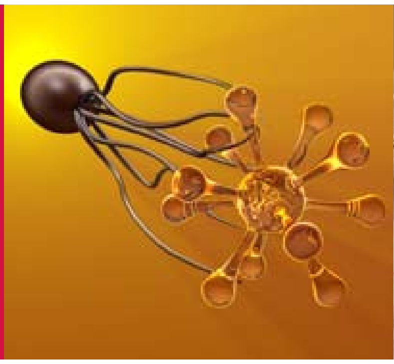
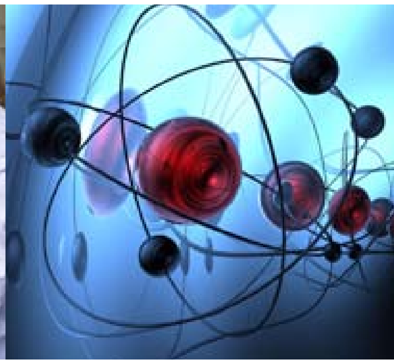
Technology Strategy Board

Driving Innovation





Nanoscale Technologies

Strategy 2009-12

The vision of the Technology Strategy Board is for the UK to be a global leader in innovation and a magnet for innovative businesses, where technology is applied rapidly, effectively and sustainably to create wealth and enhance quality of life.

Our three-year strategy for 2008-2011 is to drive innovation by **connecting** and **catalysing**. To achieve this we are focusing on three themes: challenge-led innovation, technology-inspired innovation and the innovation climate.

For more information on the overall strategy see **www.innovateuk.org.**

We have identified a number of application areas and technology areas on which to focus, and for which we are developing specific area strategies. This document presents our strategy for **nanoscale technologies**.

Foreword

The Technology Strategy Board aims to make the UK a global leader in innovation. Our job is to ensure that the UK is in the forefront of innovation enabled by technology.

Our task at the Technology Strategy Board is to *Connect and Catalyse*. As part of our challenge-led approach to innovation we treat the societal and economic challenges of the future not just as threats but also as opportunities for innovative solutions that enhance the quality of life and increase wealth.

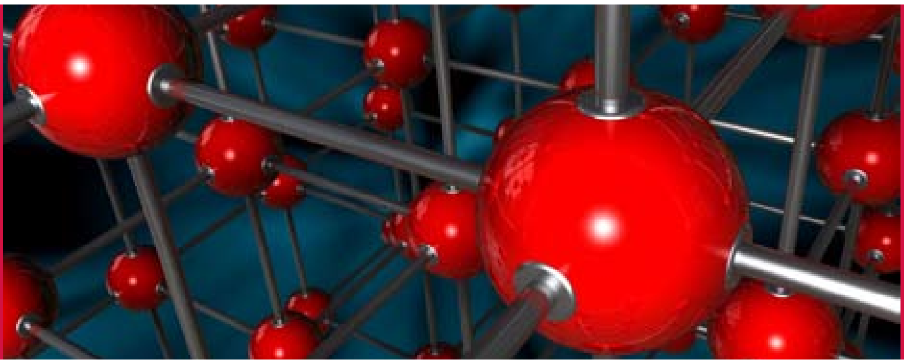
The world is changing. Globalisation, digital communications and the growth of emerging economies present profound challenges to UK manufacturing sectors. Yet where there are challenges there are also opportunities. Open access to global supply networks and emerging markets is easier than ever before; the highly skilled UK workforce, world-class science base and open-market philosophy also put us in a strong position.

Nanoscale technologies are enabling technologies that offer new functionality to products and processes. These developing technologies have a great potential to help address a number of societal challenges that we face today. The nanoscale technologies supply chain spans a broad space from primary production and processing, to product design, fabrication, measurement and characterisation, through to integration into final products and end-of-life recycling. The UK is world class in some of these activities and we must prioritise and focus on this fact through the integration of these technologies into new products and processes, addressing key areas of societal need whilst also taking into account potential environmental, health and safety concerns.

This *Nanoscale Technologies Strategy* highlights those areas that will help UK businesses to focus. I welcome this technology-inspired approach of linking nanoscale technologies to our challenge areas to give the UK the best chance of success by responsibly commercialising these exciting new technologies.

This strategy complements a number of other application and technology area strategies, primarily Advanced Materials, High Value Manufacturing, Medicines and Healthcare, Energy Generation and Supply, and Resource Efficiency. There are also strong links to our innovation platforms through Low Impact Buildings, Detection and Identification of Infectious Agents, and Low Carbon Vehicles.

Iain Gray
Chief Executive, Technology Strategy Board



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Executive summary

The purpose of this document is to set out the way the Technology Strategy Board will support UK businesses to responsibly deliver market-leading nanoscale technology solutions, channelled through high-value applications, that help to solve society's greatest challenges.

To realise this strategy the Technology Strategy Board will:

- **invest in technologies that have strong potential to address market needs that are driven by society's greatest challenges**
- **focus investment in line with those of other parties (eg research councils, regional development agencies, devolved administrations and government)**
- **foster the creation of a climate for success (regulatory, public perception, responsible development)**
- **invest only in those activities that recognise the need for sustainable development.**

Applying new technologies to meet challenges

This strategy for nanoscale technologies has been developed to set out the processes the Technology Strategy Board will use to determine how it will invest in this technology space in a way that helps UK businesses to succeed on a global scale. It is based on the fundamental premise that the technologies likely to see the most success will be those that result in developing materials and devices with new functionality that address markets driven by society's greatest challenges.

Accordingly, the Technology Strategy Board will channel its investment into nanoscale technologies that address the following three challenges:

- **Living with environmental change, including:**
  - environmental sustainability, which will cover secure global water supply and address the 'reduce, reuse, recycle' agenda in all industries
  - secure, clean and affordable energy supply, distribution and usage
  - monitoring structures and waste streams.
- **Living with an ageing and growing population, including:**
  - applying nanoscale technologies to healthcare such as drug delivery and discovery; diagnostics and imaging; disease prevention; diagnosis, treatment and management; implants; and surface cleanliness
  - food packaging and storage.
- **Living in an intelligent, connected, modern world, including:**
  - safety and security systems
  - intelligent transport systems
  - increased user interaction with products
  - next-generation computing and entertainment systems.

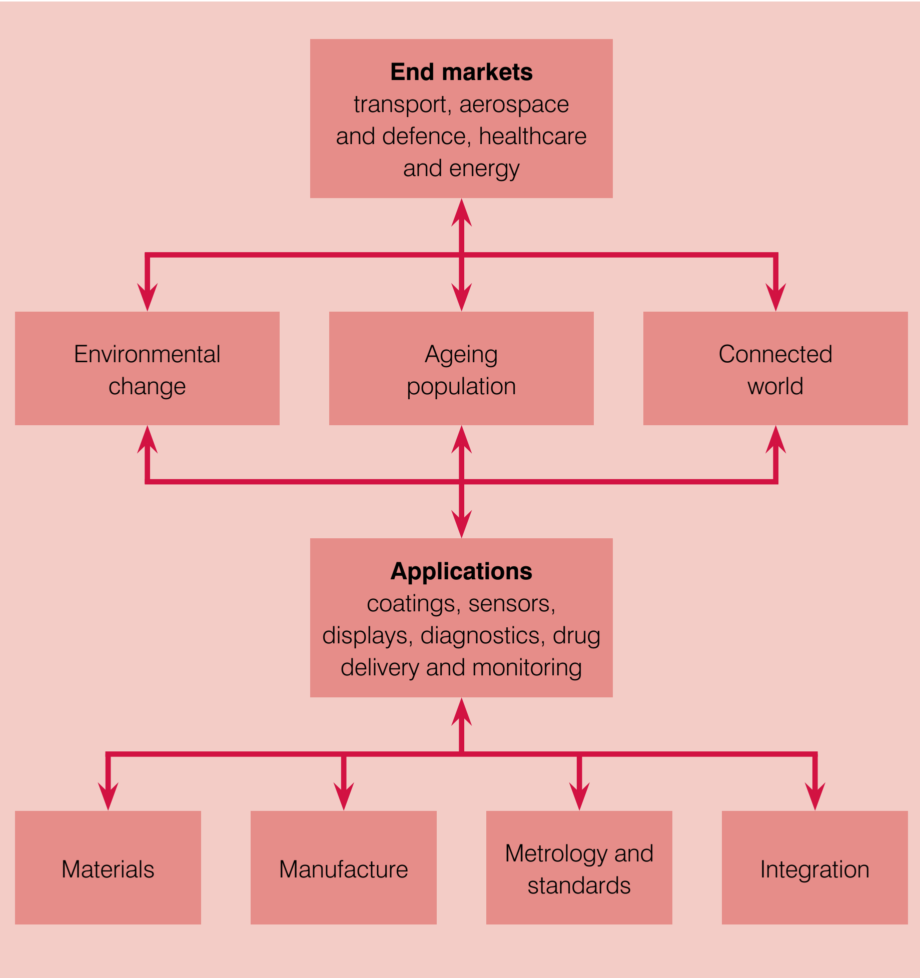
What are nanoscale technologies?

Nanotechnology is not a discrete technology in itself but covers technologies at the nanoscale. We have broken down what we call nanoscale technologies into four key sectors of primary importance: **materials**, **manufacture**, **measurement** and **integration**.

We refer to nanoscale technologies in this strategy since they are enabling technologies usually embedded into a larger scale component or system rather than products in their own right.

Nanoscale materials have one or more dimensions measuring between approximately 1nm and 100nm and have one or more specific properties that differ from those seen in bulk or larger-scale materials. They are usually **manufactured** using different techniques from those used for manufacturing bulk materials so new processes need to be developed to manufacture them, using a combination of both top-down and bottom-up techniques. To understand material properties and to achieve quality control in manufacture, **measurement** through standardised processes is key; new techniques and tools are constantly required. Usually, the added functionality offered by a nanoscale material or component will need to be designed and **integrated** into a final product to realise its value; this is where much of the added value will be created and where the UK business community should focus its efforts in order to maximise the chance of creating wealth in the UK.

Figure 1 – A technology-inspired strategy focusing on three challenge areas



What does the market look like?

Many nanoscale technologies are not new. What is new is that we are improving our understanding and our ability to control at the nanoscale by using novel measurement and fabrication techniques. This has resulted in a global race to engineer and commercially exploit the exciting and novel properties found at the nanoscale.

At present, the products on the market that incorporate nanoscale technology are generally evolutionary improvements of existing products rather than anything revolutionary. Indeed some companies have been exploiting nanoscale materials for over 100 years.

In the next 5-10 years we expect new materials to make more dramatic impacts over a wide range of market sectors, with an estimated growth from $2.7bn in 2007 to $81.4bn by 2015 according to the Nanoposts 2008 report, *Nanomaterials and Markets 2008-2015*.

Globally, public and private investment in nanoscale technologies has been growing year on year, reaching $10bn worldwide in 2007. The majority of revenue generation comes from the sale of coatings, particles, nanoporous structures, and composites.

Global leaders are considered to be the US, Japan, Germany, the UK and South Korea, measured in terms of numbers of companies able to exploit nanoscale technologies in commercial markets.

The principal market applications of nanoscale technologies are likely to be those relating to:

- coatings and surfaces
- particles
- porous structures
- composites
- treatments/medicines
- diagnostics.

All these areas are well represented by UK businesses. These can be applied across a wide range of market sectors, but with particular emphasis on:

- information and communications technology (hardware)
- automotive
- healthcare and medicines
- aerospace and defence
- food and drink.

The UK position

Within the UK, there has in recent years been significant investment into both infrastructure and R&D, through the Government's Micro and Nano Manufacturing initiative, with £150m joint investment split approximately 50:50 in micro (including microfluidics and micro electro mechanical systems) and nanoscale development. The UK has an excellent knowledge base through coordinated activity across the research councils using thematic investment to address challenges, and is taking a global lead in health, safety and the environment, standards and measurement issues. Finally, the UK is leading in public engagement, through a variety of government channels, including a high-level ministerial group, to tackle the cross-cutting issues by setting up an information gathering website on nanotechnologies at www.bis.gov.uk. This highly pervasive technology area also has a fast-developing range of UK networks and bodies to promote knowledge exchange and responsible development.

UK businesses are well placed in the manufacture, measurement and integration of nanoscale materials, at various levels of maturity, and specifically in:

- coatings and surfaces
- structural and functional materials
- modelling, design and scale-up
- controlled release, diagnostics, therapeutics
- displays, memory, sensors
- instrumentation for measurement.

What are the barriers to commercialisation?

Current technological barriers include manufacturing and scale-up, measurement, life cycle assessment, and integration into new systems and products via design at an early stage. More general issues include the need to gain a better understanding of potential impacts on health, safety and the environment, appropriate balanced public debate on risks and benefits, and a real need for cross-disciplinary and cross-industry interaction.

What should UK businesses do?

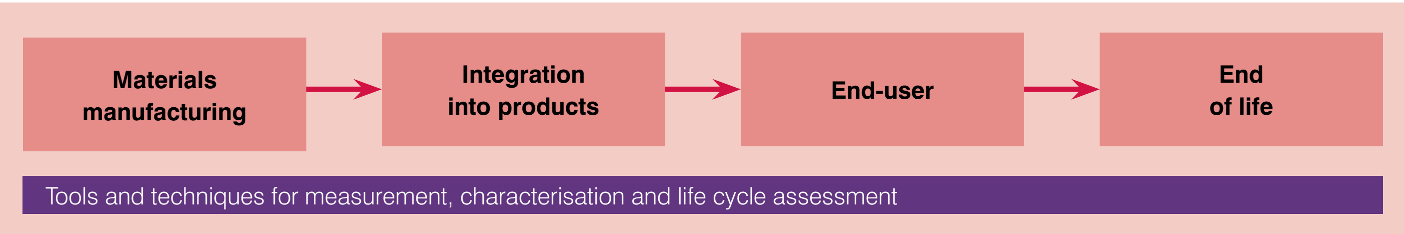
There are several ways that UK businesses could increase the chances of success in nanoscale technologies. These include:

- developing products enabled by nanoscale technologies, pulled through from the strong research base, which have improved functionality that address markets driven by societal needs
- identifying gaps in value chains, and developing/acquiring expertise across those value chains in growth nanoscale technology areas
- being in a position to understand and utilise existing infrastructure, including open access facilities and networking opportunities
- developing new products and processes responsibly, taking into account and addressing the potential risks of health, safety and the environment, life cycle analysis, and public perceptions.

Key success factors include collaboration across market sectors (for example, across healthcare, textiles and electronics), throughout the supply chain (for example, materials suppliers, integrators and end users), and finally, transferring knowledge across businesses and from the knowledge base to business.

Through all of these actions, businesses will create opportunities to succeed and gain market share in their chosen markets for nanoscale technologies.

