to enhance imaging, but also to lay the foundation for the ultimate treatment of the tumour deposits. We will also develop complementary bio-imaging to other modalities so as to improve efficacy and avoid the use of imaging methods that use ionising radiation. The long term goal will be the development of safe, low-cost imaging and therapy methods that can be used also at small District Hospitals.

The key aim is to develop a ground-breaking and clinically applicable nanotechnology MfEIT-based imaging method for diagnosis of colon cancer, as Proof of Principle, with a specificity and sensitivity that can match barium enema and colonoscopy. Having addressed the scientific and technological challenges of this novel imaging technique in stage one, we ultimately aim to exploit the binding properties of nanoparticles to cancer cells to develop therapeutic regimes to selectively destroy them.

Nanoparticles for the Targeted Delivery of Therapeutic Agents to the Brain for the Treatment of Dementias.
Dr Stephen Hart UCL £1,932,258 EP/G061521/1

This project focuses on the development of nanotechnologies for the targeted delivery of novel therapies for Alzheimer's disease, the major cause of dementia in the elderly.
We aim in this project to harness nanotechnologies for the design and delivery of new therapeutics for the treatment of Alzheimer's disease. The nanoparticle components that will be designed and synthesised will comprise novel peptides and lipids with smart properties, such as receptor targeting, stealth coatings, bioresponsive linkers for disassembly, and biocompatibility. The uptake of nanoparticles into the brain from the circulation is impeded by the blood brain barrier so we will optimise a method called convection enhanced delivery (CED). In CED the blood-brain barrier is physically bypassed by injecting reagents directly into the brain through a fine needle under constant pressure. CED has already been used to administer therapeutics, achieving widespread dispersal through the brain, but has not been optimised for nanoparticle delivery. The project combines basic studies into nanoparticle materials and biology of the brain in relation to CED, and more applied studies into nanoparticle formulation and CED-mediated dispersal studies using MRI. The output of this study will be a nanoparticle platform technology and delivery method compatible with a range of therapeutic options for Alzheimer's disease and other forms of dementia. The research team comprises scientific experts in chemistry, drug and nanoparticle formulations as well as clinical expertise in brain pathology, surgery and experimental clinical trials, and has the capabilities to succeed both in this project and a future Stage 2 therapeutic study into Alzheimer's disease. This new capability could transform the management of patients with dementias with enormous potential benefits to UK society and the economy.

Non-Attrition HAART nanoparticle therapies for HIV/AIDS Drug Delivery
Professor S Rannard Liverpool £1,353,668 EP/G066272/1

New nanomedicine approaches are being developed to significantly enhance HIV/AIDS treatments. The medicines will be aimed at targeting the virus in areas that are very diffcult for conventional drugs to reach. The work builds on previous success at the University of Liverpool and has a plan to fully engage with the public.

The project aims to utilise Liverpool nanoengineering approaches to produce nanodispersions of commercially available HAART drugs to target HIV sanctuary sites with enhanced phagocytic activity and improve bioavailability. Single and combination nanoparticles will be evaluated to establish optimum safety and efficacy. A novel high throughput assay will be developed to enable material production for evaluation. All candidate therapies will be evaluated for toxicity and biocompatibility. The main objective are 1) Develop novel, active HIV/AIDS nanotherapies,2) Significantly inform the nanotoxicology debate, 3) Engage with third party companies to establish viability of commercialisation, 4) Engage with the public on nanotechnology.

