Current and Future Applications of Nanotechnology

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1 Introduction

1.1 History

Physicist Richard P. Feynman first described the concept of nanoscience in 1959 in a lecture to the American Physical Society and the term nanotechnology was coined in 1974 by the Japanese researcher Norio Taniguchi[1] to describe precision engineering with tolerances of a micron or less. In the mid 1980s, Eric Drexler brought nanotechnology into the public domain with his book *Engines of Creation*.[2]

1.2 Definitions

As part of a major report commissioned by the UK Government from the Royal Society and the Royal Academy of Engineering in the UK, entitled "Nanoscience and nanotechnologies: opportunities and uncertainties",[3] the following definitions were used:

Nanoscience is the study of phenomena and manipulation of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale.

Nanotechnologies are the design, characterisation, production and application of structures, devices and systems by controlling shape and size at nanometre scale.

The NASA website provides an interesting definition of nanotechnology: "The creation of functional materials, devices and systems through control of matter on the nanometre scale (1–100 nm) and exploitation of novel phenomena and properties (physical, chemical, biological) at that length scale."[4]

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The Oxford English Dictionary defines nanotechnology as "technology on an atomic scale, concerned with dimensions of less than 100 nanometres".

The prefix *nano*- derives from the Greek word for dwarf and one nanometre is equal to one billionth of a metre *i.e.* 10^{-9} m. Nanomaterials are therefore regarded as those that have at least one dimension of size less than 100 nm.

1.3 Investment

Nanotechnology has received very significant investment over the past ten years with national governments providing the bulk of this investment with estimates ranging as high as $18 billion for investment between 1997 and 2005.[5] There has recently been a four-way split with similar investment in each of USA, Europe, Japan and the rest of the world with approximately $3 billion spent by governments in 2003 alone.[6] In the USA, for example, the National Nanotechnology Initiative (NNI) is a federal R&D program to coordinate the multi-agency efforts in nanoscale science, engineering and technology.

The President's 2007 budget provides over $1.2 billion for the Initiative, bringing the total investment since the NNI was established in 2001 to over $6.5 billion and nearly tripling the annual investment of the first year of the Initiative.[7] With this investment has come a large number of products, some of which are already on the market, that are based on nanotechnology or contain nanomaterials.

2 Technology

2.1 Nanomaterials

There had already been exploitation of products of particle size falling within the definition of a nanomaterial prior to these developments, but the products were simply referred to as ultrafine or superfine. These products, mainly comprising metal or metalloid oxides and carbon blacks, were primarily additives for the plastics industry in its various guises and these will be considered in some detail as they comprise the greatest body of current applications of nanotechnology. Alongside these products that have considerable sales value are many novel products, which are currently available from a range of new companies and generally started from work originating from research studies in a university. Applications of these products are wide and again these will be considered.

Nanomaterials can be considered under the following three headings:

(i) Natural
(ii) Anthropogenic (adventitious)
(iii) Engineered

Natural nanomaterials comprise those created independently of man and include a wide range of materials that contain a nanocomponent and may be found in the atmosphere such as sea salt resulting from the evaporation of water from sea spray, soil dust, volcanic dust, sulfates from biogenic gases, organics from biogenic gases and nitrates from NO_x. The actual content of any one or a combination of these nanomaterials in the atmosphere is dependent on geography.

Anthropogenic (adventitious) nanomaterials are those created as a result of action by man with the main example of this type of nanomaterial being soot resulting from the combustion of fossil fuels. Other anthropogenic nanomaterials include welding fume and particulates resulting from the oxidation of gases such as sulfates and nitrates.

These two types of nanomaterials comprise many examples, some of which have been studied in great depth especially to minimise damage to health from exposure to these materials.

The subject of this paper falls largely in the third category, *i.e.* engineered nanomaterials, which have been designed and manufactured by man. These have been synthesised for a specific purpose and may be found in one of several different shapes. As defined above, the term nano describes the size in at least one dimension so nanomaterials may have nano characteristics in one, two or three dimensions. These correspond to platelet-like, wire-like and spheroidal structures respectively. The engineered nanomaterials may be further subdivided into organic and inorganic types, with the former including carbon itself and polymeric structures with specific nano characteristics. Inorganics include metals, metal and metalloid oxides, clays and a specific subset of compounds known as quantum dots.