Figure 2 – Supply chain for nanoscale technologies



Our action plan

Action and timing	Impact
1. Infrastructure review and recommendation (joint working with regional development agencies and devolved administrations) Review 2009	An independent review of the current state of UK funded infrastructure will lead to opportunities for coordination and will help to identify exciting opportunities relating to the three challenge areas
2. Collaborative R&D 2009-11	Opportunity for high value nano-specific solutions to societal, economic, and environmental challenges linking technology-inspired areas to application and challenge led areas
3. Leverage Framework 7 programme 2009-11	Increased industrial participation in areas where European partnership is beneficial. Participation in appropriate European networks will steer future direction beyond 2013 (Framework 8) to benefit to UK businesses
4. Partner with EU and OECD initiatives for responsible development issues 2009-10	Stimulating the responsible development of nanoscale technology will help to improve understanding of the environmental, health and safety issues around nanoscale technologies across the globe. Working with European programmes will enable us to establish joint programmes and find areas where UK expertise would benefit from linking to EU expertise
5. Joint working with research councils and government departments 2009-11	Supporting the second stage of the three societally-led 'nano Grand Challenges' of energy, healthcare, and the environment will provide a structured approach across investors and will bring nanoscale technology ideas swiftly to the marketplace as new products Working with other UK organisations on nanoscale technologies to continue to develop a logical, well argued approach backed by strong science and life cycle analysis by application will help remove significant cross application barriers to commercialisation resolving issues of regulation and public perception
6. Knowledge transfer 2009-11	Successful transfer of knowledge from academia to business focused on commercial success
7. Clarity in roadmapping 2009-10	A review of the current nanoscale technology roadmaps to produce a 'super' roadmap for nanoscale technology will be valued by the business community
8. Promote UK excellence in nanoscale science and technology internationally 2009-10	Access to worldwide academic and industrial community to encourage trade, inward investment and collaboration will give rise to increased competitiveness of the UK nanoscale technologies industry

1. Background

1.1 Introduction

Many nanoscale technologies are not new; the word 'nanotechnology' was first coined in 1974[1] but has been used by scientists and engineers to mean different things. Polymer scientists, for example, would consider much of colloid science as nanoscale technology. Material scientists would expect that much of the future development of structural, functional, multifunctional and bio-based materials would almost certainly be at the nanoscale. The term 'nanoscale technologies' is used in this document rather than the word 'nanotechnology' as we consider nanoscale technologies to be a number of enabling technologies (incorporating materials, manufacturing, measurement and integration techniques) resulting in products that are usually embedded into a larger-scale component or system rather than products in their own right.

What is new is our understanding of the novel properties that can occur at the nanoscale (typically less than 100nm and greater than ~1nm), which is improving significantly through developments in fabrication, measurement and characterisation. This has led to a drive to exploit those novel properties, such as an increased surface activity and quantum effects beginning to dominate (for example, a change in energy levels and electron band structure due to electron confinement effects).The behaviour of a material can change at the nanoscale level, exhibiting different magnetic, optical and electronic properties, and the ability to spontaneously assemble (self-assembly) when compared to bulk materials.

At the same time, nanoscale technologies can be considered not as a specific technology, but more a combination of materials, manufacturing, measurement and integration technologies which enable the development of new products and enhancement of existing products, both in a wide variety of end-user markets.

According to one recent market report[2], global revenue generated by nanoscale materials in a range of market sectors was $2.3bn in 2007 and expected to grow to $81.4bn in 2015.

1.2 UK strategic context

This document sets out a strategy for nanoscale technologies for 2009-2012 and beyond. It builds on the UK investment in this area over the last 22 years, sets out our view for the future, and aims to help inform wider government activity in this space. Currently, Government is running an information gathering website to help contribute to a UK government strategy[3] to which this business-focused document contributes.

The UK Government first initiated a nanoscale technology programme in 1986 – the National Initiative on Nanotechnology, led by the National Physical Laboratory. This was followed by a LINK nanotechnology programme between 1988 and 1996 (a precursor to the Technology Programme which the Technology Strategy Board has inherited). There was no further coordinated programme in the UK until 2001, when the then Department of Trade and Industry asked an expert group, led by the then Director General of the Research Councils, Sir John Taylor, to examine the potential impact of nanotechnology and nanoscience on industry in the UK. The *Taylor Report* [4] highlighted a number of key obstacles to successful exploitation of nanotechnology and made recommendations on how these might be overcome.

The report recognised that global investment was increasing rapidly both academically and, in some countries, industrially. It was noted that the US, Japan, Korea and Germany anticipated the advantage that their industries would have if they could incorporate nanoscale technology quickly and effectively into their products. Following the T*aylor Report,* Lord Sainsbury announced that £90m would be ring-fenced for the Micro and Nano Technology (MNT) Manufacturing Initiative. One-third of this is currently allocated to collaborative research and development, and two-thirds is allocated to capital infrastructure in micro and nanoscale technologies, with significant further investment from RDAs, DAs and industry.

In July 2004, the Royal Society and the Royal Academy of Engineering published the report *Nanoscience and Nanotechnology: Opportunities and Uncertainties*[5]. This was highly influential internationally and led to the UK being seen as a world leader in its engagement with nanoscale technology. A key message in the report was that the UK was not matching its investment in exploitation with investment in other important cross-cutting issues, such as environmental, health and safety (EHS), inclusive of toxicology and metrology.

In 2005, the UK Government published its response to the report and established the Nanotechnology Issues Dialogue Group, NIDG (chaired by the Government Office for Science[6], Department for Business, Innovation and Skills, BIS) and the Nanotechnology Research Coordination Group, NRCG (chaired by the Department for Environment, Food and Rural Affairs, Defra). The NIDG is coordinating the activities described in the Government response. The NRCG is responsible for developing a cross-government research programme into the potential human health and environmental risks and overseeing the programme of public dialogue and social research.

In February 2008, the Government's ministerial group on nanotechnologies, chaired by the former Department for Innovation, Universities and Skills (DIUS), published its ministerial statement on nanotechnologies[7], which provides an update on recent progress. In November 2008 the Royal Commission on Environmental Pollution published its report *Novel Materials in the Environment: The case of nanotechnology*[8]. This highlighted the new functionality nanoscale materials can offer rather than scale alone and included the added complexity of modifying a technology without major disruption should issues arise when the technology has become established. This is referred to as 'technological inflexibility'. Through the NIDG the Government produced a response to the report in June 2009[9].

1.3 Technology context

As indicated earlier, nanoscale technologies are not new, and a number of products from established materials science and colloid chemistry already control structure on the nanoscale. There are also examples in nature where functionality is achieved by control of nanoscale structure, for example:

- bone – a nanostructured, hierarchical organic/inorganic composite with excellent damping and toughness properties

- a gecko's feet – nanoscale fibres providing 'sticky' feet due to Van der Waal's forces and the concentration of fibres in a small area

- lotus leaf – nanostructured topography, controlling the 'wettability' and liquid contact angle

- sophisticated nanoscale machines are ubiquitous in cell biology; for example, molecular motors, ion channels and ribosomes.

In their widest sense, nanoscale technologies have been used by some industries for over a century. In the semiconductor, chemicals and bulk materials sectors, for example, increased knowledge of the relationship between the structure and properties of nanoscale materials has enabled the production of materials and devices with higher performance and increased functionality. In the case of semiconductor nanotechnology, increased performance is achieved by technologies such as the nanoscale size of circuit components in modern complementary metal-oxide semiconductor (CMOS) integrated circuits, the nanostructure of giant magnetoresistance-based read heads in hard drives, and the band gap engineering done by nanostructured compound III-IV semiconductors in, for example, blue light-emitting diodes.

This progress has taken place steadily over many years and the influence of nanoscale technologies on industry, thus far, can be described as evolutionary rather than revolutionary. It is also evident that current production of nanoparticles and nanoscale materials is still small in comparison with current production of more conventional materials.

Lycurgus cup images courtesy of the British Museum – a 400AD example of early industrial use of nanoscale technologies

1.4 Relationship to microsystems technologies

This strategy does not explicitly include microsystems technologies including micro electro mechanical systems (MEMS) and microfluidics, although we recognise that these are increasingly working towards the nanoscale, and that many nanoscale technology applications will be integrated within microsystems. Microsystems technologies are addressed in the Technology Strategy Board's *Electronics, Photonics and Electrical Systems (EPES) Strategy*[10], which complements this strategy.

1.5 Relationship to emerging technologies

A potentially disruptive nanoscale technology is promised in the form of quantum computing, a concept in which it is proposed that quantum-mechanical phenomena such as superposition and entanglement are used to enable massively parallel calculations to be performed. These phenomena can also be used to give fundamentally secure communications through 'quantum cryptography'. The UK is a leader within the science base in the development of these ideas, but at present they remain some way from the point of commercial exploitation. This field is recognised in the Technology Strategy Board's *Emerging Technologies Interim Strategic Assessment*[11].

It is also important to note that many nanoscale technologies are at an early stage of development and could be considered as emerging technologies, such as nanophotonics, solar energy harvesting, bionanotechnology applications, next-generation carbon capture and use, and quantum information processing, which requires nanoscale technologies as possible routes to implementation by obtaining precise control of the interaction between electrons and photons.

1.6 The opportunities for nanoscale technologies

Applications using the enhancements offered by nanoscale technologies have the potential to help address some of the most important societal challenges faced in today's world. These include environmental, economic and social sustainability, security of energy supply and clean water, healthcare within the ageing and growing population, living with climate change, and living in a modern connected world.

The opportunities created by nanoscale technologies provide the potential for strong economic impact, across a large number of market sectors where the UK has significant activity both in the academic and industrial base. Sectors in a position to become early adopters of nanoscale technology are those that depend on:

- advanced materials and chemistry
- bioscience and biotechnology
- sophisticated analytical tools
- high specification devices enabled by advanced electronics.

There is a rich base for the commercialisation of new technologies, and many opportunities to develop collaborations across sectors for common development. However, it is also important to consider at what stage of development particular applications are; whether they are strongly rooted in the academic world, are being developed by business, or are already in the marketplace.

There are three generations of nanoscale technologies:

- first generation – passive nanoscale technologies such as antibacterial coatings and nanocomposites
- second generation – active nanoscale technologies such as controlled release drugs, moving towards multifunctional sensors and self-assembly within components
- third generation – active systems of nanoscale technologies, such as those where we envisage there will be more than one active nanoscale technology within a system.

Current exploitation is very much within the first generation and dips into second generation technologies. Overall, the move is towards materials and systems with increasing functionality and multifunctionality. Table 1 summarises some of the most promising applications for a number of end-use sectors and the current challenges that those sectors are facing, drawing information from a variety of sources.

Table 1 – A range of nanoscale technology applications

Challenge area	Sector	Technology Readiness Level (TRL)[12] 9	TRL 6-8	TRL 2-6	TRL 0-2
Security	**Aerospace and defence**	Materials for reinforcement	Flame retardant materials for aircraft, protective coatings, lighter body armour	Self repairing structures, smart uniforms, sensors for biological and chemical threat detection, electronics in spacecraft	Smart air/spacecraft
Intelligent connected world	**Electronics and ICT**	Magnetic nanoparticles for data storage Electronic nanoscale materials for dielectrics	Flexible displays, nanocomposite heat management, nanowire electronic and photonic devices	Carbon nanotube single electron transistors, non–volatile random access memory, molecular diodes, single hybrid molecular devices, semiconductor single electron devices (quantum dots), graphene based circuits	Molecular memory Solid state quantum computing
Security of supply/growing population	**Energy**	Nanocrystalline coated solar cells, nanoporous aerogels, nanoparticle additives for energy efficiency, nanostructures for novel batteries	Nanocatalysts for fuel cells Nanomembranes for fuel cells	Thermoelectric materials for heat conversion, carbon nanotube fuel cells and batteries, polymer and hybrid photovoltaics	Potential for wind power applications, next-generation carbon capture and utilisation
Ageing/ growing population	**Healthcare**	Nanotitania implants, nanoparticle drug delivery, antibacterial coatings, healing wound dressings, nanocoated stents for tissue engineering	Dendrimers in biotechnology assay kits, lab-on-a-chip, delivery systems for ribonucleiuc acid therapeutics	Biocompatible implants, magnetic nanoparticles as imaging agents, nanostructured scaffolds, non-invasive therapeutics using heat to treat cancer	Smart materials for organ and limb replacements, physiological monitoring
Low impact building	**Construction**	Strength increase/crack prevention, self healing additives to cement, exterior protection coatings, anti-graffiti coatings, self cleaning glass, nanoadditives to steel, heat blocking windows	Aerogels for insulation, heat resistant materials	Self repairing structural materials, photovoltaics	Smart sensors to monitor fracturing and flexibility, intelligent buildings

Challenge area	Sector	Technology Readiness Level (TRL)[12] 9	TRL 6-8	TRL 2-6	TRL 0-2
Healthcare, modern world	**Textiles**	Self cleaning fabrics, wound dressings, healing textiles, antibacterial garments	Fire retardant textiles	Wearable computers, smart clothing, bio-responsive clothing	Self healing textiles
Security of water supply	**Environment and water**	Air filtration, titania photocatalysts, nanoporous membranes for filtration, desalination of sea water using nanomembranes	Nanoscale absorbants	Water purification using bio-nano, nano electromechanical systems for sensing and acting on pollution, nanomaterial based products for water treatment	NA at this TRL
Growing population	**Food and drink**	Nanoemulsions, nanocomposite barrier packaging, nanoporous membranes for processing	Super hydrophobic surfaces, controlled release seed coatings, pathogen detection with nanoparticles	Nanoencapsulated nutraceuticals, programmable barriers in coatings for atmospheric control, electronic tongue	Smart paper for information display and packaging
Quality of life	**Consumer goods and household care**	Easy clean coatings for surfaces, self cleaning tiles, nanosilver cosmetics and oral care, nanoencapsulation for beauty care, nanocomposite sporting goods	Nanocoated wipes for surfaces, self cleaning sprays (short lasting)	Nanoencapsulation for household hygiene and fragrancing	Long-term self cleaning wipes and sprays, nanoelectronics in leisure equipment
Security	**Brand and product security**	Intelligent inks, nanoparticles for security printing	Paper-like electronic displays for condition information, magnetic nanoparticle tagging	Decontaminating surfaces, nanoparticle chemical markers	Smart dust for decontamination
Transport, defence	**Shipbuilding**	Nanofillers for enhancement, anti bio-fouling and corrosion resistant coatings	Thermal barrier materials for engines	Fuel cells, embedded sensors	Cloaking for warships
Low carbon vehicles	**Automotive**	Nanofillers for structural enhancement, fuel additives, scratch proof and anti-glare fogging coatings	Thermal barrier materials for engines	Shape memory alloys, fuel cells	Smart tyres

2. Technology overview

2.1 Introduction

In this section, we discuss the types of technology that constitute nanoscale technologies. These are summarised as the following four areas:

- materials
- manufacturing of materials
- measurement and characterisation of materials and processes
- device and system integration.

We also discuss some of the current barriers to, and opportunities for, exploitation of current high-profile nanoscale technologies, including the questions around the potential health, safety and environmental impacts of the exploitation of nanoscale materials.

2.2 Nanoscale materials

A nanoscale material can be described as "a material having one or more external dimensions in the nanoscale (typically 1-100nm) or which is nanostructured"[13], and which can exhibit properties that differ from those of the same material without nanoscale features. These specific properties can include:

- large surface area and hence an increased active surface
- quantum effects becoming dominant
- changes in optical, magnetic, or electrical properties.