Technologies for the Treatment of Brain Diseases

Professor I Uchegbu Sch of Pharmacy £1,264,710 EP/G061483/1
Collaborators: GSK International

The Grand Challenge is the treatment of brain diseases. The treatment of brain diseases is hampered by the blood brain barrier (BBB), a barrier between the blood and the brain which does not permit the passage of most drug molecules, due to the tightness of the intercellular capillary junctions, low uptake activity of capillary cells and the activity of efflux transporters. Previous attempts to target drugs to the brain and cross the BBB have involved the use of targeting ligands, e.g. mouse monoclonal antibodies for carrier mediated uptake or the inhibition of the above mentioned efflux transporters. However all of the particulate-based strategies (including the use of mouse monoclonal antibodies) that have been investigated over the last two decades have yet to yield any clinical products and the inhibition of the high capacity efflux transporters, which incidentally are not merely confined to the BBB, is not a viable clinical option.
Our multidisciplinary consortium drawn from academia and industry (GSK) propose a new nanoscience based strategy founded on two recent significant findings: a) chitosan amphiphile based nanoparticles significantly increase the central activity of hydrophobic and peptides drugs via the intravenous and crucially oral routes, b) apolipoprotein E targeted nanoparticles bypass the brain capillary efflux transporters and cross the BBB, increasing drug delivery to the brain. The project aims to use these data to create an optimised nanotechnology brain delivery platform for peptides and low molecular weight drugs with low brain permeability. These drug classes represent the bulk of the compounds which are trapped in the drug development bottleneck due to: a) their poor brain exposure and b) the absence of suitable brain targeting strategies. Candidate drugs to be used are potential treatments for schizophrenia, pain and sleep disorders. These compounds and their potential indications are particularly relevant to the call (targeting psychiatric diseases) and a specific output of the project is a candidate medicine for the treatment of psychiatric or neurological disorders. The project will involve a significant level of particle engineering, where particle matrix chemistry, surface chemistry (including the discovery and evaluation of other BBB targeting peptides) and particle size will be systematically varied and the impact of these variations tested using in vitro and animal models. The resulting pharmacokinetic, pharmacodynamic and mechanistic data will inform the optimisation of the platform which is the ultimate goal of the project. Fundamentally the mechanism of brain permeation of the drug cargoes will be studied and elucidated en route to the optimised nanosystem and this will also fulfil a requirement of regulators and health providers, who desire an underlying mechanistic basis for new health technologies. Stage 2 of the project (GSK fully supported) will focus on the development of a clinical medicine based on the nanotechnology platform.

7.3 - Grand Challenge 3 projects: NST for the Environment

Bio-inspired (Fe, Ni)S nano catalysts for CO_2 conversion

Prof N De Leeuw UCL £1138887 EP/H046313/1
Collaborators: Johnson Matthey Technology Centre

Despite the high thermodynamic stability of CO_2, biological systems are capable of both activating the molecule and converting it into a range of organic molecules, all of which under moderate conditions. It is clear that, if we were able to emulate Nature and successfully convert CO_2 into useful chemical intermediates without the need for extreme reaction conditions, the benefits would be enormous: One of the major gases responsible for climate change would become an important feedstock for the chemical and pharmaceutical industries!

Iron-nickel sulfide membranes formed in the warm, alkaline springs on the Archaean ocean floor are increasingly considered to be the early catalysts for a series of chemical reactions leading to the emergence of life. The anaerobic production of acetate, formaldehyde, amino acids and the nucleic acid bases - the organic precursor molecules of life - are thought to have been catalyzed by small cubane (Fe,Ni)S clusters (for example Fe5NiS8), which are structurally similar to the surfaces of present day sulfide minerals such as greigite (Fe3S4) and mackinawite (FeS).

Contemporary confirmation of the importance of sulfide clusters as catalysts is provided by a number of proteins essential to modern anaerobic life forms, such as ferredoxins, hydrogenases, carbon monoxide dehydrogenase (CODH) or acetyl-coenzyme A synthetase (ACS), all of which retain cubane (Fe,Ni)S clusters with a greigite-like local structure, either as electron transfer sites or as active sites to metabolise volatiles such as H2, CO and CO2.

In view of the importance of (Fe,Ni)S minerals as catalysts for pre-biotic CO2 conversion, we propose employing a robust combination of state-of-the-art computation and experiment in a grand challenge to design, synthesise, test, characterise, evaluate and produce for scale-up novel iron-nickel sulfide nano-catalysts for the activation and chemical modification of CO2. The design of the (Ni,Fe)S nano-particles is inspired by the active sites in modern biological systems, which are tailored to the complex redox processes in the conversion of CO2 to biomass.

