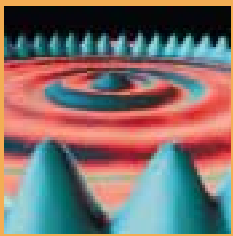
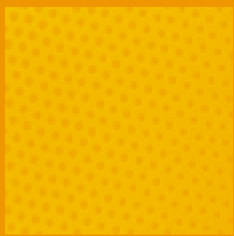
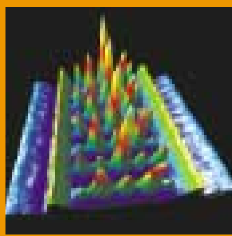
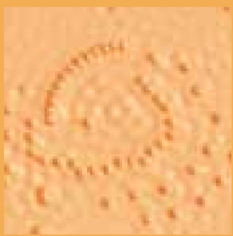
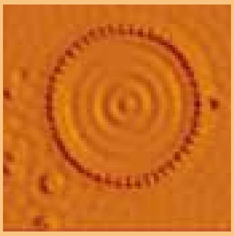
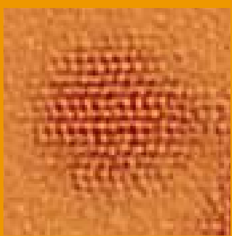
New Dimensions for Manufacturing
A UK Strategy for Nanotechnology

Report of the UK Advisory Group on Nanotechnology Applications submitted to Lord Sainsbury, Minister for Science and Innovation by Dr John M Taylor, Chairman. June 2002

Department of Trade and Industry

Office of Science and Technology

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IBM Research, Almaden Research Centre and the University of Oxford.

Preface

This report offers to Government the considered views of a group of academic and industry experts on the steps that need to be taken if the UK is to build on its current investments in nanotechnology research and become a world class player in nanotechnology applications. It gives a realistic assessment of where we stand in relation to our major industrial competitors in realising the potential of this fundamenatally new approach to manufacturing.

I have already taken steps to encourage the Research Councils to make significant increases in investments through the Interdisciplinary Research Collaborations in nanotechnology and tissue engineering and these have been backed up by the DTI award of a university innovation centre in nanotechnology to a consortium led by the Universities of Newcastle and Durham, and by Foresight LINK awards for projects in nanotechnology.

This report makes it quite clear that in order to keep pace with competitor nations we need to recast the scale and nature of our nanotechnology activities. We need to raise awareness in industry of the enormous potential impact that nanotechnology could have and ensure that investment and action by Government, industry and researchers is fully aligned to maximise the benefit for the UK.

Dr John Taylor OBE FRS FEng
Director-General of the Research Councils

Acknowledgement from the Chairman, Dr John Taylor

I should like to thank the members of the Advisory Group on Nanotechnology Applications and other experts who attended meetings and the specialist workshop, helping to form views on future scenarios as well as assisting with the preparation and critique of material for this report.

Thanks are also due to the various consultants who have contributed to the report: Oakland Innovation and Information Services Ltd, the National Physical Laboratory, the Institute of Nanotechnology, the Centre for Research on Innovation and Competition; The Technology Partnership; and Mr Michael Kenward who has undertaken the bulk of the writing.

And finally to the officials in DTI, OST and other Departments who have co-ordinated these activities, particularly Gavin Costigan, Chris Hodge and Ian Harrison.

Contents

Summary, findings and recommendations

Nanotechnology has become a topic of widespread discussion amongst researchers, in the media, among the investment community and elsewhere. While there is certainly a degree of hyperbole in some of this enthusiasm, it is no exaggeration to say that nanotechnology is set to disrupt the face of much of industry. Nanotechnology is about new ways of making things. It promises more for less: smaller, cheaper, lighter and faster devices with greater functionality, using less raw material and consuming less energy. Any industry that fails to investigate the potential of nanotechnology, and to put in place its own strategy for dealing with it, is putting its business at risk.

While the UK has excellent research credentials in nanoscience and nanotechnology, it lacks the coherent and coordinated national strategy for developing and applying the technology that characterises many of its leading industrial competitor nations. Partly as a result of this, much of UK industry has yet to respond to the challenge and to put in place its own R&D for nanotechnology.

This report, of the UK Advisory Group on Nanotechnology Applications, examines the growth of nanotechnology, its potential implications for industry in the UK, and proposes the elements of a strategy to accelerate and support the industrial application of nanotechnology in the UK.

What is nanotechnology?

Nanotechnology and nanoscience are concerned with materials science and its application at, or around, the nanometre scale (1 billionth of a metre). Manufacturing can reach the nano scale either from the top down, by 'machining' to ever smaller dimensions, or from the bottom up, by exploiting the ability of molecules and biological systems to 'self-assemble' tiny structures. It is in the conjunction of these two approaches, in the meeting of physical and chemical/biological manufacturing, that the potential for revolution lies. From the top down perspective, it interfaces with the larger-scale, more mature 'microsystems technology' being pursued very actively in the UK and around the world on a more immediate timescale.

Nanotechnology is a collective term for a set of technologies, techniques and processes - effectively a new way of thinking - rather than a specific area of science or engineering. Just as electronics and biotechnology have created their own technological revolutions, nanotechnology will have a similar impact, in some areas sooner rather than later.

Few industries will escape the influence of nanotechnology. Faster computers, advanced pharmaceuticals, controlled drug delivery, biocompatible materials, nerve and tissue repair, surface coatings, better skin care and protection, catalysts, sensors, telecommunications, magnetic materials and devices - these are just some areas where nanotechnology will have a major impact.

In effect, nanotechnology is a radically new approach to manufacturing. It will affect so many sectors that failure to respond to the challenge will threaten the future competitiveness of much of the economy, even including companies in areas such as pharmaceuticals and chemicals where the UK still has a strong position.

The likely extent of the influence of nanotechnology makes it difficult to estimate the size of the potential market, but it will be very large. Forecasts range from tens of billions to trillions of dollars.

International activities

The potential for nanotechnology has prompted large and rapidly rising government investments in R&D in leading industrialised nations. Japan recently committed itself to a central government spend of some 75 billion yen, around £400 million, for the fiscal year 2002. In the USA, the federal budget for 2002 includes $604 million for research and development in nanotechnology. California alone is investing more than $100m a year. The European Commission has also recognised the growing importance of nanotechnology and has allocated some €1.3 billion, £800 million, for the topic under the Sixth Framework Programme (FP6) over the period from 2002 to 2006.

Government spending in the UK on nanotechnology R&D in 2002 is about £30 million a year, although it is difficult to arrive at an accurate figure for this spending. This is itself a symptom of the fragmented nature of the support for nanotechnology in the UK.

Nanotechnology in the UK

The UK has a strong background in nanoscience and nanotechnology and has been active in the field for two decades or more. However, factors such as the fragmented nature of the UK's effort, the increasingly multidisciplinary nature of the subject and the patchiness of mechanisms to facilitate the transfer of science from academia to industry have impeded the development of industrial awareness of, and support for, nanotechnology.

The high cost of experimenting with an unfamiliar technology covering a very wide range of disciplines makes it hard for many companies, even large ones, to establish what nanotechnology can do for them. They tend to maintain a watching brief on academic research rather than embarking on their own exploratory and experimental developments. However, many are beginning to become aware of the huge potential of nanotechnology on their business and future products.

The Advisory Group study

The Advisory Group on Nanotechnology Applications was charged with reviewing the current state of nanotechnology applications in industry in the UK, and proposing, if appropriate, actions to accelerate and support increased industrial investment in nanotechnology exploitation. (See Remit and Terms of Reference on page 72.)

To do this, we focussed on six key application areas (out of an initial list of 14) where the UK has research strengths and industrial opportunities.

These were:

- Electronics and communications;
- Drug delivery systems;
- Tissue engineering, medical implants and devices;
- Nanomaterials - particularly at the bio/medical/functional interface
- Instrumentation, tooling and metrology;
- Sensors and actuators.

The approach was to characterise an optimistic but feasible vision for **"Success in 2006"** - how well industry in the UK could realistically be doing in these areas by 2006 if practicable support measures were put in place promptly. We did this through a series of workshops and commissioned studies, building on the wealth of other work in the area now available in the UK and overseas (see bibliography). A key aspect of this was a "road-mapping" exercise aiming to plot the likely evolution of both technologies and applications over the next few years. We then characterised the main obstacles we believe exist in the UK to realising success, what interventions (if any) Government could make to support the achievement of this vision, and what performance indicators there might be for monitoring whether the UK was on track for doing so.

Findings and recommendations

Our key findings on the obstacles to success in the UK

The UK's strengths in nanoscience and nanotechnology research provide strong foundations on which to develop nanotechnology for the benefit of companies in the UK. However, for the UK to develop a breadth and volume of industry activity which will be comparable and competitive with other leading nations, we need to address a number of key obstacles and deficiencies.

The Advisory Group has studied the many previous reports in this areas, commissioned its own studies and held wide ranging discussions and workshops. We have concluded that the main obstacles to achieving the success we believe is possible over the next few years for nanotechnology applications in the UK are:

- The lack of a stable, visible and coordinated strategy for public support for nanotechnology applications in industry
- Fragmentation and lack of critical mass in UK R&D activities, and a mismatch between our research and industrial capabilities
- Absence of a level playing field for Government support in international competition
- Lack of appropriate technology access and business incubation facilities

- Access to skilled people - training and recruitment

Our recommendations for Government action to address these issues focus on:

- National nanotechnology application strategy
- National Nanotechnology Fabrication Centres
- Nanotechnology roadmaps
- Awareness and networking
- Training and education
- International - promotion and inwards transfer

STRATEGY, AND THE NASB

The UK should develop and articulate a coherent and coordinated strategy for accelerating the application of nanotechnology as widely as possible across the economy, beginning with those areas highlighted in the report. This should be facilitated by the DTI, through appropriate sponsorship of industry and academic groupings in conjunction with Research Councils UK. The strategy should be overseen by an independent steering group from industry, academia, Research Councils UK and Government, referred to here as the UK Nanotechnology Applications Strategy Board or NASB. The NASB should be set up by the autumn of 2002.

A strategy for nanotechnology in the UK must address the key issues highlighted by the Advisory Group and in the studies that it commissioned. These issues affect three key communities and the interaction between them - industry, the academic research community and Government. To obtain the full benefits that nanotechnology can bring, the UK strategy must:

- convince firms and investors of the need to use nanotechnology to defend and improve their competitive position, and ease the path for companies to invest in the area
- increase the number of companies developing and applying nanotechnology and its applications
- ensure that industry and academia have access to the facilities needed to take the ideas that come from research and turn them into viable technologies, products and businesses, with excellent routes to market
- ensure that industry has access to well trained staff
- ensure a coherent and visible strategy of sustained public investment in nanotechnology applications that will encourage confident investment by industry and suppliers of private finance
- promote the maintenance and quality of fundamental research, with adequate critical mass in areas key to the applications where the strategy is focussed

The NASB should commission and oversee further work on scenarios for "Success in Nanotechnology in 2006 and Beyond" to identify more clearly goals and performance indicators that the UK should use to track the progress of the strategy.

NATIONAL NANOTECHNOLOGY FABRICATION CENTRES

The most important obstacle to more rapid application of nanotechnology in industry in the UK is the absence of facilities where researchers, companies and entrepreneurial thinkers can work together to assist established businesses in their adoption of nanotechnology, and to create and incubate new businesses triggered by advances in the science and technology.

Other countries provide various forms of extended public support for such nanofabrication facilities. This happens via direct government support, through defence agencies, national R&D programmes and focussed national initiatives, for example through local/regional government support; and through cooperation with large leading edge companies. Such facilities are not available or accessible in the UK at present; and the provision of such facilities does not fit comfortably with any existing DTI 'scheme'.

The provision of equivalent facilities in the UK was identified by the Advisory Group as the single most important action Government should take to "level the international playing field". (We would still have a long way to go before it was tilted in our favour.)

A major feature of what is required is access for short periods by individuals, SMEs and industry to large, expensive, multidisciplinary facilities that are staffed with high grade technologists and engineers, working close to the leading edge of what is possible. If a project begins to be successful, continuing access is needed while the evidence is generated that it is possible to develop a viable product and business. Only stable Government support for such a facility can provide access for innovative people to the range of multidisciplinary technologies and facilities they need to work up an initial idea for a nanotechnology application into a viable product and business.

Accordingly, the Advisory Group recommends setting up as soon as possible at least two **National Nanotechnology Fabrication Centres** (NNFCs).

The proposed centres should develop and operate world-class facilities where individuals and firms can prototype and fabricate potential products, based on the research carried out in universities and in businesses. The main parameters of the proposed centres are:

- The centres should be focussed around particular major areas of nanotechnology, for example, biotechnology applications, nanoparticles or electronics, rather than trying to cover all applications, technologies and approaches in one centre. However, it will be important for the centres to work together where appropriate.
- R&D engineers from other organisations can be assigned as "visiting technical staff" to the centres to seek help, training and support to develop proposals for new products or processes. Such assignments could be for a few days, a few weeks or months, or longer, and be from a wide range of sources including large companies wishing to explore new applications, through small companies to academics and others wishing to start a new business.
- The centres should have the technical facilities and support staff to take selected proposals through feasibility and design to demonstrations of pre-production volumes at practicable levels of yield, quality, volume and cost. The aim is to enable the launch of a focussed new business to its initial customers and investors.
- The centres should be able to support the incubation of new ventures for large and small companies ('intrapreneurs' as well as entrepreneurs), including networking and access to related academic researchers, management of intellectual property rights (IPR), business planning, management staffing, access to venture funding and accommodation for the initial growth phase.
- The centres will need the capability to underpin the incubation process for the extended periods often necessary in this kind of disruptive, multidisciplinary area.
- The centres should carry out baseline programmes of R&D in areas appropriate to their focus, in close conjunction with recognised academic centres of excellence in their field.

The Advisory Group has commissioned an outline business plan for such centres. This is based on creating two or more centres working with existing centres of research excellence (in particular the Interdisciplinary Research Collaborations of the Research Councils, other Research Council facilities, and the DTI funded facilities), starting this year (2002) and overseen by the NASB. The approach should be to increase funding steadily over the next few years, with management flexibility to stimulate demand and follow areas of maximum opportunity for the UK. We expect that funding for these centres should start at around £25 million of capital and recurrent spend per year in 2003 and rise to £75 million or more per year if demand justifies within five years. Public funding should be provided for the first five years with the expectation of continuing for a further five years if they are being successful.

Setting up these first two National Nanotechnology Fabrication Centres should proceed as a matter of urgency. The aim should be to secure launch funding from DTI before the end of 2002 with spending starting by April 2003 at the latest. Funding should be one of the highest priorities for the DTI. The process should be managed by the DTI Innovation Group, in close coordination with the Office of Science and Technology, and overseen by the DTI Knowledge Transfer Steering Group

The keys steps in the process should be to:

- Develop the specification and business plan templates for the centres, based on the list above and building on the business plan study already commissioned by the Advisory Group. These should lay out the topics to be covered in the business plans of the centres being proposed.

- Organise a focussed competition for consortia to bid for the centres. These could include universities, national laboratories and commercial companies.

Microsystems Technology Centres

While nanotechnology and microtechnology operate at different dimensions, many of the techniques required for nanotechnology are related to those already deployed in work on microsystems. In some applications of nanotechnology, the techniques of microtechnology will provide the early stages of production. The proposal to create National Nanotechnology Fabrication Centres (NNFCs) has to accommodate, interface with, or incorporate the existing and planned UK facilities for microsystems fabrication. It is the view of the Advisory Group that the proposals for separate micro and nano facilities should come together where practicable. However, they should not be merged as this will destroy the explicit focus on nanotechnology which the Advisory Group believes is essential. There are distinct differences as to how facilities for microtechnology and nanotechnology would interface with, and be perceived by, their target customer base. However, there could be substantial savings in co-locating the facilities and sharing common functions.

ROADMAPS - TECHNOLOGY AND APPLICATIONS

The Advisory Group strongly recommends that the National Strategy for Nanotechnology should be informed by a continuing road-mapping process. The Group commissioned an initial road-mapping exercise which was very helpful. The remarkable success of the International Technology Roadmap for Semiconductors begun by the US points to the value of this approach in tracking and communicating likely developments in the field to the wider audience of customers and investors. Nanotechnology strategy needs to track both technology and applications. The roadmapping should be carried out as an across-the-board process overseen by the NASB.

AWARENESS, ACCESS PORTALS AND NETWORKING

The National Nanotechnology Fabrication Centres will meet a focussed need to accelerate the growth of new enterprise. To succeed, any national strategy must also promote wider acceptance and uptake of the technology. This will require the promotion of linkages between all the key parties in the UK - academic, industrial and financial - and the involvement of regional organisations as well

UK NANOTECHNOLOGY STRATEGY TIMELINES

	NOW	2004	2007
INDUSTRY	Benchmark against competitors Identify opportunities for new products and processes	New fabrication facilities on stream Firms working with researchers to trial prototype products	Widespread use of nanotechnologies in manufacturing and new product development UK recognised as global leader
RESEARCH	Better coordinated effort Build critical mass	UK researchers winning major contracts in Framework 6 and with industry	Significant numbers of spin-out firms based on UK research
GOVERNMENT	Establish nanotechnology Applications Strategy Board Build industrial and public awareness Involve RDAs in cluster development Support nanotechnology through existing programmes Launch funding and set up of fabrication facilities	Fabrication facilities in place and providing nucleus for industrial applied R&D	Fabrication facilities delivering short production runs for trials of new products and processes

as national bodies. In particular, the Regional Development Agencies (RDAs) may have an important role to play in promoting local clusters of expertise and growth.

