INTRODUCTION

A unique aspect of nanotechnology is the vastly increased ratio of surface area to volume present in many nanoscale materials which opens new possibilities in surface-based science, such as catalysis. A number of physical phenomena become noticeably pronounced as the size of the system decreases. These include statistical mechanical effects, as well as quantum mechanical effects, for example, the "quantum size effect" where the electronic properties of solids are altered with great reductions in particle size. This effect does not come into play by going from macro to micro dimensions. However, it becomes dominant when the nanometer size range is reached. Additionally, a number of physical properties change when compared to macroscopic systems. One example is the increase in surface area to volume of materials. Novel mechanical properties of nanomaterials is the subject of nanomechanics research. Their catalytic activity reveals novel properties in the interaction with biomaterials.

Nanotechnology can be thought of as extensions of traditional disciplines towards the explicit consideration of these properties. Additionally, traditional disciplines can be reinterpreted as specific applications of nanotechnology. This dynamic reciprocation of ideas and concepts contributes to the modern understanding of the field. Nanotechnology is the synthesis and application of ideas from science and engineering towards the understanding and production of novel materials and devices. These products generally make copious use of physical properties associated with small scales.

Materials reduced to the nanoscale can suddenly show very different properties compared to what they exhibit on a macroscale, enabling unique applications. For instance, opaque substances become transparent (copper); inert materials become catalysts (platinum); stable materials turn combustible (aluminum); solids turn into liquids at room temperature (gold); insulators become conductors (silicon). Materials such as gold, which is chemically inert at normal scales, can serve as a potent chemical catalyst at nanoscales. Much of the fascination with nanotechnology stems from these unique quantum and surface phenomena that matter exhibits at the nanoscale. Nanosize powder particles (a few nanometres in diameter, also called nanoparticles) are potentially important in ceramics, powder metallurgy, the achievement of uniform nanoporosity and similar applications.

NANOTECHNOLOGY

The word nanotechnology comes from the term nanometer which is just a scale of measurement. Nanotechnology is an advanced technology, which deals with the synthesis of nanoparticles, processing of the nanomaterials and their applications. Normally, if the particle sizes are in the 1–100 nm ranges, they are generally called nanoparticles or materials.

In materials world, particularly in ceramics, the trend is always to prepare finer powder for the ultimate processing and better sintering to achieve dense materials with dense fine-grained microstructure of the particulates with better and useful properties for various applications. More is the fineness, more is the surface area, which increases the reactivity of the materials.

Nano-phase materials undergo phase transformation at temperatures below those of the bulk materials. This is a characteristic which has numerous applications to material processing.

Buckminsterfullerene C_{60}, also known as the buckyball, is the simplest of the carbon structures known as fullerenes. Members of the fullerene family are a major subject of research falling under the nanotechnology umbrella.

Nanotechnology refers broadly to a field of applied science and technology whose unifying theme is the control of matter on the atomic and molecular scale, normally 1 to 100 nanometers, and the fabrication of devices with critical dimensions that lie within that size range.

It is a highly multidisciplinary field, drawing from fields such as applied physics, materials science, interface and colloid science, device physics, supramolecular chemistry (which refers to the area of chemistry that focuses on the non-covalent bonding interactions of molecules), self-replicating machines and robotics, chemical engineering, mechanical engineering, biological engineering, and electrical engineering. Much speculation exists as to what may result from these lines of research. Nanotechnology can be seen as an extension of existing sciences into the nanoscale, or as a recasting of existing sciences using a newer, more modern term.

Examples of nanotechnology in modern use are the manufacture of polymers based on molecular structure, and the design of computer chip layouts based on surface science. Despite the great promise of numerous nanotechnologies such as quantum dots and nanotubes, real commercial applications have mainly used the advantages of colloidal nanoparticles in bulk form, such as suntan lotion, cosmetics, protective coatings, drug delivery, and stain resistant clothing.

The fullerenes are a class of allotropes of carbon which conceptually are graphene sheets rolled into tubes or spheres. These include the carbon nanotubes which are of interest due to both their mechanical strength and their electrical properties.