2.2 Manufacturing Processes

Nanoparticles can be produced by a variety of methods. These include combustion synthesis, plasma synthesis, wet-phase processing, chemical precipitation, sol-gel processing, mechanical processing, mechanicochemical synthesis, high-energy ball-milling, chemical vapour deposition and laser ablation.

2.3 Product Characteristics

In summary, the key characteristics of nanomaterials that define their potential applications include the following:

- High surface area
- High activity
- Catalytic surface
- Adsorbent
- Prone to agglomeration
- Range of chemistries
- Natural and synthetic
- Wide range of applications

3 Types of Nanomaterials

3.1 Carbon

3.1.1 Carbon Black. Carbon black accounts for the largest tonnage of engineered nanomaterial and carbon blacks are used in a wide variety of applications, including printing inks, toners, coatings, plastics, paper and building products. Dependent on the size and chemistry of the particles, carbon-black-containing plastics can be electrically conducting or insulating and have significant reinforcing characteristics.[8,9]

Carbon black is a very fine particulate form of elemental carbon and was first produced more than 2000 years ago by the ancient Chinese and Egyptians for use as a colourant.[10] Although carbon black is still valued today for its colouring attributes, it is primarily used to provide reinforcement and other properties, especially to rubber articles. All carbon black is produced either by incomplete combustion or thermal decomposition of a hydrocarbon feedstock.

Two important characteristics of carbon black are surface area, an indirect measure of particle size, and structure, a measure of the degree of particle aggregation or chaining. Surface areas of carbon blacks can range from *c.* 10 m^2 g^{-1}, for use as reinforcing fillers, up to *c.* 1100 m^2 g^{-1}, for use as electrically conductive fillers. Surface area and structure are dependent on the type of process to manufacture the carbon black and they define the performance of the carbon black in its application.

The mass production of carbon blacks started in the first half of the twentieth century in the wake of the expanding tyre industry. Carbon blacks were used as reinforcing fillers to optimise the physical properties of tyres and make them more durable. Even today the tyre industry uses at least 70% of the carbon blacks manufactured worldwide. The remainder finds use in a range of applications. Carbon blacks are now widely used for plastics masterbatch applications for use in conductive packaging, films, fibres, mouldings, pipes and semiconductive cable jackets. They are also used as toners for printers and in printing inks. Carbon blacks can provide pigmentation, conductivity and UV protection for a number of coating applications including marine, aerospace and industrial. In at least some of these applications the coating requires UV curing and specific formulations have to be employed to overcome the inherent UV protection given by the carbon black during this process.[11,12]

The global market for carbon blacks is forecast to rise 4% per year through 2008 to 9.6 million metric tonnes.[13] The smaller non-tyre segment will show strongest gains. This segment also commands the highest prices with applications such as conductive fillers showing greatest growth prospects. Applications for plastics containing conductive fillers include antistatic surfaces and coatings.

3.1.2 Graphite. One-dimensional carbon is classically graphite, which has sub-nano thickness layers and nano-size spacing between layers leading to use as a lubricant, where advantage can be taken of the ability of these layers to slide across one another reducing friction between two surfaces coated with this material. This spacing is being considered for use as a hydrogen store with potential application in hydrogen fuel cells. Mono-layer graphite, or graphene, has been demonstrated as having novel magnetic properties.

Graphene has a unique electronic structure and theory suggests that novel magnetic properties may be dependent on this structure. The graphene magnetic susceptibility is temperature dependent and increases with the amount of defects in the structure. Work has been done to confirm such novel properties although there has been no commercialisation of this property at present.[14]

Recent work has calculated that graphene spaced between 6 and 7 angstroms apart can store hydrogen at room temperature and moderate pressures. The amount of hydrogen stored comes close to a practical goal of 62 kg per cubic metre set by the US Department of Energy. Another advantage of this form of graphite is that the hydrogen gas can be released by moderate warming. The current challenge is to synthesise graphenes with the appropriate interplanar spacing for maximum hydrogen absorption. If this can be achieved then graphene could be a strong contender for practical hydrogen storage. It has been reported that "tuneable" graphite nanostructures could be created with different hydrogen storage properties by interposing space molecules between the graphite layers.[15,16] These spacers would have the added advantage of keeping out contaminants such as nitrogen and carbon monoxide, which can reduce hydrogen storage capacity.

