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SID 5 Research Project Final Report

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Project identification

1. Defra Project code: CB01070
2. Project title: A scoping study into the manufacture and use of nanomaterials in the UK
3. Contractor organisation(s): Central Science Laboratory, Sand Hutton, York Y041 1LZ
4. Total Defra project costs: £ 39,329
5. Project: start date .... 08 June 2005

   end date .... 07 September 2005

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Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

1. Nanotechnology is a fast emerging field of new materials that are manufactured in the size range of up to 100 nanometres (nm). Due to their extremely small size, nanomaterials (NMs) have a much greater surface area, and many NMs exhibit properties that are either novel or distinctly different from their conventional forms. This has opened up huge new opportunities for their use in a variety of industrial and consumer applications. Nanotechnology has already achieved a multibillion US dollar market, which is widely expected to grow to 1 trillion US dollars by 2015. Such proliferation of nanotechnology has also prompted concerns over the safety of NMs when released into the environment. This landscaping study, carried out in accordance with the Government's response to the Royal Society/Royal Academy of Engineering review (http://www.nanotec.org.uk/), represents an important first step towards:

- gathering and collating the information related to the companies and institutions that are currently manufacturing, processing, and/or researching NMs in the UK, with particular reference to free forms of these materials; and
- developing a database using the information generated by the review.

2. Brief outcomes of the project are outlined below:

- At the moment, there appears to be no regulatory framework that specifically covers the production and/or application of NMs. Because of this, companies involved in NM production, processing, or use are not obliged to disclose information about the nature of materials, or to indicate the existence of NMs in their products. This posed a major difficulty for the current study, and much of the information included in this report (and database) is on those companies who have released such information on their websites or in product literature. Other information was obtained from recent reviews and personal contacts. It also proved very difficult to find out the exact uses of each NM, or whether any of the materials were being imported into the UK, and if so, from where.

- The reviewers strongly recommend that a register of NMs manufactured, processed, imported, or used in the UK should be maintained, either through a voluntary industry initiative, or centrally by Government. This will enable access to up-to-date information on new materials and applications, until more scientific data on the safety of NMs, in terms of their effects on human health and the environment, becomes available. The web-enabled database may act as a central depository for such information, with any commercially sensitive information only made accessible to relevant regulators.

- Following the global trend in new NMs, UK industry and research institutions have established themselves with substantial investments and funds from the government (e.g. DTI) and other initiatives (e.g. Yorkshire Forward, EPSRC).

- The UK NM manufacturing industry is very much in the development, and currently there are only a handful of companies that are identifiable as NM manufacturers. The main emphasis of NM manufacturing industry in the UK has so far been the bulk markets in metals and metal oxides, as well as some niche markets such as quantum dots. The review clearly indicated that NMs manufacturing in the UK does not reflect the global emphasis on fullerenes, nanotubes and fibres. Instead, the emphasis is weighted heavily towards the production of nano-metals and metal oxides, with some production of carbon nanotubes and quantum dots (for applications in diagnostics, authentication markers). Currently there is no known fullerene manufacturer in the UK.

- A large number of university departments, spin-offs, and private companies have developed processes for the manufacture of NMs but may only be producing small experimental quantities for R&D purposes. However, some of these have the potential and capability to scale-up their processes to produce large quantities of NMs.

- The nanotechnology industry in the UK has a very strong R&D backup from a number of university departments and related institutions into a vast array of NMs and their applications. The current review also covered the R&D trends at such institutions, and appropriate information has been added to the searchable database that has been developed as part of this project.

- A number of companies are processing or formulating NMs in their products. However, only a few of them (e.g. manufacturers of paints and coatings, cosmetics, catalysts, polymer composites etc) may be using NMs in any significant or large quantities. With more emerging applications and markets for NM based products, this situation is likely to change in the future.

- The data and information generated by the review of the UK and worldwide NM manufacturers and processors, and UK institutions involved in NM R&D, have been used to develop a web-enabled database. The design of the database facilitates simple and straightforward querying of the data in a number of ways, including spatial references.

- In view of the emerging new NMs and applications, it is anticipated that the nature of UK nanotechnology industry will change in the near future. It is, therefore, necessary that further reviews of the situation are carried out periodically for at least 3 to 5 years. The database developed as part of this project will be maintained on CSL website which, with stakeholders agreement, can be regularly updated with the new information arising from future reviews. The database is also likely to provide a useful resource for the identification of data needs, and regulatory frameworks, to identify gaps in knowledge and needs for further research.

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other

journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:

- the scientific objectives as set out in the contract;
- the extent to which the objectives set out in the contract have been met;
- details of methods used and the results obtained, including statistical analysis (if appropriate);
- a discussion of the results and their reliability;
- the main implications of the findings;
- possible future work; and
- any action resulting from the research (e.g. IP, Knowledge Transfer).

1.0 Introduction

1.1 Background

1. Nanotechnology is a new and fast emerging field that involves the manufacture, processing, and application of materials that are in the size range of up to 100 nanometres (nm). Due to their extremely small size, nanomaterials (NMs) have a much greater surface area than their conventional forms, which in some cases results in novel or distinctly different properties. At such a small scale, quantum effects also appear to become much more important in determining the properties and characteristics of NMs. This has led to the development of novel materials with very desirable properties for a number of industrial and consumer applications.

2. NMs can be defined as substances that are less than 100 nm in size in any one dimension, as they can be spherical, tubular, irregularly shaped, or can exist in fused, aggregated or agglomerated forms.

3. Nanotechnology is a broad interdisciplinary area of research, development and industrial activity that has been growing rapidly world wide for the past decade. It is a multidisciplinary grouping of physical, chemical, biological, engineering, and electronic, processes, materials, applications and concepts in which the defining characteristic is one of size. Figure 1 shows the DTI's view of the scope of nanotechnology, which incorporates this broad vision. Much of the activity and products represented here could potentially be considered to be NMs.

4. Nanotechnology is a rapidly growing sector of material manufacturing industry that has already achieved a multibillion US dollar market, which is widely expected to grow to 1 trillion US dollars by 2015. It is, therefore, not surprising that some NMs are already used in a variety of consumer products, such as titanium dioxide (TiO_2) in paints, and zinc oxide (ZnO) in sunscreen products. A number of applications are also in the pipeline; for example, for targeted drug delivery, gene therapy, cosmetics, stain-resistant coatings, industrial lubricants, advanced tyres and semiconductors.

5. Other, more ambitious uses of NMs are also being projected, such as in bioremediation of contaminated environments. The rapid growth of nanotechnology suggests that it will not be long before a variety of new pharmaceutical, electronic, and other new industrial uses of NMs are found. Such proliferation has also prompted concerns over the safety of NMs when released into the environment, though at the moment, because of their small-scale production, the greatest concerns centre on issues surrounding occupational health and the safety of workers at manufacturing premises.