The NASB and the NNFCs should also provide and support **'Access Portals'** for individuals, companies and others who wish to explore the potential of some area of nanotechnology to meet their needs or ideas. These portals need to be highly visible: their role is to provide easy access for people from various application areas to the R&D people who might be able to work on solving their problems or meeting their needs. For example, they would be able to connect someone from the food industry, or aerospace or transport, with the right people to help them to explore how nanotechnology could be relevant to their likely future needs. Some form of light-touch Faraday Partnership process might be appropriate here, together with innovative uses of Internet facilities. It will be important to leverage the existing Research Council technology networks and the other international groups that already exist or will develop, for example as the sixth Framework Programme (FP6) of the EU starts to operate.

The UK must begin to catch up with and overtake other countries in informing and educating the business sector, universities, the media and others on the implications and possibilities that will arise from nanotechnology. The need to raise public awareness is pressing and cannot await the formation of the nanofabrication centres. Indeed, it can help to pave the way for them.

The action group recommends the immediate implementation of an awareness programme for nanotechnology. Such a programme should involve the learned and professional societies and could draw on the experience of existing publicity campaigns within the DTI.

TRAINING AND EDUCATION

The availability of trained people will be key to achieving the rapid expansion of activity envisioned in our success scenario. They will be needed at a wide range of levels, from leading edge researchers to highly skilled technicians, production and quality engineers, application developers and so on. A major campaign in training and education will be needed as part of the strategy. This campaign should involve the NNFCs but will need to be much wider. The NASB should also oversee this activity. Effective participation in the international marketplace for talent at all levels will be essential.

INTERNATIONAL - PROMOTION AND INWARD TRANSFER

The national strategy for nanotechnology in the UK should build on the growing support for the topic within the EU and in its international collaboration with such organisations as the US National Science Foundation. The UK should use the sixth Framework Programme (FP6) more strategically to develop collaborations with European industry and academics. Potential UK academic collaborations for FP6 initiatives should be developed by the NASB in close collaboration with the Research Councils.

The success of industry in the UK in exploiting nanotechnology opportunities should not be limited to research conducted by the UK science base. To be competitive, industry in the UK needs to access the best R&D anywhere in the world. It should be a key element of the national nanotechnology strategy that Research Councils UK and the DTI develop effective ways to facilitate access to this global technology network.

The UK should also promote its national research capabilities and facilities abroad to encourage collaboration and attract inward investment, particularly from major multinational companies needed to rebalance the domestic R&D scene.

Conclusion

We believe that the field of nanotechnology and its applications is crucial to the future competitiveness and productivity of the UK economy, and to the well being and prosperity of its people. We hope that the government will take forward these recommendations with urgency and we are confident the research community will be ready to play a full part in their implementation.

Introduction

Nanotechnology

Faster computers, advanced pharmaceuticals, controlled drug delivery, biocompatible materials, tissue repair, surface coatings, better skin care and protection, catalysts, sensors, optical communications, magnetic materials and devices - these are just some sectors of the economy where nanotechnology will have an impact. Indeed, there is a growing appreciation that it is difficult to find areas of manufacturing and industry where nanoscience and nanotechnology will not have an impact.

Aims of the report

This report examines the potential impact of nanotechnology and nanoscience on industry in the UK. It describes the successful outcomes that could happen in a number of important application areas and proposes a strategy for the UK to achieve these outcomes.

Advisory Group

The report was prepared by an Advisory Group set up by the Minister for Science and Innovation, Lord Sainsbury, and chaired by the Director General of the Research Councils, Dr John Taylor. The Advisory Group commissioned a series of supporting studies and organised high-level meetings that provided an opportunity for leaders in the field from business and academia to contribute their views.

Research on nanoscience and nanotechnology has been going on in the UK for at least 20 years and has already achieved much, including a number of start up companies. There is much new technology in the pipeline which is now ready to move towards application.

The key issue seen by the Advisory Group was not how to stimulate more basic research, but rather how to stimulate the growth of nanotechnology applications by industry, new and existing, in the UK.

Accordingly, the Group decided to organise its work around:

- understanding and evaluating the current situation on nanotechnology take up in the UK, by using a wide range of data sources and commissioning a survey of current research (Annex A).
- generating a vision of what the UK could achieve in nanotechnology in just five years from now.

This approach of asking "What would success in the UK look like in 2006?" is intended to:

- identify achievable but "stretch" goals
- use science and technology that is already in the pipeline - not dependent on new breakthroughs

NANOCOMPANY

NanoMagnetics

NanoMagnetics started in the research laboratories at Bristol University. Over the past couple of years the company has filed several patents, raised £6.7 million, and recruited a high powered CEO, Dr Brendan Hegarty. Earlier this year Lord Sainsbury, UK Minister for Science and Innovation, cut the ribbon at its new purpose built 10,000 sq. ft laboratories in Bristol.

Hegarty's origins give a clue as to the company's business. He spent 20 years in the magnetic disk industry with IBM and Seagate. That's all about improving hard disk for computer storage which comes down to what you do with very tiny magnetic particles.

By getting these down to nano dimensions and using a common protein to coat hard-disk drives, NanoMagnetics reckons that disk makers could cram 100 times as much information on to a drive. NanoMagnetics recently set a world record for the use of nanoparticles for magnetic storage.

"We have only taken the first steps with this technology," says Dr Hegarty. "We are looking to improve these results by a factor of five in the next six months."

http://www.nanomagnetics.com

- be realistic about the UK's capacity and capabilities to develop nanotechnology
- start from where we are and only grow as fast as is practicable
- focus on what might accelerate the process by looking at business needs

If "Success in 2006" can be visualised in outcome terms - for example, the number and size of new companies and new products in the market - another key step is then to see if we can identify indicators of progress: how will we know say three years from now if we are on track to achieve the success scenario five years from now?

For the main part of its work, the group chose to focus on six key application areas (out of an initial list of 14):

- electronics and communications
- drug delivery systems
- tissue engineering, medical implants and devices
- nanomaterials - particularly at the bio/medical/functional interface
- instrumentation, tooling and metrology
- sensors and actuators

Box 1

THE ADVISORY GROUP ON NANOTECHNOLOGY APPLICATIONS

The Advisory Group was set up by Lord Sainsbury, the Minister for Science and Innovation, under the chairmanship of Dr John Taylor, Director General of Research Councils. Its role is to advise on the actions needed to improve the UK's capability in nanotechnology and related technologies. In particular the group was asked to "advise on, and oversee, a study to benchmark UK nanotechnology capability [and] advise on the support infrastructure for nanotechnology in the UK, and the activities of Government (including the Research Councils) in promoting activities of a suitable nature and scale to attract industrial investment". (Terms of reference and a list of members are on page 72.)

The Group decided to focus on major application areas rather than particular subdivisions of the technology. Out of an initial list of 14 areas it chose to analyse just six:

- Electronics and communications: quantum structure electronic devices for memory and data storage, displays, optoelectronics, photonic crystal structures, (longer term) quantum information technology.
- Drug delivery systems: polymer-drug conjugates; nano-particles, liposome and polymer micelles and dendrimers.
- Tissue engineering and medical devices: external tissue implants, in-vivo testing devices, medical devices.
- Nanomaterials: nanostructured materials, smart composites, catalysis, biosensors.
- Sensors and actuators: medical diagnostics and implants; systems integration.
- Instrumentation, tools and metrology: tools for top down manufacture e.g. high resolution and soft lithography, nanometrology.

During August and September 2001 consultants produced a status report for the Group on each of the six application areas, assessing the UK's capability against that of our competitors.

In October key people from industry, academia and the public sector attended a workshop, considered these reports and:

- carried out road-mapping exercises to chart the likely future evolution of technologies and applications
- analysed and developed a scenario for "Success in the UK in 2006", identifying drivers and shapers
- identified the indicators that will tell us if progress towards that scenario is on track
- identified the critical success factors and the actions needed to make them happen.

The assessment and proceedings of the workshop were published in parallel with this report.
For a summary of the scenario developed at the workshop for each area see Box 4 and Annex B.

These are application areas where the UK has particular research strengths and industrial activity, but the Advisory Group recommends that the other areas should also be followed up in a similar way.

To characterise the "Success in 2006" scenarios, the Advisory Group commissioned studies conducted by the National Physical Laboratory (NPL), the Institute of Nanotechnology (IoN), and the Centre for Research on Innovation and Competition (CRIC, University of Manchester and UMIST). These studies were used as the basis for the Advisory Group to conduct its own workshop aimed at examining what actions the UK might take to accelerate and facilitate the achievement of the "Success in 2006" scenarios.

The headlines of these scenarios for the six selected areas are summarised in Box 4 and more detailed summaries are in Annex B.

NANOCOMPANY

Mesophotonics

The company is creating photonic devices by working nano-scale features into silicon chips. If Mesophotonics can stick to the timetable that it has set itself, by the end of next year it will have started production of components in small volumes. Nine months later, it will be into full production. A rapid pace for a company that started in July 2001 with a phased investment of £2.8 million from BTG.

Photonic crystals are sophisticated devices that can perform wonders on light. Light travelling along tiny glass fibres is the basis of most modern communications. Photonic crystals can be the switches and signal processors of the optical era.

Mesophotonics grew out of research by Professor Greg Parker in the Department of Electronics and Computer Science at the University of Southampton. Parker, who is the company's Technical Director while retaining his post at the university, had the advantage of working in a major semiconductor research centre.

Mesophotonics plans to use the techniques of microelectronics to to make holes in silicon. It is the arrangement of the holes that matters. And this is where the nano bit comes in. you have to get the arrangement right to those dimensions. "You can make lots of different devices by changing the patterning of the holes in the materials," explains Parker.

The company recently increased its technical staff by 50 per cent, bringing the total complement to around a dozen. By mid 2002, Mesophotonics hopes to have 'proof of principle' devices with demonstrator devices going out to potential customers about six months later.

http://www.mesophotonics.com

Structure of the report

This report is in three sections, together with supporting annexes.

Part 1: Background.

We first summarise what is meant by nanoscience, nanotechnology and nanofabrication, and look at their implications for industry and education. We then summarise the international scene, including the major public sector investments being made in the UK's key competitor countries, and give examples of the kinds of products, processes and markets that are emerging already.

Part 2: Analysis and findings

We summarise the current situation on nanotechnology-related activities in the UK, both publicly funded and industrial, and discuss a number of key issues arising from the research study we commissioned from Oakland.

We then move to consider how the UK might do better. We summarise the results from the workshop on "Success in 2006" scenarios in the six chosen application areas. This enables us then to identify the key obstacles which we believe exist to achieving these success scenarios for the UK.

Part 3: Recommendations

We then present a set of recommendations for actions which the UK Government needs to take to deal with these obstacles, in order to accelerate the take up of nanotechnology applications in UK industry and improve the UK's performance in exploiting nanotechnology over the coming decade.

Part 1 - Background

Part 1 - Background

What is nanotechnology?

In its formal sense, the 'nano' world is where science and technology reach dimensions and tolerances in the range 100 nanometres (0.1 micrometres) to 0.1 nanometres. A nanometre is a billionth of a metre which is about 10 times the size of a hydrogen atom. So nanotechnology and nanoscience are concerned with materials science and its application at, or around, the nanometre scale. A more useful definition of nanotechnology is the application of science to developing new materials and processes by manipulating molecules and atoms. It is a collective term for a set of technologies, techniques and processes rather than a specific area of science or engineering.

The potential impact of nanotechnology is so large that it is dangerous to rely on definitions that could restrict thinking. In effect, nanotechnology is a generic technology and a new way of looking at many subjects. Just as electronics and biotechnology have created their own technological revolutions, many people believe that nanotechnology will have a similar disruptive impact.

Nanofabrication: the new manufacturing

Nanotechnology is about new approaches to manufacturing - new ways of making things. There are two ways to approach the nanoscale; shrinking from the top down, or growing from the bottom up. These two models are fundamentally different, both in the approach to creating structures and in the underlying science that will make them possible.

The 'top-down' approach, entails reducing the size of the smallest structures towards the nanoscale. This essentially entails carving nano structures out of larger objects. Top down nanotechnology is in the first instance more the domain of nanoelectronics and nanoengineering. An early application of this approach could be in the development of nanophotonics, the conjunction of electronics and photonics at a nano scale. It extends techniques such as electron-beam lithography, borrowed from microelectronics, to create microelectromechanical systems (MEMS), for example. There are, though, physical limits to this top down approach. As dimensions reach the atomic scale, the manufacturing processes are trying to manipulate individual molecules. Forces and interactions between individual molecules then become significant, and new paradigms have to come into play.

'Bottom-up' techniques involve manipulating individual atoms and molecules. Bottom-up nano usually implies controlled or directed self assembly of atoms and molecules into nano structures. It resembles more closely the processes of biology and chemistry, where atoms and molecules come together to create structures such as crystals or living cells. In effect, the creation a living cell or a snowflake is nature's own nanotechnology at work.

The role of top-down techniques taken from microelectronics and adapted for nanotechnology has particular implications for the UK. These 'microfabrication' techniques are more mature than nanofabrication since they use established silicon processing techniques, and the one blends into the other. Microfabrication is more easily understood and may well have the earlier impacts on the market. Any strategy for nanotechnology in the UK has to recognise both domains and allow a creative balance between them

Unlike Japan and the USA, British industry lacks in-depth manufacturing expertise in mass market microelectronics, although the UK does have a £4 billion microelectronics fabrication industry concentrated in several niche markets. A strategy for nanotechnology will need to recognise this and deal with any resulting gaps. The UK does have significant strengths in research in microelectronics and photonics and thus has the foundations for successful development of top-down nanotechnology.

The techniques of bottom-up manufacturing will have particular implications and oportunities for the UK's major industries, especially the possibility of massively parallel nanofactories which could dramatically influence, the production of pharmaceuticals and value added chemicals.

Nanotechnology is interdisciplinary

The top-down and bottom-up nature of nanotechnology underlines its multidisciplinary nature. Nanoscience and nanotechnology depend on contributions from, among others, chemistry, physics, the life sciences and many engineering disciplines. Thus the subject inevitably crosses the boundaries of many different departments in traditional universities and research institutes and involves the research agendas of most of the UK's Research Councils. It is important to recognise this and to consider the implications for the UK's strategy for nanotechnology.

Despite recent progress, much education and training in Britain's universities still continues along more or less traditional disciplinary lines.
It is difficult for companies to recruit technologists and researchers who are comfortable in several different areas of science and engineering.

The multidisciplinary nature of nanotechnology also poses challenges for industry. While many companies have always depended on their ability to harness the intellectual efforts of different areas of science and technology, nanotechnology will take that interdisciplinarity to a new level.

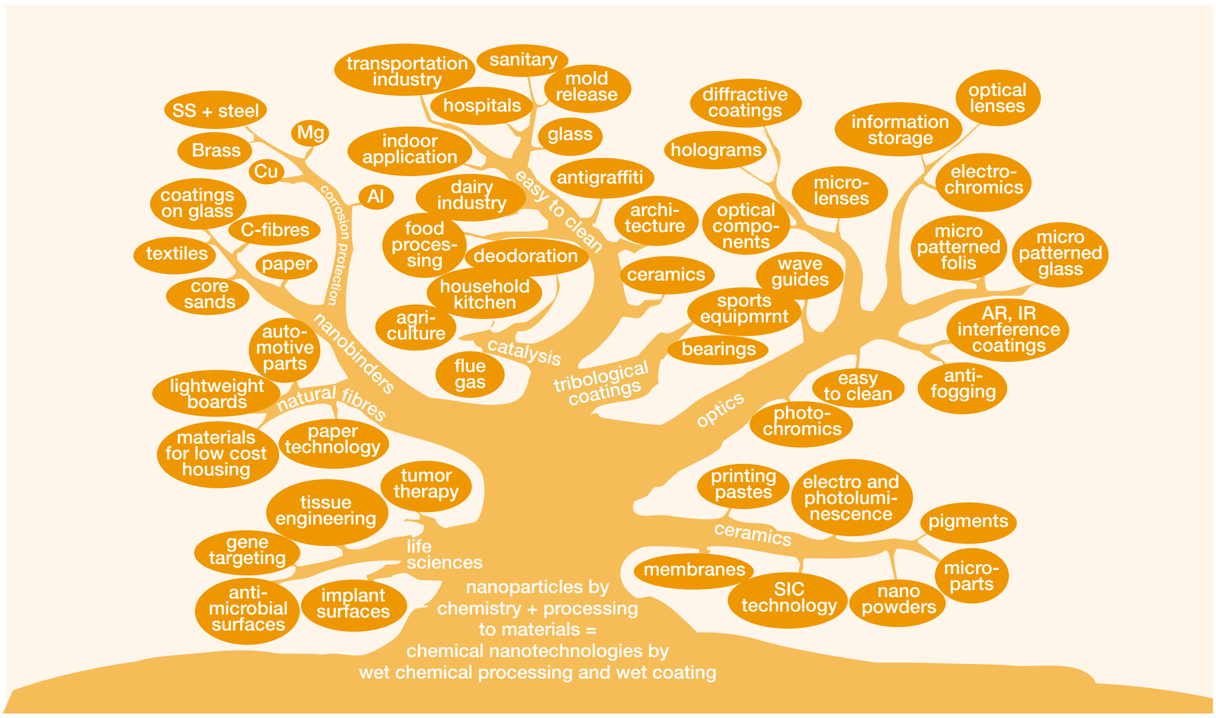
Nanotechnology is disruptive

A distinctive feature of genuinely disruptive technologies is that they can have very many different applications. This is particularly true for nanotechnology. For example, nanoparticle technology alone can influence a large number of products and services (see Figure 1 below).