The scientific outcome of the Project will be the design and development of a new class of sulphide catalysts, tailored specifically to the reduction and conversion of CO_2 into chemical feedstock molecules, followed by the fabrication of an automated pilot device. Specific deliverables include:

i. Atomic-level understanding of the effect of size, surface structure and composition on stabilities, the redox properties and catalytic activities of (Fe,Ni)S nano-catalysts;

ii. Development of novel synthesis methods of Fe-M-S nano-clusters and -particles with tailored catalytic properties (M = Ni and other promising transition metal dopants);

iii. Rapid production and electro-catalytic screening of lead nano-catalysts for the activation/conversion of CO_2;

iv. Development and application of a new integrated design-synthesis-screening approach to produce effective nano-catalysts for desired reactions;

v. Construction of a prototype device capable of catalysing low-temperature reactions of CO_2 into products at typical low-voltages, that can be obtained from solar energy;

vi. Identification of optimum process for scale-up in Stage 2, from the Economic, Environmental and Societal Impact evaluation

The target at the end-point of Stage 1 is the fabrication of a photo-electrochemical reactor capable of harvesting solar energy to (i) recover CO_2 from carbon capture process streams, (ii) combine it with hydrogen, and (iii) catalyse the reaction into product. In Stage 2 of the project, the prototype will be developed into a scaled-up commercially viable device, using optimum catalyst(s) in terms of (i) reactivity/selectivity towards the desired reaction; (ii) economic impact; and (iii) environmental, ethical and societal considerations.

Nano integration of metal-organic framework for the uptake and utilization of CO2

Dr F Marken Bath £1187427 EP/H046305/1

Carbon dioxide levels have risen steadily with the combustion of fossil fuels and additional positive feedback effects due to natural CO_2 sources. "Recycling" of CO_2 driven by solar/renewable energy is an effective approach to address the problem. In a recent edition of Science (25th Sept 2009) entirely dedicated to this problem the opportunities and potential benefits arising form CO_2 uptake from the open air (as opposed to capture during production) have been highlighted. The urgent need for capture and utilisation of CO_2 is self-evident. Research in CO_2 capture and in CO_2 utilisation is currently based on a range of separate technologies and often ineffective e.g. for amine or alkaline sequestration. By combining ("nano-integrating") capture and utilisation into a single continuous process the efficiency can be improved and at the same time the energy required to drive CO_2 reduction is minimised. This project focuses on one-step CO_2 capture and utilisation by linking catalysts directly with a novel CO_2 absorber. Nano-scale-integration of CO2 uptake and utilisation processes will provide new highly efficient single-step processes to turn CO_2 into useful products (polymers, carbohydrates, fuels). The main vision for this project is the idea of a catalyst nanostructure embedded into/immobilised onto a CO_2 supplying membrane (Metal-Organic-Framework, MOF) substrate so that enhanced localised diffusion can deliver a high rate of CO_2 into the active catalyst site.

Metal Organic Frameworks (MOFs) have emerged as a front-runner for the uptake and storage of CO_2 but have never been employed to support catalysts. Effective catalysts for the conversion of CO_2 into useful chemical products have been discovered but usually require high concentration industrial CO_2. In this project two areas of existing strength in the South-West, CO_2 absorption and catalytic utilisation, are combined to provide new nano-structured functional catalyst membranes tailored to both capture and concentrate CO_2 from the free atmosphere and convert it into useful products in a single continuous process. The developed technology based on functionalised and specifically tailored MOF-membranes will be entirely new. The catalytic processes will be driven by solar energy (photo- or bio-catalysis), renewable energy, or waste heat from carbon creating processes.