3.1.3 Carbon Nanotubes. Carbon nanotubes are fullerene-related structures that consist of graphene cylinders closed at either end with caps containing pentagonal rings. They exhibit extraordinary strength and unique electrical properties and are efficient conductors of heat along their length. They exist in single-wall and multi-wall forms. They have been used as composite fibres in polymers and concrete to improve the mechanical, thermal and electrical properties of the bulk product. They have also been used as brushes for electrical motors. Inorganic variants have also been produced.

A nanotube is cylindrical with at least one end typically capped with a hemisphere of the buckyball structure. There are two main types of nanotube: single-wall nanotubes (SWNTs) and multi-wall nanotubes (MWNTs). Single-wall nanotubes have a diameter of *c.* 1 nm and a length that can be many thousands of times larger *i.e.* to the order of centimetres.[17] Single-wall nanotubes exhibit electric properties not shared by the multi-wall variants. They are therefore the most likely candidates for miniaturising electronics past the microelectromechanical scale that is currently the basis of modern electronics. The most basic building block of these systems is the electric wire and SWNTs can be excellent conductors.[18]

Carbon nanotubes are among the strongest materials known to man, in terms of both tensile strength and elastic modulus, and since carbon nanotubes have relatively low density, the strength to weight ratio is truly exceptional. They will bend to surprisingly large angles before they start to ripple and buckle and they finally develop kinks as well. These definitions are elastic, *i.e.* they all disappear completely when the load is removed.[19] They have already been used as composite fibres in polymers and concrete to improve the mechanical, thermal and electrical properties of the bulk product. Conductive carbon nanotubes have been used for several years in brushes for commercial electric motors. The carbon nanotubes permit reduced carbon in the brush.

Multi-wall nanotubes precisely nested within one another exhibit interesting properties whereby an inner nanotube may slide within its outer nanotube shell creating an atomically perfect linear or rotational bearing. This is one of the first true examples of molecular nanotechnology. Already this property has been utilised to create the world's smallest rotational motor and a rheostat. Future applications are likely to include conductive and high-strength composites, energy storage and energy conversion devices, sensors, field emission displays and radiation sources, hydrogen storage media, semiconductor devices, probes and interconnects.[20] Some of these are already products while others are in an early to advanced stage of development.[21]

3.1.4 Carbon "Buckyballs". Fullerenes are the classic three-dimensional carbon nanomaterials. They have a unique structure comprising 60 carbon atoms in the shape reminiscent of a geodesic dome and are often referred to as "Buckyballs" or "Buckminsterfullerene", after the American architect R. Buckminster Fuller who designed the geodesic dome with the same fundamental symmetry. These C_{60} molecules comprise the same combination of hexagonal and pentagonal rings, and the name therefore has seemed appropriate. These spherical molecules were discovered in 1985 and considerable work has gone into their study. However, potential applications have been limited and include catalysts, drug delivery systems, optical devices, chemical sensors and chemical separation devices. The molecule can absorb hydrogen with enhanced absorption when transition metals are bound to the buckyballs, leading to potential use in hydrogen storage.[22,23]

3.2 Inorganic Nanotubes

Combinations of elements that can form stable two-dimensional sheets can be considered suitable to produce inorganic nanotubes and a number of inorganic chemists have been focusing on such structures.[24] Although the investment devoted to inorganic nanotubes lags behind that of carbon nanotubes, a number of reviews suggest that inorganic nanotube research is increasing rapidly.[25–27] Examples include tungsten sulfide[28] and boron nitride,[29] which may find uses where their inertness and high durability and conductivity can be exploited. Tungsten sulfide and molybdenum sulfide may have attractive lubricating properties.

Tenne was the first to report the synthesis of inorganic nanotubes[28] and has suggested a list of possible technologies that could use the unique properties of inorganic nanotubes. These include bullet-proof materials, high-performance sporting goods, specialised chemical sensors, catalysts and rechargeable batteries. As examples, titanium dioxide nanotubes have been shown to have potential as a hydrogen sensor[30] and in water photolysis.[31]

3.3 Metals

The simplest inorganic nanomaterials are metallic with a wide range of metals already produced in nano form. These include aluminium, copper, nickel, cobalt, iron, silver and gold with a wide range of potential applications including land remediation, batteries and explosives. Metal nanoparticles have been prepared for some time, but several have found significant commercial application. These include aluminium, iron, cobalt and silver.