For the past decade, the chemical and physical properties of fullerenes have been a hot topic in the field of research and development, and are likely to continue to be for a long time. In 2003, fullerenes were under study for potential medicinal use: binding specific antibiotics to the structure to target resistant bacteria and even target certain cancer cells such as melanoma. In the field of nanotechnology, heat resistance and superconductivity are some of the more heavily studied properties.

NANOPARTICLES

Nanoparticles or nanocrystals made of metals, semiconductors, or oxides are of interest for their mechanical, electrical, magnetic, optical, chemical and other properties. Nanoparticles have been used as quantum dots and as chemical catalysts.

Nanoparticles are of great scientific interest as they are effectively a bridge between bulk materials and atomic or molecular structures. A bulk material should have constant physical properties regardless of its size, but at the nano-scale this is often not the case. Size-dependent properties are observed such as quantum confinement in semiconductor particles, surface plasmon resonance in some metal particles and superparamagnetism in magnetic materials.

Nanoparticles exhibit a number of special properties relative to bulk material. For example, the bending of bulk copper (wire, ribbon, etc.) occurs with movement of copper atoms/clusters at about the 50 nm scale. Copper nanoparticles smaller than 50 nm are considered super hard materials that do not exhibit the same malleability and ductility as bulk copper. The change in properties is not always desirable. Ferroelectric materials smaller than 10 nm can switch their magnetisation direction using room temperature thermal energy, thus making them useless for memory storage. Suspensions of nanoparticles are possible because the interaction of the particle surface with the solvent is strong enough to overcome differences in density, which usually result in a material either sinking or floating in a liquid. Nanoparticles often have unexpected visible properties because they are small enough to confine their electrons and produce quantum effects. For example, gold nanoparticles appear deep red to black in solution.

Nanoparticles have a very high surface area to volume ratio. This provides a tremendous driving force for diffusion, especially at elevated temperatures. Sintering can take place at lower temperatures, over shorter time scales than for larger particles. This theoretically does not affect the density of the final product, though flow difficulties and the tendency of nanoparticles to agglomerate complicates matters. The surface effects of nanoparticles also reduces the incipient melting temperature.

SAFETY OF MANUFACTURED NANOMATERIALS

Nanomaterials behave differently than other similarly-sized particles. It is therefore necessary to develop specialized approaches to testing and monitoring their effects on human health and on the environment.

While nanomaterials and nanotechnologies are expected to yield numerous health and health care advances, such as more targeted methods of delivering drugs, new cancer therapies, and methods of early detection of diseases, they also may have unwanted effects. Increased toxicity is the main concern associated with manufactured nanoparticles.

When materials are made into nanoparticles, their reactivity increases. These more reactive particles can enter the body through the skin, lungs, or digestive tract, and may cause inflammation and damage to the lungs as well as other organs. However, the particles must be absorbed in sufficient quantities in order to pose health risks.

NANOMATERIALS

To understand how nanomaterials will be used, we need a clear look at not only how they are formed but also their various configurations. It all starts with carbon. Carbon atoms are all over the place. We find them in millions of molecules. These molecules have a wide range of properties, meaning they popup in every possible form—from gases such as propane to solids such as diamonds, the hardest material found in nature. There are three significant reasons for the wide range of properties of materials containing carbon:

1. Carbon atoms can bond together many types of atoms, using a process called covalent bonding.
2. Each carbon atom can form these covalent bonds with four other atoms at a time.
3. There is no other element in the periodic table that bonds as strongly to itself and in as many ways as the carbon atom.

BUCKYBALLS AND NANOTUBES

Buckyballs and carbon nanotubes are two types of molecules composed of carbon atoms that have many applications in nanotechnology.

