

Nanotechnology

A Scenario for Success in 2006

Ian Miles¹ and Duncan Jarvis

NPL FOREWORD

This is a report of a scenario development workshop held in October 2001. The workshop, and a benchmarking study which was undertaken to provide background material, was commissioned by Dr John Taylor, Director-General of the Research Councils, and conducted by NPL, The Institute of Nanotechnology (IoN), and The Centre for Research on Innovation and Competition (CRIC, University of Manchester and UMIST).

The report is published by the DTI on their website. This form has been prepared primarily for distribution to all those that contributed to the benchmarking study and the workshop.

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Executive Summary

This report addresses the questions: What a 'success' scenario would look like in the field of nanotechnology, in the UK, by 2006 – and how might we get there? Success is defined here as maintaining and improving the commercial strength of UK-based organisations that develop, sell, or apply nanotechnology for national and global markets, thus enhancing our relative economic progress. Success also means the UK improving its attractiveness for companies of all nationalities as a place to site value-adding activities that are dependent upon nanotechnology. There are several reasons for having such a desirable and credible vision of success in nanotechnology in 2006. The scenario presented in this report describes for the first time what a large group of UK experts believe to be the most promising areas of nanotechnology for the UK, and an estimate of the UK's capabilities in these areas. It indicates where there are points of disagreement and uncertainty, as well as consensus. Perhaps most importantly, it sets a "stretch target" for all the stakeholders. One element of the scenario is that it should give those involved in the UK science base a better idea of how a successful nanotechnology activity would exert a strong 'pull' on the science base.

This report presents the result of a substantial project to research and review relevant areas of nanotechnology that culminated in a one-day workshop in October 2001. At the workshop that involved 35 individuals; from nanotechnology-based companies operating in the UK, from relevant financial service firms, from government agencies, and from the major public research bodies in the UK, a scenario for nanotechnology in 2006 was developed. The participants at the workshop were able to draw on the background research undertaken in the months before this. The overall scenario is attractive, and more than just a continuation of current trends, but still credible, given prompt action by those concerned. Some key elements of the scenario are:

- Nanotechnology is "coming on-stream". Though the underlying technologies and their applications are still at an early stage of development – perhaps equivalent to the information technology sector in the 1960's, or biotechnology in the 1980's – there are applications emerging into the market that are already likely to be making a significant impact on the industrial scene by 2006. Nanotechnology will be of growing commercial importance, and be making contributions to quality of life as well as economic growth.
- The applications of Nanotechnology are extremely diverse, and require a wide range of enabling technologies, expertise, and skills. The UK possesses strengths in many of the fundamental scientific areas. The question is whether these strengths are in research groups with critical mass, and if they are related together in effective ways.

We focus in this report on six application areas where there is substantial opportunity for the UK to make a significant impact. For each of these, we have identified features of a "success scenario" for 2006.

In the area of drug delivery:

- much of the activity is likely to be driven by SMEs, who already have a strong presence in this field. The "success scenario" states that, for example, the UK will be strongly placed in the field, and we would be seeing many start-up companies offering nanotechnological solutions, perhaps as many as 10 per year in the UK by 2006.
- a considerable growth in university-based research is anticipated (e.g. a doubling or trebling of postgraduates in related areas), and a steady flow of patents and other contributions to technology development.

In the area of informatics:

- an increase in industrial R&D expenditures in relevant nanotechnology by 2006 is anticipated to be roughly ten times present values (and similar increases in the number of new patents). A major UK research, training effort and fabrication facility to be established with public and private support.
- substantial growth in training is anticipated, and a maintained or increased UK presence both in nanotechnology-based informatics markets and in upstream research.

In the area of instrumentation, standards and metrology:

- the UK's share of software modelling oriented to the nanotechnology market is expected to grow at 10% per year.
- It is anticipated that more than 5 UK companies will be using directed self-assembly based on new, 'disruptive' methods (e.g. soft lithographies) as a routine tool.

In the area of novel materials:

- UK industry will play a significant role in commercialising nanotechnology-based consumer products, for example in cosmetics, self-cleaning surfaces, informatics, novel decorative effects, and functional coatings.
- Novel materials applications will succeed in attracting substantial new public and industrial R&D funding, and strategic investment will be based on sound long-term analyses (roadmaps, etc.). At least 7 commercialisable new products with clear paths to the market, and 3 demonstrator projects for applications, would be in place. A significant market share in the product and process innovations from the application of novel materials to manufacturing processes should be readily detectable.

In the area of sensors and actuators:

- we could expect the UK share in nanotechnology-based sensor systems to be growing faster (say by 10% per annum) than those of our main competitors.
- we would already, before 2006, have seen the first major health field trials in a hospital of nanotechnology-using systems such as an integrated network of sensors.

In the area of tissue engineering and medical devices:

- The UK share of the international market could be at around \$1bn per annum.
- Finally, we would also anticipate that at least 1500 new jobs would have been created around nanotechnology-based tissue engineering and medical devices, with start-ups running in the order of 5 to 10 per year.

A number of generic points arose during the workshop:

- Though the picture varies dramatically across application areas, and even among different lines of applications development within these areas, there are opportunities for substantial returns to UK investment across the board. The volume of public and private funds devoted to the area needs to be increased significantly.
- The applications offer significant benefits to the quality of life (medical applications, health and safety applications, etc.), and to industrial efficiency (better instrumentation, more effective production processes). Development and commercialisation of these applications requires the fusing of knowledge from a disparate range of technical disciplines, management and other "people skills". Training needs to generate many more people able to work in such cross-disciplinary teams.

UK nanotechnology requires an infrastructure of research centres and institutes functioning at critical mass, providing training, demonstrator, prototyping and other functions, and with the agility to respond rapidly to the new challenges and opportunities that are liable to emerge in this rapidly-evolving field.

These scenarios imply major consequences for citizens, businesses and government. As scenario statements, they are based on painting a picture that is admittedly optimistic, but is also realistic. What remains is for businesses and policy makers to take some of the steps that are implied by the scenario in order to achieve these targets. Nanotechnology is moving from an esoteric field of speculation to becoming a series of generic technologies that will be deployed widely across the economy. The UK can play a significant role in shaping and benefiting from this evolution. The time to act is now.

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1 Introduction

In 2000, the US Government (then under the Clinton administration) announced a major National Nanotechnology Initiative. In the Federal year 2000 this received \$270m, in 2001 \$422m, and for 2002 a budget of some \$520m is being requested – by the time this report is published the best part of a billion dollars will have been already spent on the US Initiative. While there is substantial European work in the area, the US figures for 2001 are several times larger than the sums allocated to nanotechnology R&D by the EU as a whole.

Much as the Japanese “5th Generation Programme” galvanised strategic thinking about Information and Communications Technology research in the early 1980s, this US initiative has been the catalyst for other countries to examine and develop their own strategies for nanotechnology. In the UK many current academic research projects and more than a few industrial projects involve nanoscale science and technology. The UK Government and Research Councils are providing support for nanotechnology but there is no agreed understanding amongst policy makers, industry and the research base concerning the implications of nanotechnology for the UK economy - perhaps because the costs of involvement against the likely benefits to UK industry have to date not been quantified.

The aim of this exercise was to do exactly that - examine the potential benefits of nanotechnology for UK industry, in around 5 years from now. The study was focused on a set of application areas, selected by a DTI-convened panel of experts, on the basis that these were areas where either:

- the UK has industrial strengths, and the implication of nanotechnology needs to be analysed in relation to these strengths, or
- the UK research base was strong; and could be translated into economic benefits.

In order to select the areas for this benchmarking exercise, ten key areas of nanotechnology were initially identified using a variety of sources and methodologies. At meeting of the Ministerial Advisory Group in July 2001 this preliminary list of technologies formed the basis for a discussion in which it was agreed that the benchmarking study and subsequent scenario development should focus on **six key application areas** in particular. These six application areas were ones where it was accepted that nanotechnology would have a major influence. In alphabetical order they are:

- drug delivery
- informatics,
- instrumentation, standards and metrology,
- novel materials,
- sensors and actuators, and
- tissue engineering and medical devices.

A critical factor in the benchmarking study was the UK capability to exploit scientific knowledge and technological expertise in these application areas in industry, at present or in the near future.

1.1 What is Nanotechnology?

A nanometre is a billionth of a metre (10^{-9} m). This is about 1/80,000 of the diameter of a human hair, or the length of ten hydrogen atoms. Nanotechnology is essentially any application of science, at or around the nanometre scale. It can thus be defined in its simplest terms as ‘engineering at a very small scale’.

Nanotechnology is a particularly exciting area of technology. It encompasses a whole range of activities - from the creation of tiny structures with nanoscale features (e.g. nanomachines), to the manipulation of single atoms and molecules in order to produce new materials and devices that may have entirely new properties or be produced in new ways (these techniques may involve large-scale equipment, or new forms of extremely small scale device). Some lines of nanotechnology development are in many ways a continuation of the trajectory of miniaturisation that we have witnessed for several decades, to the point at which millionth of a metre (10^{-6} m) tolerances (microengineering) are commonplace. Results of this have been apparent in the shrinking of mobile phones, computers and camera electronics, to name but a few. These products, as well as CD's and CD-players, sensors (such as accelerometers in car airbags) and inkjet printers increasingly contain components with nanometre features. But other lines of nanotechnology development – while often depending upon such miniaturisation – are part of the evolution of knowledge and capabilities in other areas, such as in biosciences. The field is one where many different types of technological expertise converge, and whose actual and potential applications are immense.

1.2 How far are there real applications, here and now?

Nanotechnology is already impinging on our everyday lives, with benefits to, for example, our health. In medicine, nanotechnology is enabling faster, cheaper and more efficient diagnostic techniques. Instead of sending a sample of blood away to a laboratory to be analysed, it is possible already to have a diagnosis within a few minutes, using a hand-held monitor, not dissimilar to a mobile phone. More sophisticated versions of this diagnostic technique, combined with powerful computers (which also benefit from components with nanoscale features) are used for speeding up the new drug discovery process – they dramatically reduce the time taken for 'target' drugs to be quickly assessed and retained or discarded. Nanotechnology is useful in the battle against disease in other ways, too. Drugs can be administered in nanoparticle form, often with special coatings, so as to target specific diseased tissue (being activated only when they reach it); additionally, many drugs are far more effective in nanoparticle form, requiring much lower dosages.

Medical applications are important, but nanotechnology finds applications in many other areas. For example, clay minerals in nanopowder form, can be disseminated in, for example, polymers – the inclusion of only 2% of clay minerals as nanoparticles in polymer coatings (which are notoriously easily damaged) renders them tough, durable and scratch resistant. This has implications for new paints and 'varnishes'. Applications range from one extreme of space vehicles and aircraft, to everyday requirements for materials that are, say, light and easy to work with; but need to be protected from demanding environments - such as the high levels of heat and abrasion found in a typical kitchen!

Since particles at the nanoscale are below the wavelength of visible light, they can impart new properties, while being invisible themselves! Fluorescent nanoparticles (called 'quantum dots') are invisible until 'lit up' by ultraviolet light; and can be made to exhibit a range of colours, depending on their composition. They have a whole range of possible applications, e.g. for 'tagging' counterfeit articles, stolen goods, and illicit drugs, or for such health applications as tracing the course of therapeutic drugs in the human body.

Underpinning these developments are a growing range of tools for observing, manipulating and measuring the nano-world. These range from extensions of current lithography methods used in micro electro mechanical systems (MEMS) production, to a range of evolving scanning probe microscope (SPM) systems that can see and manipulate matter on an atomic scale. From these technologies of today, will emerge some of the nano-manufacturing and metrology infrastructure necessary to realise commercial applications of nanotechnology tomorrow.

In this report we occasionally refer to "bottom up" technologies. This refers to the potential developments of extremely small machines and robots, which can themselves effect changes at the

nanolevel. These changes could range from the mass production of molecules or nanodevices themselves, through surface engineering and extremely small-scale surgery. This vision has attracted a great deal of public interest, and impressive demonstrations have been made of microscopic devices. Great controversy surrounds the extent to which this vision can be realised, and the experts involved in the present study concluded that it certainly lay outside of our relatively short time-scale. The implications of such revolutionary technologies are awesome, but even the more immediate developments discussed in this report are extremely impressive. Though they might eventually be displaced by effective nanodevices, the developments we discuss here would contribute to the development of the more radical visions rather than representing alternative lines of development.

1.3 Nanotechnology, science and education

Science and technology at the nanoscale has to be 'inclusive', not 'exclusive'. To make successful nanotechnology applications requires multidisciplinary approaches: sharing knowledge, tools, techniques and information from many different areas of research and industrial practice. This point was reiterated across many, if not all, of the application areas studied here. Materials scientists, engineers, physicists and chemists need to join forces with biologists and medical researchers, and to be able to communicate effectively with managers and entrepreneurs. This has implications for our educational system, and the way we train our professionals – and not only scientists and engineers, but also managers, lawyers and accountants. This is not to say that every individual has to be multidisciplinary – deep expertise and knowledge remain vital, and superficial courses claiming to cover all of nanotechnology are to be avoided. But experts will need to be able to communicate across the boundaries of established disciplines (and to recognise the challenges of commercial discipline), and we will need to be able to forge and manage multidisciplinary teams.

1.4 Recent UK government policy supporting nanotechnology

In April 2000 the UK's Foresight Materials Panel and the Institute of Nanotechnology produced a report on 'Opportunities for Industry in the Application of Nanotechnology'. In June 2000 the Government White Paper 'Excellence and Opportunity - A Science and Innovation Policy for the 21st Century' identified nanotechnology as a vital innovative area, capable of creating new products and new industries. It recognised in particular that the UK economy can be strengthened by the research, development and production of biomedical products based on advances in nanotechnology.

In the White Paper 'Opportunity for All' (February 2001), the Government announced £7m support for a University Innovation Centre for micro- and nanotechnology in the North East of England.