Disruptive technologies are those that displace older technologies and enable radically new generations of existing products and processes to take over. For example, optical data storage, through such devices as compact disks, has changed the face of home entertainment and computing; digital cameras based on solid-state memory and imaging technologies are replacing photographic film.

Disruptive technologies can also enable whole new classes of products and markets not previously feasible, such as portable computing, mobile phones or digital imaging. New industries and new companies grow, and existing companies can continue

Fig 1. Potential application areas for nanotechnology (Institute for New Materials, Saarbrucken).



to compete if they notice and adapt rapidly. Those that do not face rapid obsolescence and decline.

Where British manufacturers build complex, high technology systems, such as aircraft, vehicles, or process plant, they will probably be able to incorporate new components based on nanotechnology that may be cheaper, faster and with greater functionality. These system integrators require an extensive base of suppliers producing the components and the sub-assemblies for them to incorporate into their products. Building nanotechnology into these components will also require a microsystems industry to interface their smaller relatives to the outside world.

A key issue therefore that could disadvantage the UK compared to some other advanced industrial nations would be a failure of its companies to appreciate that nanotechnology is really disruptive - that it will generate major paradigm shifts in how things are manufactured. Nanotechnology could lead to changes that equal the revolutions ushered in by semiconductor technology and biotechnology.

Another sign of the role that nanotechnology will play in the future economy is the increasing interest in it within the investment community. Some large investors now have specialists who follow the subject, while some smaller funds concentrate on nanotechnology in their investments. A few excellent analysis reports are available (see bibliography). There is also a growing list of start-up companies that hope to turn research into products and services, some of which are described throughout this report..

The global picture

Investment in nanotechnology is increasing rapidly. It is a subject that attracts large and small countries. More than 30 countries have nanotechnology activities and plans. As well as the major players, there are growing programmes in Singapore, Russia and the Ukraine. In Mexico there are 20 research groups working independently. Korea, already a world player in electronics, has an ambitious 10-year programme to attain a world-class position in nanotechnology.

The potential of nanotechnology has resulted in a rapid increase in interest in research and development, both academically and, in some countries, in industry. Japan, for example, recently committed itself to a central government spend on nanotechnology of some 75 billion yen, around £400 million, for the coming fiscal year (FY2002). Nanotechnology is one of four strategic platforms of Japan's second basic plan for science and technology.

The USA's federal budget for 2002 includes $604 million for research and development in nanotechnology, $199 million of it for the National Science Foundation (NSF). The request for the fiscal year 2003 is $710 million, including $221 million for the NSF. The NSF has designated "Nanoscale Science and Engineering" as one of its six priority areas.

A major landmark in the USA was the launch, in January 2000, of the National Nanotechnology

Worldwide government funding for nanotechnology R&D, US$M, (April 2002)

Area	1997	1998	1999	2000	2001	2002	2003
W. Europe	126	151	179	200	225	~400	
Japan	120	135	157	245	465	~650	
USA*	116	190	255	270	422	604	710
Others	70	83	96	110	380	~520	
Total	432	559	687	825	1502	2174	
(% of 1997)	100%	129%	159%	191%	348%	503%	

From a briefing note: Nanotechnology Funding: The International Outlook by Mihail C. Roco, Chair, White House/National Science and Technology Council/Nanoscale Science, Engineering and Technology Subcommittee, and Senior Advisor, US National Science Foundation, May 2002.

* excluding non-federal spending eg California

"Others" include Australia, Canada, China, Eastern Europe, FSU, Korea, Singapore, Taiwan and other countries with nanotechnology R&D

Initiative (NNI). In 2002-2003, the focus for the NNI will be on fundamental research through investments in investigator-led activities, centres and networks of excellence and infrastructure. The NNI's funding priority will go to: research to enable the nanoscale as the most efficient manufacturing domain; innovative nanotechnology solutions to "biological-chemical-radiological-explosive detection and protection"; development of instrumentation and standards; the education and training of the new generation of workers for the future industries; and partnerships to enhance industrial participation in the nanotechnology revolution.

NANOCOMPANY

QinetiQ Nanomaterials Ltd

A spin out from QinetiQ, formerly DERA, the R&D arm of the Ministry of Defence, QinetiQ Nanomaterials Ltd officially opened for business at the beginning of 2002. It immediately became one of Europe's largest nanomaterials and nanotechnology groups. Funds for the company came in the shape of the first substantial investment by QinetiQ Ventures Ltd, QinetiQ's own venture fund.

QinetiQ Nanomaterials makes 'nanopowders'. For its production technology, the company has picked up on another hot area of science, plasma – that's really hot gas. Tetronics developed the technology and QinetiQ Nanomaterials has an exclusive licence to use it for tiny particles and is building a plant at Farnborough to churn out nanoparticles by the tonne.

IPR is another arrow in the quiver at QinetiQ Nanomaterials. The business already has a handful of patents filed and eight or nine internal projects that could add to the portfolio.

As well as 'pyrotechnics', that's explosives to most of us, they have their eye on materials for electronics and medicine, for drug delivery for example.

The company has access to the massive resources of QinetiQ, one of the UK's largest research centres with more than 150 scientists and engineers working in nanomaterials and nanotechnology, in its search for new ideas. The plan is to develop complete technology packages for customers, and to help them to set up production plants close to their factories. "We do not want to ship large quantities around the world," says Mike Pitkethly, Commercial Director of QinetiQ Nanomaterials.

http://www.nano.qinetiq.com

The State of California alone has set aside $100 million for the creation of the California Nanosystems Institute, a 'distributed' centre with facilities at both the University of California Santa Barbara and UC Los Angeles (UCLA). Matching funds, from industry and federal sources are expected to add $200 million to this investment. IBM is providing over $100 million for a centre at NY State University at Albany.

The European Commission (EC) has also recognised the growing importance of nanotechnology. Out of a total proposed funding for FP6 of €17.5 billion from 2002 to 2006, €1.3 billion would be devoted to a priority thematic area of research on nanotechnology and nanoscience, knowledge-based multifunctional materials and new production processes and devices.

The EC has yet to begin allocating funds under FP6 to individual projects. However, it has awarded the UK's Institute of Nanotechnology a contract to promote pan European networking and educational activities. The 4th Framework Programme (1994 - 1998), funded some 80 projects involving nanotechnology. In the 5th Framework Programme, (1998 - 2002) the estimated funding level is about €45 million a year.

Within the EU, the UK was second only to Germany in public investment in nanotechnology in 2000 according to figures from the European Commission. But Germany has a much more integrated and co-ordinated system, and others, particularly France and Ireland, are taking action. For example, in 1999 Ireland invested €12.7 million in the National Nanofabrication Facility at the National Microelectronics Research Centre in Cork.

In May 2002, at a congress in Berlin the German Federal Research Minister presented the Federal Government's strategy on nanotechnology together with an overview of the country's strengths and research activities in this area. In 2001 total expenditure on nanotechnology research and development in Germany was €217.3 million. This includes €153.1 million from the public sector - both institutional and project funding - and €64.2 million from industry sources. The German government has made nanotechnology a key research policy priority and supports the exploitation of its commercial and job creating potential and a wider dialogue on the opportunities and risks.

A key element of the German strategy is to establish networks involving the best public-sector research facilities, universities and commercial companies. This includes continued support for Germany's six virtual nanotechnology competence clusters through to the end of 2003. These virtual nanotechnology networks involve 127 universities, 99 non-university research institutes, 20 industry associations or learned societies, 130 SMEs and 47 large companies. A seventh network, specialising in nano-scale materials, was founded at the initiative of the Karlsruhe Research Centre and the Federal Research Ministry.

The strategic purpose of the nanotechnology investments in the US and Japan, and to a lesser extent Korea, Germany and France, is clear. These countries recognise the advantage that their industries will have if they are early to incorporate nanotechnology into their products. They want to retain their share of high-tech manufacturing, particularly in microelectronics, and to gain share in areas where nanotechnology will turn the existing industries upside down, such as pharmaceuticals.

Some of the specific provisions being made in other countries for major nanofabrication facilities and associated business start up and incubation support are summarised in Box 2.

Box 2
Some overseas facilities aimed at supporting the development and commercialisation of nanotechnology

FRANCE
Minatec

The Minatec Centre for Innovation in Micro and Nanotechnology, in Grenoble, has the ambition "to become Europe's top centre for innovation and expertise in micro and nanotechnology".

France launched Minatec, initially called the Micro and Nanotechnology Innovation Centre, in 2000. Work began in 2001, with a planned investment of around €150 million. Regional authorities are providing about a half of the total costs.

The main objectives of Minatec are to:

Speed up and optimise the process of innovation, by:

- bringing together in the same place industry, upstream and applied research, training and innovation resources;
- strengthening pluridisciplinary working in micro-technology, software, biology, user patterns, etc.
- organizing collaborative projects and alliances with complementary centres of excellence in France, Europe as well as in the USA and Asia.
- offering industry various approaches to technology transfer: R&D contracts, joint laboratories, consortiums, start ups and so on.
- setting up initial and continuous training courses suited to the new requirements of micro and nanotechnology.
- attracting students, researchers and top grade engineers to meet growing demand by French and European firms and laboratories.
- instilling new drive in Grenoble and strengthen the area's assets.
- boosting European research improving our competitive edge in strategic fields in a keenly competitive international environment.

CANADA
National Institute for Nanotechnology at the University of Alberta

In August 2001, the Government of Canada and Government of Alberta announced that each would contribute (Can) $60 million over five years to create the National Institute for Nanotechnology at the University of Alberta. The National Institute for Nanotechnology (NINT) will employ about 200 people, and house state-of-the-art equipment and research programmes. The National Research Council, in collaboration with the University of Alberta, will operate the facility.

The NINT and its partners will directly employ a total of 150 people. Main features of NINT include NRC research, innovation and commercialization programmes, a major physical installation and state-of-the-art facilities shared by scientists from the University of Alberta and NRC, and a collaborative R&D programme

USA

Nanoscale Science and Engineering Centers

National Nanofabrication Users Network

In September 2001, the US National Science Foundation announced awards estimated to total $65 million over five years to fund six major centres in nanoscale science and engineering at Columbia and Cornell Universities and Rensselaer Polytechnic Institute in New York, Harvard University in Massachusetts, Northwestern University in Illinois, and Rice University in Texas.

The Nanoscale Science and Engineering Centers are:

- NSEC: Integrated Nanopatterning and Detection Technologies
- NSEC: Nanoscale Systems in Information Technologies
- NSEC: Science of Nanoscale Systems and their Device Applications
- NSEC: Electronic Transport in Molecular Nanostructures
- NSEC: Nanoscience in Biological and Environmental Engineering
- NSEC: Directed Assembly of Nanostructures

This is but a small part of a massive investment in nanotechnology in the USA. The federal budget for fiscal 2002 included $604 million for nanotechnology R&D, $199 million of it for the NSF. The request in fiscal 2003 was $710 million, including $221 million for NSF.

Other agencies in the USA supporting nanotechnology include the Departments of Commerce, Defense, Energy and Justice; the Environmental Protection Agency; the National Institutes of Health; and the National Aeronautics and Space Administration.

As well as the NSECs, facilities in the USA include the National Nanofabrication Users Network. The NNUN, also funded by the NSF, provides access to “some of the most sophisticated nanofabrication technologies in the world with facilities open to all users from academia, government, and industry”. The combined staffs of the NNUN have extensive experience in all phases of nanofabrication and its use in fields ranging from nanophysics to biology to electronics. The NNUN has ‘domain experts’ in micromechanics and biology to assist users in translating their ideas into experimental reality.

The NNUN, which is now more than seven years old, says of itself: “With the assistance of the NNUN, users can often fabricate advanced nanostructures within weeks of initial contact. The NNUN also provides outreach support to the community through its Research Experience for Undergraduates program and training workshops.”

The NNUN consists of two hub facilities on the east and west coasts at Cornell University and Stanford University, with three additional sites at Howard University, the Pennsylvania State University and the University of California at Santa Barbara. These centres offer expertise in specific areas. During 2001, more than 1700 users conducted a significant part of their research at the NNUN’s facilities. These users were evenly divided between local and external institutions and a large majority of them were graduate students.

In recent years, the annual a growth rate of the NNUN has been around 20 per cent. The user population has almost doubled in the past four years. In 2001, nearly 150 small companies used the resources of the NNUN.

The Director of NNUN, Sandip Tiwari, sums up the network’s role in a document that brings together some of the papers that have come out of the various centres. He says:

“We accomplish our mission by providing the nation’s researchers with effective and efficient access to advanced nanofabrication equipment and expertise. We enable research by providing state-of-the-art facilities, training, and project support. We help expand the application of nanotechnology by providing technical liaison personnel, education through workshops and short courses, and by acting as a bridge between disciplines to create research opportunities that might otherwise not be apparent to specialists in narrow disciplines.”

Box 3

ELECTRONICS MARKETS FOR NANOTECHNOLOGY

Even at this early stage in its development, people have tried to forecast the potential markets for nanotechnology. As an industry that has already demonstrated the importance of ever greater miniaturisation, it is perhaps easiest to see how nanotechnology could change electronics.

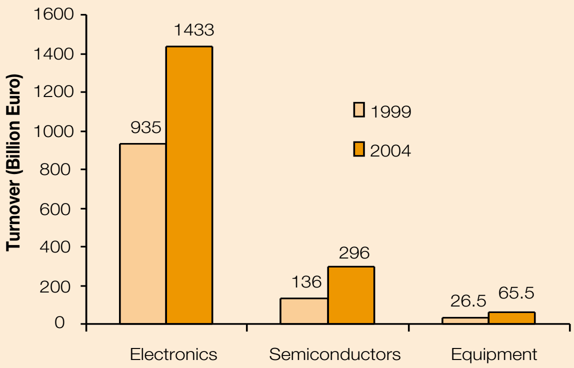
The current market for miniaturised systems is about $40 billion. It is an act of faith within the microelectronics industry that the technology will continue to follows Moore's Law. This states that the performance of semiconductor devices doubles every 18 months or so.

That progress has come from the ability to create ever finer features on chips. For Moore's Law to continue, the semiconductor industry needs new approaches. It is close to introducing 100-nm technology sometime around 2004. This is the turning point for radically new technologies, which will begin to reach physical limits.

The Technology Roadmap for Nanoelectronics, produced by the European Commission, points out that 5 to 7 per cent of semiconductors will be 'non-CMOS' by 2004, and a significant proportion of the equipment will be capable of nanofabrication down to 10 nm. The nanoelectronics market could therefore be in the range of £10 to 20 billion two years from now.

One option for the future that the roadmap sets out is to look for are mechanisms that operate at the nanoscale and exploit quantum effects.

Few products already in the market place embed nanotechnology. However, composite annual growth rates of 30-40 per cent (70 per cent for emerging



Turnover for electronic products, the semiconductor segment, and the equipment for the production of semiconductor products in billion Euro. Werner M., T Köhler, S. Mietke, J. Ilgner and G. Bachmannn, Wirrtschaftliche Bedeutung der Mikro- und Nanotechnologie, Konferenz über Nanotechnologie, Duisburg (Germany) 10/5/2000, quoted in EC Technology Roadmap for Nanoelectronics, 11/2000.

markets) are expected. The market for micro and nano systems in the telecommunication sector is in the order of $3.5 billion with rates of growth of 70 per cent although the slowdown in the telecommunications industry may have some short term impact on this [see NPL study]. Nanotechnology is projected to yield annual production of $300 billion for the semiconductor industry (and a few times more for global integrated circuit sales) within 10 to 15 years [USNSF].

Nanotechnology will influence both optoelectronics and magnetics, key enabling technologies in information technology Companies have already announced that they are working on such ideas as the use of carbon nanotubes in photonic switching devices, electronic displays and fuel-cell power sources.

OTHER MARKETS FOR NANOTECHNOLOGY

- **Pharmaceuticals** Within 10 to 15 years about half of all production (over $180 billion a year) will depend on nanotechnology [USNSF]. From microfluidics for drug assay to nanoparticles for targeted drug delivery.
- **Medical devices and biotechnology products** The total market for biotechnology products is around $50 billion per year, of which nano aspects contribute perhaps 1% ($0.5 billion). This is expected to double in the next three years across a wide range from growth of biomedical materials for tendon bandages to gene therapy [NPL].
- **Chemicals** Nanostructured catalysts have applications in the petroleum and chemical processing industries, with an estimated annual impact of $100 billion in 10 to 15 years [USNSF].

  The estimated world market for advanced ceramics is over $25 billion (in 2000), with an annual growth rate of 7.2 per cent. From this, chemical processing, nanoparticles, coatings and advanced structural mechanics have around 35 per cent of the market (the rest is within the electronic sector) [NPL].
- **Sustainability** Projections indicate that in 10 to 15 years advances in nanotechnology illumination devices, based for example on LEDs, have the potential to reduce world-wide consumption of energy by more than 10 per cent. This corresponds to a saving of $100 billion a year and a reduction of 200 million tons of carbon emissions [USNSF]. Another fertile area will be the use of nanostructured ceramics and C60 nanotubes for novel fuel cells

Nanotechnology products and markets - where are we now?