A buckyball (short for buckminsterfullerene) is a molecule containing 60 carbon atoms. Each carbon atom is bonded to three adjacent carbon atoms. However the carbon atoms in a buckyball form a teensy-weensy sphere that is about 1 nanometer in diameter as shown in Fig. 14.1 while many of the atoms in buckyballs are connected together in hexagons, some of the atoms are connected in pentagons. The pentagons allow the sheet of carbon atoms to curve into the shape of sphere. Every buckyball surface contains 12 pentagons and 20 hexagons. Researchers determined that 60 carbon atoms form a single stable molecule only if they are arranged in 20 hexagons and 12 pentagons that are linked to form a sphere. This type of spherical carbon molecule has been found in various other sizes. The fullerene family of molecules is often identified by the letter C followed by the number of carbon atoms, for example C_{60}, C_{70}, C_{80}.

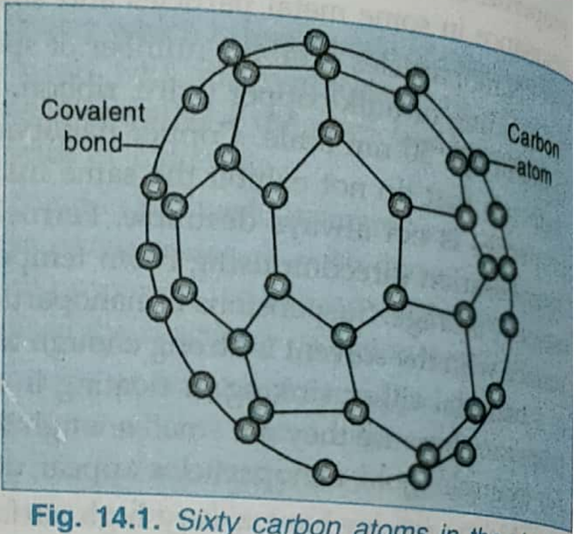

Fig. 14.1. *Sixty carbon atoms in the shape of a sphere—a buckyball.*

CREATING BUCKYBALLS

Richard smalley produced buckyballs by vaporizing carbon with a laser and allowing atoms to condense. However, this device could produce a very small number of buckyballs.

Buckyballs could be produced in larger quantities by vaporizing carbon by placing two carbon electrodes close together and generating an electric arc between them in a reaction chamber filled with a low pressure of helium or neon.

Combustion synthesis produces big enough quantities of buckyballs at a low enough cost– for use in commercial applications. This method mixes a hydrocarbon with oxygen and burns the hydrocarbon at a low pressure.

USES OF BUCKYBALLS

Buckyballs as Antioxidants

The medical field is one place that buckyballs appear to have promising future Buckyballs act as antioxidants, counteracting free radicals in the human body.

A free radical is a molecule or atom that has an unpaired electron which makes it very reactive. An antioxidant is a molecule that can supply an electron and neutralize a free radical. The human body normally has a balance of free radicals and antioxidants; a certain level of free radicals is actually necessary to make our immune system to work. However, the level of antioxidants found naturally in our body decreases as we get older. The resulting high level of free radicals roaming around our system could be the cause of certain diseases.

Buckyballs can act as antioxidants to neutralize free radicals. When a buckyball meets a free radical, the unpaired electron in the free radical pairs up with one of the buckyballs delocalized electrons, forming a covalent bond between the free radical and a carbon atom in the buckyball.

Antioxidants have to be soluble in water to be truely useful as medical applications. Buckyballs are not naturally soluble in water. To make buckyballs soluble, a water soluble molecule is added to them. This is done by covalently bonding an atom in the water soluble molecule to one of the carbon atoms in the buckyball. Bonding an atom or molecule to a buckyball to change the properties of the buckyball is called functionalization.

Drug Delivery with Buckyballs

Another use of buckyballs is to deliver drugs directly to infected regions of the body. It turns out that such regions have pH levels that differ from the pH of the healthy bits. Researchers hope to functionalize a buckyball by bonding it to molecules that react to changes in pH.