Nanoscale materials are:

- materials that have one dimension in the nanoscale (eg layers such as thin film coatings)
- materials that have two dimensions in the nanoscale (eg nanowires and nanotubes)
- materials that have three dimensions in the nanoscale (eg quantum dots and nanoparticles).

Nanoscale materials can be, and usually are, incorporated into a final component or system (eg nanocomposite materials incorporating carbon nanotubes into a polymer matrix, or nanoparticles in personal care). The nanoscale materials which are of most concern when looking at potential health and safety issues through the material's life and its application within an occupational setting are:

- 'free' forms of two and three dimensional nanoscale materials, such as nanotubes or nanoparticles in the form of powder
- materials containing two and three dimensional nanoscale materials, such as nanocomposites.

The range of material forms that make up this area of nanoscale technologies are listed below and expanded upon in Appendix 1:

- nanoparticles
- nanocapsules
- nanoporous materials
- nanofibres
- fullerenes (carbon)
- nanowires
- nanotubes (carbon – single and multi-walled)
- graphene (carbon)
- quantum dots
- nanocoatings and surfaces
- nanocomposites.

2.3 Manufacture of nanoscale materials

The production of nanoscale materials is usually very different from the bulk production of chemicals and materials. Many nanoscale materials are currently being produced solely at the laboratory scale so there is a need for production to be scaled up before many applications can be commercialised. Those nanoscale materials being produced on a commercial scale using a manufacturing process that claims to be more efficient than those processes being replaced require rigorous life cycle analysis to show that the process has net benefits over the life of the material or product.

There are a number of techniques for producing different types of material, all with various degrees of quality, speed and cost. A discussion of a number of these techniques can be found within the 2004 Royal Society and Royal Academy of Engineering report.

Different wet and dry techniques are required to produce thin films (such as chemical vapour deposition), nanoparticles (such as milling, flame pyrolysis and laser ablation), nanograined materials (such as mechanical processing), and carbon nanotubes and fibres (such as electro-explosion and electrospinning). All of these techniques produce new or enhanced materials either by taking a 'top-down' approach, for example, by etching to create circuits on the surface of a silicon micro chip, or a 'bottom-up' approach, such as self-assembly (see following). The functionalisation of surfaces is also an important component within the manufacturing and integration steps of nanoscale technologies.

Self-assembly, in which atoms or molecules arrange themselves into a structure, is of significant industrial interest as it creates less waste and uses less energy than other methods. Current understanding extends to rudimentary and widely-used systems, with industry looking to explore the use of external forces such as an electric or magnetic field, to achieve more rapid self-assembly, known as directed self-assembly. Self-assembly occurs in nature in examples such as salt and snowflake formation and is considered to be the basis for all biological processes. Top-down and bottom-up manufacturing are converging, which means that there is the potential to create exciting new hybrid methods of production for nanoscale materials and structures.

One of the significant difficulties in producing free-standing nanoscale materials is their tendency to agglomerate and form larger, micron-sized particles. If this happens, the novel properties seen at the nanoscale can be lost. There is a need to investigate agglomeration to improve understanding, and to measure and remove agglomeration risks by using novel formulation, production and metrology methods to supplement more established methods of colloid technology.

The production of carbon nanotubes and graphene is of significant current academic interest and has a wide range of potential applications such as high temperature transistors, ultra thin chemically resistant coatings and gas sensors. However, due to a lack of understanding of how to produce them effectively, and potential environmental susceptibility, selective and uniform production with specific dimensions and uniform properties has yet to be achieved.

2.4 Characterisation, metrology and standardisation for nanoscale technologies

The characterisation of materials is an important part of the industrial process. It serves two broad purposes: as quality control and assurance, and as part of the research and development of new processes, materials and products.

The science of measurement at this scale is called nanometrology, and its application underpins all aspects of nanoscale technology. The ability to measure and characterise materials at the nanoscale is vital for nanoscale materials, particularly as devices have to be produced with a high degree of accuracy and reliability for new applications to be successfully realised.

Nanometrology includes length or size measurements, with an uncertainty of less than 1nm, as well as the measurement of force, mass, electrical, chemical, bioactivity, and other characteristics including health, safety, and environmental related parameters inclusive of toxicology. Key instruments used in nanometrology include:

- electron beam techniques (scanning/transmission electron microscopy)
- scanning probe techniques (scanning probe/scanning tunnelling/atomic force microscopy/tip-enhanced Raman spectroscopy)
- surface chemical analytical techniques including x-ray photoelectron spectroscopy, time-of-flight secondary ion mass spectrometry, Auger electron spectroscopy and near-edge x-ray absorption fine structure
- optical tweezers (using a single laser beam) and surface measurement equipment
- nanofocusing beamlines and small angle x-ray analysis using synchrotron light for nanoscale materials analysis
- medium energy ion scattering and neutron scattering.

It is likely that research into nanoscale devices will suggest new measurement methods, as well as the incorporation of multifunctional effects. The atomic force microscope has, for example, had a direct effect on lithographic processes and techniques for molecular manipulation. Whilst these techniques are now becoming well established, tailored niche advances in the core equipment will be needed to support the development of specific applications and processes.

When new engineered nanoscale particles are researched or produced there are particular concerns about the potential EHS effects that need to be addressed through the application of metrology. The measurement of airborne engineered nanoparticles, for example, against a background of naturally occurring material (from natural and engineered products) in real time is a significant challenge. As with most emerging technologies, there is also a limited understanding of nanoscale properties and consequently a need for continuous development in metrology. Similarly, there are inadequate characterisation and measurement tools and capabilities to enable on-line and in-line monitoring and process control based on nanoscale features.

Making measurements with nanoscale precision poses serious challenges, such as controlling environmental fluctuations like vibration or temperature change, which have a large effect at the nanoscale. For example, any external change to the large machines used in the manufacturing of microelectronics components will affect the creation of nanoscale features and their crucially important alignment to each other. The ability to measure these influences and thereafter to minimise them is, therefore, vital.

The NRCG[14], includes a metrology task force that has identified a number of priority areas that should be addressed to help remove barriers to nanoscale technology development:

- the quantification of dose in toxicology studies
- the quantification and characterisation of engineered nanoparticles against a fluctuating background of non-engineered particles of similar size
- the characterisation of surface area and surface chemistry
- compact, rapid and inexpensive measurement methods that can form the basis for future workplace risk assessments
- documented standards describing the above methods, and appropriate reference materials to validate them.

The group is actively investigating and prioritising these areas to determine the best way forward in realising nanoscale opportunities.

The development of standards for nanoscale technologies is a significant factor in their industrialisation and uptake. The development of terminologies, nomenclatures, test methods, guidance for industry and the setting of performance criteria for nanoscale materials and nano-enabled products and applications are necessary to meet business objectives. The support and implementation of possible new regulations by underpinning standards ensures the practical realisation of the policy of safe, responsible and sustainable development. The UK has been at the forefront of developing these new standards in collaboration with international partners through the chairmanship of, and participation in, the European and international standards committees (CEN TC 352 and ISO TC 229) with the support of the former Department of Trade and Industry and more recently, DIUS. Several standards have been developed through the British Standards Institution (BSI) committee (NTI/1) including:

- seven BSI publicly available specifications (PAS) – standards on various terminologies
- one BSI published document on guidance on materials specifications
- one BSI published document on guidance to safe handling practices
- one BSI PAS – guide to labelling products containing nanoparticles.

2.5 Device and systems integration

The fourth area of nanoscale technologies is the challenge of incorporating the added functionality of the nanoscale component into a device, be it nano, micro, or macro scale. A new nanoscale material is usually bound within a system or final product, rather than existing as a free material. Examples of this are in the development of sensors, displays, and diagnostic equipment in healthcare. In these cases there is a concern about the potential 'through' life (in use) and end-of-life properties of the nanoscale material embodied within a component. Companies wishing to commercialise a nanoscale product need to conduct appropriate life cycle analysis to ensure a balanced approach to the environmental risks and potential benefits.

A significant challenge in device and systems integration is design. Design at an early stage is necessary to increase the chances of a 'right first time' product. An example of this is where a nanoscale material is incorporated into a MEMS device such as a sensor and is then packaged appropriately into a final system. If the nanoscale material is not compatible with the MEMS device and the MEMS device is not compatible with the final product through the lack of design considerations, commercialisation will be held back and any lead gained on the technological development may be lost. This will become increasingly important when the shift towards second and third generation nanoscale technologies gathers pace. Design will become a key factor and will need to be incorporated as early as possible during the development process.

2.6 Cross-cutting issues

2.6.1 Skills development across disciplines and industry

An essential component for nanoscale technologies is interdisciplinary working across academic departments and market sectors. This has been highlighted academically by the RCs, where knowledge of a number of technological, environmental, social and economic focused subjects is required. A cross-research council programme on the subject was launched in 2006[15]. This has resulted in the need for skills development to be addressed across a number of institutions (see Appendix 2) covering the academic and industrial base so that the next generation of scientists and engineers are well prepared to tackle interdisciplinary problems and challenges. As an example, bio-nanoscale technology is concerned with molecular-scale properties and applications of biological nanostructures and, as such, it sits at the interface between chemistry, biology and physical sciences.

2.6.2 Responsible development and regulation

It is the novel properties of engineered nanoparticles which have, in recent years, caused significant concern. Although fixed inside a component, a nanoscale material will need to have been researched, manufactured, used and disposed of at the end of its life (with the potential to be airborne). The questions of exposure in a variety of settings have been raised previously and are now starting to be researched, with results and questions becoming more pertinent as increasing numbers of products come onto the market[16].

If these issues are not correctly addressed, there is the potential of a significant delay to commercialisation or, at worst, a loss of consumer confidence, constraining market growth and potential solutions to societal problems. This would undermine the significant investment from governments across the globe (global government spending on nanoscale technologies in 2006 was $5.75bn[2]; increasing year on year).

In the UK, the NRCG is seeking to solve these problems by identifying a number of research objectives to tackle these issues and coordinate research across government, academic institutions, industry and the public.

Issues of EHS are not constrained to one country, however. A global initiative led by the OECD, through its working party on manufactured nanoscale materials, has set up a significant programme, with an estimated £45m investment from member states, to plug the gaps in information required to assess the health risks of manufacture, use and disposal of 14 of the most commercialised engineered nanoparticles and materials containing them. The UK is leading activity on cerium dioxide[17] and zinc oxide[18], based on the UK's current commercial strength in these areas.

The REACH[19] initiative is the European Commission's new regulation to gather hazard information, assess risks, classify, label and potentially (in high hazard cases) restrict the marketing and use of chemical substances. Nanoscale materials are currently under discussion in terms of how they would fit into this legislation as most are produced only in g/kg quantities, thereby falling under the threshold of the current legislation. It is important to recognise the fact that most producers of nanoscale materials are currently producing these small quantities and, if compulsory regulation is brought in, consideration must be given to a tiered approach depending on the level of production (research lab, to pilot scale, to full production, where full production may only be small in weight). There is a need here for government to lead a pro-active, well-considered approach to determine appropriate regulation and mitigate against overreaction in case of any issues in the future.

2.6.3 Public engagement

A further important potential barrier to commercialisation is the perceived requirement for public debate concerning nanoscale technologies. Through the Nanotechnology Engagement Group report in 2007[20] it was acknowledged that, in general, the public is positive about nanoscale technology applications as they develop, but it expressed specific concerns and made recommendations to government for ways to move forward. This is not just a UK issue and requires a coordinated approach through European and worldwide groups.

It is critically important in this respect to distinguish which aspects of nanoscale technologies are more sensitive and may require further focused public engagement. These are usually areas where nanoscale technologies may come into close contact with the end user or be released into the environment as a free material, such as in food and drink, consumer goods and personal/household care products; or the ethics of sensors that are invisible to the human eye but can detect a wide range of information. Any future engagement with the public should recognise that only some areas require increased vigilance, and should promote a balanced discussion of potential risks and benefits.

2.7 Links to other Technology Strategy Board work

Table 2 (overleaf) highlights the pervasive nature of nanoscale technologies and the significant overlap with other Technology Strategy Board activity. As an organisation, we must actively manage this overlap so that we can help realise and promote the benefits that nanoscale technologies can offer without confusing the landscape.

Table 2 – Strong links to other Technology Strategy Board work

Technology areas	Examples of areas of cross-over
High Value Manufacturing	Modelling, design, scale-up, on-line and in-line monitoring, EHS, life cycle assessment and design of new processing techniques
Bioscience	Controlled release, protective coatings, toxicology, environmental analysis, food packaging, sensors, bio-processing and life science technologies
Electronics, Photonics and Electrical Systems	Quantum dots, nanotubes, graphene, molecular memory, plastic electronics, interconnect materials, shrinkage of feature size, new analysis techniques, data storage, integration and design into microsystems, displays, heat management and sensors
Advanced Materials	Structural, functional, multifunctional, biomaterials, multi-phase modelling, microscopy, metrology and characterisation, reusability and life cycle assessment

Application areas	Examples of areas of cross-over
Medicines and Healthcare	Drug delivery mechanisms, antimicrobial coatings, smart materials, handheld diagnostic equipment, imaging, implants, tissue engineering, coatings, bio-processing, cell therapies, gene therapies and regenerative medicines
Energy Generation and Supply	Coatings and materials, such as solar cell coatings, particle additives to improve energy efficiency, thermoelectric materials, integration into fuel cell and battery technology, supercapacitors, flow cells and thermal barrier coatings, next-generation photovoltaics
Environmental Sustainability	Nanoparticles for land remediation, waste stream applications, detection and monitoring, air filtration and water treatment
Creative Industries	Sporting goods, smart textiles and clothing, flexible displays, user interaction, and multifunctionality through design
Transport	Thermal barrier materials, coatings for anti-bio fouling, protective coatings, structural enhancement, and friction control through coatings and surface texturing
Emerging Technologies	Molecular computing, next-generation measurement techniques, metamaterials and nanophotonics, nanotechnology-enabled quantum information processing and synthetic biology, solar energy harvesting, diagnostics and drug delivery, next-generation carbon abatement technologies

Innovation platforms	Examples of areas of cross-over
Intelligent Transport Systems	Displays and sensors
Low Carbon Vehicles	Structural materials, coatings, sensors, fuel cells and battery technology and supercapacitors
Low Impact Buildings	Multifunctional materials, insulation coatings for protection and maintenance, sensors for condition monitoring and renewable energy micro systems taking account of design and flexibility
Assisted Living	Sensors and handheld devices for diagnosis
Network Security	Security tagging and molecular computing
Detection of infectious agents	Sensing, controlled release, diagnostics

3. Academic and industry overview

3.1 Introduction

To analyse the industrial capabilities of UK nanoscale technology we need to consider the entire supply chain, including academia. The approach taken in this strategy is to include companies in all points of the supply chain, as all are important in successfully exploiting ideas. This can be classed as including four broad stages: research and manufacturing materials (inclusive of materials supply), integration of nanoscale technology components into an application, end user, and end of life (see Figure 2), with an underpinning requirement across the supply chain for tools and techniques to measure, characterise and assess.

The nanoscale technology industry includes a mix of university spin-outs, small to medium-sized enterprises (SMEs), and large, multinational companies that may focus a percentage (usually <2%) of their research and development work on applications incorporating nanoscale technologies.