In March 2001 the Institute of Nanotechnology organised two nanotechnology missions supported by the DTI, one to Germany, and one to the East Coast USA. These missions took leading UK academics and research scientists into overseas nanotechnology companies, academic institutions and research centres, as well as the Government agencies responsible for funding and promoting nanoscale science to gain insight into where opportunities for nanotechnology were considered to lie, and how these opportunities were being addressed in each country. The report of the missions was published in June 2001. Also in June 2001 the Research Councils announced £18m support for two new Interdisciplinary Research Collaborations (IRCs) in nanotechnology, to be led by Oxford and Cambridge universities. The Research Councils are also supporting many research projects and studentships in nanotechnology. In July 2001, three nano-related projects received £5m support under the Foresight LINK Awards. At European level, there is likely to be significant support for nanotechnology under the new Framework programme, which begins in 2002.

Other developments set the scene for the present report. In parallel to the increase in support for nanotechnology discussed above, in May 2001 Lord Sainsbury, Minister for Science and Innovation, appointed an advisory group to provide guidance on nanotechnology policy in the UK. The group is

due to report to him before the end of the year. The advisory group commissioned the benchmarking study and scenario planning exercise on which this document reports.

1.5 Developing the scenario

A “success scenario” is a view of the future that manages to be both desirable and plausible to those expert in the field. Such a scenario, then, is obviously best developed by such experts. The procedure adopted in this exercise enlisted a group of leading thinkers and practitioners in nanotechnology-related areas in the UK, and stimulated them to exchange and elaborate their views as to what success for the UK in nanotechnology applications over the next few years could be, and how this might be achieved.

This was accomplished as follows. As described, the study was organised around six application areas for nanotechnology¹. These were the basis for a benchmarking exercise, and for the scenario workshop. In the workshop, participants were assigned to one of six working groups, corresponding to each of the application areas, and much of the workshop activity was conducted in these six groups.

Material had been prepared over the course of several months to provide these working groups with a starting point for their analyses. A team of researchers from CRIC, the IoN, and NPL had developed a framework for benchmarking the situation of the UK in each application area. Essentially this was a set of questions, which researchers from IoN and NPL sought to answer – in part on the basis of examining archival and documentary material (including the nanotechnology missions mentioned above, and reports from Embassies and other sources). The questions were also used to structure a programme of interviews with expert informants in the UK and countries against which the UK was being compared. These interviews were particularly important for eliciting opinions about the future for the UK in the application areas.

These background studies formed the basis for a set of reports provided to the participants in the scenario workshop. Each participant was provided with a document providing a general overview of developments in nanotechnology application areas, together with a detailed text dealing with the area with which their working group was dealing. Through the scenario development workshop, a combination of working group and plenary sessions was used to provoke dialogue about the background documents, and to elicit views about plausible and desirable directions of development and the steps that would need to be taken to realise these. This involved setting the working groups a series of tasks, in which they were asked to identify and prioritise such elements of the scenarios as drivers of change, indicators of success, necessary steps to be taken to attain the scenario.

Membership of the six working groups is displayed on the following page. John Taylor, Director General of the Research Councils and Chairman of the Advisory Group on Nanotechnology Applications provided orientation and encouragement throughout. Additional support was provided by Ian Miles of CRIC and Chris Hodge of the DTI, with facilitation from the professionals from Projects in Partnership: Helena Poldervaart, Lynn Wettenhall and Sarah Hitchcock.

¹ The six areas were selected by the advisory group from an initial proposal of 10 areas. The proposed areas of “Quantum computing” and “Electronics” were generalised to “Informatics”, the proposed areas of “Ultra high strength materials” and “Catalysis” were generalised to “Novel materials” while the proposed areas of “Displays” and “Drug Discovery Techniques” were left for later consideration.

WORKING GROUPS AT SCENARIO WORKSHOP

Drug delivery

Dr Jane Worlock	SkyePharma plc
Professor Alexander Florence	University of London
Professor Chris Lowe*	University of Cambridge
Leah Scott	CBDE Porton Down
Dr Brian Warrington	GlaxoSmithKline
Ian Harrison	DTI (note-taker)

Informatics

Michael Hill-King	BTG plc
Dr Arnold Harpin	Bookham Technology plc
James McNaught-Davis	Advent Venture Partners
Professor John Ryan	Clarendon Lab, University of Oxford
Professor Ken Snowdon	University of Newcastle
Professor Will Stewart*	Marconi plc
Gavin Costigan	DTI (note-taker)

Instrumentation

Bryan Barnard	Thermo VG Scientific
Dr Malcolm Gower	Exitech Ltd
Professor Ian Shanks	Unilever Research Laboratory
Professor John Wood*	CCLRC
Professor Mark Welland	University of Cambridge
Professor Anthony Walton	University of Edinburgh
David Robinson	NPL (note-taker)

Novel materials

Professor Graham Davies*	University of Birmingham
Barry Murrer	Johnson Matthey plc
Dr Ray Oliver	ICI Strategic Technology Group
Professor John Pethica*	University of Oxford
Professor George Smith	University of Oxford
Clive Hayter*	EPSRC
Otilia Saxl	IoN (note-taker)

Sensors and actuators

Dr Alistair Keddie*	Department of Trade and Industry
Professor Terence Knibb	BAe Systems
Stephen Lowery	3i Investments plc
Prof Richard Palmer	University of Birmingham
Professor Roger Whatmore	Cranfield University
Duncan Jarvis	NPL (note-taker)

Tissue engineering

Professor Tony Atkinson	Chimaeron Ltd
Ken Snowden	Scottish Enterprise
Dr Peter Fitzgerald	Randox Technologies
Professor Jon Cooper	University of Glasgow
Anthony Horn	Department of Health
Paul McCubbin	BTG plc
Andrew James	CRIC (note-taker)

The following sections present the results of the analyses in the following form. For each application area we outline, first, A “benchmarking” view of 2001, based on the work carried out by IoN and NPL, and as reviewed by the workshop. This reviews:

- A description of the application area
- The current and future markets
- Technical challenges confronted
- Global competition
- UK profile, comparative aspects
- Challenges for the UK

We then go on to present the “success scenario”, a view of 2006, as developed by workshop. This focuses on answers to the questions:

- What are the drivers of change?
- What will success look like?
- What will enable us to get there?
- How will we know we are on track?²
- What do we need to do to make it happen?

The story told here then, is not a prediction about what **will** happen. But it is a believable image of what success could be like in 2006. It has been produced by taking the available public information, the collective wisdom of experienced participants in the industry, and feeding these inputs in a short but intense process of synthesis. The result should be a useful picture for orientating public and corporate policy discussions concerning nanotechnology and its applications.

² One problem with defining targets for indicators in a newly emerging area like nanotechnology applications is that we have little hard data on the current state of affairs to begin with. Thus we are aware that when we talk about a doubling of the number of personnel, for example, we are often using pretty rough guesstimates of what the current position is. This is quite a familiar situation, and one that requires much more detailed statistical analysis to resolve.

2 Drug Delivery Systems

Drug Delivery Systems (DDS) use either passive or active nano-engineered systems that enable the required dose of drug to be delivered at the correct time to the target area. This reduces unwanted side effects, improves patient compliance, leads to lower doses and opens new possibilities (that would be impossible with non-nanotechnology approaches). Nano-scale devices may also be fabricated to safely deliver material other than conventional drugs to cells – for example, DNA could be delivered to cells for gene therapy and vaccinations. (Another potential application of nanotechnology, Drug Discovery, is not included in the discussion below.)

2.1 The current position (in 2001)

The application area

Targeted delivery of drugs (and DNA for gene therapy and vaccines), using passive or active nano-engineered systems to deliver the right dose at the correct time to the precise target, is anticipated to be an important field of development. It offers numerous medical benefits: the reduction of side effects and discomfort, and of doses; the generation of new therapeutic possibilities, for example the delivery of substances that are unstable when delivered by other means. Major health problems targeted include cancer, cardiovascular and central nervous system diseases, genetic disorders (cystic fibrosis) and diseases of old age. Improved drug delivery should increase patient compliance, and provide such commercial benefits as reducing the costs required for marketing and approval of new drugs (by renewing the therapeutic use of established drugs).

Current and future markets

Currently there are 30 main drug delivery products on the market. The total annual income for all drug delivery products is approximately over \$33 billion with an annual growth of 15% (based on global product revenue). Demand for drugs is growing with an increasingly affluent and aware society with high quality of life and long lifespan expectancy. Nanotechnology offers one of the most promising routes to improving the sophistication with which medical drugs are deployed.

The use of improved drug delivery should enable lower doses of drugs to be administered, and for currently used drugs to be better targeted. Regulatory issues may not loom high, but certain applications may face competition both from other nanotechnology solutions that are being pursued (some will probably become major products, others will turn out to be dead ends), and from non-nanotechnology alternatives – genetic screening to select appropriate drugs for patients, alternative means of getting drugs into the blood system for specific organs. Drug delivery in the future is likely to involve a combination of numerous developments that are only now reaching fruition.

Technical challenges

Development of surface molecular bioengineering to develop biomimetic and bio-inspired devices to increase specificity is a major challenge. Better knowledge is required of: the biological fate and the targeting of drugs, (particularly biopharmaceuticals, macro-molecules and macromolecular delivery systems at the molecular, membrane and cellular level); of the physicochemical properties of biopharmaceuticals, macromolecules and macromolecular delivery systems and how these are modified within a biological environment; of novel materials and delivery systems to overcome such biological barriers.

Global competition

The US has strong linkage between research and applications in this area. For example, industrial consortia are attached to universities, which ensures an application-driven approach. Such methods as two-way non-disclosure confidentiality agreements are well established. Research students are very closely coupled with industry, thus learning relevant skills. Most fundamental research funding is from the NSF, which requires significant industrial collaboration as evidence that the research is worthwhile.

The US provides a strong challenge to areas of UK strength. It has taken much of the UK impetus in obtaining economic value from encapsulated and liposome drug delivery systems. The US takes the lead on nano-vectors for gene therapy, though the UK is not far from the frontier of work here. Perhaps more significantly for the future the US is taking the initiative with work on peptide nucleic acid (which can in theory reprogram the gene rather than substitute it – whether this approach will prove successful is debated, but the effort here is highly indicative of intent). The US is investing heavily in gene delivery, reflecting the wealth of information that has resulted from the human genome project – a large number of groups active on this. Japan has increasing work, some of high quality, in all areas that interest the UK and Japanese delegates are on key international advisory boards. Other players are also active in this and related application areas.

The UK's profile

The UK has been at the forefront of drug delivery technology – but, as mentioned above, has lost much of its lead some areas, such as encapsulated and liposome drug delivery systems, to the US. It is probable that a UK lead is still maintained in such applications as drug-polymer conjugates for anti-cancer and anti-inflammatories; and the UK has excellent underpinning research for nano-particles and micelles. There are reports that the UK pharmaceutical industry, despite its evident strengths, has been slow to take up new nanotechnology-related concepts, and that UK researchers have accordingly sold licences to more responsive US or European companies.

2.1.6 Challenges for the UK

The linkage of applications and underpinning research is vital, and the UK's system is less integrated than that of the US. In the US venture capital money is a minor contribution to research compared with NSF funds, but is important in setting up new companies with academics. Regulatory issues (e.g. approval of new drugs, and the role of the National Institute for Clinical Excellence, NICE, in recommending or opposing particular therapeutic regimes) are seen in the pharmaceutical industry as deterrents to new drug development. While improved drug delivery systems may be less impeded by regulatory processes than are new drugs, problems are still conceivable (especially in respect of costly treatments).

The area requires multidisciplinary skills and teams. UK research has benefited strongly from its world-class scientists in polymer and biochemistry as well as innovative medical practice and clinical expertise. Currently, teams are often assembled round schemes like LINK and these are vulnerable to dispersion when funding ends.

2.2 2006 - a credible but optimistic view

2.2.1 Drivers of change

This is a highly market-driven application area, where effectively everyone is affected by the technological developments. We all get ill and grow old, and therefore are liable to benefit from such specific applications as optimised drug delivery, individual therapy, and the use of endogenous molecules, from increased ability of doctors to diagnose diseases at early stages. There are liable to be

significant efforts to develop applications around the delivery of drugs for the treatment of cancer, asthma and respiratory problems, and pulmonary disorders. Commercially, the promise of new drug delivery systems also lies in the ability to extract more value from already discovered and approved drugs, by improving their targeting.

This leads to a second driver, one that the group labelled 5D technology - drug delivery philosophy and practice characterised by the five dimensions of the right drug, right time, right person, right place, and the right price. This would underpin much better targeting of treatment, enabling treatment of diseases we cannot treat now, and the meeting of currently unmet medical needs (which would be a high value activity). Clinical proving is vital, since the application needs to be tested rigorously for this effectiveness if it is to be taken up on a large scale. The critical issue here is the interface that developers of applications achieve with regulators, so that regulatory acceptance of new delivery systems can be achieved with “light-touch” and speedy regulatory regimes.

The UK has advantages compared to its main competitors in this application area in that pharmaceuticals is such a large and important sector. However, development of underpinning research in this field is impeded by the organisation of research funding (issues such as the peer review process and the diffusion of resources across multiple Research Councils and funding agencies were raised in this context).

What will success look like?

A success scenario in this application area can be characterised in the following terms:

- The UK will be strongly placed in the growing area of drug delivery systems by 2006. It will be a notable area of new investment. However, strong challenges will be faced from overseas, especially the USA.
- Much of the activity will be driven by SMEs, who already have a strong presence here. New SMEs will form, but their success will require tapping into sources of experienced advice to aid with dealing with regulations (where regulatory reform would also be welcome) and accessing finance.

Leading applications in the near future will include, for example, well-targeted delivery systems for oncology and similar acute conditions. The technology does not seem so applicable to long term treatments in the near future, but will gradually come to form the basis of future delivery systems for commonplace drugs.

- There will be a strong link between the development of drug delivery systems and new nanotechnology products such as materials, on the one hand, and research into biological targets and proof of principle for new treatments.

What will enable us to get there?