CARBON NANOTUBES

Carbon nanotubes are actually cylinders of carbon atoms that are formed at the sametime that the buckyballs are formed. Like buckyballs, these cylinders (called carbon nanotubes) are each a lattice of carbon atoms - with each atóm covalently bonded to three other carbon atoms. Carbon nanotubes are basically buckyballs, but the end never closes into a sphere when they are formed. Instead of forming the shape of a sphere, the lattice forms the shape of a cylinder as shown in Fig. 14.2.

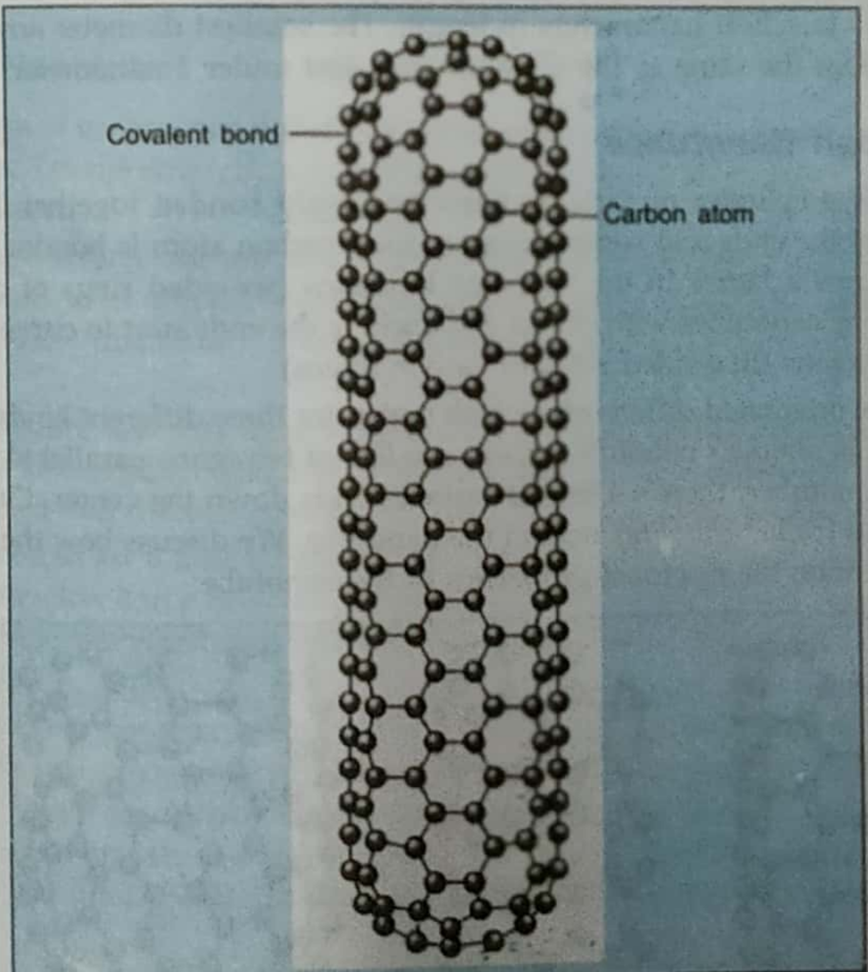

Fig. 14.2. *Illustration of a carbon nanotube.*

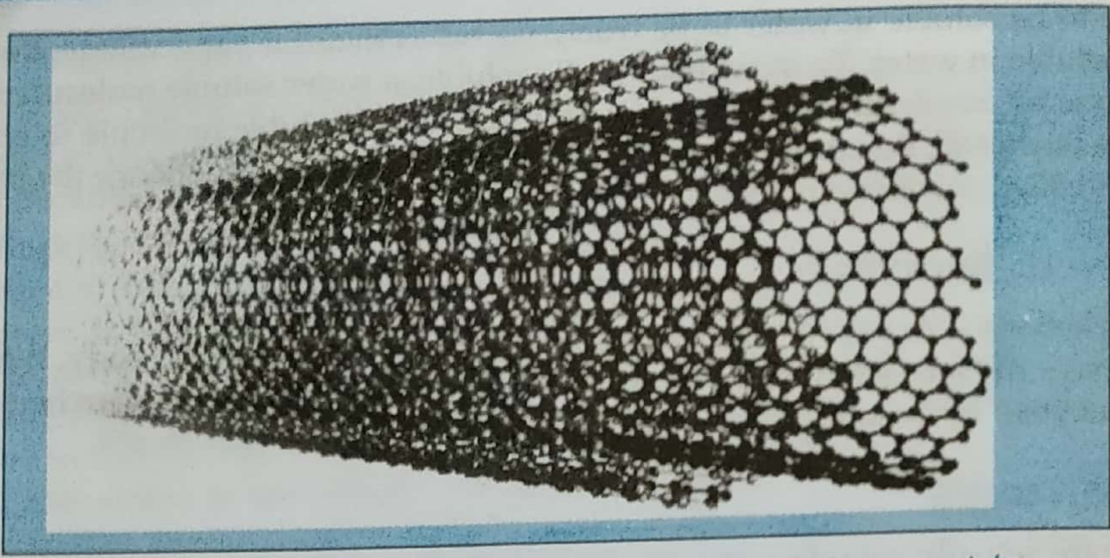

Fig. 14.3. *Illustration of a multiple-walled carbon nanotube*

Nanotubes come in a couple of varieties. They can either be single walled carbon nanotubes (SWNT) or mutli-walled carbon nanotubes (MWNT). An SWNT is just a single cylinder, whereas an MWNT consists of multiple concentric nanotube cylinders as shown in Fig. 14.3. Most of the researches are focused on developing uses for single walled nanotubes.

The length and diameter of SWNT, varies, but a typical SWNT would be about 1 nanometer in diameter and a two hundred nanometers in length. The smallest diameter anybody has ever seen in SWNT's is about the same as the C_{60} buckyball, just under 1 nanometer.

Structure of Carbon Nanotubes

A carbon nanotube is a cylinder of carbon atoms covalently bonded together. Some of these cylinders are closed at the ends and some are open. Each carbon atom is bonded to three other carbon atoms and forms a lattice in the shape of hexagons (six-sided rings of carbon atoms), except near the end. For nanotubes with closed ends, where the ends start to curve to form a cap, the lattice forms pentagons (five-sided rings of carbon atoms).

The lattice can be orientated differently, which makes for three different kinds of nanotubes. As shown in Fig. 14.4 in *armchair* nanotubes, there is a line of hexagons parallel to the axis of the nanotube. In *zigzag* nanotubes, there's a line of carbon bonds down the center. *Chiral* nanotubes exhibit a twist or spiral (called *chirality*) around the nanotube. We discuss how the orientation of the lattice helps determine the electrical properties of the nanotube.