3.3.1 Aluminium. Aluminium nanoparticles have been used for their pyrophoric characteristics in explosives.[32] Aluminium is a highly reactive metal when produced as a nanopowder and when in formulations such as metastable intermolecular composites (MIC) reacts to produce a large amount of heat energy. Aluminium powder is air stable due to a thin oxide shell that forms during production and protects the inner core from further oxidation.

3.3.2 Iron. Nanoscale iron particles have large surface areas and high surface reactivity and research has shown[32,33] that these particles are very effective for the transformation and detoxification of a wide variety of contaminants, such as chlorinated solvents, organochloric pesticides and polychlorinated biphenyls. Thus they have been used for remediation of soil and groundwater, which contains such contaminants.

3.3.3 Cobalt. Cobalt nanoparticles exhibit magnetic behaviour,[34–37] which may find application in medical imaging.[38]

3.3.4 Silver. Silver nanoparticles, which demonstrate antimicrobial and antibacterial activity,[39,40] have been used in a number of applications including medical dressings and non-smelling socks![41]

3.3.5 General. Special shaped metal nanometals hold promise for the miniaturisation of electronics, optics and sensors[42] where, for example, studies have shown that the conductance of copper nanowires is determined by the absorption of organic molecules.[43] Electrochemical deposition of palladium nanostructured films has led to potential application as calorimetric gas sensors for combustible gases.[44] In the biological sciences, many applications for metal nanoparticles are being explored, including biosensors,[39] labels for cells and biomolecules[45] and cancer therapeutics.[46]

3.4 Metal Oxides

The largest group of inorganic nanomaterials comprises metal oxides with titanium dioxide, zinc oxide and silicon dioxide as the largest volume materials.

Copper oxide, cerium oxide, zirconium oxide, aluminium oxide and nickel oxide have also been produced commercially and are available in bulk.

This category comprises the largest number of different types of nanomaterials. Conducting an internet search for nanomaterial manufacturers generates many hits, with most of the companies identified offering a range of metal oxide nanomaterials. These may or may not be currently produced in significant commercial quantities, but the manufacturing technology is generally capable of producing such materials in large quantities.

3.4.1 Titanium Dioxide. Titanium dioxide is used as a pigment in many applications including paints and paper with mean particle sizes of the order of 300 nm and accounts for approximately 4 000 000 tonnes per year. However, the existing market for ultrafine or nano titanium dioxide is about 4000 tonnes per year. The market for this material, whose mean particle size is in the range 20–80 nm, exploits the inherent strong scattering power in the UV while transmitting visible wavelengths through the crystal. The material in which ultrafine titanium dioxide is incorporated thus appears virtually transparent. Classically, the particles are coated with alumina, silica or zirconia or a combination of these oxides to ensure effective dispersion. Applications include products where protection of the substrate to the damaging rays of UV light is important. These include sunscreens, wood coatings, printing inks, paper and plastics. Rutile is the preferred crystal form of titanium dioxide for these applications, although anatase has also been used and is commercially available.

Nano or ultrafine titanium dioxide is available from a number of major manufacturers including Degussa, Kemira and Sachtleben in Europe and from ISK and Tayca in Japan.

Modified forms of titanium dioxide have also found markets. Oxonica has developed and is selling a manganese-doped titanium dioxide that exhibits significantly enhanced UVA absorption and minimises the generation of free radicals resulting from the absorption of UV light by the titanium dioxide.[47–49] This product is already being used commercially in sunscreens and cosmetics and is being evaluated for applications in coatings and plastics.