Despite nearly two decades of basic research, much activity in nanotechnology is still at an early stage. This is typical of a radically new technology developing a rising head of steam with the emphasis shifting now to the development of the underlying technologies and their applications. Nanotechnology today is arguably at about the same stage that information technology occupied in the early 1960s, or biotechnology at the beginning of the 1980s.

Researchers have demonstrated various bottom-up techniques. Laboratories around the world are working on new approaches and on ways to scale up the technology to industrial levels. There are already significant areas of progress in some parts of industry.

NANOCOMPANY

Enact Pharma

Enact Pharma plc is a development company focused on cancer and neurological diseases. Formed in April 2000 by the merger of two other companies, it has raised over £5 million in equity investment.

This may look like a traditional biotech company, but as well as cancer therapy the portfolio at Enact Pharma includes ‘nerve regeneration’, the ability to generate biologically active nerve fibres on biodegradable polymers. The company’s technology makes it possible to generate biologically active molecules on biodegradable polymers, which can then be formed into channels or tubes to provide a chemical pathway for new nerve cells to grow along.

“The nano angle is that the biodegradable polymer base is nano-sculptured and that this gives a major advantage,” says Dr Tony Atkinson, the company’s Chief Executive Officer. “The molecules used in the base are also biological nano particles.”

http://www.enactpharma.com/

For example, the first factories to manufacture carbon nanotubes and fullerenes are under construction in Japan. (Fullerenes and nanotubes are C_{60} molecules.) Last year Mitsui & Co and a consortium of Mitsubishi Corporation and Mitsubishi Chemical Corporation announced plans to build plants to manufacture fullerenes. The announcements of this production plant came soon after an announcement from NEC Corporation of Japan that it has developed a fuel cell built around nanotubes as electrodes. Samsung of Korea has also shown a prototype of a flat-panel electronic display that uses nanotubes as field emission devices. Carbon nanotubes could also act as miniature reaction vessels, enabling us to control chemical reactions to produce complex compounds.

Nanotechnology - the products

Applications of nanotechnology are already emerging and promise to make a significant mark by 2006.

Products already available:

- hard-disks - devices based on giant magnetoresistance in nanostructured magnetic multilayers dominate the market
- sun-block creams based on nanoparticles that absorb UV light
- lasers, modulators and amplifiers for telecommunications
- computer peripherals eg VCSELs, (Vertical Cavity Surface Emitting Lasers).

Applications close to the marketplace

- better photovoltaic techniques for renewable energy sources
- electronic display technologies
- glasses with scratch resistant coating
- harder, lighter and stronger materials
- ‘lab-on-a-chip’’ diagnostic technologies
- quantum structure electronic devices
- self-cleaning surfaces.
- advanced photonics devices in telecommunications

Applications that may appear within the next decade:

- targeted drug delivery enabling lower dosage and reduced side effects
- anti-corrosion coatings, tougher and harder cutting tools
- polymer electronics
- flat-panel electronic displays
- longer lasting medical implants and artificially created organs
- retinal implants
- medical sensors to monitor patients so that they can be treated at home.

In addition, many new tools and techniques will become available. Top-down techniques (ultra-precision machining, ultra-high resolution lithography, scanning probe microscopy) will make further improvements. Bottom-up "self assembly" processes will begin to become available.

Nanotechnology - the markets

It is too soon to produce reliable figures for the global market for nanotechnology. It is simply too early to say where markets and applications will come, and when. So it is important to treat all numbers with caution. However, existing forecasts do hint at the growth that we can expect (see Box 3, Box 4). Various separate predictions when taken together point to the expectation of a rapid take off in the latter part of the decade (see Table 1).

Table 1

Year	Estimated global market	Source
2001	£31 - 55 billion	German government (2001); CORDIS (1999)
2005	£105 billion	Evolution Capital (UK, 2001)
2008	£500 billion	US NanoBusiness Alliance (US, 2001)
2010	£700 billion	US Government (2001); Evolution Capital (UK, 2001)
2011 to 2015	exceed $1 trillion	US NSTC NSET sub-committee (2001)

Part 2: Analysis & Findings

In this section, we summarise the current situation on activities related to nanotechnology in the UK, both publicly funded and industrial, using a wide range of data sources and the research survey that we commissioned. We then discuss the key issues arising from them.

We then consider what obstacles exist to improving activity in the UK over the coming decade - how could the UK do better and what would it take? Our methodology for this is to choose a number of specific, major application areas and to produce for each area success scenarios for five years from now. These scenarios were generated in a focussed workshop of the Advisory Group conducted after considerable preparation of material commissioned from consultants. These “Success in 2006” scenarios are aimed at producing optimistic but realistic estimates of how well we could expect industry in the UK to take up nanotechnology in each area if all the necessary enablers were in place.

From this, we can then define the key obstacles which we believe exist to achieving these success scenarios for the UK, and to validate that they are generic across the different areas rather than peculiar to one or two.

ANALYSIS

Current activities in the UK

The UK has a strong academic background in nanoscience and nanotechnology and has been active in the field for a considerable time. The National Initiative on Nanotechnology (NION) led by the National Physical Laboratory (NPL) in 1986 was the forerunner of a number of international initiatives. A LINK nanotechnology programme followed NION in 1988 to 1996 but was not continued. The Foresight Materials Panel commissioned a report (February 2000) which set out to underline the importance of nanotechnology in the materials context, together with its relevance to industry.

The Advisory Group commissioned Oakland Innovation and Information Services to produce a benchmarking survey of nanotechnology research in the UK, both in academia and industry. A summary of the survey appears in Annex A to this report.

Public spending on nanotechnology R&D in the UK was probably around £30m in 2001, although it is hard to categorise because of the large number of disciplines involved. It is set to rise quite rapidly in 2002-3 as the new Interdisciplinary Research Collaborations (IRCs) and university technology centres start to spend (see below).

Nanotechnology research in the UK covers most aspects of the field. Much of this research can claim to be up with the world's best. The UK has particular strengths in nanoelectronics, nanophotonics and molecular nanotechnology. These are related to strong, established research fields in the UK, such as semiconductor physics, photonics, molecular biology and pharmacy.

The UK's support for nanotechnology, and the location of research, has grown around legacy institutions that were set up to support earlier technologies, such as the Central Microstructure Facility at the Rutherford and Appleton Laboratory (RAL) of the CCLRC and the Scottish Microelectronics Centre.

The Research Councils have set out to develop a strategy that builds upon recent successes in nanotechnology research. With other sponsors, they have recently set up three new Interdisciplinary Research Collaborations (IRCs):

- Oxford University with the Universities of Glasgow and York, and the National Institute for Medical Research (bionanotechnology)
- Cambridge University with University College London and the University of Bristol (in materials and measurement in nanotechnology)
- The Universities of Liverpool and Manchester jointly (in tissue engineering).

Research Council support for these centres will be £28 million over six years

A number of other smaller projects currently receive finance from Research Councils and the DTI.

There is a steady flow of new ventures from the universities, RAL and the Scottish Microelectronics Centre. This will increase with the commissioning of purpose-built incubator facilities at the three more commercially minded new centres:

- the proposed I^2 NanoTech Centre at Birmingham, including support from Advantage West Midlands, the Regional Development Agency
- the University Innovation Centre (UIC) based on the Universities of Durham and Newcastle, which aims to attract significant business support in the North-East Region
- the planned £45 million investment in nanotechnology on Oxford University's Begbroke Business and Science Park.

Another centre is planned jointly by UCL and Imperial College in London.

The independent Institute of Nanotechnology has undertaken some seminal studies, conferences and missions which have helped raise the profile of nanotechnology in the UK and Europe.

Key features of the UK situation

The Advisory Group has reviewed and debated the material we have assembled about the current status of nanotechnology in the UK. We summarise below the main characteristics we have identified.

Absence of coordinated strategy, fragmentation, lack of critical mass, level playing fields

The Oakland survey commissioned by the Advisory Group (Annex A) found that national and international perception of the UK's research in nanotechnology is coloured by its fragmented and uncoordinated nature. It is seen to be dominated by a number of internationally recognised individuals rather than there being world-leading UK centres. The UK is not recognised as having a critical mass of world-class activity, but is seen as having a thinly spread network of leading players across the full range of nanotechnology research activity. In practice, although many of these field leaders are based at the larger centres of research such as Cambridge, Birmingham, Glasgow and Oxford, the role of nanotechnology in the wider research effort is largely unrecognised.

Part of the problem may be that it is difficult to create a collective view of something as multidisciplinary as research in nanotechnology without a degree of strategic overview and coordination along traditional research department lines. Successful application of nanotechnology requires the sharing of knowledge, tools, techniques and information from disciplines including materials science, engineering, physics, chemistry, molecular biology and medical research. These disciplines need to communicate effectively among themselves and be accessible to managers and entrepreneurs and investors.

The diverse nature of the UK's research effort in nanoscience and nanotechnology makes it hard to give industry confidence that the technology is ready to develop into marketable products and processes. In particular, there are few 'portals of entry' through which individuals or companies wanting to explore the territory efficiently can access the expertise in the range of nanotechologies that might be relevant to their needs and opportunities.

NANOCOMPANY

Oxonica

An old hand in terms of nanotechnology. All of three years old, Oxonica, once called Nanox, is a spin out from Oxford University. Based on research by Professor Peter Dobson, the company's focus is on making tiny particles.

One set of particles they work on soak up ultraviolet light. That's the dangerous bit of the spectrum in sunlight. Which is why these particles could appeal to people who make sunscreen or cosmetics. Nanoparticles can absorb much more UV than conventional materials.

Oxonica is into other materials for the next electronics revolution. It has found ways of making materials that produce light and that could be used in electronic displays.

Quantum dots are the name of the game here. Little clumps of 1000 to 100,000 atoms, they have excited scientists for the past five years or so. Quantum dots can be semiconductors, metals or metal oxides and can have novel properties for electronic, optical, magnetic and catalytic applications.

http://www.oxonica.com

A key element of many discussions was the "unfair" competitive advantage that other countries derive from their provision, at public expense, of major nanotechnology fabrication facilities. These centres enable engineers and entrepreneurs from many different organisations to use leading edge facilities with high grade R&D and technical support to explore the practicability of concepts for new products and processes, and to develop them to the point where they can demonstrate commercial viability to potential customers and investors. Some key examples of such facilities in other countries were summarised earlier (see Box 3).

Consequently, large companies in the UK are poorly sighted on the implications of nanotechnology for their businesses and, as yet, provide only limited 'industry pull'. Their involvement is confined to maintaining a watching brief on an area that many perceive to be beyond their planning or engagement horizons. Thus, with some exceptions, there is little large scale industrial investment in R&D for nanotechnology in the UK. Few companies report significant in-house research expertise in the emerging nanotechnologies relevant to their businesses. The level of industrial funding for academic research in nanotechnology is also low. A further factor that depresses interest in the subject is the limited industrial base in the UK in some key areas where nanotechnology will make its greatest impact, for example microelectronics.

The relative failure of companies in the UK to perceive the importance of nanotechnology may stem partly from the fact that no top level organisation provides strategic leadership or education relevant to nanotechnology. For example, at present no UK organisation has the remit to establish direct contact with every business in the UK that could benefit from nanotechnology. Nor does the UK have institutions such as the National Nanofabrication Users' Network (NNUN) in the US, which assisted nearly 150 small companies during 2001.

NANOCOMPANY

NanoCo Technologies Ltd

A nano company in size as well as its business as we write, with a full-time staff of one, NanoCo Technologies Ltd plans to make quantum dots made with clean chemistry.

The company has its sights on one of today's hot subjects, counterfeiting, which costs the UK more than £6 billion a year. NanoCo is working with a major company to develop security applications of small particles known as quantum dots. "They came to us," says Professor Paul O'Brien, who started the company and still runs it out of his research group at Manchester University.

Quantum dots could produce colours that even the most sophisticated rip-off merchants could not copy. These high-tech particles could also end up in medical kit in diagnostics, for example. Another major British company is working with NanoCo on this one.

NanoCo's business plan calls for annual sales into the security market to reach £1 million within five years.

The NNUN dedicates significant resources to educating industry on the benefits of adopting nanotechnology - and the risks of failing to do so. Germany also has similar nanotechnology user networks. In the UK we are only just making a start, with the EPSRC supporting a number of technology networks, with around half a dozen directly aimed at nanotechnology, and the continuing efforts of the Institute of Nanotechnology which, from a very small base, has sought to maintain links between academics, business and Government.

The role of large and small businesses: value chains and supply chains

As in other areas of advancing science and technology, the industrial ecology of nanotechnology will involve companies of all sizes. Large companies will often carry out their own R&D because they understand that nanotechnology will disrupt their current products and processes and therefore need to understand the implications and control the pace of implementation. Small start-up companies that understand where new opportunities and markets may lie can play an important role in commercialising research. These companies will often find their markets in the supply chains and values chains of larger companies and so the relationship and dynamics between small and large companies is often crucial. It is vital that any new strategy for promoting nanotechnology applications in the UK understands and accommodates this.

Both small and large companies are potential customers for facilities with the appropriate nano-fabrication tools. Many potential products require techniques and fabrication facilities not readily available in industry. Some companies see the lack of such capabilities as a handicap. Where there are facilities, lack of clarity on issues of intellectual property rights (IPR) can be an obstacle.

In the Oakland survey commissioned by the Advisory Group, eight of the 14 universities consulted reported nanotechnology commercialisation activities. The survey also identified more than 20 spin-out companies.

In the past there has been criticism of the universities' approach to commercialisation. Unlike the spin-out companies they spawn, the survival of universities does not depend on commercial success but on their ability to attract research funding by maintaining high scores in the research assessment exercise. As a consequence, industry sometimes complains that universities attach higher priority to open publication of research than to solving application problems under commercial secrecy. Universities have to recognise this and take realistic approaches to the valuation of IPR and to the risk involved in turning ideas into commercial success. There are signs of progress here, with a growing number of academics branching out into the commercial arena and creating their own start-up businesses.

There can also be problems stemming from the different time horizons of industry and universities. Industry desires a rapid response while the academic world operates through research grants which can often have different time constraints.

There are now enough successful university spin-out businesses to act as role models. (For example, see the 2001 Business Higher Education Interaction Survey.) Investors also recognise the potential returns that can come from supporting the transfer of research out of an academic environment. For example, the venture capital company Beeson Gregory has also signed a deal with the chemistry department at Oxford University, under which, in return for an investment of £20 million over the next 15 years, Beeson Gregory receives a 50 per cent share of any spin-out company that builds on the department's IPR. And in May 2002, Imperial College announced a £10 million deal with the company Fleming Family & Partners to commercialise research from the college.

Clusters and regions

Companies large and small can benefit from proximity to other businesses and to academic research centres. This so-called 'cluster' phenomenon has paid dividends as industrial policy in the UK has successfully encouraged a combination of UK investment and foreign inward investment to form clusters of advanced technology businesses. High-tech clusters have grown in areas such as Cambridge, the Thames Valley, West Midlands, South Wales and Lothian. Local facilities in the cluster regions can complement national facilities in providing trained staff, particularly technicians, and in the training needed to keep local industries up with the current state of the art.

If they are to sustain their position, companies in clusters currently active in such areas as electronics and biotechnology need resources to develop microtechnology fabrication (MEMS) capabilities now and will require nanotechnology fabrication facilities for the future.

As the Regional Development Agencies in England have got under way, some, notably the North West and the North East which have set up regional Science Councils, have started to appreciate the importance of science and technology for regional business strategies. The devolved administrations in Scotland and Wales have already developed a keen awareness of this. Research Councils have taken steps to help the English RDAs to appreciate the role that science can play in regional development.

The regional dimension is a key example of where the playing field is not level between the UK and its major competitors such as the US, Germany and France. For example, while the Regional Development Agencies are beginning to play a role, we have no equivalent of the state-level investments in the US such as those in California referred to earlier, or the Laender in Germany. The RDAs could play an important role in focussing and building critical mass between industry, academia and national facilities in nanotechnology applications.

People: training and recruitment

The nature of nanotechnology has implications for the type of training available in universities. Nanotechnology is essentially an interdisciplinary subject and requires staff trained in multiple disciplines, in development and engineering. However, graduates from universities in the UK are still almost always trained in a single discipline.

A key part of the remit of the Research Councils and universities is the training of postgraduate researchers. An important element of the Oakland report commissioned by the Advisory Group (Annex A) was an assessment of current nanotechnology-related research activity in universities in the UK. The study found that some 1200 researchers are engaged in relevant research within the 14 institutions that supplied data on their staff. This figure should grow significantly in the next three years. The UK is beginning to produce small quantities of qualified personnel, including skilled technicians, and graduates with first degrees, MScs and PhDs.

Generally speaking, these are people who have moved into nanotechnology from the classical disciplines. The UK produces relatively small numbers of people, whether at technician, graduate, or post-graduate level who could be said to have majored in nanotechnology. Although this figure should grow significantly in the next three years, universities and the Research Councils need to keep under constant review the needs of the individual and of future employers because we can no longer afford the loss of time and effort that is required when people have to retrain into the latest multidisciplinary fields of science and technology.

Several universities offer anecdotal reports that nanotechnology centres face difficulties in recruiting PhD students or post-doctoral researchers of UK origin. This results from the shortage of science graduates in the UK and is said to be due in part to the unattractiveness of uncompetitive stipends to high quality people. This shortage could combine with a 'brain drain' if we fail to build a nanotechnology infrastructure in which newly trained staff can work and prosper in exciting ventures in the UK.