3.2 UK academic capability

The majority of the research into nanoscale technologies is firmly rooted within the academic base. This should also be recognised as part of UK capacity.

An analysis of the current research portfolio across the research councils highlights a total of £235m in current funding for academic research into nanoscale technologies, including the two Interdisciplinary Research Centres on nanofabrication (Cambridge) and bio-nanotechnology (Oxford). Significant areas of technology and application across the UK include the following:

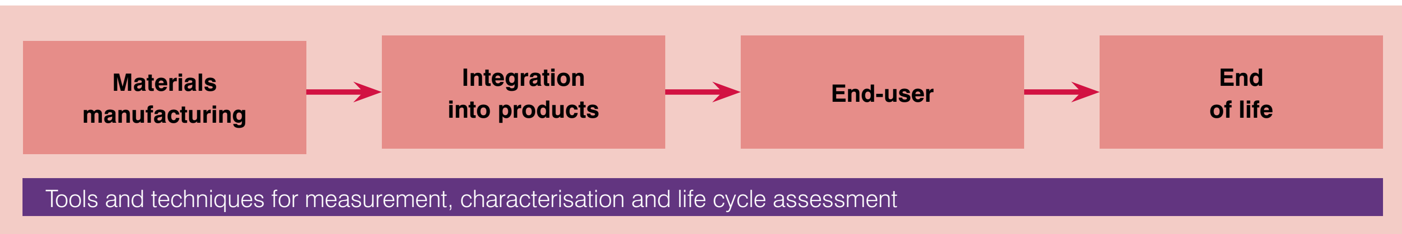
- **Technology areas:** Plastic and molecular electronics, smart and responsive surfaces, new lasers and optoelectronic devices from III/IV semiconductors, graphene, metamaterials, biomolecular self-assembly from the Biotechnology and Biological Sciences Research Council (BBSRC), structures for quantum information and new measurement instrumentation, and toxicology and ecotoxicology methods from the Medical Research Council (MRC) and the Natural Environment Research Council (NERC).
- **Application areas:** Nanomedicines[21] and tissue engineering scaffolds, sensors for health and environment, drug delivery (physical and biological methods), block copolymer nanostructures for structural and functional use, hydrogen storage materials, novel photovoltaics, and food security.

Appendix 2 shows that the majority of the Engineering and Physical Sciences Research Council's (EPSRC's) academic work in nanoscale technologies is spread across about 20 universities (as at June 2008).

The UK science base in selected nanoscale technology areas is strong and initial activities to assist commercialisation are in progress through the cross research council nanotechnology coordination group. In forthcoming years, the ability to maintain and strengthen the research base across disciplines, and to accelerate the translation of new discoveries into valuable products, will be two key factors for the UK to achieve a position as a world leader in selected areas of nanoscale technology.

Led by the EPSRC, the joint research councils' nanotechnology strategy was launched at the end of 2006. This focuses on establishing interdisciplinary Grand Challenges in areas where nanoscale technology can make a significant contribution to areas of societal importance. The first Grand Challenge, on solar energy harvesting, has recently started. The second challenge focuses on healthcare, and a third focuses on the environment. The staged approach provides an excellent opportunity for new research to be pulled through into new products and processes for the benefit of the UK economy and quality of life.

Figure 2 – Supply chain for nanoscale technologies



Other research council activities include:

- a structured, responsive approach to funding with knowledge transfer networks
- access to academic nanometrology and nanofabrication facilities
- the appointment of a strategic advisor for nanotechnology to raise the UK profile
- skills development, through doctoral training centres.

There is also significant additional support from the BBSRC and Research Councils UK's (RCUK's) basic technology programme. The BBSRC launched a council-wide priority in October 2007 aimed at funding bio-nanotechnology research that has the potential to generate significant societal and economic benefit in areas such as bio-energy, life science technologies and healthcare[22].

The MRC issued a highlight notice in April 2007[23], to stimulate proposals from universities to investigate the toxicological/ health implications of nanoscale technologies. This notice proved successful and has increased spending in this area by the MRC from zero to close to £2m. There has been a similar highlight notice from EPSRC. Both notices provide support for the NRCG research objectives. NERC, the Environment Agency, and Defra established the Environmental Nanoscience Initiative[24] to develop a community of researchers in the fields of ecotoxicology and the environmental fate and behaviour of nanoscale technologies, linking together UK and overseas research. The Economic and Social Research Council is actively engaged in issues of governance in nanotechnology.

The Science and Technology Facilities Council (STFC) has established its new Futures Programmes in the areas of healthcare, environment, energy and security to enable the translation of core skills and capabilities to UK industry. Through DIUS investment, the Harwell and Daresbury Science and Innovation Campus provides access to state of the art facilities.

In terms of training, the UK currently runs MSc courses in nanoscience and technology at Bangor, Cambridge, Cranfield, Imperial College, Leeds, Nottingham, Sheffield, and Swansea, with some (such as Cranfield) also offering short courses to industry.

3.3 UK infrastructure capability

In recent years, significant investment has been made to create a backbone for UK micro and nanoscale technology through the establishment of 24 micro and nanoscale technology facilities (the MNT centres are shown by location in Appendix 3). It should be stressed that not all of the centres focus on nanoscale technology – the split is around 50:50 between micro and nanoscale technologies. Providing open access facilities (a paid daily rate to use highly specialised capital equipment), the aim was to de-risk the development of prototype ideas and products and thus enable the faster uptake of new applications.

The Technology Strategy Board provides total funding of £54m towards the MNT centres, with a further £16m from the RDAs/DAs. Including additional contributions from industry, the investment in the facilities as a whole is about £150m over five years. Beyond this time, the majority of the facilities are expected to be self-sustaining businesses. The RDAs/DAs have also invested further into separate regional facilities.

As part of the 24 MNT centres, an initiative called Safe Nano[25] was set up and is being run by the Institute of Occupational Medicine. The objective of this initiative is to create the premier centre for health and safety information on nanoscale technologies in the UK. The Technology Strategy Board is currently reviewing the Technology Strategy Board/RDA/DA joint funded facilities.

There is an opportunity for UK business to utilise infrastructure beyond the MNT centres. An example of this is the STFC's Diamond Light Source and the new Micro and Nano Centre at the Harwell Science and Innovation Campus. There is a need here to ensure that the services the facilities have available to business are communicated appropriately through knowledge exchange activity.

The Health and Safety Laboratory, through its Centre for Interdisciplinary Nano Research, carries out extensive laboratory-based research and field studies for the EU, government and industry. Its expertise ranges from nanodust explosions to biological effects, making it uniquely placed to address potential occupational health and safety risks from nanoparticles[26].

A major UK strength is in our National Measurement System, which is delivered primarily by the National Physical Laboratory (NPL). Investment into this area has led to the UK being very strong in metrology, and consequently taking a lead in establishing common standards, design and knowledge of high-resolution analysis techniques. One example of this is through the BSI, which recently published a number of PASs and published documents on terminology and best practice for applications in nanoscale technology[27]. The NPL has also recently produced a series of measurement roadmaps for a number of societal challenges[28].

3.4 UK industrial capability

All three major global areas are actively developing applications in the areas of ICT and electronics, and life sciences and healthcare. Therefore, the UK must look to its strengths academically and industrially across the whole supply chain to identify the applications where it has the capacity to be internationally competitive. Between 2004 and 2005 there were a number of collaborative research and development competitions as part of the MNT manufacturing initiative to kick-start this. These were initially run by the DTI resulting in £30m of investment and a further £30m from industry into microsystems engineering and nanoscale technologies. Since then the Technology Strategy Board technology programme has generated significant further investment into nanoscale technologies embedded within wider technology competitions. Most notably, the 2007 Materials for Energy competition resulted in many of the funded projects having some elements of nanoscale materials research.

The UK has strong capabilities in healthcare through a combination of world-class academic and clinical research centres, numerous medical device SMEs, and several vertically integrated multinational companies. The UK is second only to the US in terms of new pharmaceutical development, producing a high level of top selling prescription medicines. It has the largest single healthcare provider in the world, the NHS, with a significant procurement budget offering a number of opportunities in stimulating wealth creation through greater innovation. From a UK perspective, there is good potential to leverage a world-class science and technology base in clinical sciences and the major global presence in the pharmaceutical and biotechnology sectors by stimulating the development of nanomedicine in healthcare applications. The Technology Strategy Board is addressing this area through the Medicines and Healthcare Application Area. Nanoscale technologies have an excellent opportunity to provide solutions in this space.

The UK EPES sectors have few international players, but are dominated by SMEs and corporate technical centres. The structure of the UK EPES sectors is a consequence of the trend for low-margin, cost-driven manufacturing, for example in the semiconductor industry, to move to parts of the world with low capital or labour costs and a favourable regulatory or tax regime. However, considerable value remains in the UK EPES sectors despite the reduction in high-volume manufacturing. This is discussed further in the Technology Strategy Board EPES strategy.

Knowledge exchange is key to unlocking the successful exploitation of nanoscale technologies. Development of a new application is very rarely done by one company or institution, and it is critical within the UK to promote a culture where ideas are shared across the supply chain. Academics and businesses need to interact in a coordinated way, to exploit the novel properties that are observed, and the technologies and applications that come with them. Moreover, businesses need to work together to translate these technologies into the high volume market sectors and users. The UK is very fortunate to have a number of expert organisations taking on different parts of this role. Now is the time to make sure that there is coordinated effort so that potential end users know where they need to go for information and ideas.

In terms of responsible development, the UK is also taking a lead on a global scale in developing a responsible nano code[29] for companies wishing to develop nanoscale technologies through best practice in economic, social and environmental issues. Many countries are looking to the UK to provide leadership on this. It is complementary to the EU code, which relates more to underpinning research.

The UK nanoscale technology industry falls into two major categories:

- businesses involved in processing/integrating nanoscale materials and nanostructures
- businesses involved in tools and instrumentation.

3.4.1 Nanoscale materials and nanostructures

The UK is generally more focused on the integration of nanoscale materials than on their primary manufacture. Those businesses that are manufacturing materials do so at a significantly smaller scale than would be normal for more conventional materials manufacturing. Examples of UK manufacturing include:

- oxide materials
- quantum dots
- silver and clays
- carbon nanotubes.

The production of materials is not necessarily where the value lies. It can be argued that more value can be generated through theoretical development, design, scaling up new manufacturing technologies for specific materials where the UK has recognisable strength, and then retaining intellectual property rights and licensing the technology to other countries for production.

The UK is strong industrially in thin film and coating technologies incorporating nanoscale materials, as well as in the area of structural and functional materials with emphasis on the use of nanocomposites. There is also strong activity in the field of drug delivery through controlled release, diagnostics and therapeutics, as well as in the integration of nanoscale materials and structures into displays, memory and sensors. In all cases, these strengths have resulted from collaboration across the supply chain.

3.4.2 Instruments and tools

The UK is a leader in developing specialised instrumentation and tools for measurement at the nanoscale. Without analytical equipment to measure and characterise novel materials and effects at the nanoscale in real life situations, understanding will not develop and applications will not be realised quickly. A number of UK companies are exploiting this requirement by providing measurement instrumentation, with a significant proportion focused on the challenging area of techniques that measure surface effects.

3.5 Worldwide industry analysis

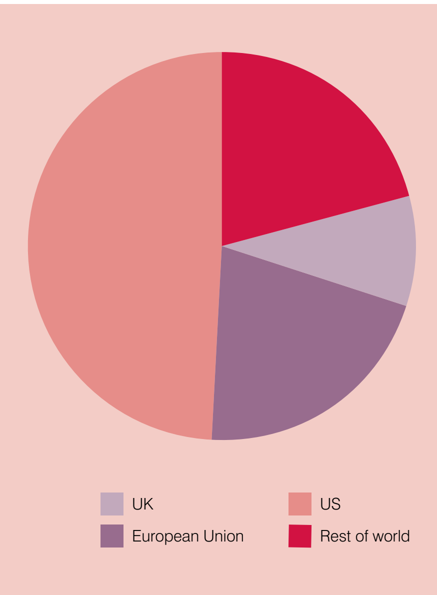
The 2008 *Nanoscale Materials and Markets* report by Nanoposts is one of many examples analysing nanoscale technology companies across the globe, by region (Europe, Asia-Pacific, and the US). The definition of a nanoscale technology company used within this report is a company that applies nanoscale technology as its main business, or as a part of its business.

Europe is leading the way in terms of company numbers with 1,100. The UK is in second place in Europe after Germany, with 223 companies compared to Germany's 415. This compares well with both China and Japan. The focus of the $1.4bn invested in 2007 in Europe is on ICT and electronics, life sciences and healthcare, and chemicals. Twenty-five per cent of European companies are developing applications for healthcare and life sciences. Most SMEs are developing products across a wide range of sectors. The majority of nanoscale technology companies within the UK are less than five years old[30], and have a turnover of less than £10m.

From the Nanoposts report it is estimated that there were approximately 900 US companies with in-house activity in nanoscale technologies with R&D funding of $1.35bn in 2007 and a focus on life sciences and healthcare, ICT and electronics, and defence and security. The Asia-Pacific region is estimated to have approximately 700 companies, with China and Japan in first and second positions with 154 and 136 companies respectively. They focus on ICT and electronics, life sciences and healthcare, and chemicals. In terms of funding, Japanese companies received the most in 2007, at $1.4bn, of a total $2.15bn split between Japan and China.

A separate study by Defra in 2006[31], shown in Figure 3, illustrates the global distribution of nanoscale technology companies in terms of materials manufacturers only. Here it can be seen that the nanoscale materials manufacturing industry is dominated by the US (49%), followed by EU countries excluding the UK (21%), and the rest of the world (21%). The UK nanoscale materials manufacturing industry makes up around 9% of the global market in terms of company numbers.

Figure 3 – Geographical distribution of nanoscale technology companies manufacturing nanomaterials



Source: Defra, 2006.

3.6 Review of voluntary reporting scheme

A recent initiative by Defra, with Technology Strategy Board support and delivered by the Nanotechnology Knowledge Transfer Network, was a review of responses to the Defra voluntary reporting scheme on the production of engineered nanoparticles within the UK. The main conclusion from the study is that, apart from a few niche producers, the UK does not appear to be focused on producing engineered nanoscale materials, but is importing materials for use within other products and processes. Some companies are looking into the suspension of metal powder oxides, where others are concentrating on surface analysis and metrology techniques. Research quantities (grammes) of materials are being produced and investigated at a number of academic institutions across the UK.

3.7 Stakeholder analysis

The UK nanoscale technologies community is growing at a fast pace with a plethora of bodies being formed as the industry grows. It is of great importance that there is a recognition and an awareness that duplication should be avoided: this can only lead to confusion in the marketplace. Appendix 4 highlights the main stakeholders within UK nanoscale technologies; however, this list is not exhaustive.

4. Market overview

4.1 Introduction

Nanoscale technology is not a market sector of its own. It is more useful to consider it as a set of enabling technologies, leading to novel properties which can be incorporated into products that are then marketed across a range of sectors. Market predictions for nanoscale technologies are uncertain, with some reports estimating that the commercial value of products containing some aspect of nanoscale technologies will grow from about $300bn in 2005 to around $3tr in 2014. Large numbers are often quoted and depend very much on how the nanoscale technologies are defined in the context of the market report – final numbers are often interpreted incorrectly, however they frequently headline in applications for funding or government reports.