Doping titanium dioxide with tungsten or molybdenum produces a material that has enhanced photoactivity and Millennium produces nanoparticulate products that have been used in applications including environmental and industrial catalysts.[50] Both these active doped titanium dioxides and undoped titanium dioxide have been used as photocatalysts. An increased rate in photocatalytic reaction is observed as the redox potential increases and the size decreases. Such additives can be used as a component in self-cleaning paints and plasters. Photocatalytic titanium dioxide can decompose organic substances when it absorbs light. One use has been in self-cleaning windows. Another is the "bathroom that cleans itself", where self-cleaning tiles treated with nanoparticulate titanium dioxide may be found. The titanium dioxide nanoparticles absorb light and microbes on the surface are destroyed. The removal of nitrogen oxides from the atmosphere using photoactive titanium dioxide[51] and removal of contaminants from water have also been reported.[52]

Nano titanium dioxide has also been used in solar cells as the active component for absorption of solar energy. The nanocrystalline titanium dioxide dye-sensitised solar cell was originally developed to overcome the problems experienced by conventional solar cell technology.[53–55]

3.4.2 Zinc Oxide. While titanium dioxide dominates the inorganic UV absorption market, ultrafine zinc oxide is used in similar applications although at smaller volumes. Products are on sale from among others BASF, Nanophase, Umicore and Advanced Nanoproducts. It is claimed that nano zinc oxide results in a more transparent coating than an equivalent coating containing nano titanium dioxide.[56] Doped variants of zinc oxide may also be produced, with Oxonica again exploring the potential for a manganese-doped material.

3.4.3 Aluminium Oxide. Nanoparticulate aluminium oxide has been produced in platelet form and has found use in cosmetics. The benefits are achieved through a uniform platelet morphology that provides superior transparency and soft focus properties.[57]

3.4.4 Silicon Dioxide. When Degussa chemist Harry Kloepfer invented a process to produce an extremely fine silicic acid in 1942, he had no idea that this would mark the first chapter in an extraordinary success story that is still continuing today.[58] Silicic acid, better known today as fumed silica and marketed under the name Aerosil by Degussa since 1943, is now produced in a large number of variants and sold to almost 100 countries worldwide, and other companies including Cabot Corporation also produce and supply their own version of the material. Kloepfer had originally developed the substance as an alternative to carbon blacks as a reinforcing filler for car tyres.

Fumed silica has a chain-like particle morphology. In liquids, the chains bond together via weak hydrogen bonds forming a three-dimensional network, trapping liquid and effectively increasing viscosity. The effect of the fumed silica can be negated by the application of a shear force, *e.g.* by mixing or spraying, allowing the liquid to flow and level out and permitting the escape of entrapped air. However, when the force is removed, the liquid will "thicken up". This property is called thixotropy and products exploiting this characteristic of fumed silica include non-drip paint. When added to powders, fumed silica aids flow and helps prevent caking so the product is also used with other fillers as additives in plastics where effective dispersion is key to performance. Such products include adhesives, coatings, cements and sealants. Fumed silica also finds use in cosmetics, pharmaceuticals, pesticides, inks, batteries and abrasives. The total market for fumed silica is in excess of 1 million tonnes per year.

3.4.5 Iron Oxide. Nano forms of iron oxide have found application in cosmetics and in catalysts, including catalysts for enhanced oxidation of diesel fuel and soot derived from diesel fuel either alone or in combination with cerium oxide. An example of this employs a combination of iron and cerium compounds that are oxidised to the oxides in the combustion chamber of diesel engines and when these oxides interact with soot in the diesel particulate filter the combustion of the soot is catalysed with the result that there is a shorter regeneration time for the filter.[59]

3.4.6 Cerium Oxide. Cerium oxide is a well-known oxidation catalyst and has been used in a variety of forms in a number of products. However, to exploit its catalytic activity most effectively, nanoparticulate cerium oxide has been used successfully as a catalyst for enhancing the combustion of diesel fuel to reduce emissions and reduce fuel consumption. A product called Envirox from Oxonica is based on nanoparticulate cerium oxide and the cerium oxide is delivered to the engine in the diesel fuel at a level of 5 ppm.[60]

3.5 Clays

Naturally occurring complex molecules such as clay can be treated to release nanometre scale platelet structures. These materials, with their ability to align to produce barrier layers, have been used in a number of applications where a gas barrier is required or where reinforcement is required in a single dimension. The essential nanoclay raw material is montmorillonite, a 2-to-1 layered smectite clay mineral with a platelet structure, and is based on magnesium aluminium silicate. Individual platelet thicknesses are just one nanometre, but surface dimensions are generally 300 to more than 600 nanometres, resulting in an unusually high aspect ratio. Naturally occurring montmorillonite is hydrophilic and, since polymers are generally hydrophobic, unmodified nanoclay disperses in polymers with great difficulty. Through clay surface modification, montmorillonite can be made hydrophobic and therefore compatible with conventional polymers.