Critical enablers to make this scenario a reality will be, on the supply side: the quality of research and the availability of skilled personnel, the ability to develop and deploy proprietary know-how; access to such infrastructure as manufacturing facilities capable of nanofabrication. Access to finance is a current problem, which needs to be overcome for commercial exploitation, as is sustained research funding (there were feelings that the treatment of multidisciplinary research proposals under current peer review systems can be both a barrier and enabler). On the demand side, policies for health services and other public sector markets can be major enablers for market development. There are many alternative drug delivery systems under development, and one key issue is to avoid all the eggs being put into one basket!

How will we know we are on track?

Realisation of this success scenario would be reflected in indicators such as the following:

- An increase in the number of UK based postgraduates in drug delivery and related topics, doubling or even trebling by 2006
- It was suggested that the critical mass of industrial expertise would be 20 people per firm per drug delivery system.
- 10 start-ups per year in the area. (A number of innovative SMEs here would probably be bought out by inward investors.)
- 1 patent per person active in research and development in the area every 3 years.

Less precisely, it was suggested that we would know that the UK is beating the competition if more money is flowing into, and being made by, drug delivery systems (losses would be becoming profits); a greater market share was obtained by UK companies; and if the portfolio value of these companies is increasing and the market capitalisation of SMEs in the field growing.

What do we need to do to make it happen?

Finally, for this scenario to be realised, such actions are needed as:

- Making postgraduate study financially attractive (for example by a stipend premium) - firms could play a role in such support. The distinction between EU and UK students with respect to postgraduate study should be reduced or eliminated. Research Councils should not discourage interdisciplinary academic research: this may mean more cross-Council working, or changes in peer review systems.
- The large pharmaceutical companies and venture capital firms have several roles to play. Corporate venturing would be an important way in which they could support this application area, as would the sponsoring of incubators.
- SMEs need several forms of support, which could be provided by government agencies and larger firms, probably working in unison. Schemes to support the transfer of knowledge between academia and industry (e.g. Teaching Company Schemes) are important; SMEs and start-ups could also be supported via interim management, mentoring, and the like.
- Better communications are needed between academics, the financial sector, and user firms concerning the potential for drug delivery systems. To some extent this can be accomplished through methods such as those mentioned above, and also through existing IRCs and by means of establishing centres of joint work (e.g. a Faraday partnership).
- Setting up "prototyping" facilities in this area should be considered, with government and industrial financing. As in other application areas, exploitation is liable to remain critically dependent on production capabilities.

3 Informatics

Electronics, magnetics and optics at the nano scale are expected to open new breakthroughs for information and communication systems. The use of quantum well lasers in telecommunications systems is already established and single-electron transistors or molecular gates are the ultimate goal in size and power reduction of digital electronics. In going to the nanometre scale, new effects arise – especially relating to quantum effects and linear superpositions of quantum states plus entanglement. These allow the possibility of quantum computing and quite novel approaches to information processing. Extremely high frequencies are expected for switching, going to communication rates in the THz region. Continued improvement in logic and memory chip performance is expected through introduction of novel technologies to displace/augment silicon. “Moore’s Law”, describing our continuing ability to make computers more and more powerful, has often been seen to be reaching physical limits, but so far has been maintained within silicon microelectronics. However, apparently inflexible limits (e.g. ~25 nm minimum lateral feature size) do lie ahead, and these are expected to curtail the rapid progress of silicon microelectronics sometime within the next 10-15 years. A disruptive technology is needed to go beyond that stage, enabling Moore’s Law to be maintained and long-term improvements in performance across the ITC sector to be continued.

The current position (in 2001)

The application area

Whether building on existing technologies or incorporating novel science, innovators seek to leapfrog present performance of devices, leading to such products as:

- Faster, smaller computers, embedded processors in an increasing range of products
- ASICS for telecommunications applications
- Lower power electronics for portability

These are enabling developments for a vast range of applications. Miniaturisation has been a predominant trend in informatics, and nanotechnology would facilitate further development of more powerful and faster information-processing equipment. Devices in their present form, with silicon circuits continuing to dominate, can sustain Moore’s law for the next 10 years. Further into the future, circuits based on single molecule and single electron transistors will appear, first in special applications. Novel complex architectures, materials, gate designs, interconnects, etc. will be required to accommodate these new devices, with radical new solutions to the problem of cooling and circuit power management. One disruptive technology would arise from the successful implementation of quantum information processing; new applications (algorithms) requiring such solutions would be likely to emerge synergistically with their development. Another disruptive technology would be “bottom up” technologies – potentially immensely important in the longer term, but not seen as likely in the near future.

Several specific applications were seen as particularly interesting as offering radical developments in areas of some UK strength. While a number of applications were seen as worthy of detailed analysis, this was not possible in the available time. Indeed, a general point in this application area was that very different market and industry structures apply to specific applications within the broad area of nanotechnology for informatics. The working group discussed a range of applications with very different features, but its output centred on:

- **Photonic Crystals**, which involve an analogy between photon propagation in 'nanocrystals' of about half-wavelength (in the material) period, typically 100-200nm, and electron propagation in atomic crystals. A phenomenon that does not exist in nature, the 'photonic insulator' which does not allow optical propagation in any direction, means that photonic integrated circuits can be nearly a million times more dense than electronic ones. The tighter confinement and novel dispersion properties also open up many new applications, particularly for nonlinear (optical) devices and very low power devices.
- **Quantum Information Processing (QIP)**. This crosses the disciplines of quantum physics, computer science, information theory and engineering, with the aim of harnessing the fundamental laws of quantum physics to dramatically improve the acquisition, transmission and processing of information. The role of nanotechnology is fundamental to such exploitation, because quantum effects only appear on small length and time-scales. QIP will exploit quantum effects in *active* ways; the technology depends on the subtle, but remarkable properties of *quantum entanglement*. Semiconductor nanostructures such as quantum dots and bio-nanostructures have enormous potential for providing the basic machinery for QIP. Possible applications range from biological sensors, ultra-fast optoelectronic switches and computers, through to future-generation applications involving the control of biological processes at the cellular level, and desktop QIP devices such as ultrasecure cryptographic systems.
- **Quantum structure electronic devices (QSDs)**. The performance enhancement achieved in QSDs arises from the spatial confinement of electrons into regions of less than 20 nm. One-dimensional confinement can be obtained routinely using epitaxial growth techniques to produce "quantum well" structures. One of the principal aims of nanotechnology is to produce three dimensionally confined QSDs, e.g. quantum wire and quantum dot devices. Some devices such as quantum well lasers are already successful. Near infrared lasers for telecommunications applications are based on III-V semiconductor quantum wells. Band structure engineering, in which quantum well width and material composition are varied, produces laser wavelengths from about 0.5 - 2 μm . High Electron Mobility Transistors (HEMTs, for low noise, high gain microwave applications) and Vertical Cavity Surface Emitting Lasers (VCSELs, for fibre optic data communications, sensors, encoding etc.), which have the highest performance of any solid state photon source, are in high volume production. Other applications, like quantum dots, are on the brink of commercialisation.

Other applications that were also considered to be highly significant included **Self-assembled fault tolerant data state and computation systems**, and **nanostructured displays** (including polymers).

3.1.2 Current and future markets

The current market for miniaturised systems is estimated at \$40bn; the market for IT peripherals is estimated to be more than \$20bn and is dominated by the USA and Japan. Though there are few nanotechnology products in the marketplace, future growth is expected to be very strong, with a predicted composite annual growth rate of 30-40%, with emerging markets around 70%. One forecast (Keindanren) puts the market for nanotechnology-based IT and electronics devices at about £70bn by 2010. The market for micro and nanotechnology systems in the telecommunication sector are estimated as being of the order of \$3,500m with an anticipated compound annual growth rate in the order of a remarkable ~70%.

- Photonic crystals could underpin major new markets. Ultra-high density optical integration will substantially reduce costs and power consumption, leading to widespread use in optical communications, a huge worldwide business. Nonlinear devices will also find applications in other areas such as sensors, potentially on very large scales.
- QIP products are likely to emerge into significant markets once the technical challenges to their development have been overcome, which looks like being a longer-term process.

- QSDs are already a success story, with larger companies taking the lead. The estimated market for HEMTs by 2002 is £600m, while that for VCSELs in 2004 is £80m; and already the quantum well laser amplifier market for 2000 is estimated at £4bn. Key products here could span a huge range – even including white light sources for domestic illumination, where QSDs could be considerably more efficient than incandescent or fluorescence sources. Other applications include those in lasers, detectors, amplifiers, and modulators for communications systems; short wavelength lasers for CD and DVD players and recorders; and ultra-high density data storage systems. Improved speed, efficiency, and controllability, with the ability to produce and work with more wavelengths, are important here.

Technical challenges

The outstanding technical challenges in this field concern methods for maintaining Moore's law, either by continuing miniaturisation of silicon-based devices, by the use of different materials, fabrication principles and/or device concepts – most pertinently molecular electronics and in particular carbon (or other) nanotubes, and, as discussed above, photonic crystals. Considerable work needs to be done to advance understanding and engineering of all of these structures.

The working group suggested that photonic research was already yielding applications such as advanced lasers, and that in the next five years or so we could expect to see such products as photonic crystal fibre (currently a niche product) achieving significant markets, two-dimensional photonic integrated circuits and photonic crystal assisted vertical cavity lasers moving out of the laboratory into commercial production, and other products such as nonlinear gates in photonic crystal fibre and/or integrated circuits moving from research to development. However, three-dimensional photonic crystal structures would be unlikely to move beyond the research phase for a decade or so.

Quantum information processing was also seen as presenting considerable technical challenges, with basic research into quantum effects being required to provide its key features. The likelihood is that quantum communication systems could be produced within the next decade, with quantum computers emerging later. A possible sequence of developments would be the next 5 years seeing entangled states in quantum dots; manipulation; coherence control; the next 10 years seeing quantum logic gates, coherent devices, and quantum integrated circuits, and quantum computers emerging in the 2020s.

Three-dimensional QSPs are a major challenge for commercialisation, since relatively complex fabrication processes are required, but quantum dot devices can be produced relatively easily and inexpensively by self-organised growth. Quantum dot lasers are now close to market, and better than order of magnitude performance enhancement is expected – and has in some cases been demonstrated. Extending the emission wavelength range to 0.35 μm has been achieved using nitride QSDs, and to 10 microns using quantum cascade lasers.

Global competition

Research into new informatics technologies is spread through the universities in the UK and USA (and much of Western Europe) and through major manufacturers in Japan and the USA who are behind recent technological breakthroughs. Many European telecommunications companies are competing successfully against Japan and the US. (Some European players are US owned, but many European owned enterprises are at the leading edge.) But relevant nanotechnology research is in most cases believed to be more advanced in the USA and Japan. Japan in particular is building up production and research facilities in Europe to compensate for domestic technological weaknesses, while simultaneously establishing its markets abroad. The European venture capital base, which is rather weak except in UK and perhaps Germany, needs to be strengthened. Japan and the USA are

home to the most innovative semiconductor companies and many other silicon fabrication plants are located in the Far East.

Japanese R&D tends to be organised according to guidelines determined by the government, with the MicroMachine Centre, an organisation supported by MITI, co-ordinating R&D on microsystems. R&D and scientific work on nanotechnology is carried out at universities as well as public research institutes and industries, and is funded by METI (in the range of 100 million US\$ in the last 5 years). The research has a longer-term focus than typical for the UK. A well-focused interest is in the field of quantum computing (QC), where some original approaches are being pursued; molecular scale electronics is another focus of interest. US efforts are also strong. Here military funding agencies are generous in their company funding - even when there is a clear commercial benefit for the companies involved.

The UK has strengths in photonics, and thus is relatively competitive as against the US and Japan (and other countries like Canada and Germany) in such novel nanotechnology applications as photonic crystals. In QIP, US spend in 2001 of around \$30m is orders of magnitude greater than the equivalent UK funding level; several major Japanese companies (NEC, Toshiba, NTT, Fujitsu etc) are investing heavily in the area (including funding research in the UK).

3.1.5 The UK's profile

UK research in this area is high quality, but faces problems of transfer to the industrial sector. The UK is strong in telecommunications, and the ICT industry is dominated by optoelectronics where the UK is strong in niche optical communications areas built on the JOERS funding scheme; optoelectronics is effectively the flagship of the UK nanotechnology / microelectronics sector. A range of companies has grown rapidly from small beginnings over the past decade, and the industry is well supported by a strong R&D base. Although promising, the market is volatile: future success depends on world markets.

In the remainder of the sector (microelectronics fabrication and information technology) the UK has a rather small presence, being weak in the computer memory field, for instance. The most successful UK companies (such as ARM) do not operate large-scale fabrication plants; they do provide the intellectual property input to design circuits and software for ASICs, which may be fabricated in foundries elsewhere. For top down developments, there seems little prospect that large UK manufacturing/fabrication operations can compete head to head with Japan; they lack the technical base, investment sources or visible past successes in this area. (However, there are promising facilities such as a modern fabrication facility in the Newcastle area.) The UK has a presence in niche areas, e.g. modelling rather than hardware development. Such niches can be highly strategic. Thus, since the cost of a new fabrication plant is immense, it is crucial to fully understand the properties of single devices and circuits based on them before the investment is made. UK expertise in fields such as modelling might then be further developed and commercialised.

Several important areas for long-term development of informatics were seen as ones where UK strengths are apparent. In the **photonic crystal** field there is strong UK R&D, reflecting past UK government support and the relative strength of the UK in photonics more generally. Several universities have world-class research, and large companies (e.g. Marconi) have interests in the field (still at a research rather than development stage); there are also SMEs active. In fields close to **QIP**, such as quantum information theory, the UK has played a leading role, many of the pioneering ideas in the subject were first enunciated here, and overseas firms are in dialogue with UK university groups in the field. While the UK retains considerable expertise, there are fears that the better funding opportunities overseas will reduce our capability to seize the major, but long-term, technological opportunities in QIP. A similar picture was presented for QSD: strong academic R&D teams were developed through Research Council funding initiatives in the 1980s and early 90s, but relevant funding has not kept pace with the international competition.