Nanotechnology is integral to this project. Metal organic frameworks (MOFs) are promising materials for the specific absorption and storage of high concentrations of CO_2. In a new approach the MOFs will be made into nanostructured membranes, which will "concentrate" CO_2 from the atmosphere and feed it directly into a nanostructured catalyst layer. As the CO_2 is reduced, fresh CO_2 will be continuously drawn in with the catalyst located in the diffusion layer (with effective hemi-spherical diffusion of CO_2 to the nano-catalyst). Three types of catalysis will be investigated for CO_2 reduction: (i) direct gas phase reduction of CO_2 to CO using a nanostructured catalyst and integrated MOF/catalyst materials for one step carbon capture and utilisation, (ii) CO_2 will be electro-reduced on platinum or copper nanoparticles (or similar nano-structured catalysts) to form ethylene and higher hydrocarbons with nanostructured catalysts increasing the selectivity of process, (iii) bio-films of cyanobacteria will be used to fix CO_2 from the MOF under illumination in a MFC setup. Nanostructuring of the conducting MOF surface with the biofilm attached is extremely important for good bacterial adhesion and function.

Stages of effective modules (e.g. producing ethylene and producing CO) will be combined into reactors to deliver products of higher value (e.g. polymers, solvents, or fuels) in the second stage of the project. Parts and the overall process will be carefully assessed by life-cycle analysis and the desired end product will be a "carbon negative process".

Nano-structured catalysts for CO2 reduction to fuels

Dr CK Williams Imperial £1675520 EP/H046380/1
Collaborators: Millennium Inorganic Chemicals, EoN Engineering Limited

Fossil fuels are society's major energy sources and the primary raw materials for the chemicals industry. However, there are significant concerns associated with their sustainability, depletion and cost. In particular, many of the UK's North Sea reserves will soon become uneconomic / depleted, so we need to find alternatives urgently. Furthermore, the combustion of fossil fuels, e.g. during energy conversion, releases carbon dioxide and other greenhouse gases that contribute to global warming. The UK is already committed to an 80% reduction in greenhouse gas emissions by 2050, but significantly greater reductions (85%) are likely to be necessary in order to prevent devastating climate change (>2 degree C increase in temperature). Energy conversion for electricity and transport is responsible for 74% of CO_2 emissions; new sustainable energy sources are essential. These new energy sources must be CO_2 neutral or, even better, CO_2 depleting. One solution is to use carbon dioxide itself as the fuel and feedstock material. Our solution is to react CO_2 with H_2 or water, using chemical, photochemical or electrochemical catalysts, to produce liquid transport fuels, such as methanol. Flue gases from power stations and/or industrial process, such as metal/alloy manufacture, are major contributors to UK CO_2 emissions and will be abundant sources of CO_2 for the foreseeable future. Many other industrial emissions also contain considerable concentrations of CO_2 including those derived from biological processes, e.g. fermentation. The hydrogen required will be produced by water electrolysis powered by solar or other renewable source of energy. The key economic issue lies in decreasing the energy required for the processes. We aim to achieve this via the development of new, highly active metal/metal oxide nano-structured catalysts, which offer superior performance due to their high surface areas, reduced loadings, low overpotentials and which can be synthesised controllably. We shall use three parallel, yet complementary, approaches to energise the process: direct chemical (thermal) hydrogenation, electrochemical and photochemical reductions of carbon dioxide and water.
Our team comprises scientist, engineers and environmental policy researchers at Imperial College London and University College London. We have expertise in chemical catalysis, electrochemistry, photochemistry, reactor engineering, materials science, nanotechnology, sustainable chemistry and environmental science. We have a significant track record in the activation and use of carbon dioxide as a resource. The project will also involve collaborations with, and be support by, the Imperial College London Centre for Carbon Capture and Storage (CCS), the Energy Futures Lab and the Grantham Institute for Climate Change.

Annex 8 - Nano Engineered Materials Initiative

The scope of this funding opportunity concerned the manufacture of materials whose performance, features or manufacturability is reliant on there being control, characterisation and a manufacturing process on the nanoscale. £5.5 million was allocated to support several projects to address this area.