Compatibilised nanoclays disperse readily in polymers including nylon, polyethylene, polypropylene, PVC and polystyrene. Applications exploit the platelet form of the nanoclay where the platelets align themselves improving barrier properties, increasing modulus and tensile properties and increasing flame retardancy. As an example of what can be achieved, nanocomposites containing nanoclays look attractive for moulded car parts as well as for electrical/electronic parts and appliance components. On the packaging side, nanocomposites can slow transmission of gases and moisture vapour through plastics by creating a "tortuous path" for gas molecules to thread their way among the obstructing platelets. Bottles and food packaging are not the only areas of interest.

Nanocomposites hold commercial benefits for reducing hydrocarbon emissions from hoses, seals and other fuel system components. Flame retardant properties of nanocomposites are of interest on many fronts. Reduced flammability of nanocomposites has been demonstrated for several different thermoplastics including polypropylene and polystyrene. One application that has novelty value is a new tennis ball produced by Wilson. This ball has a nanocomposite coating which it is reported "keeps it bouncing twice as long as a conventional one". This results from the reduction of gas transmission through the wall of the tennis ball.

3.6 Quantum Dots

A quantum dot is a semiconductor nanocrystal whose size is in the range 1–10 nm. The size of these particles results in new quantum phenomena that yield significant benefits. Material properties change dramatically at this scale because quantum effects arise from the confinement of electrons and holes in the material. Size changes other material properties such as the electrical and nonlinear optical properties of a material making them very different from those of the material's bulk form. If a dot is excited, the smaller the dot, the higher the energy and intensity of its emitted light. Hence these very small semiconducting quantum dots provide the potential for use in a number of new applications. The colour of the emitted light depends on the size of the dot: the larger the dot, the redder the light. As the dots become smaller, the emitted light becomes shorter in wavelength yielding emitted blue light.

Quantum dots may be metallic, for example gold, or chalcogenide based, *e.g.* cadmium selenide or sulfide. Given that a rainbow of colours is at least theoretically possible, dependent on the size and chemistry of quantum dots, a number of interesting applications are currently being developed. Light-emitting diodes of different colours have been produced, with white light production also possible using a combination of dots. Multi-colour lasers may be developed based on these particles.[61]

When coated with a suitable chemically active surface layer, quantum dots can be coupled to each other or to different inorganic or organic entities and thus serve as useful optical tags. The use of this characteristic of quantum dots is probably most evident in studies in biology and medicine.[62,63] The photoluminescence as defined by the combination of the size and chemistry of the quantum dot may be exploited in bioanalytical applications. Previously these applications have used organic dyes. However, the use of quantum dots may allow for high sensitivity multiplexed methods, due to their narrow and intense emission spectra. This is in contrast to organic fluorophores, which suffer from fast photobleaching and broad overlapping emission lines. This limits their application considerably.

To make quantum dots useful for such assays they need to be conjugated to biological molecules, which may then be reacted to an active species in the test. Applications include both *in vitro* and *in vivo* use. Specificity is one of the most critical criteria for measuring particular molecules and the characteristics of quantum dots lend themselves to addressing such problems.

3.7 Surface Enhanced Raman Spectroscopy

An alternative route to achieving the same specificity uses either gold or silver cores at a size of approximately 20 nm surrounded by a marker molecule such as a dye and further surrounded by a polymer or inorganic coating such as silica, which allows conjugation with appropriate biological molecules. This is Surface Enhanced Raman Spectroscopy, or SERS, and the Raman spectrum emitted from this combination in response to light stimulation is unique and offers a similar capability to determine active biological species, but a at a much lower concentration than with quantum dots. Products based on this technology are currently under development by Oxonica.[64]

3.8 Dendrimers

Although linear polymers may be considered to be of nanomeric dimensions, there is one specific group of polymers that is designed to exploit its nanomeric size and characteristics. These are dendrimers and they are large and complex molecules with very well-defined structures. They are almost perfectly monodisperse macromolecules with a regular and highly branched three-dimensional architecture. Dendrimers can act as biologically active carrier molecules in drug delivery, to which can be attached therapeutic agents. They can also be used as scavengers of metal ions, offering the potential for environmental clean-up operations.[65]