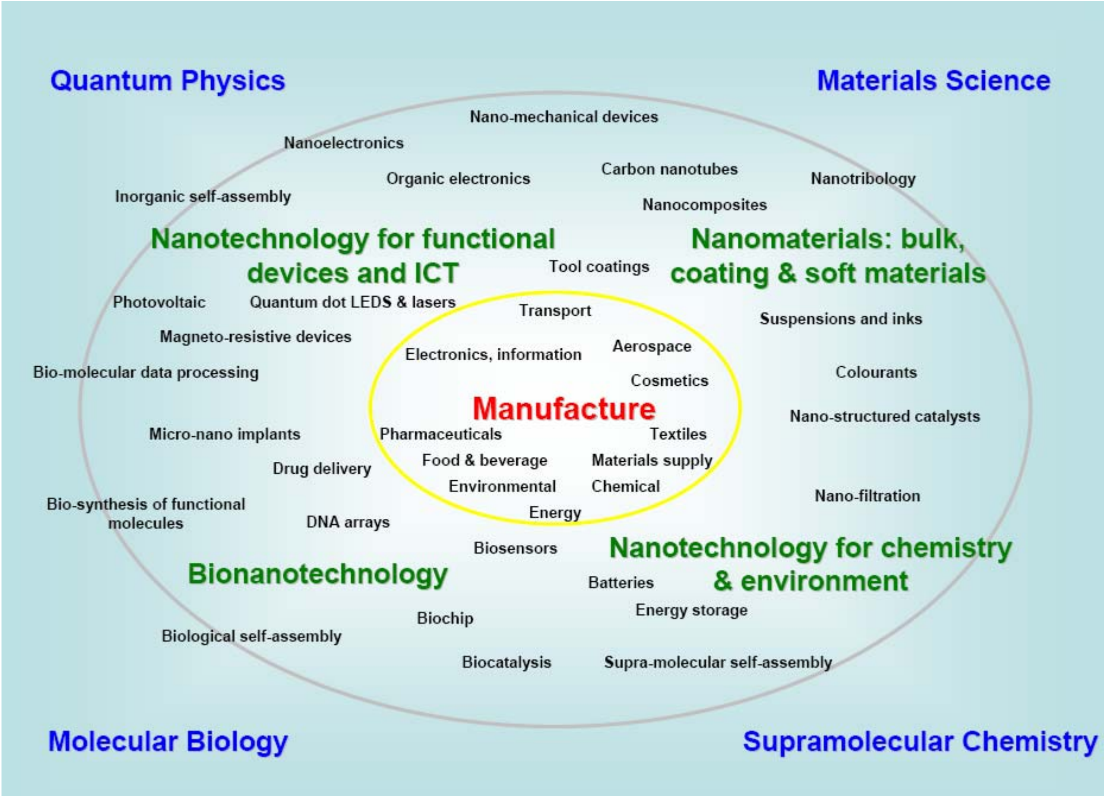

Figure 1. DTI view of Nanotechnology

6. In this context, the Government commissioned a review, in June 2003, on the environmental, ethical, social, and health and safety issues that might arise from the new technology. This comprehensive review was carried out by the Royal Society and the Royal Academy of Engineering (RS/RAEng) and was published in July 2004 (http://www.nanotec.org.uk/). The review identified a need for further research to develop a better understanding of the risks posed by manufactured NMs.

7. The Government published its response to the review in February 2005, accepting the recommendations made by the RS/RAEng. In doing so, it emphasised that while nanotechnology offers enormous benefits in terms of wealth creation, the new technology needs to be properly regulated to safeguard the benefits as well as the environment. Furthermore, it also highlighted the need for a comprehensive overview of the current manufacture and use of NPs in the UK, as an on-going project that would provide regulators with an overview of the potential areas where action may be required.

8. The current study was carried out to meet this commitment, with the aim to use the information generated to develop a web enabled database of companies involved in manufacturing, processing, and researching NMs in the UK. The study also gathered relevant information on global trends in NM manufacture and research.

2. Objectives and methodological approach

2.1 Objectives

9. The study focused on identifying NM manufacturers and processors in the UK, and to a lesser extent worldwide. It comprised two interlinked tasks that were carried out through a number of sub-tasks, as described in Table 1.

Task	Description
1	***Review the current and short-term future scope of the manufacture and use of nanoparticles and nanotubes in the UK.***
1.1	Obtain information on the main industrial processes involved in NM manufacture.
1.2	Identify UK companies and research institutions that are involved in the manufacturing, using and/or researching nanoparticles, their position in the production chain, the manufacturing processes used and the nature of their products and typical applications.
1.3	Provide this information to be included in a database.
1.4	Identify the major NM manufacturers in the world.
1.5	Identify current and future trends in NM manufacturing, use and research (global).
2	***Use the information gathered in task 1 to develop a database.***
2.1	Using the data obtained by the review team, develop a spatially-enabled database to enable the landscaping of the uses and applications of nanotechnologies in the UK.
2.2	Develop a flexible search capability to allow retrieval of information by different keywords, materials, applications or different combinations of search terms.
2.3	Develop a database interface to allow interaction with the EA database.
2.4	Develop a trial version of the database for testing by the stakeholders.
2.5	Develop a final web-enabled version of the database, after incorporation of any suggestions/comments from the stakeholders.

Table 1. Project tasks

2.2 The project Team

- **Dr. Qasim Chaudhry** (Central Science Laboratory)
  Project Lead and review of nanomaterials industry

- **Dr. Miles Thomas** (Central Science Laboratory)
  Database development and web-enablement

- **Dr. Alistair Boxall** (University of York)
  Review of the physicochemical nature and applications of nanomaterials

- **Dr. Robert Aitken** (Institute of Occupational Medicine)
  Review of nanomaterial manufacture in the UK

- **Mr. Matthew Hull (Lunar Innovations**
  Review of worldwide nanomaterials industry trends

2.3 Scope of the review

10. In line with the Royal Society/Royal Academy of Engineering review (http://www.nanotec.org.uk/), which stated, "*Currently we see the health, safety and environmental hazards of nanotechnology to discrete nanoparticles and nanotubes in a free rather than embedded form*", the review team focussed on those NMs that may, at some stage, have some potential to harm human heath or the environment. These include NMs in general, but free materials in particular. The review team also considered what may be meant by NM manufacture. A working definition included companies or organisations manufacturing NMs for commercial proposes (selling or combining in products).

2.4 Data collection

11. The sources of information about companies used in the review were:

- DTI's MNT directory http://www.mnt-directory.org/
- The website of the Institute of Nanotechnology (ION): http://nano.org.uk
- Previously published summaries of nanoparticle production and use e.g. Aitken *et al.,* 2004 (http://www.hse.gov.uk/research/rrhtm/rr274.htm)
- Individual company websites and product literature
- Personal contacts with research institutions and industry forums
- Nanotechnology and Nanoscience: http://www.nanotec.org.uk/
- Community Research and Development Information Service - nanotechnology http://www.cordis.lu/nanotechnology/
- The Foresight Institute: http://www.foresight.org
- INEX: Nanotechnology Exploitation web site: http://www.inex.org.uk
- The NanoInvestors News: http://www.nanoinvestornews.com/
- Standard scientific literature databases, such as NIOSHTIC/NIOSHTIC 2, OSHLINE, CISILO, HSELINE, CANADIANA http://ccinfoweb.ccohs.ca/bibliographic/search.html, the Barbour Index http://www.barbour-index.co.uk/content/home/ and Science Direct http://www.sciencedirect.com
- Published scientific literature was searched using online databases such as CAB Abstracts and BIOSIS.
- The review published in July 2004 by the Royal Society and Royal Academy of Engineering: nanoscience and nanotechnologies: opportunities and uncertainties www.nanotec.org.uk/finalReport.htm, and the Government's response to the review published in February 2005 www.ost.gov.uk/policy/issues/nanotech_final.pdf.
- Proceedings of a nanomaterials symposium held by the Oil and Colour Chemists Association (OCCA) on the developments and applications of NMs in the coatings industry.
- The DTI's report to the UK advisory group on nanotechnology (*New dimensions for manufacturing: A UK strategy for nanotechnology*) published in 2002.
- Web based searches were carried out using general on-line search engines such as GOOGLE (http://www.google.com) and YAHOO (http://www.yahoo.com).
- Discussions were also held with representatives of some of the companies identified to clarify queries over their materials, processes or products.
- Electronically mailed surveys to selected relevant individuals identified through on-line databases (worldwide survey).

12. One implication of the current lack of specific regulations for NMs, is that companies involved in NM production, processing, or use are not obliged to disclose information about the nature of materials, or to indicate the existence of NMs in their products. Apart from companies who have released such information on their websites, or in their product literature, obtaining detailed information on specific materials, their uses, and accurate quantities of materials, proved very difficult. In some cases, no information about the manufactured quantities was available. In others, companies named in lists as nanotechnology companies appeared to have products in larger size ranges. These difficulties may have resulted from fears, on the part of the companies, about compromising strategic business information, intellectual property or having regulatory action interfere with research activities.