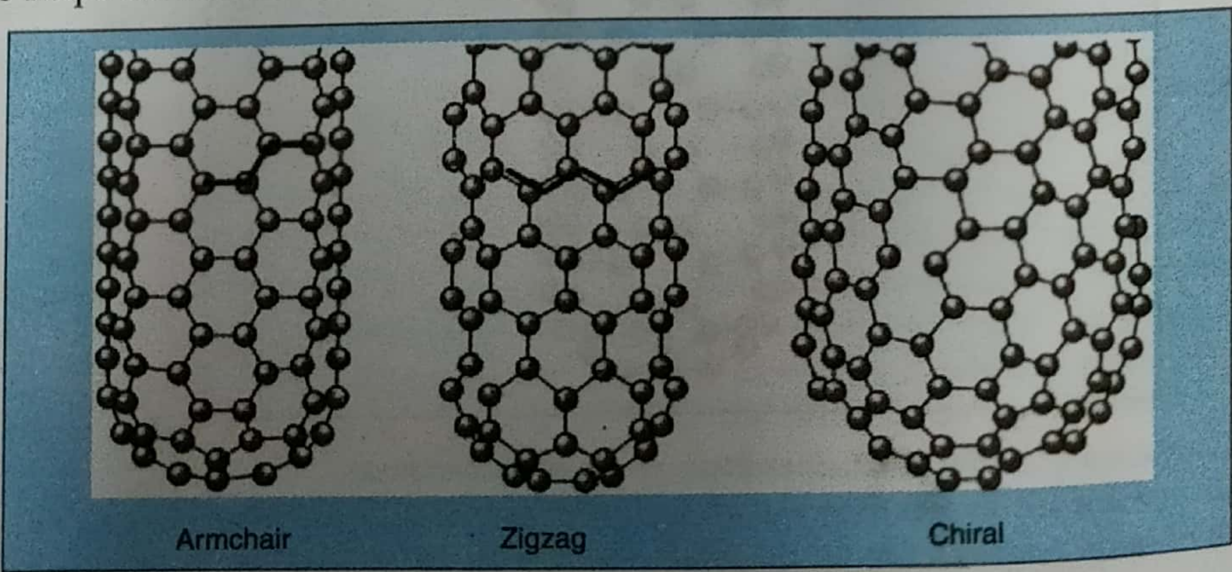

Fig. 14.4. *Armchair, zigzag, and chiral nanotubes*

Producing Nanotubes

Three methods have been developed to produce carbon nanotubes in bulk quantities and at a lower cost.

1. **High-pressure carbon monoxide deposition (Hi PCO):** This method involves a heated chamber through which carbon monoxide gas and small clusters of iron atoms flow. When carbon monoxide molecules land on the iron clusters, the iron acts as a catalyst and helps a carbon monoxide molecule break up into a carbon atom and an oxygen atom. The carbon atom bonds with other carbon atoms to start the nanotube lattice, the oxygen atom joins with another carbon monoxide molecule to form carbondioxide gas which then floats off into the air.
2. **Chemical-vapor deposition (CVD):** In this method, a hydrocarbon (methane gas) flows into a heated chamber containing a substrate coated with a catalysts such as iron particles. The temperature in the chamber is high enough to break the bonds between the carbon atoms and hydrogen atoms in the methane molecules—resulting in carbon atoms with no hydrogen atoms attached. Those carbon atoms attach to the catalyst particles where they bond to other carbon atoms - forming a nanotube.
3. **Plasma process to produce nanotubes:** Methane gas used as the source of carbon, is passed through a plasma tourch. One of the initial claims is that this process is 25 times more efficient at producing nanotubes than the other two methods.

Properties of Nanotubes

The tensile strength of carbon nanotubes is approximately 100 times greater than that of steel of the same diameter. Tensile strength is a measure of the amount of force an object can withstand without tearing apart.

Nanotubes are strong but are also elastic. This means it takes a lot of force to bend a nanotube but it comes to its original shape when released. Young's modulus for carbon nanotubes, a measurement of how much force it takes to bend a material, is about 5 times higher than for steel.

Carbon nanotubes are also light weight with a density about one quarter that of steel. Carbon nanotubes also conduct heat and cold really well (they have high thermal conductivity). It has been predicted that thermal conductivity of nanotube is more than 10 times that of silver.

Carbon nanotubes are a little bit sticky. The electron clouds on the surface of each nanotube provide a mild attractive force between the nanotubes. This attraction is called van der Waal's force. This involves forces between nonpolar molecules. A carbon nanotube just happens to be a nonpolar molecule.

Carbon nanotubes conduct electricity better than metals. When electrons travel through metal there is some resistance to their movement. This resistance happens when electrons bump into metal atoms. When an electron travels through a carbon nanotube, its travelling under the rules of quantum mechanicals and so it behaves like a wave travelling down a smooth channel with no atoms to bump into. This quantum movement of an electron within nanotubes is called ballistic transport.

Uses of Nanotubes

Researchers are developing a way to form wires out of nanotubes. In a wire made of carbon nanotubes, less energy would be wasted as heat. It would also weigh less than conventional wire, while being able to conduct huge doses of current. The impact of such wire on energy technologies could be big.