4.2 A pragmatic approach

Some recent reports attempt to give a more conservative view of the impact of nanoscale technologies within existing market sectors. As one example, *Nanoscale Materials and Markets 2008-2015* by Nanoposts in 2008 follows this approach. Based on this report, the key sectors where nanoscale technologies are most likely to have an impact are summarised above in Table 3, and expanded upon in Appendix 5. The most significant global market sales are seen to be within the ICT, automotive, aerospace and defence, agriculture, food and drink, and consumer goods sector – when interpreting 2007 figures. The total revenue of $2.3bn in 2007 is expected to grow to $81.4bn by 2015.

Table 3 – Summary of markets where nanoscale technologies have an impact

Sector	Nanoscale technology revenue in 2007 ($m)	Predicted nanoscale technology revenue in 2015 ($m)
ICT	585	41,402
Automotive	404	7,134
Aerospace and defence	323	3,768
Agriculture, food and drink	265	3,210
Consumer goods	188	6,225
Life sciences	145	5,670
Textiles	122	2,170
Energy	90	3,615
Environment and water	86	3,885
Construction	66	1,672
Brand and product security	30	2,650
Totals	**2,304**	**81,401**

Table 4 (overleaf) summarises the sub-areas within market sectors where increased revenue from nanoscale technologies is expected. There is a clear opportunity in terms of collaboration across sectors (as shown by the coloured boxes) to develop similar technologies.

The top four sectors in terms of potential revenue in 2015 are expected to be ICT, life sciences and healthcare, automotive, and consumer goods and household products. The bold numbers within the sub-areas highlight the highest predicted market revenue in 2015 for each technology area. For example, within the energy sector, the highest revenue, of $1.65bn by 2015, is in the area of fuel cells and batteries.

A further market analysis, from BCC International, is summarised in Appendix 6. It covers a similar time period to the Nanoposts report but provides a more conservative estimate of future impacts and revenues.

4.3 Conclusions

Overall, there is agreement (despite lack of agreement on actual numbers) that looking to 2015, the principal market applications of nanoscale technologies are likely to be based on:

- coatings and surfaces
- particles
- porous structures
- composites
- treatments/medicines
- diagnostics.

These can then be applied across a wide range of market sectors, but with particular emphasis on:

- ICT (hardware)
- automotive
- healthcare and medicines
- aerospace and defence
- food and drink.

Table 4 – Summary of technologies within market sector areas

Market area (market revenue in $m 2007), (potential revenue $m in 2015)	Sub areas (actual 2007 market revenue in $m), (2015 predicted market revenue in $m) (Nanoposts nanomaterials and markets, 2008 report)			
Aerospace and defence $323.5m, **$3,768m**	Nanocomposites $27m, **$910m**	Electronics & sensors $58.5m, **$182m**	Nanocoatings $165m, **$1,880m**	Energy devices and fuel additives $45m, **$376m**
	Smart materials $28m, **$420m**			
ICT $585m, **$41,402m**	Carbon nanotubes $45m, **$800m**	Nanowires $30m, **$900m**	Nanoscale memory $250m, **$21,000m**	Printed electronics $150m, **$12,000m**
	NEMS $10m, **$520m**	Spintronics $50m, **$6,000m**	Quantum dots $50m, **$650m**	
Energy $90m, **$3615m**	Photovoltaic film coatings $30m, **$760m**	Fuel cells and batteries $30m **$1,650m**	Thermoelectric materials $5m, **$445m**	Aerogels $25m, **$760m**
Life Sciences and Healthcare $145m, **$5,670m**	Nanoscale biosensors and imaging $20m, **$1,220m**	Nanocoatings on surfaces and implants $50m, **$1,800m**	Nanoparticulate drug delivery $75m, **$2,650m**	
Construction $66m, **$1,672m**	Nanoscale sensors and smart materials $1m, **$212m**	Nanocomposites $5m, **$375m**	Nanocoatings $50m, **$750m**	Additives to concrete $10m, **$335m**
Automotive $404m, **$7,134m**	1. Nanocoatings $181m, **$2,451m**	2. Composite fillers $150m, **$2,106m**	3. Additives in catalysts and lubricants $69m, **$1,740m**	4. Fuel cells $25m, **$450m**
	5. Smart materials $15m, **$387m**			
Textiles $122m, **$2,170m**	Coatings $120m, **$1,850m**	Smart materials and sensors $1m, **$125m**	Nanofibres/nanotubes $2m, **$195m**	
Environment and water $86m, **$3,885m**	Nanoporous membranes $41m, **$975m**	Chemical and bio nanosensors $5m, **$490m**	Nanoparticles $29m, **$2,000m**	Nanocoatings $11m, **$420m**
Agriculture, food and drink $265m, **$3,210m**	Nanosensors $2m, **$360m**	Encapsulation $3m, **$320m**	Nanocoatings $40m, **$495m**	Nanocomposites $180m, **$1,580m**
	Nanoporous membranes $40m, **$455m**			
Consumer goods and household $188m, **$6,225m**	Nanocomposites $67m, **$1,248m**	Nanocoatings $70m, **$1,500m**	Nanoparticles $51m, **$3,477m**	
Brand and product security $30m, **$2,650m**	Nanocoatings $10m, **$1,000m**	Nanoparticles $20m, **$1,650m**		

Note: The coloured boxes indicate technologies that have significant crossover into a number of market areas.
For example both coatings and composites apply to all transport sectors and also in the construction and defence sectors.

5. Our technology-inspired strategy

5.1 Purpose

In publishing this UK nanoscale technology strategy we aim to:

- inform UK business about our approach, and the opportunities it offers to assist them in creating UK wealth and a better quality of life
- guide the Technology Strategy Board internally in its work on nanoscale technologies and the relationship with other technology and application areas, and innovation platforms, to avoid duplication of effort
- advise other areas of government about our approach and areas of potential joint working in terms of joint initiatives, standards, EHS, public engagement and appropriate regulation.

5.2 Approach

This strategy builds on the expertise in the UK within four defined areas of nanoscale technology:

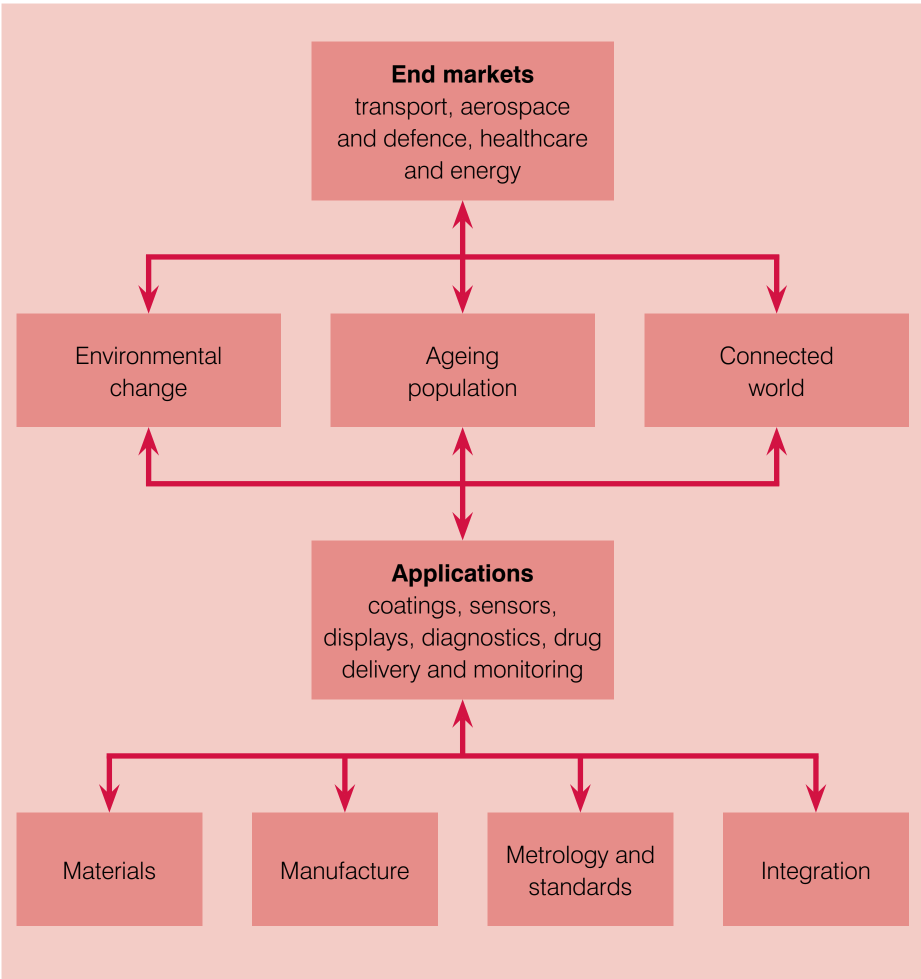
- materials
- manufacture
- metrology
- integration.

Nanoscale technologies have attracted global investment from public and private sources – reaching $10bn worldwide in 2007 alone. This implies a highly competitive landscape in terms of research and development and a requirement to build on strengths. UK business is currently well placed to take advantage of this investment, by pulling through strong academic invention and, where appropriate, partnering with other world leaders such as the US, Japan and Germany. We aim to help businesses to develop high-value products and processes which align with the Technology Strategy Board's overarching strategy of UK wealth creation and the prospect of a better quality of life through positive impact on society and the environment. The focus of this strategy is to channel high-value applications through cross-cutting challenge areas and into a wide range of end-user markets. The research councils have also embraced this approach through their nanotechnology Grand Challenges.

Our challenge areas for 2009-2012 and beyond are:

- **Living with environmental change, including:**
  - environmental sustainability including a secure global water supply, and addressing the 'reduce, reuse, recycle' agenda in all industries
  - secure, clean and affordable energy supply, distribution and usage
  - monitoring structures and waste streams.

Figure 1 – A technology-inspired strategy focusing on three challenge areas



- **Living with an ageing and growing population, including:**
  - healthcare such as drug delivery and discovery; diagnostics and imaging; disease prevention; diagnosis, treatment and management; implants; and surface cleanliness
  - food packaging and storage.
- **Living in an intelligent connected modern world, including:**
  - safety and security systems
  - intelligent transport systems
  - increased user interaction with products
  - next generation computing and entertainment systems.

5.3 Technology Strategy Board investment criteria

We have assessed the value of investment in nanoscale technologies in each of the three challenge areas against the four Technology Strategy Board investment criteria:

- the UK capacity to develop and exploit the technology
- the size of the global market opportunity
- the right potential in the right timeframe
- a clear role for the Technology Strategy Board to add value.

Fit against Technology Strategy Board criteria for investment	
UK capability	High
Market opportunities	High
Timeliness & impact	High
Added value	High

5.3.1 UK capacity to develop and exploit the technology

The UK has strong materials and high value manufacturing sectors representing a significant proportion of UK GDP (see Technology Strategy Board strategy documents for further information[32]). It is also well-positioned in respect of metrology through the excellence of the UK industrial base, the National Measurement System and standards bodies helping industries to develop niche instrumentation and tools for measurement. There will be opportunities to export niche equipment to characterise and measure surfaces and materials as well as providing on-line and in-line testing in a production environment as the use of nanoscale materials continues to grow and they start to be integrated into final products. By co-operating within these areas and using strong supply chains in markets where the UK has a global market reach and share (such as aerospace, chemicals, healthcare, automotive and construction), UK businesses will be able to begin to exploit the new functionality that nanoscale technologies – via integration into high value products – can offer. Design will also be an important factor in taking products to market. This is an area where the UK has excellence, for example within its electronics, pharmaceuticals and creative industry sectors.

Using coatings to cut costs

Could nanoscale coatings on glass in building windows and car windscreens save on air conditioning bills?

Glass specialist Pilkington is leading a collaborative R&D project that aims to do just that. The project is looking to develop and commercialise new processes to allow a range of thin film coatings with novel properties to be used in large windows and glass panels. The NanoCoat coatings would cut the amount of infrared sunlight transmitted through windows and windscreens. This would in turn mean lower heating effects inside the building or car from the sunlight and so less energy being used to maintain room temperature.

So far the project has successfully scaled up the process to a pilot scale demonstration level. It has also taken into account all safety issues involved in developing the production process for occupational health and safety in terms of working at the nanoscale.

The £0.5m of investment from the Technology Strategy Board and a total project value in excess of £1m has helped speed up the development of energy efficient glass in meeting UK energy efficiency targets, reduced the commercial and technological risk for the industrial and academic partners, enabled cross-disciplinary working and provided a focus on the supply chain.

In terms of materials development, the UK has significant strengths in surface coatings, particle technologies such as nanoparticles, nanoporous materials, and nanocomposites. These are all identified as areas that will have a major impact across all market sectors by 2015.

5.3.2 The size of the global market opportunity

The size of the nanoscale materials market looks to grow from around $2.3bn in 2007 to about $81bn in 2015, according to one source. Various reports have shown significantly different numbers but provide a consensus view that the exploitation of the new functionality that nanoscale materials can offer will give rise to a significant impact of nano-enabled products over a wide range of markets. Further information is available in Appendix 5.

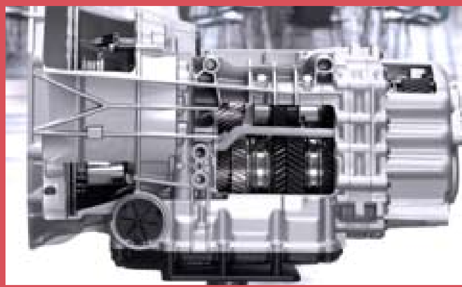
5.3.3 The right potential in the right timeframe

UK industrial capability is supported by a world-class science base with the research councils coordinating activities in nanoscale technologies and the EPSRC running a series of societally focused Grand Challenges. In the next few years this research in nanoscale technologies will require investment by business to pull new inventions through to high value products and processes. Within Europe, the uptake of Framework 7 programmes by the nanoscale technology academic community in the UK has been very high, specifically within the Nanosciences, Nanotechnologies, Materials and New Production Technologies programme, again demonstrating the strength of UK academic expertise.

Revolutionising engine performance

Oxfordshire-based company Infineum develops and manufactures chemical additives for lubricants and fuels that help to improve performance and create new functionality. With annual revenue in excess of $2.5bn, about one in three vehicles throughout the world contains Infineum additives in their engine, fuel or transmission systems.

As part of its innovation strategy Infineum has been looking to evaluate novel nanomaterial additives in relation to prospective large-scale production and value in mainstream applications. It also needs to establish a nanoparticle handling protocol to robustly ensure it takes a precautionary approach to health, safety and environmental issues.



Accessing EU funding

Infineum identified the EU Framework 7 Programme for collaborative R&D as a good way to help it to develop its nanoscale materials business, and so in 2008 led a 15-strong consortium in a proposal. The AddNano project, with more than €10m investment, is investigating the potential for certain novel nanoscale materials to be integrated into the lubricant supply chain to help reduce friction and wear.