3. Nanomaterials and their production processes

3.1 Nanomaterials

13. The development of new NMs is a rapidly progressing science and it is beyond the scope of this review to track all of these developments. However several excellent summaries are available. A recent special edition of the Journal of Materials Chemistry (Rao, 2004) published 47 papers concerning the

development of new NMs including metallic nanoparticles, germanium, ceramic and aluminium oxide nanowires, carbon, silicon and germanium nanotubes, zinc oxide nanocrystals, gold nanowafers and copper oxide nanocubes. A comprehensive overview of the whole science of NMs, including theory, synthesis, properties and applications has recently been published by Rao *et al* (2004). Nanoparticle types have also been reviewed from a health and environment perspective by Aitken *et al* (2004). Particle morphology has been used as a useful basis for categorising nanoparticles. Table 2, adapted from Jorter and Rao (2002), summarises the main categories of nanoparticle according to their morphologies, material composition, and the type of application.

Nanostructure	Example material or application
Fullerenes	Carbon
Nanotubes	Carbon
Nanowires	Metals, semiconductors, oxides, sulfides, nitrides
Nanocrystals, quantum dots	Insulators, semiconductors, metals, magnetic materials
Other nanoparticles	Ceramic oxides, metals

Table 2. Nanoparticle categories and applications

3.1.1 Fullerenes

14. Fullerenes are one of only four types of naturally occurring forms of carbon, first discovered in the 1980's (Kroto et al., 1985). The molecules are comprised entirely of carbon that takes the form of a hollow sphere or a tube. Fullerenes are similar in structure to graphite which is composed of a sheet of hexagonal carbon rings but contain diagonal pentagonal or sometimes heptagonal rings which enables the 3D structures to be formed. The smallest fullerene and the most common, is C_{60} also known as Buckminster fullerene and sometimes called Buckyballs. Fullerenes are produced in small amounts naturally in fires and in lighting strikes, however, they were first produced in the soot resulting from ablation of graphite with a laser. Such methods tend to produce a range of fullerenes including C_{60} and C_{70}, and various separation techniques are needed to purify C_{60}. Since then many other processes have been used to produce fullerenes including resist of heating or arcing of graphite, combustion of hydro carbons, thermal and non-thermal plasma pyrolysis of coals and hydro-carbons, and thermal decomposition of hydro carbons (Huczko and Byszewski, 1998). The approach that is most commonly used for the production of commercial quantities of fullerenes is based on carbon electric arc (Krätschmer and Huffman, 1990).

3.1.2 Nanotubes

15. Carbon nanotubes (CNT) are a particular form of fullerenes, first reported by Lijima (1991). They are similar in structure to C_{60} but are elongated to form tubular structures, 1-2 nm in diameter. They can be produced with very large aspect ratios and can be more than 1 mm in length. In their simplest form, nanotubes comprise a single layer of carbon atoms arranged in a cylinder. These are known as single-wall carbon nanotubes (SWCNTs). They can also be formed as multiple concentric tubes (multi-wall carbon nanotubes, MWNTs) with diameters up to 20 nm, and length greater than 1 mm. CNTs have great tensile strength and are considered to be 100 times stronger than steel, whilst being only one sixth of its weight, making them potentially the strongest, smallest fibre known (www.thomas.swan.co.uk). They also exhibit high conductivity, high surface area, unique electronic properties, and potentially high molecular adsorption capacity (Maynard *et al.,* 2004). Applications which are currently being investigated include; polymer composites (conductive and structural filler), electromagnetic shielding, electron field emitters (flat panel displays), super capacitors, batteries, hydrogen storage and structural composites.

16. One major focus of current research on nanotubes is on scaling-up of production rates to kilogram (or greater) quantities, because many of the applications require bulk quantities of the material. For production of large quantities of CNTs, chemical vapour deposition (CVD) method is the current method of choice (Singh *et al.,* 2003). Nanotubes have also been produced from other materials including silicon and germanium but the development of various forms and applications for CNTs remains the main focus of activity.

3.1.3 Nanowires

17. Nanowires are small conducting or semi-conducting nanoparticles with a single crystal structure and a typical diameter of a few 10s of nanometres and a large aspect ratio. They are used as interconnectors in nanoelectronic devices. Various metals have been used to fabricate nanowires including cobalt, gold and copper. Silicon nanowires have also been produced.

18. Most approaches to the fabrication of nanowires are derived from methods currently used in the semi-conductor industry for the fabrication of microchips. Van Zant (2000) provides a comprehensive review of microchip fabrication, which makes useful background reading. Typically they involve the manufacture of a template followed by the deposition of a vapour to fill the template and grow the nanowire. Deposition processes include electrochemical deposition. The template may be formed by various processes including etching, or the use of other nanoparticles, in particular, nanotubes.

3.1.4 Quantum dots

19. Quantum dots of semiconductors, metals and metal oxides, have been at the forefront of research for the last few years due to their novel electronic, optical, magnetic and catalytic properties (www.oxonica.com). The number of atoms in a quantum dot, which range from 1000 to 100,000, makes it neither an extended solid structure nor a single molecular entity. This has led to various names being attributed to such materials including nanocrystals and artificial atoms. Methods have been developed for the production of quantum dots and allow tighter control of factors affecting, for example, particle growth and size, solubility and emission properties. The majority of research has centred around semiconductor quantum dots, as they exhibit distinct 'quantum size effects'. The light emitted can be tuned to the desired wavelength by altering the particle size through careful control of the growth steps. Various methods can be employed to make quantum dots however the most common is by wet chemical colloidal processes.

3.1.5 Other nanoparticles

20. This category includes a wide range of spherical or aggregated dendritic forms of nanoparticles. Dendritic forms are where spherical or other compact forms of primary particles aggregate together to form chain like or branching structures. Welding fume is the best-known example of this. This category includes nanoparticles such as ultrafine carbon black, and fumed silica, which are synthesised in bulk form through flame pyrolysis methods. Nanoparticles of this type may be formed from many materials including metals, oxides, ceramics, semiconductors and organic materials. The particles may be composites having, for example, a metal core with an oxide shell or alloys in which mixtures of metals are present. Many of the production processes involve the direct generation of aerosols through gas phase synthesis, similar to flame pyrolysis but other production processes including wet chemistry methods and attrition methods may be used. This group of particles may be categorised as being less well defined in terms of size and shape, generally larger (although still within what could be considered nanoparticles), and likely to be produced in larger bulk quantities than other forms of nanoparticles.

3.2 Primary production processes

21. Nanoparticles can be formed by a variety of methods, with different methods also being used to form the same type of nanoparticles. For example, metal nanoparticles can be synthesised by laser ablation, condensation from vapour, thermal decomposition, and wet chemical reduction of the corresponding metal salts (Johans, 2003). A good overview of primary manufacturing processes presently used for the production of NMs is provided in a recent report supported by the European Commission and entitled “Industrial application of nanomaterials - chances and risks” (Luther, 2004). It

should be recognised, however, that specific methods for nanoparticle production are tightly guarded secrets of nanotechnology companies as such methods typically form the basis for valuable intellectual property. Generally, NMs are produced in two ways. In the first, a 'top-down' approach, larger bulk materials are 'broken' into smaller, nano-scale materials by mechanical, chemical or other energy-requiring means. In the second, a 'bottom-up' approach, nano-scale materials are synthesized from atomic or molecular sub-components through precisely controlled chemical reactions. Several of the specific methods involved in both approaches, the NMs generally produced by each approach, and the relative maturity level of each method are summarised in Table 3.