3.1.6 *Challenges for the UK*

The UK lacks an industrial base capable of commercialising many of the results of even high quality and well-funded research although companies such as Agilent, Marconi and Seagate are significant in specific fields. Past research programmes have been dedicated to micro and nanotechnology technologies, but at present no specific programme exists. Though R&D in the field continues to be funded through activities on related subjects, there are some concerns that the research effort lacks either critical mass or sufficient focus.

Skill shortages are widely recognised as a problem: physical sciences (chemistry, physics, and materials science) have recruitment difficulties. The exciting intellectual, economic, and social opportunities of nanotechnology, if it is an increasingly well-funded field, might offset this, attracting talented young people. Large numbers of professionals, with interdisciplinary perspectives, are required to build future nanotechnology industries in informatics as well as other application areas (we have already seen similar points being made in the drug delivery area). These will depend upon highly trained multidisciplinary teams (biology, medicine, applied and computational mathematics, physics, chemistry, electrical, chemical, and mechanical engineering). Team leaders and innovators will probably need expertise in multiple subsets of these disciplines; all members of the team will need a general appreciation of each other's fields. This will challenge the compartmentalised learning of educational institutions: the solution is not new degrees in nanotechnology that provide only a shallow overview of many disciplines. Research and demonstration programmes are needed to establish the right balance between specialisation and interdisciplinary training, and the way of delivering it. Additionally, special and often expensive laboratory facilities are required for education in nanoscience and technology. Many engineering schools cannot now offer students any exposure to nanofabrication. Innovative solutions will have to be found (e.g. new partnerships with industry; shared nanofabrication facilities across consortia of colleges, universities, and engineering schools-with web-based, remote access, etc.)

3.2 2006 - a credible but optimistic view

Drivers of change

Two issues were seen as particularly important for this application area: Fabrication and Functionality.

The importance of **Fabrication** resides in the need to be able to manufacture informatics products, and to be able to produce products of high quality in large volumes. Printing and lithography processes will continue to grow in importance, with scalability being a prominent issue. Optical lithography capability will be required for mass production at nanotechnology scale. The 70 nm level of feature size may well be reached in commercially viable devices by 2006. Contact printing may be a way forward enabling mass production using techniques similar to photocopying. (In the longer term self-assembly methods offer a potential way of breaking through the ceilings that it is anticipated will be reached by the long-established trajectories of miniaturisation. By 2006 this may be emerging.)

Functionality simply means that market needs are fundamental to the development of nanotechnology applications in informatics. Firms in the sector face intense competition in delivering functionality, through such features as device size and weight, processing speed and power, data storage and power consumption. Mobile devices for communications and computing are significant end-uses, if anything increasing in importance in 2006

The UK has some strengths in information technology industries, especially telecommunications, photonics, and software and content sectors. However, where it comes to hardware, the absence of a large native CMOS industry and associated fabrication and infrastructure capabilities, and shortages

of skilled personnel, mean that in many areas the UK lacks critical mass. Pockets of strength tend to reside in niche areas, and both capitalising on, and overcoming this is a major challenge.

What will success look like?

The success scenario developed in the workshop was characterised in terms of a number of applications developments in which the UK could anticipate playing a substantial role:

- Quantum structure electronic devices will already be important by 2006, and be growing in importance. This may build on current successes with quantum well lasers (where there is established UK expertise) and the anticipated commercialisation of (self-organised) quantum dots.

Photonic crystal structures, offering photonic integrated circuits with new functionality, will be emerging as industrially significant products.

- Nanostructured displays, including polymers, are liable to be moving toward commercialisation by 2006; by 2010 they should be highly important. The combination of high resolution and low power will be a major commercial factor.
- Quantum information technology will have a major impact on a timescale of one or two decades, and should be attracting considerable research effort in the near future. Self-assembled fault tolerant data state and computation systems are also a long-term development.

In general, devices will become smaller, cheaper, faster and have increased functionality.

What will enable us to get there?

The major factors that can help make this scenario a reality were identified as, first, the quality of basic and applied research in the contributory disciplines, but also, importantly, critical mass in research. Critical mass is also required in infrastructural and e.g. fabrication facilities – some of this may be achieved through international collaboration within and even beyond Europe. Another critical factor was the availability of skilled people.

Several other factors were also seen as significant, if less central. Availability of finance for work in this field, with investment that is sustained and consistent, is bound to remain important, and the costs associated with intellectual property rights identified as a barrier to development.

How will we know we are on track?

Indicators that the scenario of UK success in this application area is being achieved include the following (with figures in 2001 terms):

- The UK's share of all ICT products at least remains at current values (and the markets are growing), but preferably increases (from, say, 10% now to 13% in 2006).
- Industrial R&D expenditures in informatics-related nanotechnology increases by 2006 to roughly ten times the value of the 2001 figure.
- Likewise, industrial patenting in the area from the UK increases tenfold.
- Research Council expenditure in the area is around £80m per year, and capital investment for a major centre by 2006 is around £100m (or even higher – it was pointed out that Canada is establishing a national Institute for Nanotechnology at the University of Alberta in Edmonton with over £50m, intending to employ 200 people, and the Netherlands is setting up a centre for nanomaterials costing around £17m for 150 researchers).
- Training in the area occupies around 150 PhDs per year, with 300 trained technicians coming on line. Development of research expertise should result in high quality research and be

reflected in (for example) the UK holding on to its current bibliometrics/citation impact presence of around 25-30% of the world total.

3.2.5 *What do we need to do to make it happen?*

For this scenario to be realised, we need such actions as:

- Establishment of a major centre or similar facility for research, fabrication & training in nanotechnology informatics, bridging and combining both academic and industrial lines of work. Funds would be a mixture of private (say 1/3) and public (say 2/3), with substantial inputs from other countries, the EU, perhaps the European Investment Bank.
- Substantial development by universities of interdisciplinary and multidisciplinary training in related areas (including mathematics as well as physical and information sciences and engineering, and covering such business topics as intellectual property management). This also means confronting training and cross-Research Council issues such as flexible funding for foreign students.
- Academic/industry collaboration to establish supercritical research teams on key subjects.

4 Instrumentation, tooling and metrology

This application area essentially involves a set of enabling technologies and techniques. In consequence, its influence is far greater than is reflected in the size of the economic sectors producing these products. Though they are often overlooked in economic analysis, these are tools on which successful exploitation of nanotechnology will depend. They provide the instrumentation needed to examine and characterise devices and effects during the R&D phase, the manufacturing techniques that will allow the large scale, economic production of nanotechnology products, and the necessary metrology support for quality control. The requirement is for fast, versatile instrumentation and tooling for the economic production of nanotechnological devices. Instrumentation and tooling will need to evolve as long as nanotechnology is a developing field.

The various types of application in this area include:

- **Tools for top down manufacture.** These tools will support large-scale production and nanofabrication plants based on top down approaches, such as extensions of lithography methods used in MEMS production, new contact printing (so-called “soft lithography”), methods for nano feature production on a large scale, scanning probe microscope (SPM) manipulation systems (e.g. multi-tip SPMs). We can also anticipate precision engineering machines to provide large, nanoscale, controlled texture (including extremely smooth) surfaces, e.g. device substrates, optical mirrors, magnetic read/write heads.
- **Tools for bottom up manufacture.** In this case the tools support rather more futuristic approaches to large-scale production and nanofabrication - based on “bottom up” approaches such as self-assembly and nano-machine production lines.
- **Nanometrology.** Another application lies in the development of surface analysis methods. There are many potential extensions of existing characterisation methods, and these could allow for molecular reconstruction of macromolecules at surfaces, for the analysis of single atoms etc., via holographic and other approaches.
- **Software modelling.** Molecular modelling software is another application of wide-ranging applicability - it will permit the efficient analysis of large molecular structures and substrates. This can be thought of as the molecular equivalent to a CAD or FEM package.

4.1 The current position (in 2001)

4.1.1 *The application area*

In the near future, this application area will mainly feature extensions of conventional instrumentation and top-down manufacturing. This involves the macroscopic tools that will be required to manufacture, engineer, inspect nano-level devices, surfaces, etc.

More futuristic molecular-scale assembly, nanorobots, etc. would be disruptive technologies, and have received a great deal of media attention (some of it uncritically enthusiastic, some of it fairly alarmist). Though some proponents of this technology see it as just around the corner, it probably remains in large part out of the timescale of this report.

Nano-level instrumentation covers a very wide range of skills and products. In applications such as optics for steppers, x-ray optics, laser mirrors, substrate cutting and polishing, the surface is a highly important focus for nanotechnology. Methods are required to pattern surfaces at nanometre (nm) resolution, and for the production and inspection of macroscopic artefacts with ultra-smooth surfaces.

Effort put into this area is low-risk: there are unlikely to be environmental or ethical problems (the work may develop tools needed to manufacture nanodevices, but not the nanodevices themselves). There are considerable technical challenges; but even if the nanodevices cannot be realised soon, the instrumentation will still be valuable in the microelectronics world and in other fields (e.g. precision instruments, surgical devices). Thus R&D should have fairly rapid payoffs.

Current and future markets

Current global markets are large: chemical vapour deposition equipment has an annual sale of almost \$5bn with an estimated annual growth of 11%, (though this is volatile, since it is driven mainly by the microelectronics industry at present). Scanning probe microscopy sales are estimated to be \$500m; molecular modelling software almost \$2bn. All of these application markets are likely to grow considerably – demand for such instrumentation is likely to take off considerably when the mass production of nanotechnological devices starts in earnest.

Technical challenges

The major technical challenges identified in this study include:

- Chemical analysis methods for sub-100 nm lateral resolution levels (e.g. extensions of current STM, EDX, AES methods);
- Chemical analysis methods that will work in poor vacuums (these are particularly important for biological applications);
- Surface patterning techniques that will permit rapid embossing, stamping, i.e. contact printing nanoscale features over areas that are large in relation to the nanoscale (this can be compared with semi conductor wafers produced by step and repeat);
- Developments of tools and standards for nanometrology for quality control, etc.; required here are faster systems; progress in nanopositioning (transition and actuators) to characterise 3-D topography at the nanometre level, as well as characterising functionality of systems combining physical, chemical and biological functions in bio-NEMS systems.

Global competition

The application area features a very wide range of skills that are required for a wide range of products. No one country is pre-eminent in all of these applications. The USA, Japan and Germany each lead in some areas. Germany is in many ways similar to the UK in its academic research and commercial environment – like the UK, Germany faces skills shortages - scientific and engineering staff training numbers are too low, and students attracted by other careers. But it does feature specific strengths - having a major SPM manufacturer (Omicron) and semiconductor manufacturing (Siemens), and thus a strong MEMS industry. These strengths are shared by the US and Japan, which are also less liable to be heavily impeded by skills shortages.

4.1.5 The UK's profile

Instrumentation has long been an area of strength for the UK. There are strong UK academic research groups and world-class companies operating in many of the nanotechnology-related areas, supplying the instrumentation to facilitate world markets (e.g. in the semiconductor manufacturing industry). But the UK critically lacks a commercial SPM manufacturer. It also lags behind Germany in facilities for microfabrication such as MEMs foundries.

Both UK and Germany have strong nanosurface academic research and indigenous world-class manufacturers of instrumentation for chemical analysis of surfaces. In nanopositioning and nanometrology areas, too, each country has a world-class company developing nanometre domain

displacement actuators and translation stages, and national standards laboratories active in these fields. The UK's leading companies here are relatively small and few, running the risk of overseas acquisition.

Challenges for the UK

A central point made concerning this application area was that the UK's lack of a semiconductor manufacturing industry means an absence of commercial microfabrication facilities, limited exposure to MEMS development; and no home manufacturer of SPMs (which are vital to much of the instrumentation and tooling here).

The UK companies serving this application area are fairly disparate and mostly oriented to very specific niche markets. One implication is that alliances between them would not seem to be particularly profitable as a way to greater strength, in most cases. The threat of acquisition has been noted above. Shortage of scientific and engineering staff caused by better job and remuneration prospects in other careers, is a pervasive problem: the UK lacks Fraunhofer-type institutes to train and nurture skilled engineers and technologists.

4.2 2006 - a credible but optimistic view

Drivers of change

A major driver will be **demand for the applications from industry**. The emergence of techniques and devices from the research laboratories with real world applications will drive efforts to mass-produce them in a cost effective manner. Instrumentation and tooling will be required to manufacture and characterise the new products, while a coherent measurement system will be required to underpin trade and promote a viable market. As an enabling technology, much of the output of this application area is less nanotechnology-based products per se, but rather tools and techniques that enables those products to be produced. The area has high (entry) tooling costs and lots of different tools are needed. Development of instrumentation, tooling and metrology is liable to be shaped by the applications areas that emerge in other areas. These applications – some of which are treated elsewhere in this report - will be strong drivers for the instrumentation industry; conversely the availability of tools for large-scale manufacturing might be key enablers for markets to develop. The commercial success of new nanotechnology based products requires instrumentation, tools and metrology systems to support their efficient production.

As new techniques emerge, many opportunities for disruptive technologies - which can render old methods, old products (and perhaps old companies) rapidly redundant – are liable to emerge. The UK can have fresh opportunity in these areas to have world class market impact. The new techniques are likely to involve volume manufacture, making 10,000,000 devices cheaply – e.g. by *soft lithography* (contact printing) methods. The technological infrastructure will be needed to capitalise in these areas and the availability of Micro Electro-Mechanical Systems (MEMS), Nano Electro-Mechanical Systems (NEMS) and even Bio-NEMS foundries will be an important driver. The ability to have exquisite control of the production of chemical products at molecular levels but on a large scale will be a driver. Examples of specific product areas that will be supported by such disruptive technologies are devices to enable new means of energy production and storage to new approaches to food manufacture, and for new chemicals for use in personal products.

Market pull will be important - without the tools, nothing can be made. But the costs of developing the instrumentation and tooling necessary for nanotechnology based manufacture are often too high and too risky for companies to undertake without a clear high volume market for the end product. Some markets which do have this characteristic are the 'fast moving consumer goods', such as foods, drugs, micro electronic systems and devices. These are likely to spearhead the use of the applications, enabling costs to be progressively reduced.