In an interdisciplinary area such as nanoscale technologies it is imperative that a sustainable skills base is developed at all levels of education. This is what the research councils are focusing on through a range of studentship schemes, including EPSRC's Doctoral Training Centres, and CASE studentships. The Institute of Nanotechnology is also very active in this area with a number of training initiatives. Strong inter-agency co-operation will be required and the Technology Strategy Board aims to play a major role in this by using programmes such as the knowledge transfer networks and knowledge transfer partnerships.

5.3.4 How the Technology Strategy Board can add value

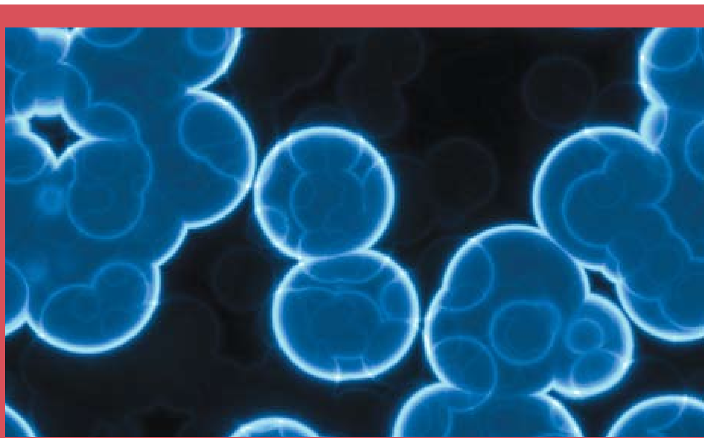
There are several ways we can add value through our work:

- **Partnerships**
  - through promoting the exchange of knowledge, coordinating and encouraging strong supply-based collaborations that utilise new and existing challenge-led collaborative R&D interventions pulling through invention from the research community, specifically in the nano Grand Challenge areas of energy, healthcare and environment including themes of materials, manufacture, metrology, and integration inclusive of design
  - through including end-users and businesses across the supply chain, both nationally and internationally, to deliver high-value products and processes.

- **Level of funding**
  - supporting existing opportunities for both funding and contract work, including collaborative R&D, knowledge transfer partnerships, and SBRI (Small Business Research Initiative) schemes and working with research councils on the second stage of the nanotechnology Grand Challenges
  - funding, with other stakeholders, technical feasibility studies and pre-product demonstrators, to help cut the risk to industry inherent in technology exploitation.
- **Policy development**
  - providing input into government departments from a UK industry perspective – on developing regulations, EHS and appropriate public engagement
  - investing only in those activities that recognise the need for sustainable development.
- **Health, safety and standards**
  - incorporating sustainable development in all investments we make in this area, addressing potential EHS and toxicology concerns
  - funding, with other stakeholders, measurement and standards development, and interdisciplinary skills development.

What is SAFENANO?

SAFENANO supports UK industry by providing independent, impartial and authoritative advice on the potential risks to the environment and human health from nanoscale materials. Due to their size and novel properties, it is clear that some types of nanoscale materials may pose additional risks compared with larger-scale materials of the same composition. SAFENANO is playing an active role in the substantial research that is currently under way to investigate these issues.



SAFENANO is one of the 24 UK MNT centres of excellence and is hosted by the Institute of Occupational Medicine in Edinburgh. The institute has been providing research, advice and services on particle risk issues since its formation 40 years ago. SAFENANO provides support through free-to-access information services and commercial scientific services in workplace health and safety, toxicology, product evaluation, regulation and training. Its facilities can be used by industry; academia; government agencies including the Health and Safety Executive, Defra and BIS; and non-governmental organisations and charities.

The SAFENANO website is the largest open access resource of information on nanomaterial risk issues in the world. Its focus is on identifying, interpreting and transferring the emerging scientific evidence about the potential of nanoscale technologies in ways which are relevant and useable to everyone involved in this area. Information provided includes news, reviews, interviews, scientific research and commentaries. It has extensive links to external sources, informal blogs and a forum for discussion of hot topics.

More information is available on the SAFENANO website at www.safenano.org

6. Our action plan

The Technology Strategy Board will:

- Encourage the development of supply chains enabling participation in our challenge-led collaborative R&D competitions, where there is an emphasis on responsibly developing new materials, processes, measurement and integration through early stage design, whilst also addressing potential environmental, health and safety, and toxicology concerns, as well as working with partners to develop standards
- Work in close partnership with the research councils, regional development agencies, devolved administrations and government departments to connect up our respective activities so that they are more effective with an emphasis on investing in the second stage of the cross research council Nano Grand Challenges focused on maximising the benefits to society, knowledge transfer partnerships, our SBRI (Small Business Research Initiative) scheme, and interpreting and developing roadmaps
- Ensure the UK facilities network, which includes government-funded capabilities, is appropriately funded, coordinated, and focused on exploitation of new technologies that can be commercialised to meet identified global market needs
- Work within Europe and globally to influence programmes for the benefit of UK industry
- Provide a business focused input into government activity on issues such as skills, regulation, environmental health and safety, and public perception
- Continue to provide ways to transfer knowledge and promote responsible development.

To do this we will progress the actions set out in the table overleaf, reviewing each on a regular basis to ensure that, collectively, they deliver this strategy.

Action and timing	Impact	Description
1. Infrastructure review and recommendation (joint working with regional development agencies) **Review 2009**	UK coordinated infrastructure (currently in progress)	An independent review of the current state of UK infrastructure, of which the 24 micro and nanotechnology centres funded by the Technology Strategy Board are part. This review is coordinated with the regional development agencies (RDAs) and devolved administrations (DAs) to identify the exploitation of exciting opportunities in the three challenge areas we have identified. Implement the recommendations of the review.
2. Collaborative R&D 2009-11	Opportunity for high-value nano-specific solutions to societal, economic, and environmental challenges	To address the three identified challenges, we are working with other Technology Strategy Board technology/application areas and innovation platforms to encourage nanoscale technology-focused businesses to apply to our competitions. We will work with other industry and academic organisations to find out where new materials, manufacturing, measurement and integration technologies are needed to help meet these challenges.
3. Leverage Framework 7 programme 2009-11	Increased industrial participation in areas where European partnership is beneficial	We are aiming to help more UK businesses take up European Framework 7 funding by coordinating competitions to suit UK-specific business needs, and where working with European partners would significantly benefit the UK. By providing input to the Framework 8 programme we will be able to help to steer future direction beyond 2013.
4. Partner with EU and OECD initiatives for responsible development issues 2009-10	Responsible development of nanoscale technology across the globe	Partnering with suitable European investments and the Organisation for Economic Cooperation and Development (OECD) initiatives, to stimulate the responsible development of nanoscale technology and help to improve understanding of environmental, health and safety issues around nanoscale technologies. Work with European programmes to enable us to help establish joint programmes to find areas where UK expertise should link to EU expertise.
5. Joint working with research councils and government departments 2009-11	Bringing nanoscale technologies to the marketplace through the swift commercialising of ideas into new products Resolving issues of regulation, public perception, and conflicting market data	Support the second stage of the three societally led ‘nano Grand Challenges’ of energy, healthcare, and the environment, alongside other research council-led nanoscale technology investments, providing a structured approach by being inclusive of the RDAs/DAs and other government departments. Work with government departments, linking with the ministerial group on nanotechnologies, to establish opportunities in public procurement through, for example the SBRI scheme, as well as opportunities for addressing potential barriers such as regulation and public perception. To address the public engagement agenda, work with other UK organisations working in nanoscale technologies to continue to develop a logical, well argued approach backed by strong science and life cycle analysis by each application, and to promote the potential benefits of nanoscale technologies through the transfer of knowledge.
6. Knowledge transfer 2009-11	Transfer of knowledge from academia to business	Work with the knowledge transfer networks and knowledge transfer partnership programme to develop ideas and pilot schemes for new ways of working (such as ‘reverse’ and ‘short’ programmes) together with others working in this area.
7. Clarity in roadmapping 2009-2010	A review of roadmaps in nanoscale technology	Review the current nanoscale technology roadmaps to produce a ‘super’ roadmap for nanoscale technology that is valued by the business community.
8. Promote UK excellence in nanoscale science and technology internationally 2009-2010	Access worldwide academic and industrial community to encourage trade, inward investment and collaboration	Showcase UK excellence in nanoscale science and technology to establish global standing and encourage research and innovation collaborations. Establish commercial partnerships to accelerate product development, process trading, and to widen market access.

Appendix 1 – Breakdown of nanoscale materials

Nanoparticles

Usually categorised as particles with a size from about 1nm up to 100nm, nanoparticles of this scale can exhibit completely new or improved properties – in areas such as chemical reactivity to optical behaviour – compared to bulk properties. Nanoparticles can be made of a wide range of materials, the most common being metal oxide ceramics (oxides of Ti, Zn, Al, Fe) and silicate (clays). A number of current applications include: stain resistant fabrics; drug delivery; antimicrobial dressings; high density data storage, tracking and tagging; clear inorganic sunscreens; lubricant and hydraulic additives; and catalysts. In 2007 sales of nanoparticles totalled $1.6bn and are expected to grow to $20.5bn by 2015.

Nanocomposites

Nanocomposites use nanoparticles and tubes in a matrix material. The use of nanocomposites often gives multifunctionality through a combination of improved mechanical properties whilst, for example, enhancing optical or thermal capability. Current applications however are at the stage of being functional, giving increased strength by using fillers, flame retardant products, and oxygen scavenging barrier materials. As such, current 2007 revenues were estimated at $437.6m, expecting to grow to $7.3bn by 2015.

Nanocapsules

Nanocapsules are generally described as nanoparticles containing a hole, where different types of substances can be added (such as fragrances, enzymes, catalysts, oils, adhesives, polymers and other nanoparticles or biological cells). Technologies for encapsulating materials have been in use for a number of years – for example the use of 130-500nm encapsulation materials in cosmetics. Polymeric nanocapsules have been recently created. Manufacturing of nanocapsules does not involve extreme chemical or thermal processes, which makes it possible to encapsulate biological material inside them for drug delivery purposes. Current applications include encapsulation for fragrances in the cosmetics sector, and anti-fouling coatings. In 2007 market revenue for capsule technology was estimated at $32m, expected to grow to $1.11bn by 2015.

Nanoporous materials

Generally, nanoporous materials are structures with holes less than 100nm in diameter and are characterised by their ability to absorb and interact with atoms, ions and molecules. They can have open or closed porosity, and can be amorphous, semi-crystalline or crystalline, with a high specific surface area. Applications for nanoporous materials are found in separation technologies for removal of contaminants and pollution from waste gas and water streams. In 2007 market revenue for nanoporous materials was estimated at $804m, expected to grow to $3.9bn by 2015.

Nanofibres

Nanofibres are generally described both as hollow or solid fibres, with lengths typically less than 1,000nm, and an aspect ratio of around 50. They have a large, easily accessible surface area, enabling them to be highly bioactive. Applications currently being exploited are through filtration and separation media, for this reason. In 2007 revenues were estimated at $10.4m, expected to grow to $1.2bn by 2015.

Fullerenes

Fullerenes are a molecular form of pure carbon discovered in 1985. They are cage-like structures of carbon atoms, built up from pentagons and hexagons. The most abundant form produced is buckminsterfullerene or buckyball (C60), the roundest molecule known, with 60 carbon atoms arranged in a spherical structure and a diameter of about 1nm. Applications for fullerenes are currently being developed within fuel cells, solar cells and batteries and in consumer goods such as cosmetics. The 2007 revenue figures are quoted at $58.5m, expected to grow to $1.9bn by 2015.

Nanowires

A nanowire is usually referred to as a cylindrical solid (unlike carbon nanotubes, which are hollow) wire or formed by the production of a row of dots, with a diameter ranging from 10nm to 100nm and a length at the micron scale. They can be made of a wide range of materials, including silicon, gallium nitride, germanium and indium phosphides. Their novel properties lie in being able to show very different optical, electronic and magnetic characteristics such as silica being able to bend light around very tight corners. Advanced growth techniques are required to produce nanowires. For example, self-assembly allows the natural formation of atoms on stepped surfaces, chemical vapour deposition on a patterned surface, electroplating, or molecular beam epitaxy. Applications are just beginning to find their way onto the market mainly through high density data storage, and electronic devices containing nanowires. In 2007 nanowire revenues were valued at $34m, expecting to grow to $1.23bn by 2015.

Single-walled and multi-walled (carbon) nanotubes

Carbon nanotubes are small cylinders of carbon atoms 'rolled up' from graphene sheets. They are not unlike other carbon materials, such as diamond or the carbon black that can be found in pencils or car tyres. They have, however, a completely different structure that gives them the potential for multifunctional capability through, for example, high strength, and excellence in conducting electricity. Normal graphite is built of sheets with a honeycomb structure of carbon atoms. These sheets are very strong, stable and flexible, but adjoining sheets lack strong cohesion. In nanotubes, however, these sheets are larger and are rolled up to form long, thin spiral patterns. On an individual fibre scale, a single carbon nanotube has been shown to have excellent mechanical properties compared to that of more traditional engineering materials, and is the subject of much academic research to achieve similar properties with bundles of fibres. Current applications are in the area of high strength polymer composites in consumer goods and in the aerospace and defence sector. In 2007 revenues were estimated to be $104m, expected to grow to $2.8bn by 2015.

Quantum dots

Quantum dots are solid-state structures confining a reduced number of electrons in a very small region. For that reason, they have been called artificial atoms. They are nanoparticles of semi conductors, with quantum effects limiting the energies at which electrons and holes can exist in the particles. This leads to them having a tuneable band gap, and hence control of optical and electronic properties. Current developing applications include the use of quantum dots in anti-counterfeiting, and security tagging, as well as healthcare applications. For 2007 revenues in these areas were estimated at $62.2m, expected to grow to $1.331bn by 2015.

Coatings and surfaces

Thin films are structures resulting from the deposition of one or more material layers onto a surface to create transparent, self-assembling coatings – giving functional and multifunctional benefits by exploiting optical, magnetic, electronic and catalytic effects. Typical production processes include physical vapour deposition, sputtering and chemical vapour deposition. Water-based coatings such as sol-gel systems offer a simple and low-cost method for coating materials, such as glass, textiles and polymers, to give easy-clean, water repellency, anti-fungal, anti-microbial and optical properties. The thickness of the thin films considered is usually below 100nm, but they may also contain nanoparticulate material that may provide its functionality. A number of applications are currently being exploited: scratch resistance; crystalline coating for solar cells; self healing, photocatalytic coatings; wear reduction and corrosion prevention; anti-graffiti; easy-clean, antimicrobial surfaces; and oxygen resistant coatings. In 2007 market revenue in this area was $814m, expected to grow to $13.7bn by 2015.