TOP-DOWN		
Process	**NM produced**	**Maturity**
Mechanical milling	Mixtures of elemental or prealloyed powders, alloys and composites	Common
Etching (chemical)	Arrays of nano-scale shapes (e.g., layers of porous silicon and alumina)	Common
Electro-explosion (thermal/chemical)	Metallic nanopowders, fullerenes, metallofullerenes, nanotubes	Common
Sputtering (kinetic)	Similar to vapour phase techniques	Common
Laser ablation (thermal)	Broad range of nanoparticles	Common

BOTTOM-UP		
Process	**NM produced**	**Maturity**
Sol-gel	Colloidal nanoparticles, oxide nanoparticles, composite nanopowders	Common
Aerosol based processes	Industrial production of nanoparticles such as carbon black, titania pigment, fumed silica and titania, optical fibres, CdS nanoparticles, some metals	Common
Chemical vapour deposition	Widely used to produce carbon nanotubes	Common
Atomic or molecular condensation	Metal-containing nanoparticles	Common
Supercritical fluid synthesis	Various nanoparticles	Emerging
Spinning	Thin polymer fibres	Emerging
Use of templates	Porous alumina, zeolites, di-block co-polymers, dendrimers, proteins and other molecules containing regular nano-sized pores or voids	Common
Self-assembly	Variety of organic and biological compounds, inorganic oxides, metals, and semiconductors	Common

Table 3. Summary of top-down and bottom-up approaches to NM production (Luther, 2004)

22. Due to the presence of distinctly different intermolecular forces at the nano-scale (e.g., Van der waals), NMs have an inherent tendency to aggregate and form larger micron-sized particles. When aggregation occurs, the unique nano-scale material properties and the ability to control them is lost. Thus, a fundamental step in the preparation of NMs for research or commercial applications is the functionalisation of nanoparticle surfaces with functional groups that stabilize particles in suspension or otherwise tailor particle characteristics for specific purposes. Several examples of this include hydroxylation of the surfaces of fullerenes for increased solubility or silica coating of colloids to reduce aggregation in suspension. Such processes require additional reagents, handling procedures, and means of disposal for spent materials beyond those necessary for the initial production of the particles.

23. Surface functionalisation is a critical step for exploiting emerging commercial applications of nano-scale materials. Such methods afford 'tuneable' solubility and other important behavioural characteristics necessary for certain applications, such as in the pharmaceutical industry, and the preparation of certain nanocomposite materials. Various functionalities are being applied to the

surfaces of many different types of NMs, particularly fullerenes and nanotubes. Early applications of such functionalised materials have included targeted drug delivery and medical imaging.

4. Products and applications of nanotechnologies in the UK

4.1 Industrial production and use

24. The full list of companies identified in the review can be accessed through the electronic database that was developed for the project (see section 6). Summary information about significant companies has also been provided below and in Table 4.

Company	Location	Materials	Applications	Comments
JR Nanotech Plc	London	Silver, copper, aluminium, zinc, tungsten, molybdenum, cobalt	Healthcare, hospital wards and operating theatres, apparels, wound dressing, personal hygiene, medical devices and implants, occupational contact dermatitis, preservation, environmental, food packaging, and cosmetics	NM manufacture, NM processing and applications
Liquids Research Ltd	Bangor	Ferrofluids and other magnetic composite materials based on ferrite and metal particles, nano iron oxides coated with biocompatible materials	Heat dissipater in loudspeaker systems, for sealing systems, in printing and in sink-float separation systems	NM manufacture and R&D
Metal Nanopowders Ltd.	Birmingham	Nanopowders (aluminium, magnesium, iron, nickel, copper, zinc, zinc oxide, Titanium, Titanium Nitride,, titanium dioxide, tin nitride)	Catalysts & hydrogen storage, solid rocket fuel, conducting paste, magnetic tapes & fluid, targeted drug delivery, metallic paint, sintering/sintering aids	NM manufacture (small-scale), NM R&D, spin off company from the University of Birmingham
Nanoco Technologies	Manchester	Nanoparticles and quantum dots, CdS, CdSe-ZnS, metal oxide and precious metals, cadmium selenide and cadmium selenide particles coated with zinc sulphide or cadmium sulphide, NanoDot™ labelled polymer beads	Security/authentication, life science and electronic applications. Anti-counterfeiting tags (CD's, packaging, fabric, documents, currency), LEDs, displays, photovoltaic, lighting, solar cell concentrators, diagnostics, high through put biological screening, luminescent dyes in microscopy, real time monitoring of biological systems	NM manufacture (small-scale), spin off company from the University of Manchester
Nanomagnetics, Ltd.	Bristol	Magnetic media for manufacturing of tape and discs for magnetic recording, magnetic particles grown inside uniform hollow protein spheres, magnetic particles (DataInkTM),	Water purification, high density magnetic recording, and medical imaging and diagnostic agents	NM manufacture (testing quantities), design and manufacture of Magnetoferritin and DataInk™

		magnetite, cobalt-platinum alloy		
Nanotecture Ltd	Southampton	Nanoporous metals and metal oxides, metals (e.g. Pt, Pd, Ni, Sn and Co) and metal oxides (e.g. TiO_2, WO_3 and MnO_2), nanostructures (e.g. nanoporous titania, 7-12 nm pore diameter)	Applications in power sources, sensors and filtration (supercapacitors, high performance battery materials, gas sensors, and molecular filters for sensing, measurement and purification)	NM manufacture, NM applications, spin out company of University of Southampton
Oxonica, Ltd.	Yarnton	Semiconductor quantum dots, cadmium selenide, CdS, cadmium sulphide gold. Nanocatalyst (Envirox) for diesel fuels, TIO_2 or zinc oxide based photostable UV absorber (Optisol)	Nanocatalysis for diesel fuel, life sciences, environmental sciences, IT and telecommunications, pigments /printing, polymers, ceramics and cosmetics. Cerium oxide based diesel fuel catalyst (Envirox™). Stagecoach New Zealand have adopted Envirox™ across its entire bus fleet. Manganese doped titanium dioxide based UV-absorber and free radical scavenger (Optisol™). Boots are the first to incorporate Optisol™ in their own-brand sunscreen products. Conducting films: ZnO, Al, NiO, $CuCrO_2$ for opto-electronic and thin film devices. Fluorescent tags and security markings	NM processing/ applications, University of Oxford spinout. One of UK's leading suppliers of nanodots, Collaborating with evident technologies USA in the manufacture and distribution of Evidots.
Thomas Swan & Co. Ltd.	Consett County Durham	Carbon nanotubes, single-wall and multi-wall carbon nanotubes (Elicarb®)	Polymer composites (conductive and structural filler), electromagnetic shielding, electron field emitters (flat panel displays), super capacitors, batteries, hydrogen storage, nanoprobes, structural nanocomposites	NM manufacture, UK's leading commercial producer of carbon nanotubes, certified as approved carbon nanotube supplier, collaboration with Cambridge University (Department of Materials Science), capabilities for functionalisation of nanotubes, scalable industrial level production facilities, commercial scale carob nanotube manufacturing, gram to kilogram quantities
QinetiQ Nanomaterials Limited	Farnborough	Nanopowders (metal and metal oxide), aluminium, copper, cobalt, zinc, silver, tungsten carbide, molydenum, zinc oxide, copper oxide, seruim oxide, titanium oxide, zirconia, yttria. Potential for producing nitrides and carbides and	Paint, textiles, printing, automotive, electronics, petroleum and defense	NM manufacture, nanometric powders in sample and bulk quantities for a wide range of established and new applications in industries as diverse as paint, textiles, printing, automotive, electronics, petroleum and defense, collaborating with Tetronics. Plasma synthesis techniques to produce commercial