There can be no doubt that the international competition for the best talent in the nanotechnology field will become even more intense in the coming years as industrial exploitation gathers pace. We already see some of the best UK start-up firms being bought out by overseas competitors and staff relocated elsewhere (generally the US). Unless the level of industrial R&D increases considerably and rapidly, the UK is likely to see a drain of talent to well rewarded work in leading edge industry labs overseas.

How to do better in the UK

If we want to understand how to improve the UK's performance we need to understand whether there are obstacles to improving UK activity over the coming decade. How much could the UK do better? What is stopping the UK doing better? What would it take to enable the improvements to happen?

Our methodology for this was to choose a number of specific, major application areas and produce success scenarios for each area just five years from now. The discipline of "just five years" is important. It removes the temptation to speculate about long term scientific breakthroughs, yet it gives time for changes in programmes, policies and funding to begin to take effect.

These "Success in 2006" scenarios were generated in a focussed workshop of the Advisory Group conducted after considerable preparation of material by commissioned consultants, the National Physical Laboratory, the Institute of Nanotechnology and the Centre for Research on Innovation and Competition (CRIC). The workshops set out to produce optimistic but realistic estimates of how well industry in the UK could take up of nanotechnology in each area if all the necessary enablers were in place. We also asked the question: if a particular outcome in 2006 looks feasible, how would we know if were on track to achieving it?

Box 4
What would "Success in 2006" look like in nanotechnology applications in the UK?

ACHIEVABLE OUTCOMES FROM A SUCCESSFUL NATIONAL STRATEGY FOR NANOTECHNOLOGY

ELECTRONICS AND COMMUNICATIONS

- The UK's share of products in information and communications technologies begins to increase
- Industrial R&D in this sector increased 10 fold, along with a similar increase in patent filing
- Annual spending by the Research Councils reaches £80 million: each year 150 PhDs, accompanied by 300 technicians, graduate from training programmes

DRUG DELIVERY

- Double or treble the number of postgraduates work in drug delivery
- 10 start-up businesses every year
- The first start-ups would approach profitability

INSTRUMENTATION, TOOLING AND METROLOGY

- A national nanotechnology centre will generate SME start-ups and provide prototyping and small-run manufacturing for 50 new customers a year
- More than five UK companies will use directed self-assembly based on 'disruptive' methods compared to one today.

NOVEL MATERIALS

- Seven new products commercialised
- Three product demonstrators at proof-of-concept

SENSORS AND ACTUATORS

- 10 per cent a year growth in the number of UK graduates in nanotechnology
- 100 per cent increase in funding for technology demonstrators
- One field trial of an integrated network of healthcare sensors in a hospital
- R&D, measured by such numbers as publications, citations and patents, to increase by 50 per cent.
- The UK's share of nanotechnology-based sensor systems grows 10 per cent faster than our main competitors

TISSUE ENGINEERING

- Five to 10 start-up businesses every year
- 10 additional multidisciplinary groups every year
- 2 per cent of a $50 billion market, worth $1 billion to the UK
- 85 to 90 per cent of UK tissue engineering companies run by UK managers
- New employment of 1500 jobs
- Eight new products commercialised

The headlines from the "Success in 2006" scenarios for each of the six chosen application areas are shown in Box 4. Each scenario is summarised in more detail in Annex B and the full report of the Workshop is available separately (see references).

The Advisory Group found this process very helpful in framing and driving its analysis and discussion of whether serious improvement in UK performance are feasible, and if so what would be needed to bring them about. Essentially it enabled us to go through several cycles of "what if" arguments which were important in testing our findings and recommendations across a wide range of technologies and applications.

Findings.

The Advisory Group concluded that the UK is indeed considerably behind its major international competitors in the industrial exploitation of nanotechnology, and in the level of UK industrial support for R&D on nanotechnology applications.

The UK's strengths in academic nanoscience and nanotechnology research provide strong foundations on which to develop nanotechnology for the benefit of companies in the UK.

A considerably higher level of successful industrial activity is both achievable and desirable if the UK is to retain a globally significant manufacturing base. However, for the UK to develop a breadth and volume of industrial activity which will be comparable and competitive with other leading nations, there is an urgent need to address a number of obstacles and weaknesses.

Having studied the many previous reports in these areas, commissioned its own studies and held wide ranging discussions and workshops,
the Advisory Group finds the following obstacles to achieving the success we believe is possible over the next few years for nanotechnology applications in the UK:

- **The lack of a stable, visible and coordinated strategy for public support for nanotechnology applications in industry**
- **Fragmentation and lack of critical mass in UK R&D activities, and a mismatch between our research and industrial capabilities**
- **Absence of a level playing field for Government support in international competition**
- **Lack of appropriate technology access and business incubation facilities**
- **Access to skilled people - training and recruitment**

Part 3: Recommendations

Our recommendations for Government action to address these issues focus on:

- National Nanotechnology Application Strategy
- National Nanotechnology Fabrication Centres
- Nanotechnology roadmaps
- Awareness and networking
- Training and education
- International - promotion and inwards transfer

Part 3: Recommendations

Nanotechnology Application Strategy, and the NASB

The UK should develop and articulate a coherent and coordinated strategy for accelerating the application of nanotechnology as widely as possible across the economy, beginning with those areas highlighted in the report. This should be facilitated by the DTI, through appropriate sponsorship of industry and academic groupings in conjunction with Research Councils UK. The strategy should be overseen by an independent steering group from industry, academia, Research Councils UK and Government, referred to here as the UK Nanotechnology Applications Strategy Board or NASB. The NASB should be set up by the autumn of 2002.

A strategy for nanotechnology in the UK must address the key issues highlighted by the Advisory Group and in the studies that it commissioned. These issues affect three key communities and the interaction between them - industry, the academic research community and Government. To obtain the full benefits that nanotechnology can bring, the UK strategy must:

- convince firms and investors of the need to use nanotechnology to defend and improve their competitive position, and ease the path for companies to invest in the area
- increase the number of companies developing and applying nanotechnology and its applications
- ensure that industry and academia have access to the facilities needed to take the ideas that come from research and turn them into viable technologies, products and businesses, with excellent routes to market
- ensure that industry has access to well trained staff
- ensure a coherent and visible strategy of sustained public investment in nanotechnology applications that will encourage confident investment by industry and suppliers of private finance
- promote the maintenance and quality of fundamental research, with adequate critical mass in areas key to the applications where the strategy is focussed

The NASB should commission and oversee further work on scenarios for "Success in Nanotechnology in 2006 and Beyond" to identify more clearly goals and performance indicators that the UK should use to track the progress of the strategy.

National Nanotechnology Fabrication Centres

The most important obstacle to more rapid application of nanotechnology in industry in the UK is the absence of facilities where researchers, companies and entrepreneurial thinkers can work together to assist established businesses in their adoption of nanotechnology, and to create and incubate new businesses triggered by advances in science and technology.

Other countries provide various forms of extended public support for such nanofabrication facilities. Such support is via direct government support, through defence agencies, national R&D programmes and focussed national initiatives, for example; through local/regional government support; and through cooperation with large leading edge companies. Such facilities are not available or accessible in the UK at present; and the provision of such facilities does not fit comfortably with any existing DTI 'scheme'.

The provision of equivalent facilities in the UK was identified by the Advisory Group as the single most important action Government should take to "level the international playing field". (We would still have a long way to go before it was tilted in our favour.)

A major feature of what is required is access for short periods by individuals or groups to large, expensive, multidisciplinary facilities that are staffed with high grade technologists and engineers, working close to the leading edge of what is possible. If a project begins to be successful, continuing access is needed while the evidence is generated that it is possible to develop a viable product and business. Only stable Government support for such a facility can provide access for innovative people to the range of multidisciplinary technologies and facilities they need to work up an initial idea for a nanotechnology application into a viable product and business.

Accordingly, the Advisory Group recommends setting up as soon as possible at least two National Nanotechnology Fabrication Centres (NNFCs).

The proposed centres should develop and operate world-class facilities where individuals and firms can prototype and fabricate potential products, based on the research carried out in universities and in businesses. The main parameters of the proposed centres are:

- The centres should be focussed around particular major areas of nanotechnology, for example, biotechnology applications, nanoparticles or electronics, rather than trying to cover all applications, technologies and approaches in one centre. However, it will be important for the centres to work together where appropriate.
- R&D engineers from other organisations can be assigned as "visiting technical staff" to the centres to seek help, training and support to develop proposals for new products or processes. Such assignments could be for a few days, a few weeks or months, or longer, and be from a wide range of sources including large companies wishing to explore new applications, through small companies to academics and others wishing to start a new business.
- The centres should have the technical facilities and support staff to take selected proposals through feasibility to demonstrations of pre-production volumes at practicable levels of yield, quality, volume and cost. The aim is to enable the launch of a focussed new business to its initial customers and investors.
- The centres should be able to support the incubation of new ventures for large and small companies ('intrapreneurs' as well as entrepreneurs), including networking and access to related academic researchers, management of intellectual property rights (IPR), business planning, management staffing, access to venture funding and accommodation for the initial growth phase.
- The centres will need the capability to underpin the incubation process for the extended periods often necessary in this kind of disruptive, multidisciplinary area.
- The centres should carry out baseline programmes of R&D in areas appropriate to their focus, in close conjunction with recognised academic centres of excellence in their field.

The Advisory Group has commissioned an outline business plan for such centres. This is based on creating two or more centres working with existing centres of research excellence (in particular the Interdisciplinary Research Collaborations of the Research Councils, other Research Council facilities, and the DTI funded facilities), starting this year (2002) and overseen by the NASB. The approach should be to increase funding steadily over the next few years, with management flexibility to stimulate demand and follow areas of maximum opportunity for the UK. We expect that funding for these centres should start at around £25 million per year in 2003 and rise to £75 million or more per year if demand justifies within five years. Public funding should be provided for the first five years with the expectation of continuing for a further five years if they are being successful.

Setting up these first two National Nanotechnology Fabrication Centres should proceed as a matter of urgency. The aim should be to secure launch funding from DTI before the end of 2002 with spending starting by April 2003 at the latest. Funding should be one of the highest priorities for the DTI. The process should be managed by the DTI Innovation Group, in close coordination with the Office of Science and Technology, and overseen by the DTI Knowledge Transfer Steering Group.

The keys steps in the process should be to:

- Develop the specification and business plan templates for the centres, based on the list above and building on the business plan study already commissioned by the Advisory Group. These should lay out the topics to be covered in the business plans of the centres being proposed.
- Organise a focussed competition for consortia to bid for the centres. These could include universities, national laboratories and commercial companies.

MICROSYSTEMS TECHNOLOGY CENTRES

While nanotechnology and microtechnology operate at different dimensions, many of the techniques required for nanotechnology are related to those already deployed in work on microsystems. In some applications of nanotechnology, the techniques of microtechnology will provide the early stages of production. The proposal to create National Nanotechnology Fabrication Centres (NNFCs) has to accommodate, interface with, or incorporate the existing and planned UK facilities for microsystems fabrication. It is the view of the Advisory Group that the proposals for separate micro and nano facilities should come together where practicable. However, they should not be merged as this will destroy the explicit focus on nanotechnology which the Advisory Group believes is essential. There are distinct differences as to how facilities for microtechnology and nanotechnology would interface with, and be perceived by, their target customer base. However, there could be substantial savings in co-locating the facilities and sharing common functions.

Roadmaps - technology and applications

The Advisory Group strongly recommends that the National Strategy for Nanotechnology should be informed by a continuing road-mapping process. The Group commissioned an initial road-mapping exercise which was very helpful (Annex B shows some examples). The remarkable success of the International Technology Roadmap for Semiconductors begun by the US points to the value of this approach in tracking and communicating likely developments in the field to the wider audience of customers and investors. Nanotechnology strategy needs to track both technology and applications. The roadmapping should be carried out as an across-the-board process overseen by the NASB

Awareness, access portals and networking

The National Nanotechnology Fabrication Centres will meet a focussed need to accelerate the growth of new enterprise. To succeed, any national strategy must also promote wider acceptance and uptake of the technology. This will require the promotion of linkages between all the key parties in the UK - academic, industrial and financial - and the involvement of regional organisations as well as national bodies. In particular, the Regional Development Agencies (RDAs) could play an important role to play in promoting local clusters of expertise and growth.

The NASB and the NNFCs should also provide and support '**Access Portals**' for individuals, companies and others who wish to explore the potential of some area of nanotechnology to meet their needs or ideas. These portals need to be highly visible. Their role is to provide easy access for people from various application areas to the R&D people who might be able to work on solving their problems or meeting their needs. For example, they would be able to connect someone from the food industry, or aerospace or transport, with the right people to help them to explore how nanotechnology could be relevant to their likely future needs. Some form of light-touch process along the lines of Faraday Partnerships might be appropriate here, together with innovative uses of Internet facilities. It will be important to leverage the existing Research Council technology networks and the other international groups that already exist or will develop, for example as sixth Framework Programme (FP6) of the EU starts to operate.

The UK must begin to catch up with and overtake other countries in informing and educating the business sector, universities, the media and others on the implications and possibilities that will arise from nanotechnology. The need to raise public awareness is pressing and cannot await the formation of the nanofabrication centres. Indeed, it can help to pave the way for them.

The action group recommends the immediate implementation of an awareness programme for nanotechnology. Such a programme should involve the learned and professional societies and could draw on the experience of existing publicity campaigns within the DTI.

Training and education

The availability of trained people will be key to achieving the rapid expansion of activity envisioned in our success scenario. They will be needed at a wide range of levels, from leading edge researchers to highly skilled technicians, production and quality engineers, application developers and so on. A major campaign in training and education will be needed as part of the strategy. This campaign should involve the NNFCs but will need to be much wider. The NASB should also oversee this activity. Effective participation in the international marketplace for talent at all levels will be essential.

International - promotion and inward transfer.

The national strategy for nanotechnology in the UK should build on the growing support for the topic within the EU. The UK should use the sixth Framework Programme (FP6) more strategically to develop collaborations with European industry and academics. Potential UK academic collaborations for FP6 initiatives should be developed by the NASB in close collaboration with the Research Councils.

The success of industry in the UK in exploiting nanotechnology opportunities should not be limited to research conducted by the UK science base. To be competitive, industry in the UK needs to access the best R&D anywhere in the world. It should be a key element of the national nanotechnology strategy that Research Councils UK and the DTI develop effective ways to facilitate access to this global technology network.

The UK should also promote its national research capabilities and facilities abroad to encourage collaboration and attract inward investment, particularly from major multinational companies needed to rebalance the domestic R&D scene.

Conclusion

We believe that the field of nanotechnology and its applications is crucial to the future competitiveness and productivity of the UK economy, and to the well being and prosperity of its people. We hope that the government will take forward these recommendations with urgency and we are confident the research community will be ready to play a full part in their implementation.

It has become almost a cliché to say that the UK is good at science, or invention, but bad at innovation, and that too much British research had to 'emigrate' to become commercial. Past failure came about partly as a result of an innovation gap - a lack of mechanisms, processes and the will to turn world leading science into successful products and services.

This pattern of past failure is changing thanks to a number of factors, including the greater availability of venture capital and a growing enthusiasm among some researchers to commercialise their own discoveries. However, the UK has yet to plug the innovation gap completely. A major aim of this proposed strategy for nanotechnology in the UK is to do just that. If we succeed, then, unlike many cases in electronics and biotechnology, for example, the UK could build on its position as a research leader in nanotechnology to become a leader in its commercialisation.

Annexes

Annex A Nanotechnology research in the UK

As a part of its investigation of the state of nanotechnology R&D in the UK, the Advisory Group on Nanotechnology Applications commissioned Oakland Innovation and Information Services Ltd to conduct a review of nanotechnology research in the UK. The study set out to produce a document that would give an insight on the:

- Centres involved in nanotechnology research
- Research community involved in nanotechnology research programmes
- Scope and quality of the research portfolio
- Involvement of industry and other organisations/companies likely to facilitate commercialisation of resulting technology

The survey included a programme of 24 structured interviews with key players in the nanotechnology university research community. In total, the survey drew out opinions from 14 UK universities, three institutions in the USA and two Research Councils in the UK. While this is not a comprehensive study, it does draw on the expertise of the UK's leading institutions in nanotechnology.

University centres of nanotechnology research

All of the universities participating in this study organise nanotechnology research via virtual, informal networks. Often referred to as 'centres', they typically span several departments but with a major component in one department. Most of the research usually happens in the departments of physics, electronic/electrical engineering and chemistry.

Well-established networks, such as that at Oxford, have collaborative projects across departments and faculties. Some centres are clustered in two or three departments, with mutual awareness but little collaboration.

The general reputation of departments involved in these centres is high, with the vast majority involving departments with a rating of 4 or better in the HEFCE 1996 Research Assessments Exercise, indeed, more than half were rated as 5 or 5*. In terms of international standing, Cambridge, Glasgow and Oxford are seen as the three strongest centres.

There is an anticipation that the recently announced Interdisciplinary Research Collaborations (IRCs) will change the organisation at the institutions that are participating in the IRCs, especially at Cambridge which is planning a physical centre of fabrication activity. The view is that sharing of work space between interdisciplinary researchers encourages cross-fertilisation of ideas.