Graphene

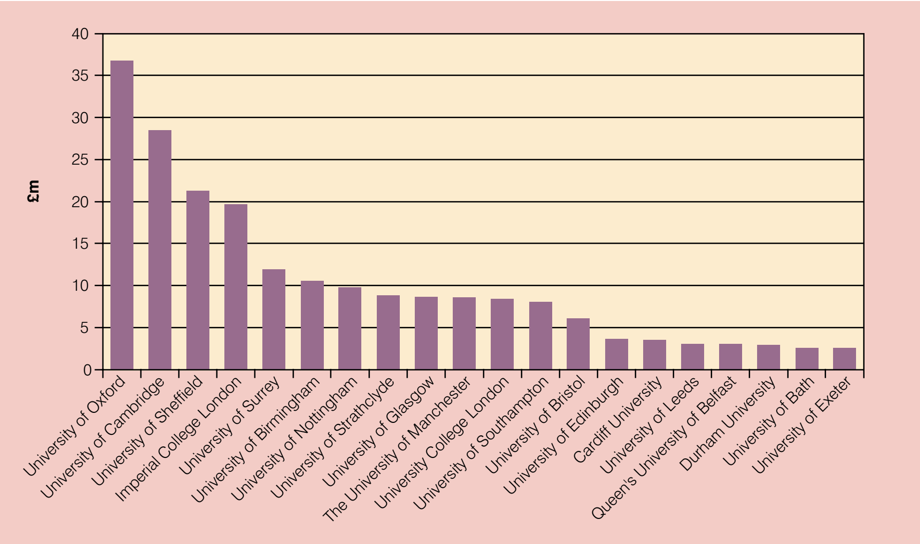
Graphene is a two-dimensional, atomically thin sheet of carbon atoms, representing the thinnest material that can be made. Discovered by Professor Andre Geim at Manchester University, graphene comprises a hexagonal array of sp2-bonded carbon atoms, as in bulk graphite. An excellent conductor of electricity and heat, graphene has the potential for use in transistors which run at higher frequencies and higher efficiency than conventional silicon-based devices. Graphene also displays high chemical resistance, which opens up the possibility of an atomically thin protective coating, and graphene is an ideal support for electron microscopy samples. The electronic properties of graphene mean they could be used in gas sensors.

Nanostructured materials

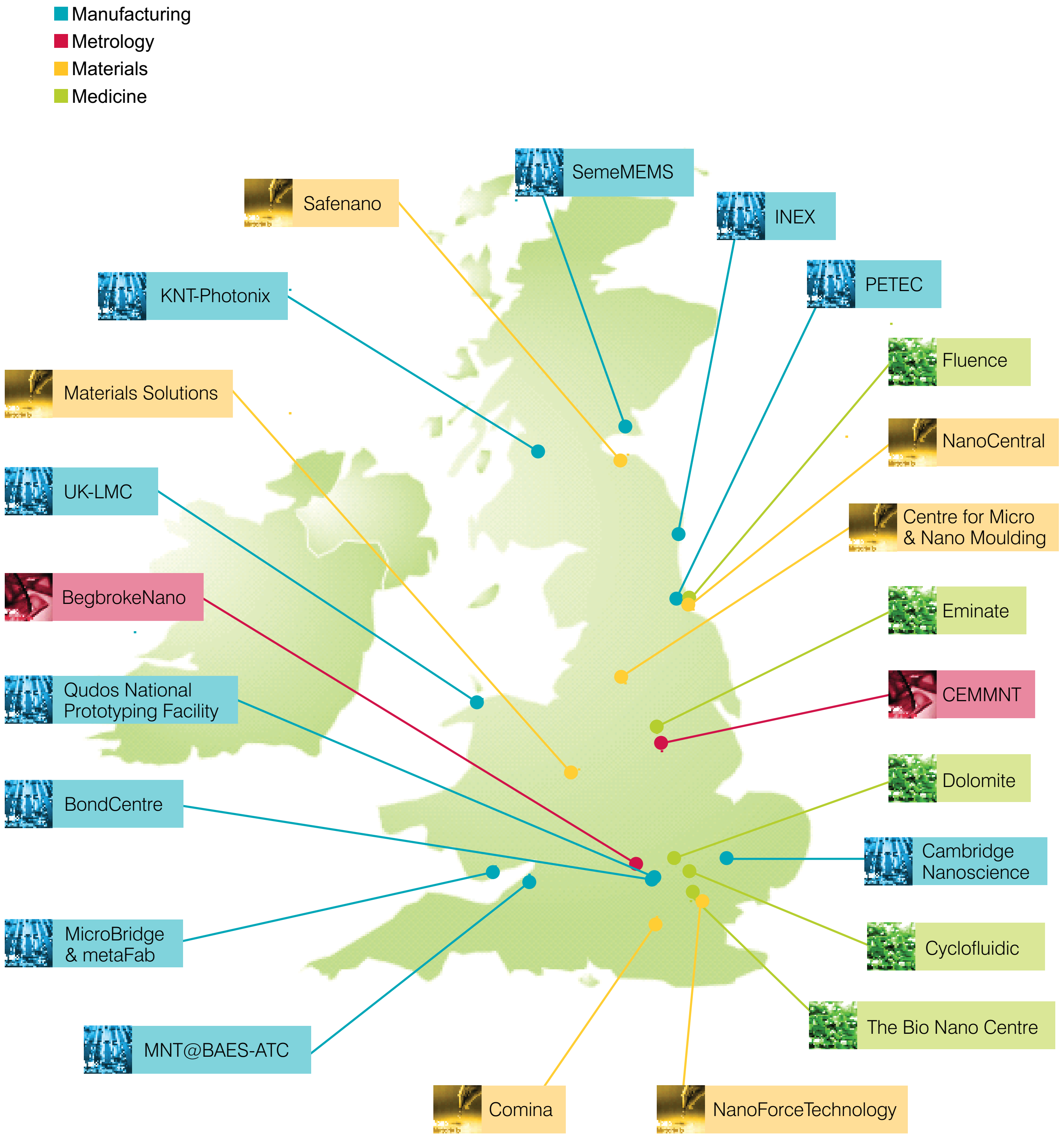
Nanostructured materials have a crystallite, particulate, void or molecular element less than 100nm. Some of the earliest polymer nanocomposites used nanoclay additives to improve stiffness and softening temperature, and improvements in dispersion and functionalisation of nanoclays promises to deliver a low cost filler for polymers and resins. Carbon nanotubes and carbon nanofibres have been added to resins such as epoxy and polyester to impart electrical conductivity, or improve mechanical performance. Using good manufacturing procedures, significant increases in conductivity and mechanical properties have been achieved for low addition levels. Carbon nanotube filled resins are being tested for carbon fibre composite aircraft wings to improve lightning strike performance and in thermoplastic fuel lines for static charge dissipation.

Appendix 2 – Analysis of EPSRC nanoscale technology funding

Analysis of EPSRC nanoscale technology funding by university (June 2008)



Appendix 3 – UK nationally and regionally funded facilities



Facility	Area of expertise	Area of expertise	Funding source
INEX Microsystems	Micro electro mechanical systems	Low	Technology Strategy Board
Bondcentre	Wafer bonding	Low	Technology Strategy Board
Cambridge Nanoscience Centre	Fabrication and characterisation	High	Technology Strategy Board
Qudos National Prototyping facility	Processing	Medium	Technology Strategy Board
MNT at BAE ATC	Micro electro mechanical systems	Low	Technology Strategy Board
Begbroke Nano	Metrology	High	Technology Strategy Board
Eminate	Nano in healthcare and food	High	Technology Strategy Board
Dolomite	Microfluidics	Medium	Technology Strategy Board
Nano Central	Materials fabrication hub	High	Technology Strategy Board
Intrinsiq Materials	Nanoscale materials fabrication	High	Technology Strategy Board
Cyclofluidics	Microfluidics	Medium	Technology Strategy Board
Laser Micromachining Centre	Micromachining	Low	Technology Strategy Board/Welsh Assembly Government
Microbridge	Machining fabrication services (micro and nano)	Medium	Technology Strategy Board/ Welsh Assembly Government
SemeMEMS	Micro electro mechanical systems	Low	Technology Strategy Board/Scottish Enterprise
KNT Photonix	E-beam lithography	Medium	Technology Strategy Board/Scottish Enterprise
MetaFAB	Laser micromachining	Low	Technology Strategy Board/Welsh Assembly Government
CEMMNT	Metrology	High	Technology Strategy Board/East Midlands Development Agency
Bio Nano Consulting	Nano in healthcare	High	Technology Strategy Board/London Development Agency
Fluence	Microfluidics	Low/Medium	Technology Strategy Board/One North East
Materials Solutions	Laser sintering fabrication	Low	Technology Strategy Board/Advantage West Midlands
Nanoforce	Polymer nanotechnology	Medium/High	Technology Strategy Board/London Development Agency
Centre for Micro and Nanomoulding	Small scale moulding	Medium	Technology Strategy Board/Yorkshire Forward
PeTEC	Plastic electronics	Medium	Technology Strategy Board/One North East
SafeNano	Health and safety	High	Technology Strategy Board/Scottish Enterprise
Scottish Microfluidic centre	Microfluidics	Medium	Scottish Enterprise
ISLI MEMS Design	MEMS	Low	Scottish Enterprise
Optocon	Microsystems packaging	Low	Scottish Enterprise
The Nanotechnology Centre	Fabrication and characterisation	High	Welsh Assembly Government
Optic Technium	Photonics development	Low/medium	Welsh Assembly Government
The Nanomanufacturing Institute, including Nanofactory	Scaling up manufacture	High	Yorkshire Forward
Jeol Nano Centre	Metrology and lithography	High	Yorkshire Forward
The Polymer Centre	Polymer materials	High	Yorkshire Forward

Appendix 4 – Organisations active in the nanoscale technologies sector

Entity	Role	Type
Ministerial group on nanotechnologies	Cross-government working on nanotechnology at ministerial level	Government
Nanotechnologies Issues Dialogue Group	Cross-departmental body reporting to ministerial group	Government
Nanotechnology Research Coordination Group	Cross-departmental body responsible for coordinating research into EHS chaired by Defra	Government
Nantechnology Stakeholders Forum	Discussion forum on nanotechnologies	Government/public
MNT RDA/DA group	Cross-regional group as point of contact to coordinate national activity in capital facilities	Government
Nanotechnology Industries Association	Trade association with European office and international activities	Industry
European Nanotechnology Trade Alliance	European trade association	Industry
Institute of Nanotechnology	Skills development, coordination of European projects, knowledge transfer	Academic/industry
Institute of Materials, Mining, and Minerals	Skills development, voice of materials for the UK and joint working with Materials Knowledge Transfer Network	Academic/industry
Nanotechnology Knowledge Transfer Network	Central focus for knowledge transfer for the UK	Industry/academic
British Standards Institution	Standards	Industry
Department for Environment, Food and Rural Affairs (Defra)	Central Government department	Government
Department for Energy and Climate Change (DECC)	Central Government department	Government
Department for Business, Innovation and Skills (BIS)	Central Government department	Government
Ministry of Defence/Defence, Science and Technology Laboratory	Central Government department and subordinate executive agency	Government
Department for Transport (DfT)	Central Government department	Government
Department of Health (DH)	Central Government department	Government

Appendix 5 – Market assessment by sector

Brand and product security

Concerns about privacy, identity theft, and data security are driving demands for reliable security solutions. Studies, such as those conducted by the International Anti-Counterfeiting Coalition, estimate yearly losses of €300bn with approximately 5-7% of all products being forgeries. Nanoscale technologies can address brand and product security, anti-counterfeiting and supply chain tracking. It is likely that the largest market penetration by 2015 will be in the area of brand and product security with the adoption of technologies such as nanoparticulate chemical markers, optical lock and key techniques, changeable inks, biometric recognition and oxygen sensors.

Electronics and ICT

European ICT market revenues according to the European Union represented 6.5% of GDP and 34% of the worldwide ICT market in 2007. Nanoscale technologies can address data storage, displays, printed electronics, heat management, and quantum computing. It is likely that the largest market penetration by 2015 will be in the area of data storage and displays with the adoption of technologies such as extended RAM (random access memory) using magnetic nanoparticles, ultra-thin, lightweight flexible displays with lower power consumption and operating voltage, and carbon nanotube field emission displays.

Environment and water

The environment and water sector encompasses a very broad range of activity, from waste and water treatment, hazardous materials treatment and disposal, and air pollution management, to in-building environment management and remediation of polluted areas. There are a number of drivers that will affect the take-up of nanoscale technology including detection and monitoring, industrial clean-up, emissions reduction, water purification, air filtration, and recyclability. It is likely that the largest penetration of the market by 2015 will be in the areas of detection and monitoring, and industrial clean-up, with the adoption of technologies such as nanosensors capable of detecting minute traces of chemicals or organic compounds, and nanoscale bimetallic particles for in situ remediation.

Energy

There are very strong drivers to move away from fossil fuels towards more renewable energy sources, as well as the possibility of using carbon sequestration and increased use of nuclear power. The energy sector can be considered in three sub areas: energy storage, energy conversion (solar in the main), and energy saving. It is likely that the largest penetration of the market by 2015 will be in areas of energy storage, and energy conversion. In the former case, relevant technologies are nanocrystalline materials and nanotubes to greatly improve power density for rechargeable batteries, nanostructured graphite materials for repeatable hydrogen absorption and desorption for hydrogen fuel cells, and porous carbon electrodes as capacitor plates in supercapacitors. In energy conversion, we expect to see adoption of technologies such as nanoporous aerogels as covers for solar collectors, photovoltaic cells of quantum dots connected with carbon nanotubes, nanocomposite-based or inorganic nanorods incorporated into organic semiconductor films, and thermoelectric nanoscale materials arranged in super lattices for heat conversion.

Life sciences and healthcare

There is a strong drive to apply nanoscale technologies in the healthcare sector as diseases have their origins at the molecular level. The sector breaks down into drug delivery and therapeutics, implants and medical devices, tissue engineering, and diagnostics. All areas have a high potential for penetration by 2015 but mainly through drug delivery and therapeutics, and implants and medical devices. Examples of technology are nanoparticles for the delivery of minute doses of highly active drugs and oxygen to poorly vascularised tissues; novel theranostic products that can be tracked and activated by conventional radiological devices, for fighting tumours for example; and new smart materials to improve performance of conventional medical devices and drugs.

Agriculture, food and drink

The use of nanoscale technology is not new to this sector. Nutraceuticals and functional food formulation, manufacturing and processing already exploit this technology. Colloid science has been applied to food materials for a long time. A number of food and drinks contain components that are at the nanoscale. In processing dairy products, for example, the manipulation of naturally occurring nanoparticles is involved. Potential new applications in the food and drink sector include four areas: packaging, processing and safety, controlled release and encapsulation, and agricultural production. It is likely that the largest market applications by 2015 will be in the area of packaging where examples of technology adoption would be in the use of nanosensors for pathogen and contaminant detection, and integration into smart systems for sensing, localisation, reporting and remote control.

Construction

The main areas of focus for nanoscale technologies in construction are in protection and maintenance, structural materials, sensors, and safety and comfort. By 2015 the most likely applications of nanoscale technologies in the construction sector will be through protection and maintenance, structural materials, thermal management and energy efficiency with technologies such as surface coatings for filtering and reflecting windows, nanoparticles for glass and concrete, nanocomposites in concrete for strength and crack protection, and nano coatings for biocidal protection.