		alloys		quantities of metal and metal oxide nanoparticles. Claimed to be UK's first production facility dedicated to the volume production of specialist nanomaterials. Two production rigs are capable of producing up to several kg of nanomaterials per hour.
DA NanoMaterials	Wrexham	Colloidal silica based nanoslurry, silicon dioxide films, colloidal silica slurry, Cu and barrier DCmP, tungsten DCmP	Integrated circuits	NM manufacture, NM applications, joint venture between DuPont (colloidal silica solutions manufacturing) and air product (particles for electronics applications)
Pilkington plc	St Helens, Merseyside	Titanium oxide coatings (self cleaning float glass (Pilkington Activ TM glass))	15nm coating of microcrystalline titanium oxide which reacts to daylight and breaks down any grime which is removed when in contact with water	NM processing, NM applications
Tetronics, Ltd.	Faringdon	DC plasma arc systems for production of nanopowders (metals, metal oxides), nanometric colloidal aluminium, micro to nano-sized powders (metals, alloys, oxides, nitrides, carbides, silicides)	NM R&D, NM manufacture (process)	NM manufacture, NM processing, NM R&D. developing processes for the production of nanometric and novel materials; e.g. nanopowders (can be produced in kg quantities)
Johnson Matthey Colours & Coatings Division	London	Nanopowders, platinum group metal products, catalysts, precious metals, fine chemicals	Colour and coatings	NM applications, NM R&D. Speciality chemicals company
Uniqema & ICI Technology	Redcar	TiO2 nanoparticles, formulation of nanoparticles in e-inks	Nanoemulsions for personal care products	NM manufacture, NM R&D
Unilever Research - Colworth (Bedfordshire)	Coleworth Ho, Bedfordshire	Nanoparticles (e.g. TiO2) and nanoemulsions, nanoparticle-stabilised emulsions as active agents in their personal care products	Personal care products	NM applications, NM R&D

Table 4. Uses and applications of nanomaterials in the UK

4.1.1 DA NanoMaterials

25. DA NanoMaterials (http://www.nanoslurry.com/index_flash.htm) was formed in 2000 as a joint venture to combine DuPont's expertise in developing and manufacturing colloidal silica sols and

particles for electronics applications with Air Product's extensive manufacturing infrastructure. The company's main manufacturing plant is in Wales. The principle products are polishing slurry for use in the Chemical Mechanical Planarization (CMP) process for silicon dioxide films used in integrated circuits. NM products include:

- Syton® OX-K Colloidal Silica Slurry, is a potassium-stabilized product with a nominal particle size of 40 nm;
- Cu and Barrier DCmP for 130 nm to 45 nm; and
- Tungsten DCmP down to 45 nm.

4.1.2 Johnson Matthey

26. Johnson Matthey (http://www.matthey.com/index.htm) is a speciality chemicals company with core skills in catalysts, precious metals and fine chemicals. The group's principal activities are the manufacture of autocatalysts and pollution control systems, catalysts and components for fuel cells, pharmaceutical compounds, process catalysts and fine chemicals; the refining, fabrication and marketing of precious metals; and the manufacture of colours and coatings for the glass and ceramics industries.

27. Colour and Coatings Division: manufacture of colours and surface coatings for a wide range of industries. Various UK facilities.

28. Precious metals division: produce wide range of platinum group metal products. Also developed proprietary technology for coating platinum group metals on a wide range of substrates. Platinum fabrication facilities are in Royston.

4.1.3 Liquids Research Ltd

29. Described as Europe's leading manufacturer of magnetic colloids, Liquids Research Ltd (www.liquidsresearch.com) manufacture and supply two main group of products that contain nanoparticles. These are ferrofluids and coated nanoparticles. Ferrofluids consist of very small magnetic particles held in suspension in a carrier liquid by a surface active layer. Liquids Research offers a wide range of ferrofluids in which the magnetic particles are one of a variety of ferrites or transition metals, such as iron and cobalt. The mean particle diameter (5 to 13 nm) can be tailored to meet customer requirements. Named applications for ferrofluids include as a heat dissipater in loudspeaker systems, for sealing systems, in printing and in sink-float separation systems. More details can be found on their website. These materials have been known since 1965 and have been supplied by the company since 1990.

30. A second, related group of products are coated nanoparticles, typically iron oxides coated with a range of biocompatible materials including antibodies, albumin and RGD Tripeptide. Customised particles for specific applications can be prepared.

4.1.4 Metal Nanopowders Ltd

31. Metal Nanopowders (http://www.metalnanopowders.com) is a spin off company from the University of Birmingham. They produce a range of nanopowders including aluminium, magnesium, iron, nickel, copper, zinc, zinc oxide, titanium dioxide and tin nitride with "exceptional" purity using a patented gas phase process. This involves evaporation of bulk or granular materials by an arc discharge method followed buy rapid cooling. Currently the company provides small scale manufacturing on a request basis although they claim that their process may be easily scaled up to large batch production. The company also offers bespoke services to clients to develop nanopowders on a design basis.

4.1.5 Nanoco Technologies

32. Nanco's (www.nanoco.biz) main activities include production of nanoparticles and quantum dots for security/authentication, life science and electronic applications. Batches of cadmium selenide and cadmium selenide particles coated with zinc sulphide or cadmium sulphide, sized to customers' required specifications. NanoDots supplied either as dry powders, dissolved in clear solvent solutions or suspended in waxy solids to enhance stability for long-term storage.

33. Nanco has a unique, patented single source precursor ('one pot') manufacturing process. Nanco owns E.U and U.S. patents protecting the company's proprietary method for the design and syntheses of mono-dispersed customised nanoparticles including compound semiconductor 'quantum dots', metal oxide and precious metals.

4.1.6 NanoMagnetics Ltd

34. NanoMagnetics (www.nanomagnetics.com) designs and manufacturers advanced magnetic particles (called DataInk™) for the magnetic media manufacturing industry. They produce a powder that the media manufacturers mix with a resin and coat flexible substrates to make tape and discs for magnetic recording.

4.1.7 Oxonica

35. Oxonica (www.oxonica.com) is one of the UK's leading suppliers of nanodots. Oxonica specialises in 'wet chemistry' routes to NMs employing traditional colloidal chemistry and organometallic processes (Green *et al.,* 2002). They have expertise in growing semiconductor quantum dots, specifically materials, such as cadmium selenide, CdS, as well as metals such as cadmium sulphide gold. Their process controls the surface and reaction routes to generate specific sized materials, which are soluble in specific solvents.

36. Oxonica's technology is protected by intellectual property and there are currently 22 filed patent details, available on its website. The technology has direct applicability to a number of markets where dispersion and/or manipulation of optical properties are important. These include catalysis, life sciences, environmental sciences, IT and telecommunications, pigments/printing, polymers, ceramics and cosmetics. Currently the company has three main nanoparticle products. Envirox is a novel nanocatalyst technology for diesel fuels. It is based on an oxidation catalyst widely recognised as a combustion improver and used for emissions control. It has been re-engineered to allow it to be used as a fuel-borne catalyst leading to a cleaner, more complete burn within the combustion chamber. This results in significantly improved fuel efficiency, reduced carbon deposits in the engine, and lower emissions. No engine modifications are required to use the product, it has no impact on lubricant performance, and the dose rate is low.

37. Oxonica's patented process modifies the structure of the titanium dioxide or zinc oxide to create Optisol, an extremely photostable UV absorber that works without the concurrent formation of free radicals, highly reactive chemical species which are implicated in skin ageing and cell damage.

38. In addition, Oxonica is co-operating with the US-based nanotechnology company Evident Technologies in the manufacture and distribution of Evidots. Evident are one of the only organisations commercially manufacturing a range of quantum dot materials - precision semiconductor nanocrystals. By manipulating the size of the particles it is possible to engineer their wavelength, absorption resonance and the semi-conductor band gap.