There is not perceived to be a critical mass of nanotechnology research of great international presence within the UK, due to insufficient Government funding. The dispersed, informal organisation of most centres adds to the international perception of a dilute research community. The introduction of high profile formal 'knowledge networks' and/or a move towards self-standing centres may be required to strengthen the UK nanotechnology 'brand'.

The international stage on which these institutions compete is dominated by the USA with the 13 centres listed below recording the highest number of citations for non UK centres deemed as world leaders.

- University of California at Santa Barbara, USA
- Cornell University, USA
- MITI at Tsukuba, Japan
- Max Plank Institute, Berlin, Germany
- University of California at Los Angeles, USA
- Stanford University, USA
- IBM Research Laboratories, USA and Switzerland
- Northwestern University, USA
- Harvard University, USA
- MIT, USA
- RIKEN at Saitama, Japan
- University of Tokyo, Japan
- University of Wurzburg, Germany

The international perspective of UK nanotechnology, which was also confirmed by many of the UK experts interviewed, is one dominated by a number of internationally recognised individuals rather than there being world-leading UK centres.

In interviews with overseas researchers, all three agreed that very good work takes place in the UK, but that the country is not regarded as a major world player. The primary reason put forward for this is the low volume of work undertaken in nanotechnology.

It was described as a thinly spread network of leading players across the full range of nanotechnology research activity. However, in practice, many of these leaders in the field are based at the larger research centres such as Cambridge, Glasgow and Oxford.

The interviewees linked the size of the UK's research portfolio in nanotechnology to limited Government funding. One respondent ranked the USA, Japan, Germany and the Netherlands as having a greater presence.

Centres in the UK claim to have some internationally leading facilities. These are evenly distributed across three main categories:

- fabrication tools - lithography, molecular beam epitaxy (MBE) and thin-film processing
- characterisation tools - microscopes, mass spectrometry and metrology
- manipulation tools - optical tweezers, molecular manipulation on scanning probe microscopes (SPMs)

These facilities are distributed relatively evenly across the institutions sampled, although Cambridge, Imperial college , Oxford, Sheffield and York all have more than one such facility.

The informal interdepartmental structure of many centres and the diversity of nanotechnology encourage collaboration. Universities in the UK have links, mostly nationally but also internationally.

Collaboration

Access to key facilities appears to be an important catalyst for collaboration, as are EC funding programmes. International collaborations are less frequent than national ones and appear mostly to involve institutions in the USA and Europe, especially Germany. Centres mentioned as being collaborators were often also cited as competitors, however the top centres in USA were most regularly cited as competitors.

The extent of collaboration appears to vary dramatically between centres in the UK. One reported having no formal collaborations with other centres; others seek partner laboratories for essentially all projects.

To an extent, the degree of collaboration is related to national facilities, such as the EPSRC's Central Facility for III-V Semiconductors at Sheffield. This currently supports 44 grants in 32 groups across the UK.

Several respondents commented that collaboration is not only good for the advancement of science, but also the best way of utilising limited resources and facilities.

The research portfolio

The perceived strengths of nanotechnology research in the UK are evenly spread across four research areas: tools, electronics, bulk materials and 'molecular'.

There is a view that electronics research is a little stronger than the other areas. There are perceived to be weaknesses in areas of electronics research. This may be due to the wide variety of topics within this area, or to intense foreign competition.

When asked about the research portfolio at their centres, interviewees presented a similarly balanced picture with no fewer than 10 institutions reporting activity for each of the four broad nanotechnology research areas. Reviewing each of the main themes in terms of the proportion of the research that was regarded as internationally leading, the UK's strength would appear to be ranked as follows:

- Electronics - 56 per cent of major research themes are regarded as internationally leading
- Molecular - 48 per cent regarded as internationally leading
- Tools - 43 per cent regarded as internationally leading
- Bulk materials - 38 per cent regarded as internationally leading

Funding

Funding for research is mostly from EPSRC. Interviewees estimate that between 70 and 80 per cent of funds coming from this source. However the BBSRC has a growing input, due to the increasing focus on biological systems. Support from the European Union is also significant - some centres indicated that up to 30 per cent of their funding comes from this source.

With respect to the priorities for funding nanotechnology in the future, there was support for the idea that the UK should focus on current strengths rather than attempt to be expert on all aspects of the subject. There was also a view that there will have to be investment in equipment and infrastructure and that better integration with other European centres and initiatives would help to ensure that Europe can compete with the USA and Japan.

After focussing, the most popular suggestion was for investment in equipment and infrastructure. Recruitment difficulties at many universities led several respondents to suggest a need for funding to train people in the necessary skills.

Of the types of research requiring particular attention for funding, interdisciplinary projects were most commonly highlighted. Reasons given for this were three-fold:

- Many breakthrough discoveries are anticipated where previously separate fields come together.
- Both cultural and equipment issues require a lot of support for truly interdisciplinary work to be successful.
- Since the UK cannot compete internationally in large, established topics such as those supporting the semiconductor industry, there is more scope to make an impact at the interfaces between topics.

Nanotechnology research community

While it is difficult to arrive at definitive figures for the number of research personnel, excluding technicians, engaged in nanotechnology research, the study found that around 1200 active researchers at the centres consulted in the study. This figure is generally expected to grow significantly, with an overall projected figure of 17 per cent in the next three years.

Glasgow, Nottingham and Oxford account for around 40 per cent of the total. It was not always possible to produce a specific breakdown of staff figures. However, drawing on the available data, the research community encompasses approximately 440 PhD students, 350 postdoctoral researchers and 330 tenured staff.

Of the 14 universities surveyed, three reported having more than 100 individuals participating in nanotechnology research. A further six universities have between 50 and 100 people in the area, and the remaining five have between 29 and 50.

Looking to the future, nine of the institutions consulted expected numbers at their centres to grow by at least 25 per cent over the next three years. Almost all of the respondents admitted to difficulties in recruitment and retention of staff.

Most new positions will be for PhD students and post-docs, both of which are in short supply. With applicants from the UK increasingly hard to attract, an increasing proportion of contract researchers are likely to come from overseas. This, and the growing difficulty of retaining researchers in British universities, could lead to a brain drain from the UK.

Many of those interviewed expressed concerns on the national origins of researchers. These related to the recruitment of a disproportionate number of non-UK citizens to departments as PhD students and postdoctoral researchers. Hence there is a risk of a nanotechnology brain drain. The latter is made worse by reported difficulties in the retention of staff.

Low pay for PhD students and high debts of fresh graduates conspire to channel graduates away from academia into companies. The most apparent skills shortage however is at the post-doctoral level. Industry currently offers far greater salaries and permanent positions. As a result, advertisements from universities for post-doctoral contracts tend to receive few or no UK applications. Indeed, most post-docs go to companies after completing their two- or three-year contract. They are sometimes 'poached' before the end of such contracts.

Trends in nanotechnology research

Many respondents commented that the absence of a universally accepted strict definition of nanotechnology allows the research emphasis to broaden, encompassing many areas of research that have previously been referred to as chemistry or biology. Researchers see funding initiatives as encouraging this broadening, which has resulted, at least in part, from the acceptance of nanoscience as an intrinsic part of nanotechnology, a term originally applied to ultra-precision machining.

These issues are generally seen as being global, with no particular differences between the UK and the rest of the world. Other worldwide trends suggested by respondents include an increasing variety of subjects, including polymers and biological molecules, and a move away from single molecular manipulation towards self-assembly.

Principal focus of research

Development of tools for fabrication and analysis at a precision and scale of less than 100nm

By far the largest number of major themes in this area are in scanning probe microscopy (SPM), including atomic force microscopy (AFM) and scanning tunnelling microscopy (STM) which together account for over one third of the 'Tools' themes. Typically this work is aimed at gathering new types of information on the nanoscale, by incorporating temperature, capacitance, magnetic resonance, optical or magnetic field sensors on SPM probe tips.

Application to new samples, such as biological materials, is also advancing SPM techniques. These machines are used in the analysis of many materials with nanometre resolution, and in molecular manipulation studies. Other microscopies under development include electron microscopy and hybrid methods.

Fabrication tools under development are mostly in the semiconductor arena, comprising epitaxial growth techniques, etching techniques, electron-beam lithography, and micromachining at sub-micron dimensions with shape memory polymers. Such equipment is used in the fabrication of very small and very fast electronic devices, intended to replace current micron-scale devices in the next ten years or so, for reasons of lower cost, higher performance and robust operation.

Ultra-rigid machining and grinding tools are under continued development, with dimensional accuracies in the nanometre range. Fundamental work in accurate displacement mechanisms and standards for distance and force measurement in nanotechnology is being pursued, with obvious implications for future fabrication and analysis tools.

Other tools under development include optical tweezers for manipulation and metrology of biological molecules, and tools for the nanoscale analysis of micromachined devices.

Fabrication and analysis of electronic devices with linewidths of less than 100nm

Approximately one quarter of the themes in the electronics area address 'traditional' inorganic semiconductor electronics. This work consists primarily of making and characterising nanostructures, such as quantum dots and wires, in III-V semiconductor materials.

Another quarter of the themes relate to optoelectronics, with a variety of topics including photonic crystals and fibres, inorganic devices - especially lasers and fundamental studies of the devices, organic devices and hybrid devices.

A smaller fraction of the themes can be loosely described as 'hybrid electronics'. This work includes metallic cluster/semiconductor single electron devices, ferromagnetic/semiconductor magneto-electronics, primarily aimed at magnetic storage devices, and the inclusion of biological elements into electronic devices as amplifiers, etc. Other materials used in hybrid approaches include superconductors and soft/hard material combinations.

Other themes include sub-micron electromechanical devices, theoretical quantum computation and emitter displays using carbon nanotubes.

Nanoscale sensors are included in the electronics area since the diverse sensing mechanisms are often housed on a semiconductor substrate and usually give rise to an electronic signal. Types of sensor under development include single-cell and single-molecule biosensors, chemical sensors, implantable sensors and conducting polymers for electronic nose applications.

Fabrication and analysis of bulk materials with structural features smaller than 100nm

Over one third of the work in themes in this area is on thin films or surface modifications. There are a range of approaches from studying fundamental properties of films, surfaces and coated materials, to their development for use in sensors or magnetic storage devices. Structural characterisation plays an important role, with groups employing techniques such as electron and scanning probe microscopies, X-ray and neutron diffraction.

The remainder of the materials work is split evenly between composites, polymers, particles, biological/non-biological interfaces, nanoporous, ferromagnetic and ferroelectric materials, superconductors and organic materials. Researchers are assessing nanoparticles for drug delivery, for example.

Research is under way into the interface between biological and non-biological materials, both at a fundamental level and in applications to sensing and diagnostics.

Ferromagnetic and superconducting materials are under investigation on the nanometre scale. One aim is to use them in hybrid devices in the field of 'spintronics'.

Organic materials are under investigation for their structural and light-emitting properties, and the properties of bulk biological materials are being analysed at the nanometre scale.

Properties of molecular assemblies and applications of molecular nanotechnology

Approximately one quarter of the research under the 'Molecular' theme is in molecular manipulation. Most of this work employs SPMs to direct single metallic or semiconducting nanoparticles, atoms, Fullerenes or other molecules over a flat substrate.

The researchers aims to expand the range of molecules and substrates, to increase the temperature of operation to room temperature, to measure single molecule properties and to form nanostructures from the 'bottom up'.

Self-organised systems, especially biological in nature, account for another quarter of 'Molecular' research. Surfaces receive a nanoscale texture through lithography or etching, and the researchers then study the effects of thee surfaces on cells and other biomolecules.

Non-biological self assembly is represented by work on metallic nanoparticles to form regular arrays, and on polymers to form 3D macromolecules via lithographic templates.

Other 'Molecular' work covers a diverse range of systems. Three themes centred on Fullerenes, C60 materials, examine the synthesis and fundamental properties of these molecules, and their application in gas storage.

Assembly with the assistance of nucleic acid of nanostructures, electronic and structural properties of cell membranes, and molecular motors represent the other biological themes.

Work on biomimetics and bioanalogues is using biological models to create novel devices, and ultimately this concept underpins many of the biological themes - the aim is to understand nature on the nanometre scale and to use or adapt the observed principles in furthering our technologies.

Most of the work in this area is more nanoscience than nanotechnology, with the exception of self-assembly. Several respondents commented that in order for nanoscale processes to be viable for commercialisation, there must be some element of self-assembly involved, since single molecule methods are enormously slow.

Commercialisation of nanotechnology

Eight of the 14 universities surveyed reported commercialisation activities: Bath, Cambridge, Glasgow, Imperial College, Newcastle, Nottingham, Oxford and Warwick.

Staff-related implications of spinning out companies are sometimes cited as a factor that might hinder commercialisation. Licensing is often seen as a more attractive proposition.

Many respondents expressed concerns about the process of forming a company. It takes a long time and can requires the lead academic to either leave or compromise their post. Licensing is seen by some as a suitable alternative.

The importance of an existing culture of commercialisation seems to be important in encouraging spin-outs, Oxford and Cambridge being perhaps the best example among participating universities.

Several respondents stated that commercialisation of research via industrial collaboration is a preferable method to forming a new company, possibly due to the lengthy and difficult process of starting up a new business. Venture capitalists are not closely involved in many centres, although most university innovation groups have such links.

During the survey, researchers mentioned over 35 companies as having formal or informal contact. However, while there is some investment in the technology, most companies are not funding nanotechnology research in UK universities, preferring instead to lend support in kind.

Companies reported as funding nanotechnology research included: GlaxoSmithKline (UK), Asahi Chemicals (Japan), BAE Systems (UK), Gene Logic (US), BNFL (UK), the Toppan Printing Company (Japan), Marconi (UK), Loadpoint (UK), Druck (UK), Domino (UK), Xaar (UK), IriSys (USA), Polatis (UK), Hitachi (Japan), Toshiba (Japan) and SDL/JDS Uniphase (USA). Additional companies supporting research in collaborations include Agilent, Johnson Matthey, Thomson CSF, Fiat, Protovik, TDK, Senstronics, BT, Bookham, JJ Electronics, Nortel, Communiweb, Epigem, Filtronic Compound Semiconductors, Peratech, BP (Sunbury), Pfizer, Kodak, Unilever, Carpenter Technology, and Morgan-Matroc.

Opinion is divided over whether companies based in the UK are more short-term in their outlook than other multinationals. Some researchers felt that US companies are more forward thinking. Most of the 37 companies named as collaborators and funding sources during this study are of UK or European origin, although they tend to be large, multinational concerns.

There is widespread consensus that much fundamental work still needs Government funding before industry will take a serious interest in supporting nanotechnology, as the risks to them are still too great.

One respondent noted that greater interest from companies might be forthcoming if they had clear, balanced information available to them, giving a realistic impression of what might be realistic uses for nanotechnology. The ‘hype’ resulting from advances in nanoscience was considered to be, in a sense, a barrier to commercial involvement.

Conclusions

The impression gained from the survey is that the UK is not a world player in nanotechnology. It lags countries such as the USA, Japan and Germany. However, the UK has internationally leading individuals, rated as strongly as any of their peers, but these leaders are thinly spread across the spectrum of nanotechnology research. Hence the UK lacks ‘critical mass’ in any one domain of the subject.

Looking at the overall portfolio, it is best described as balanced with the perception being that the UK is relatively strong in all areas, though with electronics perhaps slightly ahead of the others.

Analysing the activities within individual institutions suggests that the UK has more research programmes running in the electronic and molecular nanotechnologies. In addition these two areas appear to have a higher proportion of programmes of international standing.

To compete internationally on a limited budget, there may be merit to a more focused portfolio, perhaps around one or both of these main themes.

Many of those interviewed recognised the merit of focusing the portfolio.

The observation that it is too late to compete in applications such as semiconductors also provides food for thought. In assessing this focus, the strengths of UK industry should also be considered - the significance and health of the UK pharmaceutical and biotechnology industries presenting a particular opportunity.

Should a more focused strategy be adopted, a key issue that needs to be addressed is of if/how Research Councils balance their need to fund research purely on the basis of quality with the need to encourage focus.

The UK’s nanotechnology community is thinly spread across a wide range of research themes and dominated by a relatively small number of internationally recognised individuals. This means that the UK is threatened by researcher mobility. The movement of one lead player in the UK would significantly dent our international standing.

Most of those interviewed expected significant growth in the UK’s nanotechnology community over the next three years. Although this is a positive development, there were concerns as to the origins of these recruits. Typically those interviewed characterised their centres as comprising staff of which only 50 per cent were UK nationals, with the balance mostly coming from Asia and Europe. The UK risks a nanotechnology ‘brain drain’, a risk that is likely to be heightened by the anticipated growth in the sector.

Informal, virtual networks dominate the UK whereas many of the centres in the USA have a recognised physical presence. The distributed and informal nature of the UK’s nanotechnology community may in itself be limiting the development of the discipline and compromising the international perception of the UK’s role in this critical field.

Much of the growth of nanotechnology is expected to rely on interdisciplinary activity. The day-to-day sharing of space and facilities is probably the most effective way of facilitating these interactions.

The survey revealed that the UK has a good base of facilities of international standing. However, as these resources are distributed across many university centres, the UK might benefit from a more formalised and high profile network, focusing on better inter-institutional utilisation of these resources. Such a network could be further enhanced if it were part of an integrated European network. The latter would help to stimulate further cross-fertilisation of ideas and also offer routes to additional funding via the European Commission.

Either strategy is likely to improve the international perception of the UK’s nanotechnology, offering some ‘brand image’. In so doing it is also likely to address some of the concerns of the recruitment and retention of staff.