Proposals were focussed on moving laboratory based processes towards the factory, where there is a need for increases in volume of production, size, consistency, reliability or sustainability. Applications were encouraged to build on existing capabilities and expertise, such as in fabrication or characterisation facilities and research.

Goals included demonstrating a route to application for instance through proof of concept that can be taken further (for example to the pilot plant stage so that knowledge gained might be exploited through the involvement in the project by industrial users.

Funded projects

Flexible Plastic Industrial-Scale Photonic Crystals for Functional Colour

Professor JJ Baumberg	Univ. Cambridge	£970,897	EP/E040241/1
Professor O Hess	Univ. of Surrey	£213,024	EP/E040322/1

Collaborators: De la Rue, Unilever, Kodak, DSTL

We have invented a new process for making plastic films which have appealing structural colours, that can be scaled up to industrial production levels. It is based on making periodic arrangements of stacked nano-spheres with a different optical density to their surroundings, called 3D photonic crystals. Until now, there has been no way to make industrial-scale cheap photonic crystals. Our method is based on making plastic sphere precursors which can be heated and extruded together in such a way that they slide over each other into perfectly packed arrays. By adding tiny nano-particles (hundreds of times smaller in size) in between the spheres we can make an enormous variety of new sorts of materials or fibres which have 'smart' colour. For instance, the films are elastic and they drastically change colour when they are stretched, or are bent.

In order to realise the possibilities in our discoveries, we need to find out how to properly control this shearing-assembly of polymer nanoparticles, by testing out the extrusion on a reasonable scale while measuring optically how it is taking place. We also need to develop ways to extrude fibres that could be used for making iridescent fabrics. Only when we understand the mechanisms in detail will we know enough to scale up production to the level that industry wants to see before investing further in commercial manufacture. We can also make a variety of even more intriguing films, including ones which glow with different colours, or are magnetic. We also need to show how the films might decompose to see what environmental issues might be raised by releasing such material on a widespread basis. Finally we need to develop a plan for which particular applications that we should concentrate on, in collaboration with a number of large companies.

Everyone who we show these rubbery iridescent films to, wants a piece to take away with them. We want to be able to provide films to everyone, by commercialising our nanomaterials research and development.

Development of Bulk Nanostructured Aluminium Alloys for High Strength Applications

Professor G Smith	Univ. Oxford	£922,660	EP/E040608/1

Collaborators: Rolls Royce PLC, RSP Technology, Prodrive, IAPEL SA, Neil Brown Engineering, Niobium Products Company GMBH

The proposed research addresses the key requirements of the aerospace, defence and automotive industries for a step-change in the performance of lightweight materials for greater efficiency, reduced emissions and environmental impact. Two different categories of nanostructured aluminium alloys will be studied: bulk nanoquasicrystalline alloys and nanofibril metal-metal composites, which represent a new and exciting way of achieving elevated temperature capability and high strength in light materials. Small-scale laboratory research on these nanostructured materials has already proven extremely promising, and it is therefore timely to explore their scale-up towards commercial quantities. Moreover, a wholly novel combined nanoquasicrystalline and nanfibril alloy will be studied in order to achieve a lightweight alloy with high strength, stiffness and toughness up to 400C. The project will involve the close monitoring and control of manufacturing conditions, and the use of some of the most advanced nanocharacterisation methods available in order to develop reproducible and reliable materials for subsequent engineering evaluation.

We will demonstrate the viability of the materials developed and their associated manufacturing routes for bulk manufacture by testing real engineering components in real applications. In the final year of the programme, alloy composition/process combinations will be chosen for developing demonstrator components such as pistons, inlet valves, compressor blades and plates. We have brought together a partnership between university researchers and industrial scientists from the advanced materials supply chain, in order to ensure the scientific understanding developed is exploited with maximum impact.