39. Oxonica offers a range of novel nanocrystalline luminescent materials. These materials have been engineered to emit in a very narrow wavelength range, giving clear, clean colours. Oxonica is

able to manipulate the particles to achieve different colours with no requirement to control the particle size. The materials are based on non-toxic inorganic compounds and are therefore highly stable. There are many applications for these products including fluorescent labelling, covert marking, flat panel displays and solid state lighting.

4.1.8 QinetiQ Nanomaterials Ltd

40. QinetiQ Nanomaterials Ltd (www.nano.qinetiq.com) working in conjunction with Tetronics (http://www.tetronics.com) have developed plasma synthesis techniques which can produce commercial quantities of metal and metal oxide nanoparticles. Their site is described as the UK's first production facility dedicated to the volume production of specialist NMs. The company has two production rigs, which are capable of producing up to several kilograms of NMs per hour.

41. In the QinetiQ process, precursor materials are fed into a high-temperature plasma (typically in the temperature range of 4,000-9,000°C). The feed stock material is vaporised on contact with the plasma and is carried away from the hot zone on a gas stream. The vapour is rapidly quenched which causes the material to be condensed and solidified to form nanometre size powder particles. These are carried through to a collection system, based on a bag filtration system. After synthesis the bag filter system is reverse pulsed and the form of material is collected into a hopper. The process is capable of producing dry powders in bulk quantities to a consistent quality and can produce metals to a high purity. Pure metals, passivated metals (metals with a thin oxide layer), oxides, nitrides and other alloys can be produced using this method. Processing conditions can be varied to control particle size, size distribution and composition. Materials that have been produced include alumina, zirconia, yttria, zinc oxide, seruim oxide and titanium oxide. A range of other materials including nitride and carbides can be formed.

42. Typically these are described as loosely aggregated nanometre particles. The primary particle size is 100 +/- 50 nm. Depending on the details of the process used, the primary particles may be almost spherical or of more irregular shape. The size of the aggregates is typically described as from 5-200 microns.

4.1.9 Tetronics Ltd

43. Tetronics (www.tetronics.com) has a wide range of technologies for the production and processing of powders in general and for nanopowder production specifically. Manufacturing processes are based on DC Plasma arc technology. Tetronics have developed a range of techniques for the production of NMs based around single plasma torches, graphite electrode systems or Tetronics unique Twin Torch process.

44. Processes have been used to produce particles with average particle size between 10 - 60 nm and specific surface area between 15 - 40 m^2g. Examples of nano and novel materials produced, include zinc oxide, aluminium nitride, silicon nitride, silicon carbide, mixtures of silicon carbide and silicon nitride, magnesia, alumina, zirconia, titania, zirconium silicate, calcium chloride, and carbon black.

4.1.10 Thomas Swan & Co. Ltd

45. Thomas Swan and Co (www.thomas-swan.co.uk) is the leading commercial producer of carbon nanotubes (CNT) in the UK. Their new facility has been developed in collaboration with Cambridge University (Department of Materials Science) and is described as the UK's first commercial manufacturing process for high purity single wall CNTs. The plant uses an injection chemical vapour deposition process. In this process, precursors are injected into a two stage furnace and the nanotubes are grown in quartz substrates. After synthesis they are removed by mechanical means under controlled conditions.

46. The main commercial product is Elicarb™SW, described as purified single wall CNTs with an average diameter of less than 2 nm and an average length in the micro-metre range. It is formulated as a dry powder and is advertised as being available in packs of 1 gram up to 1 kilogram at a price of around £200 per gram. Other Elicarb™ products including multiwalled CNTs are available or will be available in due course. The company also offers to produce CNTs tailored to client's specific requirements.

4.2 Nanomaterial research in UK universities

47. In total, 55 research establishments were identified in the review as actively researching NMs. In order to draw together expertise from a range of disciplines, a number of establishments (including Cambridge University, University of Sheffield, University of Birmingham, University College London, Newcastle University, University of Bristol and Imperial College) have also established cross-departmental (or cross University) centres in the nanotechnology area.

48. The institutions are researching a wide range of material types (including metallic and carbonaceous nanomaterials) (Table 5). A wide range of applications are being explored with prime areas of research including gas/fuel storage, semiconductors, catalysis, sensor technology and nanomedicine.

Materials
Nanomagetic materials, nanorods, nanotubes, metal nanowires, metal nanoparticles, diamond nanoparticles, carbon nanotubes, nanofibres, fullerenes, Si nanowires, filled carbon nanotubes, boron nanomaterials quantum dots, colloidal nanoparticles, InSb quantum dots, InAsSb quantum dots, Fe nanoclusters, Co nanoclusters, Ni nanoclusters, metal oxides, clay/polymer nanocomposites, graphite/polymer nanocomposites, TiOH nanospheres, pigment nanoparticles, SnO_2 nanocystals.
Applications
LEDs, gas absorbents, fuel storage, superconducting technology, electroceramics, marine biofouling, smart pipes, catalysis, drug delivery, imaging applications, sensors, plastic processing, conducting plastics, lab-on-a-chip, spray systems, nanopipettes, gene therapy, diagnostics, vaccine carriers, molecular sieves, solar cells, emulsion stabilisation, bone tissue scaffolds, magnetic recording, environmental clean up, defence, fire retardants, sunscreens, fuel additives, pottery, optics, batteries, nanopower generators, ceramics.

Table 5. Materials researched by academic institutions

5.0 The products and applications of nanotechnologies: a worldwide perspective

5.1 Global manufacturers

49. The review focused on sampling key global manufacturers, both large and small, that are presently distributing to consumers, diverse types of NMs (in free form), for a wide range of end-use applications. In this effort, the review team recognised that, given the present maturity level of the nanotechnology industry, most NMs, particularly those with new or otherwise distinctly different material properties, are being applied primarily in limited quantities in academic, government, and industrial research laboratories.

50. Of the definitive NMs that are presently being applied in commercial applications, the nano-scale metal oxides (e.g., TiO_2, iron and aluminium oxides, etc.), various nano-scale polymers, and polymeric nano-composite materials are those being manufactured and applied in the greatest quantities (i.e., kilograms to multiple tons). However, rapid scale-up of fullerene production also has

been reported. Mitsubishi Corporation opened a large-scale fullerene production plant in Japan (Frontier Carbon Corporation), which uses a combustion-based process that, according to a recent press release, will increase production of fullerenes from 4 to 40 tons/year. This claim has neither been verified nor is it presently clear where such vast quantities of these fullerenes will be applied, given the current limited nature of commercial markets for them. A new process called HIPCO (high-pressure carbon monoxide) has been developed for multi-kilogram-scale production of single-walled carbon nanotubes, and has been licensed to a US based company, Carbon Nanotechnologies Inc.

51. While the worldwide NM manufacturing landscape is presently inundated with small technology start-up companies, large volume manufacturing of high-quality NMs will most likely occur at larger multinational companies such as DuPont, BASF, or Mitsubishi Chemical (Forbes/ Wolfe, 2004).

5.2 Situating the UK in the global context

52. Figure 2 shows the global distribution of nanotechnology companies. It can be seen that the nanotechnology industry is dominated by US companies (49%), followed by Europe (21%) and rest of the world (21%). UK NM industry only makes around 9% of the global nanotechnology sector. In view of the huge number of emerging new materials and applications, this situation is likely to change in the near future.