Annex B - Nanotechnology scenarios*

1. SUCCESS IN ELECTRONIC, COMMUNICATIONS & INFORMATICS

What it is

Informatics includes hardware, design and modelling relating to large-scale integrated electronics and information and communications technology (ICT).

Ever greater miniaturisation has been the key to developing faster, cheaper and more portable systems in informatics. 'Moore's Law,' which says that the power of computing chips doubles every 18 months or so, describes our continuing ability to make semiconductors, and therefore the systems based on them, more powerful. While there have long been suggestions that the era of Moore's Law is coming to an end, microelectronics has so far sustained this pace .

Silicon technology will, however, within the next 10 to 15 years enter a new 'near-molecular' regime – as feature sizes approach 25 nm for example. This could slow, or even curtail, the rapid progress of silicon microelectronics in which the fundamental science and not just the manufacturing technology changes and we will need radically new approaches. Some nanotechnology will begin to impact much earlier than this, particularly in photonics where miniaturisation is already more constrained by physics.

A disruptive technology will then be required to continue performance improvements in informatics. Nanotechnology in many forms could be essential for the further development of more powerful and faster information-handling equipment. For example, the move into the nano regime will result in circuits based on single-molecule and single-electron transistors. These will appear first in special applications.

It will take novel complex architectures, materials, gate designs, interconnects, and so on to accommodate these new devices. We will also need radical new solutions to the problem of cooling and circuit power management.

One disruptive technology could arise from the successful implementation of quantum information processing (QIP).

Another disruptive technology would be 'bottom up' technologies. While these have the potential to be immensely important in the longer term, they are not likely in the near future.

A number of applications exemplify the potential for nanotechnology in informatics:

- **Photonic crystals and photonic integrated circuits** could pack in individual components a million times more densely than conventional 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), crosses the disciplines of quantum physics, computer science, information theory and engineering. The aim is to harness quantum physics to dramatically improve the acquisition, transmission and processing of information. The role of nanotechnology is fundamental to such exploitation, because quantum effects appear on small length and time-scales.
- **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) can confine electrons into regions of less than 20 nm, enhancing their performance. Epitaxial growth can create one-dimensional confinement, producing 'quantum well' structures. A principal aims of nanotechnology is to produce three-dimensionally confined QSDs, for example, quantum wire and quantum dot devices. Some devices are already successful such as: quantum well lasers for telecommunications; High Electron Mobility Transistors (HEMTs) for low noise, high gain microwave applications; and Vertical Cavity Surface Emitting Lasers (VCSELs), for data communications, sensors, encoding and so on. Other applications, such as quantum dots, are on the brink of commercialisation.

* These 6 scenarios were developed at a workshop of experts facilitated by a consortium led by NPL.
A fuller version is available in hardcopy from Ms E. Prah, DTI (020 7215 1462).

Current and future markets

The market for miniaturised systems is estimated at $40 billion. The market for IT peripherals, dominated by the USA and Japan, is more than $20 billion.

There are few nanotechnology products in the marketplace, but growth is expected to be very strong, with a predicted composite annual growth rate of 30 to 40 per cent. One forecast puts the market for devices for IT and electronics based on nanotechnology at about £70 billion by 2010. The market for micro and nanotechnology systems in telecommunication are of the order of $3,500m with an anticipated compound annual growth rate in the order of a remarkable 70 per cent or so.

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 £80 million; and already the quantum well laser amplifier market for 2000 is estimated at £4 billion. 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 challenges concern methods for maintaining Moore's law for electronics and extending it to photonics, either by continuing miniaturisation of silicon-based devices, by the use of different materials, fabrication principles or device concepts - such as molecular electronics, carbon (or other) nanotubes, and photonic crystals.

Research in photonics is already yielding such devices as advanced lasers. In the next five years or so such products as photonic-crystal fibre, currently a niche product, could achieve significant markets. Two-dimensional photonic integrated circuits and photonic crystal assisted vertical cavity lasers will also move out of the laboratory into commercial production. Other products, such as nonlinear gates in photonic crystal fibre and integrated circuits, are moving from research to development.

Quantum information processing also presents considerable technical challenges, with a need for basic research into quantum effects. The likelihood is that quantum communication systems could appear within the next decade, with quantum computers emerging later.

Global competition

Research into new informatics technologies is spread through the universities in the UK, the USA and much of Western Europe, and through major manufacturers in Japan and the USA who are behind recent technological breakthroughs.

Japan and the USA are home to the most innovative semiconductor companies and many other silicon fabrication plants are located in the Far East. Many European telecommunications companies compete successfully against Japan and the US. However, in most cases research related to nanotechnology is probably 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.

Japanese R&D tends to be organised according to guidelines determined by the government, with the MicroMachine Centre, an organisation supported by METI, the Ministry of Economy Trade and Industry, 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, to the tune of about US$ 100 million in the past five years. The research has a longer-term focus than is typical for the UK. there is a well focused interest in quantum computing, where some original approaches are being pursued. Molecular scale electronics is another focus.

The US's efforts are also strong. Here military funding agencies are generous in funding companies, even when there is a clear commercial benefit for the companies involved.

The UK has strengths in photonics, and thus is relatively competitive against the US and Japan in such novel nanotechnology applications as photonic crystals. In QIP, the US spent around $30 million in 200, 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.

The UK's profile

Research in the UK is of high quality, but faces problems in the transfer to industry. The UK is strong in telecommunications. Optoelectronics, where the UK is strong in niche optical communications areas, dominates the ICT industry. Optoelectronics is effectively the flagship of the nanotechnology and microelectronics sector in the UK.

A range of companies has grown rapidly from small beginnings over the past decade. The industry is well supported by a strong R&D base. Although promising, the market is volatile: future success depends on world markets.

The UK is strong in several important areas for long-term development of informatics. In the field of photonic crystal, there is strong R&D, reflecting past UK Government support and the relative strength of the country in photonics.

Challenges for the UK

The UK lacks an industrial base that can commercialise many of the results of even high quality and well-funded research. While there have been research programmes dedicated to micro and nanotechnology technologies in the past, at present there are no specific programme. Though the UK continues to fund R&D in the field through activities on related subjects, there are concerns that the research 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.

It will take large numbers of professionals, with interdisciplinary perspectives, to build nanotechnology industries in informatics as well as other application areas. These businesses will depend upon highly trained multidisciplinary teams. 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, education in nanoscience and technology will require special and often expensive laboratory facilities. Many engineering schools cannot now offer students any exposure to nanofabrication. We will have to find innovative solutions, such as new partnerships with industry; shared nanofabrication facilities across consortia of colleges, universities, and engineering schools, with web-based, remote access, and so on.

Drivers of change

Two issues are particularly important here: fabrication and functionality.

The importance of fabrication resides in the need to be able to manufacture informatics products of high quality in large volumes.

Printing and lithography will continue to grow in importance, with scalability a prominent issue. We will need the capability for optical lithography for mass production at nanotechnology scale. Feature size may well be reached 70-nm level in commercially viable devices by 2006.

In the longer term self-assembly offers a way of breaking through the anticipated ceilings for 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, with 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 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 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, should be moving toward commercialisation by 2006, becoming highly important by 2010. 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.

What will enable us to get there?

The major factors that can help to make this scenario a reality are: first, the quality of basic and applied research in the contributory disciplines, but critical mass in research is also important. Critical mass is also required in infrastructural and, for example, fabrication facilities. Some of this may be achieved through international collaboration within and even beyond Europe. Availability of skilled people will be another critical factor.

Several other factors will also be significant, if less central. Availability of finance, with investment that is sustained and consistent, is bound to remain important. The costs associated with intellectual property rights could also be 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 (with figures in 2001 terms):

- The UK's share of all ICT products remains at least at current values (and the markets are growing), but preferably increases (from, say, 10 per cent now to 13 per cent in 2006).
- Industrial R&D expenditures in informatics-related nanotechnology increases by 2006, to roughly 10 times the value of the 2001 figure.
- Likewise, industrial patenting in the area from the UK increases tenfold.
- Expenditure by Research Councils reaches around £80 million a year, with capital investment for a major centre by 2006 is around £100 million.
- Training occupies around 150 PhDs per year, with 300 trained technicians entering the workplace. Development of research expertise should result in high quality research and be reflected in, for example, the UK holding on to its current bibliometric and citation impact.

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 and training in nanotechnology informatics, bridging and combining academic and industrial lines of work. Funds would be a mixture of private and public, with substantial inputs from other countries.
- 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.
- Academic/industry collaboration to establish 'supercritical' research teams on key subjects.

2. SUCCESS IN DRUG DELIVERY SYSTEMS

What it is

Drug delivery systems deliver drugs to specific pharmacological targets in the body, at the correct time and with a controlled dose. This is hugely safer and more effective than just spreading a drug through the body, even if this is practical. One difficulty is that the targets in the body may be small and widely distributed.

Effective drug delivery reduces unwanted side effects and can lead to lower doses, which can encourage patients to follow the correct dosing regime. Better targeted delivery could also allow the use of new therapeutic possibilities, for example, using drugs that would otherwise be too toxic.

Drug delivery systems 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.

Nano-scale devices may also be able to safely deliver to cells material other than conventional drugs - for example, DNA could be 'inserted' into cells for gene therapy and vaccinations.

While the benchmark exercise did not investigate it, nanotechnology could also play a part in drug discovery.

Current and future markets

The global market for drug delivery is some $33 billion per annum, with an annual growth of approximately 15 per cent. In the UK the market is around $8 billion. There are 30 main drug delivery products on the market.

Regulatory issues may not loom high, but certain applications may face competition both from other nanotechnology solutions, and from alternatives that do not depend on nanotechnology, such as genetic screening to select appropriate drugs for patients, alternative means of getting drugs into the blood system for specific organs.

Technical challenges

A major challenge is to develop surface molecular bioengineering leading to biomimetic and bio-inspired devices to increase specificity. We need better knowledge 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 a strong connection between research and applications. Industrial consortia are attached to universities, ensuring an application-driven approach. Two-way non-disclosure confidentiality agreements are well established.

Research students are closely coupled with industry, thus learning relevant skills. Funding of fundamental research is mostly 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 impetus away from the UK 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 frontiers of research here. Perhaps more significantly for the future, the US is taking the initiative with work on peptide nucleic acid. The US is investing heavily in gene delivery, reflecting the wealth of information that has resulted from the human genome project.

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 has lost much of its lead some areas to the US. The UK probably maintains a lead in such applications as drug-polymer conjugates for anti-cancer and anti-inflammatories. The UK also has excellent underpinning research for nano-particles and micelles.

There are reports that the pharmaceutical industry in the UK, despite it evident strengths, has been slow to take up new concepts related to nanotechnology, and that UK researchers have accordingly licensed their research to more responsive companies in the US or European.

Challenges for the UK

It is essential to have strong connections between applications and underpinning research is vital. 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. The pharmaceuticals industry sees regulatory issues as deterrents to new drug development. While regulatory processes may be less of an obstacle in the development of improved drug delivery systems, there could still be problems, especially in respect of costly treatments.

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

Drivers of change

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 drugs that have already been approved, 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, enabling us to treat diseases that we cannot treat now, and to meet currently unmet medical needs.

Clinical proving is vital. A new application needs rigorous testing for effectiveness if it is to be taken up on a large scale. The critical issue here is the interface between the developers of applications and 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, the organisation of research funding hinders the development of underpinning research, through such issues such as the peer review process and the diffusion of resources across multiple Research Councils and funding agencies.

What will success look like?

Success in the application of nanotechnology to drug delivery 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, it will face strong challenges overseas, especially the USA.
- SMEs already have a strong presence and will drive much of the activity. 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 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 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 problem, which needs to be overcome for commercial exploitation, as is sustained research funding. There were feelings that under current peer review systems there can be barriers in the treatment of proposals for multidisciplinary research.

On the demand side, policies for health services and other public sector markets can be major drivers for market development. Many alternative drug delivery systems are under development. A 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.
- One patent per person active in research and development in the area every three years.

Less precisely, 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); UK companies would take a greater market share; and 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?

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

- Make postgraduate study financially attractive - firms could play a role in such support.
- 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.

We need better communication on the potential for drug delivery systems between academics, the financial sector and user firms.

Setting up "prototyping" facilities in this area should be considered, with Government and industrial financing.
As in other applications of nanotechnology, exploitation is liable to depend on production capabilities.

3. SUCCESS IN INSTRUMENTATION, TOOLING AND METROLOGY

What it is

Instrumentation, tooling and metrology 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 that produce these products.

Successful exploitation of nanotechnology will depend on these tools. 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.

Current and future markets

Current global markets are large. Chemical vapour deposition (CVD) equipment has an annual sale of almost $5 billion with an estimated annual growth of 11 per cent. Sales of scanning probe microscopy are estimated to be $500 million. Software for molecular modelling has annual sales of around $2 billion. All of these application markets are likely to grow considerably. Demand for such instrumentation is likely to take off when the mass production of nanotechnological devices starts in earnest.

Technical challenges

The benchmarking study identified the following major technical challenges:

- Chemical analysis methods for lateral resolution levels below 100 nm
- 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, that is contact printing nanoscale features over areas that are large in relation to the nanoscale
- Developments of tools and standards for nanometrology for quality control, and so on. The requirement here is for: 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-nanoelectromechanical systems (NEMS) systems.

Global competition

Instrumentation, tooling and metrology requires a wide range of skills 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 are attracted to other careers. But Germany does feature specific strengths. It has a major manufacturer of scanning probe microscopes SPM (Omicron) as well as semiconductor manufacturing (Siemens), and thus a strong MEMS industry.

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 areas related to nanotechnology. However, the UK lacks a commercial manufacturer of SPMs. It also lags behind Germany in facilities for microfabrication, such as MEMs foundries.

The UK and Germany have strong academic research in nanosurfaces and indigenous world-class manufacturers of instrumentation for chemical analysis of surfaces. In nanopositioning and nanometrology, too, each country has a world-class company developing displacement actuators and translation stages for the nanometre domain, and national standards laboratories active in these fields. The UK's leading companies are relatively small and few, running the risk of overseas acquisition.

Companies in the UK that serve this application area are disparate and mostly oriented to specific niche markets. One implication is that alliances between them would not seem to be particularly profitable as a way to greater strength.

Shortage of scientific and engineering staff caused by better job and remuneration prospects in other careers, is a pervasive problem: the UK lacks institutes such as the German Fraunhofer Institutes to train and nurture skilled engineers and technologists.

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.

Development of instrumentation, tooling and metrology is liable to be shaped by applications that emerge in other areas. Conversely, the availability of tools for large-scale manufacturing could be key enablers for markets to develop.

An important driver will be the availability of foundries for microelectromechanical systems (MEMS), nanoelectromechanical systems (NEMS) and even Bio-NEMS.

Another driver will be the ability to have exquisite control of the production of chemical products at the molecular level. Such disruptive technologies will support such products as devices to enable new means of energy production and storage, new approaches to food manufacture, and new chemicals for personal products.

Without the tools, nothing can be made. But the costs of developing the instrumentation and tooling for manufacture based on nanotechnology are often too high and too risky for companies to undertake without a clear high volume market. Some markets with 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 progressive cost reduction.

What will success look like?

A success scenario can be characterised in the following terms:

- In 2006 the UK's instrument and tooling industry will be selectively serving global markets for 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. High-resolution lithographic equipment will be available, 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 per cent. 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. This will be based on the use of nanotechnology, and tools derived from it, and instruments that provide manufacturers with exquisite control over structure and reproducibility. This type of production will generate less pollution while

supporting many new products. The new paradigm should eventually have major effects on GDP, but these will only become apparent on a timescale beyond five 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 that 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. There will have to be ways to work around the small size of the UK semiconductor industry.

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 UK is to achieve this scenario 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.
- Co-ordinated commercial facilities would be established that service growing SME start-ups. 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 one SME
  - enabling training of 50 or more new designers and nanoengineers per year
  - providing prototyping & small-run manufacturing for 50 new customers per year
- The UK's share of software modelling for the nanotechnology market will be growing at 10 per cent per year from its current base of 25 per cent, by 2006.
- The first novel material or structure based on these applications will have been developed and mass-produced in the UK by 2006.
- More than five UK companies will be using directed self-assembly based on 'disruptive' methods as a routine tool by 2006 (from a base of one today).

What do we need to do to make it happen?

- Establish institutes that are closer to the German model of the Fraunhofer Institutes than to Faraday Partnerships; provide these with start up funding of £50m (on a Government/private-public partnership basis)
- Preferential grants for students in science, technology and engineering. In addition to Government, industry could play a role in funding schemes.
- Training programmes for science teachers in schools oriented 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)
- Develop and improve technology roadmaps in a range of areas of nanotechnology, to help to pull through demand for specific instrument technologies 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 Government, the EC, academics and research and technology organisations and industry.
- Research Councils should fund directed research programmes in the manufacture of novel structured materials.

4. SUCCESS IN NOVEL MATERIALS

What it is

Materials underpin 70 per cent of the GNP of the industrialised nations, in one way or another, and are therefore vital to the economy. Nanotechnology provides a route to the creation of almost limitless kinds of novel materials in a variety of ways.

Nanomaterials can be described as 'novel materials whose size of elemental structure has been engineered at the nanometre scale'.

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.