Processing of Polymer Nanocomposites

Professor E Harkin-Jones	QUB	£745,874	EP/E040446/1
Professor PD Coates	Univ. of Bradford	£550,776	EP/E040667/1

Collaborators: Smith and Nephew Healthcare Plc, Danone Research, Innovia Films, Boran Mopack, JGB Perrite

The principal aim of the proposed project is therefore to achieve a fundamental understanding of the interactions between material formulation, processing and properties of polymer nanocomposites and to apply this to the development of proof of concept applications which provide generic processing information for industry and academia alike. The work will include statistically designed experimental studies using pilot scale polymer processing equipment and validation trials on industrial scale equipment. Parameters to be studied include extruder shear and temperature profiles, screw design, additives such as anti-oxidant, post extrusion deformation such as biaxial extension and cooling rates. We will characterise the materials in terms of structure, mechanical, thermal and barrier performance in order to link process to structure and structure to performance.

We will utilise the combined processing, characterisation and analytical skills and facilities existing in Queen's University Belfast (QUB) and the University of Bradford (UoB), partners who have worked together successfully on large collaborative projects, in the past and currently, and have an excellent national and international track record in polymer processing research.

High performance nanotube fibres

Professor V Stone	Napier Univ.	£197,115	EP/E04204X/1
Professor A Windle	Univ. Cambridge	£890,057	EP/E04218X/1

A process to make carbon nanotube fibres in a single operation has recently been demonstrated by the Cambridge team. The potential of the process (announced in "Science") for making high performance fibres has led to considerable interest worldwide, both from the existing fibre industry, for whom it represents a disruptive technology, and from fibre users. However, the 'technology pull' is such that our insight into the process at a basic level needs to catch up. We need to be able to produce nanotubes of predetermined dimensions as the first stage towards a fibre product with highly consistent properties. The reason for the exceptional properties seen is not fully understood, nor is the relation between process parameters and the resultant structure. A deeper understanding is also necessary as a basis for scale-up strategies, which will be critical in estimating the likely industrial cost of the product, and thus the future risk.

The first stage of the project will be to build a fully instrumented production rig, to learn more about the nanotube growth and the origin of defects which are a source of inconsistency in measured properties. Key experiments will be undertaken to determine the best approach to scale-up, in particular a second reactor will be built to evaluate to miniaturise the process as a scale-up strategy. There is so much yet to be understood. Kilometre lengths of fibre will be produced so that the applications can be externally assessed.

Carbon nanoparticles provide opportunities for medicine: drug delivery and cancer treatment being two examples. However, the enthusiasm of pharmacologists and oncologists is balanced by cautionary notes from toxicologists. The properties which make nanoparticles unique lead to effects in vivo which may either be beneficial or detrimental. In the case of nanotubes, the latest toxicological studies indicate that they are no more toxic than particles from (say) a laser printer, however, it is recognised that the human body may have difficulty in eliminating nanotubes in the long term. From the business angle, any nanoparticle scare, whether well founded or not, may hold development back and at worst put investment at risk. As we take this work forward the materials researchers at Cambridge will work closely with toxicologists at Napier University and the IOM.

Annex 9 – Science and Innovation Awards.

9.1 Imperial College London and University College London (2006)

£5.6 million for Professor Tim Jones (Imperial) and Professor Gabriel Aeppli (UCL) to develop new tools for nanoscale characterisation and metrology. The project will be based at the London Centre for Nanotechnology (LCN), a joint venture between Imperial College and University College London. The Centre brings together two internationally leading institutions in nanoscience and nanotechnology and has a unique operating model that accesses the combined skills of the departments of chemistry, physics, materials, medicine, electrical and electronic engineering, mechanical engineering and earth sciences across the two universities.