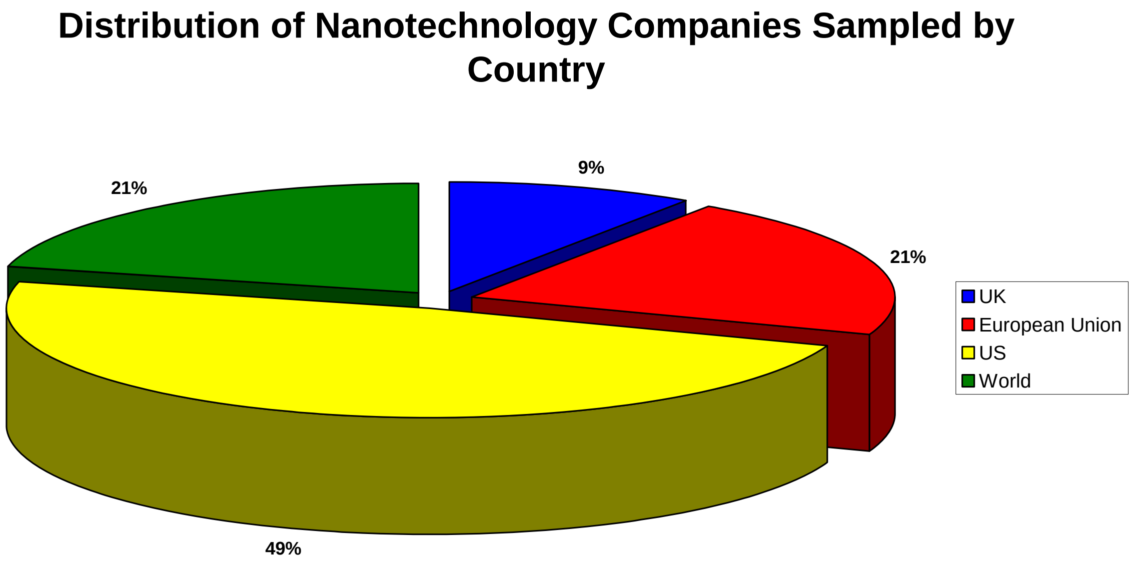

Figure 2. Distribution of nanotechnology companies

53. Figure 3 shows the distribution of the NMs manufacturers according to the general type of NM products they produce. These products are free NMs, prior to blending or integration into secondary products. From this figure, it is clear that the global focus, at least in terms of the number of different manufacturers, is in fullerenes, nanotubes and fibres, and nanoscale metals. The average global distribution of companies is skewed by the large number and diverse nature of US manufacturing companies. NM manufacturing in the UK, on the other hand, does not reflect the global emphasis on fullerenes, nanotubes and fibres. Rather, the emphasis is weighted heavily towards production of nanoscale metals and metal oxides (i.e., >50% of NMs manufacturers in the UK produce nanoscale metals).

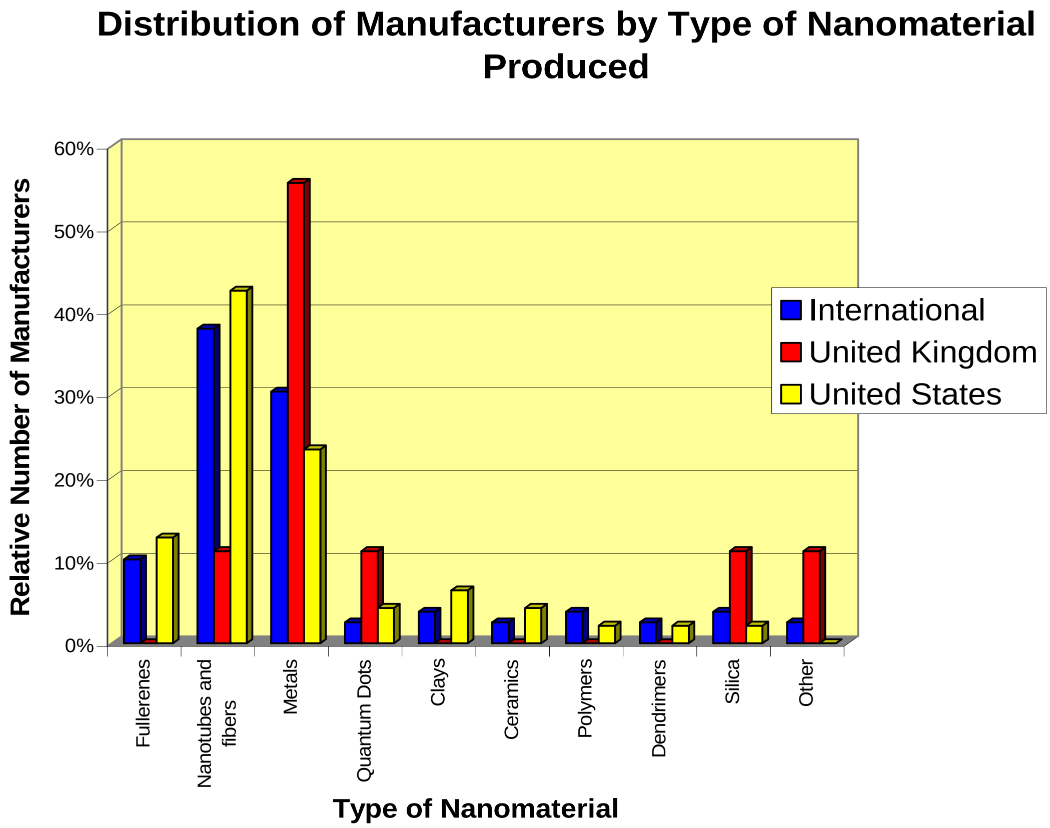

Figure 3. Distribution of NMs manufactures globally, in the UK, and in the US, according to type of NM manufactured

5.3 Future applications

54. Currently, it is difficult to predict accurately the specific long-term research and development trends of the nanotechnology industry. What is clear, however, is that since R&D is intrinsically reliant on access to the materials of interest, near and long-term R&D trends, and ultimately successful commercial applications, will favour those NMs that can be produced in large quantities - i.e., it is difficult to research or develop new applications for materials that are not readily accessible. For example, one of the most broadly applied NMs, titanium dioxide, which is used in numerous commercial products from sunscreens to paints, can be readily manufactured on a large-scale. Conversely, carbon nanotubes, which are more difficult to manufacture (and even more difficult to replicate from batch to batch or from one manufacturer to another) have not yet encountered such commercial success, though their commercial potential is enormous. In fact, only in recent years have scientists managed to keep nanotubes from aggregating into clumps in aqueous suspension - a tendency that also has obstructed the utility of many other NMs in commercial applications (www.nanoelectronicsplanet.com). Thus, near-term R&D trends will focus on optimising and refining manufacturing processes for NMs of presently limited production capability.

55. Manufacturing processes used to fabricate some NMs have matured more rapidly than for other nanoscale materials. Figure 4 comparatively illustrates the maturity of manufacturing processes for several major classes of NMs. In general, manufacturing of nano-scale metals, polymers, silica, clays, and ceramics involves relatively mature processes capable of generating large quantities of materials.

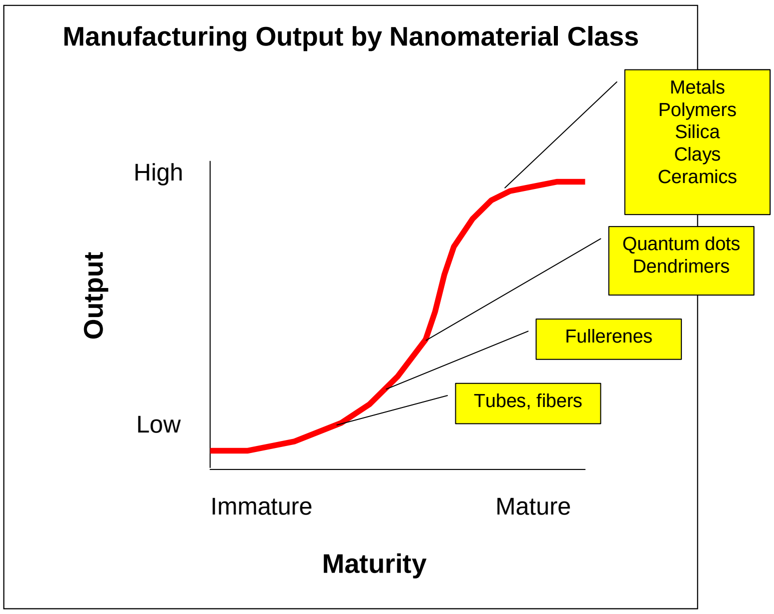

Figure 4. Maturity of manufacturing processes for several major classes of NMs. Availability of materials ultimately will influence the direction of R&D trends. Currently, some materials are more readily manufactured than others

56. The R&D trends in nanotechnology are likely to focus on applications of NMs to social priority areas tied to large-value commercial or public sector markets such as human health, defence, and the availability of clean water. Nevertheless, availability of materials, funding, social priorities and market value are all factors that ultimately will work together to dictate direction of near and long-term R&D worldwide.