4.2.2 *What will success look like?*

A success scenario can be characterised in the following terms:

- In 2006 the UK instrument and tooling industry will be selectively serving global markets for these applications in areas where the UK is strong – for example, drugs, optoelectronics, solar power, healthcare.
- There will be opportunities to create major new markets where there are disruptive technologies, such as in soft lithography and software modelling. (These will create both threats and opportunities for other parts of UK industry.) High-resolution lithographic equipment will be available (including soft lithography, e.g. nano-contact printing) producing 50 nm scale devices over surfaces of 25 mm and more (thereby producing 10,000,000 devices on the surface). Software (organic) models will be available, with the UK's share of the market growing rapidly from a base of 25%. However, the UK will not manage to gain a significant presence in the scanning probe microscope (SPM) market.
- There will be global markets with a high export content. These will be served in the UK by new start-up companies, in a non-traditional industry using new technologies. The skilled people to service these markets will be available as a result of initiatives to address current shortages. The infrastructure (foundries) to fabricate demonstrator products will be in place, serving a growing SME base.
- A new paradigm will emerge in chemical and biochemical production methods. This will be based on the use of nanotechnology and nanotechnology-derived tools and instruments that provide manufacturers with exquisite control over structure and reproducibility. This type of production will generate less pollution, as well as supporting many new products. The new paradigm should eventually have major effects on GDP, but these will only become apparent on a timescale beyond 5 years.

What will enable us to get there?

Critical factors that can enable the realisation of this scenario will be the availability of skilled people and fabrication facilities, along with a market structure which responds to the likely disruptive nature of the technologies (such as with a strongly supported SME base). It will be necessary for industry to capitalise on the innovative academic resources. Ways will be needed to work around the small size of the UK semi-conductor industry, and the problems this entails.

Another important enabler is finance for the development of these applications. "Joined up" government in the area should address this, and especially the perceived gap in infrastructure and funding for producing demonstrators.

How will we know we are on track?

If the scenario is to be achieved we should see developments in the years from 2001 to 2006 along the lines of those reflected in the following indicators:

The increased application of 'top down' ultra-precision machining to a huge range of industrial manufacture, improving numerous "traditional" high technology products as well as generating new products.

2. Co-ordinated commercial facilities would be established that service growing SME start-ups in the area. Such facilities would enable demonstrator production and manufacturing, and use of MEMS fabrication technology. They could also be facilitating new disruptive NEMS and bio-NEMS fabrication tools. Indicators relevant to this could be that such a facility would be:

- generating new spin-offs and start-ups growing at a tenfold increase per year from a base of SME
 - enabling training of 50 or more new designers and nanoengineers per year
 - providing prototyping & small-run manufacturing for 50 new customers per year
3. The UK's share of software modelling for the nanotechnology market will be growing at 10% per year from its current base of 25%, by 2006.
 4. The first novel material or structure based on these applications will have been developed and mass-produced in the UK by 2006.
 5. More than 5 UK companies will be using directed self-assembly based on 'disruptive' methods (e.g. soft lithographies) as a routine tool by 2006 (from a base of 1 today).

4.2.5 *What do we need to do to make it happen?*

A range of illustrative actions are outlined below:

- Establish institutes that are closer to Fraunhofer than to Faraday model; provide these with start up funding of £50m (on a government / private-public partnership basis)
- Preferential grant treatment for science, technology and engineering students (in addition to government, industry could play a role in funding schemes)
- Training programmes for science teachers in schools oriented so as to encourage more awareness of, interest in, and recruitment of promising students into fields related to this application area. (Again, in addition to government, industry could play a role in such schemes)
- Technology roadmaps should be developed and improved in a range of nanotechnology areas, to help pull through demand for specific instrument technology and indicate the required tooling and metrology infrastructure that will be needed for production – taking account of possible disruptive technologies. There is a role here for UK government, the EU, academics and RTOs, and industry.
- Research Councils should fund directed research programmes in the manufacture of novel structured materials.

EU institutional funds should be acquired to support equipment validation (an example suggested here is the SEA initiative). In the first place this would involve Industry and RTOs, but ultimately this would be an opportunity for Fraunhofer institute type organisations and support facilities as discussed above.

5 Novel Materials

Materials in the nanometre size range exhibit fundamentally new behaviour, as their size falls below the critical length scale associated with any given property. Intervention in the properties of materials at the nanoscale permits the creation of materials and devices with hitherto undreamed of performance characteristics and functionality. The interface itself between the nanoscale 'building blocks' and even the voids can be critical to creating new performance characteristics.

One particularly exciting area of new materials development involves combining inorganic and organic materials in a variety of ways to provide novel properties. Other promising areas include intercalating polymers with other materials that can be introduced into living cells; research into sol-gel technology for creating functional coatings and other new materials; using biomimetic techniques for the creation of stronger and lighter functional materials, etc.; and 'smart materials', which will have wide applications.

Nanotechnology is therefore leading to the development of novel materials with extraordinary properties. More functionality will be achieved with less material, and often with longer-lived, more durable materials. There will be opportunities in both bulk and niche manufacturing and markets, with high net returns viable in each sphere.

5.1 The current position (in 2001)

5.1.1 *The application area*

Innovation in industrialised nations has a major dependency on materials. Consequently, novel materials will feature in numerous application areas, with a huge range of end-uses. There are several routes to applications. Below are some of the leading routes:

- Nanostructured materials based on processing of nanoscale powders, for improved hardness and toughness improved performance and functionality. (Timescale: current - 2 years)
- Nanolayered composite coatings which may have from a few to hundreds of thin layers (5 - 20 nm) of different materials giving improvements in toughness, hardness and durability, with applications in machine tools and in thermal and optical applications. (Timescale: current - 2 years)
- Combining inorganic and organic materials in a variety of ways to provide novel properties. For example, novel characteristics at the interface between surfaces can dictate such properties of the material as a whole as stiffness, temperature resistance, toughness and electrical properties, while requiring very little bulk material interaction. Controlled dispersal is the key, and may be accomplished by self-assembly or bottom-up techniques. (Timescale: 2 years)
- Intercalating polymers with other materials (DNA, drugs, fluorescent substances) that can be introduced into the living cell for toxicity testing, drug delivery and drug performance analysis. (Timescale: 3 - 5 years).
- Sol-gel technology for creating functional coatings and other materials, where inorganic and organic components can be combined in a variety of ways to provide customised properties. (Timescale for new materials: 3 - 5 years).
- Biomimetics for stronger and lighter functional materials, through scaffolds combined with layered structures for high strength structural applications, such as artificial bones and teeth. Another field of application is biocompatible adhesives. (Timescale: 3 - 5 years)

- The integration of novel materials with sensing, processing, actuation and control techniques that respond to external conditions, creates smart materials, which have lifestyle applications (smart clothing and personal diagnostics). (Timescale: 3 - 5 years).

Nanoparticles for nanoparticle-based biosensors, for self-assembled nanoparticle arrays and as a means of creating dyes and inks with spectacular properties. (Timescale: 3 - 5 years)

Current and future markets

There is a large and rapidly growing market for new materials - including speciality chemicals, catalysts, pigments, coatings, ceramics, ceramic powders and metal oxides. In 1994, the estimated world demand for advanced ceramics for the year 2000 is over \$25 bn, with an annual growth rate of 7.2% bn. The total value of the US advanced ceramics component market was estimated for 1996 as \$6.3 bn, and expected to increase to \$9.2 bn by 2001 (growth rate of 7.9%). Of this market, the electronic segment comprised 66% in 1996, chemical processing & environmental ceramics 20%, ceramic coatings 8%, and advanced structural ceramics 6%. Of course, as applications proliferate, this market structure is liable to change. In the UK major markets for materials (including paints, pigments, ultrathin coatings, fillers & additives, anti-corrosives, adhesives, biocompatible materials and ceramics) include medicine, telecommunications, construction, electronics, aerospace, automotive and defence. The future chemical industry globally will employ novel materials using nanotechnology as the basis of commodity products for large user companies (optics / display / automotive, etc.).

Technical challenges

The key technical challenges identified in the study were:

- Design, synthesis, characterisation and property evaluation of nanocomposites, nanolayered coatings and nanostructured materials using neutron and x-ray scattering, NMR, dielectric spectroscopy, positron annihilation, ion beam analysis, scanning probe microscopy and electron microscopy.
- Molecular and mesoscopic modelling.
- Development of self-assembly and biomimetic techniques for nano-functional and nano-structured materials.
- Establishment of knowledge concerning use of sol-gel and colloidal chemistry as the basis of novel functional materials.
- Controlled nanoparticle production (in terms of the size and features of the nanoparticles), i.e. reproducibility, reliability and scalability; the development of directed deposition techniques and new methods of catalyst characterisation.

Analysis and emulation of biological deposition techniques (i.e. application of biomimetics to novel materials).

Global competition

This is an application area where it is of limited value to generalise across a wide range of specific application fields. It is also quite difficult to isolate UK performance from Europe. Taking some leading classes of materials:

In *biomaterials* the US is at the forefront in tissue engineering and advanced controlled release. In other areas of such as molecular sensors and diagnostics, Europe is in a strong position.

- In *ceramics*, Japan and the US lead. Japan dominates in manufacturing, the US in basic research; and there is also strong research and development activity in Germany. There is

much attention is paid to new materials in the US, and a recent benchmarking activity on materials highlighted nanostructured materials as an important growth area.

In *magnetic materials*, research has declined in the US, but Europe and Japan have sustained their interest in these fields, and invested in infrastructure

- In *metals*, with new developments in synthesis, behaviour, performance, processing etc, the US is leading in many areas, but the UK as well as France, Germany and Japan are recognised as having significant capability.
- *Electronic and optical-photonic materials*: in the area of semiconductor technology, the US does well, but Japan leads in most areas of display technology. Nanotechnology is leading to materials with unusual electronic and optical properties derived from their feature sizes; many of which are being developed in the US. Organic materials (polymers) have become the subject of much exciting research is receiving global attention, and the US is not expected to lead in this field. However, in many other optical-photonic and electronic areas, the US has benefited from facilities set up by the NSF.
- *Polymers*. There is strongly developed research in Germany and Japan; and the US is slipping due to short-termism in this area. However, main areas of growth include separation media, barrier coatings and packaging; drug delivery and implants, displays and resists.

The US benefits from fast-tracking innovations through 'development companies' – which link industry and research, and survive mainly on state projects. These companies take research ideas from universities and turn them into commercial 'products' that can be sold on. Germany was arguably the first country to use nanotechnology as the basis of new materials development, though according to some commentators the industrial environment is presently not conducive to rapid growth. Several networks exist which bring together companies and research organisations for exchange of information, which is particularly helpful to SMEs.

Germany has major nanomaterials users such as VW, and Daimler Chrysler in the automotive sector; Bayer, Merck, Degussa, and BASF in Chemicals, other companies such as Henkel and features SMEs in high-technology areas such as optics, electronics, and data communications, together with large electronics companies such as Siemens and Bosch.

The UK's profile

Overall, the UK's position in materials is widely perceived as being relatively weak, but as improving in several respects. There are strengths in polymers, catalysts and biocompatible materials, and in the underpinning colloidal science. The UK has leading companies in coatings and hard materials, and real strengths in producing some nanoparticles (e.g. metal) and in creating catalysts. Much innovative work is underway in academia; some firms, including several small and medium firms (some being new start-ups) are particularly active, though major users are not prominent. (In Europe generally, new materials are utilised through SMEs.) - In the UK, it is likely that applications of nanomaterials will be pulled through by the aerospace, biomedical and defence sectors. This is an application area where most applications are not dependent on a large electronics industry, so the relative weakness of UK here is not a major issue. The UK's academic community in biomimetics has a large potential for commercial development, which needs to be catalysed.

Challenges for the UK

The science base here is seen as excellent, but may be jeopardised by a threatened brain drain, and slow translation into commercial products. Skill shortages are a problem in this application area as others, and core physical sciences (chemistry, physics, materials science) have had recruitment problems of late. New materials development in the future will be the product of multidisciplinary research. It is not just that we need to ensure a stream of scientists, engineers and technicians for

future industries based on novel materials; these professions require an interdisciplinary perspective: and work in multidisciplinary teams. Points almost identical to those made in the discussion of informatics, above, were made concerning the requirements for cross-disciplinary communication to support the necessary fusion of knowledge associated with commercialising these applications of often-compartmentalised knowledge. New approaches to research and education are needed to establish the right balance between specialisation and interdisciplinary training, and new methods in managing these new ways of working.

Most UK companies are still in the early stages of deciding what their strategy will be in nanotechnology; so most research in universities is speculative, and links between the research base and industry are still underdeveloped in the main. The research councils do not require that individuals commercialise their research, and offer them little help to do so. Better linkages are required if the UK's research strengths are to be reflected in (more costly) development; and the model of the US development companies could be worth emulating. How will funding for commercialisation emerge, given a perceived bias in the UK against manufacturing, and a weak materials industrial infrastructure to pull developments through?

5.2 2006 - a credible but optimistic view

Drivers of change

Two drivers were highlighted as particularly important. First was **access to materials technology**, the rationale for this being the importance of materials in underpinning innovation in manufacturing, medicine, construction, and some services industries. As in informatics, manufacturing *capability* was seen as critical here – “if you can't make it you can't sell it”! – one key strength in Japan. A central issue is the ability to make new materials, and to develop such materials in such a way that IP is defensible. Priorities have to be defined about which types of novel material and applications to focus on. The UK has some very clear strengths and larger companies – especially chemicals, pharmaceuticals and other medical companies, which can use new materials. (It will be important for such companies to examine the potential environmental impacts of various materials, alongside purely commercial considerations). As noted, the development and management of appropriate (sets of) skills is vital also.

The second driver considered important here is the roles of **local and global markets and competition**. These markets are the source of economic value for the applications; and drive much of the science. Given the wide range of materials applications, the probable routes to market are either through existing world class players, or new companies with niche market potential. The relative size of different opportunities would be valuable for setting priorities. The new products will need to move through, and gain acceptance by, supply chains – which means winning support from pivotal actors in these chains. They will need to be convinced that nanotechnology can deliver benefits as compared to other approaches and demands for investment.