9.2 University of Strathclyde and King's College London (2006)

£4.3 million to advance the emerging field of nanometrology, for applications in molecular science, medicine and manufacture. Led by Professor David Birch at the University of Strathclyde and in collaboration with Professor John Pickup's team at King's College London, the project will facilitate the multidisciplinary research environment required to develop the extra capacity needed to make the UK a leader in nanometrology. The award will facilitate the recruitment and support costs of at least three lecturers, six research fellows and six PhD students, to be spread across the two institutions.

9.3 University of Manchester (UoM) and Lancaster University (2008)

£5.3 million for the Centre for Innovation Through Materials Science, Chemistry and Engineering
Lead - Professor Simon Gaskell, VP Research (UoM)
Co-Investigators - Professor Andre Geim, Manchester, Professor Trevor McMillan, Pro-Vice Chancellor, Lancaster

Graphene, discovered in Manchester in 2004, is an isolated atomic plane made from carbon atoms. The electronic properties of graphene have led to research into its use as a possible replacement for sensors, transistors and semi-transistors. Researchers now increasingly believe graphene may have uses in many other areas. This centre will examine possible applications in relation to material science, chemistry and engineering.

9.4 University of Exeter and University of Bath (2008)

£4.86 million for Graphene: Fundamental Research and Applications in Nano-electronics, Photonics and Bio-Sciences
Lead - Professor Roger Kain, Pro-Vice Chancellor, Exeter
Co-Investigators - Professor SJ Bending, Bath, Professor Kevin Edge, Bath, Professor Alexander Savchenko, Exeter

The Centre will act as an international focus for graphene science, supporting both academic and industrial research activities. It will create new academic positions and provide a state-of-the-art equipment base, equal to that found in any laboratory worldwide, to attract leading researchers from around the globe. The Science and Innovation Award will fund staff, infrastructure and top-of-the-range equipment. A broad spectrum of multi-disciplinary and complementary experiments will be supported by theoretical investigations.

Annex 10 - Interdisciplinary Research Centres and Collaborations

Three recent IRC programmes are of major relevance to the area of Nanoscience

10.1 Bionanotechnology IRC

The aim of the IRC is to learn from nature - to understand the structure and function of biological devices and to utilise nature's solutions in advancing science and engineering in areas as diverse as biosensors, genomics, the discovery of new medicines, diagnostics and drug delivery.

Academic partners: Prof J Ryan, University of Oxford, University of Southampton, MRC National Institute for Medical Research, Imperial College London, University of Nottingham, Marie Curie Cancer Care, University of Glasgow

Grant GR/R45659/01 £9.7 million April 2002 - March 2008 *Funded by EPSRC, BBSRC, MRC and MoD*
Collaborators: *GSK International, Schering-Plough Research Institute*
Website: http://www.bionanotechnology.ox.ac.uk/

Abstract

The IRC aims to investigate biomolecular systems, from the level of single molecules up to complex molecular machines, to establish the principles of their function and apply this knowledge to produce artificial electronic and optical devices:

Molecular motors are proteins in which enzymatic activity such as energy conversion and self-assembly are integrated to produce highly efficient linear or rotary motion on a nanometre length scale. The combination of structural biology, molecular genetics and biophysics will allow the mechanisms to be characterised and potential applications to be identified.

Membrane proteins can be viewed as one of evolution's main attempts at nano-engineering: they include ion channels, hormone receptors and photoreceptors. High resolution (spatial and temporal) studies of ion channels and related membrane proteins will be made via novel time-resolved optical spectroscopy and single molecule techniques.

Molecular genetic analysis needs efficient ways of comparing sequences: to search for mutations it is necessary to scan entire gene sequences. Combined nano-fabrication and genetics methods will be used to produce patterned surfaces, and more sensitive methods of detecting interactions will be developed in order to push toward the single molecule limit.

Single-molecule electronics and photonics will be used to develop novel devices, networks and sensors.

Single molecule and scanning probe experimental techniques including AFM, STM, optical and dielectric traps, FTIR, and SNOM will underpin the entire IRC programme. Theoretical approaches with common themes will be developed and applied - including Monte Carlo methods, atomic force models, and techniques derived from semiconductor device simulations.