57. Recognising that future trends are reliant on the interaction of many complex factors that are difficult to predict, particularly for such an immature and evolving industry, more near term nanotechnology R&D trends have clearly emerged in areas such as human health, defence, energy, agriculture, and environment. These primary areas represent the intersection of several important variables including high market value, high social priority, and availability of relevant materials. Several key current nanotechnology R&D areas are summarised below:

- **Human Health:** drug delivery, imaging, cancer therapeutics
- **Defence:** energetic materials, lightweight armour composites
- **Energy:** hydrogen storage, improved efficiency, catalysis
- **Agriculture:** increased crop yields, secure packaging, chem./bio detection
- **Environment:** water filtration, reduced air emissions, remediation

58. One of the most active current trends of the nanotechnology industry is the application of NMs in chemical and biological sensing, due to the high reactivity, good selectivity, small size and high specific surface area (Shi *et al.,* 2004). This research has included the use of various nano-scale materials ranging from semi-conducting single-walled carbon nanotubes for electrochemical sensing (Collins *et al.,* 2000) to quantum dot-based fluorescent probes for optical sensing (Murphy, 2002). The near-term intensity of participation in this research space has been fuelled by the fact that only relatively small quantities (milligram to gram) of materials are required to explore many sensing applications. More importantly, however, national governments have provided enormous financial resources to develop advanced, nanotechnology-enabled sensing instrumentation to aid the global war on terror.

59. Some analysts have suggested that within the next 10-20 years, the best opportunities for broad scale application of NMs would be in health care and electronics (Figure 5). However, the energy generation and storage sector is also expected to have a more near-term impact in the commercial marketplace within three years (http://www.batteriesdigest.com/id391.htm).

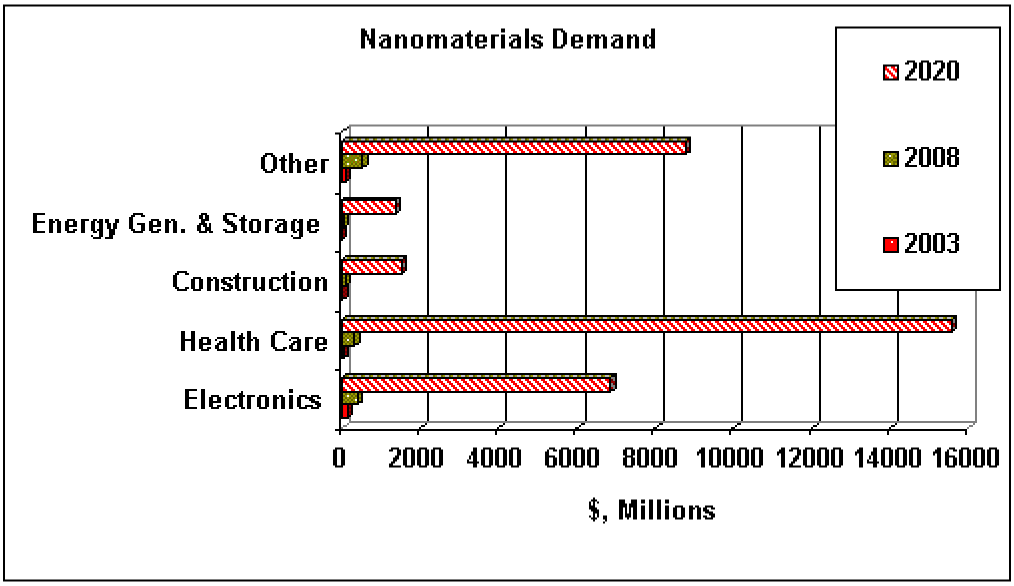

Figure 5. Estimated distribution of NM applications within 10-20 years

6. Development of NM database

60. The data and information generated by the review was used to develop a web-enabled database. The design of the database facilitates simple and straightforward querying of the data in a manner entirely intuitive to the user using a variety of search combinations, including spatial references. To ensure that the database is a sustainable investment for the long-term, its design has built-in flexibility with capacity for upgrades and improvements to accommodate future developments. With stakeholders agreement, the database will be maintained on CSL website, and regularly updated with new information as and when it becomes available. The database is likely to provide a resource for identification of future data needs, and regulatory frameworks to identify gaps in knowledge and needs for further research.

7. Conclusions and recommendations for future research

61. Regulatory agencies can take important first steps to improve our ability to characterise the nature of the emerging NMs manufacturing industry. Extensive global nanotechnology databases can be found on the web that can provide invaluable sources of information for the conduct of landscaping research as well as facilitate collaboration among researchers, manufacturers, business development personnel, and consumers/end-users. Some particularly valuable sites found during the conduct of this research included http://www.nanoinvestornews.com/, www.nanoforum.org and www.nano.org.uk. Despite the utility of these sites, however, the most important and useful information for a research effort of this kind can only be found under confidentiality with both producers and end-users of NMs. Thus, regulatory involvement will likely be necessary to obtain this information. It is strongly recommended that a register of NMs manufactured, processed, imported, or used in the UK be maintained, either through a voluntary industry initiative, or centrally by Government. This will enable access to up-to-date information on new materials and applications, until more scientific data on the safety of NMs, in terms of their effects on human health and the environment, becomes available. The web-enabled database developed as part of this project may act as a central depository for such information, with any commercially sensitive information only made accessible to relevant regulators. In addition, as appropriate, producers may be required to provide precautionary safety labelling, specifically tailored for nano- rather than bulk-scale particles. Regulators might also request information of a similar nature from end-users, with an additional requirement for describing in a general sense,

how the materials are being applied. Without this level of information, it will be difficult to more precisely gauge the nature of the NMs manufacturing or applications in the UK or elsewhere.

62. The outcome of this study has shown that UK NM manufacturing industry is currently very much in the formation. In anticipation of the emerging new NMs and applications, it is likely that this situation will change in the coming years. It is, therefore, necessary that further reviews of the situation are carried out periodically for at least 3 to 5 years, and the database is updated with new information as and when it becomes available.

63. General trends were evident from our assessment of the worldwide and UK-based NMs manufacturing industry. Globally, there appears to be a focus (at least in terms of the number of different manufacturers) on the production of nanotubes and fibres, fullerenes, and nanoscale metals. This is the likely result of a number of independent and at times interacting factors ranging from high-value end markets, mature manufacturing processes (e.g., for metals), or the lack of a dominant manufacturing player (particularly for nanotubes). The UK NMs manufacturing industry deviates from the global trend, however, in that it appears that there are no fullerene manufacturers based in the UK. This has obvious implications either for the significant import of these materials into the UK or the small-scale synthesis of these materials in UK research laboratories. Conversely, nanoscale metals clearly dominate the UK NMs manufacturing landscape, comprising more than 50% of the companies sampled. Unlike the UK NMs manufacturing industry, UK research institutions are actively pursuing a diverse array of research applications involving virtually all major classes of NMs. Collectively, these results have significant implications not only with respect to NMs import/export in the UK, but also with respect to global competitiveness of the UK NMs manufacturing industry. Further research should be undertaken to verify the nature of the UK manufacturing industry, to monitor new developments in this field, and to justify gaps in the manufacture of certain classes of nanoscale materials.

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9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

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