Some of the specific applications that could be anticipated (apart from the obvious) are in such fields as housing, security, transport, communication, space technology (the Government has just announced a £10 million investment in space research) and the health sector. There are links with sensors and drug delivery systems. By 2006 we could expect demonstrators to be showing key aspects of applications of novel materials in healthcare, IT systems, and in new processing technologies.

5.2.2 *What will success look like?*

A success scenario can be characterised in the following terms:

- By 2006, UK industry will play a role in commercialising achievable consumer products, such as those in drug and fine chemical processing, cosmetics, durable and self-cleaning surfaces, informatics, novel decorative effects and functional coatings.

- Demonstrators should emerge from the new Interdisciplinary Research Collaborations (or other developments) that help to establishing the viability of new nanotechnology products and of the IRCs themselves. Demonstrators will also be useful for introducing UK companies to the new technologies they will need in order to maintain competitiveness.

R&D in the area will be increased substantially, with government and industry support. Strategic investment in commercially viable areas will be in place, with long-term benefits for UK industry firmly in mind.

- Critically, industry and the utilities must be prepared to buy innovative UK products (water industry, the National Health Service, transport etc) or development will be arrested before it starts.

While, in the longer-term, nanotechnology products are liable to become cheaper and easier to produce, the putting in place of basic manufacturing techniques is likely to remain high cost in our time horizon. It is anticipated that the UK could have a significant presence in some of the new markets – for a success scenario, the number of these markets, and the scale of the UK presence, should both be growing. This will require investment, the ability to formulate novel materials and development of know how to undertake processing.

What will enable us to get there?

To make this scenario a reality it will most centrally be important to attain a **critical mass of commercialisable research** efforts in some areas of novel materials, linked to sustained industrial pull-through in the applications. Since the span of applications and of the novel materials themselves is very wide, choosing specific areas to focus on can be difficult. But there is an immediate role that could be played to expedite the process of focusing research and entrepreneurial interest on promising avenues for progress. This involves rapidly preparing “roadmaps” and similar tools for benchmarking and identifying critical areas where technical opportunities coincide with UK industrial strength, capabilities in research and commercialisation, and market opportunity. This will help enable the necessary convergence between the high quality research that exists, and must be maintained, and the concerted investment in the field that is necessary.

This is on the understanding that the best or most useful research does not necessarily occur in universities! Most useful research (in the sense of being close to applications) comes from industry, and some of this is among the best research in terms of scientific quality and approach to fundamental problems.

How will we know we are on track?

If the scenario is to be achieved, we can expect to see developments such as the following:

- In the very near future, a matter of months, existing roadmaps for nanotechnology would be considerably improved or surpassed. These roadmaps would enable innovators and entrepreneurs to form more soundly based views of the sustainability and profitability of various applications (i.e. to undertake “value modelling”), and allow researchers and educators to identify training needs and infrastructure requirements. The European context of UK activities in the area would be firmly established.
- In a slightly longer timescale, but still months rather than years, well-grounded position statements would be produced for Research Councils and other bodies to identify major research areas in terms of costs, timescales, resources required. Provision needs to be made for non-university based research support.
- Also in the very near future – less than a year – new incentives for helping the creation of SMEs and spin-offs in the area should be established.

- Following the above, within 2 years we could expect to see a national infrastructure for novel materials research – including commercialisation facilities – being established, with appropriate levels of investment and training provisions. (“Sustech” in Germany is in many ways a model for this). A related step, which could already be in place within 6 to 18 months, would be the identification and establishment of centres of excellence in the field, including industrial centres.
- Results that should then follow could include, for example, the generation of 7 commercialisable new products and processes by 2006, with clear paths to the market, and 3 demonstrator projects for applications already in place. (New manufacturing processes employing novel materials should be developed in the relatively near future (say 2 – 3 years), and a significant market share in the product and process innovations should be readily detectable).

5.2.5 *What do we need to do to make it happen?*

The illustrative actions outlined here are related to the indicators presented above:

- Production of roadmaps and analyses of key research areas requires that an impartial but knowledgeable body marshal and co-ordinate relevant area experts. They can also be used to inform our key representatives on European fora as to lines for development of EU programmes (as well as using such representatives as sources of information about these programmes and their rationales and likely evolution).
- Industry needs to take action to move new products through the development stage, apply novel materials in processes and ultimately to achieve significant market share. Policymakers and other relevant information bodies need to take steps to ensure greater industrial awareness and understanding of the scope for nanotechnology to enhance products and performance: roadmaps can be useful for such communication, but need to be supplemented by a great deal more.
- Funds should be set aside for building the infrastructure and demonstrators: this will need to involve inputs from the DTI, Research Councils, and industry.

Appropriate incentives and early stage assistance for industry, SMEs and spin-offs in the area are mainly a matter for the Treasury, though attention can be paid to seedcorn funding and similar mechanisms.

There needs to be willingness by traditionally conservative buyers in service industries to purchase innovative products.

6 Sensors and actuators

There are wide ranging applications across the economy for sensors that can support industrial processes (and those in construction, extractive industries, agriculture, health care, and the like) and be incorporated into new or existing products. Sensors may model various parameters, including:

- physical parameters (temperature, displacement, acceleration, flow etc.);
chemical and biochemical parameters (gas/ion/molecular concentrations, molecular interactions)

The application of nanotechnology to this area should allow for improvements in functionality (in particular, new biosensor technology can be combined with micro and nanofabrication technology, with a huge range of potential applications) and of much decreased size (enabling them to be integrated into many other devices). Sensor/actuator combinations will deliver “smart” and precise functions in products and processes. There is also liable to be considerable interest in actuators which give controlled, precise nanoscale movement. For example, nanofabrication and inspection tools require sensors and actuator systems capable of positioning objects with nanometre accuracy. Sensors and actuators thus in part constitute another enabling technology.

6.1 The current position (in 2001)

The application area

There are large discrete markets for sensors and actuators in several sectors with overlapping requirements. Among the largest of these are: health (where nanotechnology applications will yield quick diagnostics, novel implants and surgical devices), the automotive industry (improved safety and comfort features), aerospace, consumer electronic goods, and IT peripherals, of growing importance are liable to be food (improved monitoring of safety), and in environment applications (improved monitoring ability). Two of the most promising area where growth is extremely likely - biosensors and MEMS sensors - already draw on nanotechnology.

Many key future developments depend on shrinking the dimensions of products, and of the things they measure and transformations they effect, from the micro to the nanoscale. In addition to this miniaturisation, another major development trajectory is the successful marriage of biotechnology and micro/nanotechnology fabrication techniques. This would underpin numerous applications in health, environment, and related fields.

Current and future markets

Biosensors are still novel products, with, so far, only a handful of products on the market worldwide. We anticipate considerable growth in the markets for such products, but as many of them will be extremely new to the market, it is very hard to forecast the scale of this with any confidence. If the history of microelectronics-based sensors and actuators is anything to go by, we could expect massive markets to open up rapidly. For example, a number of established highly successful MEMS sensor/actuator products have world markets in the region of \$30bn.

However, for the immediate future nanotechnology products are liable to be relatively expensive. Manufacturing costs of sensors and actuators tend to be high - thus successful products will need to be produced in high volumes to achieve low cost products. If this can be achieved, markets are liable to be huge. The question is whether their increased capability will be sufficient to open up large markets

fast – and thus engender a rapid decrease in costs? A related question is whether there will be scope for small firms to produce sensors and actuators based on nanotechnology?

6.1.3 Technical challenges

The major challenges in the manufacture of these devices were identified as:

- Achieving greater affordability (e.g. in progression from MEMS to NEMS, nanoscale surface structuring over large areas)
- Achieving greater reliability (e.g. of manufacturing routes, and repeatability of functional responses)

Developing effective biocompatible materials, materials for harsh environments, packaging and integration into macro systems

Fostering a successful marriage of bio and micro/nanotechnology technologies

6.1.4 Global competition

The UK suffers one major disadvantage compared to major competitors, since these have strong Microsystems Technology (MST) infrastructures. For example, Germany has MST research strengths and manufacturing capability. There is much activity in the interface between nanotechnology and biotechnology: Germany has growing strengths and capabilities in both fields, and major research efforts are now being focused on their interfaces in both the US and Japan. More competition is also emerging from Taiwan, Korea, Singapore and China, rendering this a hotly contested field.

The UK's profile

There is considerable expertise on the design side of sensors and actuators in the UK. But there is little strength in manufacturing - MST capability largely resides in the research base, and there is a lack of skills to take ideas forward into products.

Pockets of world class research may be identified in the underpinning technologies. For instance, the UK has strengths in functional materials, nanofabrication, nanometrology, biomolecular and biomimetic technology. Exploitation of biosensor technology is being pursued by start-up and small companies, but no significant products exist yet. Industry pull for these applications is not as strong as in competitor countries.

Challenges for the UK

Despite the difficulties adduced above, there is potential for technology to be developed, for example, through spin-off companies. A number of organisational changes could improve the climate, particularly more seed funding, and better technology licensing arrangements. As noted in other application areas, links between users and the research base are not seen to be very effective. Skills shortages have also been identified as a problem once more, particularly manufacturing skills as well as multidisciplinary skills; in addition low workforce mobility may be a problem.

The challenge will be to maintain and develop a strong UK research base, in such a way that it can complement areas of strength in the industrial base. This is needed to give the UK a leading position and good world market accessibility in these fields, while the US is hampered by ITARs.

2006 - a credible but optimistic view

Drivers of change

The availability of a wide range of increasingly sophisticated but cheap sensors will promote increasingly complex monitoring systems. The system builders rather than the sensor designers will drive the applications. Sensors will permeate all levels of society. Three major drivers can be cited – health, security, and environmental concerns.

A first driver for the adoption of nanotechnology-derived products in this area will be **health** - our concern for a greater quality of life to a greater age. The population of the developed world has increasing life expectancy, and should be prepared to invest their increasing wealth to maintain their health further into old age. As the new technology becomes more commonplace and more affordable, demand for such products will increase from all parts of the world. The market is demand led and long term – “the more you provide the more they will want”. Examples of specific applications that will emerge are personal health monitors, devices for on-site trauma treatment, devices for a ‘barefoot doctor’ and a wide range of aids for geriatric care.

A key issue for this driver is increasing the availability of the technology - reducing cost of each use and increasing accessibility. The primary restraint on the driver will be the clinical approval of the systems that emerge both for safety and cost effectiveness. The driver will also be restrained by concerns over how the vast amount of data that could be collected will be interpreted and collated. There will be conflicts between personal privacy and the interests of society as a whole.

Security is the second driver here. In the same way that nanotechnology-based sensors can provide ever more information on a person’s state of health then they can also be used to provide more data to confirm a person’s identity or indicate the provenance of an object or document. Systems using these sensors will be used increasingly for protection and to detect fraud. Examples of specific applications that will emerge are: people sensing, asset tracking and identification and chemical and biological agent detection.

A key issue for this driver is reliability - false negatives are unacceptable, while too many false positives cause stress and inefficiency, and quickly cause warnings to be ignored (“crying wolf”). The primary restraint on the driver will be public acceptability - concerns over privacy and civil liberties will dominate.

After monitoring ourselves for signs of failure, and others for signs that they intend us harm, our attention turns to our **environment** which we will want to monitor for changes that could threaten us, our descendants, or features of the natural world that we cherish. Examples of specific applications that will emerge are systems for monitoring and controlling industrial processes and waste dumps. Other distributed systems will monitor large areas looking for unexpected changes but they will depend critically on the technology to network a large number and variety of sensors, correlate the readings and produce reliable interpretations.

A key issue for this driver is regulation, which is a major incentive pressuring polluters (or other responsible parties) to monitor emissions, environmental impacts, environmental quality, etc. The primary restraint on the driver will be the cost of the systems - the lower the cost, the more parameters will be monitored.

What will success look like?

A success scenario can be characterised in the following terms:

- In 2006 the UK will be taking the lead in supplying integrated multi-sensor systems. The UK will be strong in sensor development though manufacture itself may be global. The industry

will be characterised by niche sensor developers supplying large company system integrators, although there is potential for global consolidation in later years.

The industry will depend on multi-function sensors (that can be used across multiple species, for example, to detect multiple agents). Detectors that are required in large volumes will be supplied from numerous sources from across the world; while tied suppliers will supply high specification detectors for niche products to the system integrators. Developments in sensors will be driven by what the technology can provide; developments in systems will be determined by the requirements of a given application. The customer will typically approach the system developer to design a system to meet some general objectives, rather than a sensor maker to produce a specific detector. The IT tools to support systems and data analysis will need to be developed in line with the sensor development. Here the UK strengths in fields such as neural networks will be a significant advantage.

Reliability is essential in the key application areas and regulation and after sales service will be key differentiators in meeting insatiable market demand.

Overall the scenario should be characterised by healthier, safer people.

What will enable us to get there?

The quality of research that can be accessed by UK companies is a critical feature here; but so, too, is access to appropriate sources of finance (especially for technology demonstrators), and supportive policy frameworks for the health service and other public sector markets. Other important factors include the availability of skilled people, access to fabrication facilities, regulation (environmental, health and safety, etc.) and the organisation of the industry and markets. Rather less important, but nonetheless significant enabling factors include instrumentation and standards, ownership of research (public/private and issues of intellectual property regimes) and the public acceptability of innovations (especially in the light of privacy concerns).

How will we know we are on track?

If the scenario is to be achieved we will see the following indicators in the years from 2001 to 2006:

- 10% per annum growth in the population of trained graduates in relevant areas of UK nanotechnology. (This requires output, recruitment and retention to all be addressed).
- 100% increase in the funding for technology demonstrators by 2004.
- The first major health field trials of nanotechnology-using systems - such as an integrated network of sensors - in a hospital by 2004.
- Demonstrated improvements in research and development related to this area, e.g. publications, citations, IP increasing by 25% by 2004 and 50% by 2006.

The UK share in nanotechnology-based sensor systems growing faster than our main competitors by 10% per annum in 2006.

What do we need to do to make it happen?