A dendrimer is a macromolecule which is characterised by its highly branched three-dimensional structure. The structure is always built up around a central multi-functional core molecule and this extremely regular structure contributes to its near-perfect spherical shape. Due to their size, *c*. 15 nm, and branching architecture with a relatively hollow core surrounded by a compact surface, dendrimer molecules could be utilised for sensing, catalysis or biochemical activity. They may also find application as light-harvesting antennae and as molecular amplifiers.[66] It has also been suggested that when drug molecules are attached to the periphery, the dendrimer can be used as an efficient drug-delivery platform. Studies have demonstrated potential application of dendrimers as gene carriers.[65]

4 Bio Applications

Nanotechnology provides the tools to measure and understand biosystems. Applications of nanotechnology to biotechnology, biomedicine and agriculture include biocompatible implants, manipulation of molecules within cells, biocompatible electronic devices and "smart" controlled release delivery of nutrients.[67–69] Nano-oncology offers promise in cancer treatment with the potential for delivery of anticancer drugs and the localised killing of cancerous and precancerous cells[70] or for more general drug delivery[71] with some potential for drug delivery across the blood–brain barrier.[72] Nanotubes have also been considered for delivery of active species or for separating and collecting active species, but this technology is still in its infancy.[73]

5 Nanocatalysts

Cerium oxide is only one example of a nanocatalyst. Many nanocatalysts derive their activity simply from the large increase in surface area associated with nanoparticles. The global market for nanocatalysts is projected to approach $5 billion in 2009.[74] Commercially, well-established nanocatalysts such as industrial enzymes, zeolites and transition metal nanocatalysts accounted for about 98% of global sales in 2003. Newer types such as transition metal oxides, metallocenes, asymmetric carbon nanotubes and others are expected to grow significantly through to 2009. The refining/petrochemical sector was the largest user in 2003 with over 38% of the market, followed by chemicals/pharmaceuticals, food processing and environmental remediation.

6 Nanotechnology Reports

6.1 Forbes/Wolfe Nanotech Reports

Forbes/Wolfe produce a monthly newsletter on nanotechnology called Nanotech Report and at the end of each year report on the top 10 nanotech products of the year. In 2004, the products included a nanotechnology-based footwarmer containing a nanoporous aerogel, golf clubs using "titanium fullerene materials" in the head of their new driver, nanosilver-containing wound dressings with improved antibacterial effectiveness, an additive from BASF that improves the hydrophobicity of building materials and silica nanofillers in dental adhesives.[75]

In 2005, the follow-up report on the top 10 nanotech products led with Apple's iPod Nano as the number one product, but whether this product represents nanotechnology or is simply marketing hype was the question to consider.[76] The report concludes that the answer to both parts of the question is a resounding "Yes" in that the nano connection certainly attracted attention, but inside the product there are memory chips that are produced with precision less than 100 nm.

Given the range of cosmetics using nanoparticulate metal oxides primarily for UV protection it is interesting to note a cosmetics product containing fullerene in the list. In this case the fullerene is claimed to have antioxidant properties. Carbon nanotubes have been used as a reinforcing component in a new baseball bat. Silver nanoparticles feature again, this time in socks where enhanced bonding of the 19 nm silver particles to the polyester fibres is claimed to provide enhanced and longer-lasting antimicrobial and antifungal performance. A novel chewing gum having chocolate flavour, which is apparently difficult to achieve, has been produced using "nanoscale crystals" of unknown chemistry to enhance the compatibility of the cocoa butter with the polymers that are used to give the gum elasticity. So-called self-cleaning windows and paint surfaces are also included in the top 10. These are based on photoactive titanium dioxide with the windows gaining a further benefit when it rains, with the hydrophilic film created being washed off leaving a clear surface.

6.2 Woodrow Wilson

The Project on Emerging Nanotechnologies is an initiative by the Woodrow Wilson Center and the Pew Charitable Trusts in 2005. As part of this initiative the Project has launched The Nanotechnology Consumer Products Inventory.