Nanomaterials include clusters of atoms (quantum dots, nanodots, inorganic macromolecules), grains that are less than 100 nanometres in size (nanocrystalline, nanophase, nanostructured materials), fibres that are less than 100 nanometres in diameter (nanorods, nanoplatelets, nanotubes, nanofibrils, quantum wires), films that are less than 100 nanometres in thickness, nanoholes, and composites that are a combination of these. The composition can be any combination of naturally occurring elements, with the more important compositions being silicates, carbides, nitrides, oxides, borides, selenides, tellurides, sulfides, halides, alloys, intermetallics, metals, organic polymers, and composites.

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.

Technical challenges

The key technical challenges are:

- 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 production of nanoparticles (in terms of the size and features of the nanoparticles) for reproducibility, reliability and scalability; the development of directed deposition techniques and new methods of catalyst characterisation.
- Analysis and emulation of biological deposition techniques, that is the application of biomimetics to novel materials.

Global competition

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.

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

In metals, with new developments in synthesis, behaviour, performance, processing and so on, the US leads 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. In many areas of optical-photonic and electronic materials, the US benefits from facilities set up by the NSF.

The US benefits from fast-tracking innovations through 'development companies,' which link industry and research, and survive mainly on state projects

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 to exchange 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

The UK's position in materials is perceived as being relatively weak, but 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 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, SMEs arte the driving force in the use of new materials.

In the UK, the aerospace, biomedical and defence sectors are likely to drive the applications of nanomaterials. In this context, the area of nanomaterials, most applications do not depend on a large electronics industry, so the UK's relative weakness there is not a major issue.

The UK's science base is seen as excellent, but may be jeopardised by a threatened brain drain, and slow translation into commercial products. The UK's academic community in biomimetics has a large potential for commercial development, which needs to be catalysed.

Skill shortages are a problem in this area as others, with recruitment problems in core physical sciences.

Multidisciplinary research will drive new materials development in the future. Future industries based on novel materials will require professionals with an interdisciplinary perspective working in multidisciplinary teams.

Most UK companies are in the early stages of deciding what their strategy will be in nanotechnology. As a result, most research in universities is speculative. Links between the research base and industry are underdeveloped. 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 development

Drivers of change

Two drivers are particularly important: access to materials technology; and the roles of local and global markets and competition

Access to materials technology is important because it underpins innovation in manufacturing, medicine, construction and some services industries. A central issue is the ability to make new materials.

It will be important to set priorities. The UK has some clear strengths and larger companies -

especially chemicals, pharmaceuticals and other medical companies - that can use new materials. It will be important for such companies to examine the potential environmental impacts of various materials, alongside purely commercial considerations.

The second important driver is the roles of local and global markets and competition. The probable routes to market are either through existing world-class players, or new companies with the potential to supply niche markets. The new products will need to move through, and gain acceptance by, supply chains. They will need to be convinced that nanotechnology can deliver benefits as compared to other approaches and demands for investment.

Some applications, apart from the obvious, could be in such fields as housing, security, transport, communication, space technology 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.

What will success look like?

By 2006, UK industry will play a role in commercialising achievable consumer products, such as those in processing drugs and fine chemicals, 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. Such demonstrators will help to establish the viability of new nanotechnology products and of the IRCs themselves. Demonstrators will also be useful for introducing companies in the UK to the new technologies they will need to maintain their competitiveness.

R&D will have 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 (water industry, the National Health Service, transport and so on) must be prepared to buy innovative UK products 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 cost of putting basic manufacturing techniques in place is likely to remain high. 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's 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 important to attain a critical mass of commercialisable research in some areas of novel materials, linked to sustained industrial pull-through in applications. Since the span of applications and of the novel materials themselves is very wide, choosing specific areas to focus on can be difficult. Here we can expedite the process of focusing research and entrepreneurial interest on promising avenues for progress by preparing roadmaps and similar tools for benchmarking and identifying where technical opportunities coincide with the UK's industrial strengths, capabilities in research and commercialisation, and market opportunities.

How will we know we are on track?

If we achieve this scenario, we can expect to see developments such as:

- In 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, 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, there should be well grounded position statements for Research Councils and other bodies to identify major research areas in terms of costs, timescales, resources required.
- Also in the very near future - less than a year - there should be new incentives for helping the creation of SMEs and spin-offs.
- Following the above, within two 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 six 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 seven commercialisable new products and processes by 2006, with clear paths to the market, and three demonstrator projects for applications already in place. New manufacturing processes employing novel materials should be developed in the relatively near future, say two to three years, and a significant market share in the product and process innovations should be evident.

What do we need to do to make it happen?

- Production of roadmaps and analyses of key research areas requires that an impartial but knowledgeable body marshal and co-ordinate relevant area experts.
- Industry needs to move new products through development, to apply novel materials in processes and ultimately to achieve significant market share. Policymakers and relevant information bodies need to ensure greater industrial awareness and understanding of the scope for nanotechnology to enhance products and performance.
- 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.
- Traditionally conservative buyers in service industries need to be willing to purchase innovative products.

What they are

Sensors pervade many aspects of modern living. They are built into many consumer electronic devices, cars, medical devices, security and safety devices and systems for monitoring pollution and environmental conditions. Many applications demand miniaturisation to reduce power consumption for integration into portable devices. Affordable mass production is also a prerequisite for sensors for consumer products and for disposable devices such as sensors for medical diagnostics and pollution monitoring.

Sensors support applications across the economy - industrial processes, and those in construction, extractive industries, agriculture, health care and so on - and can be incorporated into new or existing products.

Sensors can model various parameters: physical parameters such as temperature, displacement, acceleration, flow and so on; and chemical and biochemical parameters, such as concentrations of gases, ions or molecules, and molecular interactions)

The application of nanotechnology to sensors should allow improvements in functionality. In particular, new biosensor technology combined with micro and nanofabrication technology can deliver a huge range of applications. They should also lead to much decreased size, enabling the integration of 'nanosensors' into many other devices.

We can also expect to see actuators that control movement on the nanoscale. Sensor/actuator combinations will deliver 'smart' and precise functions in products and processes. For example nanofabrication and inspection tools require sensors and actuator systems that can position objects with nanometre accuracy. In this way sensors and actuators constitute another enabling technology.

Current and future markets

Biosensors are still novel products with only a handful of products on the market. We anticipate considerable growth in the markets for such products, but their novelty means that it is very hard to forecast the scale with any confidence. If the history of sensors and actuators based on microelectronics is anything to go by, we could expect massive markets to open up rapidly. For example, microelectromechanical systems (MEMS) have led to a number of successful products, with world markets in the region of $30 billion.

For the immediate future, nanosensors could be relatively expensive, with high manufacturing costs for sensors and actuators. If we can achieve high volumes and low-cost products, the markets could be huge. The question is whether the increased capability of nanosensors will be sufficient to open up large markets quickly, and thus engendering 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.

Technical challenges

The major challenges in the manufacture of these devices are:

- Greater affordability, for example, in progression from MEMS to NEMS and nanoscale surface structuring over large areas
- Greater reliability, for example manufacturing routes, and repeatability of functional responses
- Effective biocompatible materials, materials for harsh environments, packaging and integration into macro systems
- Fostering a successful marriage of bio and micro/nanotechnology technologies

Global competition

The UK suffers one major disadvantage compared to major competitors, since these have strong infrastructures for Microsystems Technology (MST). For example, Germany has research strengths and manufacturing capability in MST.

There is much activity in the interface between nanotechnology and biotechnology. Germany has growing strengths and capabilities in both fields. The US and Japan are now focussing major research efforts on these interfaces.

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. The capability in MST largely resides in the research base, and there is a lack of skills to take ideas forward into products.

The UK has pockets of world-class research in the underpinning technologies. For example, the UK has strengths in functional materials, nanofabrication, nanometrology, biomolecular and biomimetic technology.

Start-ups and small companies are pursuing biosensor technology, but no significant products exist yet. 'Industry pull' for these applications in the UK is not as strong as in competitor countries.

Challenges for the UK

Despite the difficulties, 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 arrangements for technology licensing.

As with other areas, there are ineffective the links between users and the research base. We have also identified skills shortages as a problem once more, particularly manufacturing skills as well as multidisciplinary skills.

The challenge will be to maintain and develop a strong research base in the UK in such a way that it can complement areas of strength in the industrial base.

Drivers of change

The availability of a wide range of increasingly sophisticated but cheap sensors will promote increasingly complex monitoring systems. System builders rather than sensor designers will drive the applications.

Health, security, and environmental concerns will be major drivers.

In health, in the developed world there is increasing life expectancy. As the new technology becomes more commonplace and more affordable, global demand for products will increase. The market is demand led and long term. Examples of specific applications that will emerge are personal heath monitors, devices for on-site trauma treatment, devices for a 'barefoot doctor' and a wide range of aids for geriatric care.

The primary restraint on increased use of sensors in health will be clinical approval, both for safety and cost effectiveness of the systems that emerge. Concerns over the use of the vast amount of data that could be collected will also be a restraint on the adoption of sensors in health care.

Security is the second driver for sensors and actuators. In the same way that nanosensors can provide ever more information on a person's state of health, they can also provide more data to confirm a person's identity or indicate the provenance of an object or document. Examples of specific applications that will emerge are: people sensing, asset tracking and identification and chemical and biological agent detection.

A key issue for security is reliability. 'False negatives' are unacceptable, while too many 'false positives' cause stress and inefficiency, and quickly cause people to ignore warnings. 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 the use of environmental sensors is regulation, which is a major incentive on polluters, or other responsible parties, to monitor emissions, environmental impacts, environmental quality and so on. The primary restraint here 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 take the lead in supplying integrated multi-sensor systems and will be strong in sensor development, though manufacture itself may be global.
- The industry will depend on multi-function sensors. Detectors that are required in large volumes will come from numerous sources 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 and by customer demand rather than suppliers. It will be important to develop IT tools to support systems and data analysis. Here the UK's strengths such in fields as neural networks will be a significant advantage.
- Reliability is essential, 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 UK companies can access 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 markets in the public sector.

Other important factors include the availability of skilled people, access to fabrication facilities, regulation of environmental, health and safety issues, and the organisation of the industry and markets. Rather less important, but nonetheless significant enabling factors include instrumentation and standards, ownership of research and the public acceptability of innovations, especially in the light of privacy concerns.

How will we know we are on track?

If we achieve this scenario, we will see the following indicators in the years to 2006:

- 10 per cent per annum growth in the population of trained graduates in relevant areas of UK nanotechnology.
- 100 per cent increase in the funding for technology demonstrators by 2004.
- The first major health field trails 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, for example through publications, citations, patent filings increasing by 25 per cent by 2004 and 50 per cent by 2006.
- The UK's share in nanotechnology-based sensor systems growing faster than our main competitors by 10 per cent per annum in 2006.

What do we need to do to make it happen?

If we are to achieve this scenario, we need the following:

- A considerable increase - perhaps a doubling - of research funding for sensors and actuators by 2004; new lines of funding for technology demonstrators; 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; longer term funding for individuals who can demonstrate the quality of their work and its relevance to user requirements; improved support for graduates.
- Regulations should be reviewed to examine their impact on innovation. In some cases we need more rapid approval process, ensuring that a device meets regulatory requirements, though it is important to retain public confidence in the regulations.
- Mechanisms to foster more effective technology transfer and better communication of technological opportunities and user requirements.

6. SUCCESS IN TISSUE ENGINEERING, MEDICAL IMPLANTS AND DEVICES

What it is

Nanobiotechnology offers the key to faster and remote diagnostic techniques - including new high throughput diagnostics, multi-parameter, tunable diagnostic techniques, and biochips for a variety of assays. It also enables the development of tissue engineered medical products and artificial organs, such as heart valves, veins and arteries, liver and skin. These can be grown from the individual's own tissues as stem cells on a 3-D scaffold, or by the expansion of other cell types on a suitable substrate.

Nanobiotechnology provides methods, too, testing the compatibility 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.

The applications which seem likely to be most immediately in place are external tissue grafts; dental and bone replacements; protein and gene analysis; internal tissue implants; and nanotechnology applications within in-vivo testing devices and various other medical devices.

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.

There has been much speculation and publicity about more futuristic developments such as nanorobot therapeutics, but these do not seem likely within our time horizon.

Current and future markets

The demand for medical devices has grown rapidly, especially in the developed world, and will continue to expand as the population ages and with increasing expectations of healthcare.

There will be more emphasis on tailoring treatments to particular patients, whilst keeping costs low. Miniaturisation is key to this and to devices that reduce waste, accelerate diagnosis and minimise discomfort. Tissue engineering will attract increasing attention.

Estimates of the total cost of biotechnology products represent around $50 billion per annum, with nanoaspects contributing perhaps around 1 per cent of this total. This contribution could double in the next three years. Investment in bio- and nanotechnologies that can underpin the next batch of applications is critical for UK manufacturing in this field.

Technical challenges

The UK requires research across a spectrum of technically challenging fields, including work 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. However, restrictive regulations on stem cell research may drive some researchers to the UK.

The US's strength in microfabrication could make it the leading source of products. 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 puts the combination 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 producer of these applications of nanotechnology. They draw on areas of traditional strength in the UK, especially in biology and biochemistry. The UK has a strong science base in molecular biology and expertise in drug discovery.

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 Interdisciplinary Research Collaborations 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. The UK can make a big impact in terms of innovating new methods.

The investment for tissue engineering in the UK is roughly proportionate with the total spend in nanotechnology, at around 15 per cent. The UK has been slow in exploitation of this research compared to countries such as Japan and the US. There is a fear 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 tissue engineering, medical implants and devices is the danger of aggressive acquisition of companies in the UK. The prospect then is that the commercial exploitation of knowledge generated in the UK will happen abroad.

Problems with IPR protection could also cause discoveries to go abroad. The lack of microfabrication efforts and facilities, coupled with skills shortages and poor exploitation strategies, threaten existing areas of excellence.

Drivers of change

Two sets of issues are important here, market demand and access to the technology.

Market demand could manifest itself 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'. Growing demands and shortages of medical staff are a constant problem health care, leading to pressure to adopt more labour-saving and effective techniques. Here relief can come from such developments as faster and more accurate diagnosis, more rapid surgical techniques and products that can be used on an out-patient basis.

Second, if market pull is to shape the application area, there has to be access to the technology. This may prove the limiting factor in development.

Nanotechnology may itself enable breakthroughs in other areas, but development of tissue engineering and medical devices based on nanotechnology could be limited without advances in other areas. The combination of technological challenges makes multi-disciplinary knowledge essential, combining engineering, biology and other fields for example.

The UK has advantages in this application area, for example through its large industrial infrastructure in healthcare and the NHS's centralised purchasing system.

There is a strong research base in universities, companies and health providers. There is also growing experience with the successful operation of incubators and similar ways of linking research and markets.

However, there are also problems in capitalising on these advantages. For example, there are shortages of management skills, together with a deficit in capacity for nanotechnology manufacturing and the risk averse tendencies in the NHS. This can make it slow to change and to adopt new methods. There is some sense, too, that research remains fragmented, with breakthroughs occurring on a university-by-university basis more than as results of combined and concerted efforts.

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 and clinical devices. But some medical devices, such as cochlear implants, will also have reached the market.
- The development of the sector will be largely driven by SMEs, saving money for the NHS and other health services. A number of companies in the UK will be clearly profitable and achieving sustained success.
- 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 per cent compound.
- The multi-disciplinary nature of nanotechnology has been confronted with improved management and training in research and industry.

What will enable us to get there?

It will take a wide range of factors to enable this scenario to become a reality.

One set of factors concerns the availability of appropriate skills. This goes beyond skills in R&D functions, 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 interface between the public and private sectors.

Demand is extremely important. For this to materialise, products based on nanotechnology will have to demonstrate their clinical effectiveness and that they can deliver substantially greater efficiency.

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:

- Five to 10 new start-ups in the UK per annum in tissue engineering, medical implants and devices.

- Five to 10 multidisciplinary groups established each year in UK companies and universities.
- The UK achieves some 2 per cent of a $50 billion market by 2006.
- 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 eight 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 by universities and resources from the DTI, Research Councils and even the DfEE.

There is also a need to upgrade the quality of technology transfer offices and related facilities at universities.

The Department of Health and NHS should build more awareness of nanotechnology into setting research priorities and support for research more generally.

Regulatory frameworks should be examined to see how far they support or impede innovation.

Finally, recommendations that have emerged already from the Foresight process need to be circulated more widely and acted on by all parties identified.

Annex C
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Marconi plc

Professor John Wood
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Remit and Terms of Reference

Remit

1. Mindful of the growing importance of nanotechnology for present and future science, technology and industrial application, the Department wishes to establish a clear mechanism for steering its actual and potential involvement with relevant activities in nanotechnology.

2. The Department will establish, *inter alia*, a steering group of experts in relevant fields, including actual or potential industrial users, together with representatives of DTI, other Government bodies .

3. The Group will be chaired by the Director-General of the Research Councils.

4. The Group will advise on, and oversee, a study to benchmark UK nanotechnology capability and carry out a gap analysis with respect to leading competitor nations in the field.

5. The Group will advise on the support infrastructure for nanotechnology in the UK, and the activities of Government (including the Research Councils) in promoting activities of a suitable nature and scale to attract industrial investment.

Terms of reference

1. The Group will provide advice, through its chairman, and the Director-General, Business Competitiveness Group, DTI to the Minister for Science and Innovation on the actions that need to be taken to improve the UK's capability in nanotechnology and related technologies.

2. The Group members will be appointed for one year, in the first instance.

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