If the scenario is to be achieved the following actions are required:

- More funding needs to be available. More precisely: a considerable increase – perhaps a doubling – of research funding for sensors and actuators by 2004 (this is a task for the government and Research Councils); new lines of funding for technology demonstrators (the responsibility here would be shared between capital markets and government departments such as the DTI and DOH); and industrial investment in prototype systems.

Universities should be encouraged to support the area. Practical steps include: liberation of university staff time for R&D (which again could involve funds from government and industry to “buy out” staff time); longer term funding for individuals who can demonstrate the quality of their work and its relevance to user requirements (from Research Councils); improved graduate support (one suggestion is “golden hellos” such as debt clearance – again government and industry could contribute to this).

- Regulations should be reviewed to examine their impact on innovation in this field. In some cases more rapid approval process (ensuring that a device meets regulatory requirements) need to be instituted, though it is critically important to retain public confidence in the regulations. Government and industry panels could perform such an inspection, and social scientists might input knowledge concerning public perceptions of risk and trust or distrust of expertise and different regulatory frameworks.
- Mechanisms to foster more effective technology transfer and better communication of technological opportunities and user requirements – the responsibility is shared between universities, government, and industry.

7 Tissue Engineering, medical implants and devices

Drug delivery is far from being the only medical application area for nanotechnology – some of the applications of sensors and actuators are in the health area, as we have seen above. This section of the report goes on to discuss applications to medical equipment, and in the important area of growing and restructuring living tissues.

There is considerable investment in the alleviation of the effects of degenerative disease in Western societies whose population is ageing, increasingly aware of advances in medical technology, and seeking access to more effective new treatments. Nanobiotechnology offers the key to faster and remote diagnostic techniques - including new high throughput diagnostics, multiparameter, tuneable diagnostic techniques, and biochips for a variety of assays. It also enables the development of tissue engineered medical products and artificial organs (heart valves, veins and arteries, liver, skin, etc.). These can be grown from the individual's own tissues via stem cells on a 3-D scaffold, or by the expansion of other cell types, either autologous or allogeneic, on a suitable substrate. Nanobiotechnology provides methods, too, for compatibility testing of organs from donor animals and humans, to new materials for replacement bone and teeth. Nanobiotechnology is also paving the way for retinal, cochlear and neural implants and nanopatterned substrates to encourage the growth, regeneration and repair of tissues. These are dramatic new developments in medical treatments, with huge scope for diffusion.

7.1 The current position (in 2001)

The application area

The applications which seem likely to be most immediately in place are external tissue grafts (e.g. artificial skin); dental and bone replacements; protein and gene analysis; internal tissue implants; and nanotechnology applications within in-vivo testing devices and various other medical devices (e.g. for surgery). Nanotechnology is applied in a variety of ways across this wide range of products - smaller chip arrays will ensure faster analysis for proteomics and genomics; artificial organs will demand nanoengineering to affect the chemical functionality presented at a membrane or artificial surface and thus avoid rejection by the host.) More futuristic developments such as nanorobot therapeutics have been the subject of much speculation and publicity, but do not seem to be within our time horizon.

Current and future markets

The demand for medical devices has been growing rapidly, especially in the developed world, and will continue to expand as the population ages and expectations of healthcare grow. Emphasis will grow on tailoring treatments to particular patients, whilst keeping costs low: miniaturisation is key to this and to devices which lower waste, speed up diagnosis and minimise discomfort. Tissue engineering will attract increasing attention. Estimates of the total cost of biotechnology products represent around \$50bn per annum, with nanoaspects of this contributing perhaps around 1% of this total. It is anticipated that this contribution will double in the next 3 years, as well as the whole sector continuing to grow. Investment in the bio- and nanotechnologies that can underpin the next batch of applications is seen as critical for UK manufacturing in this field. The integration of science and medicine will intensify.

Technical challenges

Research is required across a spectrum of technically challenging fields. More work is required to improve capabilities of creating and working with nanofunctionalised materials and surfaces, and achieve novel surface patterning. Nanobiomimetics is seen as an important locus of development, where understanding and applying the structures and processes already evolved naturally at the nanolevel is a vector of creative effort and applications development. More generally, improved understanding of tissue structure and functioning is essential for progress, and proteomics is seen as a particularly important field for development.

Global competition

The US has considerable strength in relevant high technology areas. There are numerous conferences and workshops, and the intellectual level is high. The US utilises imported labour much more than the UK, and is a particularly attractive base for many. (However, restrictive regulations on stem cell research may drive some researchers to the UK.) The US strength in microfabrication makes it plausible that most of the leading hardware products will emanate from that country. Another factor tending to foster US leadership in developing applications in this area is its large private health care system, which allows for expensive treatments. Biotechnology is also a major US strength, and its coupling with nanotechnology provides a subject that is at a level where investment and skills are at a premium. Thus in tissue engineering, nanotechnology is applied in concert with other technologies, such as microtechnology and molecular biology. US investment in high technology is strong and funding is reportedly more simply organised - through the NSF as opposed to the multitude of funding bodies in the UK. There are relatively numerous US companies in tissue engineering, and their applications seem to be closer to market.

The UK's profile

The UK will be a large user and – despite the US strength noted above - producer of these applications of nanotechnology. They draw on areas of UK traditional strength (especially in basic sciences - biology and biochemistry). The UK has a strong science base in molecular biology, and drug discovery expertise. The UK is internationally strong in pharmaceuticals, and in medical devices, facilitated by collaborative research between industry and academia. Networks in the UK are good when well organised, but there are problems in developing interdisciplinary teams: the investment in IRCs should produce world-leading science, but the US is already at the frontier. The analytical side to nanotechnology aspects of tissue engineering is very important, and the UK can make a big impact in terms of innovating new methods. The levels of investment for tissue engineering in the UK are roughly proportionate with the total spend in nanotechnology (around 15%). The UK has been slow in exploitation of this research compared to other countries such as Japan and the US; it is feared that the decline in the numbers of science graduates may reduce this further.

Challenges for the UK

Among the major risks to the UK in these application areas are the danger of aggressive acquisition of UK companies by other countries. The prospect then is for the commercial exploitation of knowledge generated in the UK to be largely taken out of the country. Another problem that can lead to discoveries going abroad is IPR protection. The lack of microfabrication efforts and facilities, coupled with skills shortages and poor exploitation strategies, threatens existing areas of excellence.

7.2 2006 - a credible but optimistic view

7.2.1 *Drivers of change*

Two clusters of issues were thought to be important here. First, **Market demand** is of course a central force, probably being manifest in pressure to move products forward in fields such as cochlear implants, in-vivo monitoring, artificially created organs, retinal implants, nerve regeneration and wound healing, and needle endoscopy/delivery of nano-products. The ageing population will drive demand for “spare parts”. While health demands are growing, and improvements in delivered quality of life are feasible, medical staff shortages are a problem. Thus, there is also pressure to adopt more labour-saving and effective techniques in the NHS and elsewhere – for example by faster and more accurate diagnosis, more rapid surgical techniques, products that can be used on an out-patient basis. Note that many of the markets here are combinations of public and private decision-making (regulatory and ethical issues could be very important), and are global ones (implying also global competition to produce and supply successful products.)

Second, for these market pulls to shape the application area productively, **Access to technology** is critical. This may prove the limiting factor in development. Nanotechnology may itself be an enabler for breakthroughs in other areas, but without breakthroughs in other areas, development of nanotechnology-based tissue engineering and medical devices in the UK may be limited. The combination of technological challenges means that multi-disciplinary knowledge is vital (e.g. combining engineering, biology, and other fields), as is the ability to control intellectual assets through IPR and royalty stacking.

The UK has advantages in this application area, for example our large industrial infrastructure in healthcare and the NHS’s centralised purchasing system. There is a strong research base in universities, companies, and health providers, and growing experience with the successful operation of incubators and similar ways of linking research and markets. But there are also problems in capitalising on these advantages, for example shortages of management skills, the deficit in nanotechnology manufacturing capacity, and the risk averse tendencies in the NHS, rendering it sometimes slow to change and use new methods. There is some sense, too, that research remains fragmented, with breakthroughs tending to occur on a university-by-university basis more than as results of combined and concerted efforts.

7.2.2 *What will success look like?*

A success scenario can be characterised in the following terms:

- Some preventative diagnostic products will already be in use in the UK by 2006 - diagnostics in general have a less difficult regulatory route to market than do surgical / clinical devices. But certain medical devices such as cochlear implants will also have reached the market.
- The development of the sector will be largely SME driven, saving money for the NHS and other health services. A number of UK companies will be clearly profitable and achieving sustained success. More companies will be purchased by large companies for their technology – UK companies will purchase foreign companies and vice versa
- The world market will be worth some \$50bn by 2006, with the UK gaining 2% of this, mainly in niche applications (that will allow for the growth of large markets).
- IP brokerage will lead to a fewer number of better-equipped companies compared to the broader biotechnology sector. IPR alliances are liable to develop. Because IP and innovation will largely come out of quite basic research, the return on investments will come from taking advantage of niche opportunities, probably through the development of spin off companies. Investors will have achieved a return on investment of 30% compound.

- The multi-disciplinary nature of nanotechnology has been confronted with improved management and training in research and industry.

7.2.3 *What will enable us to get there?*

This scenario will be enabled to become a reality by a wide range of factors. One set of factors concerns the availability of appropriate skills. This goes beyond skills in R&D functions. As noted in the preceding application areas, it also includes more general management capabilities, being able to mobilise and motivate multidisciplinary teams and relate intellectual effort to user requirements. An important issue here is the ownership of the research, the ability to leverage access to knowledge and appropriate value from innovations. This may require new ways of working across the public-private interface. Demand is extremely important of course, and for the underlying demand for technologies that can promote greater health and deal more thoroughly with disease is the need to demonstrate the clinical effectiveness and (substantially) greater efficiency of the new products that nanotechnology makes possible.

How will we know we are on track?

If the scenario is being achieved, we can expect to developments such as the following in the years to 2006:

5 to 10 new start-ups in the UK per annum in this area of nanotechnology application

- 5 to 10 multidisciplinary groups in the field established in UK companies and universities per year

The UK achieving some 2% of a \$50bn market by 2006 (i.e. a \$1bn share)

- A growing IPR portfolio in nanotechnology in this area – perhaps an average of 100 patents per year by the end of the period

The establishment of attractive multidisciplinary training programmes in universities, and a substantial increase in the number of undergraduate and postgraduate courses with a serious and substantial nanotechnology component

- A high proportion – perhaps 85-90% - of UK-based companies in the area being run by UK managers, with new employment in the sector by 2006 reaching or surpassing the level of 1,500.
- New products have been launched onto the markets for tissue engineering and medical appliances, deriving from work carried out on as result of collaborative development programmes – perhaps an average by 2006 of one product per 8 programmes set up over the period.

What do we need to do to make it happen?

Many of the actions required to meet such targets involve concerted effort by government and universities. For instance, improved and more relevant training of scientists, technicians and managers: new courses and course content along the lines mentioned above; improved financing for doctoral researchers in this field; and better career structures for scientists & technicians in life sciences - these all require action from universities and resource inputs from the DTI, Research Councils, and even the DfEE. Similar responsibilities apply to the necessary upgrading of the quality of university technology transfer offices and related facilities. The Department of Health and NHS should be encouraged to build more awareness of nanotechnology in research priority-setting and support for research more generally. Regulatory frameworks should be examined to see how far they support or impede innovation, along the lines already mentioned in the discussion of drug delivery systems, and of sensors and actuators. Finally, recommendations that have emerged already from the Foresight process need to be circulated more widely and acted on by all parties identified.

8 Generic actions leading to success

The UK has some strengths in all of the six application areas considered above, and considerable strengths, “punching above our weight” in several of them. Some of the application areas are essentially or largely enabling technologies, which can support the take-off of other applications and many of the underpinning areas of research strength contribute to several of the applications areas. The nanotechnology train is moving, and the UK needs to retain its hard-won place in the face of intensified international competition because of the importance of nanotechnology across practically the whole economy.

The underlying knowledge involved in nanotechnology is creating numerous generic *technology platforms*, in the same way that Information and Communications Technologies, and Biotechnology, do. These platforms are bound to change the possibilities for production processes and the goods and services that they generate across a wide range of industries – in utilities such as water and in services such as telecommunications, health and environmental remediation as well as in manufacturing industry. This makes them important technologies in which to be involved, as generators of underlying knowledge, as competitive and innovative suppliers, and as effective users. At present – and in most respects in the period up to 2006, the majority of visible economic effects of this development will be concentrated on the supply side. It is likely that impacts on the user side will only become apparent as the new platforms diffuse widely. Major changes are liable to follow from experience being gained about how to implement these new platforms effectively and about what sorts of new end-markets can be created. Investment now in R&D and vanguard applications is likely to be an important factor conditioning the ability of the UK to continue to master the technologies in the decades after 2006, as the full implications of nanotechnology become apparent in industry, health services and elsewhere.

We have discussed requirements for success in each of the application areas. Now we conclude by considering some issues that were repeatedly identified in the workshop as applying to the nanotechnology applications as a whole, or at least to a broad range of them. We group these below under a series of main headings.

8.1 People, skills and management

The quality of R&D workers and the training they receive is an important UK strength, and is at the core of our future role in nanotechnology applications. There are problems in attracting young people to nanotechnology-related careers, and in retaining them once trained. These problems are experienced in many areas of physical science in particular, and there are hopes that the excitement associated with nanotechnology can help to reverse this drift. (A clear policy implication is to do everything possible to make this excitement manifest and widely felt.) The problem does not just apply at the research scientist level, but also in terms of technicians and technical staff. A particular problem is that of mustering the sorts of interdisciplinary capability that is needed to make progress with by many applications of this technology. Some sectors of the UK economy are highly R&D intensive, for instance the pharmaceuticals sector is both successful and R&D intensive but relatively few UK companies undertake much R&D, and this reflects both general management attitudes and a lack of qualified R&D personnel.