Carbon nanotubes can also be used to detect chemical vapors. The way this would work would be that molecules that make up a chemical vapor would land on the nanotube and attach themselves to it by forming covalent bonds with carbon atoms in it. This would change the electrical conductivity of nanotube by decreasing or increasing, the number of delocalized electrons available for conduction.

Sensors using carbon nanotubes have been shown to detect chemical vapors with concentration on the parts per billion (ppb). In order to ensure that sensors are detecting the right chemical, nanotubes are coated with a polymer that allows certain molecules to reach the nanotube and blocks others.

There is also the possibility of storing hydrogen in nanotubes. Imagine a material that can absorb hydrogen like sponge absorb water. This material could be used as a fuel tank for hydrogen fuel cell-powered cars.

Researchers are looking at using nanotubes as well as other nanosize materials, to make transistors memory cells and wires. Currently narrowest device or wire used in computer chips is 90 nanometers. With nanotubes and nanowires we could produce transistors and memory devices about a nanometer wide. Wire made from nanotubes is not the same as nanowires. Nanowire is a nanoscopic solid wire made of various metals—too small to be seen by human eye. Wire made from nanotubes is like a woven fiber made from many nanotubes and that could be as big as standard electrical cord.

APPLICATION

Cancer

The small size of nanoparticles endows them with properties that can be very useful in oncology, particularly in imaging. Quantum dots (nanoparticles with quantum confinement properties, such as size-tunable light emission), when used in conjunction with MRI (magnetic resonance imaging), can produce exceptional images of tumor sites. These nanoparticles are much brighter than organic dyes and only need one light source for excitation. This means that the use of fluorescent quantum dots could produce a higher contrast image and at a lower cost than today's organic dyes. Another nanoproperty, high surface area to volume ratio, allows many functional groups to be attached to a nanoparticle, which can seek out and bind to certain tumor cells. Additionally, the small size of nanoparticles (10 to 100 nanometers), allows them to preferentially accumulate at tumor sites (because tumors lack an effective lymphatic drainage system).

Other

Although there has been much hype about the potential applications of nanotechnology, most current commercialized applications are limited to the use of "first generation" passive nanomaterials. These include titanium dioxide nanoparticles in sunscreen, cosmetics and some food products; silver nanoparticles in food packaging, clothing, disinfectants and household appliances; zinc oxide nanoparticles in sunscreens and cosmetics, surface coatings, paints and outdoor furniture varnishes; and cerium oxide nanoparticles as a fuel catalyst.

However, further applications which require actual manipulation or arrangement of nanoscale components await further research. Though technologies currently branded with the term 'nano' are sometimes little related to and fall far short of the most ambitious and transformative technological goals of the sort in molecular manufacturing proposals, the term still connotes such ideas. Thus there may be a danger that a "nano bubble" will form, or is forming already, from the use of the term by scientists and entrepreneurs to garner funding, regardless of interest in the transformative possibilities of more ambitious and far-sighted work.

Another large and beneficial outcome of nanotechnology is the production of potable water through the means of nanofiltration. Where much of the developing world lacks access to reliable water sources, nanotechnology may alleviate these issues upon further testing as have been performed in countries, such as South Africa. It is important that solute levels in water sources are maintained and reached to provide necessary nutrients to people. And in turn, further testing would be pertinent so as to measure for any signs of nanotoxicology and any negative affects to any and all biological creatures.

IMPLICATIONS

Due to the far-ranging claims that have been made about potential applications of nanotechnology, a number of concerns have been raised about what effects these will have on our society if realized, and what action if any is appropriate to mitigate these risks.

One area of concern is the effect that industrial-scale manufacturing and use of nanomaterials would have on human health and the environment, as suggested by nanotoxicology research. Groups such as the Center for Responsible Nanotechnology have advocated that nanotechnology should be specially regulated by governments for these reasons. Others counter that overregulation would stifle scientific research and the development of innovations which could greatly benefit mankind.

Longer-term concerns center on the implications that new technologies will have for society at large, and whether these could possibly lead to either a post scarcity economy, or alternatively exacerbate the wealth gap between developed and developing nations.