Automotive

Key drivers within this sector include cost reduction, reduced air pollution, recyclability, safety, better performance with increased engine efficiency to save fuel, aesthetics, and longer service life. In terms of nanoscale technology, the sector breaks down into four potential sub-sectors consisting of coatings, fuel economy and energy, structured materials, and sensors. It is likely that the largest penetration of the automotive market by 2015 will be through new coating technologies, and fuel economy and energy technologies, with structured materials also having a reasonable penetration. Examples of technologies in these three areas are evident in scratch resistant, self-healing coatings, thermal barrier materials for higher temperature engines, nanoparticles as additives in fuel for efficiency, and the greater use of nanocomposites as high-strength, lightweight, structural materials.

Textiles

The EU was until recently the world's largest exporter of textile products, accounting for around 15% of the world market, and the world's second largest importer of textiles, accounting for 20% of the world market. Increased competition from low-cost countries, and the proposed abolition of all import quotas for textiles and clothing, is forcing the industry to restructure and to specialise in high quality products to compete on a global scale. The main focus of this industry will be for critical applications, eg health and survival, and luxury applications (with niche consumer markets).The potential for nanoscale technologies is in hygiene, healing, protection, communications, and aesthetics. It is likely that the main adoption of technologies will be in the hygiene and healing areas of the textiles market by 2015, with examples of the use of nanosilver coated fibres, antibacterial clothing and nanosilver wound dressings.

Consumer goods and household care

The consumer products market is only just beginning to exploit the potential of nanoscale technology. It is also one of the areas that needs to be sensitive to public opinion. Most real nanoscale technology-based consumer products are based on fillers and coatings, and the potential that is expected from investment into nanoscience research has not yet reached the consumer. There are five sub-sectors where nanoscale technologies could be applied: household care, beauty products, leisure goods, personal care, and baby care. The likely penetration into this market by 2015 will be through household care with examples of adoption of technologies of antiseptic and antifungal paints, washing powders, floor cleaning/wash products, and incorporation of controlled release technology for fragrances.

Aerospace and defence

Nanoscale technology applications in the aerospace and defence market break down into five potential sub areas including: coatings, structural materials, sensors, electronics, and energy and emission reduction. By 2015 it is likely that the coatings and structural materials sub-sectors will see the most significant impacts from nanoscale technology, with examples such as protective and self repair coatings; use of lightweight, high strength nanoscale materials for weight reduction and hence energy saving; and the enabling of multifunctional materials, whilst also allowing potential changes in wing design.

Table 5 – Potential high value-added products across many market sectors

Sector	Market size in terms of nanotechnology revenue ($m)	Living in an intelligent connected modern world	Living with environmental change	Living with a growing/ageing population
Aerospace and defence	$323.5m in 2007 to $3,768m in 2015	Sensors for biological and chemical threat detection, electronics in spacecraft, smart uniforms, smart air/spacecraft	Flame retardant materials for aircraft, protective coatings, composites for structural reinforcement, self repairing structures	
Electronics and ICT	$585m in 2007 to $4,1402m in 2015	Magnetic nanoparticles for data storage, molecular memory, flexible displays, nanocomposite heat management, nanowire electronic and photonic devices, carbon nanotube single electron transistors, non volatile random access memory, molecular diodes, single hybrid molecular device, semiconductor single electron devices (quantum dots)	Environmental monitoring	Healthcare enabled by remote nano-sensors
Energy	$90m in 2007 to $3,615m in 2015	Energy scavenging for 'smart dust' type applications	Nanocatalysts for fuel cells, better batteries through nanoscale materials, nanocrystalline coated solar cells, flexible low cost photovoltaics, nanoporous aerogels, nanoparticle additives for energy efficiency, thermoelectric materials for heat conversion, nano-enabled fuel cells and batteries, nano enabled hydrogen storage, wind power applications, thermal barrier coatings	
Life sciences and Healthcare	$145m in 2007 to $5,670m in 2015	Sensors for continuous real-time diagnostics. Point-of-care diagnostics connected directly to remote monitoring	Environmental monitoring	Biocompatible implants, magnetic nanoparticles as imaging agents, nanocoated stents for tissue engineering, non-invasive therapeutics using heat to treat cancer, nanotitania implants, nano-particle drug delivery, antibacterial coatings, healing wound dressings, lab-on-a-chip, smart materials for organ and limb replacements, dendrimers in bio-technology assay kits, nanopores for sequencing

Sector	Market size in terms of nanotechnology revenue ($m)	Living in an intelligent connected modern world	Living with environmental change	Living with a growing/ageing population
Construction	$66m in 2007, to $1,672m in 2015	Smart sensors to monitor fracturing and flexibility, intelligent buildings, self repairing structural materials	Aerogels for insulation, heat resistant materials, strength increase/crack prevention, self healing additives to cement, exterior protection coatings, anti-graffiti coatings, self cleaning glass, nanoadditives to steel, heat blocking windows, micro renewable energy solutions	Technologies for assisted living
Textiles	$122m in 2007, to $2,170m in 2015	Self cleaning fabrics, wearable computers, smart clothing, self healing textiles	Fire retardant textiles	Bio-responsive clothing, wound dressings, healing textiles, antibacterial garments
Environment and water	$86m in 2007 to $3,885m in 2015	Environmental monitoring, land remediation	Nanoscale absorbants, air filtration, titania photocatalysts, nanoporous membranes for filtration, NEMS for sensing and acting on pollution, desalination of sea water using nanomembranes, nanomaterial-based products for water treatment	Water purification using bio-nanotechnologies
Agriculture, food and drink	$265m in 2007 to $3,210m in 2015	Electronic tongue, smart paper for information display and packaging	Controlled release seed coatings, pathogen detection with nanoparticles	Super hydrophobic surfaces, nanoencapsulated nutraceuticals, programmable barriers in coatings for atmospheric control, nanoemulsions, nanocomposite barrier packaging, nanoporous membranes for processing
Consumer goods and household care	$188m in 2007 to $6,225m in 2015	Nanoencapsulation for beauty care, nanocomposite sporting goods, nanoelectronics in leisure equipment		Nanoencapsulation for household hygiene and fragrancing, easy clean coatings for surfaces, self cleaning tiles, nanocoated wipes for surfaces, self cleaning sprays
Brand and product security	$30m in 2007 to $2,650m in 2015	Intelligent inks, nanoparticles for security printing, paper-like electronic displays for condition information, magnetic nanoparticle tagging, nanoparticle chemical markers	Smart dust for decontamination	Decontaminating surfaces

Sector	Market size in terms of nanotechnology revenue ($m)	Living in an intelligent connected modern world	Living with environmental change	Living with a growing/ageing population
Automotive	$404m in 2007 to $7,134m in 2015	Displays, sensors, smart materials	Thermal barrier materials for engines, smart tyres, shape memory alloys, fuel cells, nanofillers for structural enhancement, fuel additives, scratch proof coatings, anti-glare fogging coatings, friction control through low friction coatings and surface texturing	
Tools development[34]	$1,425m in 2007 to $5,870m by 2015	Optical nanolithography, near-field optics, nanomanipulators, and other nanotechnologies for sub-wavelength optical imaging	Nanomachining tools, near-field optics, nanomanipulators	Optical nanolithography, near-field optics, nano-manipulators

Appendix 6 – BCC Market report data

Global nanoscale technology market by type, 2007 to 2013[33]

	2007 ($m)	2008 ($m)	2013 ($m)	CAGR% 2008-2013
Nanoscale materials	10,140	10,770	18,695	11.7
Nanotools	1,488	1,891	7,952	33.3
Nanodevices	24.0	26.2	366.2	69.5
Total	**11,649**	**12,688**	**27,013**	**16.3**

Global nanoscale materials sales by type, 2007 to 2013

	2007 ($m)	2008 ($m)	2013 ($m)	CAGR% 2008-2013
Nanoscale thin films	6,684.8	7,045.4	10,126.0	7.5
Solid nanoparticles	1,743.9	1,860.6	4,169.5	17.5
Nanostructured monolithics	1,398.6	1,496.4	2,350.2	9.4
Nanocomposites	309.8	368.0	1,305.7	28.8
Nanotubes and other hollow nanoparticles	<1.0	<1.0	743.3	–
Total	**10,137.1**	**10,770.4**	**18,694.7**	**11.7**

Global market for commercial nanotool applications, 2007 to 2013

	2007 ($m)	2008 ($m)	2013 ($m)	CAGR% 2008-2013
Advanced optical nanolithography tools	1,100.0	1,415.8	5,000.0	28.7
Nanomanipulators	250.0	300.0	746.5	20.0
Near-field optics	55.0	59.5	88.3	8.2
Nanomachining tools	20.0	22.0	35.4	10.0
Total	**1,425.0**	**1,797.3**	**5,870.2**	**26.7**

Global market for developmental nanodevice applications 2007 to 2013

	2007 ($m)	2008 ($m)	2013 ($m)	CAGR% 2008-2013
Nanosensors	<1.0	<1.0	159.9	–
Drug production and mixing systems	0.0	0.0	16.0	–
Nanoholographic memory	0.0	0.0	150.0	–
Total	**<1.0**	**<1.0**	**325.9**	**–**

Appendix 7 – The UK in a global and European context

Investment

Internationally, nanoscale technologies have a high profile worldwide, with a high degree of spending globally. This is due to their potential in helping to overcome the key global challenges of climate change, ageing population, and security in a connected world. Figure 5 shows a breakdown of global spending on nanotechnology R&D in 2004 by public, private, and associated state spending. It can be seen that the US and the EU are comparable at $3bn each, with Japan third at $2.3bn. The money invested in nanotechnology within the US is more than the budget of NASA.

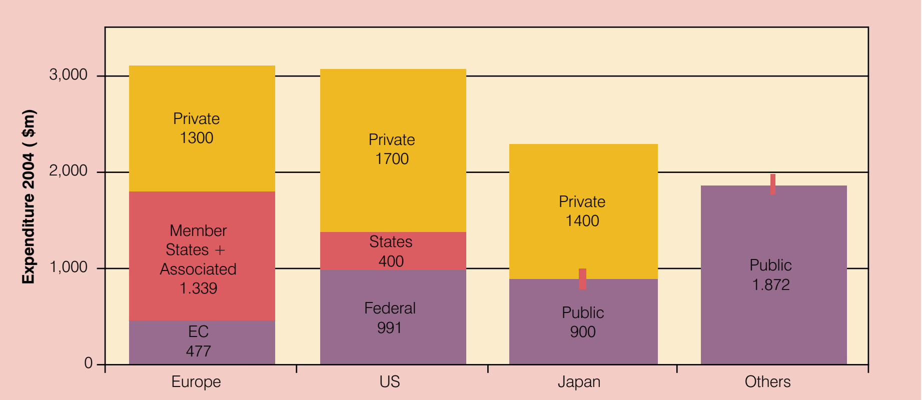
It can be seen that the EU provides much funding for nanoscale technologies, currently through its Framework 7 programme. About 50% of funding in the programme overall is focused towards nanosciences and nanotechnology (covering the so-called nanoscale technologies) with the Nanosciences, Nanotechnology, Materials and Production programme being just one part of this. (It also involves ICT, biosciences, and health and safety etc.) The National Contact Point service provides resources to disseminate the content of competitions, at **www.fp7uk.co.uk.**

Typically, countries address nanoscale technology in one of two ways: established nanoscale technology players with large investment budgets, such as the US and Japan, have set broad technology strategies covering most areas of nanotechnology. Countries with more limited funds, such as Germany, France and including the UK, have previously developed focused technology strategies that aim to exploit their areas of key scientific and industrial strength rather than dilute funding across a broad range of activities.

Governments are investing heavily (and still intend to despite the economic climate). They are aiming to coordinate developments in an effort to gain a strong position. The US issued the 21st Century Nanotechnology Research and Development Act (passed in 2003) which allocated $3.7bn of funding to this area between 2005 and 2008.

Internationally, substantial investments to improve the science base have been complemented with further investments in the ability to commercialise. In Germany, focused industrial R&D programmes and facilities support commercialisation of nanotechnology in a range of nationally important sectors such as automotive and lighting. In the US, national laboratories and multiple new nanotechnology centres offer assistance in developing products across large areas of nanotechnology, supporting existing industries and enabling new business opportunities to be exploited. Lux Research[34] reports on the nanoscale technology activity and technology development strength for 14 countries and puts the US, Japan, South Korea, and Germany as dominant forces, with the UK, France, and China showing significant nanoscale technology activity.

Figure 5 – Worldwide funding of nanotechnology R&D (Lux Research)



Source: European Commission (2005) : Private figures based upon Lux Research

The European Commission is committed to increasing nanotechnology R&D across Europe. In its report *Towards a European Strategy for Nanotechnology* (2004)[35] the EU characterises the European nanoscale technology capability as containing a small number of 'centres of excellence' on the scale of those in the US and a lower level of private R&D funding from industry compared to the US and Japan.

Patents and research

The European Commission completed a study of the economic development of nanoscale technology in 2006[36], which included a study into patents by country worldwide in 2003. The UK overall was fourth in terms of number of patents applied for, after the US, Japan, and Germany and fifth in terms of inventor (researcher) ranking after South Korea. When considering individual areas, the UK was very strong in nanooptics, placed third after the US and Japan (and one place ahead of Germany) and fourth on nanoscale materials after the US, Japan, and Germany. The UK was placed lower in nanobiotechnology, nanoelectronics, nanodevices, and has no appearance in nanomagnetics. Further data from the same report highlights scientific publications in nanoscience, and subfields including nanoscale materials, superconductivity and quantum computing, and chemical synthesis, ranked the UK as fifth behind the US, Japan, China, and Germany (showing the UK ranked second within Europe).

Glossary

BIS	Department for Business, Innovation and Skills (note this government department was created in 2009 and is now responsible for the Technology Strategy Board's work and activities previously under DIUS)
BSI	British Standards Institution
DA	Devolved administration (England, Scotland, Wales and Northern Ireland)
Defra	Department for Environment Food and Rural Affairs
DIUS	Former Department for Innovation, Universities and Skills, now scrapped
EHS	Environmental health and safety
EPES	Electronics, Photonics and Electrical Systems
EPSRC	Engineering and Physical Sciences Research Council
ICT	Information and Communication Technology
KTP	Knowledge transfer partnership
MEMS	Micro electro mechanical system
MNT	Micro and nano technologies
OECD	Organisation for Economic Cooperation and Development
RC	Research councils
RCUK	Research Councils UK
RDA	Regional development agency
SME	Small or medium-sized enterprise
TRL	Technology Readiness Level

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15 Report of the Nanotechnology Strategy Group, www.epsrc.ac.uk/CMSWeb/Downloads/Other/NanotechStrategy.doc

16 www.nanotechproject.org/ Reported that more than 800 consumer products were on the market as of August 2008

17 CeO_2 is a fuel-borne diesel additive that has been developed by Oxonica, a UK-based start-up company. Large-scale trials in collaboration with Stagecoach successfully demonstrated a significant decrease in the release of noxious gases and carbon particulates, combined with an increase in fuel efficiency. Johnson Matthey also has an interest in CeO_2 catalysts.

18 Johnson Matthey has an interest in ZnO for thin film application. ZnO is also approved as a sunscreen ingredient that enhances the sun protection properties in the majority of countries around the world.

19 http://ec.europa.eu/environment/chemicals/reach/reach_intro.htm

20 N*anotechnology Engagement Group final report*: www.involve.org.uk/democratic_technologies

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