This is the first online inventory of nanotechnology consumer products and contains some 212 manufacturer-identified nanoproducts. The inventory can be accessed online at www.nanoproject.org/consumerproducts and at least some of the products and applications described here are listed in this inventory. Others include reinforced tennis, squash and badminton racquets containing carbon nanotubes, cultured diamonds, non dirtying clothes, razors, automotive and other coatings, cosmetics, microprocessors, golf balls, silver colloids and photographic paper.

7 Future Opportunities

7.1 Nanoroadmap

The Nanoroadmap Project has been co-funded by the European Commission as part of their Framework 6 initiative and has produced a document in late 2005 as a report in four parts, *i.e*. Nanoporous Materials, Nanoparticles/Nanocomposites, Dendrimers and Thin Film and Coating.[77] The reader is directed to this report for the detail. Nanoparticle applications are considered under the headings power/energy, healthcare/medical, engineering, consumer goods, environmental and electronics, and potential applications are considered through to 2015. Some of these are based on technologies discussed here and include solar cells, fuel cells and automotive catalysts, fungicides, nanoclay/polymer composites, inks, chemical sensors, photocatalysts, optoelectronic devices, biolabelling and detection and new dental composites.

Nanostructures including thin films and coatings are also considered and applications there reflect at least some of the opportunities for nanoparticles in the future such as solar cells and self-cleaning surfaces, but also include superconductivity applications and thin-film transistors.

7.2 SusChem

The European Technology Platform (ETP) for Sustainable Chemistry (SusChem) was initiated jointly by Cefic and EuroBio in 2004 to help foster and focus European research in chemistry, chemical engineering and industrial biotechnology. The SusChem vision foresees a sustainable European chemical industry with enhanced global competitiveness, providing solutions to critical demands and powered by a world-leading innovative drive. SusChem unites a wide variety of stakeholders around this common vision. This process is designed to elicit programme areas that should be funded by the EU as part of its Framework 7 initiative to begin in 2007. Thus needs have been identified and potential programmes are sought to align with those needs.

A recently published document represents the current Strategic Research Agenda of SusChem and the Materials Technology section focuses on six areas of need for the future.[78] These are Energy, ICT, Healthcare, Quality of Life, Transportation and Citizen Protection. Underpinning the product development to address the needs for the future in each of these six areas are new materials with nanoscience seen as the basis for development of the new materials. In general the potential of nanoscience lies in the ability to provide new applications in the fields of catalysis, higher reactivity in synthesis, better biocompatibility and enhanced electrical and mechanical properties. Industry was encouraged to think of nanotechnology as an innovation toolkit that can lead to new materials at the nanoscale which spawn new products and ideas for the market and assist in creating new markets.

7.3 Lux Research Market Forecast

Lux Research is a leading research and advisory firm specialising in the business and economic impact of nanotechnology and related emerging nanotechnologies. They have recently produced a report forecasting that the value of products incorporating nanotechnology will total $2.6 trillion in 2014.[79] They define nanotechnology as a set of tools and processes for manipulating matter that can be applied to virtually any manufactured goods. They consider that the value of basic nanomaterials will be of the order of $13 billion in 2014.

Through 2009, electronics and IT applications are considered likely to dominate as microprocessors and memory chips built using new nanoscale processes come to the market. They envisage that nanotechnology will become commonplace from 2010 onwards as commercial breakthroughs over the next four years are converted into products. Healthcare and life sciences applications will most likely become significant during this period as nano-enabled pharmaceuticals and medical devices come to the market.

8 Nanomaterials Companies

For those interested in seeking out the wide range of companies that are currently producing nanoparticles of many different types, the reader is advised to check the following website: www.nanovip.com/enventory.Materials/index.php. There a brief overview of each of the companies listed is accompanied in many cases by a detailed profile of the company.

9 Future

If the forecast from Lux Research is to be believed, then there will be further very significant growth of the use of nanomaterials and a reliance on nanotechnology over the next ten years and beyond. The major companies that have been active in nanomaterials for many years continue to invest heavily in new products, and in Japan and China there has been a very significant growth in investment in this whole area that will inevitably lead to products that may not even have been considered today. Given the range of products and applications described here and this investment for the future, future applications of nanotechnology will be many and will excite the scientist and consumer alike.

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