10.2 Nanotechnology IRC

The nanotechnology IRC has provided an underpinning interdisciplinary activity in nanotechnology with the theme of understanding and controlling the physical properties of nanostructures and devices by fabrication at single molecule precision. **Academic partners:** Prof M Welland, University of Cambridge, University College London, University of Bristol.

Grant GR/R45680/01 £9.8 million January 2002 - December 2008 *Funded by EPSRC, MRC, BBSRC and MoD*
Website: http://www.nanoscience.cam.ac.uk/irc/index.html

Abstract
The Universities of Cambridge and Bristol with University College London will establish an Interdisciplinary Research Collaboration (IRC) in Nanotechnology. The IRC is directed at the very core of nanotechnology and as such will aim to provide an underpinning interdisciplinary activity with the general theme of accurately controlling the physical properties of nanostructures and devices by nanofabrication with single molecule precision. Central to the ethos of the IRC will be the development of research themes and strategies that uniquely combine expertise from currently disparate fields. The consortium will develop the basic tools to organise molecules at the hard/soft interface (the growth of 'soft' molecular structures off 'hard' substrates) by natural and other means, including self-assembly and soft lithography. Characterisation of structural properties of the interface and their inter-relationship with electronic properties is also central, and an appropriate range of tools will be available. This includes scanning-probe methods, optical, fluorescence and electron-beam microscopy, theory and modelling. Such a range of tools and techniques is not found in a single university department, and the purpose of the IRC is to tackle research problems that cut across the traditional divides between all science and engineering disciplines.

10.3 Quantum Information Processing Interdisciplinary Research Collaboration (QIPIRC)

The scientific theme of the IRC is the controlled transfer of quantum information between static and propagating forms.
Academic partners: Prof G Briggs, University of Oxford, Prof N Linden, University of Bristol, University of Cambridge, University of Hertfordshire, Imperial College London, University of Sheffield, University College London, University of York, University of Leeds

Grant GR/S82176/01 and **GR/S82169/01** £10.6 million April 2004 - March 2009
Website: http://www.qipirc.org/

Abstract (Oxford)
The IRC will bring together a multidisciplinary team of researchers in the UK to address key challenges in quantum information processing. The theoretical studies will range from the most fundamental concepts of QIP to theoretical analysis of how QIP can be implemented in practice, together with modelling of specific experimental configurations. The experimental research will focus on the interaction between static and flying qubits, something that will be crucial for successful exploitation of QIP. Ways will be sought to enhance the inherently weak interaction between photons and static qubits in microcavities and arrays, and to implement photon-photon entanglement via conditional detection. Information transfer in ionic and atomic systems will be studied. Electrons in solids will be investigated as candidate short range flying qubits.

Abstract (Bristol)
The possibility of quantum algorithms that outperform classical algorithms, the concept of quantum information and the idea that entanglement represents a novel resource are fundamental insights that formed key building blocks in the development of the new field of quantum information science. These ideas have revolutionized our notion of information and computation. However in each of the key areas of quantum entanglement, quantum communication and quantum algorithms the new developments have given rise to significant open questions.
The interdisciplinary Bristol theory group, from departments of computer science, mathematics and physics, will address a number of key issues in these areas. This work provides an underpinning theoretical programme for the IRC in quantum information processing. Dynamical aspects of entanglement will be investigated both for interactions of small numbers of systems and for larger collections in interacting particles. We aim to develop new cryptographic protocols for example in the areas of state encryption, key distillation and novel cryptographic primitives. We will investigate the mathematical structure of quantum algorithms with a view to their generalisation and search for new problems which might gain quantum enhancement. We also plan to design new small-scale experiments demonstrating quantum information processing, for example providing novel tests of fundamental quantum effects, both bi-partite and multi-partite.

As well as providing insights into fundamental aspects of quantum information processing, we aim to provide new results with direct application to current and forthcoming experimental work, both within the IRC and more widely.