- Multidisciplinary groups, and interdisciplinary R&D, are essential to the application areas covered here. This raises several issues where institutional reform may be necessary. First, systems such as the Research Assessment Exercise, which despite a stated intention not to discriminate against multidisciplinary work, is widely seen as having this effect, should be restructured so as to mitigate against this. Second, conventional discipline-based academic departments increasingly need to be complemented by research-based groups that span these

traditional interests. Third, research training needs to include components that can allow practitioners to acquire improved capacity of communicating across conventional disciplines and across the academic-industrial “divide”. Fourth, skills in managing multidisciplinary teams need to be cultivated and brought to bear.

Technician skills should be improved; the availability of technicians increased; and the scope for using the American strategy of having basic technical functions undertaken by graduate students should be explored.

New centres of expertise in the field (see below) should exist to produce nanotechnology designers and engineers with multidisciplinary skills – a good target could be at least 50 graduates per year by 2006. The stress placed on such major institutes should not preclude support for high quality R&D in smaller groups. The UK needs to establish systems which can provide longer-term funding for the work of proven/established innovative researchers either by rewarding research careers with more stability or by freeing up the time of lecturers and professors from administration and the more routine elements of teaching.

The systems of student grants should be examined to see whether there is scope to increase the attractiveness of science, technology and engineering courses and postgraduate training by means such as “golden hellos” and nanotechnology “Graduate Challenge” programmes. Similar means could be used to encourage the acquisition of multidisciplinary capabilities via conversion courses.

Finally, many of the choices that young people are making are conditioned very much by their experience in school. Training needs to be provided for schoolteachers, to enable them to stimulate the school children who will be tomorrow’s innovators. Visits from researchers in nanotechnology fields to schools, and to fora such as the BAYS, should be used to communicate the excitement and potential of the field; research groups could provide mentoring for teachers.

8.2 Commercialisation, academic-industry links, and intellectual property

The UK is widely seen as having great strengths in creating technologies and the underpinning scientific knowledge. More difficulties are experienced in creating, commercialising, capturing value from, and effectively utilising new technologies that can establish significant markets. A key issue for nanotechnology in the UK is the ability to translate technological knowledge, whether stemming initially from the UK or from other sources, into products and services that are commercially marketable (including, of course, meeting the real needs of public markets such as the NHS).

The firms that are taking the lead in the supply and use of nanotechnology-based applications are heavy users of outputs of the publicly-funded science base such as skilled graduates, and of course ‘technology transfer’ – which does not just (or often) mean adopting products developed in Universities. Technology transfer is a process involving a range of industry-university interactions such as research collaborations and expert advice. Established patterns of interaction between industry and the science base will need to evolve to keep pace with nanotechnology developments. The UK’s science base is not only of high quality in international terms, it is also highly connected to the science base in other countries. Thus UK firms can draw on global science and technology, and the UK can be an attractive location for firms to locate in to pursue nanotechnology applications development.

With the challenging range of knowledge bases and resources that are required to bring nanotechnology applications to market in effective ways, collaborations and joint ventures of various kinds are necessary. The workshop identified a number of actions to support development across a wide range of application areas:

- Establishing (and regularly updating) reliable “roadmaps”, right across the field of nanotechnology applications, to better inform those in charge of directing research efforts,

examining opportunities for financing development, etc. Such strategic intelligence requires expert teams drawn from industry and academia, with some input from government: the Foresight programme could be one vehicle for such development, but the production of roadmaps should not be dependent on this programme.

Guided by such strategic intelligence, proactive teams could be established who would work to “kick-start” commercial developments from university research. This might be best undertaken by consortia of several firms and universities working together, possibly on a regional or sectoral basis.

A UK Nanotechnology Industry association should be established. This could provide city briefings, lunch meetings and seminars, etc., and further develop the strategic intelligence required to grasp developments in the area.

Provision of demonstrators and, quite possibly, central facilities for prototyping nanotechnology-based materials and other products, which could be used to raise awareness of technical viability, industrial utility, and commercial opportunities in the applications (as well as serve training and test functions).

University researchers should be encouraged to undertake business initiatives – not impeded from so doing by criteria that focus on a very narrow range of scholarly outputs. Sources of finance for SMEs (see below) should be aided in consideration of university spin-offs, especially in respect of assessment of the technical feasibility and commercial potential of proposed innovations.

- Better linkages between HEIs and industry would follow in part from such initiatives. But it also depends in part upon more effort from universities to motivate, mobilise, and enhance the quality of their technology transfer officers and related functions. Teaching Company Scheme-type projects should bring industrial teams to universities, while CASE and similar schemes should provide inputs from academia to firms. A general goal should be to increase the porosity and flexibility of the industry-academia interface, so as to allow people and ideas to be rapidly moved into new configurations as opportunities and challenges arise.

Companies working in the nanotechnology field correspondingly need to increase their collaboration with UK Universities, funding research, soliciting postgraduate placements, and exploring scope for fruitful collaborations.

Companies and researchers alike will need to emphasise that their nanotechnology products have real benefits for customers, rather than focus on the new science or technology platforms that are being deployed.

Companies require stable and effective intellectual property rights regimes that give them incentives to innovate while not stifling the diffusion of knowledge. Harmonisation of patent schemes, and simplification of procedures is a widely recognised ambition for reform of IP systems.

Universities should examine the possibility of pooling IPR (and it might be possible to facilitate similar actions among SMEs and other firms). Another sphere for potential collaboration across universities and between them and business is in consortia to provide nanotechnology-related training.

8.3 Small and medium-sized enterprises

While large firms are bound to take the lead in many nanotechnology developments, small firms are likely to play an important role in enabling these large firms to move forward rapidly and flexibly. There are also many niche and emerging application areas where smaller firms can play significant roles, and indeed where they may dominate. Start-ups and spin-offs are likely to play a prominent role in nanotechnology applications, as they have done in ICT and biotechnology over recent decades.

Thus the workshop considered it important to support the development of SMEs in this field by such means as:

- Encouraging larger firms to support SMEs in terms of finance and investment (e.g. through corporate venturing, corporate incubators), and through collaborations and knowledge-pooling mechanisms, assistance with regulatory hurdles, etc.

Encouraging those developing and applying Teaching Company schemes to place their Associates into SMEs active in the nanotechnology applications areas (including SMEs who have the potential to use nanotechnology in these areas, but are not yet so doing).

SME-based R&D should be encouraged by an extension of current tax credit systems, by support for their research from regional and national bodies (and international ones such as the European Investment Bank and the EU); and in some cases by Research Council schemes. German and American taxation systems for SMEs were thought to carry some lessons for the UK. Lower Capital Gains and Corporation taxes and share options policies are especially important for new technology-based small firms, though they are relevant to innovative companies in general.

Support for prototyping and commercialisation of SME-derived innovations with seed funding from “business angels”, universities (in the case of spin-offs), and venture capital.

Improved opportunities for management training for innovative SMEs, including strategic advice and capabilities concerning issues such as IP, “exit routes”, and dealing with large firms. One vital skill is that of “marketing” the innovation to sources of finance. There is a role for providing support here from the DTI as well as from business schools and management colleges – as well as private training and consultancy companies.

More of an American-style set of attitudes to risk taking and entrepreneurship should be encouraged. It is hard to engineer a cultural shift, but various ways of encouraging such attitudes can be envisaged. For example, it should be made clear that failure is not a sin, but an inevitable by-product of a culture of innovation, and a vital opportunity for learning; tax regimes should be examined to ensure that they promote more investment, and other means (such as awards and promotion of innovators as role models) should be explored.

The scope for “clusters” in nanotechnology application areas at the level of UK regions needs to be explored.

8.4 Consortia, collaborations and finance

UK R&D funds in nanotechnology fall behind those of main competitors. This is most easy to track via public research programmes, where the term “nanotechnology” is more likely to be employed in ways that allow us to distinguish relevant research from the larger pool of R&D funding, but there is good reason to think that other than the most R&D-intensive sectors, there is less effort from UK industry here than in competitor countries. Perhaps equally as important, the centres of excellence that do exist are largely dispersed. With a few exceptions, there is a lack of the critical mass needed to support advanced facilities and to be able to respond rapidly to emerging opportunities. A case was made strongly for the establishment of new centres for demonstration and prototyping, which would allow for the consolidation of efforts and strengths that are currently seen as being too disparate in the UK. A possibly more ambitious formulation is that government should be seeking to establish, or at least co-ordinate, a “joined up” infrastructure for nanotechnology, spanning centres, training strategies, public procurement (see below) and industrial support.

- New centres need to be established, along the lines of current IRCs (Interdisciplinary Research Collaborations) or on the model of Germany’s Fraunhofer Institutes, to help build the critical mass necessary for progress across the various and diverse areas of nanotechnology application examined in this study. While a lead from government is necessary, industry

should also be involved in financing and setting directions for such bodies. They would provide a basis for training, prototyping, demonstration, and focusing research efforts so that the UK science base is able to respond effectively to emerging challenges in this rapidly evolving field.

- Levels of support from the public science budget for nanotechnology work – with engineering as prominent as the fundamental science – should be competitive with those in other advanced countries, and the UK should ensure that it is able to secure at least juste retour from EU research programmes. (UK consortia should be in a position to lead projects in the new Framework Programme.) Real new money is required, rather than simply rebadging existing funds: a figure of perhaps £100m per year for nanotechnology R&D was cited as a ballpark figure by some workshop participants. A cross-Research Council programme is likely to be appropriate.

“Proof of concept” programmes should be associated with public R&D funding, following on the experiences and lessons gained from such principles in Scotland. (The Proof of Concept Fund, established in 1999, is aimed to turn research into successful commercial ventures, linking with “cluster teams” in areas such as biotechnology, communications, and emerging technologies).

Levels of funding for R&D in private industry – whether from conventional R&D funding or via venture capital – need to be increased substantially. (It would be helpful to continue efforts to develop new statistics that could identify expenditures in nanotechnology – and indeed in other emerging technology areas: this would allow for more precision in estimates of how UK research compares to that in competitors.) Additionally, efforts should be made to stabilise such funding, so that it is not so dependent upon cyclical capital markets and volatile attitudes of investors that have limited access to sound knowledge on which to base decisions. Here roadmaps, and perhaps other means of enhancing strategic intelligence (such as formal ways of inputting expertise about technical and applications opportunities into the financial sector) would be valuable.

Social science research should be directed towards helping develop interdisciplinarity, knowledge management, an understanding of user requirements, market development and considering the social issues and public acceptance of nanotechnology.

8.5 Regulations, public procurement

The public sector is a major user of new technologies, and has typically pioneered leading-edge technologies. It can play important roles in standards-setting and the consolidation of design platforms, in fostering trials, demonstrators and awareness. Nanotechnology applications will be important to such public services as defence and health, and such services can help provide the demand-pull and concept testing that allow the supply side to become an attractive site for entrepreneurship, investment, and careers.

Regulatory frameworks are also important in shaping innovation. They may act to impede it, by imposing delays or providing inadequate IP protection for innovators. They may facilitate innovation, by building public confidence in new technologies, and by helping to avert problems that may stem from uncontrolled developments that raise ethical or safety concerns. The most effective regulatory systems will in general be those that are clear and consistent, reduce lengthy delays in the approval process, and impose fewer financial or administrative burdens on innovators.

Several recommendations have already been developed for procurement and regulations in the work of the Foresight Programme – in the report *Opportunities for Industry in the Application of Nanotechnology* and in work from panels such as Materials and Information, Communications and Media. Though developed in the framework of a longer-term view than the current report, these

recommendations generally provide a good starting point for action, and those that have been neglected should be taken up. Additionally the workshop argued that:

- Credible and transparent regulatory frameworks need to be put in place, preferably at Europe-wide levels, to govern developments in nanotechnology application areas. Those entrusted with regulation must have a dual mandate of building and maintaining public confidence, while championing innovation. Harmonisation of European patenting is one element of this.
- Interdepartmental working groups are required to share knowledge and increase mutual understanding between parts of government concerned with innovation, regulations, taxation, health, etc., so that the policies they formulate with respect to nanotechnology can be co-ordinated.
- The NHS should be a major player in offering innovative treatments applying nanotechnology for drug delivery, medical devices, instrumentation, and biotechnology-related health interventions such as those associated with tissue engineering. This can support the activity of UK-based firms in pharmaceuticals, medical devices, etc., and allow them to develop and demonstrate effective products for improving the quality of life **and** gaining large overseas markets. Strong leadership will be required to diffuse information about best practice and emerging diagnostic, monitoring and therapeutic techniques: the role of the National Institute for Clinical Excellence is liable to be critical. Government could fund nanotechnology demonstrators within the health sector.
- The aerospace industry is a major vanguard user of new materials and electronics technologies, and since the defence sector is extremely important for this industry in the UK, it will be important to examine the implications of defence research and procurement decisions for civilian nanotechnology, and for the development of nanotechnology applications more generally.

There may be a need to initiate a review of competition policies that are likely to restrict the scope for the new consortia and collaborations that are required in these application areas.

9 Glossary

	Auger Electron Spectroscopy
	Application-Specific Integrated Circuit
	Computer Aided Design
CMOS	Complementary Metal-Oxide Semiconductor
EDX	Energy-dispersive X-ray analyser
	Finite Element Modelling
HEMT	High Electron Mobility Transistor
	Information and Communication Technology
IP	Intellectual Property
	Interdisciplinary Research Collaborations (UK scheme)
ITARs	International-Traffic-in-Arms Regulations (US based)
JOERS	Joint Optoelectronics Research Scheme (a UK scheme)
LINK	The LINK scheme is the UK Government's principle mechanism for promoting partnership in pre-competitive research between industry and the research base.
MEMS	Micro electro mechanical systems
METI	The Japanese Government's Ministry of Economy, Trade and Industry
	The Japanese Government's Ministry of International Trade and Industry
	Microsystems Technology
NEMS	Nano electro mechanical systems
NICE	National Institute for Clinical Excellence (a UK Government organisation)
	National Science Foundation (a US Government organisation)
QC	Quantum Computing
	Quantum Information Processing
QSDs	Quantum Structure electronic Devices
	Scanning Probe Microscope
	Scanning Tunnelling Microscope
VCSEL	Vertical Cavity Surface Emitting Laser